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7. GI/ITG KuVS Fachgespräch

Drahtlose Sensornetze

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am 25. und 26. September 2008 in Berlin

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Inhalt

Vorwort

In dem vorliegenden Tagungsband sind die Beiträge des Fachgesprächs Drahtlose Sensornetze 2008 zusammengefasst. Ziel dieses Fachgesprächs ist es, Wissenschaftlerinnen und Wissenschaftler aus diesem Gebiet die Möglichkeit zu einem informellen Austausch zu geben – wobei immer auch Teilnehmer aus der Industrieforschung willkommen sind, die auch in diesem Jahr wieder teilnehmen.

Das Fachgespräch ist eine betont informelle Veranstaltung der GI/ITG-Fachgruppe „Kommunikation und Verteilte Systeme“ (www.kuvs.de). Es ist ausdrücklich keine weitere Konferenz mit ihrem großen Overhead und der Anforderung, fertige und möglichst „wasserdichte“ Ergebnisse zu präsentieren, sondern es dient auch ganz explizit dazu, mit Neueinsteigern auf der Suche nach ihrem Thema zu diskutieren und herauszufinden, wo die Herausforderungen an die zukünftige Forschung überhaupt liegen.

Das Fachgespräch Drahtlose Sensornetze 2008 findet in Berlin statt, in den Räumen der Freien Universität Berlin, aber in Kooperation mit der ScatterWeb GmbH. Auch dies ein Novum, es zeigt, dass das Fachgespräch doch deutlich mehr als nur ein nettes Beisammensein unter einem Motto ist.

Für die Organisation des Rahmens und der Abendveranstaltung gebührt Dank den beiden Mitgliedern im Organisationskomitee, Kirsten Terfloth und Georg Wittenburg, aber auch Stefanie Bahe, welche die redaktionelle Betreuung des Tagungsbands übernommen hat, vielen anderen Mitgliedern der AG Technische Informatik der FU Berlin und natürlich auch ihrem Leiter, Prof. Jochen Schiller.

Berlin, im September 2008 Hartmut Ritter

Bug Hunting in Sensor Network Applications

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ABSTRACT

Testing sensor network applications is an essential and a difficult task. Due to their distributed and faulty nature, severe resource constraints, unobservable interactions, and limited human interaction, sensor networks, make monitoring and debugging of applications strenuous and more challenging.

In this paper we present KleeNet — a Klee based platform independent bug hunting tool for sensor network applications before deployment — which can automatically test applications for all possible inputs, and hence, ensures memory safety for TinyOS based applications. Upon finding a bug, KleeNet generates a concrete test case with real input values identifying a specific error path in a program. Additionally, we show that KleeNet integrates well into TinyOS application development life cycle with minimum manual effort, making it easy for developers to test their applications.

1. INTRODUCTION

As with any software, testing of wireless sensor network applications is an essential part of development life cycle. The main goal of this engineering task remains the same: finding and fixing program bugs as early as possible.

Currently, sensor network application developers are confronted with a number of domain specific complications. The constrained memory and CPU resources on sensor nodes result in using low-level, type-unsafe languages without dynamic type checking and memory protection. Similarly, because the applications are highly data-flow oriented, the correct exception handling at full coverage is a challenging task. Moreover, due to highly distributed and faulty nature of sensor nodes, some of the program bugs are detected only after the software is deployed.

C language has been the main choice for developing sensor network applications. It provides great flexibility, expressiveness, and in particular, the required low resource footprint. However, the absence of dynamic type checking necessitates very careful programming because many sensor OS's do not support memory protection. We argue that, besides the particular sensor application semantic, the majority of bugs comes from general programming flaws such as memory out-of-bounds references, null pointer dereferences, or wrong type conversions. Especially, the widely used casting between pointers to structures may lead to well-hidden type errors. But in most cases, the given language features are simply misused by novice programmers.

Starting with *lint* [8] tool nearly three decades ago, there has been enormous effort spent on the error removal in C programs. Many techniques have been developed ranging from static code analysis, formal verification, to full state model checking. Numerous tools exist and are freely available to use [4, 5, 7, 15]. Hence, our first step was to employ them for testing sensor network software written in widely spread TinyOS platform [12]. We encountered the following problems due to which the available tools are mostly not used at all, and the developers fall back on manual code debugging techniques:

- Sensor network applications are tightly integrated with the whole operating system leading to time-consuming manual code modification in order to perform the actual testing.
- Most of the tools perform only static code analysis with limited support for C semantics. Since sensor network applications mainly process data from the environment, possible runtime errors might stay undetected.
- None of the tested tools can offer a push-button bug finding technology and the usage learning curve is mostly too steep for a typical developer.

We have discovered that recent research efforts in the area of C code checking are now targeting the usability and full automation as primary design goals [1, 2]. The philosophy is to detect only definite errors, but automatically, at full execution path coverage, and with minimum manual effort by employing symbolic checking techniques [9]. We think that these efforts could finally achieve the integration of sound testing tools into the application development process.

2. RELATED WORK

To the best of our knowledge, currently there are no frameworks for automatic bug detection in sensor network applications *before deployment* at bit-accurate C semantics. For bringing memory safe executions of applications at *runtime*, we only know of the related efforts [6, 10], where the sole representative with fined-grained memory safety at C level is Safe TinyOS.

Safe TinyOS adds dynamic memory checks during compilation which allows to catch unsafe pointer and array operations without corrupting the RAM. Overall, this results in

Features	Safe TOS	KleeNet
Automatic code instrumentation	−	+
Target platform independence	−	+
Assembly level bug detection	+	−
Off-line bug detection	−	+
All possible input values checked	−	+
Automatic test case generation	−	+
Runtime safety enforcement	+	−
No additional resource usage	−	+

Table 1: Comparison: Safe TinyOS and KleeNet

13% increase in the code size and 5.2% increase in CPU usage. As with any dynamic assertion checking, Safe TinyOS can detect program bugs only eventually after the software is deployed. Therefore, still many corner-case bugs circumvent this testing technique. KleeNet, on the other hand offers offline bug detection with automatic code instrumentation. In doing so, it doesn't consume any system resources and ensures memory safety by treating the inputs symbolically i.e. checks any program variable for its all possible input values. As the core engine of KleeNet interprets a virtual instruction set, it cannot detect hardware platform dependent assembly level bugs nor enforce runtime memory safety. Thus, KleeNet complements the beneficial features of Safe TinyOS allowing altogether even more rigorous application testing (see Table 1).

Overall, we make following contributions: First, we integrate an effective bug finding tool into the event-driven TinyOS programming model with usability as a primary goal. Second, we show that, apart from the general checks already available, Klee can easily be extended to incorporate further checks useful for testing sensor network applications. And third, we practically demonstrate that sound testing techniques can be used *throughout* the application development process with minimum manual effort.

3. SYSTEM OVERVIEW

In this section, we present an overview of our system. First, we introduce Klee, which we use for symbolically executing C applications. We continue by discussing how we automatically instrument source code without the help of application developers. We conclude this section by presenting our extension of Klee to enable struct type checking in sensor network applications.

3.1 Klee

Klee is a symbolic execution tool for C programs based on LLVM [11]. In contrast to common runtime testing where the program input is (manually) generated, Klee runs the code on symbolic input initially allowed to be "anything". The programmer only needs to specify which memory locations in his code are input-derived, e.g. an incoming network packet. During code execution, all paths and operations on symbolic variables are tracked. If a bug is detected, Klee automatically generates a test case with concrete values causing the bug. For example, consider a simple application code in listing 1 and the associated KleeNet output in listing 2.

At the current state of its implementation, Klee reports only memory reference and division by zero errors. It has been developed to be scalable and to support all sorts of unsafe type operations including pointer casts and pointer arithmetics.

```
...
call Timer1.startPeriodic(500);
...
int a[10];
unsigned i;
klee_make_symbolic_name(&i, sizeof(i), "i");

event void Timer1.fired()
{
    call Leds.led1Toggle();
    // here we violate memory safety
    // on the 11th signal of this event
    if (i < 11)
        a[i++] = 1;
}
...
```

Listing 1: Array index out of bounds bug

```
$ make kleenet test
KLEE: ERROR: memory error: out of bound pointer
$ make kleenet display
BlinkFailC$i: '10'
```

Listing 2: KleeNet detects the memory error and generates a concrete test case

3.2 Automatic Code Instrumentation

As discussed earlier, one of the major limitations associated with most software testing tools is the lack of user friendly interfaces. Most of the available tools are either not properly integrated into software development process, or they even require manual code modifications for testing the code.

One of our major design objectives is to provide an easy to use bug finding tool for sensor network applications which is strongly integrated in the software development life cycle. For this purpose, we use grammar based automatic code instrumentation. We extend ANTLR [13] based GNU C grammar to automatically insert symbolic annotations (i.e. to mark the memory locations to be checked by Klee) in the C source code. The user only needs to provide a high level configuration stating the variable names that has to be checked inside the code. However, providing a configuration to insert annotations in the code to perform additional checks is optional, as our solution performs some built-in checks to detect common bugs in sensor network applications. For example, struct type cast checking (discussed in section 3.3) and memory checks on received packet buffers.

3.3 Struct type checking

Type conversions in C using type casts is a very common practice, and, definitely not an error. But since type safety is not guaranteed, programmers can interpret each memory region to be of any type. Especially, the casts between pointers to different structure types make the code maintenance difficult [3, 14].

One of the main objective of sensor network applications is to collect and process data from the sensors. The received data is at first available only as an untyped bit stream. Afterwards the pointer to this data is casted to a known structure type based on particular bit fields. During code execution further casts on this memory location are executed. We have extended the functionality of Klee to check the struct type equality during casting operations. This check is optional, but nevertheless the warnings as shown in listing 4 are useful and facilitate program comprehension.

```
...
NewRoute* msg = (NewRoute*) payload;
// message processing
call Queue.enqueue(msg);
...
RouteUpdate* msg =
  (RouteUpdate*) call Queue.dequeue();
// further message processing
...
```

Listing 3: Casting between pointers to different structure types

```
$ make kleenet test struct
KLEE: WARNING: Struct types don't match
KLEE: %struct.NewRoute* -> %struct.RouteUpdate*
```

Listing 4: KleeNet warnings

4. INTEGRATION INTO TINYOS

We decided to integrate Klee into TinyOS by adding a virtual *KleeNet* platform based on the TinyOS *null* platform. This approach allows us to easily add different modules to a platform, that automatically marks sensor value input and incoming packets as symbolic.

Since TinyOS applications are event-driven, parts of the code are executed only eventually after particular events are fired. In order to cover all possible program control flow paths during testing, we have extended our virtual platform with an automatic event signaling mechanism. Once an application is booted, all implemented events are signaled and processed. Finally, after processing the last event TinyOS scheduler is stopped.

Figure 1 shows an overview of KleeNet's build process. First, a user can optionally specify in a configuration file which variables in his code should be marked as symbolic. For this purpose we parse the C-code after NesC compilation and insert calls to `klee_make_symbolic` function. Second, all incoming packet buffers are also marked symbolic automatically. Third, the instrumented code is then passed to Klee which builds the C-object file. Finally, Klee interprets this object file and terminates when no bug is detected. Otherwise a test case with real input values is automatically generated. Running this concrete test case with the unmodified version of the code will cause the deployed sensor network application follow the same path and hit the same bug.

Please note that, as we apply code instrumentation to C source-code, therefore, this process is neither bound to a certain hardware platform nor to TinyOS and NesC. Hence, our approach can easily be integrated into any other sensor network development platform and operating system.

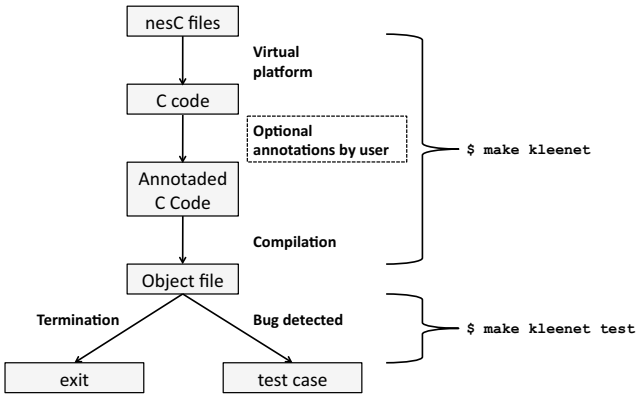

Figure 1: Integration of KleeNet into TinyOS platform

5. EVALUATION

We first checked the BlinkFail application from the TinyOS source repository. It is used to test if the Safe TinyOS toolchain installation is working properly. After marking the array index variable as symbolic we immediately detected the known out of bound pointer error.

```
...
int ratio;

event message_t* Receive.receive(message_t* bufPtr,
        void* payload, uint8_t len) {
  if(len!=sizeof(receive_fail_msg_t)){return bufPtr;}
  else{
    receive_fail_msg_t* rcm=
      (receive_fail_msg_t*)payload;
    // possible division by zero here,
    // depending on received message
    ratio = rcm->good / rcm->total;
    return bufPtr;
   }
}
...
```

Listing 5: Possible division by zero error

```
$ make kleenet test
KLEE: ERROR: divide by zero
```

Listing 6: KleeNet detects the div by zero error

In listing 5, we demonstrate the usability of KleeNet for finding possible bugs without annotating application source code any further. A received message is processed without sanitizing the received message which is a typical fault of students new to programming. KleeNet rapidly detects this mistake and warns the developer (Lst. 6).

Overall, after our initial tests, we have confirmed the following key benefits of KleeNet:

Usability: A programmer can test the code with minimum manual effort and without any previous knowledge about the checking tool.

Coverage: KleeNet covers all possible execution paths and checks all possible data values before application deployment.

Integration: KleeNet is invoked by simply adding an extra build flag enabling the *permanent* code checking during the application development process.

Efficiency: It is fast for everyday use.

6. CONCLUSION AND FUTURE WORK

In this paper, we presented our technique and prototype implementation for automatic testing of sensor network applications before deployment. It is important to fully test (taking all possible inputs into account) embedded applications, such as sensor networks, where the cost of occurring undetected errors after deployment could be fatal. We have demonstrated that it is possible to close the gap between the testing and development community by providing a user-friendly, automated bug finding tool which is strongly integrated in the system development life cycle. We gave an overview of our system design and of the preliminary evaluation results achieved.

Strenuous deployment requirements and resource constrained nature of sensor hardware, e.g. inadequate power supply and limited computational power, demand even more rigorous testing of sensor network applications. Incorporating further useful checks in Klee, such as runtime monitoring of long loops and computationally intensive tasks by adding time annotations, is future work. Similarly, verifying the distributed behavior of sensor network protocols — such as correct state transitions — remains to be addressed. Moreover, apart from TinyOS, we will apply our solution to other sensor network operating systems and development platforms.

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Over-the-Air Programming of Wireless Sensor Nodes

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ABSTRACT

Self-organizing Wireless Sensor Networks (WSNs) have gained much attention in recent research and industrial activities. Such WSNs enable measurements and information dissemination over large areas. A common node in a WSN is usually equipped with a microcontroller and a radio transceiver. A challenge in large networks is to keep the firmware of the nodes up to date. Once the network is deployed, it is hardly possible to access every node physically and to upload a new firmware. Therefore, this paper describes a technical solution for this problem using the radio transceiver for the upload procedure. The presented solution focuses on heterogeneous WSNs that contain several groups of nodes and where each group fulfills a different task.

Keywords

WSN, OTAP, Network Reprogramming, AirFlash.

1. INTRODUCTION

WSN technology is a promising candidate to provide monitoring over large areas and for long time periods. The network consists of a large number of small and inexpensive nodes. Each node contains a sensing-, computation- and communication unit. The WSN technology will be applied in dangerous areas where human beings have no access. Therefore, network maintenance or even firmware updates cannot be accomplished based on a physical access to the nodes and to the network. But the nodes can be accessed over a wireless connection. Thus, in order to update the firmware on a single node or in the entire network, a procedure based on wireless access will be used.

In this paper, an Over-the-Air-Programming (OTAP) technique will be used, which is based on the wireless access and transmission scheme. In this case an image of the node firmware will be transmitted via the wireless link. The image information will be stored inside the node. The node will then load this new image and execute it. These tasks already imply the main challenges in designing an OTAP application. The OTAP application presented in this paper is called AirFlash and is especially designed to maintain experimental networks. These are networks, which vary very much in size and are reprogrammed quite often. Additionally, such networks are mostly heterogeneous, i.e. the nodes inside the network run different applications.

The next section introduces the concept and features of the AirFlash application. This includes also a comparison with already known OTAP applications. After that, the used node platform is introduced and important implementation aspects are addressed.

2. AIRFLASH CONCEPT

In a lab environment a node is reprogrammed by connecting it via cable to a PC that directly uploads the new firmware into the node's memory.

Instead of a cable, AirFlash uses a wireless connection to the node to upload the firmware. This connection is established by a so called Gateway node, which is connected to the PC via a serial port. The Gateway then sends out the firmware image to an addressed node. The node will receive the image, load it into its memory and execute it. These are the main functions of the AirFlash application. These functions are controlled by a host software running on the PC. (see Figure 1).

Figure 1. Overview of AirFlash

For experimental WSNs a few more features are needed, which will be listed below:

1. Several images on a node
2. ID of image names and versions
3. Check AirFlash-compatibility of an image
4. Golden Image
5. Easy setup of nodes for AirFlash
6. Support heterogeneous networks
7. Background Execution

The first feature describes the storage of multiple firmware images on a node, where each image may contain a different application. This allows selecting which application to run by a simple wireless command. The second feature is necessary to trace the versions of images stored on a node. This is especially useful during development, when a node contains different versions of the same image. The features three and four avoid malfunctions while using AirFlash. Before a node is programmed with an image, AirFlash must check the image for compliance with the current AirFlash version, such that no incompatible images will be loaded. A Golden Image [1] is an application that resides in a predefined part of the node's memory and provides basic AirFlash functionality. If something goes wrong during wireless reprogramming, the Golden Image is automatically executed on the node. Thus, the node will stay accessible. The fifth feature is the one-step preparation of the node for AirFlash. This includes formatting of the nodes memory and installation of the Golden Image. Also, as feature six points out, an image should not be flooded to all nodes in the network. It should be possible to address nodes individually, so that various applications can be

present inside the WSN. And finally, since AirFlash is only used for reprogramming, while the node normally executes its usual measurement application, AirFlash should stay in the background if not used and claim as few resources as possible.

All these features named above are highly useful for running and maintaining a WSN. They are all included in the AirFlash application discussed in this paper. This feature combination is unique to the presented AirFlash and is not found in other OTAP implementations like Crossbow OTAP [2] or Deluge T2 [3]. For example neither Crossbow nor Deluge support feature three and five. Deluge additionally does not support feature six. And Crossbow has the disadvantage that it consists of proprietary code.

These are some of the reasons why AirFlash was created. The implementation of all the listed features into AirFlash will be introduced in the following sections.

3. PLATFORM

AirFlash is realized and tested for the IRIS node [4] as an example. This is a wireless node with a 2.4 GHz radio transceiver and an ATmega1281 microcontroller that contains 128kB of internal program memory (Flash) and 4kB of internal EEPROM [5]. Additionally, the IRIS node provides 512kB of external flash memory, which will be used to store multiple firmware images. AirFlash partitions the external memory into three so called slots of 120kB for firmware images and a fourth slot of 20kB for the Golden Image. The remaining 132kB can be used by data logging applications. For programming of the node the open-source framework TinyOS 2.x is used [6]. The choice for TinyOS was made, since it provides powerful high-level interfaces to access the node's hardware.

4. AIRFLASH IMPLEMENTATION

At the node's location, there are three basic tasks, which must be performed by AirFlash:

- Receive image via wireless transfer
- Store image in external slot
- Load image from slot to program memory

For the last task, the microcontroller's internal and external memory must be accessed. For this purpose, usually a so called bootloader application is used. This bootloader resides in a dedicated partition (8kB) of the program memory of the ATmega1281 and is able to access the remaining 120kB of memory and execute applications therein. The bootloader is also able to access the external memory (see Figure 2). Since the partition dedicated for the bootloader is too small to contain the complete AirFlash functionality, task one and two of the above list must be performed by an additional software module. Such an AirFlash module that controls the wireless image transfer must be included into the node's main application. There it stays in the background and is only activated when awoken by a wireless command. If the AirFlash module is woken up, it can receive an image via radio and store it into a memory slot. By another command, the module can afterwards invoke the bootloader that loads the image from the slot, overwrites the old application (including module) in the program memory and starts the new application contained inside the image (see Figure 2).

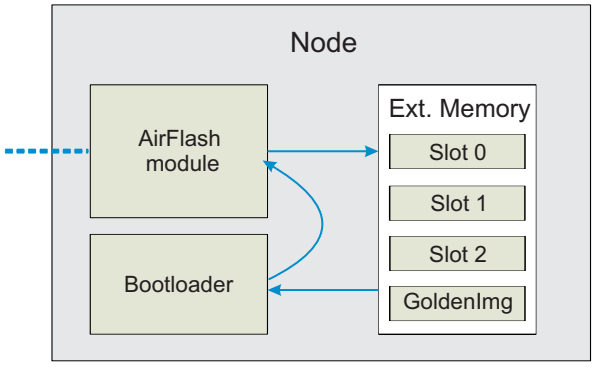

Figure 2. AirFlash components inside node

The implementation of the bootloader and the AirFlash module will be discussed in the following.

4.1 Bootloader

The bootloader has the main purpose to read an image from the external memory, process an error check and then write the image file into the upper part of the microcontroller's program memory.

The bootloader is invoked from the main application by setting the program counter to the bootloader's start address. The information from which slot to load an image from the external memory is passed to the bootloader via a command flag in the microcontroller's EEPROM. These flags are also used to signal the application if the image was successfully loaded. This information has to be passed through the EEPROM since the RAM of the microcontroller will be reinitialized when changing between main application and bootloader. Before starting to write the image into the internal program memory, the bootloader checks a flag in the EEPROM, if a previous write operation failed. Additionally, all CRCs of the image are verified. To this end, an image slot inside the external memory is organized in pages of 256 bytes where each page contains a 2 byte CRC. A slot also contains an additional 2 byte CRC, which is used to verify the CRCs of all pages. Thus, the integrity of an image can be guaranteed. If everything is correct, the selected image is written to the program memory. The bootloader then sets the status flags and resets command flags in the EEPROM and the program counter is set to the start address of the transferred image. The application inside the image is then executed.

If an error is detected in the image to load, the bootloader will not write it to the program memory and sets the respective error flags in the EEPROM. Then the control is given back to the main application.

There is still the possibility that an undetected error occurs while writing to the program memory. If this happens and the program counter is reset to the application, it will skip these illegal code parts and return to the bootloader. There, the exceptional invocation is detected, since the command flags are not properly set. Then the bootloader loads the Golden Image. The fourth slot in the external memory is reserved for this. The Golden Image contains the main AirFlash functionality and provides a fall-back solution, if something fails during reprogramming.

Still, it has to be discussed, how the image packets are received at the node and how they are written into the slots of the external memory. This is the task of the AirFlash module, which is described in the following.

4.2 AirFlash Module

The AirFlash module is implemented as a TinyOS component and therefore can be integrated into any TinyOS application. The integration of this module needs less then 6kB of additional program memory. It uses the node's radio to receive image data from the host PC and to transmit status information. The radio device is shared between the AirFlash module and the main TinyOS application. The main application possesses the master control over the radio. The request and release of the radio by AirFlash is signaled to the main application by events. The AirFlash module can assume three main states (see Figure 3): In order to save resources, the AirFlash module works in the background of the main application and is mostly in the sleep state.

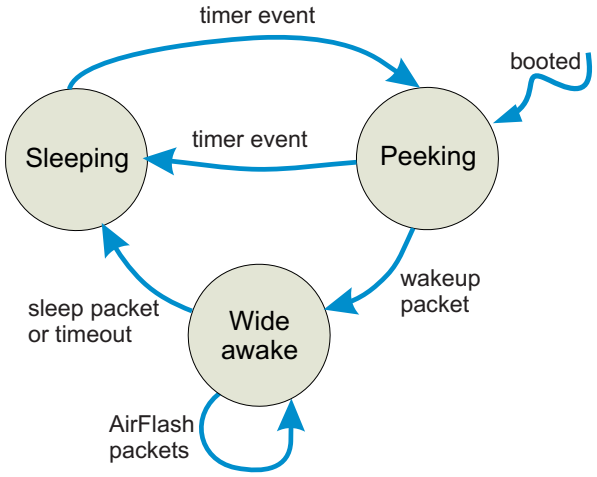

Figure 3. Sleep-wake cycle of AirFlash module

The module periodically enters the peeking state to listen for AirFlash-related packets. If nothing is received, the module goes to sleep after a while. If a so called enumeration packet is received, the module sends a status message back to the host. If a wakeup packet is received, the module steps into the "Wide awake" state. Inside this state it is ready to receive image data and to write it into the external memory. The module goes to sleep again if the host sends a sleep packet or if a timeout occurs.

In the following, the AirFlash protocol that handles the image transfer between host and node will be explained. First, the host transmits a wakeup packet, in order to put the node into the "Wide awake" state. The awoken node answers to the host. Then the transmission of the image file can start. This process is depicted in Figure 4. Since the image is up to 120kB in size, it must be fragmented. Each fragment contains 256 Bytes, which is also the size of a page in the memory. Each AirFlash packet (see Figure 5) contains 16 bytes of image data, a so called subfragment. Thus, to transmit one fragment of 256 bytes, 17 AirFlash packets are necessary, where the last packet contains a CRC checksum to verify the fragment.

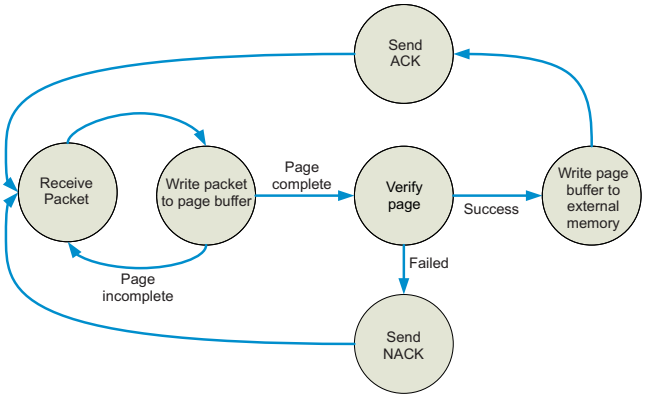

Figure 4. Image transfer from the node's perspective

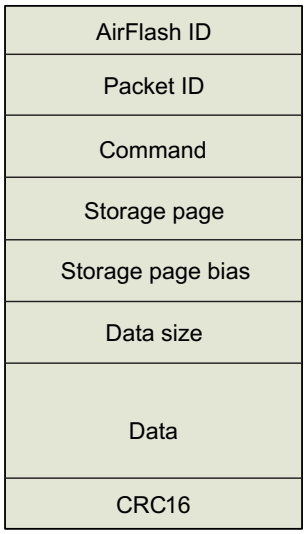

Figure 5. AirFlash packet format

All received subfragments are buffered in the RAM of the node. The CRC from the 17th packet is then used to verify the whole fragment. If verification fails, a NACK packet is sent to the host and the whole fragment is retransmitted. If verification is successful, the fragment is written to the respective page of the external memory and an ACK packet is sent to the host. This buffering of whole fragments of the image has two benefits: First, only a few ACKs are needed, which improves transfer speed. And second, most data corrections take place inside the RAM which extends the lifetime of the external memory.

When the image transfer is finished, the host can invoke the bootloader by sending a special command. This command also contains the number of the slot to be loaded. This information is stored in the EEPROM to preserve it for the bootloader.

After the description of the transfer process, a closer look at the AirFlash packet is taken:

The first field contains the AirFlash ID that distinguishes between up- and downlink of an AirFlash connection. Thus, other nodes with AirFlash connections are not disturbed by packets from other nodes.

The Packet ID is a simple counter, which is used for packet ordering. The Command field contains commands to the AirFlash module. The Storage page identifies the current page to write and the offset points to the actual subfragment of this page. It follows the data size and the data field, which can contain up to 16 bytes. The last field is a CRC checksum to detect packet errors.

Summarizing, the main features of the AirFlash module are listed below:

- Implementation as component, thus easy integration in TinyOS applications
- Runs as background process
- Writes received images to external memory
- Can jump to bootloader after successful image reception
- Provides AirFlash status for host

This leads us to the last part of the AirFlash application, namely the host software. This software runs on a PC and controls the image transfers to all nodes.

4.3 Host Software

The implementation of the host software can be divided into three main parts: The first part is an interface to the serial port of the PC that transmits packets to the radio Gateway. The second component processes the AirFlash protocol. The last component realizes a user interface. In this paper, only the basic functionality of this application is presented. For further details please refer to [7]. In order to transfer an image to a node, the image file is loaded from the PC's hard drive into the application. The integrity of the image is verified by checksums. It is also checked, if the image would fit into a slot. In a further check, the so called AirFlash signature (10 bytes) is read from the image file which is only present in AirFlash-capable images. If this signature is missing, the image will not be transferred, since the node will not be reachable via AirFlash after being reprogrammed with a non-AirFlash image. A second signature contains information about the AirFlash version the image was compiled with. This ensures that also the host software is compatible to the image. Additionally, the AirFlash version of the image must be the same as the version of the Golden Image on the node. The only possibility to upgrade the AirFlash version on the node is to exchange its Golden Image via AirFlash.

Before starting the image transfer, the necessary number of pages inside the node's memory is calculated as well as CRC checksums for each page. Then a command to erase the selected slot on the node is sent. After an ACK is received the image transfer starts. This process is analogous to the one described in chapter 4.2. If an error occurs that cannot be handled by the protocol, the process is aborted and must be restarted via the user interface.

5. PERFORMANCE

Finally, the transfer performance of AirFlash is evaluated. To test the upload speed, images of 16kB, 32kB, 64kB and 120kB were transferred multiple times to a node. The elapsed times were collected and averaged. If the radio channel is not frequently used by other applications, the transfer durations are almost constant for a fixed image size. In average, a transfer rate of 1,1 kB is achieved.

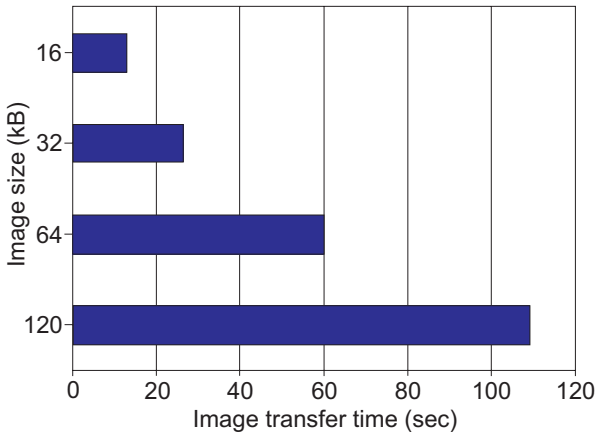

Figure 6. Transfer times for various image sizes

6. CONCLUSION

The discussed AirFlash application is well suited for experimental networks, since it allows the programming of heterogeneous networks. The use of a Golden Image makes the application very reliable if used in the field. An additional advantage is that the AirFlash module can be easily integrated into any TinyOS application. There, it stays in the background when not needed and thus keeps the main application running smoothly. Furthermore, additional features can be easily implemented, since the TinyOS part is completely open source. A feature that is going to be added is the capability to disseminate an image to a whole WSN at once.

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Deadlock-free Resource Arbitration for Sensor Nodes

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Abstract
Sensor network hardware designs consist of a central microcontroller, to which sensors and communication peripherals are connected. Resource arbitration and concurrency management must be implemented in software. Existing hardware arbitration mechanisms use explicit locking to protect against resource conflicts. Explicit locking may lead to deadlock, which must be avoided for long-term sensor network deployments. We present a power-saving resource arbitration architecture that is deadlock-free, portable, and resource-efficient. The architecture explicitly manages inter-device dependencies to know what devices to power down.

Categories and Subject Descriptors
D.4.7 [**Operating Systems**]: Organization and Design - Real-time systems and embedded systems

Keywords
hardware abstraction, resource arbitration, fault-tolerance, operating systems, wireless sensor networks

1 Introduction
Sensor network hardware designs consist of a central microcontroller to which sensors and communication peripherals, such as radio transceivers, are connected. Because peripherals are used both by applications and by the operating system, access to the peripherals must be controlled with an arbitration mechanism.

We present a power saving resource arbitration architecture and hardware abstraction layer (HAL) that provides portability of applications and drivers between different hardware platforms. Unlike existing resource arbitration architectures [3] [7], our architecture is deadlock-free by design.

As illustrated in Figure 1, introduction of a hardware abstraction layer (HAL) increases portability of operating system and application code through common, well-defined device interfaces. High-level device drivers can reuse low-level drivers and do not need to provide their own implementation. To further reduce operating system complexity, we integrate resource arbitration and power management into the HAL as part of the operating system. Most operating systems for wireless sensor nodes provide no hardware abstraction at all. Even those who do, require cooperative interaction of user applications, which need to take care of resource arbitration. This increases development overhead and vulnerability to uncooperative or erroneous applications.

Energy is a scarce resource on wireless devices. To reduce the energy consumption, every circuit and peripheral has to be powered off when they are not used. An optimal power saving strategy can only be implemented when the dependencies between devices are known; to switch off a shared bus, all devices that use the bus must be switched off first. Our architecture explicitly encodes device dependencies to determine when to switch off devices and shared busses.

2 A Deadlock-free Resource Arbitration Architecture
The purpose of our resource arbitration architecture is both to provide a hardware abstraction layer on top of the underlying hardware, and to make it possible to switch off hardware peripherals when they are not used to conserve energy. The operating system and its applications can run on different platforms using platform-specific implementations of the HAL.

Stackable hardware platforms like the ScatterWeb MSB-430 [1], that allow run-time addition of new boards and hardware devices, present a novel challenge for the resource arbitration architecture and HAL. The architecture must be able to dynamically adapt to new device drivers being added at run-time, potentially stored in on-board memory of the additional hardware. Our architecture supports this by using one-way dependencies and allows for run-time extension.

Our resource arbitration architecture is deadlock-free by design. Existing approaches to resource arbitration for sensor nodes [7] rely on explicit locking to determine when a peripheral should be switched off. Explicit locking can, however, lead to deadlock. In contrast, our architecture uses atomic

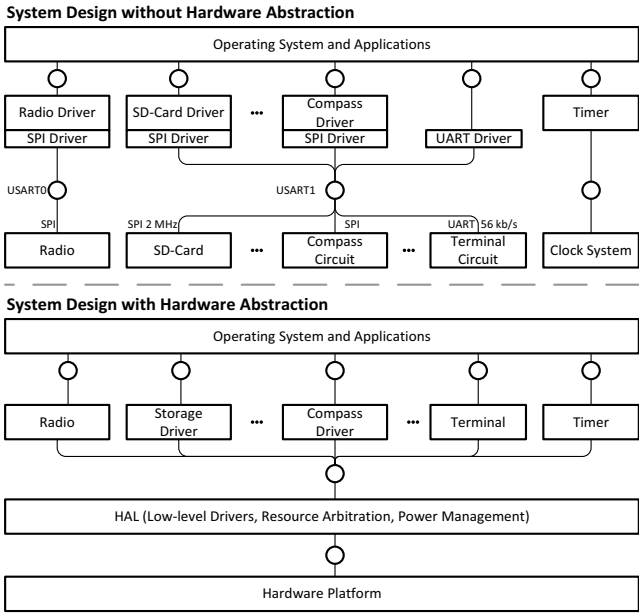

Figure 1. System architecture without and with hardware abstraction layer

operations to ensure deadlock-free operation. Every access to a hardware resource, such as reading a sensor or sending a packet over the radio, is atomic and cannot be interrupted by another operation.

The resource arbitration architecture does power management of all hardware peripherals by switching off peripherals when they are not used. The architecture has knowledge of when devices can be powered off because it keeps track of device dependencies and all access to peripherals goes through the resource arbitration architecture.

2.1 Hardware Devices versus Virtual Devices

Our hardware abstraction layer can implement device drivers for devices that do not have a hardware equivalent. This is useful for simulation or application development without access to the target hardware. We refer to all software devices that may or may not have their representation in hardware as virtual devices.

Virtual devices can be implemented using four techniques: emulation, virtualization, or layering. Emulation is used when no device of the desired class exists. The device functionality is either emulated with an existing hardware device or simulated in software. Virtualization is used to increase the number of devices of a specific type. A larger number can be provided by software multiplexing. Multiplexing is done transparently to the application. Layering is used when one or more hardware devices provide functionality that can be combined or extended to a more powerful high-level device.

2.1.1 Structural Design Elements

Hardware devices are shared resources that usually correspond to physical devices. Each hardware device is represented by a unique device entity in software. Different method implementations are used to access a hardware device. This is useful for devices that can handle more than one protocol. Each implementation can be used by multiple virtual devices to minimize platform specific code.

We use *device entities* to model inter-device dependencies and to provide per-device power control. Dependencies are modeled as trees. Each device entity keeps a list of devices it depends on. The owner marks device entities when the device entities are in use. Root entities are owned by virtual device entities and descendants are owned by their root.

We use *virtual device hubs* to implement device sharing. Different virtual devices may operate on the same shared device. Each virtual device may require a different configuration of the shared resource such as data rate or protocol. Virtual device hubs contain all state information necessary for multiplexing a shared device entity between an arbitrary number of virtual devices. A single virtual device can be selected as default and will be active, whenever no other device is active. The device selection is also used to forward interrupts to the right virtual device. A hub does not have a list of connected devices, which allows introducing new virtual devices dynamically at runtime.

A *virtual device entity* is an abstract software device. It is specialized by virtual device classes and is not intended to be used stand-alone. It extends the device entity. In this way the virtual device becomes a unique device entity itself, can reference its dependencies and provide its own power and configuration management. It can be connected to a virtual device hub, which then functions as a switching facility for all virtual devices operating on the same shared device.

A *virtual device class* represents a set of virtual device entities with a common interface. Usually a common functionality is also assumed. Typical classes found on embedded devices would be serial byte I/O (e.g. communication ports, peripheral connections) or memory (e.g. EEPROM, external flash card). Depending on the implementation, access to the underlying hardware can be shared, exclusive, virtualized or emulated.

To create a virtual device class the virtual device entity is extended to a virtual device class with its own class specific set of methods, callbacks, configuration and state. Callbacks will usually be triggered by interrupts and are directly forwarded to a consumer. State is dynamic information, while configuration is static. A virtual device class has a well known set of methods which is implemented platform dependently. From outside driver code, virtual devices are strictly to be accessed only by the API.

2.1.2 Using Virtual Devices

The structures we discussed so far can be kept slim to be implemented on a resource limited device without much impact on usability. However, defining an adequate interface specification for virtual device classes that fulfils our requirements, uses only a small amount of memory and still can be implemented in the C programming language is a challenge.

For each device class a minimum and maximum set of operations can be found. The minimum set contains all atomic operations which are absolutely necessary and found on every hardware device. The maximum set will also contain more

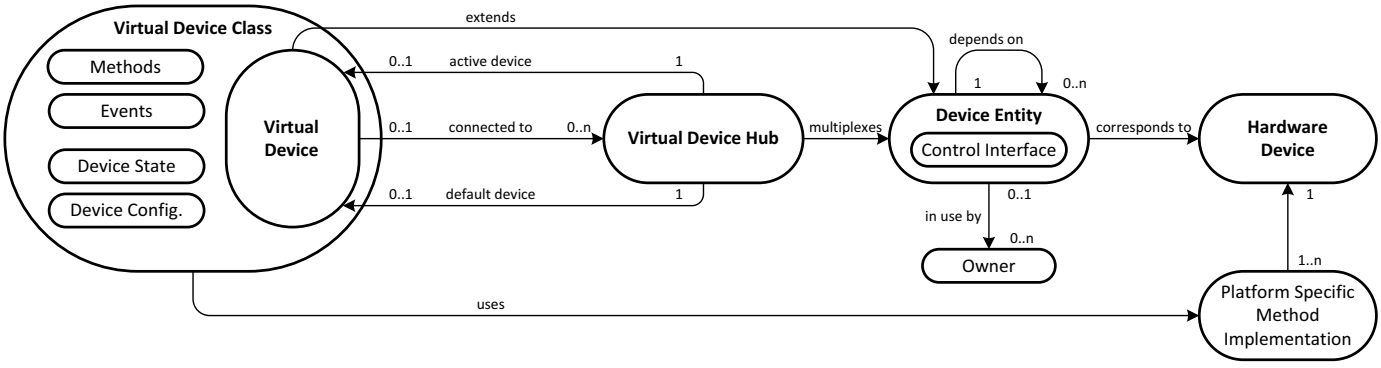

Figure 2. Simplified entity relationship diagram of the compositional architecture; multiplicity in Chen notation, omitted for 1:1 relations

high-level operations that may only be supported by some devices. Functionality not supported by the hardware needs to be emulated in software. A selection of these sets needs to be defined as methods of the virtual device. Implementations for all these functions need to be polymorphic and implemented for each hardware platform. Multiple virtual devices can use the same implementation. Upon this interface a second set, the API functions, which is independent of the hardware platform can be defined. This API can explicitly export virtual device methods or define high-level functionality upon these.

2.2 Behavioral Design

We have shown the structural composition of our hardware abstraction layer architecture. To bring these structures to life and enforce the requirements, implicitly given by the structural design, we introduce a central actor for device management. This actor takes part in all API calls to ensure proper device configuration and power management completely transparent to the application. Fault-tolerance is given by the fact that layers above the HAL do not need to care about switching power, configuring busses and devices, but can simply use them. Using them in an unstructured way will generate more overhead, but the HAL core will ensure that all virtual device operations are possible.

Based on our experience with numerous hardware platforms and several operating systems for wireless sensor networks we designed the HAL core for non-preemptive systems although the structural architecture can support these as well. Small energy efficient microcontrollers used in sensor networks do not provide virtual memory controllers for true preemption. The overhead necessary for fault-tolerant deadlock handling and device access scheduling can be saved. For energy efficiency operating systems are built event-based and driven by hardware interrupts. Data processing can be synchronized by means of a processing loop. Interrupt code is executable from lower-power modes and kept short to allow for other interrupts. A processing loop is running in full-power mode and switches the system to low-power when processing is done. In this programming model interrupts are used for notification (e.g. timers, completion of an operation) or for receiving data (serial connection) and to trigger actions which are executed outside the interrupt. Only for strict real-time requirements it may be necessary to perform actions inside of interrupts. Our architecture can handle all processing transparently when used from outside interrupts. Some extra care is needed, for special cases where interrupt code must access virtual devices.

2.2.1 Defining Atomic Operations

We implement the basic set of operations on a virtual device as atomic. Most of them directly access the underlying hardware. Depending on the specific hardware and its protocol, interrupting an atomic operation and reconfiguration of a shared resource may cause errors or leave the hardware device in an undefined state.

To ensure uninterrupted function each atomic operation has to indicate this condition to the system kernel. The system kernel needs to deactivate interrupt handling and preemptive scheduling accordingly. When developing the device driver the developer has to decide which measures are appropriate for each operation.

2.2.2 Managing the State of Virtual Devices

This management of virtual devices and the state of their associated device entities provides fault-tolerant resource arbitration and allows the application developer to use a complex hardware platform without caring about shared resource or individual power management. The HAL core functionality is completely hidden behind the virtual device API and thus transparent to the application.

We define the HAL core device management upon a state-machine graph (see Figure 3) of a virtual device with the following states and transitions.

- *Active*: the device is powered on, configured and ready to use.
- *Inactive*: The device is still powered on and configured. It is no longer in use and can be powered off or reactivated instantly.
- *Powered off*: The device hardware is powered off, if supported.

Before a virtual device method is accessed by the API, the device must be *activated*. If it is inactive, it can be *reactivated* immediately. Otherwise the HAL ensures that all requirements are met and activates the device. After the API operation has finished, the device is *deactivated*. It is left to the power management to *power down* inactive devices later. During both activation and power down the optional control functions of involved devices are called.

Activation of virtual devices from powered off state is a key operation. It is based on the fact that API operations are synchronous and no other API operations are to be invoked from within interrupts. For few operations it can be necessary to access virtual device methods from interrupts (e.g. timers). At this point it is up to the developer to manually activate another device and switch back to the previous one afterwards. Special care has to be applied to verify that any device, which might be preempted during an operation, is able to pause and continue.

2.2.3 Multiplexing Virtual Devices

Using hubs, virtual devices are multiplexed on a shared resource. Only a single virtual device can be selected at a hub at any time. This addition is necessary, when interrupt events need to be forwarded to the device which currently uses the associated device and to provide a mechanism for default configuration. Hubs also help to reduce overhead for device deactivation, because usually all virtual devices on a hub de-

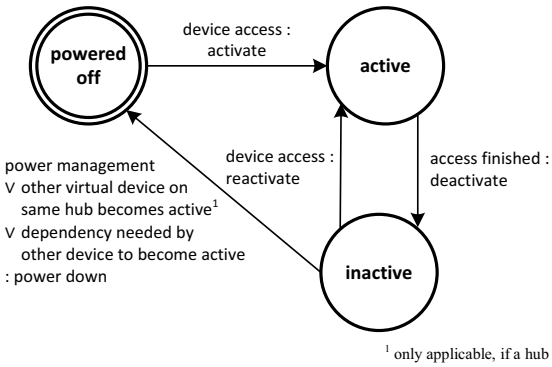

Figure 3. Virtual device State-Machine diagram

pend on the same device entities. Virtual devices may be used without hub.

Interrupt handlers shall use hubs to forward any event or data to the associated handler of the currently active device on the hub.

2.2.4 Power Management

We propose a fine grained multi-layer power management. Each layer uses the same power down API such that the virtual device state (compare Figure 3) remains consistent at all times.

- *Device Implementation*: Devices can deactivate themselves immediately after an operation transparent to the HAL core. This is especially reasonable for devices that consume a lot of power and complete in a single operation. Examples are AD converters or some temperature sensors.
- *Virtual Device Hub*: The HAL core powers down a virtual device if another device becomes activate on the same hub or a device has to be deactivated due to conflicting dependencies.
- *Operating System*: The system kernel powers down inactive devices, before the microcontroller is set to low-power mode.

Virtual devices that are selected as default on a hub will never be inactive and thus are not powered down by the kernel. For kernel power management the HAL needs to keep track of inactive devices. Depending on the microcontroller architecture it can be effective to disable all unused circuits to safe power.

3 Related Work

A fully grown operation system as Linux already provides broad set of services including device identification, enumeration and hot-plugging [3]. It needs to use explicit locking to support hardware multi-tasking and preemption and still has to be tolerant against faulty applications. Its hardware abstraction and driver model is too large to focus on the energy and efficiency aspects that are crucial to small embedded devices.

The TinyOS 2.0 operating system provides both resource arbitration and hardware abstraction suitable for sensor nodes [4] [5]. The combination of both roughly covers the same endpoints as our solution. Using the nesC language, two layers of device interfaces are defined [6]. A Hardware Presentation Layer (HPL) provides a device specific set of functions that encapsulates the immediate hardware access such as register names. On top of the HPL, a HAL is defined as a device specific abstraction. Finally, a high-level Hardware Interface Layer (HIL) provides a device independent interface. The abstraction level of the HIL corresponds to our virtual device methods abstraction.

While defining interfaces using nesC, which cannot be expressed in ANSI C helps structuring the API by adding semantics, it does not provide additional functionality. The additional coding layer with its compiler allows semantic checks during compilation that are not performed without. However, this so-called wiring is completely static. It is not possible to change callbacks or load new functionality at run-time, whereas we also support dynamic modification loading of new virtual devices at run-time.

The Integrated Concurrency and Energy Management (ICEM) proposed by Klues et al. in [7] shifts responsibility from the application to the core which reduces application complexity. In ICEM, shared resources are explicitly acquired and released by clients, which cooperatively use locked resources. For reliable operation a deadlock recovery strategy needs to be added to this approach. Power management is done by special devices which are selected as default devices. I/O request queues are used to optimize switching. Our architecture has a very small overhead between consecutive operations on the same shared (virtual) device, so we can do without the additional complexity and administrative overhead introduced by queuing requests. Completely transparent use of our HAL removes complexity from applications, while still being efficient.

4 Conclusions

We present a novel deadlock-free resource arbitration for sensor nodes that integrates configuration and power management completely transparent to the application. By designing a deadlock-free architecture, we remove a hazard for system failure. We are currently implementing this HAL on the Contiki operating system [8] for the ScatterWeb MSB-Av2 platform.

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An Approach towards Adaptive Payload Compression in Wireless Sensor Networks

[Extended Abstract]

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ABSTRACT

Most nodes in current wireless sensor networks are battery-powered and hence strongly constrained in their energy budget. While a variety of energy-efficient MAC protocols specifically tailored to sensor networks has been developed, the data rate limitation of the underlying hardware still represents a lower bound for the time required to transfer packets, and thus directly contributes to the energy requirement for transmissions. Further energy savings for given platforms can only be achieved by downsizing the packet, e.g. by means of in-network processing or data compression. In this paper, we present our approach towards an adaptive packet compression framework for sensor network applications that compresses sensor data with the locally optimal energy efficiency ratio.

1. INTRODUCTION

Wireless Sensor Network (*WSN*) deployments commonly comprise sensor nodes which distributedly take measurements, process the data, and subsequently forward the results to other nodes or external sinks [1]. Most existing platforms are powered by batteries, and hence inherently limited in their energy budgets. Once the entire battery charge has been consumed, the nodes stop operating and need to be replaced. Assuming a constant battery charge, there is a linear relation between power consumption and node lifetime, wherein the lifetime decreases with rising current consumption. Even solar powered nodes, such as the Trio platform [4], cannot completely tackle this challenge, as they rely on deployment in areas regularly exposed to direct sunlight.

It follows from the correlation between current consumption and node lifetime that maximizing a node's lifetime can only be achieved by minimizing its overall energy requirements. As available sensor node platforms commonly employ dedicated radio transceivers, sensors and peripherals, selectively disabling these components allows to measure the node's energy consumption in different configurations. Exemplarily, the current consumption figures for the widely used *tmote sky* platform have been taken from the datasheet [9] and were plotted against each other in Figure 1. It is clearly visible that the radio transceiver exhibits a power consumption that is about one order of magnitude higher than the corresponding values for the used microcontroller.

As the employed CC2420 radio transceiver does not provide low-power modes, a common solution to the problem of its comparably high energy consumption is limiting the time of its operation and putting it into sleep mode for the remaining period. Energy-efficient MAC protocols specifically tailored to sensor networks, such as [7, 11, 3, 6], make use of such schedules and thus allow for significant energy savings. We anticipate that combining such MAC protocols with supplementary extensions to minimize the number of packet transmissions and the corresponding payload sizes can lead to even higher savings and an extended node lifetime.

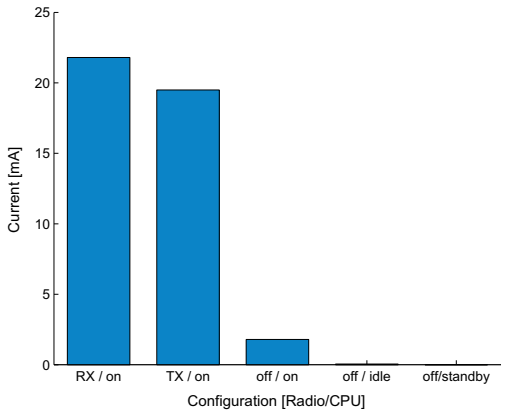

Figure 1: Power consumption of tmote sky nodes (numbers taken from [9])

This paper compares two methods to reduce traffic in sensor networks (see Section 2) and outlines their mode of operation. Special emphasis is put on their applicability in WSNs, as resource-constrained devices generally exhibit characteristics that differ from common desktop computers. Subsequently, we present our approach towards an adaptive packet compression framework for sensor network applications in Section 3. By compressing sensor data with the locally optimal energy efficiency ratio, energy can be preserved and thus the node lifetime extended. The description of our vision is followed by an analysis of related work. Finally, conclusions and an outlook will be presented in Section 4.

2. REDUCING TRAFFIC IN THE WSN

Although several methods of reducing the size or number of packets in WSNs exist, we introduce two common solutions in this section. Data aggregation tries to optimize the number of transmissions throughout the sensor network, while data compression strives for a local optimization of the amount of transmissions and their payload size.

2.1 Data Aggregation

If incoming packets and locally generated data are addressed to the same destination, combining these data sets into a single packet can effectively reduce the number of transmissions required [5]. For example, consider the linear topology depicted in Figure 2. The rightmost node (S) acts as a sink to sensor readings from the remaining nodes (A, B, C).

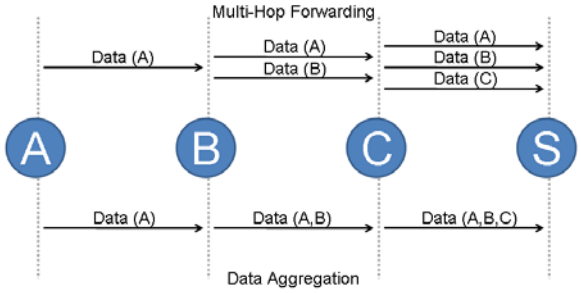

Figure 2: A linear sensor network topology

If only one-hop connectivity is given, a total of six transmissions are required to forward all measured data to the sink (depicted as the multi-hop forwarding case). Another downside of this issue is that node C, located next to the sink, must forward a higher count of packets than A or B and will thus most likely deplete its energy budget first.

Aggregating the incoming sensor data with local readings and forwarding these results to the sink can reduce the required number of transmissions from six to three in this basic scenario, hence achieving savings of 50% in the number of transmissions. This is indicated in the lower part of Figure 2, where only a single aggregated data packet is forwarded by each node.

Although node distributions in real deployments might considerably differ from this example, it should be remarked that the number of packets cannot increase by applying data aggregation.

2.2 Data Compression

Opposed to the previously described mechanisms of data aggregation, data compression targets to locally reduce the packet payload size by increasing the information density within a packet. In general, compression algorithms can be classified as either lossless or lossy. While some applications (such as software updates) require a bitwise correct transmission of data, intrinsic offsets in sensor hardware might reduce the achievable accuracy and thus provide an application area for lossy compression.

A variety of different approaches exist, and will be briefly introduced in Section 3.1. While generic compression algorithms often achieve good average compression ratios on various types of input data, algorithms adapted to specific applications often provide better performance, however at the cost of being limited to a narrow application area.

A common metric to evaluate the savings achieved by data compression is the energy cost per bit. Data compression is only feasible in terms of energy efficiency if the computational efforts to reduce the payload size by one bit are lower than the energy required for transmitting this additional bit. Depending on the used components, current sensor node platforms can perform 4.000 to 2.000.000 CPU cycles [8] instead of transmitting a single byte, while still maintaining a positive energy balance.

3. VISION

The vision of our research is to develop a *modular compression framework*, which can be deployed on nodes in a WSN. It comprises a set of different compression and decompression algorithms, which can be adaptively selected, and even combined to achieve additional savings. By compiling the algorithms into packages, different compression methods can be dynamically selected, exchanged and updated during runtime.

As many current sensor network applications follow predefined structure definitions in their output data formatting, different compression algorithms will typically produce differently sized output. The framework can either rely on application-defined preferences regarding the preferred compression engine, or compress an exemplary set of sensor data with its available compressors prior to selecting the algorithm with the highest energy efficiency. While this analysis might consume more energy before regular operation, it only needs to be performed once and will subsequently use the locally optimal compression algorithm.

Additionally, applications can also specify delay bounds for the compression of their packets. This mechanism ensures that lengthy algorithms are avoided when low latency transmissions are required. The framework is targeted to allow dynamic updates and modifications of the compressors and/or compressor parameters during runtime. This allows to exchange slow implementations of algorithms with optimized ones and tune parameters to fulfill the application's needs.

3.1 Related Work

A variety of data compression (and decompression, respectively) algorithms are well-known, although only few of them were specifically tailored to fit the needs of sensor networks. The emerging field of sensor networks however poses different constraints on resulting algorithms than common desktop computers do. Both processing power and available memory are tightly limited in sensor nodes, and their tight energy budget must additionally be considered. For these reasons, heavyweight compressors, such as partial predictive matching (PPM), or similar algorithms that require big dictionaries to be stored in RAM, cannot be run on the nodes. The even more sophisticated PAQ compressor quotes a minimum RAM consumption of 35 megabytes, although

values range up to 1712MB[1]. Barr and Asanović performed an analysis of several compression algorithms on a Compaq Personal Server handheld device in [2]. The platform featured a 233MHz CPU with 32 megabytes of RAM, rendering a direct mapping of the results to sensor node platforms equipped with low-power CPUs and a few kilobytes of RAM impossible.

Other authors have noticed this discrepancy between highly demanding but efficient compression algorithms and sensor node capabilites, and have thus designed algorithms specifically adapted to sensor networks, such as S-LZW [8] and SBZIP [10]. However, Tsiftes et al. have mainly regarded software updates that were compressed before deployment in [10]. Software updates are deployed less frequently than data packets, and even when a higher number of packets are required to transmit an application image, the necessity to compress packet payloads still persists.

4. CONCLUSION

Limited energy budgets of sensor network nodes make data compression a necessity when energy savings are required. However, it is very likely that there is no universally optimal compression algorithm for sensor network data. Instead, the need to adapt to the payload contents and dynamically choose the appropriate compression algorithm that yields best compression rates whilst preserving energy is arising to keep the energy consumption low and thus enhance node lifetime.

Compression algorithms implemented for desktop computers are generally not suited for sensor nodes, as they have high requirements towards CPU and memory size. However, a lot of existing approaches and concepts can be applied in sensors networks in modified forms. We propose the use of a modular compression framework that can be dynamically updated during runtime, while automatically detecting the locally optimal compression scheme for application-specific data.

When data from different sources is present in sensor nodes, generic compression algorithms will not always yield optimum results. In such application scenarios, we expect our compression framework to outperform solutions that rely on a single static compressor and thus achieve high energy savings.

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Connectivity-aware Neighborhood Management Protocol in Wireless Sensor Networks

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ABSTRACT

Neighborhood relations are changing over time in wireless sensor networks due to different hardware or environmental effects. These effects and memory limitations require a balanced neighborhood management to ensure agility, stability, symmetry, and connectivity. The proposed neighborhood management protocol Mahalle is optimized with regard to these four criteria. Agility and stability are achieved by ALE, a new adaptive link estimator.

1. INTRODUCTION

Many applications or algorithms for wireless sensor networks depend on a priori knowledge of neighborhood information. This encompasses information about neighborhood relations, i.e., which nodes can communicate with each other, and information about the link quality and reliability between those nodes. Self-stabilizing algorithms are a prominent example of algorithms that highly depend on neighborhood information [3]. The quality of neighborhood information can be described by four criteria: agility, stability, symmetry, and connectivity.

Before accounting a node as a neighbor the quality and reliability of the communication link between the nodes must be assessed. Many parameters of the environment, e.g., multipath effects, lead to a variation of these link properties over time. Due to the characteristics of the wireless channel, neighborhood relations are not known a priori and can only be gathered after the deployment when the network is in operation.

The local view upon the neighborhood of a node forms the topology of the network at the global scope. Variations in hardware, changes in the environment, or node failures lead to dynamic changes of the topology. Therefore, neighborhood relations are not fixed during the whole lifetime of the network. Frequent topology changes lead to a degradation of the algorithms or applications running on top of the formed topology. This aspect of the quality of a neighborhood protocol is captured by the concepts of agility and stability. Agility measures the speed of adapting to desirable events, such as failure of a node respectively a link or deployment of a new nodes. Stability is the ability to ignore transient failures.

Despite variation over time the neighborhood relations must be consistent between nodes. This requirement is expressed by the symmetry property. In particular, if node A is in the neighborhood of B, then node B must also be part of the neighborhood of node A. Otherwise the resulting topology is not useable in most cases. Reason for such an asymmetrical neighborhood relation is the existence of different link qualities caused by different noise levels due to fluctuations in hardware accuracy. Another reason lays in the memory restriction of sensor nodes. Memory restrictions are an important topic in regard to ensuring connectivity. If the density of the network is higher than the number of neighbors that a node can store, a simple neighborhood protocol can lead to disconnected network.

Therefore, a neighborhood management must ensure these four quality criteria. This paper presents Mahalle, a new neighbor management protocol based on adaptive link estimator. Mahalle optimizes the neighborhood relations according to agility, stability, symmetry, and connectivity.

2. RELATED WORK

Research has mainly focused on link estimation so far. Link quality can be assessed by the physical or logical properties. Currently available hardware is providing these physical properties with a high accuracy [2]. The link quality indicator (LQI) or received signal strength indicator (RSSI) are determined by the radio transceiver. However, the values of these metrics are highly hardware specific and must be calibrated for each hardware setting.

Packet reception rate (PRR) is a widely used logical property indicating the link reliability [5]. PRR is calculated from the rate of successfully received periodical broadcast packets. Periodic sending is done by discretizing time into rounds. In each round every node send its broadcast packet. Besides an identifier of the sender these packets contain a sequence number that is used to determine packet loss. In contrast to the physical properties, PRR is the link reliability experienced by applications, but comes at the extra effort of periodical broadcasts. The main drawback of all metrics representing the link behavior is that they exclusively describe a snapshot of the state involving only the recent past. They can not be used as a reliable estimate of the near future, which is needed to provide stability.

Taking the considerations above into account estimating the PRR by evaluating the packet reception rate of periodical broadcasts is the most appropriate way for a solution independent from hardware and environment. In [4] several link

estimation methods are evaluated and compared. The exponentially weighted moving average (EWMA) is one of the most appropriate methods related to fast response, mean error and memory usage. PRR is estimated by PRR $\leftarrow$ PRR $\cdot\, \alpha + (1 - \alpha)$ if a packet was successfully received, and PRR $\leftarrow$ PRR $\cdot\, \alpha$ if a packet loss occurs. A single or consecutive packet loss is detected by a timeout or on the basis of sequence numbers.

The behavior of EWMA is controlled by the parameter α ranging from 0 to 1. For $\alpha = 0.99$ EWMA is called stable and has a high accuracy with a low mean square error but with a high crossing time. The metric crossing time is defined by the time the estimator needs after detecting a new link to come up with a PRR value having an error of at most ϵ. In the following ϵ is assumed to be 0.05. For $\alpha = 0.915$ EWMA is called agile. This value leads to a much shorter crossing time and a smaller reaction time to link changes, but suffers from a high variation with a high mean square error. In [4] the stable EWMA is preferred to the agile in order to produce more stable link estimations over time. On top of such a link estimator in [5] a neighborhood protocol that is aware of asymmetrical links is described. The realization of this, especially with a neighbor table size of 40 entries, is not further explained.

TinyOS 2.x uses the Link Estimation Exchange Protocol (LEEP) to estimate link reliability and manage neighborhood information [1]. The Extra Expected number of Transmissions (EETX) is used as a link-quality metric. EETX is the expected value of a geometrically distribution with the probability PRR not counting the successful transmission. Therefore, EETX is defined as EETX = (1/PRR) − 1. The bidirectional EETX value is based on the product of inbound and outbound packet reception rate that are discrete recursively estimated. Inbound PRR is estimated as the reception rate at node A by receiving packets from node B. The reception rate from node A at node B is the outbound PRR of node A. The neighborhood table size is limited to 10 neighbors in TinyOS. To share the outbound quality information the complete neighborhood table must be exchanged. If the complete link information does not fit into one packet, a round-robin schedule is established. If the neighborhood table is full and a new node is detected, the neighbor with a low EETX value if existent is evicted. This policy is simple, but can lead to disconnected topologies in dense networks.

3. ADAPTIVE LINK ESTIMATOR

Since the proposed adaptive link reliability estimator can be used independently from the neighborhood management protocol, it is specified separately in this section. As described in [4] the PRR is estimated by observing the successful delivery of periodical broadcast packets. If application-specific packet rate is sufficient, the estimator information can be sent piggybacked in the data packets in order to reduce the periodical broadcast packets. EWMA in agile mode is a fast responding link estimator while in stable mode a low mean square error is achieved. The main goal of the adaptive link estimator proposed in this paper is to combine the strength of both modes.

The adaptive link estimator (ALE) uses EWMA as a basis. It has the capability to adjust the parameter α depending on the current estimated link quality. To improve the crossing time the initial PRR is set to the threshold value PRR_{bad}, whenever the first packet is received from a node. In this paper PRR_{bad} is set to 0.5. Additionally, when the PRR is below PRR_{bad} or a new link must be estimated the agile mode is used in order to estimate quickly the real link quality. ALE switches from agile into stable mode after 30 rounds in case that the PRR is greater than PRR_{bad} during this period for a more accurate estimation. This mechanism is called raising mechanism, which improves the crossing time of ALE compared to EWMA. In Figure 1 the crossing time of the different estimators is compared. The crossing time of the stable EWMA is very high compared to the agile mode. Due to the threshold PRR_{bad} and the raising mechanism the crossing time of ALE is even faster than the agile EWMA, especially for good links. Observe that the crossing time of ALE is smaller than 30 for all high values of PRR. This justifies the choice made above for the number of rounds to switch from the agile to stable mode.

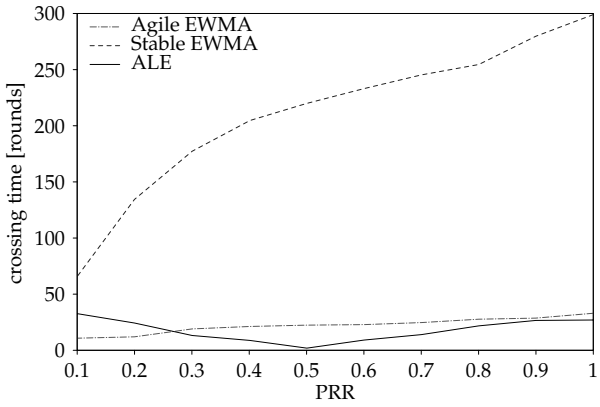
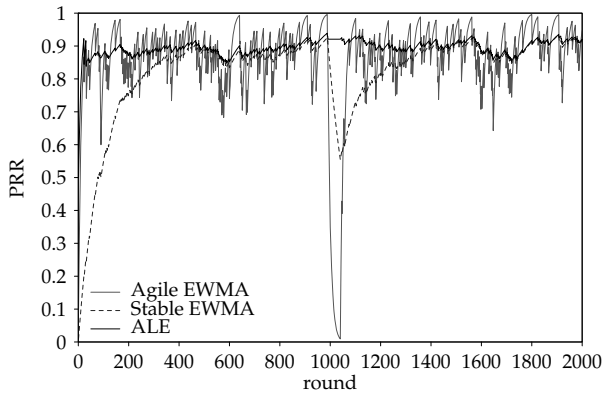


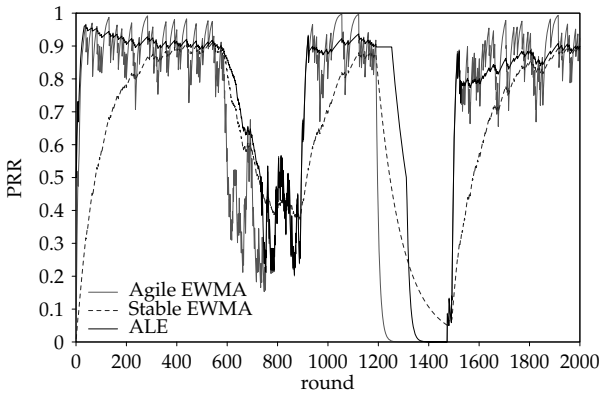
Figure 1: Crossing Time

Another mechanism that improves ALE is the so called dropping mechanism. With this mechanism a good link is trusted even if currently no communication is possible. Doing so the stability of the resulting network topology is increased. Whenever a good link, with PRR > PRR_{good} suffers from consecutive packet loss, the PRR is kept constant for 60 rounds. This number is a parameter of ALE and specifies the time that is conceded to a node to recover from a transient failure.

In Figure 2 the behavior of EWMA and ALE is compared over time. As shown in both figures, ALE outperforms the agile mode of EWMA in terms of mean square error. Figure 2 (a) shows a link with a fixed real PRR of 0.89 and a short link interruption of 50 packets in round 1000. This figure depicts the improvements during startup of ALE and especially during the short interruption compared to stable EWMA. Figure 2 (b) shows a link with a PRR of 0.89, which is dropping during round 600 and 900 to a PRR of 0.4 and is interrupted during round 1200 and 1500. Here the improvements introduced by the dropping mechanism are depicted. If the PRR is dropping below PRR_{bad} the estimation mode of ALE switches back to the agile mode in order to react faster on link changes.



(a) Real PRR = 0.89 and short message lost



(b) Variation of PRR over time

Figure 2: Comparison between EWMA and ALE

Normally a link is considered as a neighbor if the link quality is above a given threshold, here defined by PRR_{good} and is often set to 0.8. In contrast, a neighbor is disregarded if its quality drops below PRR_{good}. Doing so oscillation effects can occur. Therefore, a hysteresis is used to decrease oscillation effects as much as possible. Several simulations revealed that a range of ± 0.06 is a good choice between oscillation and size of the hysteresis. This leads to $\text{PRR}_{in} = 0.86$ and $\text{PRR}_{out} = 0.74$.

4. NEIGHBORHOOD MANAGEMENT

The neighborhood management protocol Mahalle uses the information about link qualities between nodes provided by the adaptive link estimator described in the previous section. ALE delivers only information about one direction of a communication link. If node A receives packets from node B it can calculate the PRR of node B at node A by using ALE. But this information is of no significance for the PRR of node A at node B. To ensure symmetry of the communication links between neighbors the PRR values of both directions of the link must be exchanged.

The PRR is normally exchanged between nearby nodes by using periodical broadcasts. In general, three different approaches exist. The simplest way is to put the estimated PRR values of all known nodes in each packet. The main drawback of this approach is the required size of such a packet. Due to the high bit error rate, the probability of packet loss is increased, which influences the PRR estimation. The second approach is to send only the PRR values that have changed lately. This decreases the amount of information sent in one packet, but the size varies. If a packet gets lost, the information must be resent even if the PRR is unchanged. The complexity of this approach is thereby increased. Another approach is to send only fractions of the PRR values in a round-robin schedule. Doing so, all packets are equally sized and every PRR value is broadcasted with a fixed schedule. Mahalle uses the last approach to exchange link information between neighboring nodes. One additional benefit of this is that additional information can be included into the broadcast packets, e.g., the node state needed by self-stabilizing algorithms [3].

The node table consists of entries to store the neighbor list and the preparation list. The neighbor list contains the nodes that are treated as neighbors. All other entries in the node table are used by the preparation list, where potential neighbors are stored in order to be able to estimate their link quality. At startup the whole node table is occupied by the preparation list. If a node is evicted from the node table, it is inserted into a blacklist for some time in order to prevent them to reenter immediately. The number of entries in the node table (N_t) and the ratio between the maximum number of entries in the neighbor list (N_n) and the preparation list (N_p) are compile-time parameters of Mahalle and correlate to the expected average network density.

In every round each node broadcasts a neighborhood packet. This packet contains the identifier of the node, a sequence number, and one entry of the node table. This information contains of the identifier of the neighbor and the estimated PRR. The round-robin schedule consists of N_t rounds, so that each entry of the node table is rebroadcasted in every N_t'th round. This information is used by the nodes that are receiving the packets.

Node table entries contain of the following information: a flag that indicates if the node is in the neighbor list, estimated inbound PRR, the received outbound PRR, the number of neighbors and overlapping neighbors, a flag indicating symmetry, and the age of the entry. Whenever a node receives a broadcast from a node that is contained in its node table, the corresponding entry is updated. Each packet is used to estimate the inbound PRR. When the packet contains the identifier of the receiving node, the outbound PRR in the packet is stored in the table. From all packets during N_t rounds the node can also identify the number of neighbors of the sending node and the number of overlapping neighbors, the nodes that are common for both.

When a packet is received by an unknown node and the node table has a free entry, the node is inserted into the preparation list (if the node table is full the packet is ignored). If the estimated PRR of the inserted node is above PRR_{in} the

node is a candidate to be placed into the neighbor list. If the node stays longer than 50 rounds in the preparation list without entering the neighbor list, the node is deleted from the preparation list and added to the blacklist. If a node is in the neighbor list and its PRR is below PRR_{out} the node is removed from the list and added to the blacklist.

If the neighbor list is full and in the preparation list a link with PRR > 0.86 exists an entry from the neighbor list must be evicted to provide space for the new potential neighbor. Therefore, a screening process exists to choose the most appropriate neighbor that is evicted from the neighbor list. The following rules are applied to the list containing all neighbors and the candidates from the preparation list. The rules are processed one-by-one until a single node remains. If the new potential neighbor is selected the neighbor list is kept unchanged and the node is inserted in the blacklist and removed from the preparation list.

Rule 1: Select asymmetry links

Rule 2: Select nodes with neighbors

Rule 3: Select highest overlapping

Rule 4: Select less unknown neighbors

Rule 5: Select lowest bidirectional PRR

Rule 6: Select newest neighbors

The first rule tries to evict nodes that are asymmetric from the list. If several nodes are found or none of the entries are asymmetrical, the next rule is applied. This rule protects those nodes from being removed that have no other neighbor. The next rule selects those nodes that have the highest number of overlapping neighbors, since those nodes are connected via one of the common neighbors with a high probability. If there are still several nodes having the same properties those nodes are selected, which provide the smallest number of unknown neighbors. Those nodes are not that important for insuring connectivity. These last two rules are protected by a hysteresis in order to prevent an oscillation effect. In rule 5 the nodes with the lowest bidirectional PRR are selected to be removed from the neighbor table. This PRR is the product of the estimated inbound and received outbound PRR. If still more than one node is selected the newest neighbors are preferred, since the older neighbors insure more stability. If still several nodes are in the list after applying the last rule, a node is picked randomly.

The ns-2 simulator is used for validating Mahalle. To compare the connectivity awareness of Mahalle a simple neighborhood management protocol is also implemented, which uses only the inbound and outbound PRR values provided by ALE. Additional the LEEP [1] protocol integrated in TinyOS 2.x (see Section 2) is ported to ns-2. Several different densities with 200 randomly placed nodes are investigated. For each density 50 different topologies are used. The used propagation model provides around 15% of asymmetrical links, which means that the inbound and outbound PRR differs more than 0.15. In Figure 3 the results for a density of 24 is shown. 180 Nodes are started at round 0 and 20 nodes where added after 1750 rounds. The connectivity

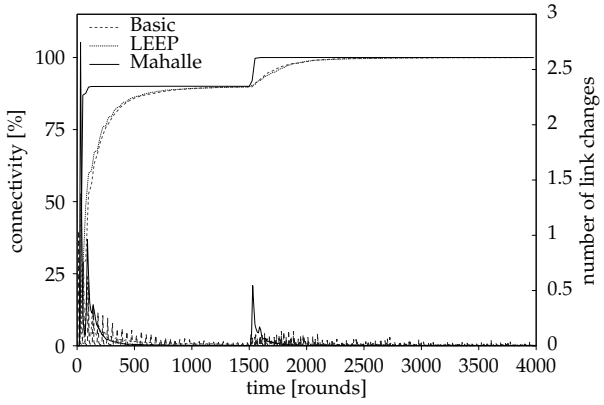


Figure 3: Comparison with network density 24

and the number of link changes are shown over time. Mahalle provides very fast neighborhood detection and reaches 100% connectivity. Due to the large density of 24 potential neighbors, LEEP and the basic protocol are providing only a slow convergence. Connectivity is not fully reached by these two approaches after adding nodes. The number of link changes during the stable phases is also decreased in Mahalle.

5. CONCLUSION

The presented neighborhood management protocol Mahalle and the underlying adaptive link estimator have shown good results in terms of agility, stability, symmetry, and stability. Mahalle outperforms in terms of stabilization speed. The next steps will be porting Mahalle to TinyOS and using it in a real long-term deployment at our campus.

6. ACKNOWLEDGEMENT

We would like to thank Ting-Fu Chen for his help in developing a preliminary version of Mahalle.

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Challenges in Short-term Wireless Link Quality Estimation

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Abstract

Identifying reliable low-power wireless links for packet forwarding in sensor networks is a challenging task. Currently, link estimators mainly focus on identifying high-quality stable links, leaving out a potentially large set of intermediate quality links capable of enhancing routing progress in a multihop network.

In this paper we present our ongoing work on short-term link estimation that captures link dynamics at high resolution in time. A short-term link quality is calculated based on the recent transmission characteristics of a link. This short-term quality of a link, combined with its long term reliability enables to determine if an intermediate quality link is temporarily available for transmission. Consequently adapting the neighbor table of a node and offering more forwarding choices to routing protocols.

1 Introduction

Instability in low-power wireless sensor networks (WSN) connectivity has so far been regarded as a difficult problem that existing routing algorithms try their utmost to avoid. In doing so, they forego a large class of potentially valuable communication links. An understanding of the patterns underlying the seemingly irregular variations of the wireless channel would enable algorithms to make use of this previously disregarded class of links.

To achieve better connectivity and reliable packet communication, today's link estimators restrict communications only to the neighbors with constantly high-quality links. These high quality links are identified based on the long term success rate of a link, typically collected over a time frame on the order of minutes. However, this approach has certain pitfalls. First, neighbors with intermittent connectivity might reach farther into the network. Their use would therefore reduce the number of hops, reduce energy usage in the network, and increase its lifetime. Second, in a sparse network with a low density of nodes, a node might have no high-quality neighbor in its communication range, requiring a mechanism to deal with unstable connectivity.

In this paper we present our on going work on short-term link estimation (STLE) [2] that takes fine-grained link dynamics - in the order of milliseconds - into account and increases the prediction quality for successful packet transmissions, especially, for highly dynamic links. STLE integrates into routing protocols by adapting neighbor tables to accurately reflect the current situation of a dynamic link. Overall, short-term link estimation has three key contributions: (1) to predict the probability of successful packet transmission of any link type by taking short-term dynamics into account, (2) to suggest links of low to intermediate quality for routing when they have become temporarily reliable, and (3) to integrate easily with today's long-term link estimators and routing protocols.

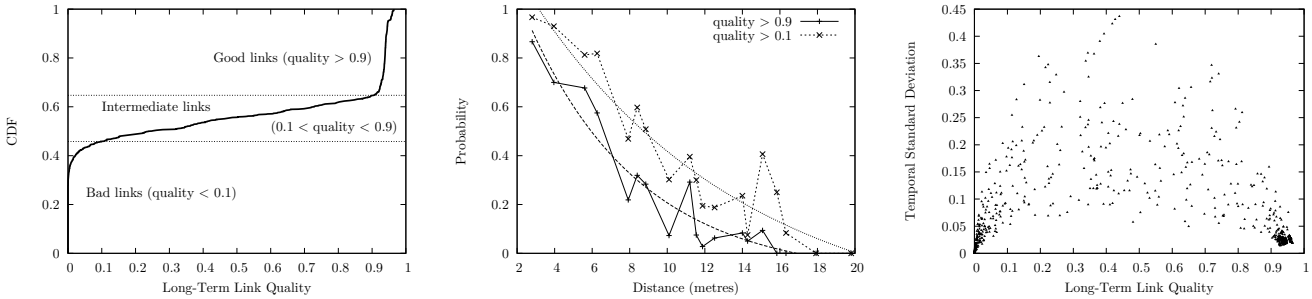
2 Related Work

The identification of reliable links in WSN has received much attention in the recent years. However, to the best of our knowledge, there is no thorough analysis of short-term dynamics in link quality. This paper aims to fill this gap by quantifying their extent and characteristics.

While investigating several approaches for online link estimation, Woo et al. [20] identified window mean estimator with an exponentially weighted moving average (WMEWMA) to be an optimal choice to aggregate packet reception rate as an indicator of link quality. Four-bit link estimation [6] extends this WMEWMA estimator into a hybrid link estimator that accumulates information from all layers of the sensor node networking stack. However, estimation techniques based on WMEWMA performs poorly on medium quality links. These links often offer the highest routing progress [3] suggesting the need for more precise estimation methods for medium quality links.

The assumption underlying the majority of existing link estimation concepts is that packet losses inside one measurement period occur independently of each other (*i. e.*, they follow a Bernoulli distribution). This assumption has been challenged before in research [4, 14]. The analysis of our data in Section 4 supports the hypothesis that the assumption of independent packet losses is not appropriate at the fine-grained time-scales dealt with in this paper.

In addition to online link estimators, there has been significant research in link modelling and link measurements for WSN [1,13,15–17,21–23]. For example, Koksal et al. [9] develop metrics to model long-term link quality and short-term link dynamics. Additionally, Cerpa et al. [3] provide statistical models of radio links in WSN, including short-term and long-term temporal characteristics.In contrast to these approaches, STLE does not aim to provide link models, but to identify phases of reliable or unreliable connectivity at runtime.



(a) Empirical distribution of long-term link quality in our testbed. Intermediate quality links comprise roughly one third of all useful links.

(b) Probability of finding a high-quality or medium-to-high-quality neighbor depending on physical distance in our testbed.

(c) Temporal variation of link quality. Each point represents a (directional) node pair.

Figure 1. Low-power radio links in sensor networks exhibit inevitable fluctuations in their quality.

Approaches such as Solicitation-based forwarding (SOFA [10]) remove the need for long-term link estimation and test link availability by sending a short hand-shake packet as a probe before sending any data packets. However, our evaluation of STLE in Section 4 shows that a successful hand-shake should not be taken as a success guarantee for subsequent data transmissions and indicate a need for more sophisticated models.

3 Short-term Link Estimation

In this section we introduce short-term link estimation in detail, putting a special focus on its integration into long-term link estimators and routing protocols. We present our approaches on the identification of temporarily available and unavailable links and evaluate these in Section 4. Our interest in short-term link estimation is motivated by two key observations indicated by research [3,13,21] and our own measurements: (1) Links of intermediate quality amount to about half the number of high-quality stable links (see Figure 1(a)) and (2) this percentage grows with the physical distance (see Figure 1(b)).

Although links of intermediate quality offer further choices for routing and often promise long distance connectivity, Figure 1(c) shows that this class of links is subject to large and frequent temporal variations. Their dynamic connectivity poses a special challenge to any link estimator. Long-term link estimators are not designed to identify short-term link dynamics. As a result, they adapt slowly to changing link conditions, limiting their use to the identification of long-term stable links.

3.1 Deriving a Short-term Link Estimator

Commonly, links in a wireless network can be classified into three categories: good links that are reliable in the long term; intermediate, unreliable links often with frequently changing quality; and bad links that very seldom transmit a packet successfully. Figure 1(a) shows that the ratio between good links and intermediate links is 2:1 in our testbed measurements. Furthermore, our measurements indicate that any link – no matter of what long-term quality – can temporarily change its characteristics and thereby temporarily become a reliable link for routing or become an unreliable one.

We consider an intermediate or broken link temporarily available when it successfully transmits a number of packets over a short interval. We define a corresponding threshold based on the link's long-term reliability: for example, a link of intermediate quality needs to transmit less packets before being considered temporarily available than a link of bad quality. Similarly, a number of successfully transmitted packets indicate that a reliable link is currently available, while failed ones indicate that a link is currently not available. Overall, we expect that a single successful transmission indicates that a long-term reliable link is currently available.

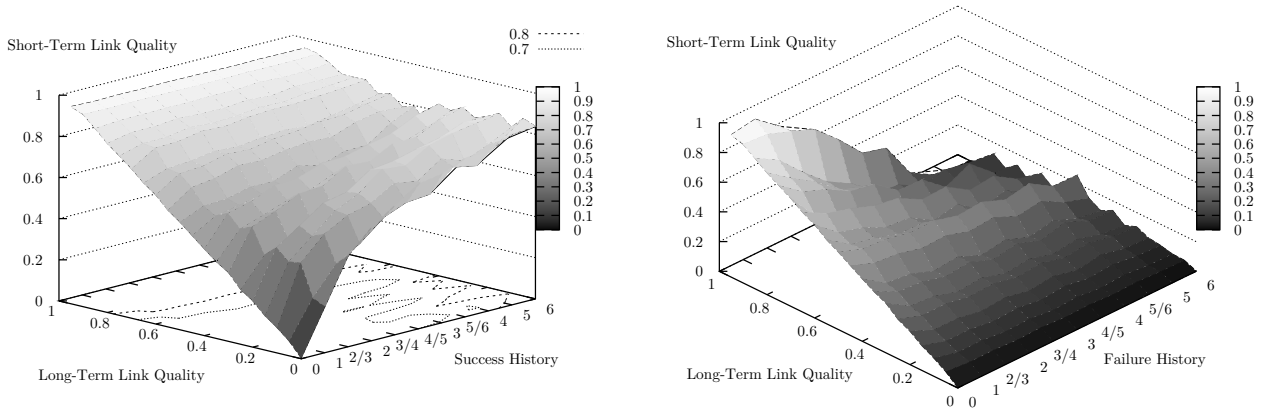
Furthermore, short-term link estimator does not send probe packets to test for link availability, it bases on packet overhearing. Hence, a node overhears packets sent by neighboring nodes and collects statistics on the current reachability. When a node considers the incoming direction of an unreliable link temporarily stable and concludes that it offers a routing improvement, it sends a message to the link neighbor to inform it about a short-term link availability. The neighboring node may then consider routing subsequent packets over the newly available link. If the node is selected as next hop, link-layer acknowledgments continuously provide information about link availability.

We expect that the probability of a successful packet transmission depends on the success rate of any recently sent packets, i.e. the more packets were transmitted successfully in the recent history, the higher the probability is that an upcoming packet is transmitted successfully, too.

3.2 Integration with Long-Term Link Estimators and Routing Protocols

STLE is designed to embed deeply into the routing protocol and to cooperate with long-term link estimators. Modern sensor network routing protocols such as BVR [7] use the number of expected transmissions to a destination as routing metric, computed by combining the distance (in hops) and the number of expected retransmissions. Both long-term and short-term link estimation aim to predict the number of necessary retransmissions on a link, each on their respective temporal granularity. Consequently, when no short-term estimation for a link is available, the routing protocol will use the long-term prediction as fallback, probably resulting in conservative link selection.

As explained above, neighboring nodes overhear ongoing data flows and may suggest themselves to the forward-



(a) Influence of recent transmission success rate on short-term link quality. A label of k/h stands for k successes during the last h transmissions, and h is a shorthand for h/h.

(b) Influence of recent transmission failure rate on short-term link quality. A label of k/h stands for k failures during the last h transmissions, and h is a shorthand for h/h.

Figure 2. Influence of success and failure of recent transmissions events on short-term link quality.

ing node as next hop alternatives, when they (1) identify the link from the forwarding node as short-term reliable and (2) conclude that they offer a better routing choice for the ongoing flow. As a result, the forwarding node has an increased number of choices for routing. Apart from the number of expected transmissions to a destination as used in BVR, other routing metrics such as link load, queue length or battery levels can be integrated similarly.

3.3 Use Case for STLE

Packet overhearing technique employed in STLE can benefit from the bursty traffic patterns observed in WSN. Typical applications [8, 11, 18, 19] of WSN involve monitoring environment for events that are of interest to the users. Although these events occur rarely, but their occurrence results in large bursts of packets that represent major fraction of the overall network traffic. In such situations, STLE, after overhearing first few packets, can identify intermediate quality links temporarily available for transmission.

For example, consider a sensor network based fence monitoring system [19]. During normal conditions, i.e. when there is no intruder breaking into the fence, the network will generate very limited or no traffic. However, as soon as an intruder is detected by the system, large bursts of packets will be generated by the distributed event detection algorithm. In this situation, STLE recognizes intermediate quality links currently stable for transmission, and informs routing algorithm of the availability of such links by online adaptation of neighbor tables. We believe that this technique will significantly reduce the hop count a packet has to traverse from its source to destination. Thereby minimizing the energy consumption and increasing network life time.

4 Evaluation

To evaluate the concept of short-term link estimation, we executed a number of experiments in our indoor testbed. The testbed consists of a regular 6×6 grid of Telos B motes [12] with a spacing of approximately 2.80 m inside a $20\,\text{m} \times 20\,\text{m}$ indoor auditorium. Every node transmitted a burst of 20 sequentially numbered packets with a length of 15 bytes at -25 dBm. We ran this experiment for 5,500 seconds.

To calibrate STLE we need to identify a *threshold* when an intermediate or bad link should be considered temporary reliable. Figure 2(a) depicts the probability of a successful packet transmission based on the average long-term link quality and a short-term history of consecutively transmitted packets. The figure indicates that e. g. for a link with 10 % long-term link quality, the transmission success probability for the next packet exceeds 80% when the four preceding packets were transmitted successfully. We consider links of such instantaneous quality useful for routing, thus STLE suggests such a 10 %-quality link for routing. In the same way, STLE considers a 60 %-quality link to be short-term reliable after just one successful transmission.

Figure 2(b) depicts the probability of a successful packet transmission based on the average long-term link quality and a short-term history of consecutively failed packet transmissions. It indicates that for two or more consecutive losses any link should be temporarily considered broken and be removed from the routing table.

5 Future Work and Challenges

Although our evaluation shows that STLE can reliably identify when unstable links have become temporary stable and vice versa, only an integration can fully evaluate the benefits of STLE. Thus, we are currently implementing STLE extensions to the link estimator in the Beacon Vector Routing (BVR) protocol to analyze performance improvements of STLE.

Cerpa et al. [5] discuss the impact of packet size on packet reception rate. In our experiment, all packets sent were of the same length. The effect of different packet sizes on packet reception rate remains to be investigated.

In practice, nodes do not transmit at the same short intervals used during our measurements. We have yet to investigate whether the correlations derived in section 4 hold

for longer intervals between reception events. Devising other mechanisms, such as sending probe packets to evaluate link quality, could also be used but it will raise the communication overhead significantly.

6 Conclusion

Intermediate quality links constitute a significant fraction of wireless links in low-power WSN. STLE captures short-term link dynamics of these links at a high resolution in time and predicts their temporary availability or unavailability. Our measurements indicate that these intermittent links, if utilized, can significantly improve the performance of routing algorithms by offering further choices for forwarding packets. Moreover, STLE is more suitable for networks showing bursty traffic patterns such as in typical applications of WSN.

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SomSeD: An Interdisciplinary Approach for Developing Wireless Sensor Networks

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ABSTRACT

The research field "Self organized mobile Sensor and Datanetworks" (SomSeD) is introduced. Its purpose is the investigation of Wireless Sensor Networks (WSN). It benefits from interdisciplinary exchange between various institutes of the Hamburg University of Technology (TUHH). Due to different design constraints (such as energy-efficiency and package size) compared to well known classical computer networks, all aspects of the development of WSNs must be reconsidered. This paper describes the advantage of having experts of various faculties both in computer science and electrical engineering in a single research field. In addition to the introduction of the participating institutes, the deployment of a WSN on the TUHH campus will be outlined.

1. SOMSED

Since the foundation of the Hamburg University of Technology a unique organization structure has been applied. On the one hand teaching is distinguished in classical deaneries. Research on the other hand is performed over boundaries of faculties in distinct research fields. Thus, teaching and research are related to each other in a matrix organization structure.

One of these research fields is "Self organized mobile Sensor and Data networks" (SomSeD). Its benefits, goals and challenges will be described in this paper. Besides the coordination on the level of the university teachers, the cooperation of undergraduate and Ph.D students is encouraged. Within SomSeD the so called "Junior" group has been created, in which Ph.D candidates design and develop a WSN. The degree of freedom is high, all decisions regarding the system design are made by the participants themselves. Thus the launch of SomSeD-Junior leads to a great motivation and an appreciable progress.

Deploying a WSN for long-term measurements is one objective of SomSeD. This network is intended to be a platform to integrate all results from research. The TUHH campus is well suited to sustain a WSN due to its continuous area. A permanent installation will support practical demonstrations for various applications and technological concepts of WSNs. This encourages the interest in SomSeD.

2. INSTITUTE COOPERATION

Developing WSNs demands contributions from all experts in the field of electrical engineering and computer science, because all components in both hardware and software have to be aligned to each other. While Quality of Service criteria such as goodput and latency of classical networks can be loosened, energy-efficiency, reliability in adverse conditions, low complexity and the size of single sensor nodes are the most important challenges. Classical models such as the OSI-reference model are given up to allow a crosslayer design: The application has a very strong influence on all layers of abstraction, e.g., routing and media access control (MAC) must be considered together when energy-efficiency shall be achieved [2].

To fulfill these demands, a strong cooperation between different faculties is necessary to define interfaces and redesign all components. Although the individual nodes are very small, the overall complexity of WSNs and the bandwidth of research topics is still high; beginning with hardware aspects such as sensor design and autonomous energy supply and reaching to software methods like data-gathering and visualization. The following institutes participating in SomSeD represent a unique aggregation of competence in WSN development.

The Institute of Telematics has been active in research of WSNs since 2004 [3]. It is obvious, that Telematics is the best choice to supervise the research field and to build the bridge between communication and information engineers.

The Institute of Telecommunications has its traditional research activities in radar development and broadband communications. While the radar technique already performed

[1]Institute of Telecommunications
[2]Institute of Telematics
[3]Institute of Automation
[4]Institute of Control Systems
[5]Institute of Measurement Technology
[6]Institute for Security in Distributed Applications
[7]Institute of Communication Networks
[8]Institute of Microsystem Technology
[9]Institute of Nanoelectronics

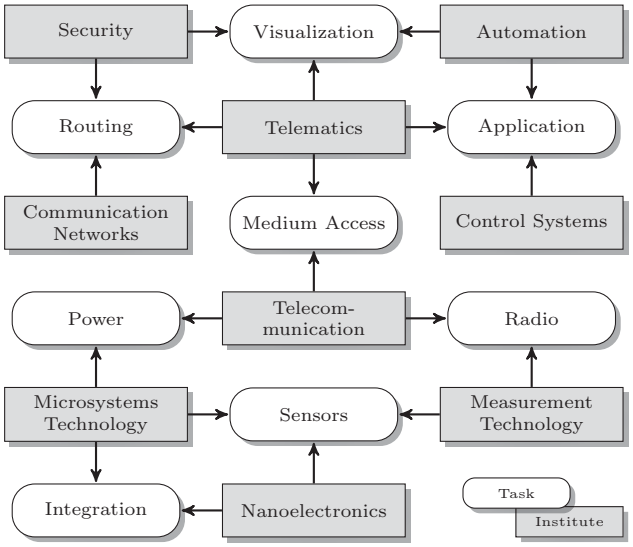

Figure 1: Hardware Overview

the transformation from large rotating antennas with huge transmit power into small and cheap automotive equipment, the communications section is also gaining more and more interest in wireless sensor networks.

Sensors are a major component of WSNs. Hence, it is natural to include the Institute of Measurement Technology into the research field. Besides a profound knowledge about various sensors, the Institute offers a great experience in field testing.

Another crucial point is Networking. The Institute of Communication Networks plays an important role in developing suitable routing and networking algorithms. Careful design of these algorithms helps to decrease protocol overhead and retransmissions and thus improves energy-efficiency.

Cheap and small sensor nodes can only be realized, if a high integration can be achieved. The Institute of Nanoelectronics offers the complete competence in the design of integrated circuits in up-to-date process technology.

The Institute of Microsystem Technology is capable of building very complex and sensitive sensors with small size. A focus lies on the design of medical sensors that are distributed all over the human body. An obvious application for a WSN.

The robustness against malicious network influences is investigated by the Institute for Security in Distributed Applications. Operating mostly in ISM frequency bands and using only low transmission power, WSNs are sensitive to all kinds of interferers, but a wilful disturbance of the network must also be inhibited.

Many decisions depend on the chosen network application. Long-term stability, autonomous operation of the network, and maximum tolerable delays to establish stable control loops are necessary investigations performed by the Institute of Automation and the Institute of Control Systems.

3. CAMPUS NETWORK

One important goal of the research field SomSeD is the deployment of a WSN on the TUHH campus. An entire network of sensor nodes will be installed permanently at the buildings to cover the whole main campus. The density will be chosen to guarantee a connected network, even if some nodes experience permanent failure. The well known IRIS platform is utilized and TinyOS 2.x [1] forms the basis for the software development. This demonstration system gives the opportunity to gather long-term measurements of the behavior of WSNs. It will fulfill two major tasks:

Collecting status information of the network itself, such as neighborhood link quality, successful packet transmission rates, and power-supply monitoring. Running for several months, a good estimation on stability and reliability of such a WSN can be achieved.

Besides status monitoring, convenient applications will be demonstrated. All nodes are regularly measuring the temperature, which is graphically displayed. The network will also be able to forward position information of mobile nodes that are equipped with GPS-receivers.

The architecture is based on a routing tree with one distinct data sink. All acquired data is stored inside a database and visualized using Google Maps. In a first version most nodes are battery-equipped, and a few nodes are powered by an autonomous supply unit developed at the TUHH. This unit uses a solar cell that is dimensioned to guarantee a stable power supply of the backbone routing network even under unfavorable weather conditions.

3.1 Applications

Hardware and software development for WSNs will be validated by performing long-term tests on the campus network. Gathering statistics about the network topology, link qualities, and power consumption is an important application of the experimental system. Once a stable network is established, the WSN can support the facility management of the TUHH by automatically forwarding meter readings and monitoring temperature, humidity, and carbon dioxide in lecture rooms. Thus, a green campus will be realized.

For a university of technology it is extremely important to fascinate visitors for technical study paths. The GPS application offers a convincing show case which will encourage pupils to choose the career of an engineer.

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Multi Client Systems in Wireless Sensor Networks

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ABSTRACT
In this paper, parts of ongoing work of visualization and maintaining tools for wireless sensor networks (WSN) are briefly described. An initial graphical user interface (GUI) will be introduced as well as the foreseen backbone architecture. The current implemented GUI can be used to modify rules stored on individual nodes. This rule editor can be displayed on several user displays of different client systems and the related concept is therefore called Multi Client Systems (MCS).

Categories and Subject Descriptors
H.4.3 **Communications Applications**

General Terms
Management, Measurement, Design, Reliability, Experimentation, Human Factors, Languages

Keywords
Wireless Sensor Networks, Visualization, Management, Rule Management, IEEE 802.15.4, Networks

1. INTRODUCTION
In the recent years, the networking of home appliances like PCs, smart phones, or multimedia devices and thus the access to WSN or home automation systems for instance climate or lighting control is evolving rapidly. The data exchange between various devices of different vendors is not a problem nowadays. Several standards have been published in the past years like IEEE 802.15.4 [1], ZigBee [2], or ZWave [3]. However, the rich quantity of proprietary and standard protocols, which cannot communicate to each other, can decrease acceptance of potential users of WSN systems. Especially users of a new system need often to study a user manual first. Therefore, a more or less autonomous architecture for the networking of different WSN and other networking components in the home area is required. For this purpose, the German project Autonomous Home Networking (AutHoNe[1]) has been established and is funded by the German Ministry of Education and Research (BMBF). One of the goals of AutHoNe is to provide users a consistent and transparent approach to access data sources and services in the home range in an easy way including functions for the definition of rules and constraints to influence the autonomous behavior of the network elements. A suitable graphical user interface for these functions will be one result of the project and it is introduced in this paper. This kind of user interface will help normal users to use and manage their home networks, even in the complex network environments of the future.

The remainder of this paper is structured as follows: Chapter 2 presents related work. Chapter 3 describes the developed graphical user interface with its functionality. Section 4 introduces the foreseen backbone architecture for the Multi Client System. Chapter 5 will give an outlook for further implementations and will conclude this paper.

2. RELATED WORK
The project e.home [4] contains a home network on the basis of Local Operating Networks (LON). This technology allows an information exchange between single devices and the creation of scenarios for single actuators. In [5] a home automation system is presented. This system allows to get information of surrounded sensors and to put actuator states at a central place. As a central user control unit a device with the name "Funk-Haus-Zentrale FHZ 1300" was developed.

3. MULTI CLIENT SYSTEMS
Usually, networks in a home environment should work autonomous without the intervention of users. Nevertheless, it is also necessary for users to have the possibility to access the communication infrastructure and attached components. Sometimes it could be interesting to have knowledge about the network state or to control individual devices manually. Therefore, a development has been started to implement Multi Client Systems.

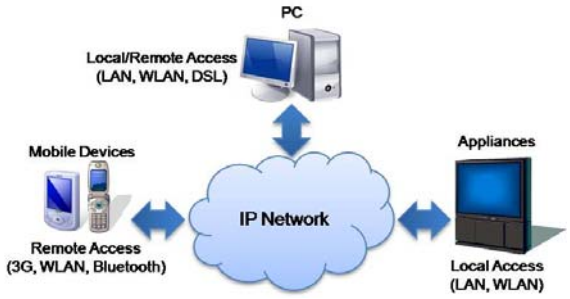

Figure 1: Multi-Client User interfaces

3.1 Client Systems
Different end devices respectively clients with different capabilities are planned for the MCS. At a first choice mobile end devices like mobile phones, smart phones, or pocket PCs are good candidates because of their mobile handset characteristics. These devices should have access to the gateways over a local WiFi or Bluetooth connection or over a 3G (GPRS, UMTS) link. Other

[1] BMBF AutHoNe label 01BN0702

possible MCS devices are standard personal computer environments like desktop PC, notebooks, ultra mobile PCs or at least PC based appliances for instance TVs or touch screens.

3.2 Graphical User Interface

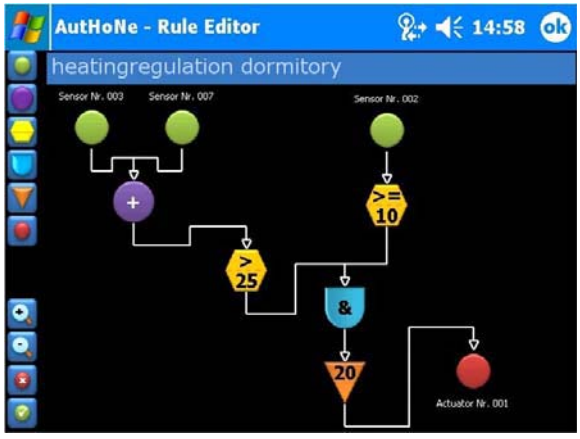

Figure 2: Graphical User Interface for rule edition

The MCS user interface in the upcoming approach will have several modes of usage reflecting the different roles a user can have while interacting with the home network environment in an intuitive way via the MCS. Therefore the following user modes are defined:

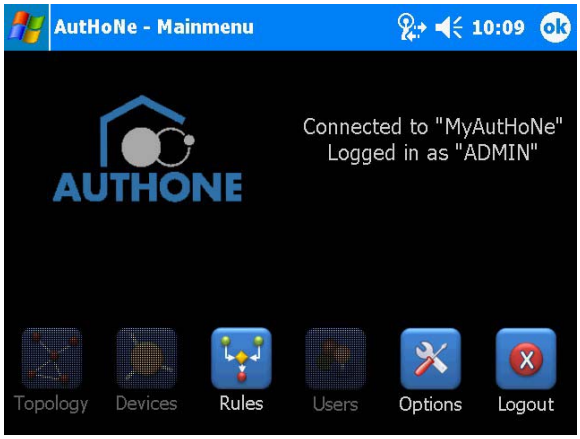

Figure 3: Main menu of the user interface

In the *General-Mode* users are allowed to do their registration at the gateway and to get an overview of the whole system. The handling of the own profile is also permitted. In the second mode, called S*tandard-Mode* (easy, as autonomous as possible, less impact through the user), users are allowed to get a report of all existing networks and network elements such as devices, sensor, and actuators. Furthermore, the configuration of rules, thresholds and events can also be done in the S*tandard-Mode*. Finally, the *Profi-Mode* (complex, less autonomous, strong impact of the user) is suitable for the advanced users like network administrators. This mode is the same as the *General-Mode* plus the following additional functions – will be developed: Configuration of the devices, the whole network and its parameters, setup of the data gathering behavior as well as the configuration of the actuator behavior. The administration of the user profiles is included in this mode too. The current state of the graphical user interface implementation of a MCS is shown in Figure 2 with the rule editor interface.

4. BACKBONE ARCHITECTURE

This section describes the envisioned backbone architecture of the AutHoNe project. The backbone architecture design follows a two-tier approach. On the lowest level (the first tier) several wireless technologies can exists using different kinds of communication technologies. These technologies are connected through a second full meshed WiFi/WLAN network to bring them into the IP world. This IP infrastructure is the second tier.

To build up a WLAN backbone for the WSN technologies, the routers WL500gP from ASUS are used (266MHz, 8MB flash). The routers are able to perform ad-hoc networking including mesh networking based on OLSR [6]. This system is running on a Linux operating system based on OpenWRT [7]. In the prototype evaluation of the system the routers has been equipped with the Integration CompXS USB IEEE 802.15.4 dongle. This dongle is fully compliant to the ZigBee 2006 specification [8] and allows a full speed USB 2.0 communication. It has an integrated antenna and the typical transmission range is above 30m. An Xbee module is included for a second revised version of the gateways. This provides an USB port and gives the opportunity to use antennas for enlarging the observing area. To enlarge the covered area a seven dBi omnidirectional rod antenna has been used. For testing purposes a RFID reader, a Bluetooth device and an UMTS/GPRS modem for 3G connections has been included and tetsted.

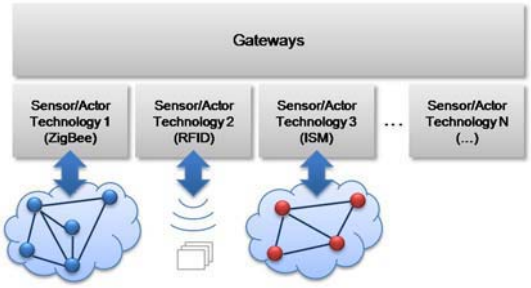

Figure 4 Backbone architecture

4.1 OLSR Mesh based on IEEE 802.11

The system uses a WLAN mesh protocol based on the optimized link state routing protocol (OLSR) implemented by the olsr.org community [9]. This routing protocol is part of the used OpenWRT distribution called kamikaze. To visualize the mesh backbone network, the system uses an add-on provided by [10]. This add-on allows a user to analyze the link quality between several meshed Wifi nodes. This can be used to build up a stable working backbone network.

4.2 OLSR on Multi Client Systems

It is possible that every MCS can be become part of the WiFi meshed network. At least for two aspects, attention has to be paid. On the one hand, the end device needs of course an interface for IEEE 802.11(a/b/g) [11] and on the other hand an implementation of the OLSR routing protocol is required. Several devices are being tested with the implementation of the olsr.org community.

A development for Windows mobile clients from [12] is also tested. For testing purposes, a network was installed with over 15 Asus routers, several Notebooks running Windows XP™ and also one mobile pocket pc client. It was shown that all clients were able to communicate to each other also in the multi-hop manner.

5. CONCLUSION & OUTLOOK

In this paper an approach for Multi Client Systems (MCS) for management of wireless sensor networks has been presented. The first MCS implementation for a mobile device running on a Windows Mobile operating system was introduced as well as the foreseen backbone architecture. The wireless backbone on the second level is build up on full meshed WLAN router based on OLSR. It is shown that also the MCS can be part of this network.

Future work will contain further development of the Multi Client System including user right management (for e.g. guest, habitant, and administrator). Topology visualization in form of a typical tree view or similar graphical representations on top of a bitmap like a floorplan is planned too. Studies of user acceptance are planned as well to get feedback for the enhancement of the GUI in the wireless sensor networking domain.

6. ACKNOWLEDGEMENT

The presented work will be part of the AutHoNe project results. AutHoNe is a BMBF (German Federal Ministry of Education and Research) funded project. In the German part of the project the Partners are Fraunhofer FOKUS, Hirschmann Automation and Control GmbH, Siemens CT, and TU Munich. The project is being carried out as part of a CELTIC cluster within a EUREKA initiative.

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Implicit Sleep Mode Determination in Power Management of Event-driven Deeply Embedded Systems

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Abstract

Energy consumption is a crucial factor for the lifetime of many embedded systems, especially wireless sensor networks. In this paper we present an approach for power management in embedded systems, based on the event-driven operating system REFLEX. In contrast to other systems the implicit power management is mostly hardware independent and efficiently chooses the optimal power saving mode of the microprocessor automatically. First experiments yield promising results comparable to existing implicit power management concepts.

1 Introduction

Typical sensor net applications such as environmental monitoring mostly demand that nodes should work for years with a single battery. Thus, saving energy is essential to attain this goal. Even in embedded systems with external power supply, saved energy helps to reduce costs. For minimal power consumption the appropriate hardware must be chosen. But the hardware must be appropriately utilized, too. This is a complex task that should not be the application programmer's burden. There is a wide range of low-power microcontrollers available, for example the Texas Instruments MSP 430 series[1]. These processors provide the programmer with fine grained control over components and sleep modes. To utilize these features the operating system should at least be able to provide the application with power saving mechanisms. It would be even better to do this implicitly without any need of control from the programmer. Event-driven operating systems can potentially go into sleep mode if no event is pending and the hardware can wakeup the rest of the system upon the occurrence of an event. Since most microcontrollers support a variety of sleep modes with different energy footprints, the selection of the mode can have a perceptible effect on the lifetime of battery powered devices. If the decision was wrong, the energy savings could be marginal or, even worse, events can get lost.

The rest of the paper is structured as follows. In section 2 the related work is presented. Section 3 gives a short overview over the REFLEX operating system. In section 4 the power management mechanisms of REFLEX are described. Early evaluation results are presented in section 5. Finally, a conclusion is given in section 6.

2 Related Work

The most common operating system for wireless sensor nodes is TinyOS[2], which is event based. The power management sends the controller to sleep if the `task-queue` is empty. To determinate the deepest possible sleep mode, the scheduler evaluates a `dirty-bit`, which is set by every driver-module by calling the `McuPowerState.update()` function. This results in a re-computation of the lowest possible sleep mode by reading all device registers. The update operation is executed atomically and thus can produce a significant overhead [3]. Additionally the function is hardware depended and must be implemented for every platform.

Other event-driven sensor node operating systems like SOS[4] and Retos[5] leave the power management to the programmer and do not implement any deepest sleep mode computation. Contiki[6] can not take advantages from any sleep mode because of its polling methodology for interrupt handlers.

3 Reflex

REFLEX (**R**eal-time **E**vent **FL**ow **EX**ecutive) is an operating system implemented in C++, targeting deeply embedded systems and wireless sensor nodes. It is based on the so called event flow model presented in [7]. Activities are the schedulable entities, which are triggered if something was posted to their associated event buffers. Initial source of all activity in the system are interrupts.

Figure 1 shows a simple example containing the elements of a common REFLEX application. The interrupt handler in the timer component writes data into the event buffer of the AD Converter component using an event channel, which forces the activity of the converter to sample a value. When the value is available the ADC interrupt arises and is handled by writing the value to the event buffer of the application logic component. The associated activity implements the threshold logic which sends the data over the serial interface component if necessary.

4 Power Management in Reflex

The power management in REFLEX has two views, a user view and a system view. The user view allows the programmer do define modes of operation utilizing different parts of the hardware and even software components. This makes it possible to divide the execution of an application into different phases. The system provides the class `EnergyManageAble` from which every part of the system

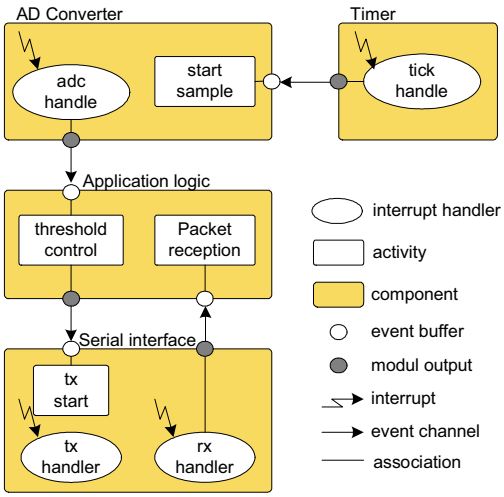

Figure 1. REFLEX application example

that should be included into power management must be derived. Manageable objects can be interrupt handlers as well as event channels. The programmer is responsible for changing the modes. E.g. a timer driven module can be used for mode changes.

At startup, each manageable object is registered with the power management and assigned to one or more groups. During operation groups can be independently activated and deactivated. If a manageable object is member of multiple groups it is only deactivated when all of these groups are deactivated.

The system view is used for the determination of the deepest possible sleep mode. Every instance of a component has a variable which specifies the deepest possible sleep mode that may be used when it is active. This value is assigned during initialization for non hardware specific objects or hard coded for hardware specific objects. The power manager contains a table with counters for every available sleep mode of the microcontroller used. If a component is enabled it signals its deepest possible sleep mode to the power manager by increasing the corresponding counter in the sleep mode table. If a component is disabled, the counter of its sleep mode is decreased.

If no event is pending, the power manager iterates the sleep mode table starting at the lightest mode. The first value different from zero is the deepest possible sleep mode. To guarantee this, the table is initialized with zero for all counters except the deepest mode which is initialized with one.

In contrast to TinyOS, it is not necessary to evaluate the complete machine state, which makes the changing of the lowest possible sleep mode very lightweight.

A state override is possible to prevent the system to go below a certain sleep mode or to sleep at all. This is possible by using an energy manageable object which increments the counter in the power management table for a certain wanted mode. This may be useful for reducing wakeup times.

The sleep mode counter table is the only hardware specific part of the power manager, since it can have different sizes depending on the used microcontroller.

5 Evaluation

To show the efficiency and compatibility of the presented power management scheme, we devised a simple experiment. In the next section we first explain the experimental setup. After that the results will be discussed.

5.1 Experimental Setup

The measurement setup is shown in figure 2. Besides the device under measurement, the setup contains a shunt, an adjustable power supply unit, an oscilloscope and a PC. The PC is used to control the oscilloscope and the power supply unit. The energy consumption P is calculated by the voltage and current which flows into the board (formula 1). Because direct measurement of the current is not possible it is determined by using formula 2.

$$P = U_{board} * I_{board} dt \quad (1)$$

$$I_{board} = -U_{shunt} / R_{shunt} \quad (2)$$

The start of a measurement can be accurately determined by using a trigger signal generated by the application running on the microcontroller itself.

It must be pointed out that the region of the measured values leads to a certain amount of noise. Thus there could be an error of about 10%, but the values are suitable to show trends.

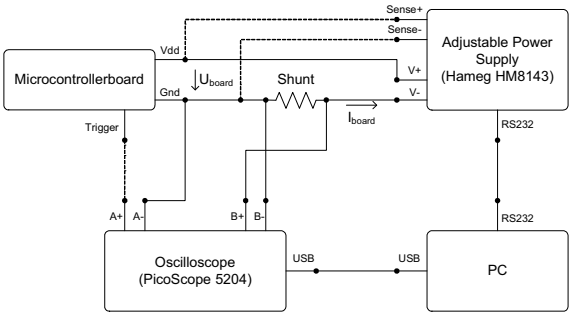

Figure 2. Measurement Setup

The measurements where done using a TMoteSky[8] equipped with a Texas Instruments MSP 430 series microcontroller, which has special hardware support for low-power applications e.g. detailed sleep modes and fast wakeup times.

We used a simple experimental application, which sends data over the serial connection every second. This application was chosen because it shows the characteristics of a typical sensor net application, such as a low duty cycle and periodically sending data over an interface.

5.2 Results

In figure 3 and table 1 the power consumption for different versions of the power management schemes in REFLEX are compared. With deactivated power management, there is no difference in power consumption regardless of whether the serial port is active or not. In contrast, deactivating the idle core (the highest possible sleep mode called lpm0) makes the send activity clearly identifiable and shows a significant amount of energy savings. This simple power management

reduces the energy consumption to about 16% of the unmanaged version. Using the power management approach presented in section 4 consequently to utilize the deepest possible sleep mode reduces the energy consumption to 7%.

	Reflex		
	w/o	lpm0	full
TMoteSky 2,2V @ 1MHz	2.825	0.451	0.195
TMoteSky 3V @ 1MHz	7.445	1.053	0.258

Table 1. Average power consumption of Reflex

Due to the quadratic influence of voltage, the overall power consumption at 3V is higher, but as table 1 shows, the effect reduces with better power management, which was not expected. Reasons for this could be, that the percental influence of the analog parts to the power consumption rises with deeper sleep modes. These do not fall under the CMOS power consumption formula ($P \sim P_{static} + \alpha CV^2 f$) and thus can behave different. At last, the formula is idealized.

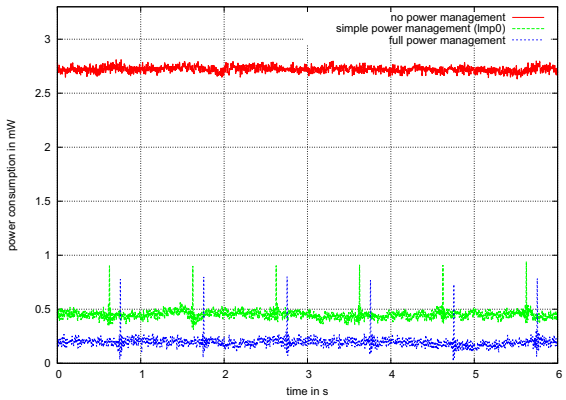

Figure 3. Power consumption of Reflex power management schemes for at 1MHz and 2.2V

For comparison purposes TinyOS 2.0.2 was used. The same application was implemented and utilized only implicit power management. The results are shown in figure 4 and table 2.

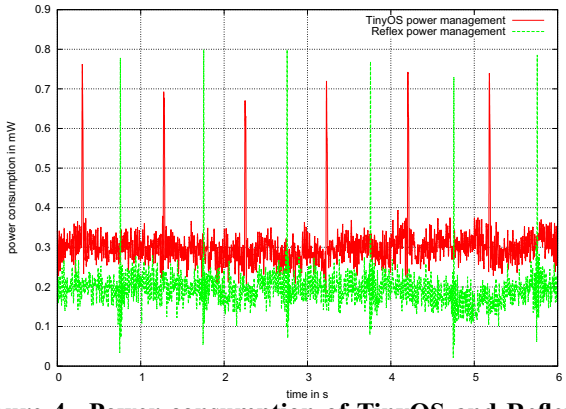

Figure 4. Power consumption of TinyOS and Reflex at 1MHz and 2.2V

For the given application the results show that the power management of REFLEX is more effective than the one from

	Reflex	TinyOS
TMoteSky 2,2V @ 1MHz	0.195	0.324
TMoteSky 3V @ 1MHz	0.258	0.588

Table 2. Average power consumption of TinyOS and Reflex

TinyOS. The REFLEX power management consumes about 41% respectively 56% less energy, depending on the voltage. The main reason is that the power consumption during sleep is higher in TinyOS than in REFLEX. Due to the driver module for the serial connection it is not possible to determine if the receiving direction is used, so an automatic deactivation of receiving is not possible. In contrast, the driver module in REFLEX knows that it is used because it is part of the event flow. Additionally the receiving driver module is managed by the underlying group management and, thus is only active when implicitly activated.

6 Conclusion

We presented an efficient way of determining the deepest possible sleep mode in event driven systems and its implementation in the REFLEX operation system. The presented power management is lightweight and hardware independent. Measurements show that this approach seams to perform around 50% better than the one of TinyOS for the given application and regardless the noise of the measurements.

Further examination of additional applications is needed to confirm the results.

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Tab WoNS: Calibration Approach for WSN based Ultrasound Localization Systems

Extended Abstract

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ABSTRACT

Accurate localization of objects is often very important, thus various methods and systems exist. Unfortunately, some support easy deployment but are less accurate while others are more accurate but require a complex and time-consuming deployment stage. When the localization system meets some demands, a widely self-organizing deployment becomes possible. This paper describes which pre-conditions and abilities are required, how self-configuration could be realized for such a system and which minimal number of calibration steps are required during deployment.

1. INTRODUCTION

Lots of application scenarios for wireless sensor networks (WSNs) are in need of accurate knowledge about current positions of several objects. Because this can be such an important basic requirement for the system's successful operation, not only different approaches were proposed, but also based on these solutions various localization systems were built and successfully proven (c.f. [1, 4, 5, 6, 7, 10, 11, 12]). Indeed, the sometimes costly deployment process of such a WSN was hardly analyzed so far. Yet, deployment can be very time-consuming and cost-intensive, especially when numerous beacons have to be mounted and calibrated quite precisely. That's why this paper presents a self-deployment strategy for beacon-based localization systems to save time and costs. Therefore section 2 defines some basic requirements for the self-deployment procedure, whereas section 3 introduces the localization system SNoW Bat [4] to form the basis of our further research. Section 4 specifies our deployment approach Tab WoNS, which is quite similar to the localization stage of SNoW Bat. Our thoughts and results for the calibration during deployment stage are presented in section 5 and finally a conclusion in section 6 closes this paper.

2. SYSTEM REQUIREMENTS

The self-deployment strategy presented in this paper requires the desired localization system to comply with the following requirements. First of all, the sensor nodes of the localization system are classified as *beacons* (i.e. anchor nodes with known and constant position) and *clients* (i.e. mobile nodes with unknown and variable position). To derive basic conditions for efficient calibration during the self-deployment stage, our approach presumes that the beacons are aligned in a regular pattern. For this paper a roughly grid-like[1] layout is analyzed.

The underlying localization system uses ultrasound signals (so called *chirps*) for distance measurement. But it is sufficient – even for deployment stage – if beacons are just able to receive ultrasound signals whereas only clients are capable of transmitting ultrasound for distance measurement. There will be no need for the anchors to generate ultrasound signals, which saves energy and reduces environmental pollution by ultrasound emitted from the quite large number of beacons in such systems. Besides we are just interested in three-dimensional localization, the two-dimensional equivalent would be much easier but less realistic. However, for simplification we will assume that the anchors are fixed at the common ceiling plane and a mobile client moves freely thereunder within a certain distance range (cf. Fig. 1). Additionally the distance between ceiling and mobile client is not necessarily known.

3. LOCALIZATION SYSTEM

This section introduces the underlying localization system SNoW Bat. It operates based on the thunderstorm principle, where radio packets correspond to lightning and ultrasound signals to thunder. According to the requirements from section 2, all sensor nodes are divided into beacons and clients. After deployment each beacon knows its position and is able to detect ultrasound signals, whereas no client knows any coordinates a priori. However, each client is able to generate ultrasound signals and to initiate the following localization procedure:

1. If a client wants to know its current position, it broadcasts a radio packet containing its ID and the time difference between this radio message and the subsequent ultrasound chirp.
2. Each anchor receiving this synchronizing radio packet activates its ultrasound receiver and thus expects the client's ultrasound signal after the specified waiting time.

[1] If the anchors are adjusted to an exact grid, each anchor can already determine its position if only one single anchor knows its position and if the anchors have additional knowledge about their placement, orientation, etc.

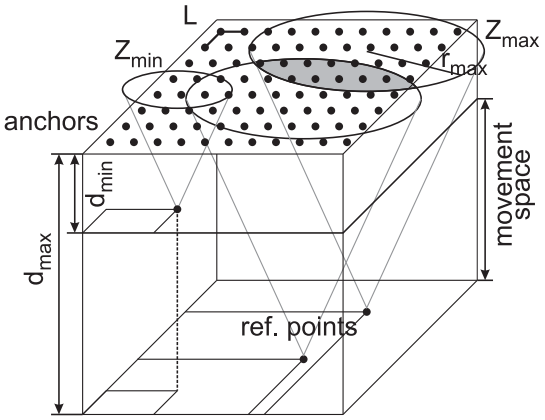

Figure 1: Schematic system design: anchors are at the ceiling along a grid-pattern with grid constant L, clients are thereunder. The ultrasound signal is emitted as spherical sector, which defines a coverage zone Z with radius r.

3. The mobile client transmits the ultrasound chirp as denoted in the previous radio broadcast.
4. Each beacon which detects this ultrasound signal calculates its distance towards the mobile client from the time difference of arrival between the radio and ultrasound signal. If an anchor just receives the initiating radio message but no chirp, it aborts measurement and waits again for further clients to be localized.
5. Each beacon, which successfully completed its distance measurement, passes this result together with its known position to the requesting client as unicast. This is done by the self-organizing communication protocol HashSlot [2, 3].
6. By using for example multilateration, the client can estimate its three-dimensional position autonomously from at least four such distance measurements.

4. DEPLOYMENT STRATEGY

Inspired by the localization procedure, we head for the deployment stage. The main idea of our deployment approach is reversing the roles of anchors and clients during deployment. That is, just during deployment a *reference client* below the anchor plane knows its position, whereas every beacon doesn't yet know its coordinates. The remaining requirements from section 2 are retained: only the (reference) client generates ultrasound signals, which can be detected by the grid-aligned beacons at the anchor plane. The deployment procedure will than be as follows:

1. The reference client is situated at a known position (so-called *reference point*) and broadcasts a radio packet containing its ID, its current position and the time difference between this radio message and the subsequent ultrasound chirp.
2. Each beacon with yet unknown position receiving this synchronizing radio packet activates its ultrasound receiver and thus expects the client's ultrasound signal after the specified waiting time.
3. The reference client transmits the ultrasound chirp as denoted in the previous radio broadcast.
4. Each beacon which detects this ultrasound signal calculates its distance towards the mobile client from the time difference of arrival between the radio and ultrasound signals. If an anchor just receives the initiating radio message but no chirp, it aborts measurement and waits again for radio packets of the reference client.
5. If a beacon successfully completed at least four distance measurements to non-collinear reference points, it estimates its fixed position, e.g. by using multilateration. From now on, this beacon knows its position and is available for locating mobile clients with unknown position as described in section 3.

Obviously, deployment (this section) and regular operation (section 3) are very similar. Their only differences are the knowledge of the nodes' position and the handling of the distance information. In comparison to the procedure during the localization stage, no replies from beacons to clients are required anymore. This way, the hardware for clients and beacons remains the same for deployment and localization. Still, this deployment procedure implies two open issues which need a closer examination:

1. First, the reference client needs exact knowledge about its own position now. For example, this can be done manually, but an inaccuracy of a couple of millimeters already produces drastic errors during localization.
2. Next, the number of required known positions of the reference client during deployment should be kept as small as possible to save energy, time and costs, mainly manpower.

Because the first item depends on the craftsmanship of the calibrating persons as well as the accuracy of the used measuring instruments, we will initially focus on the second item in the next section.

5. CALIBRATION

In this section we address the localization system calibration after installation of the static beacons at the anchor plane. The goal is to determine accurate anchor positions while achieving a short duration for this exceptionally important process. As already described in section 4, we use certain carefully selected reference points at well known positions to allow each anchor-to-be to measure at least four distances in a three-dimensional space. Of course, increasing this number yields higher precision but also consumes more time and power. Thus, the number of reference points shall be minimized but must still allow proper and complete operation. Therefore we define the ratio

$$Q := \frac{|\text{anchors-to-be}|}{|\text{reference points}|}$$

as central metric for the solution's quality and try to maximize Q.

Since we consider a grid-like pattern for the anchors, we also expect a regular pattern for the optimum reference point

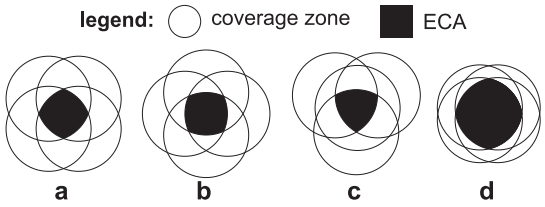

Figure 2: Some basic layouts, each consists of four overlapping circles of equal radii forming an explicit coverage area (solid black).

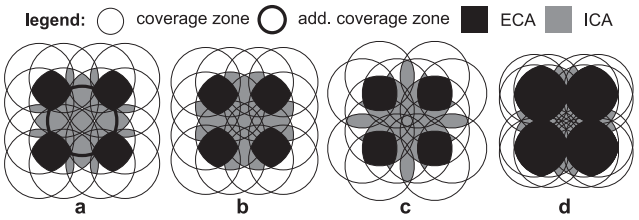

Figure 3: Slightly different alignment strategies when using basic layouts a, b and d from Fig. 2.

alignment. SNoW Bat uses a regular grid for several reasons. It is easy to install, contributes to the performance of the self-organizing HashSlot [2, 3] wireless communication protocol, and allows easy adaption to the environmental conditions. The last point allows to easily provide complete localization service coverage throughout the entire operational area. As figure 1 shows, the selected grid constant L depends on the minimum distance d_{min} of the mobile objects from the anchor plane and the resulting minimum ultrasound coverage zone Z_{min}. According to [3], L is computed to always guarantee a minimum number of four nodes within an ultrasound coverage zone Z independent from its overlay position within the grid. Thus L stays fixed after system installation and obeys to the spatial geometry and hardware constraints during system design. On the other hand, d_{max} limits the maximum number of anchors within the largest possible ultrasound coverage zone Z_{max}. Unfortunately, no analytical solution for the exact number of grid points within a circle is yet known. However, approximations for the so called *lattice point problem* are presented in e.g. [8, 9]. Anyway, the reference points must obviously be placed at distance d_{max} from the anchor plane. Then, their final number decreases along with increasing difference $d_{max} - d_{min}$. Still, the optimal alignment remains to be found.

The idea so far is to initially place four non-collinear reference points in a way to maximize the intersection area of all resulting coverage zones, Fig. 2d shows an example. This intersection produces the so called *explicit coverage area* (ECA). Then, the just created *basic layout* is repeated with a certain distance to implicitly cover the anchors in-between the explicit areas (*implicit coverage area*, ICA), too. Fig. 3d shows a corresponding alignment of reference points. Indeed, this special basic layout is rather adverse, since several reference points are close to each other and the implicitly covered areas are very small. If we increase the space between the basic layouts to enlarge the implicit coverage areas, we might require some additional reference points to keep fourfold coverage (e.g. the bold circle in Fig. 3a).

During our analysis we found that the proportion between explicitly and implicitly covered areas should be roughly balanced to omit extra reference points. Then, implicitly and explicitly covered anchor sets with about the same size alternate. Fig. 3a-c shows some more basic patterns with balanced proportion.

Regarding the metric describe above, table 1 shows that the quality Q is exceptionally good for these balanced alignments since few reference points are required for calibrating many anchors. Hence, pattern 3a offers the best quality of the analyzed strategies, although it requires additionally reference points.

Table 1: Quality Q of various alignment strategies for $r_{max} = 9L$

Strategy	Q
Fig. 3a	42.44
Fig. 3b	41.17
Fig. 3c	39.06
Fig. 3d	39.59

Still, the achievable precision for each anchor's position estimation needs careful consideration. Indeed, the calibration accounts significantly to the accuracy of the localization system's regular operation. Thus, we recommend the following method for checking the anchors and to perform partial recalibration of the anchors by additional measurements where necessary:

1. Calibrate the system as described above.
2. Operate the system to localize objects at some additional well-known test points by using each anchor at least once.
3. Compare the correct, known position to the estimated one and recalibrate these anchors which were involved in deviations larger than an acceptable threshold.

6. CONCLUSION AND FUTURE WORK

In this paper we presented an efficient strategy for the deployment of an ultrasound based localization system. Therefore some basic system requirements were defined. E.g. the static anchor nodes must be mounted along a grid-like pattern above the observed mobile clients. One benefit of our strategy is the usage of identical hardware for calibration during deployment as well as for localization during regular operation. Just the roles of anchors and mobile clients will be reversed.

Since the anchors initially do not know their coordinates, the basic idea of our approach is to use a reference node at well known positions for measuring some distances to these anchors, which then calculate their static position. The problem is to find a minimal set of reference points and to still

provide a sufficient number of distances for complete anchor coverage. We showed, that this problem is not trivial and does not only depend on the system accuracy and parameters (grid constant, etc.) but also on the reference node's positions during the calibration process.

So far, we just analyzed a few different reference point layouts and strategies. The next step is to integrate the deployment procedure as described above into the existing localization system SNoW Bat. Analyzing systems with arbitrarily aligned anchors is another interesting issue. Hence, we want to proof some upper or lower bounds for the number of required reference points within such systems.

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Improving Response Time of Sensor Networks by Scheduling Longest Flows First

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ABSTRACT

When deploying (wireless) sensor networks, sink-trees are a natural topology choice. However, those networks have an intuitive drawback: the deeper down in the tree a network node is, the higher its delay becomes, due to the data being multiplexed with flows from other nodes higher up in the tree, and because of forwarding delays. This leads to a very uneven distribution of experienced delays, both worst- and average-case; however, this is rarely necessary or desirable behavior. Often, all data from a network is equally important, and a high penalty for "outliers" endangers the network's utility.

To remedy this, and to provide a worst-case behavior closer to the average case, we propose a multiplexing scheme giving flows with a longer traveled distance priority over flows that have passed fewer hops. We will show that this scheme improves fairness in sensor networks, while adding little complexity to their analysis.

1. INTRODUCTION

When looking at a sink-tree from the perspective of a single flow of interest, the resulting characteristics are as shown in Figure 1. As can be seen, the flow is multiplexed with more and more flows as it gets closer to the sink. Under multiplexing schemes like FIFO, or when using arbitrary multiplexing, this results in potentially high delays favoring flows with a shorter route to the sink. However, in most sensor network applications where all data is equally important, that kind of behavior opposes the requirements.

This becomes even more of an issue when dimensioning a network based on its worst-case behavior, e.g. by using (Sensor) Network Calculus [1, 2] (a short introduction can be found in the appendix). In that case, the whole network design depends on the nodes experiencing the worst service, which may lead to a vastly overdimensioned network. As was shown in earlier work [3], the worst-case behavior of a network may deteriorate rapidly with the network's diameter.

This can be avoided by giving priority to certain flows in a way that balances delay times for all nodes, reducing the variance of that metric. However, this requires keeping and analyzing the state of all flows. In environments with restricted resources like sensor networks, this may impose a significant additional load to the network nodes, reducing the network's lifetime and utility; thus, a balancing scheme needs to be as simple as possible. Simplicity is especially called for when trying to improve a worst-case bound, since especially with low network load, that bound may be encountered only rarely, if ever. So spending a large amount of resources would be a waste in the average case.

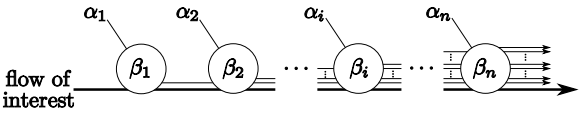

Figure 1: Typical characteristics of a sink-tree network with feed-forward characteristics. As a flow of interest traverses servers on the way to the sink, it gets multiplexed with other flows, and remains so until reaching the sink.

2. LONGEST FLOW FIRST SCHEDULING

The proposed multiplexing scheme is very simple: When flows are multiplexed, the flow that has passed more hops at the multiplexing node gets priority over the "younger" flow. This has the advantage of being very easy to implement with little overhead, since all that is required is a "hop counter" in each data frame, which gets incremented by each server that forwards the frame. The scheduler can then be a simple priority queue. Since data packets usually carry a header, adding that counter should be trivial in most cases.

Another common scheme would be to prioritize flows that have the most hops left until their destination. However, that fails in sink-tree networks, since at any given node, each passing flow will have the same distance left to travel to a given sink.

2.1 LFF in Network Calculus

Multiplexing in Network Calculus is handled by reducing the minimum service curve offered by a network node by the sum of all maximum arrival curves that can possibly be scheduled before the flow of interest. In the following, let $\alpha_{n,f}$ be the input bound of flow f at node n, and $F_{n,f}$ be the set of flows interfering with f at node n according to the rules of the analysis method. The effective service curve offered to a flow of interest f^* at node n can then be given as:

$$\beta_{n,eff} = \left[\beta_n - \sum_{f \in F_{n,f^*}} \alpha_{n,f} \right]^+$$

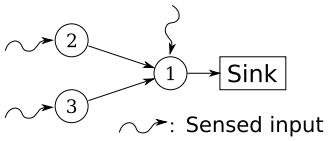

Figure 2: Simple feed-forward network.

To implement LFF, it is only necessary to filter F_n so that only flows that have passed at least the same number of hops as the flow of interest. To that end, we define the function $h_n(f)$ as the number of hops passed by flow f at node n. Define the set $F'_{n,f} = \{f' \in F_{n,f} : h_n(f') \geq h_n(f)\}$. The effective service curve offered to a flow of interest then becomes:

$$\beta_{n,eff} = \left[\beta_n - \sum_{f \in F'_{n,f*}} \alpha_{n,f}\right]^+$$

The expected results of that scheme are improved delay bounds for longer flows, while the bounds for the shortest flows show no significant change. This can be intuitively explained by LFF only removing potential interference from the longer flows, while still considering all cross-traffic for the shortest ones. No flow exeriences a penalty.

For illustration, we look at a small network which is shown in Figure 2, and calculate the delay bounds for the flows originating at the nodes 1, 2, and 3, which will be called d_i with $i \in \{1, 2, 3\}$. Each node generates input limited by a token-bucket arrival curve $\alpha = \gamma_{1,1}$ and exhibits a forwarding behavior lower-bounded by a rate-latency minimum service curve $\beta = \beta_{4,1}$. The PMOO analysis under arbitrary multiplexing yields:

$$\begin{aligned} d_1 &= h\left(\alpha_1, [\beta_1 - ((\alpha_2 \oslash \beta_2) + (\alpha_3 \oslash \beta_3))]^+\right) = 5 \\ d_2 &= h\left(\alpha_2, \beta_2 \otimes [\beta_1 - \alpha_1 - (\alpha_3 \oslash \beta_3)]^+\right) = 5 \\ d_3 &= h\left(\alpha_3, \beta_3 \otimes [\beta_1 - \alpha_1 - (\alpha_2 \oslash \beta_2)]^+\right) = 5 \end{aligned}$$

Under LFF, flows 2 and 3 get priority over flow 1, and the term for d_2 and d_3 becomes:

$$\begin{aligned} d_2 &= h\left(\alpha_2, \beta_2 \otimes [\beta_1 - (\alpha_3 \oslash \beta_3)]^+\right) = 4 \\ d_3 &= h\left(\alpha_3, \beta_3 \otimes [\beta_1 - (\alpha_2 \oslash \beta_2)]^+\right) = 4 \end{aligned}$$

We see an improvement for the longer flows. There is no improvement for the whole network owing to the simplistic example. To demonstrate the potential for overall improvement, we will now show results from larger network topologies.

3. RESULTS

We compared the results of LFF vs. arbitrary multiplexing by implementing the scheduling discipline in the DISCO Network Calculator tool [4, 5], using the concepts from above.

For scenario generation, we used the generator as used for [6] to generate random sink-tree networks with a single sink, a tree depth of 5 levels, with each node having one to five child nodes. Arrival- and service curves for each node are $\alpha = \gamma_{0.01KB/s,1KB}$ and $\beta = \beta_{15KB/s,0.5s}$. We then calculate

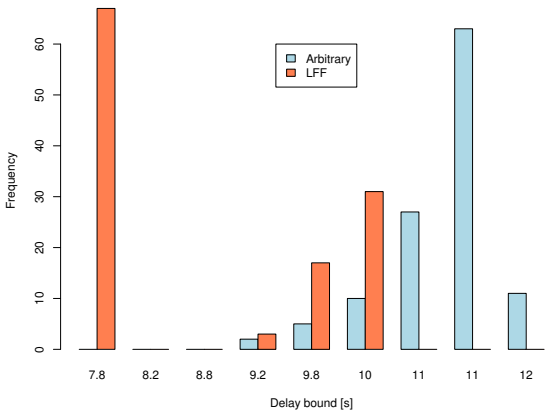

Figure 3: Frequency of delay bounds in an example network.

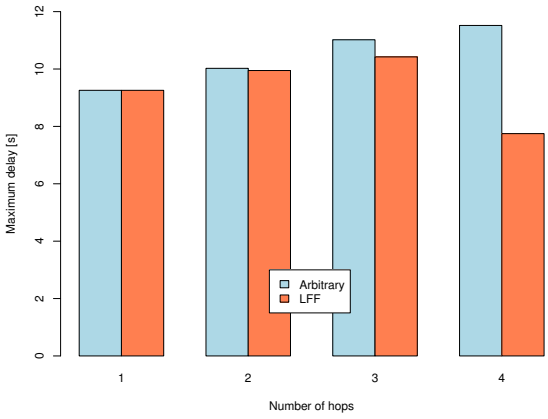

Figure 4: Comparison of the maximum delay bounds per flow length in an example network.

the delay bound for each flow using the Pay Multiplexing Only Once Analysis (PMOOA, [7, 8]), both under arbitrary and LFF multiplexing.

An example of the change in the delay bounds resulting from LFF scheduling is shown in Figure 3. Many flows have an upper delay bound of over $11s$, with a maximum of $11.52s$, while LFF scheduling results in a maximum delay bound of $10.42s$. This makes for a 9.5% lower delay bound under LFF. It is interesting to notice the large amount of flows that got a significant improvement. More detailed analysis shows that especially the longest flows get a boost. Figure 4 shows a comparison between the worst-case bounds per flow length. The topology had data flows that passed 1 to 4 hops. Under arbitrary multiplexing, the maximum delay bound for a given hop count increases with the number of hops. Under LFF however, the longest flows have a very low bound. This is clearly *overcompensation* for the original penalty incurred by longer flows. This will be further discussed below.

Calculating the overall upper response time bounds for 100 randomly generated networks with over 15000 flows in total, and with a topology as described above resulted in improvements ranging from 0% (no improvement at all) to

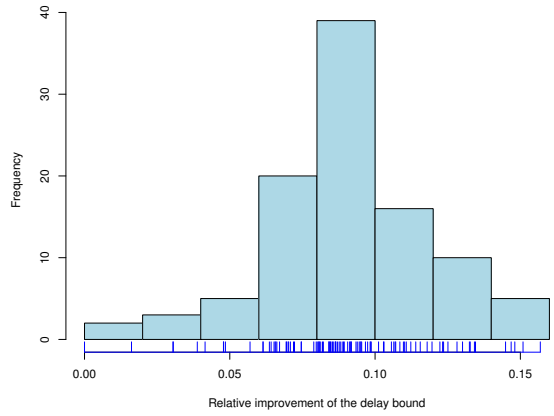

Figure 5: Improvement of the delay bound by LFF over arbitrary multiplexing.

15.7%, with a mean of 9%. The distribution of the improvements is shown in Figure 5.

4. DISCUSSION

We have shown that scheduling long flows before shorter flows often yields an improvement of the worst-case response time, at the cost of minimal data and processing overhead. The observed improvement with an average of 9% may seem small, but earlier results showed benefits of over 30% in some cases when *scaling* was taken into account [6]. The results are also taken from a limited set of topologies. It is evident that even small changes in parameters can have a large influence on the results of a Network Calculus analysis. This calls for a closer examination of the conditions under which LFF has a significant advantage over arbitrary multiplexing. It would of course also be interesting to analyze the impact of LFF on a real network, where the worst case is usually rarely encountered. We hope to present results of the average-case impact in the near future.

Overall, the exhibited behavior is overcompensation. The longest flows benefit the most, while the shortest flows do not show any improvement. This is of course different from the intended result, which is to balance the delay bounds for all network participants as well as possible. A few strategies to reach the goal could be:

- *Data scaling [6].* By taking data transformations like compression or aggregation into account, the nodes close to the sink may experience a vastly lower load than in a model that just forwards data unaltered.
- *Topology adaptation.* If a node becomes backlogged for too long, it may decide to skip a hop in the original network topology, e.g. by using a higher transmission power. This may serve to avoid bottlenecks, but of course there may be issues with medium access due to larger collision domains.
- *Priority Injection.* When a node is backlogged with upstream data for a certain time, it inserts local data instead of strictly following the LFF definition. This tries to avoid the worst case by introducing a guaranteed service for data entering the network, based on the assumption that bottlenecks only occur very close to the sink, where a lot of flows with high priority exist.

We want to investigate te last point in a little more detail.

4.1 Impact of Priority Injection

To model the impact of a minimum service guarantee to data entering the network, we introduce the notion of a *backdoor service curve.* Intuitively, we want to achieve that after an amount of time T, an original data packet is scheduled, even if there are other packets from other (higher priority) flows scheduled. With M as the maximum packet size, and C as the link capacity, this can be modelled as a rate-latency curve $\beta_{bSC} = \beta_{\frac{M}{T}, T+\frac{M}{C}}$. A node i following that scheme and with an input α_i then offers a minimum service curve $\beta_{i,eff} \vee \beta_{i,bSC}$ to its own traffic, while offering $\beta_i - (\alpha_i \vee \beta_{i,bSC})$ to forwarded flows.

If we now model the simple network from Figure 2 with $\beta_{bSC} = \beta_{1,2}$ at each node, we get:

$$\begin{aligned} d_1 &= h\left(\gamma_{1,1}, \beta_{2,3} \vee \beta_{1,2}\right) = 3 \\ d_2 = d_3 &= h\left(\gamma_{1,1}, \left[\beta_{4,1} \wedge \beta_{3,\frac{2}{3}} - \gamma_{1,2}\right]^+\right) = 4 \end{aligned}$$

which means an improvement for the whole network, since it allows node 1 to forward its own data even though it is experiencing heavy load from nodes 2 and 3. At the same time, overcompensation is avoided.

Further study of priority injection is the subject of future work.

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APPENDIX

A. BASIC SENSOR NETWORK CALCULUS

This is a very basic overview of the Sensor Network Calculus (SNC). Detailed explanation of the SNC can be found in [2].

To apply the SNC, the network topology has to be known to some degree. For example, a tree-structured network topology with a sink at the root and n_i sensor nodes can be used. Next, the network traffic has to be described in terms of so-called arrival curves for each node. An arrival curve defines an upper bound for the input traffic of a node. Leaf nodes in the network have to handle traffic according to the sensing function they perform; for example, a node might sense an event and create a data packet at a maximum rate of one packet every second. This sensing pattern can be expressed as an arrival curve α_i. Non-leaf nodes handle traffic according to their own sensing pattern and the traffic they receive from other nodes .

To calculate the output, the so-called service curve β_i is used. The service curve specifies the worst-case forwarding capabilities of a node. The necessary forwarding latencies are defined by the nodes' forwarding characteristics.

From the arrival and service curves, it is possible to calculate output bounds for each node. Using those bounds, it is possible to compute the effective input $\bar{\alpha}_i$ for each node. Thereafter, the local per-node delay bounds D_i for each sensor node i can be calculated according to a basic network calculus result given in [9]:

$$D_i = h(\bar{\alpha}_i, \beta_i) = \sup_{s \geq 0}\{\inf\{\tau \geq 0 : \bar{\alpha}_i(s) \leq \beta_i(s+\tau)\}\}$$

To compute the total information transfer delay $\bar{D}_i$ for a given sensor node i, the per node delay bounds on the path $P(i)$ to the sink need to be added:

$$\bar{D}_i = \sum_{j \in P(i)} D_j$$

Clearly, the maximum information transfer delay in the sensor network can then be calculated as $D = \max_{i=1,\ldots,N} \bar{D}_i$. The whole procedure is called *total flow analysis* (TFA) because all of the traffic arriving at a given node is treated in an aggregate fashion.

Examples for the use of this calculus can be found e.g. in [10, 11, 12].

A.1 Advanced Sensor Network Calculus

While the TFA is a straightforward method for applying network calculus in the domain of wireless sensor networks, there is room for improvement with respect to the quality of the calculated performance bounds. This is due to the fact that the concatenation result for consecutive nodes offering service curves is not exploited by the TFA. In particular, we can exploit and even extend the concatenation result towards a so-called Pay Multiplexing Only Once analysis (PMOOA) described in [13], to compute an end-to-end service curve for a specific flow of interest from one sensor node to the sink. Due to the sink-tree structure of the network, all flows that join a flow of interest remain multiplexed until the sink, making it possible to calculate the total information transfer delay $\bar{D}_i$ for a given sensor node i by using a flow-specific end-to-end service curve. PMOOA can be shown to deliver a tight bound for sink-trees [7] of homogeneous nodes. When compared to the addition of the nodal delay bounds as done by the TFA, this results in considerably less pessimistic bounds as each interfering flow's burst has to be taken into consideration only once.

Design Concepts of a persistent Wireless Sensor Testbed

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ABSTRACT

In this paper we introduce our work-in-progress wireless testbed. The testbed consists of hybrid nodes. Each node contains a sensor node and a mesh router. We present concepts which exploit the features of an existing wireless mesh network for the wireless sensor network. The concepts include the *wireless sensor testbed integration* (WSTI) which simplifies the management and provides a basic infrastructure for the sensor network and experiments. The integration into the Linux kernel is realized by the *wireless sensor kernel interface* (WSKI). *Network check points* (NCPs) enable long-term experiments that may span several weeks although they cannot be done in one continuous session.

1. MOTIVATION

Wireless sensor networks (WSN) have been in the focus of research in the last decade and are deemed mature for many application areas for which they were intended to. Several fundamental problems have been identified, e.g. routing, addressing, transport layer issues, and middleware, various approaches are consequentially proposed. Unfortunately, most knowledge and understanding is based either on simulation studies or small deployments of wireless sensor networks.

Few real world WSN deployments resemble the envisioned kind of networks where vast numbers of nodes solving a collective task have to rely on limited energy resources. While these setups are existing, e.g. wild life monitoring [13], many installations are in urban environments. The sensors monitor decrepit bridges and buildings, support elderly in assisted living facilities, or are part of home automation systems. These kind of applications demand WSNs to integrate into existing network infrastructures like a wireless mesh network (WMN). New challenges emerge since the application specific devices are often performance limited and use feature reduced operation systems. They were not developed with integration and support of common often heavyweight protocols in mind. We discuss the integration aspect twofold. On one hand the WSN can be part of the overall architecture provided by an existing infrastructure. On the other hand the WSN hardware can also be beneficial for the WMN.

Furthermore, there is a lack of long-term experience with wireless sensor network applications, since many studies are limited in time or use small setups only. Few reports about long-term performance studies, reliability, and maintenance of wireless sensor networks have been published. Though,

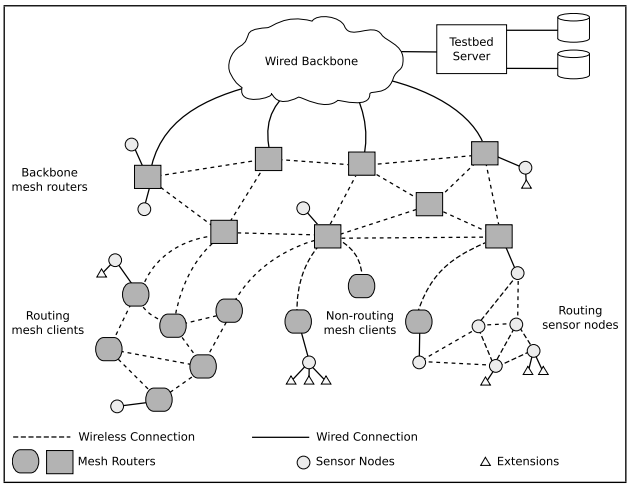

Figure 1: Architecture of the hybrid testbed consisting of mesh routers, mesh clients, sensor nodes, and the testbed server hosting management components including databases. Sensor nodes may be connected with wired extensions.

there are many real world applications with an intended runtime of several years. Life cycles of up to 10 years are a common demand in facility or animal monitoring. But how can we execute experiments of adequate time span? We present an approach to save and restore the network state at particular times.

The remainder of the paper is organized as follows. In Section 2, the architecture of the *Distributed Embedded Systems* (DES) testbed is introduced. Subsequently, in Section 3 we discuss our design concepts for integration. We compare our architecture and approach to other testbed setups in Section 4. The paper ends with a conclusion in Section 5.

2. HYBRID TESTBED ARCHITECTURE

At the time of this writing we are in the process to set up a hybrid testbed [9] at the *Freie Universität Berlin*. The testbed consists of hybrid nodes containing a wireless mesh router and a wireless sensor node in one shared enclosure. So far we installed 35 of these hybrid nodes in our office rooms spanning three floors with the goal to deploy 100 nodes in total. The WSN is our contribution to the European Union

WISEBED [3] project. This multi-level infrastructure of interconnected testbeds pursues the integration of heterogeneous small-scale devices for research on large scale. The European Union OPNEX [1] project in contrast is focused on the design of architectures and protocols for multi-hop wireless mesh networks based on IEEE 802.11 technology. The corresponding mesh routers are used as foundation of the hybrid testbed.

Figure 1 depicts our general system setup which is based on a three tier architecture. Mesh routers and sensor nodes are deployed in our institute in a planned but not uniform manner. As part of future extensions adjacent buildings will be comprised. The stationary mesh routers build the core backbone network representing tier 1. Tier 2 comprises the clients connected to a backbone router which may or may not provide a routing service themselves depending on the test run configuration. The usual mesh client is regarded as mobile. Tier 3 encompasses the sensor nodes which are connected by wire to a mesh router or client. A subset of sensor nodes may be operated independently of the mesh network infrastructure with alternative power supply, creating an even more dynamic topology.

2.1 Testbed Server and Network Management

The testbed server is connected by ethernet to the mesh routers and provides their root filesystem over the network using NFS. Log files and evaluation data for mesh and sensor network test runs are stored on the testbed server in a PostgreSQL database. The testbed server hosts a management console implemented in the Java programming language which provides the user interface to both networks. The management console enables the configuration and maintenance of the network components, realized with a combination of SSH remote command execution and the SNMP service. SNMP agents running on the mesh routers offer a convenient way to configure and debug the network state. The testbed server is also responsible of the task to schedule experiments and their execution. In order to have a uniform and easy-to-read way of defining reproducible experiments, we started to develop a domain specific language (DSL) based on XML. The DSL comprises meta information and experiment specific settings both for sensor and mesh network in an uniform structure.

2.2 Wireless Mesh Router

The mesh router component of the hybrid nodes is based on an Alix2c2 mainboard, featuring a 500 MHz AMD Geode LX800 CPU and 256 MB RAM. A customized Debian Linux is used as operation system. A minimum of three IEEE 802.11 based NICs are attached to a mesh router over a powered USB hub. Due to experimental results and driver availability [7] for Linux we chose Logilink WL0025 adapters based on the RT2501U [2] chipset.

2.3 Wireless Sensor Network Node

Our current generation of sensor nodes is called *MSB-A2* and was developed at the *Freie Universität Berlin* as part of the ScatterWeb [5] working group. The sensor nodes are connected to each hybrid node via USB. The ARM7 based devices can be configured dynamically at runtime up to 60 MHz depending on the sensor network application and energy requirements. The Chipcon CC1100 transceiver in our configuration uses the ISM band at 868 to 870 MHz with a maximum data rate of 500 kbps. The WSN nodes can be equipped with a multitude of sensors using either simple general purpose input/output pins (GPIO) or an on-board mini USB port. Additional peripheral devices can also be connected to the mesh routers. We aspire full integration of WPANs, TETRA and cellular networks (GSM). Our current research projects have taught us that convergence of WSNs and other technologies is crucial for industrial adoption and to solve real world problems.

3. TESTBED DESIGN CONCEPTS

In this section we discuss the integration of the sensor nodes into our existing wireless hybrid testbed. We elaborate the possibilities in regard of configuration and management.

3.1 Exploiting the Infrastructure

The mesh routers connected by ethernet to the testbed server constitute the backbone infrastructure for the wireless sensor network. The core part of our *wireless sensor testbed integration* (WSTI) approach consists of the USB connection between sensor node and mesh router which provides a serial terminal and flash interface. The latter is utilized to reprogram all sensor nodes with an updated firmware image or additional software, since experimentation with sensor networks requires frequent reprogramming with additional and bug-fixed software. Additionally approaches to distribute binary images in a sensor network do already exist [11]. We intend to use them as a foundation to implement an over-the-air flashing feature. In case such an over-the-air flashing process fails, we fall back to the wired infrastructure and make use of the described flash interface provided by the USB connection, therefore minimizing the need of manually handling the sensor nodes. This will be achieved by placing a firmware image on the testbed server. The mesh routers access the firmware image and flash it on their locally mounted sensor node.

The serial terminal interface, also provided by the USB connection, will be used to monitor the state of the wireless sensor network. The hosting mesh router sends commands to the sensor node in order to trigger a desired behavior in the context of an ongoing experiment or to retrieve the current information about its state. As mentioned in section 2.1 we implement these features with a combination of SSH remote command execution and the SNMP service. An SNMP agent responsible for the sensor node will enable real time configuration and debugging. Information regarding the sensor network state will be gathered periodically, while additional requests can be issued on demand. These sensor node log files will be stored locally on the mesh routers. The logged data is then transferred to the testbed server periodically as well as after the completion of experiments. Therefore the testbed server functions as a central data storage point for the sensor node log files.

With our management console hosted at the testbed server we will have a powerful tool to maintain and configure the locally distributed sensor nodes centrally in a very convenient way minimizing the need of physical access. Sensor nodes can be selected and configured on demand to satisfy the means of a given experiment. Therefore, it will also be

possible to run concurrent experiments with a subset of sensor nodes. Further we extend the management console with the feature to monitor the sensor network state in real time and interact with the sensor networks behavior by sending commands to sensor nodes.

3.2 Long-term Experiments

Safety and security critical applications require long-term experiments and studies that seldom are possible in a continuous manner. Due to several reasons it might be necessary to interrupt and continue test runs at arbitrary times. Often we need to have a comparable environment during the whole experiment without much variance in interference and fading. These kind of experiments usually have to be done at night shift when no link interruptions due to crowds of people exist or interfering radio devices are operated. To expand the time span over the duration of a night we have to make a snapshot of the whole network state that can be restored later on. The continuation after hardware failures and software updates are similar scenarios to be considered. These issues are addressed by our concept under the name of *network check points* (NCPs). The restoration of the latest consistent network state also avoids repetition of interrupted experiments. In many cases only selected time intervals containing particular events of experiments are of interest. Using NCPs it will be possible to observe and evaluate how different implementations perform under the same given circumstances, e.g. an update of a routing protocol. This event-oriented experimentation is usually only achievable by configuring all nodes of the network manually and defining their states one after another. With our approach we will be able to record a successful experiment run and make use of the gathered information for future application scenarios.

To provide such a feature our system has to be able to save each node's state at arbitrary times. That includes global variables, stack content, CPU and transceiver status. One of the arising challenges is to do this operations in the shortest time possible. The sensor nodes have to continue to be an active part of the network with minor downtime. In contrast, the restoration of the state is not time critical but requires a network wide switch to signal all nodes to continue their tasks. NCPs rely on a shared timebase for all sensor nodes which can be provided by the mesh network.

We are still undecided whether such a feature will interfere with the WSN and introduce short but unwarranted downtimes of nodes. An initial evaluation will examine if periodical NCPs in discrete time intervals are feasible or just infrequent ones are tolerable.

3.3 Interfacing the Sensor Nodes

One of our more ambitious concepts focuses on the integration of the used radio transceiver into the Linux kernel as a driver module. The sensor node shall be provided as an additional network interface card. In the context of the ISO/OSI reference model the sensor node represents the lower two layers (physical and data link). This feature will offer us additional channels in the ISM frequency band that are orthogonal to IEEE 802.11. Recent reports [6] and our own measurements [8] have identified this aspect as one of major concerns for multi-transceiver based research. Interference does exist even between orthogonal channels. Some operation system related changes and extentions are required both on the sensor node as well as the mesh router side.

We will use a stripped down version of our ScatterWeb OS. Most interrupts have to be switched off for low latency except the ones used for transceiver and serial line handling. One USART interface of the microcontroller is connected to a USB to serial converter chip. Data sent from the host to the sensor node has to be relayed with minimal handling to the transceiver and vice versa. Media access and queuing of frames shall remain in the firmware, but everything else has to be handled by the Linux kernel. We call this integration *wireless sensor kernel interface* (WSKI). There are two ways to implement the WSKI. Right now the sensor node is represented as a type writer device (e.g. ttyUSB0). With a custom-tailored serial communication protocol we send arbitrary data via the transceiver. This solution is simple and requires no code changes, but complicates a seamless integration. While sending data between sensor nodes each packet has to be extracted from the Linux kernel protocol stack and channeled into the type writer device. After transmitting packets as payload of frames the process has to be done in reverse order at the destination host. Each received frame has to be injected into the stack. In contrast, our preferred solution aims at the integration of the sensor node into the Linux kernel as a common network device. By providing a new networking interface no kernel modifications are required and route discovery and packet forwarding features can be exploited. Furthermore, this approach is on par with kernel modules that drive USB host-to-host network cables or USB ethernet converters.

Adaptation of the Address Resolution Protocol (ARP) to our host-to-network layer and the deviant Maximum Transmission Unit (MTU) of frames using the sensor node as network device are remaining problems. In addition, we need to provide configuration programs alike the wireless-tools in up-to-date Linux distributions. These shall enable users e.g. to switch channels, configure power settings, set the data rate, and scan for networks using a unified, well-known interface.

In the long-term the integration also offers the potential to run the upper layer sensor network protocol implementations via emulation or as native compiled binaries on the mesh router on top of WSKI. This will simplify debugging and monitoring of the entire WSN. As an outlook a port of the ScatterWeb OS as kernel module might even be possible.

3.4 Tracing and Simulation

The ethernet backbone connection provides virtually unlimited storage capacity, which enables to trace network traffic over long periods of time. As one of the important aspects of the WISEBED project the collected data will be used as input for simulative experiments and as comparative results. Data gathered from real world experiments is vital to evaluate and improve simulation models. The testbed server runs the *data gathering and management* (DGM) service and will be responsible to configure the granularity of traces and data logging. The mentioned DSL in section 2.1 supports the specification of desired trace data.

4. RELATED WORK

The Deployment Support Network (DSN) [4] developed at the ETH Zürich consists of an additional wirless backbone network formed by DSN-Nodes and allows monitoring and managing of a deployed WSN. The wireless setup provides the possibility to attach a DSN to sensor networks in locations which lack a wired infrastructure. A DSN-Server provides a client interface to communicate with the DSN. Each DSN-Node has exactly one wired connection to one sensor node of the attached WSN. The wired connection is realized using a hardware UART interface mounted on the DSN-Nodes. To avoid interference with the monitored WSN, backbone traffic uses Bluetooth radios. Since the DSN-Nodes are battery powered and considering the high power consumption of Bluetooth radios, long-term observation may be limited. Experiments revealed that the limited memory of the DSN-Nodes restricts backbone traffic because only a small amount of packets can be buffered on each node at a time. To avoid debug message loss at backbone level, in a setup with 25 DNS-Nodes, each DNS-Node could send no more than one packet every two seconds. Thus scalability problems might arise. The TKN Wireless Indoor Sensor network Testbed (TWIST) at the TU Berlin [10] provides a large scale testbed for wireless sensor devices. So far about 90 sensor nodes have been deployed. Network Attached Storage (NAS) devices called super nodes form the backbone of the sensor network by providing a power source and functioning as gateway to wired infrastructure. Multiple xeyesIFX and Telos off-the-shelf sensor nodes are attached to a super node via USB hubs and cables. An important feature is the power supply control, which according to the USB Hub Specification 2.0 enables software side port power switching. With this feature the simulation of dynamic topologies common in sensor networks caused by unresponsive, moving, or newly deployed nodes becomes very convenient. While the super nodes run a customized Linux, TinyOS is in use for the sensor nodes with extensions to offer remote procedure function calls (RPC). The Korea Advanced Institute of Science and Technology (KAIST) [12] reports that their wireless mesh network called WiSEMesh is used as backhaul network for a WSN but no publiction with further information does exist.

5. CONCLUSION

In this paper we described the integration of our wireless sensor network into an existing IEEE 802.11 mesh network infrastructure. The work-in-progress hybrid testbed offers advanced features once the initial setup phase has been finished. We presented the concept of architectural integration of the wireless sensor networks with our *wireless sensor testbed integration* (WSTI) approach. We discussed the benefits for the mesh network gained through the kernel interface WSKI. Our concept of *network check points* (NPCs) will simplify long-termed and disrupted experiments and help to understand and evaluate networks and protocols. The extensive data gathered by our testbed shall provide more realistic simulation input. Finally, an XML-based domain specific language to specify, execute, and evaluate experiments in both parts of the testbed is being developed.

6. ACKNOWLEDGEMENT

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Klassifikation von sicherheitsrelevanten Einsatzszenarios für drahtlose Sensornetze

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ABSTRACT

Mit der wachsenden Bedeutung von drahtlosen Sensornetzen in der Praxis wird auch das Thema Sicherheit in Sensornetzen wichtiger. In der Vergangenheit wurden eine Fülle von Sicherheitsmechanismen für drahtlose Sensornetze vorgeschlagen. Die Umsetzung von solchen Sicherheitsmechanismen in der Praxis ist aufgrund abweichender technischer Voraussetzungen häufig mit Schwierigkeiten verbunden. Ein geplantes BSI-Projekt soll wesentliche Einsatzszenarios für Sensornetze identifizieren und Sicherheitsmechanismen auf Eignung in diesen Szenarios prüfen. Der Ansatz dieses Projekts soll hier präsentiert und zur Diskussion gestellt werden.

1. EINFÜHRUNG

Das Thema "drahtlose Sensornetze" erlebt seit einigen Jahren einen rasant wachsendes Interesse in der Informatik. Ursprünglich wurden Sensornetze für militärische Zwecke konzipiert, heute werden Sie auch und vor allem für zivile Einsatzzwecke betrachtet. In der Vergangenheit waren tatsächlich realisierte Sensornetz-Systeme eher prototypischer Natur, was darauf hindeutet, dass noch viele praktische Probleme für einen robusten Einsatz von solchen Netzen zu lösen sind. Es ist jedoch abzusehen, dass drahtlose Sensornetze in der Praxis zunehmend an Bedeutung gewinnen werden. Ihre Flexibilität macht sie attraktiv für eine Vielzahl von *Einsatzszenarios*, insbesondere dort, wo Umgebungsdaten auf unkomplizierte und kostengünstige Art und Weise erhoben werden müssen.

Mit der zunehmenden Verbreitung von Sensornetz-Applikationen, gewinnt das Thema Sicherheit in Sensornetzen an Bedeutung. Das Stichwort "Sicherheit" umfasst zwei Ausprägungen. Zum einen ist damit die Ausfallsicherheit, d.h. die Verfügbarkeit gemeint, zum anderen die Informationssicherheit (also die Gewährleistung von Integrität, Authentizität und Vertraulichkeit von übermittelten Informationen bzw. der Schutz vor bösartigen Angriffen). Die Umsetzung von Sicherheit ist in Sensornetzen mit besonderen Herausforderungen verbunden. Die aus Kostengründen vergleichweise leistungsschwache Hardware und der begrenzte Energievorrat auf Sensorknoten machen die Umsetzung von Sicherheitsmechanismen (neben der eigentlichen Funktionalität) relativ schwierig.

Es existiert zwar eine Vielzahl von Publikationen zu *Sicherheitsmechanismen in Sensornetzen*, häufig wird jedoch nicht klar, für welchen Einsatzzweck die vorgeschlagenen Mechanismen konzipiert sind oder ob sich die technischen Voraussetzungen für einen Mechanismus erfüllen lassen. Dies gilt umso mehr angesichts der Tatsache, dass die unterschiedlichen Einsatzszenarios für Sensornetze zu ganz unterschiedlichen technischen Lösungen/Realisierungen führen. Konkrete technische Merkmale können jedoch dazu führen, dass bestimmte vorgeschlagene Sicherheitsmechanismen nicht mehr anwendbar sind.

Ziel eines geplanten Projekts des Bundesamts für Sicherheit in der Informationstechnik ist es, eine Bestandsaufnahme über praxisrelevante Einsatzszenarios von drahtlosen Sensornetzen zu gewinnen, diese geeignet zu klassifizieren, den Schutzbedarf für unterschiedliche Anwendungsklassen festzustellen und schließlich geeignete Maßnahmen zur Umsetzung der Sicherheitsziele zu empfehlen. Im Januar 2008 hat das BSI hierzu ein Workshop organisiert, an dem einige Institutionen teilgenommen haben, die im Bereich Sensornetze tätig sind, und auf dem erste Ideen zum Vorgehen zusammengetragen und diskutiert wurden. In diesem Abstract sollen die dort diskutierten Ideen und das geplante Vorgehen im o.g. Projekt vorgestellt werden. Im folgenden Abschnitt 2 sollen kurz beispielhaft einige Einsatzszenarios für Sensornetze und mögliche technische Merkmale diskutiert werden. In Abschnitt 3 soll ein Überblick über unterschiedliche Sicherheitsmaßnahmen verschafft werden. Schließlich wird in Abschnitt 4 das Vorgehen im Projekt erläutert.

2. EINSATZSZENARIOS FÜR DRAHTLOSE SENSORNETZE

Drahtlose Sensornetze werden unter anderem für den Einsatz in der Umweltbeobachtung, im Katastrophenschutz, in der Infrastruktur- und Gebäudeüberwachung, im Gesundheitwesen in der Logistik oder für die Grenzüberwachung vorgeschlagen. Im folgenden sollen beispielhaft einige dieser Szenarios konkretisiert werden.

2.1 Stabilitätsprüfungen

Ein Einsatzszenario, das intensiv untersucht wird, ist die Stabilitätsprüfung von Bauwerken, insbesondere Brücken. Bauwerke sind in vielen Fällen starken mechanischen Belastungen ausgesetzt, sei es durch Benutzung (schwere Fahrzeuge, die über Brücken fahren) oder ungünstige Umwelteinflüsse (Erdbeben, Stürme etc). Dies macht eine ständige Prüfung der Integrität solcher Bauwerke erforderlich. Häufig werden solche Prüfungen mit Hilfe fest verbauter kabelgebundener Sensorsysteme realisiert. Hier bieten sich drahtlose Sensornetze als kostengünstige und flexible Alternative

an. In [6] wird ein Überblick über die zahlreichen protoypischen Systeme dieser Art gegeben. Messungen werden hierbei in den meisten Fällen mit Hilfe von Beschleunigungs- bzw. Erschütterungssensoren oder Dehnungsmessstreifen erhoben. Im ersten Fall müssen die Messungen (zumindest zeitweise) mit einer relativ hohen Samplingrate durchgeführt werden. Viele Systeme können Messungen direkt auf den Knoten verarbeiten (dazu sind z.B. FFT oder Wavelet-Transformationen notwendig), was Energievorteile gegenüber einer direkten Übertragung der Meßwerte an eine Basisstation hat. Häufig wird auch eine zweischichtige Gesamtarchitektur der Systeme vorgeschlagen. Auf der unteren Schicht befinden sich die eigentlichen Sensorknoten, die die Meßwerte erheben. Einer Gruppe solcher Knoten wird jeweils ein Zentralknoten auf der oberen Schicht zugeordnet. Dieser sammelt und verarbeitet die Meßwerte der Sensorknoten. Die Zentralknoten verfügen über leistungsfähigere Hardware und können auch untereinander (über größere Distanzen) kommunizieren.

2.2 Patientenüberwachung

Die Verfügbarkeit von konstengünstigen und nicht-invasiven medizinischen Sensoren macht den Einsatz von Sensornetzen zur Patientenkontrolle in Kliniken interessant. Solche Systeme lassen sich dazu nutzen, Patienten (oder Krankenhauspersonal) schnell zu lokalisieren, Notfälle rechtzeitig zu erkennen und dadurch die Versorgung von Kranken und Verletzten zu verbessern. Systeme zur Patientenlokalisierung sind bereits kommerziell verfügbar [1]. In [7] wird eine konkrete Architektur für ein derartiges System vorgestellt. MICA2-Sensorknoten werden dort mit einem Pulsmesser und Oximeter ausgestattet. Die Vitaldaten werden entweder per Ad-Hoc-Routing an eine Basis oder direkt an PDAs, die Ärzte mit sich führen, übertragen. Fest installierte Lokalisierungsknoten erlauben die ungefähre Ortung eines Knotens. Das Routingprotokoll muss den hohen Grad der Mobilität der Knoten berücksichtigen.

2.3 Grenzüberwachung

Die Eignung von drahtlosen Sensornetzen für Grenzüberwachungsszenarios wurde in unterschiedlichen Projekten untersucht. Im Rahmen des Projekts ExScal [2] wird ein entsprechender Protoyp beschrieben, der aus mehr als 1200 Sensorknoten besteht. Das System soll Personen und Fahrzeuge in einem 1.260×288 m großen Areal zuverlässig detektieren, klassifizieren und nachverfolgen. Zu diesem Zweck sind die Sensorknoten mit Passiv-Infrarot-Sensoren, Magnetometern und Mikrofonen ausgestattet. Die Gesamtarchitektur entspricht einer dreischichtigen Hierarchie und besteht aus den eigentlichen Sensorknoten (Schicht 1), Aggregationsknoten (Schicht 2) und der Basisstation (Schicht 3). Die Knoten werden per Hand in einem Raster in besagtem Areal angeordnet. Meßdaten der Sensoren auf Schicht 1 werden auf den Knoten vorverarbeitet, um Fehlalarme möglichst auszuschließen. Die Daten werden über Schicht-2-Knoten an die Basisstation weitergeleitet, wo eine entsprechende Aggregation und Klassifikation der Daten stattfindet. Über die Basisstation kann das Verhalten sämtlicher Knoten konfiguriert werden.

2.4 Designmerkmale

Betrachtet man obige und weitere Einsatzszenarios genauer, stellt sich heraus, dass sich die dort realisierten Systeme in vielen *Designmerkmalen* unterscheiden [3, 9]. Nachfolgend sind einige der wesentlichen technischen Merkmale aufgeführt.

- Kommunikationstopologie
  Die Kommunikationstopologie beschreibt, welche Knoten mit welchen anderen Knoten direkte Funkverbindungen aufbauen und auf welchen Pfaden Nachrichtenpakete zu anderen Knoten gelangen. Mögliche Topologien sind z.B. die Sterntopologie (Sämtliche Sensorknoten kommunizieren direkt mit einer Basisstation) oder die Baumtopologie (Pakete werden über mehrere Zwischenknoten an eine Basis geleitet).

- Heterogenität der Knotenhardware
  Eine Applikation kann aus gleichförmigen Sensorknoten bestehen, oder es existieren Knoten mit unterschiedlicher Hardware, die verschiedene Aufgaben wahrnehmen.

- Kommunikationsrichtung
  Werden Nachrichtenpakete stets von den Sensorknoten an die Basis geschickt oder auch in anderer Richtung von der Basis zu den Knoten?

- Aktivitätszyklus
  Anwendungen können höchst unterschiedliche Anforderungen an den Aktivitätszyklus eines Knoten stellen. Anwendungen zur Klimabeobachtung z.B. erfordern i.d.R. Messungen im Stunden- oder Minutenabstand, die Stabilitätsprüfung von Bauwerken benötigt mehrere hundert Messungen pro Sekunde (über einen begrenzten Zeitraum). Knoten können darüber hinaus ausschließlich zeitgesteuert oder durch äußere Einflüsse aktiviert werden.

- Größe des Netzes
  Die Anzahl der eigesetzten Sensorknoten kann zwischen einigen wenigen und mehreren Hundert schwanken.

- Vorhandene Infrastruktur
  Sensornetze verfügen in der Regel über ein oder mehrere Datensenken, an die letztlich die erhobenen Daten übermittelt werden. Es ist darüberhinaus denkbar, dass dezidierte Router oder Zwischensenken existieren.

- Mobilität der Knoten
  Knoten können über die gesamte Betriebszeit entweder ortsfest sein oder sich (aktiv oder passiv) bewegen.

- Vorhandene Aktorik
  Sensornetze können (ohne menschliches Eingreifen) aktive Regelungsfunktionen übernehmen und z.B. Ventile, Klimaanlagen oder Alarmeinrichtungen ansteuern.

- Datenaggregation
  Meßdaten können entweder direkt an eine zentrale Basisstation übermittelt werden, wo sie dann ausgewertet werden, oder sie können (lokal) auf bestimmten Knoten vorverarbeitet werden (z.B. Berechnung des Durchschnitts, Minimums oder Maximums unterschiedlicher Meßwerte), um das Kommunikationsaufkommen zu verringern.

- Netzdynamik
  Die Menge der eingesetzten Knoten wird gewöhnlich schon zu Beginn festgelegt. Ein System kann aber auch so eingerichtet sein, dass während des Betriebs ohne großen Aufwand zusätzliche Knoten hinzugefügt werden können.

- Zeitmessung
  Sensorknoten können entweder über lokale (synchronisierte) Uhren verfügen, oder sämtliche Zeitmessungen werden (wenn nötig) zentral vorgenommen.

- Lokalisierung
  In den allermeisten Einsatzszenarios ist man an der geographischen Position der Sensorknoten interessiert. Diese kann z.B. durch dezidierte Hardware auf den Knoten ermittelt werden (GPS-Receiver). Andere Möglichkeiten sind verteilte Lokalisierungsverfahren (die auf Signalstärke oder -laufzeiten beruhen) oder eine manuelle Positionszuordnung.

- Rekonfigurierbarkeit
  Das Ausmaß, in dem Knoten während des Betriebs rekonfigurierbar sind, kann unterschiedlich groß sein. Knoten können in ihrem Verhalten festgelegt sein, oder es kann geändert werden. Die Spannbreite reicht dabei von einzelnen Parametern, die geändert werden können (z.B. Länge der Meßintervalle), bis zu einem (fast) vollständigen Austausch des Programms (OTAP).

Es soll bemerkt werden, dass zwei unterschiedliche Implementierungen innerhalb desselben Einsatzszenarios auch zu unterschiedlichen Ausprägungen der genannten technischen Merkmale führen können. Dennoch hat in der Regel das jeweilige Szenario einen entscheidenden Einfluss auf das Design des Systems und legt dieses in weiten Teilen fest, weswegen man von den *Desginmerkmalen eines Einsatzszenarios* sprechen kann. Sollten die oben genannten Szenarios tatsächlich breit in der Praxis umgesetzt werden, spielen automatisch Sicherheitsfragestellungen eine Rolle. Dies betrifft sowohl die Informationssicherheit als auch die Ausfallsicherheit. Die Ausprägung der technischen Merkmale hat bedeutenden Einfluss auf die Auswahl geeigneter Sicherheitsmechanismen.

3. SICHERHEITSMECHANISMEN

Die oben genannten Einsatzszenarios werfen eine Reihe von Sicherheitsfragestellungen auf. Im Fall der Patientenlokalisierung dürfen Unbefugte z.B. nicht beliebig auf sensible Patientendaten zugreifen können. Das Grenzüberwachungssystem darf durch einen Angreifer, der das Gebiet passieren will, nicht außer Betrieb gesetzt werden, und bei der Gebäudeüberwachung sollten absichtliche Fehlalarme nach Möglichkeit verhindert werden. Die Sicherheitsanforderungen, die in Sensornetzen von Belang sind, lassen sich in den allermeisten Fällen auf die abstrakten Anforderungen Integrität, Authentizität, Vertraulichkeit von Nachrichten und Verfügbarkeit zurückführen. Die ersten drei Anforderungen werden in IT-Systemen durch kryptographische Verfahren realisiert, die vierte in der Regel durch Infrastrukturmaßnahmen. Im Falle von Sensornetzen muß bei Sicherheitsmechanismen insbesondere die Ressourcenbeschränkung der Hardware berücksichtigt werden.

In der wissenschaftlichen Literatur wurden in den letzten Jahren zahlreiche Sicherheitsmechanismen und -protokolle für drahtlose Sensornetze vorgeschlagen. Hierzu gehören Verfahren zur Schlüsselvereinbarung und -verteilung, zum authentischem Broadcast, zum sicherem Routing und zur sicheren Aggregation, zur sicheren Lokalisierung, zur Erkennung von DoS-Angriffen und zur Detektion von geklonten Knoten. Diese werden meistens jedoch unabhängig von einem konkreten Einsatzszenario vorgeschlagen. Ebenso wie sich die technischen Merkmale in obigen Applikationen unterscheiden, gehen die vorgeschlagenen Sicherheitsmechanismen von ganz unterschiedlichen technischen Voraussetzungen aus. Einige Beispiele:

- μTESLA [8], ein Verfahren zur Authentisierung von Broadcasts, setzt synchronisierte Uhren auf den Sensorknoten und einer Basisstation voraus.

- Das in [5] vorgeschlagene Verfahren zum sicheren Routing und zur Sperrung kompromittierter Knoten setzt unveränderliche Nachbarschaftsbeziehungen der Knoten voraus, d.h. Knoten müssen statisch sein, und es können keine Knoten in späteren Phasen hinzugefügt werden.

- Verfahren wie [4], die auf gegenseitiger Kontrolle der Sensorknoten beruhen, setzen für ein akzeptables Sicherheitsniveau voraus, dass das Netz über eine große Anzahl an Knoten und jeder einzelne Knoten über hinreichend viele Nachbarn in Funkreichweite verfügt, also dass die Topologie ausreichend dicht ist.

- Einige Schlüsselvereinbarungsverfahren wie etwa [10] benötigen einzelne leistungfähige Knoten als Clusterheads, was zu heterogener Hardware im Netz führt.

Damit ist häufig nicht klar, für welches Einsatzszenario sich ein konkreter Sicherheitsmechanismus tatsächlich eignet (oder ob so ein Einsatzszenario überhaupt existiert). Zudem bauen einige Verfahren auf anderen auf, z.B. wird für viele abgesicherte Routingverfahren eine anfängliche Schlüsselvereinbarung zwischen benachbarten Knoten angenommen, so dass diese höherwertigen Verfahren wiederum auf solche Szenarios einschränkt sind, die das zugrundeliegende Verfahren erlauben.

4. KLASSIFIZIERUNG VON EINSATZSZENARIOS

Aus den oben beschrieben Gründen plant das BSI das genannte Projekt zur Klassifizierung von Einsatzszenarios für Sensornetze, in dem darüber hinaus Einsatzempfehlungen für konkrete Sicherheitsmechanismen in den einzelnen Szenarios entwickelt werden sollen. Diese Klassifizierung soll einerseits Hilfestellung bei der Auswahl von Sicherheitsmechanismen in der Praxis bieten und andererseits noch zu lösende Forschungsfragen hinsichtlich Sicherheit in drahtlosen Sensornetzen offenlegen. Darüber hinaus soll die Klassifizierung eine Vergleichbarkeit unterschiedlicher Mechanismen erlauben. Das Projekt gliedert sich in zwei Teile.

Zunächst soll eine systematische Übersicht über Einsatzszenarios für Sensornetze, die schon umgesetzt wurden oder von

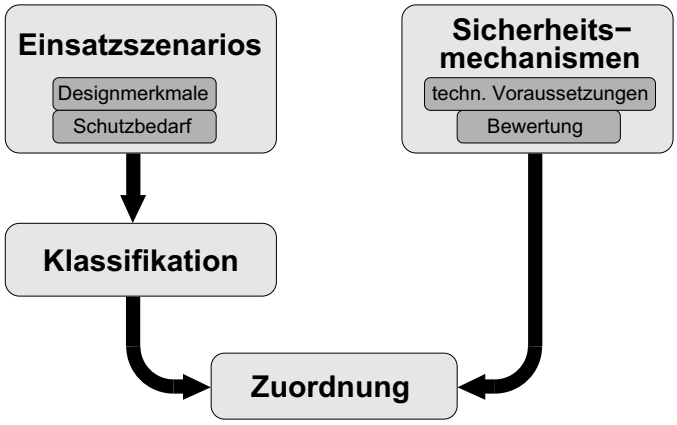

Abbildung 1: Vorgehen zur Klassifikation von Einsatzszenarios

denen dies in naher Zukunft zu erwarten ist, erstellt werden. Dabei soll versucht werden, die technischen Designmerkmale (Abschnitt 2.4), die durch das Szenario festgelegt werden, zu bestimmen. Für ein konkretes Einsatzszenario kann auch eine gewisse Bandbreite bei einem Merkmal vorliegen, d.h. unterschiedliche Implementierungen führen zu unterschiedlichen technischen Merkmalen. Gleichzeitig soll möglicher Schutzbedarf in den einzelnen Szenarios ermittelt werden, d.h. es soll geprüft werden, welche Gefährdungen im jeweiligen Einsatzszenario auftreten können und wie gravierend diese Gefährdungen sind (Beispielsweise hat ein System zur Grenzüberwachung einen hohen Schutzbedarf, ein System zur Umweltüberwachung ein eher niedriges).

Anhand der gefundenen Merkmalsausprägungen soll anschliessend eine Klassifikation der Einsatzszenarios stattfinden. Eine Klasse soll dabei aus Szenarios bestehen, die ähnliche oder die gleiche Ausprägungen der Designmerkmale bei einer Implementierung erfordern. Die Klassifizierung soll die Grundlage der in den folgenden Phasen zu findenden Handlungsempfehlungen für Sicherheitsmechanismen bilden.

In der zweiten Projektphase sollen möglichst umfassend veröffentlichte Sicherheitsmechanismen und -protokolle, die für den Einsatz in drahtlosen Sensornetzen konzipiert wurden, zusammengestellt und hinsichtlich ihrer Anforderungen untersucht werden. Falls möglich, soll jeweils eine Einschätzung über das durch den Sicherheitsmechanismus bereitgestellte Schutzniveau geliefert werden. Anschließend soll untersucht werden, ob sich ein Sicherheitsmechanismus einer (oder mehrerer) der gefundenen Klassen von Einsatzszenarios zuordnen läßt. Notwendig hierfür ist natürlich, dass die technischen Merkmale der Szenarios einer Klasse die Voraussetzungen der Sicherheitsmechanismen erfüllen. Zu berücksichtigen ist auch, ob ein Mechanismus den gewünschten Schutzbedarf in einem Szenario erfüllen kann. Auf diese Weise entsteht ein Katalog von Einsatzempfehlungen für konkrete Einsatzszenarios, und es lassen sich leicht noch offene Forschungsfragen ableiten, etwa, wenn für eine Klasse keine geeigneten Sicherheitsmechanismen gefunden wurden.

Im Rahmen des Projekts sollen ausdrücklich nicht vollständige Sicherheitsarchitekturen für einzelne Einsatzszenarios entworfen werden. Zunächst soll nur festgestellt werden, welche einzelnen Mechanismen für verschiedene Klassen überhaupt zur Verfügung stehen. Diese sollen dem Anwender beim Entwurf einer konkreten Sicherheitsarchitektur unterstützen.

5. ZUSAMMENFASSUNG

In drahtlosen Sensornetzen kann eine große Spannbreite an unterschiedlichen Techniken und Architekturen zum Einsatz kommen. Bei der Auswahl und dem Entwurf von Sicherheitsmechanismen ist dies zu berücksichtigen. Mit dem vorgestellten Klassifikationsansatz hoffen die Autoren, Informationssicherheit in Sensornetzen beherrschbar zu machen.

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Real-time, Bandwidth, and Energy Efficient IEEE 802.15.4 for Medical Applications

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ABSTRACT

The recently standardized IEEE 802.15.4 protocol provides many appealing features, such as low power, low cost, low data-rate, simplicity, and timeliness guarantee for delay-bound, energy, and bandwidth critical applications. However, when treating applications with such requirements as in the medical field, several problems arise, triggering the need of an efficient enhancement of the IEEE 802.15.4 protocol including the fine tuning of its parameters. In this paper, we discuss the suitability of the protocol and explore its limitations for health care applications. We propose a solution to overcome those limitations and derive the most efficient IEEE 802.15.4-based network parameters setting for urgent medical services.

Categories and Subject Descriptors

C.2.2 [**Computer-Communication Networks**]: Network Protocols

General Terms

Design, performance, standardization

Keywords

IEEE 802.15.4, real-time, bandwidth, energy efficiency, medical applications.

1. INTRODUCTION AND MOTIVATION

Recent trend towards achieving communications between short range devices has laid down the foundation of a simple, low cost, low power, low QoS, and low data-rate communication network called as low-rate wireless personal area network (LR-WPAN). IEEE 802.15.4 [1], which deals with the PHY and MAC layers for such networks, is an emerging protocol for multidimensional applications, such as surveillance and security, home automation, flood, fire, seismic detection, and health-care scenarios. Though, its pertinency and usage to many application areas has already been witnessed, many open questions are there to be answered, before IEEE 802.15.4-based networks can be efficiently utilized on a large scale, especially for the environments where timeliness is vital. For example; a sensor node embedded in an e-textile worn by patients should automatically, but timely alert doctors or emergency services when the patient suffers from severe disease; and nodes must lively inform the security and emergency services about the persons, wounded by a terrorist bomb blast. In such applications, usually many short-range and battery-operated devices are deployed. Hence, the bandwidth and energy efficiency also demand special attention, so that many devices can communicate at a time and can survive longer without any human interaction.

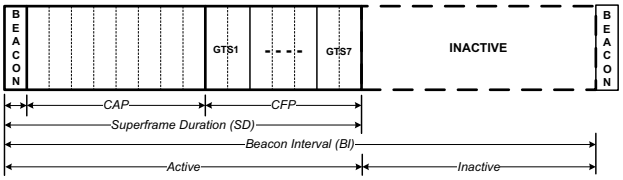


Figure 1: The MAC superframe is divided into 16 equally sized slots. Optionally, it can have an active and an inactive part. The active part is further divided into the CAP and the (optional) CFP part.

In clinical diagnostics, traditional paper based patient monitoring is difficult, complex, and expensive. The increase in the world population, diseases, and the natural and non-natural incidents, and with the inadequate number of doctors and clinicians available around, especially in the third world countries, highlights the need of an automatic system. Such system should efficiently but timely alert medical staff for any mishap or remind them for their scheduled check-ups, regardless to the personal's physical location. It can also be used to store patient records for the future research and automatic medication purposes.

In this paper, we discuss the suitability of an emerging IEEE 802.15.4 protocol in the medical field, especially its timeliness and bandwidth related features. We explore the limitations of the protocol and conclude that the standard compliant IEEE 802.15.4 protocol needs enhancements, before it can be applied to urgent medical applications. We propose an efficient solution to overcome those limitations and derive optimal parameter settings to enhance the IEEE 802.15.4 network performance in the medical field.

The remainder of the paper is organized as follows. In Section 2, we discuss IEEE 802.15.4 with its suitability to medical applications and limitations concerning latency, bandwidth, and energy issues. Afterwards in Section 3, we elaborate the state of the art related to our work. Subsequently in Section 4, we define our system model and propose solution to those limitations. We discuss performance evaluation in Section 5 and finally conclude the paper in Section 6.

2. IEEE 802.15.4 OVERVIEW

The IEEE 8021.5.4 protocol defines the PHY and MAC layers for LR-WPAN. It supports data rates of 20, 40, 100, and 250 Kbps within the range of around 10 meters and uses 16 channels in the 2.4 GHz band, 30 channels in the 915 MHz band, and 3 channels in the 868 MHz band. It supports both star and peer-to-peer operation with fully and reduced function devices (FFDs and RFDs). Handling the radio transceiver and physical medium, energy detection, link quality, channel selection, clear channel assessment are the main features of the PHY layer. Whereas, the MAC layer features include the beacon management, channel access, guaranteed time slots (GTS) management, frame validation, acknowledgments, association, disassociation, and the security mechanisms. The MAC protocol supports two operational modes selected by the coordinator. The *non beacon-enabled* mode, in which MAC is simply ruled by non-slotted CSMA/CA and the *beacon-enabled* mode, in which beacons are periodically broadcast by the coordinator in the MAC superframe.

The MAC superframe structure is defined in Figure 1. The beacon is always transmitted in the first slot and is used to synchronize the attached devices and to describe the superframe structure. During the contention access period (CAP), the devices compete with each other using a slotted CSMA/CA mechanism. For the applications having latency and specific bandwidth requirements, the coordinator may dedicate portions of the active superframe to that application. These portions are called guaranteed time slots (GTSs) and they form the contention-free period (CFP), which appears at the end of the active part following the CAP. The coordinator may allocate up to seven of these GTSs, and a GTS may occupy more than one slot period. The structure of the superframe is described by the two variables, beacon order (BO) and superframe order (SO). BO describes the interval at which the coordinator transmits its beacons, i.e. Beacon Interval (BI) and is given by (1). SO describes the length of the active portion, i.e. Superframe Duration (SD) and is given by (2). The parameter *aBaseSuperframeDuration* depends on the frequency range. SD and BI are the decisive parameters to define the duty cycle of the network.

$$BI = aBaseSuperFrameDuration * 2^{BO} \qquad 0 \leq BO \leq 14 \tag{1}$$

$$SD = aBaseSuperFrameDuration * 2^{SO} \qquad 0 \leq SO \leq BO \leq 14 \tag{2}$$

2.1 IEEE 802.15.4 Suitability and Limitations for Medical Applications

Figure 2 shows an health-care scenario, where different patients are to be treated in a room. The traffic generated by the nodes deployed in the room can be classified in two types: periodic and aperiodic. Periodic traffic contains the routine check-up values for the patients and physical status of the room. Usually, these values don't have strict timeliness requirements. Therefore, normal contention access method (CSMA/CA) is used for such traffic. However, the aperiodic traffic, which is generated on the basis of some unexpected event occurred with the patients or within the room, is very critical and needs guaranteed access to the channel and bandwidth as they must report before a worse case situation happens. The examples for such traffic are dramatically increase/decrease in the blood-pressure or an heart-attack to the patient, and unexpected temperature change in the room and the GTS services are used for such traffic. It looks straight forward to implement IEEE 802.15.4 in such scenarios, but following limitations of the protocol must be figured out before attempting this.

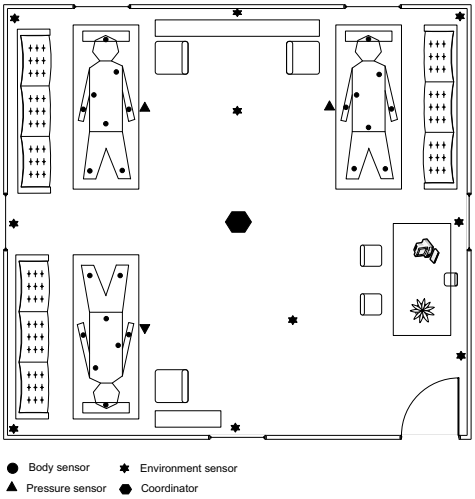


Figure 2: An health-care scenario, where some nodes are attached to the patient body to measure different biological parameters, such as heart and pulse rate, blood pressure, blood oxygen saturation, electrocardiogram (ECG), and electroencephalograph (EEG) values. Other nodes are deployed inside the room to measure the physical parameters, such as temperature, air pressure, humidity, and the light values. The pressure sensors, deployed under/near the patient bed, timely alert the medical staff for an unexpected downfall of the patient. The coordinator is responsible to collect and forward the traffic generated by these nodes.

The first and foremost problem with the current GTS allocation is the bandwidth under-utilization. Most of the time, device uses only a small portion of the allocated GTS slots, the major portion remains unused resulting in an empty hole in the CFP. Moreover, the protocol explicitly supports only seven GTS allocations. In the medical field, where one illness usually boost-ups other illnesses, many devices should be able to reach the coordinator via such guaranteed services. Also, the current protocol only supports first come first serve based GTS allocation and does not take into account the traffic specification, delay requirements, and the energy resources. In medical scenario, many critical events may occur at a time, and some of them are more critical and need most urgent response. With the current protocol, the device can request for all seven GTS slots, even if it is not really needed. Such unbalanced slot distribution can block other needful devices to take such timeliness advantages. Moreover, the protocol uses GTS expiration on

the basis of some constant factors and the assigned GTS slots are broadcast for the constant number of times in the superframes. Such restrictions also cause unnecessary energy consumption and CFP slots blockage for longer time. Even if CFP is not present in the superframe, the beacons transmitted by the coordinator always use unnecessarily one byte of the CFP, resulting in energy inefficiency. Last but not least, the current superframe structure contains at least *aMinCAPLength* (a constant) size CAP. For most urgent scenarios, we may need flexible size CAP rather than the fixed one.

3. RELATED WORK

Most of the IEEE 802.15.4 related research has been subjected to the CSMA/CA, and general performance evaluation. Only a small amount of the literature deals with the timeliness and bandwidth issues. An implicit GTS allocation scheme (i-GAME) for the time-sensitive WSN is proposed in [6], where the coordinator uses an admission control algorithm to decide whether to accept a new GTS request or not, based on the traffic specification of the flows, and their delay requirements. Using Network Calculus formalism in [7], two accurate models for the service curve are proposed and the delay bounds guaranteed for GTS allocation is provided. An expression of the duty cycle as a function of the delay is also presented. Based on those results, the impact of the BO and SO on the maximum throughput and delay bound is analyzed. In [4] adaptive GTS allocation (AGA) scheme is proposed, which considers low-latency and fairness. There are two phases for the proposed scheme. In the classification phase, devices are assigned priorities in a dynamic fashion based on recent GTS usage feedbacks. Devices, that need more attention from the coordinator, are given higher priorities. In the GTS scheduling phase, GTSs are given to devices in a non-decreasing order of their priorities. A starvation-avoidance mechanism is presented to regain service attention for lower-priority devices that need more GTSs for data transmissions. A simulation model and an analytical model are developed to investigate the performance of AGA scheme. The work in [5], suggests a multi-beacon superframe (MBS) structure with multiple sub-beacon intervals for different slot sizes in a superframe and a greedy GTS allocation (GGA) algorithm, where device determines the most appropriate slot sizes based on their traffic characteristics. They claim to have significant improve in the bandwidth utilization at the expense of only a very small increase of the device's active periods. A distance-based, real-time off line periodic message scheduling algorithm is proposed in [9], which generates BO, SO, and GTS information to schedule the given message set.

4. SYSTEM DESCRIPTION

We consider an IEEE 802.15.4-based network, which works in star topology with beacon-enabled mode and uses 2.4 GHz frequency band with O-QPSK modulation [8]. The coordinator collects data from its CFP regarding the devices, that need GTS slots, assembles the beacon, and transmits it. After that CAP starts which follows the optional CFP. On the other hand, the device first synchronizes itself with the coordinator, makes its receiver on just before the beacon arrival time, and receives the beacon. That follows CAP and then CFP, where the device first checks for its GTS slots and if it finds its GTS entry, it can utilize it by sending/receiving data. After using its GTS slots, the device makes its radio off again. The device can send new GTS request via its CAP to the coordinator and if the request is accepted, its GTS entry will be added to the upcoming beacon. The node requests for GTS slot by specifying its data, delay, and energy conditions and the coordinator, who runs an admission control (AC), decides the fate of the request.

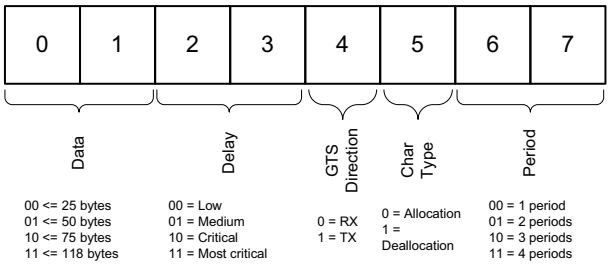
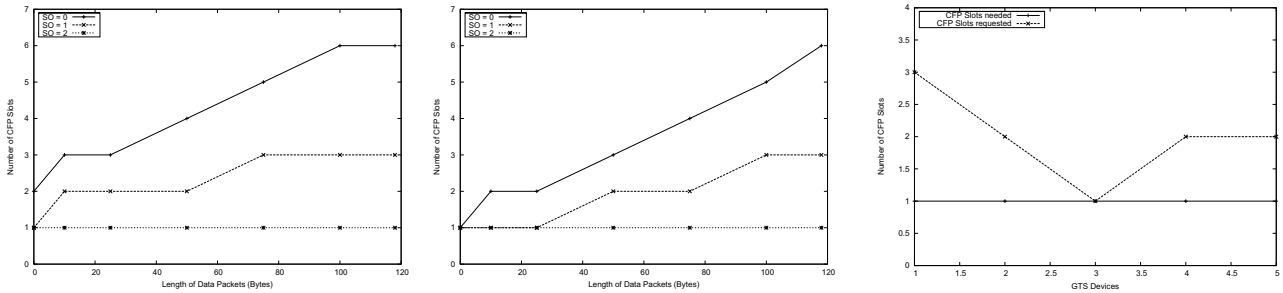


Figure 3: Revised GTS characteristics field, where first two bits specify the length of a data packet and the next two bits define the delay condition of the packet. Bits four and five, taken from the original standard, define the GTS direction and GTS request type. The last two bits are used for periodic applications.

In order to cope with the aforementioned limitations of the protocol, we change the bit structure of 8-bit GTS characteristic field, where the device, rather than sending fixed slot length, sends its data and delay specification to the coordinator, as shown in Figure 3. The coordinator, who runs an AC, decides the slot length for the device. AC works on the basis of total cluster load, remaining CAP size, device's data and delay specifications, and device's recent CFP usage. In this way, bandwidth under-utilization and the restriction of entertaining at most seven GTS requests are avoided. To annul the constant GTS expiration, the coordinator uses the period bits of the GTS characteristics field and performs GTS expiration dynamically. Rather than using one whole byte in the superframe to indicate the presence of the CFP part, we use one available reserve bit in the superframe.

5. PERFORMANCE EVALUATION

We have implemented the IEEE 802.15.4 protocol on the Tinyos 2.x [3] platform based on our system model. Moteiv Tmote [2] nodes with Chipcon CC2420 transceivers are used for the implementation. Now we will discuss our analysis for the application-specific optimal parameters setting. The values of BO and SO vary between 0 and 14, whereas, the values of BI and SD lie between 15.36 ms and 251.6 s. We can decide for an application-specific value of BI. For example, the value of BI can be 12 for the periodic application, where nodes send their data at an interval of 60 seconds. The maximum number of CFP slots for the different values of SD can be calculated by Equation (3). In order to calculate the number of slots actually needed to the device, we first calculate the total length of data packets, which are generated by the device. The upper layers of the device generate the data frame of at most 118 bytes long, which is passed to the MAC as a MSDU (MAC Service Data Unit). The MAC layer adds its header (MHR) of 9 bytes, converts it into MPDU (MAC



(a) (b) (c)

Figure 4: The number of CFP slots actually needed for the length of given data packets with acknowledgment request is shown in (a), whereas (b) depicts the same for unacknowledgment request. The comparison for the bandwidth-underutilization problem of the original standard with our approach is shown in (c), which highlights the major improvement given by our approach.

Protocol Data Unit), and passes it to the PHY layer, which also adds the header (PHR) of 6 bytes. Further 11 bytes are required for an (optional) acknowledgement request. To receive acknowledgment, device needs *aTurnaroundTime* (12 symbols) to change its radio from the TX to RX mode (or vice-versa).

Additionally, we have to consider the interframe spacing (IFS), which separates two successive frames sent by the device. Its value is 12 symbols for the MPDU $\leq$ 18, otherwise it is 40 symbols. The number of CFP slots required for the device is shown in Equation (4). For an application, where the devices generate data frames having length of 10, 25, 50, 100 or 118 bytes, we calculate the required CFP slots with the acknowledgment transmission in Figure 4(a). We calculate same for the unacknowledgment transmission in Figure 4(b). In both figures, we consider the value of SO as 0, 1, and 2. It is clear that, even for the maximum size of data packet, we need only one GTS slot, if we use SO of 2. For SO of 1, we need at most three GTS slots. Now, to validate the improvement given by our approach for bandwidth under-utilization problem, consider an example, where five devices are generating data packets, each of 100, 75, 50, 100 and 25 bytes and request for 3, 2, 1, 2 and 2 GTS slots respectively. Figure 4(c) confirms that our technique outperforms the original protocol in terms of bandwidth utilization and thus more devices can take benefit of the guaranteed services.

$$MaxCFP_{avail} = \frac{15 - aMinCAPLength/60}{aBaseSlotDuration * 2^{SO}} \quad (3)$$

$$CFP_{req} = \frac{2 * Data + IFS + aTurnaroundTime}{aBaseSlotDuration * 2^{SO}} \quad (4)$$

$$where \quad Data = MSDU + MHR + PHR + ACK$$

6. CONCLUSION

In this paper, we have elaborated the suitability and limitations of the IEEE 802.15.4 for low-latency, bandwidth, and energy related critical medical applications. The protocol needs definite enhancements before it could be applied to the medical field and our simple approach deals with almost all of those limitations. Application-specific optimal parameters setting for the health-care scenario is also discussed, where we have found that the GTS slots length requested by the devices mostly causes bandwidth under-utilization problem. The coordinator should assign GTS slots depending on the traffic, delay, and energy constraints to the device. Even for the maximum data packet length, the device needs only one CFP slot for the SO value of 2.

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A Closer Look at the Association Procedure in Low Power 802.15.4 Multihop Sensor Networks

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ABSTRACT

IEEE 802.15.4 proposes the advantage of a standardized low power low data rate communication stack and is therefore also an option for deploying low power wireless sensor networks (WSNs). Most studies of 802.15.4 based WSNs concentrate on the *operational* phase and neglected the *initial* startup phase. This bears however also potentials for energy savings, as the 802.15.4 association procedure has to be executed to make the network operational and is not optimized for low power networks. In this study, we point out directions how to perform the association in a self organizing and energy saving way.

1. INTRODUCTION

Among the existing standardized wireless communication solutions, the IEEE 802.15.4 standard [5] seems to be the most suitable for WSN purposes, as it is targeted at low power, low bandwidth networks, characteristics which match most sensor network applications. For home automation and industrial control purposes, the ZigBee Alliance [2] and the HART Communication Foundation [1] respectively specified higher layer protocols based on the 802.15.4 PHY and MAC. These protocols enhanced 802.15.4 and made it very popular for commerical applications with limited battery power and small throughput requirements.

In the academic community, the interest for 802.15.4 has also grown and numerous studies focused on the performance evaluation of the WPAN standard made its benefits and deficiencies well known. If, however, 802.15.4 WNS running on batteries shall become reality, one major problem resides. If the network is running in the *beacon mode*, a central coordinator broadcasts beacons, i.e. special command messages for synchronization purposes to all nodes in the network. This enables all devices to operate with superframes consisting of an active and a passive phase, where devices can be put to sleep mode. In the absence of a central coordinator, this fixed structure is not existing in the *nonbeacon mode*, which enables larger and more flexible topologies and is hence a good choice for 802.15.4 WSNs. If the network shall enable a distributed routing solution, no energy saving options for the nonbeacon mode are given in [5]. In earlier works we therefore investigated the effects of a simple sleep scheduling solution, where the sensor nodes duty cycle at a regular schedule and loosely synchronize with their neighbors. Allowing the sensor nodes to sleep a fraction $1 - p_w$ of a fixed epoch length T, this algorithm operates between the 802.15.4 MAC and a ZigBee routing layer and promises acceptable packet delivery ratios even at low duty cycle for the price of an increased end-to-end delay [7].

The question how such a duty cycle network can successfully start up both autonomously and efficiently, has not yet been considered. Each sensor node wanting to join a 802.15.4 network (also called personal area network (PAN)), has to *associate*, i.e. exchange a sequence of organizational messages with the PAN coordinator or with an other node which already has associated with the PAN. This procedure is mandatory for 802.15.4 networks and has not been designed under consideration of duty cycled or lossy networks. A closer look on the energy optimization potentials of the association procedure will therefore be presented in the following: In Section 2 we review related work. In Section 3, we formalize the association procedure using an analytical framework. In Section 4 we present some early simulation results, before we conclude in Section 5 and outline our future research.

2. RELATED WORK

One of the first performance evaluations of 802.15.4 in ns-2 [9] is reported in [11]. This code is still the base of the actual 802.15.4 WPAN ns-2.33 simulation framework we adapted for our purposes. Among other mechanisms, the association procedure was also studied in [11]. The association process as outlined in the standard is not optimized for the case of large, duty cycled or lossy networks with only one coordinator: It does e.g. not handle the situation, that a node wanting to join a PAN does not receive a beacon upon its active channel scan. To solve this issue, [11] proposes each device which is unable to associate at first attempt to retry to associate after an $associationRetryInterval\ a = 1$ sec later. As the authors focus on beaconed networks, and the sensor nodes do never go to sleep state, those results are of limited use for the case of non-beaconed low power networks.

In [6], the authors establish analytical models for computing the time and energy consumptions for 802.15.4 specific mechanisms. Furthermore, typical power consumptions and goodput for devices and coordinators are derived and verified by simulation. The reassociation procedure, i.e. the case where a node loses the contact to the coordinator it associated with, is handled, the initial association procedure is not covered. Furthermore duty cycling nodes are not considered, the analysis is thus difficult to apply to our problem.

The authors of [4] exploit the hierarchical dependency resulting from the 802.15.4 association procedure for a establishing a hierarchical routing scheme. HERA, as this algorithm is called, outperforms AODV, which is proposed by the ZigBee Alliance for self organizing 802.15.4 networks,

in simulations in terms of packet loss, delay and energy consumptions. This is mainly due to routing overhead, as HERA gets the initial routes for free by exploiting the association messages. The authors do not mention whether HERA can be extended to duty cycling networks and do also not analyze the association procedure. Their interest is just on the operational phase of the network lifetime, demonstrating the benefits of the association procedure. Together with an optimized energy efficient association procedure, HERA could be a promising approach for low power networks.

3. ANALYTICAL FRAMEWORK

3.1 Problem Description

In the last section, we presented some examples out of the numerous energy efficiency studies of 802.15.4 algorithms. They are good example for all studies we know of, as they mainly concentrate on the operational phase of the network. For this purpose, the network is in general assumed to be associated and routes stable. A reasonable approach, if e.g. the average delay of a packet routed in a WSN is of interest. As the association procedure of 802.15.4 networks is a vital MAC layer functionality [5], we will concentrate on the initial phase of a 802.15.4 WSN in the following.

A good description of the association procedure can e.g. be found in [11], we only recall the most important facts: Sensor node n activated in a nonbeacon-enabled multihop PAN will start an *active channel scan*, i.e. it broadcasts a *beacon request command* and waits for a response for an application specific time. This procedure will be repeated on all or some of the available channels. The PAN coordinator or a device which has already associated, will send a beacon, containing information about the PAN it belongs to, in response to this request. After having scanned all channels, n chooses a PAN for associating among the PANs it got to know of and exchanges a sequence of command messages with the sender of the corresponding response.

As mentioned earlier, [11] proposes each device which is unable to associate at first attempt to retry to associate after an *associationRetryInterval* $a = 1$ sec later. For the case of a self organizing duty cycled network which may be not synchronized at the beginning, this solution is not always successful. Especially in sparse and low duty cycled networks, a node may have *physical* neighbors, i.e. nodes within its range, but may be *temporally* isolated, as it does not share waketime with the nodes in its radio range. Using a fixed a will thus very likely not result in a successful association.

In this initial work we will point out directions for enabling a low power association procedure, investigating the following strategies:

1. choose a at random, but dependent on the duty cycle, e.g. $a = U(0, xp_w)T$, where $0 < x \leq 1$,
2. choose a at random, but independent from the duty cycle, e.g. $a = U(0, x)T$, where $0 < x \leq 1$,
3. choose $a = x$, where x is an arbitrary constant.

Above, $U(a, b)$ stands for a random variable, uniformly distributed in the interval $[a, b]$. Those simple choices already result in a vast parameter space, we postpone the investigation of advanced options, like deriving from the fixed duty cycling schedule therfore to future works.

3.2 Evaluation

To compare the benefits and trade-offs of the different solutions, we will use the following metrics for all nodes n of a WSN topology. Numerical values for the metrics are obtained as averages from ρ simulation runs.

- $s_A(n) \in \{0, 1\}$ indicates if n was able to associate during a target time Δ. Averaging $s_A(n)$ over ρ runs clearly leads to $0 \leq s_A(n) \leq 1$.
- $t_A(n)$, gives the time when n is associated.
- $E_A(n)$ denotes the energy n consumes until it is associated.

Obviously, these metrics vary heavily between nodes of the same topology. But the influence of the duty cycle, the starting order of the nodes, the used transmission output power, the network density and more factors make it hard to obtain a general closed form analytical expression. Before we evaluate the different association strategies in topologies with varying characteristics in a simulation, we have a closer look at the different metrics.

3.2.1 *Association Success* $s_A(n)$

The most straightforward metric of our model is the association success or percentage: Given a typical initial tolerance interval Δ, with which probability are the nodes able to associate? In the optimal case, $s_A(n) = 1$ for all nodes, but in some scenarios it could happen, that not all nodes are able to associate to the network resulting in $s_A(n) < 1$.

3.2.2 *Association Time* $t_A(n)$

The association time is obtained from simulations, but it may be broken down analytically, too:

$$t_A(n) = t_0(n) + n_A(n)t_{scan}(c) + (n_A(n) - 1)a + t_a. \quad (1)$$

The first component of $t_A(n)$, $t_0(n)$ denotes the randomly distributed time, node n waits between the deployment of the network and its first attempt to associate. The number of association attempts $n_A(n)$ is greater or equal than 1. Node n will thus scan $n_A(n)$ times the channel, needing a time $t_{scan}(c)$ which is application specific [5] depends additionally on the number of channels to scan, c, which we adopt to be equal to 3 [11]. Upon an unsuccessful association attempt, n will wait for a before retrying, until it requires finally a timespan t_a for exchanging the association command messages [5].

3.2.3 *Association Power Consumptions* E_A

Our interest is on layer 3 and below, we therefore neglect power consumptions for data acquisition, handling etc. and focus on estimating the energy consumptions of the transceiver. For this purpose, we abstract the sensor node radio unit to a state machine and use the periods, a sensor node spends in each state to estimate the transceiver power consumptions. For 802.15.4 performance evaluations, this approach which has been introduced by [3]. We extend upon this model by including the results of [10]. The authors propose to use a simplified radio control state machine extracting values for current consumptions and times required in states or for state transitions from transceiver data sheets and using a typical voltage of $U = 1.8V$. By measurements, they showed that that this so called Communication Subsystem Energy Consumption Model (CSESM) is exact enough

for an analysis. In Fig. 1 we show the corresponding simplified state machine for Texas Instruments' CC2420 [8], which is a widely used 802.15.4-compliant transceiver module. The durations and power consumptions of states and transitions are taken from [8] or estimated as the average of the two initial and final state for the transition [10].

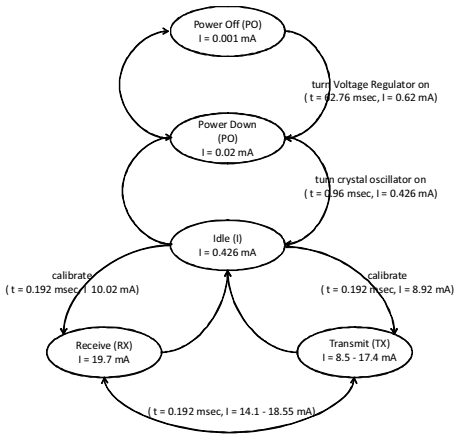

Figure 1: Simplified state machine of CC2420

For analyzing $E_A(n)$, we focus on node n and neglect the costs the node which with n associates has for sending the association beacons to n. As CSESM is not yet implemented in our simulation framework, an estimation for $E_A(n)$ is obtained using Eq. (1):

$$E_A(i) = E_{start} + n_A(i)E_{scan}(c) + (n_A(i) - 1)E_R + E_a, \quad (2)$$

where E_{start} denotes the energy required for the transition from "Power Off" to "Receive" state. In our simulation, nodes always transmit at maximum power, we therefore overestimate E_{scan} and E_a by multiplying t_{scan} and t_a respectively by U and $I_{RX} > I_{TX}$ [8]. The energy consumed during the period where the node waits for a retry to associate is obtained by adding the energy consumptions for transitions from and to "Power Save" state to the energy consumptions in "Power Save" for the remaining time of a.

4. SIMULATION RESULTS

For analyze the performance the 802.15.4 association procedure under varying conditions, we simulate it in ns-2.33. To reduce side-effects, we concentrate on a very simple topology: 9 sensor nodes and one sink node, taking the role of the PAN coordinator, are situated on a line, separated by either 4 or 5 m. We use node IDs from 0 to 9, for the sink node and the sensor nodes in increasing distance from the sink. The node with ID 9, has thus the greatest distance to the PAN coordinator. Using the default loss-less ns-2 two ray ground channel model with the radio characteristics of CC2420, and considering varying transmission output powers, each node can communicate with 1 to 4 neighbors per direction. Furthermore, we chose $\Delta = 5$ min for $T = 1$ sec. To obtain repeatable results, we use the seeds from 1 to 20 for 20 simulation runs which were found enough to result in satisfying confidence intervals for all considered mean of the considered metrics. For sakes of clearness, confidence intervals are thus not shown.

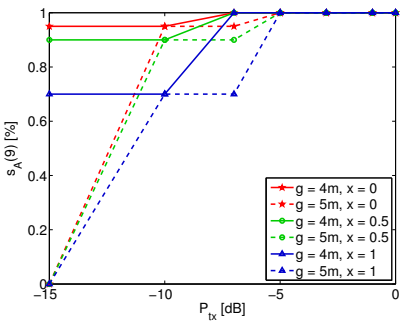

Figure 2: $t_A(9)$ for strategy 3

A self organizing PAN initialization is simulated as follows: The nodes 1-9 are activated in a random order, with a time of $U(0,1) \cdot 60$ sec between the start times. After having started, each node tries to associate to a PAN using the procedure described in Section 3.1. During most of our simulation runs, Δ was found to be enough for all nodes to associate. Only for $p_w < 5\%$, a transmission output power resulting in the smallest connectivity degree, and nodes close to the sink starting last, it occured, that the outmost nodes were not able to associate. The association success of node 9, $s_A(9)$ for the extreme scenario $p_w = 1\%$ is thus a good metric for the quality of an association strategy. In Fig. 2, we illustrate the percentage of simulation runs, node 9 was able to associate under varying transmission powers, inter node spacings and parameters for setting a according to strategy 3, i.e. $a = x$. Different colors and markers show different values for x. Sparser topologies, i.e. with the inter grid spacing $g = 5$ m are shown by dashed lines, solid lines are used for $g = 4$ m. The monotonic increase of the curves and the fact that the association success for $g = 4$ m and the same value of x is always greater or equal then for the same x and $g = 5$ m, illustrates, that the association success is increasing with the connectivity of the network. While this is an obvious result, another observation is more surprising: The highest association success is guaranteed for $a = 0$, i.e. if node 9 immediately retries to associate after an association failure. Our studies showed, that in denser topologies, this behavior leads to unnecessary channel contentions, choosing a larger, but randomized a is more advantageous in these scenarios.

Fig. 3 illustrates how the time required for successful association varies with the relative position of the node and the duty cycle in a topology where all nodes can only communicate with their direct neighbors and under strategy 1, with $x = 0.1$, i.e. $a = U(0, 0.1p_w)T = 1$ sec. We use a surface plot and study the influence of very small duty cycles more closely. Observe, that $t_A(n)$ is increasing strongly with the distance from the sink and the sleep time $(1 - p_w)T$. This increase was observed for all chosen parameterizations of a and all topologies, but differs in magnitude for varying radio range and parametrizations of a. Keep in mind, that the surface plot shows mean values obtained from 20 simulation runs: the results obtained from the individual runs varied more strongly, as t_A depends strongly on the startup time of the different nodes.

Eq. (2) makes clear, that the energy a node consumes

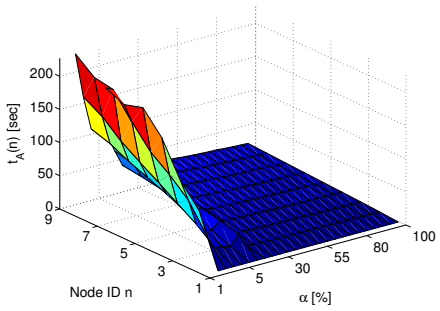

Figure 3: t_A for varying activity and strategy 1

associating to the network is proportional to the number of association attempts $n_A(n)$ it has to make. Our studies showed, that in most cases, node 9 has to make the most association attempts, the energy consumptions of node 9 are thus suitable as benchmark metric. We illustrate the association energy consumptions of node 9, $E_A(9)$ for a transmission output power of -15 dBm which corresponds to a node being able to communicate with its next hop neighbor in Fig. 4. Estimations for the energy consumptions were obtained from Eq. (2) under strategy 2, i.e. $a = U(0, x)T$ are presented. The most straightforward observation is that energy consumptions obtained for $g = 4$ m are smaller than for $g = 5$ m. This is in accordance with Fig. 2, as an increased network density reduces $n_A(n)$. Next, the curves representing results for the same g intersect indicating, that the optimal length of a depends on the activity ratio p_w. Moreover, the curves increase strongly for $p_w < 5\%$, leading to association energy consumptions in the range of 10 J and make it hard to identify the most advantageous strategy. This illustrates, that more studies for very low duty cycles and more sophisticated algorithms for the association procedure are necessary.

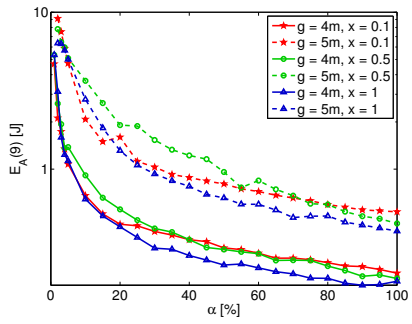

Figure 4: $E_A(9)$ for strategy 2

5. CONCLUSION

In this paper, we examined possibilities for enabling the association process in a self organizing low power 802.15.4 nonbeaconed sensor network. To our knowledge, this problem has not been studied before. We pointed out directions for an efficient solution, by examining three different simple strategies for proceeding after the initial association attempt fails. To compare the benefits and trade-offs of the individual solutions on the performance of the WSN startup phase, we used three metrics suitable for characterizing the qualitative and quantitative performance of a specific association solution.

Our results illustrate the inherent energy saving potentials of the often neglected start up phase of a 802.15.4 sensor network. In dependence of the strategy and the network connectivity, the association retry interval has to be chosen with care in order to avoid wasting energy: We found, that, under some conditions, too short retry intervals lead to unnecessary channel scans and beacon collision, thereby deteriorating the association performance. Under other conditions in contrast, shorter retry intervals are speeding up the association procedure significantly. Our results thus demonstrated, that extensive studies on a wide range of parameters are necessary, as many interacting factors influence the performance of the association process and that an optimal strategy has to consider a huge range of aspects. An extensive factor screening for comparing the benefits and trade-offs of different association mechanism will therefore be the topic of future works.

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A Novel Approach for a Lightweight, Crypto-free Message Authentication in Wireless Sensor Networks

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ABSTRACT

In this paper, we propose a system leveraging the peculiarities of the wireless medium, such as the broadcast nature of wireless communication and the unpredictability of indoor signal propagation to achieve effective protection against attacks based on the injection of fake data in wireless sensor networks (WSNs). Using a real-world WSN deployment and a realistic implementation of an attacker, we analyze this protection scheme and demonstrate that neither position change, transmission power manipulation, nor complete knowledge of wireless parameters can help an attacker to successfully attack the network. As a result, this work demonstrates how the chaotic nature of radio communication, which is often considered a disadvantage in regard to security objectives, can be exploited to enhance protection and support implementation of lightweight security mechanisms.

Keywords

Security, Wireless sensor networks, Radio propagation, Authentication, Implementation

1. INTRODUCTION

Consisting of sensors for measuring temperature, pressure, air humidity and other environmental conditions, wireless sensor networks (WSN) provide means for various applications to increase comfort and security within private and public residences. By accumulating data of many sensors, a sophisticated system capable of triggering complex application-specific tasks can promptly react to environmental changes, for example, fire spreading, water or gas leakage, and other origins of catastrophes can be detected and countermeasures promptly initiated (e.g., the room airing if gas leakage is detected, closing the water valve to prevent further flooding, or calling emergency in case of human injuries). Hence, residential monitoring is among the most important emerging applications for WSN. However, shifting such critical decisions to an automated system increases the importance of its security. By abusing the broadcast nature of wireless communication, an attacker could easily impersonate sensor nodes and inject fake sensor data into a WSN without even being physically present inside the residence. Continuous aggregation of fake data may lead the system to wrong decisions and provide vectors for more sophisticated attacks, e.g., sending fake packets to emulate gas leakage and initiate room airing may be exploited for physical intrusion.

Traditionally, security in computer networks has multiple objectives and attempts to equally satisfy authentication, confidentiality, and integrity goals of transmitted data. When following such "one size fits all" approach, the cost of key exchange, identity verification, and data encryption puts high demands on protocol complexity, its implementation, and computational power. While such requirements can usually be met by the relatively high-performance devices in common computer networks, in a WSN the security costs become more tangible through decreased battery life and various vulnerabilities from depletion of computation or memory resources.

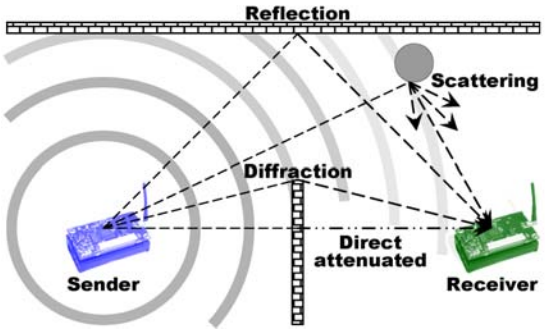
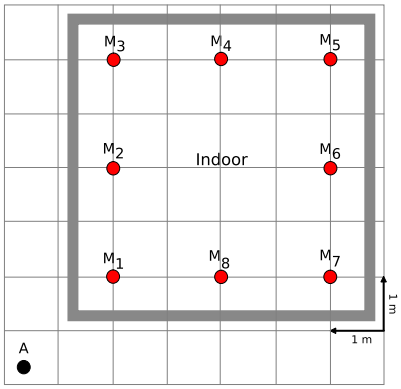


Figure 1: Indoor radio propagation and different propagation phenomena: reflection, diffraction and scattering result in unpredictability of signal propagation within real-world environments.

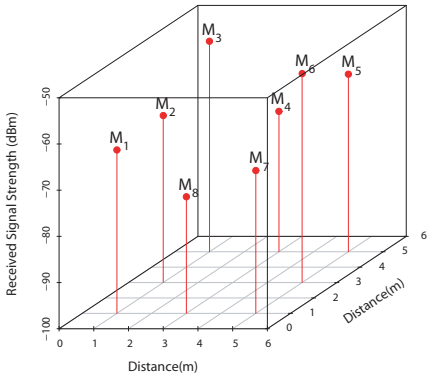
Operating within an indoor environment, a WSN may take advantage of access control offered by the "physical world", where walls, locked doors or other barriers for preventing physical intrusion establish the border between an outdoor attacker and the legitimate sensors. Although radio signals are able to trespass such barriers, the radio signal received from outside is strongly biased by various propagation effects such as reflection, absorption, diffusion, and scattering and therefore tainted with a significant amount of randomness (see Figure 1). Other than the attacker, legitimate senders and receivers within the WSN are positioned in an indoor area and their radio transmission has to penetrate fewer obstructions. By a planned placement, it is even possible to achieve line-of-sight (LOS) between legitimate WSN nodes. Consequently, signal propagation within an indoor WSN is more controllable and predictable than a signal arriving from outside.

2. SECURITY BY WIRELESS

In this section, we deploy a real-world indoor WSN network in order to empirically evaluate the diversity of signal propagation. Our testbed is a network installed in our university lab using 8

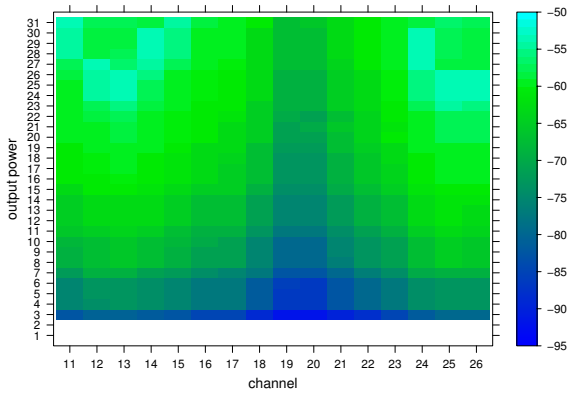


(a) WSN scenario

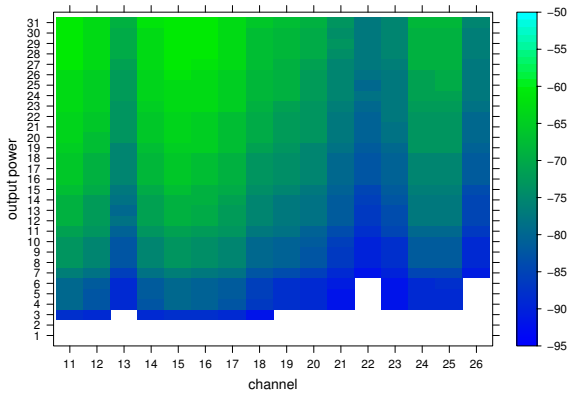


(b) Measured RSS on indoor sensors

Figure 2: Residential monitoring scenario (Fig. 2(a)): a WSN with 8 sensors is deployed within a residence (indoor), while an attacker A attempts to inject fake data from outside. RSS unpredictability (Fig. 2(b)): signal strengths measured from an outdoor transmission on indoor sensors (refer to topology shown in (a)). The order of measured RSS is dominated by physical characteristics of environment and signal propagation effects.



(a) Position 1



(b) Position 2

Figure 3: Results of sampling RSS on all available wireless channels on two different physical positions (both receivers are $< 2m$ from the sender). The darker area shows lower signal strength (right vertical scale depicts measured dBm values), while lack of coloring implies 100% frame loss.

wireless sensor sensors and an attacker placed outside the room, as shown in Figure 2. The wireless senors are based on a MicaZ platform with CC2420 radios, allowing for 32 different transmission power settings and 8-bit resolution of received signal strength. The power measurements are reported in RSSI (Received Signal Strength Indicator), yet the conversion to dBm is easily computed by $P_{dBm} = RSSI_{VAL} + RSSI_{OFFSET}$, where $RSSI_{OFFSET} \approx -45$.

2.1 Unpredictability of Signal Propagation

A real-world radio propagation will be subject to any combination of the aforementioned phenomena, resulting in a transfer function depending on many variables. By traveling along several paths, over different distances and consequently arriving with different phases, a signal exhibits *multipath propagation* properties, resulting in constructive or destructive interferences; the received signal strength may be weakened or amplified compared to LOS propagation. Considering the topology of the testbed depicted in Figure 2, an idealistic free-space model would provide the strongest RSS for the sensor which is in the attacker's closest proximity (M_1), while the most distant sensor (M_5) would measure the weakest RSS from the attacker's transmission. However, when looking at real-world measurements, the results are significantly different. The outdoor transmission which passes through different obstacles and is altered by various signal effects arrives highly randomized in an indoor environment. Hence, the order of RSS received at indoor sensors is completely shuffled. Figure 2 (b) shows measured RSS on every sensor using the topology from Figure 2 (a) averaged over 100 transmission. The sensor with the strongest RSS is M_3 ($\approx -55\,dBm$) and the one with the weakest RSS is M_8 ($\approx -75\,dBm$). In a free-space model, M_8 would have measured the second strongest RSS; moreover, this RSS relationship between sensors and attacker is changed with *any* alteration of sender's configuration of antenna orientation, physical position, or even a transmission frequency. To demonstrate the impact of frequency changes on RSS, we sampled transmissions on every wireless channel without changing the positions of the sensors. The results measured at two different receivers are depicted in Figure 3(a) and (b). So for example, if the transmission is changed from channel 13 to channel 19 (i.e, 2405 MHz to 2445 MHz), one receiver experiences an RSS decrease of $\approx 20\,dBm$ (Figure 3(a)). Yet, if the transmission is changed from channel 13 to channel 22, another receiver mea-

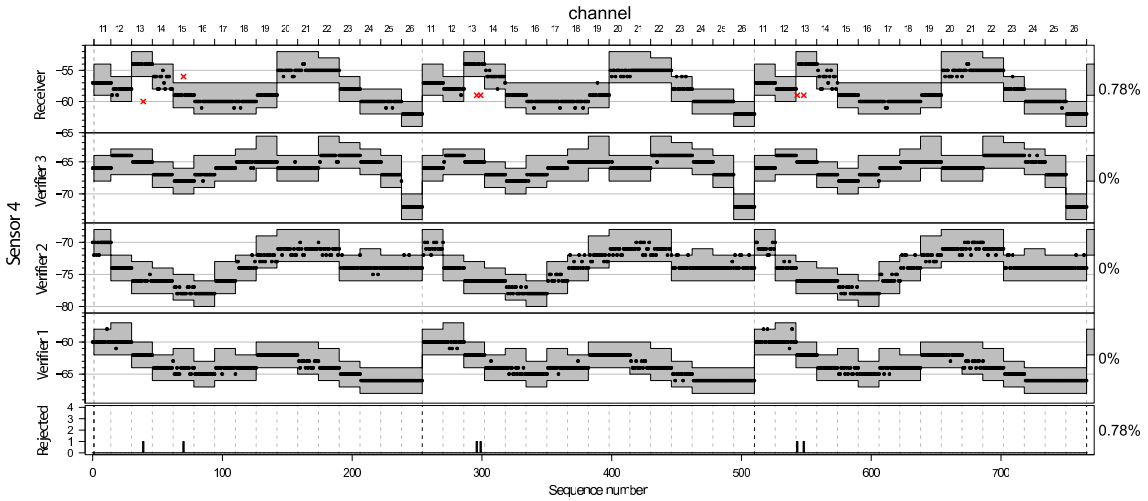


Figure 4: Time-line of legitimate transmissions verified by 3 sensors and 1 receiver. The figure shows acceptance intervals at each node (gray area) and received frames (black dots as accepted frames, crosses as rejected). Using the same PRNG seed each sensor periodically changes the transmission frequency and thus it dynamically changes its acceptance intervals. The amount of false positives, i.e., legitimate frames discarded due to signal variation is low at 0.78%.

sures an RSS increase of $\approx 10dBm$ (Figure 3(b)). Consequently, a single frequency change may cause RSS to increase or decrease on different indoor receivers at the same time and the same position of the sender. This finding has important implication in a security context, it allows us to shuffle the order of sensors' RSS merely by switching between different transmission frequencies without changing the placement of the sensors. For example, if both indoor sensors transmit on channel 11, the order of their RSS is approximately equal, i.e., $M_1 \approx M_2$. However, changing the transmission frequency, e.g., using channel 19, results in $M_1 > M_2$. This property we exploit to establish a dynamic configuration feature in our protection mechanism.

3. COUNTERACTING INJECTION ATTACK BY WIRELESS

Leveraging the unpredictable and chaotic nature of signal propagation, our protection method is based on a single assumption – *two wireless transmissions from different physical positions cannot produce exactly the same signal propagation properties*. To facilitate this wireless peculiarity, we propose and implement two mechanisms for crypto-free authentication of frames exchanged within an indoor WSN: (i) *acceptance intervals*, and (ii) *dynamic configuration.* The acceptance intervals are used to detect frames whose transmission properties are significantly different from those of legitimate sensors, while the dynamic configuration of transmission properties within a WSN increases the unpredictability of signal propagation. Similar to Figure 2 the legitimate sensors were deployed on the ceiling of our university lab and the experiment was divided in two phases:

1. *Deployment phase:* Installation of sensors and configuration of transmission parameters, including initial measurements using different power levels and transmission frequencies for defining acceptance intervals.

2. *Monitoring phase:* The network is in regular operation while being subject to an injection attack executed from various physical positions outside the deployment area.

The acceptance intervals are defined as $[\mu - k\sigma, \mu + k\sigma]$ and based on empirical data measured during the deployment phase, where μ is the sample median, σ the standard deviation of a sample, and $k > 1$ is an environment-dependent constant defining the width of the interval, i.e., it describes within how many standard deviations the RSS is still considered to be legitimate. During the deployment phase, each sensor uses initial transmissions to create acceptance intervals on every other sensor (i.e., similar to *signalprints* used in [3] and a more advanced approach discussed in [1]). To successfully inject fake frames into the network, an attacker must find an appropriate *configuration* of wireless parameters, such as physical position, transmission frequency (wireless channel), and a transmission power level to produce the received signal strength which satisfies the acceptance interval on all sensors. If any of legitimate sensors detects the impersonation (i.e., it measures an RSS of a frame not included in acceptance interval), the receiver is notified by a warning frame disclosing a sequence number of the injected frame.

Dynamic configuration is used to hinder an attacker in its brute-force search for a successful configuration. All WSN sensors are instantiated with the same PRNG seed which allows them to permute different transmission parameters defined during the deployment phase. So for example, one configuration would be to transmit on channel 15 with a transmission level 10, another to transmit on channel 22 with a transmission level 15. As a result, different configurations are assigned with different acceptance intervals. Even if an attacker is able to inject frames with a certain configuration, the attack is only successful during the same acceptance intervals.

To allow periodic change of acceptance intervals the WSN uses a simple synchronization method where a basis station periodically broadcasts a beacon to signal the change of the transmission parameters (e.g., every 2 minutes). An example can be seen in Figure 4 which shows a time-line of monitoring phase without the presence of an attacker. The sender's transmissions are verified on four sensors (three sensors and a base station). Although the acceptance intervals dynamically change (gray areas), the legitimate sender has

No. of sensors	Scenario 1 Interval width 2	4	6	10	Scenario 2 Interval width 2	4	6	10	Scenario 3 interval width 2	4	6	10
1	5	2	2	0	7	2	1	0	5	2	0	0
2	12	8	6	2	14	6	1	0	9	4	2	0
3	15	14	10	8	16	13	13	5	13	8	7	6
4	15	15	15	12	16	15	15	14	16	14	12	11

Table 1: Number of *secure channels,* i.e., channels immune to injection attacks if one channel is "broken" .

no problem of correctly changing its transmission properties to fulfill acceptance intervals on other four sensors.

3.1 Attack Scenario

To analyze the impact of dynamic configuration change during an injection attack the PRNG seed, the transmission frequencies, and the attacker's RSS on legitimate sensors is made public, hence this protection method does not depend on any secret. The single assumption is that an attacker cannot gain a physical access to the indoor WSN and cannot transmit from the same physical position as an impersonated sensor. To increase the efficiency of injections we manually searched for an appropriate configuration of physical position, antenna orientation, and power level until we were able to use at least one frequency to successfully inject fake frames at the receiver. We were interested in the number of acceptance intervals on other verifying sensors which are successfully "broken".

The results of a thorough empirical sampling of various physical positions used to attack the WSN network with different number of verifying sensors are presented in Table 1 as the number of *secure wireless channels*, i.e., the frequencies which did not result in an acceptance of any fake frames. So for example, a WSN with only two verifying sensors (one sender, one receiver), and an interval width of $4dBm$, enables an injection of fake frames on eight channels, while the other eight are not possible to attack using the same configuration of transmission properties. Similarly, using three sensors to verify the transmission, and the width of acceptance intervals set to $2dBm$, the attacker could use only three wireless channels for successful injection, while its attack is not effective on the other 13 channels. Hence, there is a simple tradoff provided by this scheme; by increasing the number of sensors we can increase the number of secure channels even in environments with a high variance of RSS (which results in larger σ and wider intervals). In the deployed WSN network, using five or more sensors we could not find any position that resulted in a single successful injection even if acceptance intervals were set to $10dBm$ allowing very high RSS variations (for more implementation results see [4]).

4. CONCLUSION

The main purpose of this paper was to briefly demonstrate how the chaotic nature of wireless communication can be used as an advantage and how it can assist in increasing security of WSNs. Rather than implementing additional protocols necessary for traditional security mechanisms, we designed practical and lightweight protection without requiring more features than the communication itself provides. To successfully inject fake frames, the attacker is forced to search for an appropriate configuration of a physical position, antenna orientation, and transmission power. However, even if the configuration for a successful attack is found, it is promptly invalidated by a dynamic change of acceptance intervals. Additionally, the design allows for a simple, yet effective tradeoff depending on the security objectives of a particular scenario – increasing the number of sensors, results in increasing the security of a WSN and its resilience against injection attacks.

Our solution neither requires specialized hardware, nor introduces complex message exchange. Probably, the closest research to our work is tackled by Demirbas et al. in [2]. While in their work, the authors attempt to minimize the randomness of signal strength by comparing the ratios of RSSI values, in this work we take a different approach and show that protection can be based on supporting the randomness and using it against an attacker. Further instantiations of the paradigm *security by wireless*, as we call it, is demonstrated in [6] and [5], in which properties of wireless communication are used to assist in providing various security objectives adapted to the peculiarities of wireless networks.

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Reliable Multicast in Wireless Sensor Networks*

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ABSTRACT

Multicasting in Wireless Sensor Networks (WSNs) is an efficient way to disseminate the same data to multiple receivers. For critical tasks such as code updates, reliability would be a desirable feature, in order to use multicasting for such scenarios. Due to the nature of WSNs, several problems exist that make realizing an efficient, reliable and energy consumption friendly implementation a challenging task. In this paper we describe the challenges of such an implementation and propose a solution for designing a reliable multicast solution based on IP Multicast and Overlay Multicast. We discuss several scenarios and depict the different advantages and limitations of the solutions proposed.

1. INTRODUCTION

1.1 Wireless Sensor Networks

A Wireless Sensor Network (WSN) consists of a number of sensor nodes, which are limited in terms of energy, CPU power, and memory. On the sensor nodes may run different applications for different tasks such as event detection, localization, tracking, and monitoring. Such applications should be configured and updated during the life-time of the sensor nodes and over the network [1]. An update with many unicast connections to the nodes is very inefficient and consumes resources such as bandwidth and energy. Thus it is obvious that multicast communication the management of WSNs may benefit by reducing the number of transmitted packets and by saving energy. To access WSNs via the Internet, a IP-based communication is required [2]. Thus multicast communication should be IP-based as well.

1.2 Multicast

Multicast is an efficient way to disseminate data to a group of receivers that are interested in the same content. Contrary to unicast, where the sender has to transmit the data for each receiver individually, multicast requires the sender to transmit the data only once. Thereafter, the network or other hosts interested in the data will replicate when required and forward the data to the receiving group members. In the Internet, the multicast paradigm has been implement in the form of IP Multicast. Interested receivers send an IGMP group join message, the routers process these messages according the IP Multicast protocol used (RSVP, PIM, etc.) and build the distribution tree among them. A sender now only sends a UDP Multicast packet to the group's address and the routers in the network then distribute the data according to the multicast tree that has been setup before. Although IP Multicast has been available for a while, it has not been widely deployed in the Internet today due to different reasons (configuration, ISP agreements, etc). To offer multicast functionality to the end-user, the concept of Application Level Multicast[3] (ALM), often also called Overlay Multicast, has been introduced. With ALM, which is based on the Peer-to-Peer[4] (P2P) paradigm, end-systems build the multicast tree among themselves, rather than relying on routers to handle multicasting on their behalf.

Numerous research has been done about multicast in WSNs. In [5] a multicast protocol called BAM (Branch Aggregation Multicast) is presented, which supports single hop link layer multicast and multi-hop multicast via branch aggregation. VLM^2 (Very Lightweight Mobile Multicast) [6] is a multicast routing protocol for sensor nodes, which is implemented on-top of the MAC protocol. It provides multicast from a base station to any sensor node, unicast connections from a sensor node to the base station, and supports mobility. In [7] the authors present an effective all-in-one solution for unicasting, anycasting and multicasting in wireless sensor networks and wireless mesh networks. The authors of [8] adapt ADMR (Adaptive Demand-driven Multicast Routing), a multicast protocol for MANETS, on a real wireless sensor node (MICAz). They show that the adaption is not a trivial task and a number of problems have to be solved. The authors of [9] analyze IP Multicast and show that it is possible to use it in WSNs. Further there are several multicast solutions for WSNs which are based on the geographical position of the sensor nodes in the network [10, 11].

1.3 Structure of the Paper

The remainder of the paper is structured as follows. In the next Section multicasting in WSNs is described showing the challenges, different designs of multicast, and a protocol stack for IP-based communication is proposed. Section 3

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discusses the advantages and limitations of our proposed solutions. An outlook in Section 4 closes this paper.

2. MULTICAST IN WIRELESS SENSOR NETWORKS

2.1 Challenges

Due to the nature of WSNs, the IP Multicast implementation can not be simply ported from existing solutions for wired networks. In WSNs energy, memory and CPU power are limited. This implies the following challenges for multicast in such environments. In wired networks, routers are handling packet replication and forwarding, clients just send and receive simple IP UDP datagrams. On the other hand, WSNs would need to introduce the router functionality for IP Multicast management into each sensor node. Group management is normally concentrated on the routers that communicate with each other to handle multicast trees. The management for multiple groups and multicast trees requires memory and processing power, which is limited on sensor nodes. Also the default implementations of IP Multicast are designed to scale on large network groups with multiple receivers and senders. In practical WSNs typically the amount of nodes is rather low. Also the amount of active trees and general management communication should be kept to a minimum. Existing Overlay Multicast [3] solutions (such as Scribe/Pastry, CHORD, Bayeux) are normally not taking the wireless nature and limited capabilities of sensor nodes into account. In general it is also a bad idea to have overlay connections established all the time, which would lead to higher energy consumption and therefore reduces the lifetime of WSNs. Several other issues concerning liveliness, wireless communication and collisions exist. Also reliability for a WSN multicast solution would also be desirable, because code updates and other critical tasks could then be solved efficiently using multicast.

2.2 Designing Multicast in WSNs

Multicasting in WSNs can be designed in different ways. We will look at two approaches, reliable IP Multicast and Overlay Multicast. For both approaches we will look at source-driven and receiver-driven designs, both centrally managed as well as de-centrally organized. Generally we will distinguish between two node types. Branching nodes have to duplicate packets and store state information about receivers and/or about other branching nodes. Forwarding nodes have less or no information about the multicast state and just forward the multicast data to one neighbor. We will also limit our discussion to core-based trees, where only the dedicated root node will disseminate the data, while other senders would need to transmit the data to the root node first for dissemination. An example topology with some branching nodes, forwarding nodes and three group members is shown in Figure 1.

2.2.1 Overlay Multicast

For the source driven scenario we can use a de-centralized as well as a centralized approach. Generally we distinguish between active and inactive multicast trees. While data is transmitted to a multicast group, the tree is in the active state with all required TCP connections for the overlay links established. New nodes are not allowed to join the group

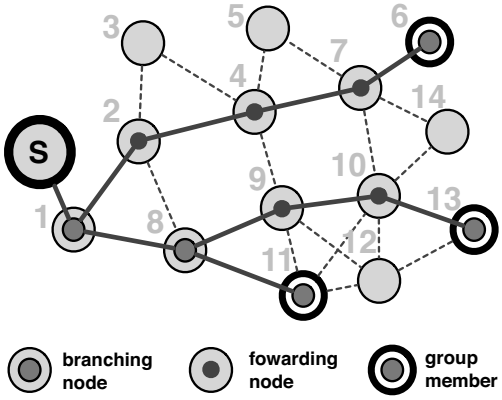

Figure 1: Example topology showing branching nodes, forwarding nodes and group members

while its tree is active, though the joins are cached and processed later. When no data needs to be transmitted, the tree is inactive and all required TCP connections to build the distribution overlay are closed. Nodes can only join to a multicast group while its tree is inactive. This limitation ensures, that subscribed members get all data for a dissemination session, because late joins are avoided.

In the de-centralized and source-driven approach, the source sends the list of all receivers of the multicast data to its one-hop neighbors. The neighbor nodes then check if all receivers in the list can be reached through a single of their next-hop neighbors. In this case, such a node just forwards the list to its next hop and remembers that it acts as a forwarder for that multicast group. If nodes from the list can be reached via different neighbors, the list is split accordingly and the partial lists (with the node's own address as source of the message) are forwarded to the respective neighbors. The node splitting the list becomes a branching node and opens a TCP connection for the overlay link to the sender of the original list, when the corresponding tree is activated. Finally, if such a list message arrives at the receiver (group member), then that node prepares the overlay link to the source of the message (normally the last branching point). Therefore, TCP connections for the overlay network links are only established between the source, branching nodes and the receivers (see also Figure 1) when the corresponding multicast tree becomes active. New nodes are added to the multicast tree by sending a list message including the new nodes as described before. Only when a tree is inactive, new nodes can be added, Therefore, no connections are established directly, but potential new overlay links are just prepared and only established upon activation of the tree. If a branching node now receives a list message with new nodes, it changes the source address of the list message, splits the list if required, and forwards it/them further. If a forwarding node has to become a branching node, it prepares the overlay link to the source of the list message, splits the message and forwards the new list messages further as described before. This new branching node tells the source of the original list message which receivers it handles in the future. Therefore, the previous branching node removes the overlay link that previously was using this new branching node as forwarder. Upon reactivation of the modified tree, the overlay link connections are opened from the source, via

branching nodes to the the receivers. New and old receivers then become aware of their new group membership or of the change of branching nodes for existing group memberships. Nodes can also be removed using remove list messages accordingly and the forwarding and branching nodes have enough information (as with adding new nodes) to modify the resulting tree.
In the source-driven centralized approach, the source node determines all required branching nodes ahead. Therefore, the source also creates the complete distribution tree that is required for a multicast group. The branching nodes are then notified, process the information and further forward these notifications. If new receivers need to be added to a tree while it is inactive, the source calculates the new and/or modified branching nodes. Only these nodes are notified about the changes in the tree, branching nodes that do not need to be changed require no notification. Removing receivers from the tree is done similarly, branching nodes that need to be modified or removed are notified accordingly.
For the centralized receiver-driven approach, the join messages from the receivers are forwarded to the source, which manages the tree as described for the source-driven centralized approach.
In the receiver-driven de-centralized approach, receivers send the join message to their neighbor responsible for the default route. If this node is not a forwarder or branching node for that group it becomes a forwarding node (only knowing that it is on the path of an overlay link when the tree would become active) and forwards the join message further. Intermediate nodes, which are already branching nodes of the requested group drop the join message and prepare the overlay link to the new receiver. Forwarding nodes receiving join messages, become new branching nodes, prepare the new overlay link and send this information (about becoming a branching node) towards the source, dropping the original join message. A branching node receiving such a message modifies its overlay link in that direction. Therefore, the overlay link of which the new branching node has been acting just a forwarder before, is removed and replaced by an overlay link to this new branching node. Receivers that want to leave a group send a leave message towards the source. Forwarders on the path update their status for that group and forward the leave message further. Branching nodes receiving a leave message update their status, remove the overlay link to the leaving node, and discard the leave message. If the branching node has just one overlay link left, it has to change its status to a simple forwarding node for the remaining receiver and removes the affected overlay link. Further, it sends a notification towards the source and all intermediate nodes update their states accordingly. They forwarding the message until it reaches a branching node, which then establishes the overlay link to the remaining receiver.
To support end-to-end reliability in overlay multicast, the receivers have to acknowledge the receipt of each multicast message or acknowledge the receipt accumulated after a series of messages. Branching nodes aggregate and forward the acknowledgments. In case of missing acknowledgments, they send negative acknowledgments further towards the source. Branching nodes also take care of retransmission of lost packets and therefore need to cache the multicast data up to a certain degree. Hop-to-hop reliability is supported by underlaying protocols as described in Section 2.2.3.

2.2.2 Reliable IP-based Multicast

Contrary to Overlay Multicast (which uses TCP) we do not have a reliable end-to-end transport protocol. Instead we are using UDP. End-to-end reliability is realized using acknowledgment messages as described above. Branching nodes know only that their one-hop neighbors are forwarding the packets on their behalf. Acknowledgments be handled on one-neighbor basis (hop-to-hop), and not between branching nodes as for Overlay Multicast.
For the source-driven de-centralized approach the source sends the join list to its direct neighbors that should act as forwarders. The next forwarder is determined on a hop-to-hop basis. If a node has to become a branching node, it remembers from which neighbors it expects acknowledgments. Joins and leaves are handled by appropriate messages that could cause forwarders to become branching nodes (and vice versa) triggering a modification of the expected acknowledgments state for a node.
In the centralized source-driven approach the source sends the list of all branching nodes to the closest branching node, which processes and forwards them further to the nearest branching nodes on the path. Intermediate nodes become forwarders and store the status for the involved multicast group. Acknowledgments are handled directly between the branching nodes. Additional joining nodes trigger an update of the affected branching nodes all initiated directly by the source. Leaves are handled accordingly triggering updates of the branching and forwarding nodes involved.
In the receiver-driven centralized approach joins are sent to the source, which then acts as in the source-driven centralized approach. In the de-centralized receiver-driven approach, joins cause intermediate nodes to react as in the Overlay Multicast case. They either become forwarding nodes for that group if they are not handling that group yet or become branching nodes if applicable. Acknowledgments are handled the same way as described above in the de-centralized source-driven approach.

2.2.3 Protocol Stack

Figure 2 shows a possible protocol stack for reliable multicast in WSNs. End-to-end reliability for reliable IP-based Multicast is ensured by REMC (Reliable Multicast) and for Overlay Multicast by SNOMC (Sensor Network Overlay Multicast). To avoid unnecessary end-to-end retransmission or caching in branching, we use a hop-to-hop reliable network protocol realized by H2HR (Hop-To-Hop Reliability) in combination with the MAC protocol. This allows to directly delete cached packets after successful transmission to the next hop. To optimize the mentioned protocols, information is exchanged across different layers using the cross layer interface. For example, the MAC layer informs H2HR about the successful (or unsuccessful) transmission of a packet. H2HR is caching the packet until it has been transmitted successfully. Additional neighborhood information for deciding how to forward multicast packets and the involved paths is also requested from the cross layer interface by REMC and SNOMC. TSS (TCP Support for Sensor Nodes) [2] supports optimizations of TCP-specific mechanisms, such as intermediate caching, local retransmission and acknowledgment recovery and regeneration. Additional energy-saving is achieved by disabling the radio interface by the MAC layer when no transmission is required.

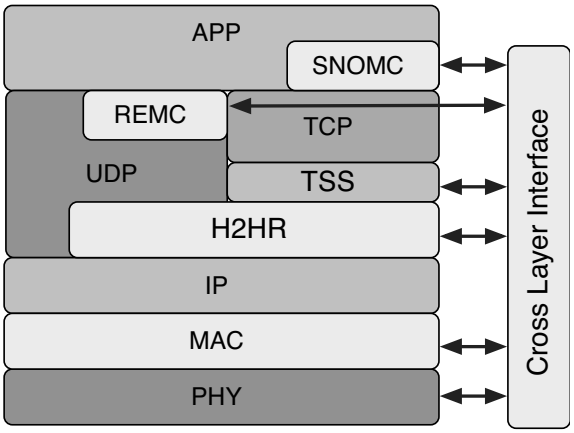

Figure 2: Protocol stack of a wireless sensor node using reliable unicast and multicast communication

3. DISCUSSION & CONCLUSION

We have shown several possible design concepts for reliable multicast in WSNs. Each approach its own advantages and limitations, depending on the scenario in which it is used.
For small scale WSNs, the centralized approach helps to save energy and resources on the sensor nodes because the source (generally the base-station) is handling the tree management. The sensor nodes do not need to store a lot of status information.
The de-centralized approach is useful in large scale environments, where robustness and easier tree construction can be achieved by letting the sensor nodes manage the tree construction and group handling themselves.
The Overlay Multicast approach is easy to implement but triggers more control messages in the underlaying layers as well as in the overlay management layer. By distinguishing between active and inactive trees, we can reduce the energy consumption due to the fact that we only establish TCP connections when data has to be transmitted. This results in an Overlay Network established on demand.
On the other hand, reliable IP-based multicast using UDP could be even more efficient and energy-consumption friendly, but requires more cross layer interactions and higher implementation effort.

4. OUTLOOK

There are still many open questions regarding the design of multicast support in WSNs. When using reliability on end-to-end basis, problems such as acknowledgment implosion, handling of negative acknowledgments, etc. have to be analyzed in more detail. Generally also congestion control and the resulting limitations have to be considered. Multicasting on the link-layer could also improve the performance in combination with our presented approaches. To determine efficiency, energy consumption and overall performance, we plan to simulate the different scenarios and solutions in the OMNET++ simulator [12]. Both approaches should be implemented on real sensor nodes using Contiki [13] as operating system.

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First Results of a Performance Comparison of Dynamic Source Routing versus Greedy Routing in Real-World Sensor Network Deployments

[Extended Abstract]

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ABSTRACT

This work covers our first results of an empirical performance comparison between dynamic source routing and greedy routing in a real-world wireless sensor network deployment. The test environment is based on a 7×7 grid of 49 battery operated Tmote Sky sensor nodes. We briefly sketch the protocol implementations and the experimental setup used in this work, and present our findings from the measurement data we have gathered so far.

1. INTRODUCTION

This work describes our recent advances in providing real world measurements of basic wireless data communication primitives in wireless sensor networks. At the time of writing we have been focusing on end-to-end communication between a source and destination node. We believe that a basic understanding of such basic primitives will as well provide insights in more advanced sensor network specific data collection primitives. Moreover, sensor networks are not only about data collection trees. For instance, a data sink issuing a sensor request into a specific geographic region, a data sink issuing a request to a certain area identified by a specific node, or a data source trying to connect to a specific actuator are just a few examples which show that sensor networks require basic unicast communication primitives as well.

Data communication protocols can be classified in topology based and geographic ones. Surveys can be found in [9] and [3], respectively. Topology based communication requires either proactive or reactive exchange of global information before message forwarding from source to destination can take place. Geographic message communication in contrast does not require such global message exchange. In such routing mechanism it is assumed that each node knows its current physical location. Based on this additional information a routing decision can be performed in a pure localized manner, i.e., a forwarding decision requires only information about the position of the current node, its immediate neighbors, and the message destination. It is believed that such localized protocols provide scalable solutions, that is, solutions for wireless networks with an arbitrary number of nodes. Future sensor networks, for instance, might consist of thousands or ten thousands of nodes.

Research on localized algorithms has focused mainly on theoretical investigations and simulation. While both form an important aspect in getting a thorough understanding on what is going on, a critical part has widely been neglected so far. It is of paramount importance to evaluate such protocols in the domain where they are supposed to be applied. Localized algorithms are not supposed to run in Ns2, Omnet, or Qualnet. They are supposed to run on real hardware platforms like MicaZ, or Tmote Sky nodes.

What follows is just a drop in a bucket, to provide some numbers of real-world measurement for comparing the domain of localized versus topology based data communication. We focused at first on two protocols, greedy routing and dynamic source routing. The protocols and how we implemented them are described briefly in Section 2. Then we describe our experimental setup in Section 3. The results are presented in Section 4. We conclude our work in Section 5.

2. PROTOCOL IMPLEMENTATIONS

We implemented dynamic source routing and greedy routing in nesC [4] under the TinyOS 2.0 execution environment [6]. Wireless communication between immediate neighboring sensor nodes and wired serial communication between sensor node and host computer is implemented on the basis of Active Messaging [1]. The maximum allowed message size was fixed to 64 bytes payload. The following provides a brief outline on both implemented protocols and motivates the rationale behind our implementation decisions.

2.1 Dynamic Source Routing

2.1.1 The Algorithm Principle

Dynamic source routing [7], DSR in short, basically works as follows. The source node sends out a route request message RREQ which is repeated by all intermediate nodes once they receive it for the first time. Additional RREQ receptions are just ignored. Every RREQ message copy stores the sequence of nodes it has visited so far. In this way several copies of the RREQ message will eventually reach the destination node which can then pick up one of these messages to send a route reply RREP back along the reverse of the path stored in the RREQ messages. To achieve this, the RREP message just stores the sequence of nodes which have to be visited from source to destination. Once the message arrives at the source

node, the reverse of the path stored in the RREQ message can finally be used to send data towards the destination node.

2.1.2 Implementation

Route setup in DSR requires some time. In order to allow immediate service of DSR, we provided the source node with a slightly increased message buffer size. We set the buffer size to 8. Our implementation buffers the messages coming from upper layers until the first RREP message arrives. From there on messages are immediately sent out to the next hop node until the route gets invalidated.

Our DSR implementation provides a timeout which can be used to invalidate the current route from source to destination. This means when using this timeout a new route discovery will be initiated periodically. However, this is just an optional feature which is useful to adapt proactively to a dynamically changing network topology; due to mobility or any kind of fading effects.

So far we were interested in performing measurements in a single source single destination traffic pattern. Thus, we have not implemented DSR route caching strategies so far.

2.2 Greedy Routing

2.2.1 The Algorithm Principle

The greedy routing principle [10, 2, 8] works as follows. Each node is supposed to know its own location in terms of some given coordinate system. Messages store the location of the destination node as well. A current forwarding node has to acquire the position of its one hop neighbors and then choose the next hop as the neighbor whose location is the best one with respect to the current node's location, the final destination's location, and the localized metric being applied. If the current node is the best one, the message will be dropped.

2.2.2 Implementation

In greedy routing each node is supposed to know the locations of the nodes in its vicinity. In this work we focused on the so called beacon less greedy routing variant [5]. However, we implemented the following active neighbor selection variant. As long as a node has not to forward anything, it is not supposed to know its neighbors. As soon as a message gets in, the neighbors have to be determined first. The node will broadcast a neighbor discovery message NDSC first. Any neighbor node receiving an NDSC message will send a unicast reply message NREP which includes the node's ID and location. To avoid collision at the receiver, an NREP will be sent out after a short random period between 0 and 16 msec.

In a static topology, neighbor discovery needs to be performed only once. As soon as the first message was handled, the other messages coming in can use the already determined set of one hop neighbor nodes. In a highly dynamic scenario, however, this set will be outdated and a new neighbor discovery gets necessary. To support any topology properties between those two extreme cases we implemented a timeout based scheme where the neighbor set is invalidated periodically. Thus, message handling within one period requires neighbor discovery only once. The timeout period can be set as a protocol parameter.

The behavior of a greedy routing scheme is highly affected by the implemented routing metric. A variety of different metrics aiming on different aspects like success rate, latency, or energy efficiency have been considered in the literature. In this work we focus on the basic metric from [2]: send the message to the node which minimizes the distance to the destination. However, here we suspect main improvement potential in future experimental studies and anticipate incorporating other metrics in future performance studies as well.

Location information is an important ingredient of any localized data communication protocol. Here we focused on the data communication aspects only. We implemented a TinyOS module which provides an interface to request a node's position. The current implementation just returns a preconfigured location value which is set in the phase of mote flashing.

3. EXPERIMENTAL SETUP

The following described experiments were performed on a regular 7×7 grid of 49 battery operated Tmote Sky sensor nodes (see `www.sentilla.com`). The network was deployed indoors in a single room. Nodes were located on the ground. No obstacles have been placed in between them.

Greedy routing does not require absolute node positions. Any virtual coordinate system which supports computing distances between nodes is sufficient. We have set the node positions according to increasing integer values for x- and y-coordinates in the 7×7 grid.

The distance between two neighbors on the grid nodes was set to 25cm. To have a reasonable multi-hop experiential scenario, transmission power of each node was set to 2 (out of a range between 0 and 31). We investigated that a transmission power 1 rendered many message losses due to weak signal strength. A signal strength above 2 kept too many nodes connected thus rendering the topology almost fully connected.

To control the experiment, the node at the top left and the node at the bottom right of the 7×7 grid have been attached via USB to a notebook computer. We implemented a Java application to generate the traffic, and collect measurement data from the final destination node. The Java application tells the attached source node at the top left corner to send a data packet periodically to the destination node at the bottom right corner. The time interval between two message transmissions was set to 2 seconds.

4. RESULTS

The graphs depicted in Fig. 1 compare the performance of DSR and greedy routing in terms of message delay, success rate and hop count. The measurements are plotted against different invalidation times for DSR route caches and greedy neighborhood tables. Each point in the graph is the average of 1000 measurements.

Figure 1a shows the average delay from source to destination

we observed for varying cache invalidation times. Clearly, a longer invalidation delta supports a lower delay. Routes can be used for a longer time before route discovery is initiated by DSR or neighbor rediscovery is initiated by Greedy, respectively. However, compared to Greedy, DSR is more susceptible for short route invalidation times. Delay is increasing significantly in this case.

Those large delays come from large setup times until the DSR route is established. We were interested as well how long it takes until a DSR route is established. Figure 1b depicts the average setup time over the route invalidation time. If invalidation time decreases (for invalidation time 0, route discovery starts for each new message), the setup time increases significantly. We interpret this result by the fact that route discovery will overlap with previous ones, thus it may take a longer time until a message is handled by a node.

We were also interested in the performance of DSR compared to Greedy after the route of DSR is established. As depicted in Figure 1c, once the route is established, DSR performs with a lower delay compared to Greedy.

Figure 1d shows the success rate of Greedy and DSR over the invalidation timeouts. We observed a low and almost invariant success rate of about 20 % for Greedy, while the success rate increases for DSR over invalidation timeout length. Route setup in DSR favors good path over bad ones automatically. In Greedy we select the neighbor node closest to the destination. We believe that Greedy can be improved significantly at this place, by selecting a different metric, i.e., a metric which also favors high quality links over bad ones.

We observed a higher success of DSR on one hand but on the other hand DSR does not provide as much of the pay load which is provided in Greedy packets. DSR has to store the entire route from source to destination in the message as well. We were thus interested in the question how many bytes per second can be transmitted with DSR and Greedy, respectively. As depicted in Figure 1e, Greedy achieves a better data rate than DSR for low cache invalidation times. We think that using a metric as discussed previously will enable greedy as well to perform as good as or even better than DSR when invalidation times are increased.

Finally, we were interested on the length of the paths taken by DSR and Greedy. Figure 1f shows that Greedy takes about one hop more than DSR. We observed that the paths taken by DSR are often following the network boundary. By the time of writing for Greedy our log files do not reveal the paths taken.

5. CONCLUSION

In this work we presented an empirical performance comparison between a localized and a global routing approach. Although, this work is not the first one providing measurements in a real-world sensor network deployment, we think that in answering the question on what are the advantages and disadvantages of localized over globalized approaches, such empirical results are still lacking.

Our intention is to substantiate advantages and disadvantages of localized over centralized data communication protocols with real-world measurements. We focused on one representative of localized and one representative of global routing so far. The space of possible future investigations is endless and we anticipate a discussion on the most interesting ones to follow.

We think that a final justification when localized is better than a globalized approach requires many independent measurements coming from independent research groups. Even measurements repeating experimental setups and experiments of certain protocols are of importance here. We advertise that a single result of one paper should not exclude other papers performing the same measurements and probably achieving varying results. This is however often not that accepted in network research like it is accepted in other disciplines like physics, for instance.

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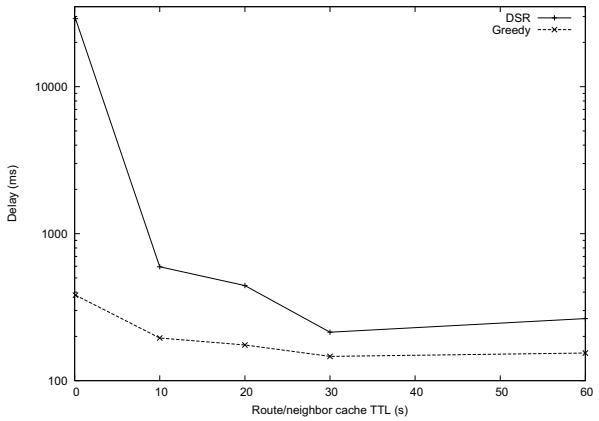
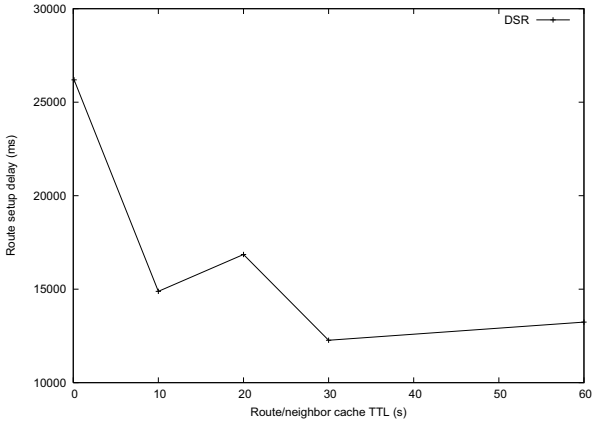
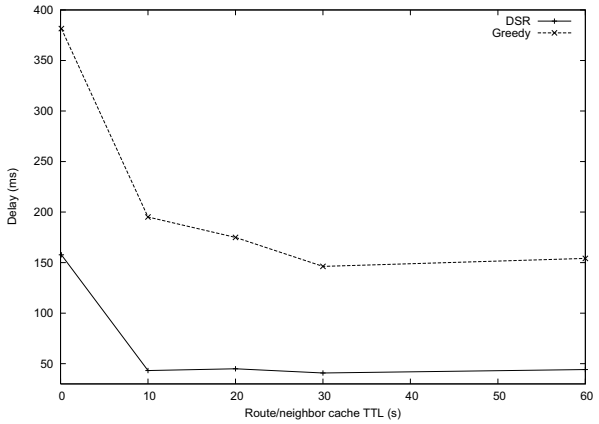


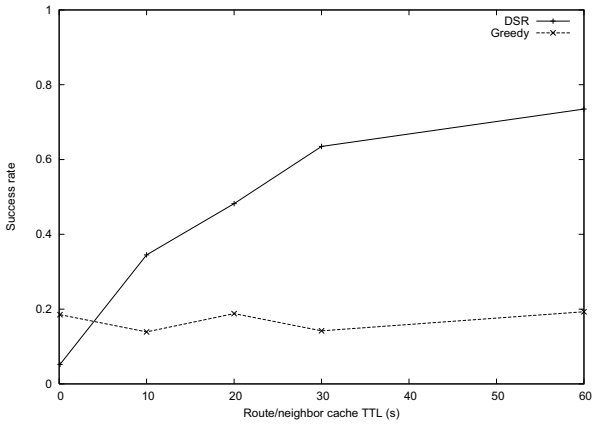
(a) Average delay of DSR and Greedy.



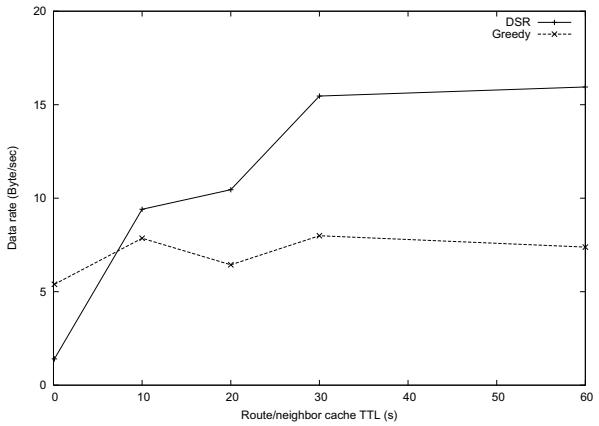
(b) Average route setup time of DSR.



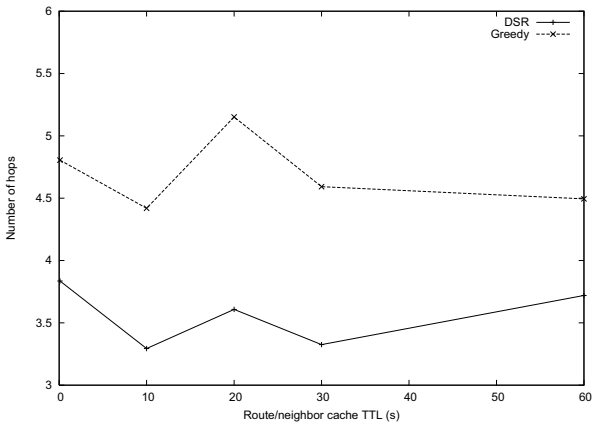
(c) Average delay of DSR after route discovery and Greedy.



(d) Success rate of DSR and Greedy.



(e) Average data rate of DSR and Greedy.



(f) Average Hop count of DSR and Greedy.

Figure 1: First results showing the performance of dynamic source routing and greedy routing under different route cache and neighbor cache invalidation intervals.

How to Take Advantage from Correlated Node Movement in Mobile Sensor Networks

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ABSTRACT

Many applications are designed for mobile scenarios which have high demands on the routing protocol. Frequent topology changes are the consequence of the short transmission range and high mobility of the nodes. However, the number of link breaks and topology changes can be reduced in a significant way if the forwarding nodes along a route are chosen carefully.

In this paper an approach is introduced which decreases the number of topology changes by taking advantage from correlated node movement. The approach is based on deferring routing messages and can be used for many popular routing protocols to increase their performance. Its impact on the end-to-end reliability and the selection of forwarding nodes in high mobile networks is simulated by adding the method to the Ad-Hoc On-Demand Distance Vector (AODV) and the Statistic-Based Routing (SBR) protocol.

Categories and Subject Descriptors

D.2.2 [**Network Protocols**]: Metrics—*Routing Protocols - delay based routing metrics.*

General Terms

Algorithms, Management, Performance, Reliability, Theory

Keywords

Mobility, Routing, Wireless, Metric, Delay

1. INTRODUCTION

The number of link breaks usually corresponds to the movement speed of the nodes in the network. Therefore, mobility is often considered as a major problem in wireless networks since it is mainly responsible for topology changes. Nonetheless, in dense mobile networks there is a high probability that several nodes move along in the same direction with similar speed. Thus, the relative movement speed of these nodes is quite small compared to their absolute speed.

In the following, a look at the structure of an urban network is taken. On one hand, there are hotspots in urban areas e.g. pedestrian areas or areas around places of interest where the user density is very high. On the other hand, there are low density areas in the outlying districts of a city. The nodes in such a scenario can be divided into two major groups. The first group consists of slow moving or fixes nodes that remain within the area close to a hotspot. The other group is represented by nodes which move more or less directly and fast from one hotspot to another. If two users in one hotspot decide to move on to the next hotspot, they will be able to directly communicate with each other during the travel due to their correlated movement.

This paper is organized as follows. Related work is discussed in Section 2. The approach that takes advantage from correlated node movement is introduced in Section 3. Furthermore, the section includes a description how to implement the method in AODV and SBR. Simulation results are presented in Section 4. Finally, we summarize the results and conclude with our fields of research in the future.

2. RELATED WORK

Routing protocols that are designed for mobile wireless networks have to deal with frequent topology changes. It is clear that the number of topology changes corresponds to the transmission range and the mobility pattern of the nodes. A shorter transmission range decreases the average number of neighbors of a node. In addition, the neighborhood of a node changes more often since nodes that pass by remain a shorter amount of time within the coverage area of the node. However, usually it is not possible to modify the transmission range or the movement of a node. The routing protocols can follow different strategies to deal with the mobility problem.

One strategy which is used by a large number of protocols is to predict the movement and the connectivity of the nodes in advance to minimize the number of link breaks and the amount of routing overhead. The prediction can be based on several characteristics e.g. bit error rate, packet loss, received signal strength, location information obtained from the Global Positioning System (GPS), or learned movement patterns as shown by [3]. The Flow Oriented Routing Protocol (FORP) [4] uses the GPS information to predict the mobility in advance. Therefore, it is able to compute the link expiration time for each hop along the route. The predicted link expiration time is used to calculate the route expiration time which can be regarded as a metric to evaluate an end-to-end route in respect to stability and reliability. Other routing protocols like Location-Aided Routing (LAR) [5] utilize the GPS information to reduce flooding overhead. Learning algorithms can be used to predict the movement pattern of the nodes in the case that they have enough computational power and are able to store the position information. These algorithms are often based on hidden markov models [3] or on large databases [6].

Another strategy to reduce the number of topology changes is to select a forwarding link according to different met-

rics like reliability [7], node speed or link duration [8]. It has to be kept in mind that the most reliable or stable path does not necessarily result in the shortest possible path in respect to the number of hops.

The method that is presented in this paper prefers slow moving nodes over fast moving nodes. It is inspired by several observations made by [8] and [9] which analyze different mobility models. The papers show that the link duration and the number of topology changes strongly depend on the used mobility model and its configuration. Furthermore, the presented node speed histograms reveal that the link duration is correlated to the speed of the nodes. Thus, slow moving nodes should be selected as forwarding nodes since their links tend to be more stable than the links of fast moving nodes. Section 3 introduces the functionality of the approach and shows its capability to take advantage from the fact that the node speed is not uniform distributed in many scenarios due to restricted path selection.

3. DELAY BASED APPROACH

The end-to-end reliability in wireless networks strongly depends on the mobility of the network. The faster the movement speeds of the nodes, the more link breaks occur in the network. Gerharz et. al. [8] simulated the probability distribution function of the link duration time in a network where the nodes move according to a random waypoint mobility model. They showed that the end-to-end reliability can be increased by selecting the next hop depending on the estimated link duration time. Another approach is to take advantage from nodes with correlated movement since relative movement speed is mainly responsible for link breaks. These nodes should be selected as next hop due to their more reliable links as a consequence of their correlated movement.

The problem is to detect the correlated node movement if no position information is available. Consider a scenario on a highway in one direction. There will be some fast driving cars, some with average speed, and some slow moving trucks. On one hand, if there are more trucks on the road than other cars, the routing protocol should prefer trucks to forward data since their movement is strongly correlated resulting in a high link duration time. On the other hand, fast movement cars are also able to build a stable network if they represent the majority of cars on the highway. Thus, a metric is required that is able to estimate the current relative movement speed of a node. Each node is able to estimate its speed by keeping track of the presence of its surrounding nodes. A change in its neighborhood indicates that the node has moved away from the other nodes or the other nodes are moving away from it.

However, routing or data traffic are required to detect changes in the neighborhood. Otherwise, the nodes are not able to keep their neighbor lists up to date. In general, the routing traffic is sufficient to maintain fresh information in the neighbor list since even reactive protocols like AODV transmit hello messages periodically.

The basic idea of this delay based approach is to defer the forwarding of routing messages depending on the change of the neighborhood. More changes in the neighborhood result in a higher delay of the routing messages. Therefore, the routing protocols choose nodes with a lower relative node speed since these nodes forward routing information more quickly. It is obvious that a mobile node or a cluster of mobile nodes with correlated movement may have peaks in their neighborhood change if they move through certain areas e.g. crossing of a road or an area of high node density. Thus, a mechanism is required to reduce the variation of the metric and make it robust against short temporary changes. The exponential weighted moving average algorithm is used to minimize the impact of peaks. The neighborhood change metric ϵ, is calculated according to Equation 1 which was empirically determined from a set of mobile scenarios with different mobility models, node densities, and traffic patterns.

$$\epsilon_\tau = \alpha \cdot \epsilon_{\tau-1} + (1-\alpha) \cdot X_\tau, \alpha = 0.9 \quad (1)$$

The chosen smoothing factor α represented the best trade-off between reaction time and peak suppression in the simulated scenarios. X_τ is the number of changes in the neighbor list during the last observation interval.

3.1 Neighborhood Change Detection

Changes in the neighbor list are counted during each observation interval. The counter is increased by one each time a node is added to the list or removed from it. Depending on the routing protocol or design of implementation the approach can be integrated in the protocols or implemented as a cross-layer. If the approach is integrated in the protocols it can use already existing neighbor lists to calculate the neighborhood change. In the case, that the approach is implemented as a cross-layer it has to keep track of the changes in the neighborhood by itself. In the following, the focus lies on the cross-layer approach since it is independent of the routing protocol and the mac protocol.

3.2 Neighborhood List

The neighborhood list consists of neighbor entries. Each entry stores information about the neighbor e.g. time of first contact and time of last contact. However, the approach presented in this paper only requires the time of the last contact. If a node receives a packet of another node it checks whether the originator of the packet is in the list. In the case that the node is not in the list a new entry is created and inserted in the list. Otherwise, the existing corresponding entry is updated.

3.3 Neighbor Expiration

The neighbor expiration time has to be chosen carefully since it depends on the traffic pattern and the routing protocol. Many protocols keep track of the surrounding nodes by periodically transmitting hello messages. To minimize changes in the neighbor list if some nodes are temporarily unavailable, the neighbor expiration time is set to four times the duration of the hello message interval of the routing protocol. The value was empirically determined from a large set of scenarios.

3.4 Observation Interval

The observation interval has a large impact on the approach since its duration mainly affects the neighborhood change and thus the forwarding delay of the routing messages. The duration has to be chosen in respect to the topology change and link break rate. Duration of twice the hello message interval of the routing protocol provided the best performance in the set of test scenarios. It has to be kept in mind that the duration affects the reaction time of the approach to changes in the neighborhood.

3.5 Forwarding Delay

The time a node defers the forwarding of a routing message is in the following referred to as forwarding delay. The delay δ is calculated from the neighborhood change metric ϵ, of the last observation interval. Equation 2 is used to calculate the forwarding delay in the simulated scenarios in Section 4.

$$\delta = \frac{\Delta h}{\lambda} \cdot \left(1 - \frac{\phi}{\epsilon_\tau + \phi}\right) \quad (2)$$

The quotient of the hello message interval Δh and λ represents the maximum forwarding delay. Thus, λ covers the function of a delay limiter. The second factor of (2) is influenced by ϕ, and is used to divide the maximum forwarding delay into smaller steps. A smaller ϕ value increases the delay for a smaller number of neighbor changes. A ϕ value of ten is used in the simulations since it results in a good accuracy of differentiation in a large spectrum of neighbor list changes. The additional delay has to be chosen according to the net diameter in number of hops, the underlying medium access layer, and the traffic load of the network. In most scenarios, an additional delay of several milliseconds is quite sufficient to modify the topology of the network. The impact on the end-to-end delay of data traffic is minimized due to the fact that the cross-layer approach only defers routing messages. Proactive protocols are less affected by the artificial delay of the routing messages since end-to-end routes are maintained between all nodes in the network. However, the duration that is required to establish a new end-to-end route in reactive and hybrid protocols is increased by the additional delay. Nevertheless, the routes are more stable which results in less link breaks. Therefore, the number of route repairs is minimized. Thus, the overall end-to-end delay can be reduced while achieving a higher end-to-end reliability.

4. SIMULATION RESULTS

The OPNET Modeler 14.5 is used to simulate the impact of the cross-layer approach on the end-to-end reliability and the selection of forwarding nodes of AODV and SBR in respect to their current relative speed. Instead of using the OPNET AODV model, the model is implemented as specified in the RFC. The physical layer is replaced by a disc model to minimize side effects. Furthermore, the radio range of the nodes is set to 200 meters and the transmit data rate is set to 256 kb/s. The nodes use Carrier Sense Multiple Access (CSMA) as Media Access Control (MAC) protocol with a simple back-off algorithm. At the beginning of each simulation 100 mobile nodes are randomly placed on a square of 1000 by 1000 meters.

All nodes move according to a random waypoint model with a constant pause time of zero seconds and a minimum node speed of 1 m/s. The maximum node speed is increased from 2 m/s to 20 m/s in steps of 2 m/s. 10 nodes in the network select a uniform destination at the beginning of the simulation. These nodes generate packets according to an exponential distribution with a mean value of 2 seconds and a constant packet size of 1024 bits. The traffic model is started after 300 seconds to minimize the impact of the transient phase of the random waypoint model.

The duration of the simulations is set to 1400 seconds. Statistics are collected after 400 seconds to allow the stabilization of the network. The results are calculated from 20 simulation runs with different seeds of the traffic and mobility model. All error bars show the 99 percent confidence level of the collected statistics whereas histograms represent the average of 20 simulation runs. The configurations of the routing protocols are shown in Table 1 and Table 2. The chosen configurations leave enough room for performance improvements of the end-to-end reliability of the protocols.

Table 1: AODV Configuration

Active Route Timeout	1.5 s
Hello Message Interval	0.8 s
Net Diameter	12
Net Traversal Time	1.4 s
Node Traversal Time	0.02 s

Table 2: SBR Configuration

Active Route Timeout	3.0 s
Hello Message Interval	4.0 s
Decrease Routing Interval	4.0 s
Short Hello Message Interval	4.0 s
Short Hello Message TTL	1
Hello Message Time-To-Live	12

Three different delay metrics are used to simulate the impact that the deferring of routing messages has on the next hop selection and on the reliability. The first metric forwards the routing messages immediately. The second metric calculates the forwarding delay according the approach presented in Section 3 and is in the following referred as Relative Speed Estimation (RSE) metric. The forwarding delay of the third metric is chosen in respect to the current absolute node speed.

4.1 Node Speed Distribution

The end-to-end reliability of routing protocols is strongly correlated to the movement pattern of the nodes in the network. For that reason, a closer look is taken on the absolute speed of the nodes at the time they forward a packet. Figure 1 and Figure 2 present the normalized histogram of the absolute speed of the nodes when forwarding a packet. The results of both figures show that slow moving nodes forward more traffic than faster nodes. This behavior is independent of the protocol and the used metric. The shape of the distribution results from the node speed distribution which is caused by the random waypoint mobility model [8].

Furthermore, the figures point out that the node speed distribution of the forwarding nodes can be modified by deferring the routing information. However, a lower absolute node speed does not necessarily result in a higher end-to-end reliability. If a cluster of nodes move in the same direction with similar the speed their absolute speed can be neglected in contrast to their relative speed.

4.2 End-To-End Reliability

Routing protocols are often rated by their achieved end-to-end reliability and delay. Nonetheless, the focus of this subsection lies on the reliability due to the fact that our testing scenarios revealed that the deference of the routing messages has no significant impact on the average end-to-end delay. Figure 3 and 4 show the reliability of the different metrics and protocols depending on the maximum speed of

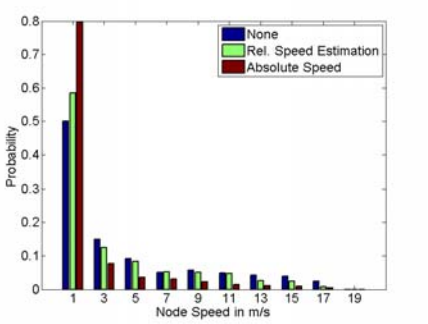

Figure 1: AODV Node Speed Histogram

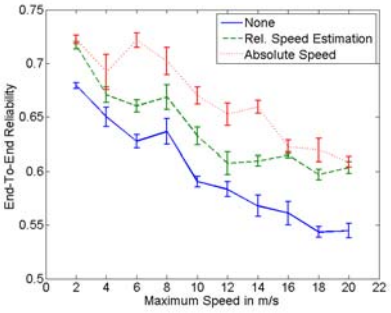

Figure 3: AODV End-To-End Reliability

the random waypoint model. The results of Figure 3 indicate that the RSE and the absolute speed metric increase the performance of AODV in the case of more mobile scenarios. The higher reliability results from more stable routes as a consequence of the longer link duration time.

The SBR protocol achieves the highest end-to-end reliability if its routing messages are deferred according to the RSE metric which is in contrast to AODV where the absolute speed metric offered a slightly better performance than the RSE metric. This effect can be explained as follows. Hello Messages are periodically flooded by the SBR protocol in the network which results in a higher routing overhead. Thus, the nodes have more precise information of their neighborhood. For that reason, the SBR protocol takes more advantage from the deferring of messages than AODV.

5. CONCLUSION AND OUTLOOK

In this paper, a new delay based approach was introduced that is able to increase the end-to-end reliability of protocols in mobile networks by deferring the forwarding of routing messages. Optimized configurations were used instead of using the default ones since these configurations only achieve acceptable performance in networks with low mobility.

A closer look was taken on the speed of the nodes that are selected by the protocols to forward data traffic. The simulation results showed that the nodes are able to estimate their relative movement speed by keeping track of changes in their neighborhood lists. Furthermore, the results pointed out that it is possible to modify the topology of a network by deferring the forwarding of routing information.

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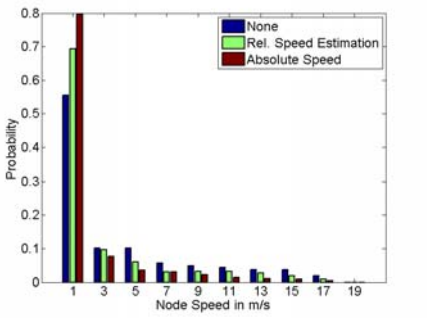

Figure 2: SBR Node Speed Histogram

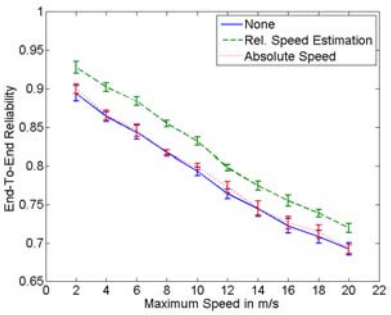

Figure 4: SBR End-To-End Reliability

Ghost: Software and Configuration Distribution for Wireless Sensor/Actor Networks

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ABSTRACT

Wireless sensor and actor networks commonly consist of a rather large number of more or less widely distributed nodes. The resulting spatial complexity arises severe software related maintenance problems like application code and configuration updates. This paper presents the Ghost subsystem for efficient remote software maintenance in such networks. Besides safety, security and operation in heterogeneous environments we also address practical aspects like performance and resource requirements. Some results from a real-world installation will close this paper.

1. INTRODUCTION

In order to achieve a long lifetime for sensor/actor networks (henceforth simply called WSN), these distributed systems are subject to regular maintenance cycles. Besides hardware related issues like the renewal of power supplies or the replacement and attachment of modules, software related modifications are also very common. The latter allow application updates for integration of new functionality or for fixing bugs. Sometimes, there is just the need to reset a node or to modify its configuration for changing its behaviour or individual role in the overall system.

The problem's scope and intensity differs according to the evolution stage of the system. During software development, frequent updates (test versions) for few nodes can be expected. The frequency diminishes rapidly with the final release but then affects significantly more nodes within the original environment. But still, several updates might be required suddenly during the system runtime. It is similar with hardware. During development there are commonly few nodes but possibly they are already of different architectures. Often, these nodes are densely placed and easily accessible. After system deployment their number and heterogeneity increases within a quite ample environment. Then, some of them are hardly or not accessible at all. The conventional method to update sensor nodes on demand by means of mobile computers and debug-interfaces is safe and secure indeed but in any case extremely complex, annoying or even impossible. To counter this problem, the Ghost subsystem offers an efficient method for accomplishing software and configuration modifications via image distribution over the communication infrastructure which is available anyway within such networks. Since data dissemination protocols have received wide attention within the WSN community, several similar approaches like Typhoon [7], FiGaRo [8] and Deluge [6] already exist. Yet, such systems commonly provide their own customized communication/routing protocol or even require a special runtime environment on the nodes. In our opinion, both premises are adverse, since remote maintenance is important indeed but should neither define the actual application's communication nor affect the overall system performance. This is why Ghost was designed to use any available protocol and needs no modifications or extension of the used operating system. Instead, our focus aims on resource-aware integration into any software besides providing efficient and reliable operation. In this paper we present the central concepts of the Ghost remote maintenance subsystem but refer to radio communication for our concrete real world test bed.

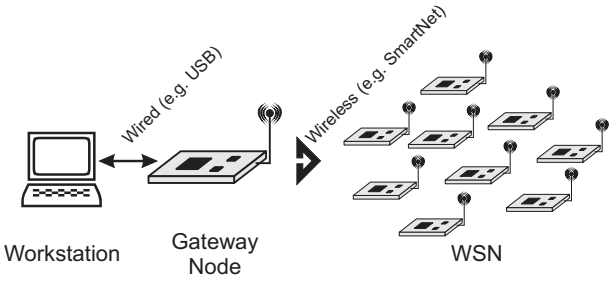

Figure 1: Ghost infrastructure for wireless remote maintenance

2. CONCEPTS AND OPERATION

Figure 1 shows wireless remote maintenance as one possible Ghost infrastructure. In this case, data is transferred from a workstation computer to a dedicated gateway node. The gateway creates data packets and transmits them to the destination nodes by any network protocol available in the WSN. Depending on this protocol, unicasts and broadcasts including routing are possible. If supported, groupcasts offer the special possibility to modify software in a role specific manner simultaneously for certain subsets of nodes.
Ghost is implemented as add-on for integration into any WSN application. To be always available for remote commands, it runs in parallel to each node's individual software and performs three basic operations:

1. reception and integrity check of Ghost command and data packets (image fragments) from any of the node's communication interfaces (radio, infrared, ethernet, CAN, etc),
2. direct execution of Ghost commands and buffering of images in an external flash memory, and finally
3. reprogramming of affected memory blocks (haunting).

Therefore, the Ghost subsystem is organized in two modules (→ Fig. 2): Steps 1 and 2 are executed during regular node operation (high level task). During step 3 the operating system along with the entire application is stopped (low level functions). After haunting, the device is reset.

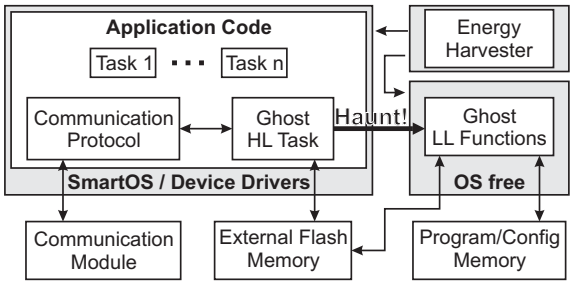

Figure 2: Ghost integration with WSN applications

2.1 Ghost Functionality

Always keep in mind, that software based remote maintenance subsystems stay passive for most of the entire system uptime whereas the fraction of their active operation time is relatively small. Thus, the complexity and permanent resource requirements (CPU, RAM, ROM) must be adjusted carefully to the available performance of the nodes and a well balanced cost-benefit-ratio is required.

This is why the high level module runs as regular task and requires no further adaptation of the remaining software. This task accepts five basic commands from virtually any communication channel:

1. **New**: initiates a new image transmission by sending the preconditions required to run or use the image (e.g. CPU type). This is required to avoid accidental installation of incompatible software or configurations which would render the node inoperable.
2. **Data**: successively transmits data fragments until the entire image is transferred. The fragments are limited by the payload size of the underlying network protocol.
3. **Reset**: is used for explicit restarting of nodes.
4. **Query**: retrieves application, hardware and runtime related information about the node. This always includes application type, version, build number, CPU type, remaining energy and uptime. Additional data is optional and node-specific but always limited by the payload of a single network data packet.
5. **Haunt**: initiates updating of program and/or configuration by any previously received image. This is done in Ghost low level mode and finally invokes an implicit node reset.

Figure 3a shows an example for a possible remote software update procedure via a gateway node. Depending on the requirements and remaining memory resources, an additional clone-function can be statically linked into the Ghost subsystem:

6. **Clone**: requests the currently running application code from a node.

By first sending a query, a node can check its neighbourhood for available software types and versions. Thereby newly deployed nodes can integrate themselves almost autonomously into a running WSN by requesting the appropriate software from neighbour nodes. Figure 3b shows an example. Yet, this autonomy requires that

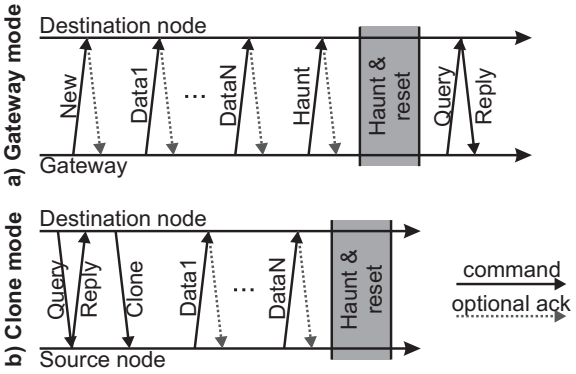

Figure 3: Ghost communication process

each new node is equipped with a certain initial application containing the Ghost subsystem and the knowledge about its future role in the WSN. This role is defined by the application type, which is unique for each kind of software and hardware combination (e.g. router for TelosB nodes, ultrasound sensor for SNOW5 nodes, etc.). Likewise, nodes can stay up-to-date by observing their environment for newer versions of their own software. In contrast to the common method, where a source node (gateway) pushes the software to each affected node, cloning allows updates to be pulled over the whole network without explicit routing or flooding. This desired virus like spreading is extremely useful for very large networks where the individual handling of each single node would become too complex. Of course, the network protocol must remain compatible between versions to support any kind of long term self-maintenance.

2.2 Security

Secure data transmission is very critical in wireless sensor networks. This is especially true for the deployment and maintenance of software and configuration images since a tapping attacker might draw conclusions about operation and vulnerabilities of the overall network. Of course, prevention of hostile code injections or node takeovers is also mandatory.

The obvious technique is to encrypt all communication. Yet, the used algorithm must provide an adequate security level at appropriate resource requirements. Furthermore, the key selection needs careful consideration. Where an individual key for each node provides highest security (especially, if nodes can be stolen along with the secret), a simultaneous updating of several nodes by a single encrypted image is not possible any more. The same holds for cloning, since key exchange methods among today's low-power nodes are not practicable. Thus, common keys increase the performance while significantly reducing the network load altogether with energy consumption.

Our current implementation focuses on usage during WSN development in research and education. Thus, we prefer performance to security and use either no encryption at all or the TEA algorithm [12] for a minimum of security. Then, the password is not necessarily node specific, but can depend on the application type, version and build number. This way and despite of a regular password change with each update, it is still possible to supply several nodes simultaneously with new software. At receiver side, the high level task validates the packets regarding encryption and CRC checksum before executing control commands or buffering new images.

2.3 Safety and Reliability

Safety and reliability are other important factors in remote maintenance systems. This includes the guaranteed and complete reception of command and data packets at the desired destination nodes. Concerning the communication, Ghost completely relies on the used network and routing protocol. This accounts for compactness and flexibility of the Ghost subsystem. Just the data packets are successively numbered with each new transmission.

While communication is shifted to a WSN specific protocol, Ghost integrates some mechanisms to guarantee smooth completion of the actual update process and to prevent the node's total breakdown caused by unpredictable errors while haunting. This is why the Ghost subsystem is divided into two parts.

As the high level task runs as part of the application and in parallel to the user tasks it is permanently ready to process Ghost packets (→ Fig. 2). If a haunt command arrives, the Ghost task checks for sufficient remaining energy to perform the expensive update operation. If energy is low, haunting is deferred to allow a possibly available energy harvester to recharge the power supply. As soon as enough energy is available or if the charge level can not be determined at all, the Ghost task stops the operating system and passes control to the low level functions for haunting the system.

Checking the remaining energy before each update is very important since many sensor nodes are based on microcontrollers with program flash ROM. Besides, many applications are statically linked and hard to modify at runtime. In both cases, the node's program memory must be erased before installing the new software. A power breakdown between erasing and complete reflashing would indispensably corrupt the node and require manual repair – if this is possible at all. Indeed, the energy requirements for updating a node may not be underestimated. They depend on the electrical characteristics of program and flash memory and on the image size. The latter defines the number of read/write cycles and in consequence the total duration of this critical process. Section 4 shows the energy requirements of a concrete Ghost implementation.

Yet, underestimated energy resources as well as other unpredictable problems can still lead to node reset or hanging during the update. Thus, the Ghost low level functions configure an available watchdog timer to force an reset in case of a hanging node. A reset always leads to a well defined system state, since the Ghost low level part will never be erased from the ROM. In particular, it contains an emergency function (→ Fig. 4), which is automatically executed at node start-up to recover from awkward situations. First, it tests a flag indicating the state of the last update. On success, the regular application is started and the operating system takes over control. On failure, the power supply is again checked repeatedly until there is sufficient energy to restart the update.

3. IMPLEMENTATION

As useful and indispensable remote maintenance is for large scale or frequently updated sensor networks, as complex are the resulting requirements and challenges for a concrete implementation. Thereby, some problems are rooted in the underlying network (hardware and protocols), in the node's architecture and in the applied operating system. Our implementation of Ghost uses the SNOW5 [2, 5] sensor node and the *Smart*OS [3] operating system. Within the test application presented below we used the *Smart*Net wireless communication protocol.

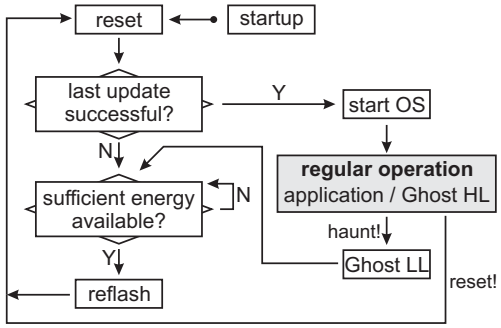

Figure 4: Ghost low level operation during system runtime

The SNOW5 [2, 5] nodes integrate a MSP430F1611 [10] controller with 10 kB RAM and 48 kB ROM running at 8 MHz. An external 2 MB flash memory allows simultaneous buffering of various Ghost program and configuration images. Communication is done via a CC1100 [9] radio transmitter supporting data rates up to 500 kbps.

*Smart*OS [3] was developed for real-time operation of low-power and low-performance devices like sensor nodes. The preemptive scheduling of prioritized tasks allows prompt processing of internal and external events. Altogether with the sophisticated resource management policy, it allows the easy composition of arbitrary tasks to still efficient applications. Thus, *Smart*OS based software can easily be extended by the Ghost subsystem.

Finally, *Smart*Net was developed for both, CSMA/CA or slotted wireless communication. It allows broadcasts, groupcasts, the integration of routing protocols and self-organizing communication via e.g. HashSlot [1]. The *Smart*Net high priority task processes incoming data packets and redirects them to the appropriate receiver tasks. Similar to TCP ports in IP networks, this is done by each packet's port ID and destination address. In turn, the receiver task is signalled and reactivated by *Smart*OS according to its priority.

Fig. 2 shows the integration of the Ghost subsystem into a *Smart*OS based software. Since *Smart*OS is fully preemptive, it is sufficient to link the Ghost modules into the the WSN application. Besides adding the high level task, the linker also places the low level module adequately to start the execution of the emergency recovery function at system start prior to the operating system. The required memory (RAM/ROM) adds up of the Ghost modules plus the communication protocol and the flash memory driver. However, the last two components are often part of the application anyway and thus mean no extra system load. Yet, a slim and OS independent version of the flash memory driver is required within the low level module to gain read access to this device. In general, performance losses caused by Ghost are negligible since only the relatively rare Ghost commands trigger the execution of the high level task. As already mentioned in section 2.3, an energy harvester is optional but can account significantly to the system stability during memory update processes.

4. TESTBED AND RESULTS

For evaluating the just described techniques under real world conditions, we used a SNoW Bat [4] indoor localization system comprising 45 nodes. In this section we will present some results concerning update speed, resource requirements and energy efficiency.

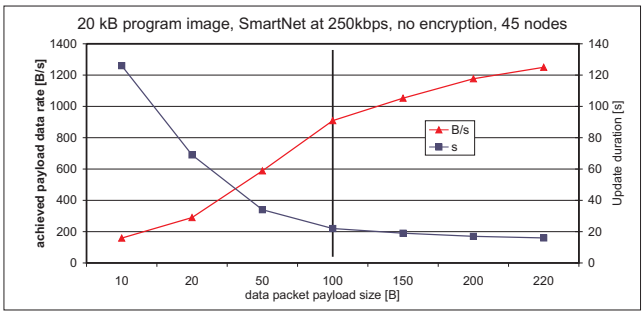

Figure 5: Ghost performance for program image update

In fact, these metrics are not only Ghost dependent but also reflect some characteristics of the applied communication protocol, the node's software architecture and hardware components.

Regarding the ROM size, our current Ghost implementation takes <880 B without and <1 kB with clone functionality (depending on the compiler's optimization level). The RAM requirements of the high level module are about 126 B fixed plus the buffer size for the data packet payload. As figure 5 shows, the latter has significant impact on the data dissemination time. Thus, we commonly chose 100 B for trade-off between speed and memory consumption.

When updating the software within our test bed, we found that *Smart*Net managed to deliver the data very reliable, though the nodes' main application also made intensive use of wireless communication during the remote maintenance process. Finally, reprogramming all 45 nodes by an image groupcast commonly took the same time as reprogramming a single one (approx. 22 sec). In comparison, manual flashing of the same WSN system via JTAG successively node by node took approximately 1 hour and was simply too much time-consuming. In fact, this expected speed-up was the initial main motivation for developing the Ghost system at all.

Finally, table 1 shows the energy requirements of a single node during various operation modes. One can see clearly, that updating the program memory imposes significant load on the power supply compared to regular operation. Yet, intentionally provoked node breakdowns due to current peaks or empty batteries were safely handled by the low level recovery function.

5. CONCLUSION AND OUTLOOK

In our paper we presented the Ghost remote maintenance subsystem for wireless sensor and actor networks. We showed, that efficient and fast software and configuration updates are possible without the need for a predefined communication protocol or especially modified system software. Instead, Ghost integrates easily into any WSN application and accepts data from arbitrary sources (wired or wireless). Thereby it requires little memory and computational power. Besides, it supports role specific software deployment by either direct transmission via a gateway or by autonomous self-maintenance of the nodes via cloning. This way, simultaneous updates are even possible in heterogeneous networks. Finally, the sophisticated low level module along with the optional encryption allows extremely safe and secure operation for reliable remote maintenance. Our current work in this field addresses viral data dissemination techniques, power aware operation in general and energy harvesting in particular.

Table 1: Energy requirements during sensor node operation

low system load (no radio)	17mW
heavy system load (no radio)	26mW
data reception (radio) and buffering (flash)	69mW
haunting process (copy flash to ROM)	81mW

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Positionierung und Sensor Web Enablement in Geosensornetzwerken

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Drahtlose Sensornetzwerke, Geosensornetzwerke, Positionierung, Sensor Web, OGC, Sensor Web Enablement, Frühwarnsystem, Hangrutschung

1. Einleitung
Der Begriff „Digitale Erde“ wurde im Jahr 1998 maßgeblich geprägt und malt eine dreidimensionale Repräsentation der Erdoberfläche verschiedenster Auflösungen zur Unterbringung ausgedehnter Mengen von georeferenzierten Daten aus (OGC, 1998). Grundbestandteil dieser Digitalisierung ist eine, zum Teil bereits heute gegebene Allgegenwärtigkeit von untereinander vernetzten Sensoren. Die fortwährende Miniaturisierung von Hardware, die Effizienzsteigerung der Ressourcennutzung und die Verfügbarkeit preisgünstiger massentauglicher Sensorkomponenten erschließt ein immer breiteres Anwendungsfeld für den Einsatz von Sensornetzwerken. Zukünftige Sensornetzwerke bestehen aus großen Mengen von einfach auszubringenden Sensoreinheiten, die sich selbst organisieren, drahtlos miteinander kommunizieren, Messungen durchführen und auswerten können und die Beobachtung verschiedenster Gebiete und Phänomene ermöglichen. Ziel dieses Beitrags ist es, Aspekte des Einsatzes von Sensornetzwerken vorzustellen, die im Rahmen von Forschungsprojekten der Professur für Geodäsie und Geoinformatik der Universität Rostock entwickelt werden.

Zentraler Ansatz des seit Frühjahr 2007 vom Bundesministerium für Bildung und Forschung (BMBF) im Rahmen des Geotechnologien-Programms geförderten Verbundprojekts *SLEWS* (Sensor based Landslide Early Warning System) ist die Konzeption und prototypische Entwicklung von Methoden und Technologien für flexible und ressourceneffektive Alarm- und Frühwarnsysteme unter Verwendung eines drahtlosen Sensornetzwerks am Beispiel von Hangrutschungen.

Im Zuge des DFG-Projektes *GeoSens* wurde ein Lokalisierungsalgorithmus für drahtlose Sensornetzwerke entwickelt, der auf geodätischen Ausgleichungsansätzen beruht und den Berechnungsaufwand sowie den Energieverbrauch auf ressourcenlimitierten Sensorknoten bei gleichzeitig signifikanter Erhöhung der Positionierungsgenauigkeit deutlich reduziert.

2. Drahtlose Geosensornetzwerke
Reichenbach (2007) beschreibt ein Sensornetzwerk als eine Menge von Knoten, die über eine bestimmte Fläche platziert werden und physikalische Daten eines Phänomens von Interesse messen. Auf einem Knoten sind Detektoren installiert, deren Signale stellvertretend für eine Messgröße stehen. Jeder Knoten ist durch einen ressourcenlimitierten Controller mit beschränkter Speicherkapazität, Prozessorleistung und Kommunikationseinheit auslesbar (Bill et al., 2008). Erfolgt die Kommunikation zwischen den Knoten funkbasiert, wobei Messdaten über die direkten Nachbarn bis zu einer Datensenke übertragen werden können, spricht man von einem drahtlosen Sensornetzwerk (DSN, engl. Wireless Sensor Network; WSN, siehe hierzu Akyildiz et al., 2002). Ein Geosensornetzwerk (GSN), als spezielle Ausprägung eines DSN (Heunecke, 2008), verknüpft ein drahtloses Sensornetzwerk mit der Notwendigkeit, die Position eines oder mehrerer Knoten in einem übergeordneten Lagebezugssystem zu bestimmen (siehe hierzu Kapitel 3). Drahtlose ad hoc Geosensornetzwerke werden zukünftig aus tausenden winzigen, elektronischen, kostengünstigen Sensorknoten bestehen, die ihre Umgebung überwachen, einfache Rechenschritte ausführen und miteinander kommunizieren können. Das Geosensornetzwerk konfiguriert sich unmittelbar nach Ausbringung der Knoten selbst. Jeder einzelne Knoten ist in der Lage, bei Bedarf aktiviert zu werden und solange zu arbeiten, wie seine Energiequelle ausreicht. Mittels Methoden wie Selbstheilung und Selbstorganisierung reagiert das Netzwerk auf Knotenausfälle und Störungen. Je nach Auswahl der Detektoren ist ein GSN als universell anpassbares Instrument zur Beobachtung verschiedenster Phänomene einsetzbar, welches die großräumige Erfassung von Umweltphänomenen in unterschiedlichsten Umgebungen, z.B. auch in schwer zugänglichen Regionen und bei sich bewegenden Objekten, erlaubt. Geosensornetzwerke sind zukünftig als Quelle automatisierter Datengewinnungsmethoden für verschiedenste GIS-Anwendungsfelder sehr interessant (siehe hierzu Kapitel 5).

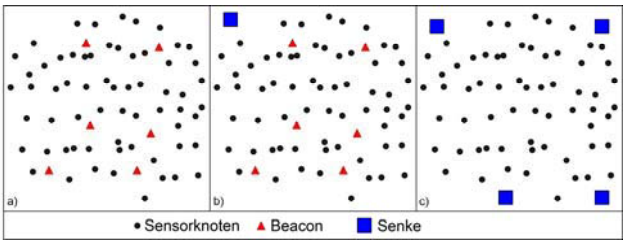
3. Positionierung in Geosensornetzwerken
Eine der wichtigsten Aufgaben für eine raumbezogene Datenauswertung ist bei einer zufälligen Ausbringung der Sensoren die Bestimmung der Position jedes Einzelnen. Ungenaue Eingangsgrößen wie z.B. Distanzmessungen und die sehr eingeschränkten und begrenzten Energie- und Rechenressourcen eines jeden Knotens sowie die hoch miniaturisierte Hardware und geringe Batteriekapazität erfordern die Entwicklung robuster, energieeffizienter und präziser Lokalisierungsalgorithmen. Dieses Kapitel gibt einen Überblick über die aktuellen Forschungen an der Universität Rostock auf dem Gebiet der Lokalisierung in Geosensornetzwerken (GSN) und beschreibt Methoden zur

Standortbestimmung von Sensorknoten sowie der Verbesserung ihrer Position durch Ausreißerdetektion.

3.1.1 Netzwerktopologien

Der Lokalisierungsprozess in einem drahtlosen GSN basiert auf unterschiedlichen Netzwerktopologien (Abbildung 1), welche im Folgenden kurz beschrieben werden sollen. Allen gemein ist dabei, dass einige wenige energie- und rechenstärkere Knoten mit existierenden Positionierungssystemen (Global Navigation Satellite System (GNSS), Global System for Mobile Communications (GSM)) ausgerüstet sind. Diese Knoten werden im Folgenden als Beacons bezeichnet. Nachdem diese Beacons ihre Position ermittelt haben, bestimmen die restlichen Knoten ihre Position, z.B. durch Streckenmessungen, eigenständig.

Abbildung 6: Ad hoc vernetzte Sensorknoten: a) mit Beacons, b) mit Beacons und einer festen Senke (freies Netz), c) ohne Beacons und vier Senken (Infrastrukturfall).



In dem ersten Fall (Abbildung 1a) besteht das Netz aus ad hoc vernetzten Sensorknoten und den Beacons. Hier wird der Lokalisierungsalgorithmus entweder auf allen Sensorknoten und/oder zusätzlich auf den Beacons durchgeführt. Das bringt den Vorteil mit sich, dass jeder Knoten seine Position mit dem geringsten Kommunikationsaufwand im Netz selbst bestimmt.
Im Gegensatz dazu senden im zweiten Fall (Abbildung 1b) alle Sensorknoten ihre Daten zur Senke (z.B. einem Server, PC) im Netzwerk. Die Senke übernimmt dabei alle Berechnungsschritte der komplexen Lokalisierungsalgorithmen. Die Nachteile dieser Vorgehensweise sind der extrem hohe Kommunikationsaufwand im Netzwerk sowie die Anfälligkeit bei Unerreichbarkeit der Senke durch deren Ausfall oder Blockade der Weiterleitung. Vorteil ist allerdings, dass die Senke Teil einer Infrastruktur ist, die die Bestimmung eines geodätischen Datums (Ursprung, Rotation, Translation und Maßstab eines Referenzkoordinatensystems) ermöglicht. Damit kann die Position eines einzelnen Sensorknotens in einem weltweiten Referenzsystem (z.B. WGS84) wiedergegeben werden.
Beide Techniken haben den Nachteil, dass sie entweder einen hohen Kommunikations- oder Berechnungsaufwand mit sich bringen. Im dritten, dem günstigsten Fall (Abbildung 1c) ergibt sich eine Mischtopologie, in der der weniger komplexe Teil der Lokalisierung auf den Sensorknoten durchgeführt und der energieaufwändige Teil, im Hinblick auf möglichst geringe Kommunikationskosten, auf die Senke ausgelagert wird. Dieser hybride Algorithmus muss flexibel genug sein, um alle möglichen Knotenausfälle zu kompensieren und damit sowohl eine dauerhafte, verteilte als auch eine zentralisierte Berechnung zuzulassen, was zu einer längeren Lebensdauer des Netzwerkes führt.

3.1.2 Lokalisierungsmethoden

In der Literatur wird zwischen zwei Möglichkeiten unterschieden, um eine Lokalisierung in Sensornetzwerken zu ermöglichen (Born et. al. 2008). Die approximativen Algorithmen nutzen entweder Näherungsbeziehungen oder nur sehr ungenaue Positionen bzw. Distanzen als Eingangsdaten und bestimmen eine eher grobe Position mit wenig Rechenaufwand. Dazu nutzen sie zum Beispiel Schwerpunktbildung (WCL) (Blumenthal et. al. 2005) oder Flächenüberlagerung (APIT) (He et. al. 2003). Sie können Fehler einfacher verzeihen und sind damit i.A. sehr robust. Allerdings ist der Algorithmusfehler selbst dafür verantwortlich, dass sie auch bei fehlerfreien Eingangswerten nie eine exakte Position ermitteln.
Dies ist wiederum ein Vorteil der zweiten Klasse - den exakten Algorithmen. Sie können bei entsprechend genauen Eingangswerten auch exakte Ausgangswerte produzieren (Born et. al. 2006). Jedoch benötigen sie dafür i.A. viel Rechenzeit und Speicher, wodurch eine uneingeschränkte Ausführung auf ressourcenlimitierten Sensorknoten nicht möglich ist. Dennoch gibt es erste Ansätze, die durch z.B. eine sinnvolle Verteilung der Subaufgaben („Distributed Least Squares“-Algorithmus (DLS)) (Reichenbach et. al. 2006), die Algorithmen bei gleichbleibender Präzision vereinfachen. Der DLS benutzt Distanzen zwischen den Knoten und basiert auf einer anschließenden überbestimmten Trilateration. Durch eine geschickte Verteilung der Berechnungen, komplexe Aufgaben (Matrixinversionen) werden auf die ressourcenstarken Beacons ausgelagert und nach Fluten dieser ins GSN auf den Sensorknoten die sparsame Nachberechnung (Multiplikation, Addition einer 2x2-Matrix) ausgeführt, wurden Einsparungen von bis zu 86% im Ressourcenverbrauch im Vergleich zu etablierten exakten Methoden erreicht.

3.1.3 Ausreißer

Messungen, wenn sie denn durchgeführt werden, sind immer fehlerbehaftet. Gerade die bekannten Distanzmessverfahren (z.B. Signalempfangstärkemessung (RSS)) in GSN sind sehr fehleranfällig und können eine große Zahl Ausreißer produzieren (Reichenbach und Timmermann 2006). Wie im Kapitel 2 aufgezeigt, können auf den Sensorknoten diverse Sensoren zur Erfassung physikalischer Phänomene installiert sein. Diese Sensormesswerte können, wenn sie mit definierten Regeln mathematisch mit räumlichen Eigenschaften in Verbindung gebracht werden, zur Verbesserung der Position eingesetzt werden. In (Reichenbach et. al. 2008) wird der „Anomaly Correction in Localization“-Algorithmus (ACL) vorgestellt, mit dessen Hilfe Sensormesswerte zur Ausreißerdetektion genutzt werden. Dafür wird über dem Gebiet von Interesse eine Footprintkarte in Sensorintervalle unterteilt, die z.B. durch Luft- oder Satellitenbilder gewonnen wurde. Die gemessenen Werte werden dann mit den Positionen verglichen, die mit durchgeführten Trilaterationen erreicht, auf die Footprintkarte abgebildet und somit den a priori definierten Sensorintervallen zugeordnet wurden. Stimmen die Sensormesswerte mit den erwarteten überein, werden die Beobachtungen zur weiteren Lokalisierung verwendet. Im Falle einer Diskrepanz wird die Trilateration als Ausreißer verworfen. Allerdings ist es auch möglich, dass ein Sensorintervall auf mehrere räumlich getrennte Flächen aufgeteilt wird, um verschiedene Gebiete mit dem gleichen Sensorprofil auszustatten. Diese getrennten Flächen verhalten sich aber im Wesentlichen wie getrennte Sensorintervalle, mit dem Unterschied, dass Positionen, die in einer Teilfläche liegen, jedoch zur anderen gehören, nicht als Ausreißer erkannt werden.

4. Sensor Web

Ein Schwerpunkt bei der Untersuchung der Anwendungsbereiche von Geosensornetzwerken ist die Adaption des Grundkonzepts des Sensor Web. Im Rahmen von Forschungsprojekten der NASA prägte sich der Begriff „Sensor Web“ für die Zusammenarbeit heterogener und räumlich verteilter Sensorsysteme und Sensorplattformen zur Nutzung als Makro-Instrument (Delin, 2002). Vor allem im Bereich der Beobachtung und Vorhersage von Naturkatastrophen zeichnet sich dadurch ein hohes Potential ab, bestehende Systeme und Konzepte maßgeblich zu verbessern

Weltweit existiert jedoch eine große Anzahl verschiedener Hard- und Softwarestandards für den Umgang mit Sensorik und Sensordaten, begründet in der breiten Menge von Sensortypen, Nutzergemeinschaften und teilweise proprietären Technologien und Softwareanwendungen. Seit dem Jahr 2000 beschäftigt sich das Open Geospatial Consortium (OGC) im Rahmen der Sensor Web Enablement-Initiative (SWE) mit der Erstellung von standardisierten Schnittstellenprotokollen und Datenmodellen (siehe Tabelle 1), um alle Arten von verfügbaren Sensoren und Instrumenten, aber auch Archive von Sensordaten über das WWW auffindbar, zugreifbar und wenn möglich auch kontrollierbar zu machen (Botts, 2007).

Tabelle 1: Spezifikationen der OGC SWE-Reihe

Spezifikation	Anwendung
Observations & Measurements Scheme (O&M)	Beschreibung von Sensorbeobachtungen
Sensor Model Language (SensorML)	Modellierung von Sensorik und Sensorprozessen
Transducer Markup Language (TML)	Modellierung von Messwertgebern
Sensor Observations Service (SOS)	Lieferung von Sensorbeobachtungsdaten
Sensor Planning Service (SPS)	Anforderung und Planung von nutzerbasierten Datenanfragen
Sensor Alert Service (SAS) / Web Notification Services (WNS)	Übermittlung sensorbezogener Meldungen

Ziel der SWE-Spezifikationen ist jedoch nicht der Ersatz notwendiger Spezialanwendungen zum Betrieb von Sensorik, sondern deren Kapselung, um den einheitlichen Zugriff, unabhängig von der unterliegenden Umsetzung, zu gewährleisten.

Primärer Nutzen ist die verbesserte Auffindbarkeit von Sensorsystemen und ihre automatisierte Verwendung als Informationsressource. Ohne erforderliches Vorwissen können Sensoren und Messwerte anhand von zeitlichen, räumlichen oder phänomenbasierten Kriterien ausfindig gemacht und komplexe Informationen über Detektoren (z.B. Kalibrierung), Arten von Messungen (Messreihen) und Beschaffenheit von Messdaten (Datenqualität) eingeholt werden.

5. GSN in Frühwarnsystemen

Ziel des Projekts SLEWS ist die Umsetzung eines dienstbasierten Frühwarn- und Informationssystems unter Ausbringung massentauglicher Detektoreinheiten über ein funkbasiertes Geosensornetzwerk zur Detektierung von Hangrutschungen (siehe Arnhardt et al., 2007). Die Verwendung eines GSN verspricht eine gute räumliche Abdeckung in einem akzeptablen Verhältnis zum Installationsaufwand. Der Einsatzbereich der zugrunde liegenden Geodateninfrastruktur (GDI, siehe Nebert et al., 2004) umfasst die Datengewinnung und Aufarbeitung, die Datenanalyse zur Informationsschöpfung und Visualisierung, bis hin zur Verteilung von expliziten Warn- und Hinweismeldungen an entsprechende Organe des Katastrophenschutzes. Dabei soll die Orchestrierung flexibler, über das WWW verbundener Dienstkomponenten den Funktionsablauf von klassischen, „black box“-artigen Frühwarnsystemen emulieren und erweitern. Vorteile sind sowohl in der Austausch- und Skalierbarkeit der Dienstkomponenten als auch in der Entkopplung von anfälligkeitsbehafteten hierarchischen Informationsstrukturen solcher monolithischer Systeme zu sehen. Die Anpassung des Konzepts an die Ziele der Sensor Web-Initiative verspricht die Erschließung neuer Anwendungsdimensionen für das GSN und ermöglicht den dynamischen Import und Export von Dienst- und Datenressourcen von und zu weiteren interoperablen Sensor- und Informationssystemen.

5.1.1 Echtzeitanforderungen

Eine zentrale Problemstellung bei der Realisierung ist die Nutzung als Echtzeitbeobachtungssystem. Klassische Echtzeitsysteme erfordern meist eine strikt bidirektionale Prozesskommunikation, durch die nutzerbasierte Messbefehle zeitnah von der Sensorik ausgeführt und Messergebnisse über ereignisbasierte Push-Kommunikation vermittelt werden können. Ein selbstorganisiertes, ressourcenlimitiertes GSN ist größtenteils unidirektional ausgelegt (Knoten → Datensenke) und erlaubt nur eine begrenzte Fernsteuerbarkeit. Zusätzlich handelt es sich bei SWE-Diensten wie dem SOS, der von zentraler Wichtigkeit für die Verfügbarkeit von zeitkritischen Messdaten ist, um einen passiven Server, der parameterbasierte Anfragen eines Clientsystems beantwortet (Pull-Kommunikation). Die SWE-Spezifikationsreihe bietet mit den Diensten SPS und SAS grundlegende Mittel, um diese Probleme zu adressieren, jedoch wird weiterhin die Entwicklung spezieller Gateway- und Clientsysteme notwendig sein.

5.1.2 Semantische Anforderungen

Die semantisch eindeutige Verwendung von Ausdrücken ist einer der wichtigsten Punkte bei der korrekten Erstellung von Datenmodellen in SensorML- und O&M-Dokumenten. SWE-Spezifikationen beschreiben zwar den syntaktischen Aufbau von Informationen, jedoch nicht ihren semantischen Inhalt. Die semantisch unscharfe Verwendung von Ausdrücken erschwert die automatische Verarbeitung und Lesbarkeit für Außenstehende. Um die verwechslungsfreie Anwendung von Begriffen wie Phänomennamen, Sensortypen und Einheiten zu gewährleisten, ist die Schaffung von kontrollierten Vokabularen notwendig. Ein kontrolliertes Vokabular ermöglicht das Spezifizieren von Begriffen durch die Verknüpfung mit Metadaten und die Zuordnung in spezielle Anwendungsbereiche.

6. Fazit

Die Entwicklung ressourcensparender, präziser Lokalisierungs-algorithmen erhöhen die Skalierbarkeit und Robustheit von autonomen ad hoc Geosensornetzwerken. An der Universität Rostock wurden im aktuellen Projekt Algorithmen entwickelt, die in einem GSN energieeffizient zur Lokalisierung eingesetzt werden können. Eventuelle Ausreißer und grobe Fehler sind in

einem ersten Schritt mit dem ACL-Algorithmus aufgedeckt und eliminiert worden. Die geodätische Ausgleichung stellt hierbei Mittel zur Verfügung, die für die weitere Verbesserung vorgestellter Algorithmen eingesetzt werden können. Dabei stehen eine genauere Betrachtung der erreichten Genauigkeit sowie der Einfluss fehlerbehafteter Distanzmessungen im Vordergrund. Der vorgestellte DLS-Algorithmus ist um einige Besonderheiten erweitert worden, weist aber auf dem Gebiet der Mobilität von GSN Schwächen auf, die im weiteren Verlauf der hier beschriebenen Projekte eliminiert werden sollen.

Das Projekt SLEWS arbeitet an der Weiterentwicklung von Technologien und Methoden für den Einsatz von Beobachtungs- und Frühwarnsystemen bei Hangrutschungen. Die OGC SWE-Initiative liefert mit Spezifikationen und Datenmodellen umfangreiche Werkzeuge zur Integrierung von Instrumenten wie Geosensornetzwerken in ein interoperables Sensor Web. Die Verwendung offener Standards und Schnittstellen sichert Herstellerneutralität, verbessert systemübergreifende Interoperabilität im Kontext nationaler und internationaler Frühwarnsysteme und führt zur Entkopplung von anfälligkeitsbehafteten hierarchischen monolithischen Informationsstrukturen. Wesentliche Herausforderungen bestehen in der funktionellen Kombination der SWE-Dienste zur Lieferung von Echtzeitdaten und in der semantisch eindeutigen Schaffung von Namensräumen für Phänomen- und Sensorparameter in SWE-Datenstrukturen.

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Self-Adaptive Load Balancing for Many-To-Many Communication in Wireless Sensor Networks

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ABSTRACT

New scenarios in wireless sensor networks, where several independent sinks can ask for different kinds of data, are currently emerging. Former algorithms that route data to a centralized sink, are not appropriate for these scenarios. First solutions for these multi-source to multi-sink scenarios simply create independent trees for each source. As a result, some nodes become hot-spots, since they are included in several trees, whereas nodes around them remain unused.

In this paper, we propose a new algorithm that balances the load evenly in the network, extending the network lifetime, while still providing a small delay in packet delivery. Based on the information of one-hop neighbors and the number of hops to the sinks, the algorithm attempts to reduce both the delay and the power consumption. We present the cost function used to select the next hop(s) towards the sinks. The evaluation of the protocol demonstrates its ability to fulfill its target.

1. INTRODUCTION

A wireless sensor network (WSN) is a multi-hop ad hoc wireless network, composed of hundreds or even thousands of autonomous nodes, with disposable batteries and sensors attached. These sensor nodes provide physical information about the environment, such as acoustic, light or temperature measurements.

Due to new capabilities offered by more powerful sensor nodes, new scenarios are emerging, where data must be delivered to several sinks. Consider a wireless sensor network which can provide several kinds of data. Independent agents, with different kinds of applications running on them, can access the network and ask for a certain kind of data, each one independent from each other. Hence, each source has to deliver its information to a certain group of sinks, which can be different for each source. Another example is the increasing use of actuators in WSN, where each actuator requires different kinds of information from the network. These new scenarios require a many-to-many communication paradigm.

Unfortunately, current protocols used for many-to-one communication [4] [5] are not appropriate in case data must reach several sinks. Most commonly, they simply duplicate the same solution. Recently, some new protocols deal with the problem of routing data to several sinks in WSN. Nevertheless, they usually create a tree with the source at the top and the sinks as leaves. However, these trees are created independently from each other. Hence it is possible that some nodes are included in many paths between sources and sinks. As a result, such nodes spend too much energy forwarding packets and their batteries get exhausted quickly. Whereas the total amount of energy spent by the WSN can be optimal (if each of the trees is also optimal), this expense can be concentrated among a small number of nodes. This means that such nodes deplete their batteries very fast, while other nodes remain almost unused. Finally, this can lead to the partition of the network, avoiding the transmission of data.

Our goal in this paper is to enable the adaptation of routing paths for many-to-many communication, appropriate for these new multi-sink scenarios. In order to select the next node(s) towards the sink, a cost function is evaluated. This cost function maintains a trade-off between low delay and low power consumption, while keeping the load of the network evenly balanced. The function takes into account the number of hops to the sinks, as well as the load produced by all the sources in the network. It balances the load based only on one-hop information, a requisite in WSN. It does not require a setup phase, because the different parameters in the cost function change according to the traffic in the network. This cost function uses different weights for each one of its parameters, which can be updated by the sinks. Therefore, an agent could set a higher priority for one of the metrics against the other ones, e.g. low-delay with high energy consumption.

The remainder of this paper is organized as follows. Related work is reviewed in the next Section. In Section 3, we present our algorithm and motivate all the parameters taken into account. Furthermore, we present the cost function used to select the next node(s) to the sinks. Section 4 shows an evaluation of our protocol. Finally, Section 5 presents some conclusions and the next steps in our work.

2. RELATED WORK

Regarding scenarios with multi-source and one sink that address load balancing, the protocol presented in [7] forms an initial tree that gets adapted using topological knowledge.

In some scenarios where several sinks exist, the task consists of simply routing the packets from the sources to only one of the sinks. Normally, the closest sink is selected in order to save energy and make the communication more reliable. In [2], the authors present an algorithm for maximizing the lifetime of sensor networks by reducing the total

energy consumption and balancing the energy usage among sensor nodes.

In [1], an algorithm for sending information from multi-sources to multi-sinks is presented. It considers that sources address the same sinks. The protocol merges the paths that lead to the same sinks, so as to avoid the replication of messages. Nodes aggregate their readings with the ones they receive, until the maximum capacity is reached. Similarly to us, they use the notion of paths and sinks. Nevertheless, in our scenario, a source can potentially route its readings to an independent group of sinks. Hence, aggregation is not possible. Additionally, our approach tries to separate the trees created for each source in order to balance the load.

There exist some approaches [3] [6] that address one-to-many communication in WSN, but they do not take into account the existence of several trees. In [3], its authors propose a feedback learning approach, where nodes explore different possible routes and provide feedback to previous nodes. It identifies lowest cost paths and alternates the use of these discovered paths in order to save energy. It needs a setup phase. In [6], an algorithm to trade-off the power consumption and the delay created from sources to sinks is proposed. It uses a hop count vector to support the routing decision.

3. LOAD-BALANCING ALGORITHM

3.1 Metrics

When creating a routing protocol for a WSN scenario, two different metrics can be optimized: the delay transmission from sources to sinks and the power consumption in the network.

If the delay from sources to sinks is to be minimized, the number of hops between source and sinks must also be minimized. The simplest solution consists of finding the shortest individual paths to each sink. For each one of the sinks, the neighbor which offers less hops to each sink, is chosen as the next hop towards this sink. This approach offers a minimum delay, although the number of intermediate nodes can be very high.

In case the power consumption is to be minimized, the main strategy is to combine multiple transmission paths, so that they are split as close to the sinks as possible, in order to avoid the replication of packets. Although the total number of relay nodes is minimized, this can highly increase the transmission delay.

Both approaches explained above only take into account the tree created by a single source. Nevertheless, when there are more sources sending their readings, the trees are created independently.

3.2 Motivation

The algorithm that we present takes into account several parameters in order to maintain a trade-off between the energy consumption and the delay. These parameters are motivated below.

If both metrics are to be optimized, the number of hops must be close to the minimum. Because when the number of intermediate nodes increases, the probability of losing a packet in such an unreliable medium increases accordingly. If paths are split too far from the sinks, more nodes are involved in the routing of messages, increasing the computational and energy cost.

There exist some other parameters that can be useful to balance the load among all nodes in the network:

When choosing the next hop, it is preferable to use lightly loaded neighbors, so as to reduce the number of collisions and not to exhaust the energy of nodes. An equivalent metric to the number of messages sent is the number of sources a node serves. Additionally, the number of served sources is more stable than the messages sent, as it considers the traffic coming from a source, independently from the sinks it is addressed to.

It would be desirable to have certain information about what the path looks like in the next hops, before choosing a certain neighbor. Since the information available in sensor networks is rather expensive to get and to store, nodes can only count on local information. The number of paths is defined as the number of source-sink paths passing through a given node. By counting the number of paths, a node can get an insight of how loaded the next nodes will be, because at some moment, these paths are split.

In order to balance the load evenly through the network, neighbors that have little remaining energy should be avoided as relay nodes. As a metric for measuring the remaining energy, we consider the number of messages a node has sent since it is operative. In case the batteries are replaced, this counter is reset.

In case a highly loaded scenario is considered, the influence of contention and collisions must also be taken into account. In such a case, it is desirable to avoid sending messages to nodes that have detected such problems, because a high probability that these packets get lost exists. Measuring the times a message could not be sent because the medium was busy, gives a good measurement of contention.

3.3 Assumptions

Each sink defines its interests about a certain kind of sensor reading and disseminates this information through the network. Each source has a list of all the sinks it must serve and each node knows the number of hops necessary to reach each sink from each neighbor.

Each node maintains a list of its neighbors and their associated information, i.e. number of sources, number of paths, the consumed energy and the high load indicator. This information is piggybacked in the data packets that nodes transmit and is overheard by all neighbors. This consumes at the most 4 bytes of the payload. We define an epoch as the amount of time between two successive updates of this information. Nodes always transmit their information of the previous epoch.

3.4 Cost function

In our approach, we have defined the cost function depicted in Equation 1. The neighbor or set of neighbors that mini-

$$cost(n_j, s_k) = w_1 \cdot \sum_k hops(n_j, s_k) + w_2 \cdot N + w_3 \cdot \frac{sources}{N} + w_4 \cdot \frac{paths}{N} + w_5 \cdot \frac{energy}{N} + w_6 \cdot highload \quad (1)$$

mize this cost function are chosen as forwarding nodes. Each parameter of the function cost derives from the parameters explained in Section 3.2. Except for the first two parameters, that depend on the network topology and that are assumed to be fixed, the rest are adapted during the whole routing process, according to the information of the adjacent nodes. Hence, a setup phase is not required.

The first two parameters, the most significant ones, are calculated at some point after getting the number of hops to each one of the sinks (only once). Let x be the minimum number of hops from a node to a certain sink, only neighbors that offer at most $x+1$ hops to this sink are taken into account as possible next hops. In this way, nodes which are farther away from the sinks than the routing node are not considered as next hops.

In order to explain how combinations of next nodes are created, let us consider a simple scenario with two sinks, S_1 and S_2, and a node, X, with two neighbors, N_1 and N_2. N_1 offers node X a path to sinks S_1 and S_2 with 3 and 5 hops, respectively. N_2 offers node X a path to sinks S_1 and S_2 with 4 and 3 hops, respectively. With this information, node X creates several combinations. If the packet must be routed to S_1, the next neighbor can be either N_1 with 3 hops or N_2 with 4 hops. When routing a packet to S_2, the next neighbor can only be N_2 with 3 hops. In case the packet must be routed to S_1 and S_2, there exist two combinations: N_1 for S_1 and N_2 for S_2 with a total cost of 6, or N_2 for both S_1 and S_2 with a cost of 7.

Among the possible combinations, only those K combinations that provide a lower number of hops are stored. The higher K is, the more different possibilities a node has to forward a packet, however a larger computation delay is also expected. If the delivery delay must be minimized, this parameter must have a large weight.

Each combination has associated a number of neighbors, N in Equation 1. The smaller the weight of neighbors is, the larger the probability that the paths remain unsplit, keeping the total energy consumption low.

The energy of the nodes is independent from the rest of the parameters, as it measures the number of messages a node has sent (or forwarded) since it is active. A large weight for the energy means that load in the network is more balanced. The three remaining parameters are closely related to each other.

The number of sources a node has served in the last epoch is related to the high load indicator. The maximum number of served sources is not known before hand. When this number is reaching its maximum, the number of contentions increases and, therefore, the load indicator is active. As long as the number of served sources is far from its maximum (load indicator is not active), the cost due to the number of messages sent only depends on the number of sources and w_3. However, when the number of sources is close to its maximum (load indicator is active), the cost due to the messages sent also depends on the high load indicator and w_6. The cost in this case must be much higher, because such nodes should not be chosen as next nodes; thus, w_6 must be much larger than w_3.

The number of paths of a node is also related to the number of sources the node is serving, as for each source, there is at least one path. Since it only gives an insight of how loaded the next nodes could be on their way to the sinks, a small weight must be assigned to this parameter.

The weight of each parameter ($w_1, \ldots, w_6$) can be either preprogrammed on the nodes or established by a sink. Because of this, the routing in the network can be adapted to the needs of the users. For instance, if the delay is the metric to be minimized, w_1 must be the prevailing weight. If, on the contrary, it is fundamental to maintain an even load in the network, w_5 must have a significant weight. When trying to avoid contention problems, w_6 gains importance.

4. EVALUATION

Network lifetime is the most important criterion in sensor networks. We define network lifetime as the time until some percentage of the nodes die, possibly causing the partition of the network. In order to maximize the network lifetime, two conditions must be fulfilled: the total amount of energy spent in the network must be minimized and the difference between the individual node energy consumption and the average consumption must also be minimal.

The main quantities that have been evaluated are:

- Percentage of packets delivered to the sinks.
- Total energy spent by the network, in terms of the amount of messages sent in the network.
- The standard deviation of the node energy consumption.
- The delay in the network, in terms of the number of hops until a message reaches the sinks.

The algorithm has been implemented on top of TinyOS [8], and evaluated using the TOSSIM [9] simulator. For the first experiments, a regular grid has been used, where the nodes can communicate with their four neighbors. The algorithm has also been evaluated with a random topology, where the number of neighbors varies from 2 to 8.

All scenarios comprise 100 nodes, 20 nodes are data sources and 8 are sinks. Each sink asks for information of 10 different sources. Sources send a reading every 5 seconds (they are not synchronized with each other). Each simulation lasted 2500 s, which means that each source sent 500 readings. The

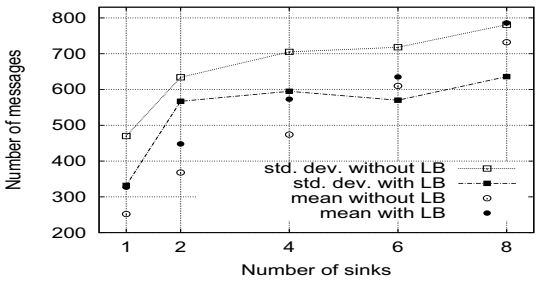

Figure 1: Standard deviation of the node energy consumption in terms of sent messages

experiments have been repeated at least five times and the presented results represent their average.

Several configurations have been tested, but due to lack of space, only some significant results are presented in this paper.

In Fig. 1, we compare an approach where the load balancing is not considered (i.e. in cost function w_3=w_4=w_5=w_6=0) with another approach that minimizes contention and balances the load in the network (i.e. w_1=80, w_2=100, w_3=8, w_4=1, w_5=1, w_6=40). We can see how the standard deviation improves with our approach. For the case of 6 sinks, the percentage of delivered packets to the sinks even increases 10%, while the total energy consumption only increases 4%.

This promising results show how our algorithm is able to balance the load in the network, while maintaining the energy consumption and delay low.

5. CONCLUSIONS AND FUTURE WORK

In this paper, we presented a routing algorithm tailored to scenarios with multi-sources and multi-sinks in WSN, which balances the load in the network. We proposed a cost function used by nodes to select the forwarding node(s) towards the sinks. This function uses local information to balance the load among the neighboring nodes, while not increasing the delay significantly. As the total energy consumption in the network only rises slightly, the network lifetime is maximized.

Our future work includes further experimentation with several weights, as well as the inclusion of some other parameters in the cost function, such as the number of collisions registered by the MAC-layer.

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From Academia to the Field: Wireless Sensor Networks for Industrial Use

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ABSTRACT

Fundamental differences exist between academic research on wireless sensor networks and industrial wireless sensor networks as envisaged by the BMBF-funded project ZESAN. Their requirements and underlying assumptions are described to bridge the gap between research and industrial application.

1. INTRODUCTION

Wireless sensor networks have been a hot research topic ever since the vision of smart dust was articulated. Nowadays, sensor networks are on the verge to industrial use. Several aspects of wireless sensor networks are appealing for industrial use: there is no need for wiring (which may be a huge cost factor or simply not practical, e.g. in the case of moving parts), and as the installation is very flexible it can be used also for temporary installations. However, it is hard to transfer results of the latest research directly to industrial wireless sensor networks as assumptions on the setup and environment made by research are significantly different compared to important industrial application scenarios.

Section 2 describes three typical industrial use cases for wireless sensor networks. Section 3 sets into contrast assumptions and requirements of academic sensor networks and industrial sensor networks in several areas. Section 4 concludes the paper.

2. SCENARIOS

Some typical use cases are described that are drawn from process and factory automation industry (used e.g. in refineries or manufacturing automation) to illustrate typical industrial application environment of wireless sensor networks.

2.1 Condition Monitoring

A condition monitoring system supervises a set of machines to obtain information about their condition and to schedule maintenance only if needed, thereby reducing down time of machinery and costs.

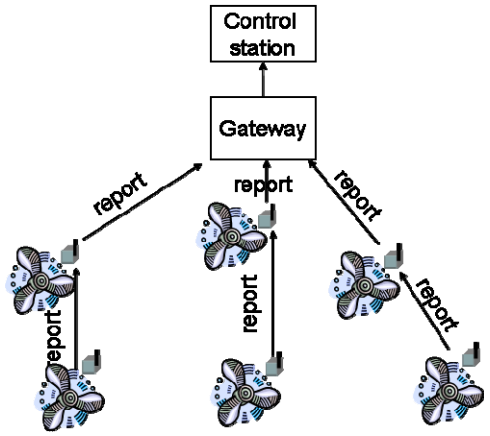

Figure 1. Condition monitoring of events

Sensor nodes are attached to the machines to analyze the current state of the machine, see Figure 1. The number of sensor nodes is likely to be rather small as only a single machine or a manufacturing cell will be monitored by a single wireless sensor network. For example, it may be analyzed if a vent is out-of-balance. Sensor nodes periodically send reports to a central server (control station) where they are evaluated by a plant operator. If a problem is identified, maintenance may be scheduled.

2.2 Temporary Monitoring

In process automation, mass losses may occur from time to time. It may be hard to localize the source of the mass loss by observation or using only the measurements of installed sensors. A temporary monitoring system like the one shown in Figure 2 may be used to locate the source of mass loss. The monitoring system uses wirelessly connected sensors, e.g. ultrasonic flow sensors, that can be easily installed where and when needed (and removed again when the leakage has been found). The temporarily installed monitoring system provides temporally and spatially more fine-grained information as the placement of temporary sensors can be denser than the placement of regular (built-in) sensor nodes.

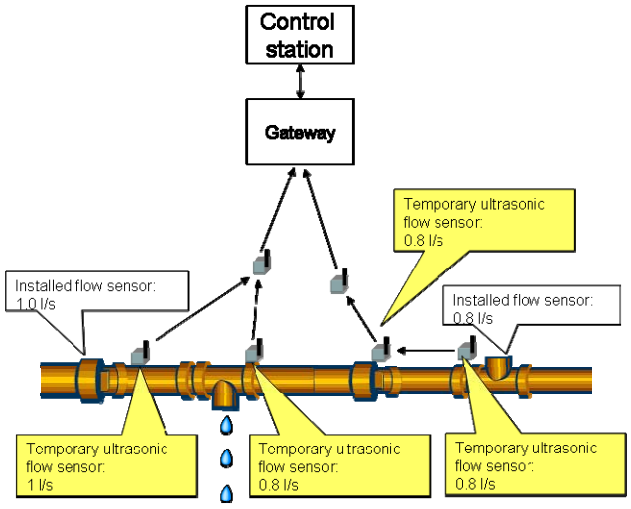

Figure 2. Temporary monitoring in process automation used to find source of mass loss

2.3 Decentralized Process Control

Intelligent field devices and an industrial sensor network can be used to implement decentralized control mechanisms. To do so, sensors measure actual values and send them to intelligent field devices acting as local controllers. These field devices check if actual values match specified values and react if necessary. Additionally, the sensor nodes report measured values to the control station so that the plant operator can react depending on the state of the overall process. Figure 3 shows an example in which four local controllers and the control station receive measurements from sensors over the sensor network.

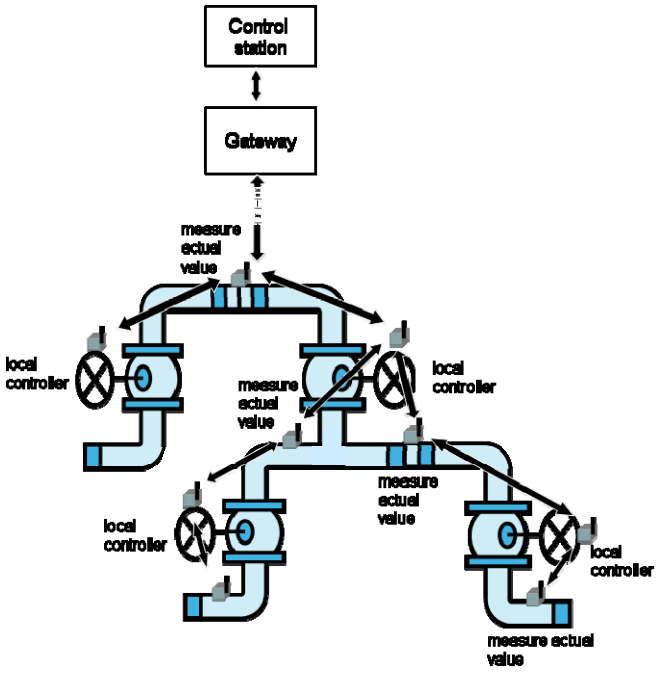

Figure 3. Decentralized control in process automation

3. Academic Assumptions vs. Industrial Applications

Significant differences exist between assumptions made for wireless sensor networks in academic research and wireless sensor network applications envisaged for process and factory automation and other industrial applications. The differences of the underlying assumptions made regarding deployment, use of infrastructure, operation, self-organization, integration, and number of nodes are described.

3.1 Deployment

The first difference arises regarding the deployment of sensor nodes. Plants are carefully planned and the employed networks are engineered. A well-planned network is cost-efficient, reliable, and predictable. Hence, a planned deployment of industrial sensor networks is often a must-have. In the scenarios described above, sensor nodes are carefully placed at distinct locations (e.g. in vicinity of a machine, near the expected source of mass loss, at a point of measurement …). However, current research often assumes a random deployment of sensor nodes, e.g. sensor nodes are assumed to be air-dropped. While this assumption is true for applications such as disaster management, military intelligence, and environmental monitoring, a random deployment cannot be expected e.g. for process and factory automation.

3.2 Infrastructure

Most sensor network research assumes that the sensor network is decentralized and uses no infrastructure for its operation (besides a central data sink). In an industrial environment, often infrastructure components as e.g. gateways or range extenders are available that can be used for controlling and optimizing the operation of the sensor network (e.g. to minimize communication path length, to minimize energy use of battery powered devices, to support security …). In fact, as wireless sensor networks used in industrial applications are planned networks, the infrastructure components can be placed in an optimized way. In all three scenarios described above, the function of the sensor network includes reporting to the plant operator via a gateway. Infrastructure components are likely to be placed in a way that optimizes the coverage of the industrial wireless sensor network.

Figure 4 shows a typical industrial sensor network setting: several sensor nodes communicate with one of multiple gateways (GWs). The gateways are connected to the (wired or wireless) factory intranet. These gateways are placed in a way that minimizes the path length in the industrial sensor network.

The use of infrastructure is also advantageous because plant operators usually require access to devices for information and debugging purposes.

3.3 Operation

In academic research projects it is often assumed that a wireless sensor network is deployed in a public space and – once deployed – works without administration and unsupervised. In industrial applications, hoverer, and in particular in process and factory automation, wireless sensor networks are usually deployed in access-restricted areas.

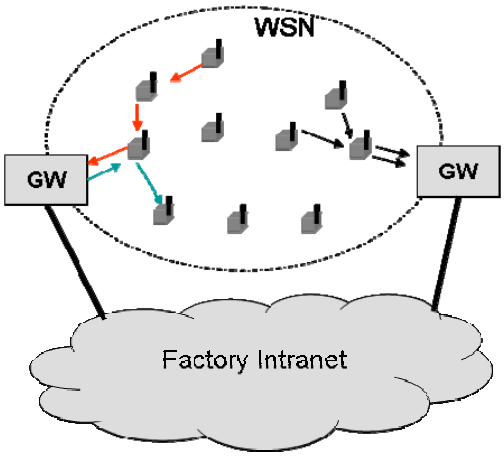

Figure 4. Typical industrial wireless sensor network setting with two gateways

Plant premises are rarely accessible without physical access control. This affects the security design of industrial wireless sensor network protocols as a corruption of a sensor node due to physical access is less likely. To ensure an uninterrupted uptime of a plant, an industrial sensor network will typically not be unsupervised but rather be watched carefully 24/7. A typical sensor network used in industry is administered and, if problems arise, maintenance staff has access to every single sensor node.

3.4 Self-Organization

Self-organization is a big issue in academic research. For industrial applications of wireless sensor networks, a reliable, controllable and predictable operation is of high importance. The plant engineers, plant operator, and maintenance staff need a way to plan and supervise the sensor network. Self-organization has to be designed so that reliable and predictable, comprehensible operation is ensured. Even a self-organized industrial WSN needs to report its state to allow for maintenance if required. In some situations, self-organized behavior is not feasible; rather, the system must be able to identify such situations and ask for external intervention.

3.5 Integration with Infrastructure Systems

Industrial wireless sensor networks are likely to be integrated into other – sometimes already existing – systems. Usually, these systems base on standards, such as a certain fieldbus protocols or Profinet which– compared to office IP networks – have differing requirements regarding determinism. Often the higher level systems follow a cyclic polling approach which is in contrast to the event based model used in research networks. Care has to be taken that the plant operator can access all necessary data at all times. In contrast, the integration with other networks is often not covered in academic research. In the described industrial scenarios, the wireless sensor networks are connected to the plant's control system.

3.6 Number of Nodes

Another objective addressed in current research on wireless sensor networks is scalability to tens of thousands of sensor nodes. For industrial applications, wireless sensor networks, however, are likely to comprise only some tens to at most hundreds of sensor nodes. Industrial wireless sensor networks are usually quite small. For example, in condition-based monitoring the network can be expected to have only some tens of sensor nodes (at most). It is also likely that a factory complex does not house one single large sensor network, but instead several independent sensor networks in parallel. The factory network control system takes care of distributing data to where it is needed. Hence, solutions are needed that are suitable for small to medium size sensor networks consisting of tens or hundreds of nodes.

3.7 Summary

Table 1 summarizes main differences between academic wireless sensor networks and industrial wireless sensor networks.

Table 1. Summary of differences between academic wireless sensor networks and industrial wireless sensor networks

	Academic WSN	Industrial WSN
Deployment	random	planned
Infrastructure	often no	yes
Operation	unsupervised	supervised
Application area	public spaces	access restricted areas
Self-organization	yes	only to a certain extent
Integration	usually no issue	big issue
Number of nodes	10.000+	tens or hundreds

It is necessary to carefully consider these differences when designing a solution for industrial wireless sensor networks to determine to what degree research results are suitable for envisaged industrial usage scenarios of wireless sensor networks.

4. CONCLUSION

Three typical applications of wireless sensor networks in an industrial setting have been described. Their usage environment was compared with the assumptions often made by academic research work. The BMBF-funded ZESAN project develops solutions for reliable, energy-efficient, and self-organizing wireless sensor networks addressing requirements of prominent industrial application scenarios. The gap between topics addressed by academic research and the needs of the envisaged industrial applications needs to be closed. Industrial wireless sensor networks are usually planned, get deployed in a deterministic way, and are supervised during their operation, and can make use of infrastructure components. Some of those infrastructure components are used to integrate the industrial wireless sensor network into the plant system. And, finally, the number of nodes used in industrial sensor networks is likely to be lower than assumed in some academic research and will typically range from tens to at most some hundreds. The assumptions made by academic research make it sometimes difficult to transfer the results to industrial applications having different requirements and side conditions.

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Vergleichbarkeit von Ansätzen zur Netzwerkanalyse in drahtlosen Sensornetzen

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Kurzfassung

In diesem Dokument wird die Vergleichbarkeit verschiedener Netzwerk-Simulatoren, -Emulatoren und theoretischer Analyse in drahtlosen Sensornetzen untersucht. Die Ergebnisse dieses im Rahmen des ZeuS-Forschungsprojektes durchgeführten Experiments zeigen die Stärken und Schwächen der verschiedenen Ansätze auf.

1. EINLEITUNG

Im Rahmen des ZeuS-Forschungsverbundes[1], einem Projekt zur Erforschung von Grundlagen zuverlässiger Kommunikation in drahtlosen Sensornetzen, werden an den beteiligten Instituten Simulationen und Evaluierung mit verschiedensten Werkzeugen durchgeführt. Neben einer Netzwerksimulation mit GloMoSim kommen auch die Eigenentwicklung KSNSim sowie der Emulator des TinyOS-Betriebsystems TOSSIM zum Einsatz. Zusätzlich wurde in einer formalen, theoretischen Analyse der Konnektivitätsgraph verschiedener untersuchter Topologien durch Markovketten modelliert und mittels Prism [6] analysiert. Um die Vergleichbarkeit der so auf unterschiedliche Weise gewonnenen Ergebnisse auch über die einzelnen Teilprojekte hinaus zu gewährleisten, wurde ein *gemeinsames Experiment* durchgeführt. Der folgende Bericht dokumentiert dieses Experiment und stellt eine Auswertung der Ergebnisse und der daraus gewonnenen Erkenntnisse dar.

Nach einem Überblick über verwandte Forschungsarbeiten in Kapitel 2 wird der Versuchsaufbau des durchgeführten Experiments in Abschnitt 3 beschrieben. Es folgt mit Abschnitt 4 eine Diskussion der Besonderheiten der einzelnen eingesetzten Werkzeuge. Eine Analyse und Zusammenfassung der Ergebnisse in Kapitel 5 schließen diese Arbeit ab.

2. VERWANDTE ARBEITEN

Cavin et. al haben 2002 bereits einige MANET-Simulatoren verglichen [4]. Die dort verwendeten Simulatoren *OPNET Modeler*, *NS-2* und *GloMoSim* überschneiden sich jedoch nur in einem Fall mit den bei uns verwendeten Werkzeugen. Weiterhin beschränkt sich diese Arbeit nicht auf reine Simulatoren, sondern greift mit TOSSIM auch auf einen Emulator und mit der theoretischen Analyse formale Ansätze auf.

3. VERSUCHSBESCHREIBUNG

Untersucht werden im Folgenden verschiedene Parameter die sich in einem Netzwerk durch einfaches *probabilistisches Fluten* einer Nachricht N bestimmen lassen: der Energieverbrauch, die Anzahl versendeter bzw. empfangener Nachrichten, die Wahrscheinlichkeit, dass einzelne Knoten die Nachricht erhalten haben und besondere Eigenschaften/Messgrößen die das betrachtete Programm unterstützt, abhängig von der Simulationsumgebung (siehe Abschnitt 4). Die Topologien wurden so gewählt, dass die Auswirkung von probabilistischem Fluten auf symmetrische und unsymmetrische Sensoranordnungen (Abbildung 1c) untersucht werden kann.

In allen betrachteten Topologien bekommt Knoten A von der Basisstation die Nachricht N und leitet diese mit Wahrscheinlichkeit $p = 1$ weiter. Bei allen übrigen Knoten wird beim Empfang eines Paketes „gewürfelt“ (d.h., eine Zufallszahl $0 < p_Z \leq 1$ wird gezogen) und entsprechend dem Ausgang ($p_Z < p$) das Paket mit der Wahrscheinlichkeit p an alle Nachbarknoten weitergeleitet.

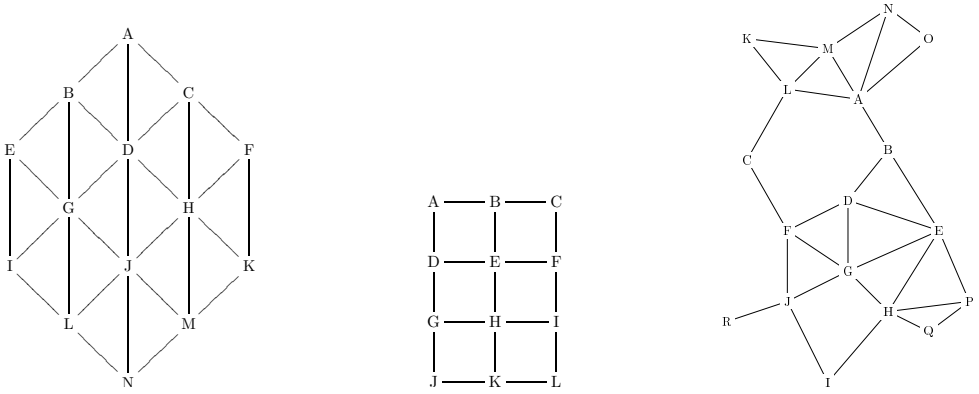
Um präzise Daten und eine gute Vergleichbarkeit zu erhalten, soll eine möglichst geringe relative Standardabweichung in den einzelnen Ergebnissen erzielt werden. Dazu sollten mindestens 200 Durchläufe für jede Konfiguration durchgeführt werden.

3.1 Topologiewahl

Das Experiment wurde mit unterschiedlichen Topologien durchgeführt. Für diese Arbeit wurden drei Topologien (Abb. 1) ausgewählt, die deutliche Unterschiede bezüglich Aufbau, Symmetrie und Vernetzung zeigen.

Die Kanten innerhalb der Topologien repräsentieren den Konnektivitätsgraph (*Routing-Baum*), also den Weg, den die Nachricht N im Netz zurücklegen soll. Die Distanz zwischen den Knoten, für die eine Verbindung (Kante im Konnektivitätsgraph) existiert, soll höchstens 10 Meter sein. Die zu flutende Nachricht N beträgt exakt 56 Byte (maximale Paketgröße in TinyOS). Mit Beginn der Simulation befinden sich alle Knoten im eingeschalteten Zustand und warten auf Nachrichten. Die Position der einzelnen Sensorknoten werden für alle Topologien in einer Szenariobeschreibung definiert, so dass diese allen Experimenten als Ausgangsbasis zur Verfügung stehen. Neben den Topologien wird auch die Wahrscheinlichkeit p einer Weiterleitung variiert, wobei $0{,}2 \leq p \leq 1$ in Schritten von je $0{,}2$ simuliert wird. Abhängig von den Möglichkeiten der verwendeten Werkzeuge werden weitere Parameter spezifiziert. Alle wichtigen Simulationsparameter sind in Tabelle 1 zusammengefasst.

[1] http://www.zeus-bw-fit.de



(a) Topologie 1 (b) Topologie 3 (c) Topologie 5

Figure 1: Verwendete Topologien

Nachrichtenlänge	$l = 56$ Bytes [5]
Weiterleitungs-wahrscheinlichkeiten	$p \in \{0{,}2; 0{,}4; 0{,}6; 0{,}8; 1{,}0\}$
MAC	CSMA/CA
Sendereichweite	$r = 10$ Meter
Höhe der Antenne	$h = 1{,}5$ Meter
Datenrate	$R = 38400$ Bit/s [5]
Stromverbrauch	
Funk	$I_{Funk} = 16$ mA [5]
CPU	$I_{CPU} = 5$ mA [1, 3]
Energieverbrauch	(siehe Abschnitt 3.2)
Nachricht versenden	$P_m = 185{,}2$ μAs
Nachricht empfangen	$P_m = 42$ μAs

Table 1: Simulations-Parameter

3.2 Energie

Die wohl interessanteste Metrik in Sensornetzen, den Energieverbrauch, mit unterschiedlichen Simulatoren zu erfassen, ist eine Herausforderung für sich. Einerseits soll der simulierte Verbrauchswert nahe an der Realität liegen, andererseits ist beim Einsatz verschiedener Werkzeuge darauf zu achten, dass die Ergebnisse vergleichbar bleiben: Da einige der eingesetzten Simulatoren nur auf Netzwerkebene arbeiten, bleibt als gemeinsame Datenbasis leider nur Paketempfang und -versand übrig. Daher wurden diese Operationen auf realen Knoten (MICAz) vermessen.

Um den Eigenschaften der Energieressource Rechnung zu tragen, wurde die der Batterie entnommene Ladung mit Hilfe eines NI-USB-6210 [9] gemessen. Dem Empfang einer 56 Byte großen Nachricht wurde ein Ladungswert von 42 μAs und eine Dauer von $1{,}85$ ms im Durchschnitt zugeordnet, gemessen vom Beginn des Empfangs am CC2420 bis zur Benachrichtigung der Anwendung. Der Versand eines Pakets derselben Größe dauert hingegen im Durchschnitt $8{,}34$ ms und benötigt dabei $0{,}185$ mAs an Ladung, gemessen vom Zeitpunkt, an dem die Anwendung den Sendeauftrag erteilt, bis zur Versandbestätigung der TinyOS Netzwerkschicht.

Nicht berücksichtigt werden hier Energiewerte für den Mikroprozessor und das An-/Ausschalten des CC2420, da diese für den Vergleich der Werkzeuge nicht relevant sind. Der Stromverbrauch beim Lauschen auf Pakete sowie zusätzlicher Energieaufwand bei Kollisionen bleibt ebenfalls unberücksichtigt, da die notwendigen Zahlen nicht von allen verglichenen Werkzeugen geliefert werden. Deshalb stellen die Energiewerte aus den Simulatoren sehr kleine untere Schranken für den Energieverbrauch von MICAz Knoten dar, die in der Praxis nicht erreicht werden können. Die damit in verschiedenen Simulatoren errechneten Werte lassen sich jedoch gut vergleichen.

4. AUSWERTUNG

Im Folgenden werden die einzelnen Experimente und die Besonderheiten der einzelnen Werkezuge vorgestellt.

4.1 GloMoSim

Die Implementierung des Versuchs erfolgte als Protokoll auf Anwendungsebene. Die von GloMoSim bereitgestellten Implementierungen der niedrigeren Netzwerkschichten wurden unverändert übernommen und lediglich in ihrer Parametrisierung gemäß den Vorgaben angepasst.

Die Knotenplatzierung wurde direkt aus den einheitlich definierten Szenariobeschreibungen übernommen und in der Konfiguration mit *NODE-PLACEMENT-FILE* referenziert. Die Signalausbreitung wurde mit dem in GloMoSim vorhandenem *TWO-RAY-Modell* simuliert, welches ein *PROPAGATION-LIMIT* von -111 dBm vorsieht. Die Parameter zur Funkschnittstelle wurden entsprechend der MicaZ-Spezifikation angepasst. Insbesondere wurde das *SNR-BOUNDED* Modell zum Empfang von Datenpaketen ausgewählt, welches Signale über dem *RADIO-RX-SNR-THRESHOLD* von 10 dB fehlerfrei zustellt und sonst verwirft. Als *MAC-PROTOCOL* kommt *CSMA-CA* zum Einsatz. Die Simulationsergebnisse sind Mittelwerte von je 1000 Durchläufen mit variierenden *SEEDs* des GloMoSim Zufallsgenerators.

4.2 TOSSIM

TOSSIM ist ein Simulator, der von TinyOS bereitgestellt wird. Sein Radiomodell basiert auf der Signalverstärkung (*gain*), die jeweils zwischen zwei Knoten festgelegt wird. Da die Signalstärke mit der Entfernung abnimmt, ist *gain* immer negativ. In diesem Experiment haben wir die *gains* mit Hilfe der von TOSSIM bereitgestellten Hilfsmittel generiert. Als Eingaben dienten die Koordinaten der Knoten und mehrere Umgebungsparameter (*path-loss exponent*, *noise floor*, *white Gaussian noise* usw), die dem Tutorial [12] entnommen wurden.

TOSSIM simuliert Umgebungsrauschen und Interferen-

```
global a : [0..1] init 1;

module SensorA
 // Local State
 // (0=idle, 1=forward, 2=drop, 3=sleep)
 la: [0..3] init 0;

 [](a=1)&(la=0) -> pf:(la'=1)&(b'=1)&
                       (d'=1)&(c'=1)
                + 1-pf:(la'=2);
 [](a=1)&(la=2) -> (la'=2);
endmodule
```

Figure 2: Prism Modell eines Moduls, das einen Sensorknoten repräsentiert

zen mit Hilfe des *Closest Pattern Matching (CPM)* Verfahrens [8]. CPM braucht als Eingabe sogenannte *noise traces*, die zum Teil mit TinyOS mitgeliefert werden. Die von uns verwendete mitgelieferte Datei beinhaltet die *noise traces* der Meyer Library an der Stanford University [11]. Das Rauschen in dieser Umgebung ist hoch wegen vieler WLAN Access Points. Somit wird der Empfang der Packete durch den *gain* zwischen dem Sender und dem Empfänger, die Interferenzen mit anderen Nachrichten, und durch das Umgebungsrauschen bestimmt.

Da sich das obige Modell zum Empfang von Datenpaketen erheblich von den Modellen in allen anderen von uns verwendeten Simulatoren unterscheidet, ist nicht klar, wie und ob in TOSSIM die Modellparameter so gewählt werden können, dass sie in etwa zum Beispiel denen von GloMoSim entsprechen. Außerdem kann man die Sendereichweite in TOSSIM im Gegensatz zu anderen Simulatoren nicht ändern, da diese Eigenschaft noch nicht implementiert wurde. In unseren Experimenten lag die Sendereichweite zwischen 10 und 18 Metern.

4.3 Formale Betrachtung

Die theoretische Analyse wird mit Markov-Ketten durchgeführt, wodurch sich die auftretenden Wahrscheinlichkeiten mit hoher Präzision (ohne Standardabweichung) berechnen lassen. Die Modellierung und Evaluation erfolgt mit Prism [6] für jede Topologie getrennt. Die berechneten Größen lassen sich als untere Schranke für die zu messenden Werte verstehen und betrachten den optimalen Fall, in dem Kollisionen, Sendewiederholungen und andere störende Effekte ausgeschlossen werden. Auf die Bit-Übertragungs- (*physical*) und die Sicherungs-Schicht (*data link*) wird bei der Modellierung verzichtet.

Jeder Knoten wird als Modul (Abbildung 2) mit jeweils einer lokalen Variable modelliert, die den jeweiligen Zustand für *Idle*, *Forward* und *Sleep* repräsentiert. Um die Modellkomplexität zu reduzieren[2] wird auf eine explizite Darstellung des Sender-/Empfängermodells verzichtet. Dennoch konnte für Topologie 5 keine Erreichbarkeit auf einem Rechner mit 32GB RAM wegen Speicherüberlauf berechnet werden. Die Modellierung sieht für die Kommunikation zwischen den Knoten das Setzen eines globalen Nachrichten-Bits vor, um so den Paketempfang zu betrachten.

Das so konstruierte Modell entspricht dem Konnektionsgraphen für die Topologien, wie sie Abbildung 1 zeigt.

[2]bei einer Netzgröße von 14 Knoten wächst das Modell auf $124 \cdot 10^6$ Zustände und $1{,}5 \cdot 10^9$ Transitionen

Hierzu wird keine Sendereichweite definiert, sondern die Konnektion aus der Topologievorgabe verwendet. Ein Paketverlustmodell wird nicht betrachtet, denn wie durch Experimente [2] gezeigt wurde, lässt sich bei einer Sendeleistung von $3,99 \cdot 10^{-17}$ mW ($-163{,}98$ dBm) eine *Bit Error Ratio* von 10^{-6} messen, die für die vorliegenden Experimente vernachlässigbar klein ist.

4.4 KSNSim

Der JAVA basierte *Karlsruhe Sensor Networking Simulator (KSNSim)* wurde mit dem Ziel entwickelt, Mechanismen zur relationalen Anfrageverarbeitung in Sensornetzen schnell und ohne Spezifikation von Netzwerk-, Energie- oder Betriebssystemparametern auf ihre Funktionstüchtigkeit zu testen. Ein weiteres Entwurfsziel bei der Entwicklung des Simulators ist die Schnittstellen-Kompatibilität mit dem auf den Sun SPOT [10] verwendeten Java SDK, so dass entwickelte Programme ohne Portierungsaufwand auch in einem realen Sensornetz aus Sun SPOT Knoten genutzt werden konnten. Ziel war es also nicht, drahtlose Kommunikation möglichst realitätsgetreu nachzubilden oder besonders ausgefeilte Kommunikationsmechanismen bereitzustellen.

Das Netzwerkmodell zur Simulation von drahtloser Kommunikation ist daher so einfach wie möglich: Sensoren werden an explizit definierten Punkten in einem virtuellen Raum platziert und haben eine Sendereichweichte r. Als Kommunikationsmodell dient ein Unit-Disk-Graph mit Radius r. Alle Knoten, die einen Abstand größer als r zum Absender einer Nachricht haben, werden von der Kommunikation nicht beeinflusst.

Auf Grund der extrem einfachen Modellierung der Kommunikation ist es daher vor allem zu erwarten, dass die Anzahl der empfangenen Nachrichten überschätzt wird, da keinerlei Paketverlust simuliert wird. Diese erwartete Überschätzung der empfangenen Nachrichten bewirkt eine Überschätzung der Anzahl erreichter Knoten und des Energiebedarfes.

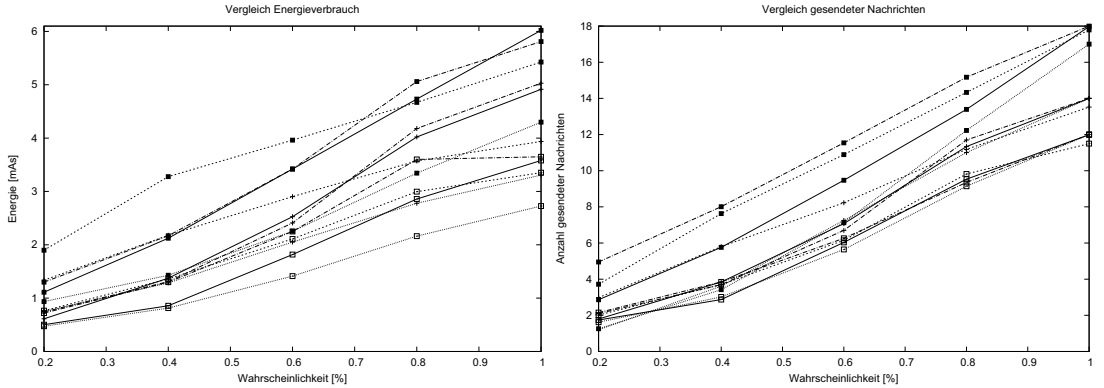
5. ZUSAMMENFASSUNG

In Abbildung 3 werden die Ergebnisse des Experiments zusammengefasst. Alle Diagramme verwenden die selbe Legende, die in Abbildung 3d dargestellt ist.

Abbildung 3a zeigt die Resultate des Energieverbrauchs, den die verschiedenen Werkzeuge für die ausgewählten Topologien errechnet haben. Trotz fehlender vollständiger Übereinstimmung, sind Parallelen erkennbar, etwa bei der Reihenfolge der Topologien bezüglich ihres Energieverbrauchs. Einem direkten Vergleich der Energieverbräuche stehen zudem die in einigen Werkzeugen fehlenden Möglichkeiten, Kollisionen und Paketwiederholungen mit einzubeziehen, entgegen.

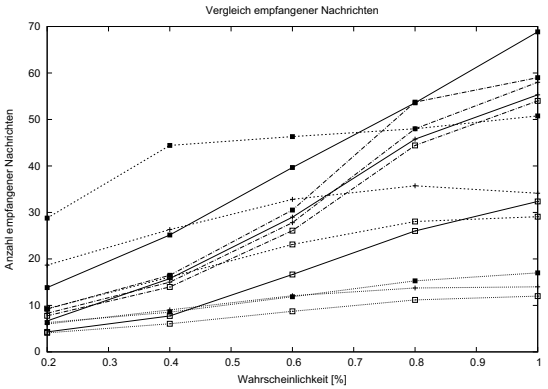
Weitere Details sind durch Aufschlüsselung der Ergebnisse in versendete und empfangene Pakete in den Abbildungen 3b und 3c erkennbar. Die Unterschiede im Energieverbrauch sind demzufolge hauptsächlich auf Differenzen bei der Zahl der empfangenen Pakete zurückzuführen, was auf die teilweise unterschiedlichen Sendereichweiten (und damit veränderte Konnektivitätsgraphen) und Paketverlustmodelle zurückzuführen ist.

Letztendlich gibt es deutliche Unterschiede bei der Zahl der erreichten Knoten (Abbildung 3d), die neben den

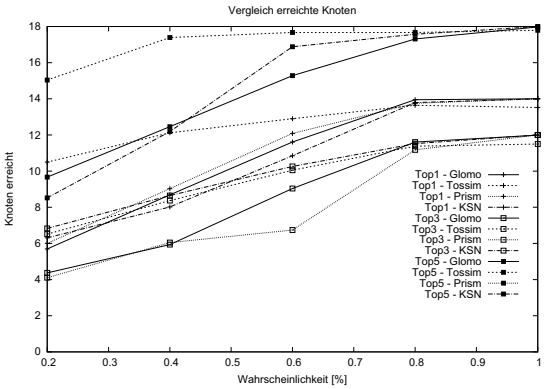


(a) Energieverbrauch im Vergleich

(b) Zahl der versendeten Pakete



(c) Zahl der empfangenen Pakete



(d) Anzahl der erreichten Knoten

Figure 3: Evaluationsergebnisse

bisher genannten Ursachen auch auf starke Varianzen der Ergebnisse bei geringem p zurückzuführen ist.

Die Ergebnisse zeigen insgesamt, dass eine grundsätzliche Vergleichbarkeit schon jetzt gegeben ist. Deckungsgleiche Ergebnisse werden jedoch durch die stark unterschiedliche Flexibilität und Konfigurierbarkeit der verwendeten Werkzeuge sowie das stark vereinfachte Energiemodell verhindert.

Um realistische Werte des Energieverbrauchs ermitteln zu können, ist die Energieabschätzung zur Laufzeit und Energiemessungen der Knoten in einem Testbett [7] interessant. Das wird ermöglicht durch eine Erweiterung des verwendeten Betriebssystems (TinyOS) bzw. durch eigene Hardware zur Knotenverwaltung. Beide Ansätze werden gegenwärtig implementiert und in zukünftige Publikationen einfließen.

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FRONTS - Foundations of Adaptive Networked Societies of Tiny Artefacts

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ABSTRACT

The European project FRONTS aims at understanding adaptive large-scale heterogeneous wireless sensor networks acting in a dynamic environment. This includes designing different mathematical models beyond the state of the art for such networks. Based on these models, a new network infrastructure will be developed, followed by a large set of algorithms solving global tasks like exploration of unknown areas or target tracking. We provide a coherent package consisting of a simulation framework, hardware, and a remotely accessible testbed, building a powerful tool for evaluation and validation of the results of FRONTS. Our framework allows for easy exchangeability between simulation and real-world experiment, as well as rapid engineering.

Keywords

Wireless Sensor Networks, Simulation, iSense, Shawn

1. INTRODUCTION

We are now on the verge of Wireless Sensor Networks (WSNs) leaving the landrush phase and becoming more and more mainstream. Many complex issues have been addressed, and we see a number of operating WSNs. This shifts the focus from initial questions about how to get working networks at all, to those about the shape of future networks and their applications. Being relieved from dealing with complex low-level issues, we now can concentrate on high-level applications and protocols.

It is our belief that soon sensor networks will exist with a number of properties:

Heterogeneity: WSNs will no longer consist of identical devices. The need to maintain networks over long periods of time will result in different software and hardware generations from one family to coexist. Also, there will be completely different devices in networks due to interactions between networks, the need for specialized sensory in certain areas, and because networks will grow organically.

Dynamics: Other than in today's networks, different kinds of dynamics will happen at the same time in a network. Some nodes may enter and leave the network due to off-duty cycling. Others are moving with some external carrier like vehicles, animals, or water flows. Finally, some nodes may actively move around to investigate events, help bridging communication gaps, or populate unexplored areas with passive nodes. Another source of dynamics is the environment. In long-lasting networks, there may be huge changes in the surroundings and therefore in the constraints and objectives of the network.

Massive Sizes: When issues about information exchange between neighboring sensor networks are solved, huge sensor networks arise instantly. Also, continuously decreasing hardware costs, and ongoing research on real sensor nodes lead to the feasibility of obtaining a great amount of nodes. Hence, current algorithms that were tested on mostly a few hundred nodes must also scale up to hundreds of thousands of nodes.

The FRONTS project [2] is part of the European Seventh Research Framework Programme (FP7, [1]). It is a collaboration of 11 European working groups, aiming at investigating the algorithmic foundations of future WSNs and providing answers for questions that arise now. The participants have a great deal of experiences with the fundamental theory of wireless sensor networks. Together, we will contribute research to the following issues:

- Development of validated mathematical models for large-scale wireless sensor networks beyond oversimplifications such as Unit Disk Graphs, infinite-capacity links, random waypoints movements.
- Design of dynamic and adaptable network infrastructures, including enabling security by developing appropriate algorithms, protocols, and strategies.
- Design of algorithms for solving global tasks like collective exploration of unknown areas, or target tracking in dynamically changing environments.

The paper is structured as follows. The project FRONTS itself and its aims are described in more detail in the following Section 2. The IBR at the Braunschweig University of Technology and the ITM at the University of Lübeck participate in FRONTS. The practical parts of the project are our responsibility. It is our aim to get valuable feedback from implemented algorithms, protocols, and applications that are developed within the project. Feedback will be

achieved by evaluations and validations. Therefore we will build up the Experiments Repository, which will consist of an appropriate simulation package for wireless sensor networks as well as at least one physical testbed. It will be remotely accessible via the Internet for all project partners. The requirements concerning software and hardware technologies, and the technologies to cope with these needs are described in Section 3.

2. EUROPEAN PROJECT FRONTS

The aim of FRONTS is to understand the theoretical backgrounds of large-scale adaptive heterogeneous wireless sensor networks. These networks consist of nodes that provide different capabilities and act in a dynamic environment. Dynamics can either be active or passive. When dealing with active mobility, nodes are able to move autonomously to designated parts of the network. Passive mobility means that nodes are connected to moving objects like vehicles or human beings. With FRONTS, we will be able to get a clear grasp of such networks. It will be crucial not only for understanding the net behavior, but also for supporting algorithm development in nearly all related areas.

The goals of FRONTS can be summarized as follows:

- Design a unifying framework,
- Obtain a set of design rules,
- Provide distributed adaptation techniques,
- Provide laws on adaptation,
- Obtain knowledge of combining heterogeneous nodes,
- Provide a set of algorithms, and
- Evaluate with both simulation and experiments.

The main issue is to develop mathematical models that describe the focused adaptive large-scale networks of heterogeneous nodes in dynamic environments. Such models include mobility for dealing with different kinds of dynamics, computation models that consider the limited memory and limited knowledge of the nodes, and cooperation models that cover homogeneneous, hierarchical, and diversified systems. With the aid of the resulting unifying framework we intend to get a consistent working set of design rules of such systems. These rules will help us to develop adaptation techniques for which we provide basic laws. This includes the effect of adaptation on the system performance, the cost of distributed coordination regarding adaptation, the communication overhead, overhead in terms of energy consumption, and possible trade-offs. However, these adaptation techniques will help designing a dynamic and adaptable network infrastructure to cover nodes that adapt to each other and to changing needs. This includes both the communication structure between nodes, and general data access even when the data moves dynamically in the network.

Another objective is the combination and interaction of heterogeneous nodes to obtain a useful global behavior. A network of nodes that have different capabilities should combine the various strengths resulting in a net that is much more powerful than a network of homogeneous nodes can ever be. A crucial issue here are strategies for role assignment that act dynamically according to the current needs of the system. Different capabilities of nodes lead also to new approaches for security. For example, work can be outsourced to more powerful nodes in the network, or completely new protocols, algorithms, and strategies can be designed.

Building on the previous work, the participants of FRONTS will examine strategies and algorithms, which are focused on solving global tasks in the network. This will result in a set of algorithms that contain a collective exploration of an unknown area by considering both active and passive mobility in the network, algorithms for target tracking in dynamic environments with either a moving sink to which data must be sent, or a mobile agent that follows the target, and algorithms for network connectivity maintenance with actively moving nodes.

3. EXPERIMENTS REPOSITORY

The previous section described the project objectives. A decisive point are the practical aims of the project, such as evaluation and validation of developed algorithms. We will contribute an *Evaluation Package* to obtain valuable feedback for the project's theoretical insights. This package will consist of a WSN simulator, appropriate hardware, and at least the provision of one sensor network testbed composed of about 50 sensor nodes. The common central testbed will be accessible via Internet for all project partners to test protocols, algorithms, and applications.

We had to cope with the following requirements concerning suitable software and hardware technologies:

- We need a simulation framework that aims particularly at high level algorithms and a quick and easy development process.
- We need a simulator that copes with simulations of large-scale networks with tens to hundreds of thousands of sensor nodes in an adequate time frame.
- We need a simulator that realizes realistic and universally valid, i.e. hardware-independent, evaluations.
- We also need working and easily maintained hardware for our practical evaluations.
- To narrow the gap between virtuality (simulations) and reality (experimentations on real hardware) it is desirable to have the possibility of easy transfers of implemented algorithms from one to the other.

In the following, technologies that address our above specified needs are described. They will be part of our *Evaluation Package*.

Shawn [4] is a discrete event simulator for sensor networks. It has been primarily designed for simulating large-scale networks with up to a million of nodes, with an algorithmic point of view. Instead of simulating a phenomenon itself, it simulates the effects. This approach leads to an essential performance gain. Shawn finishes simulations in minutes where, say, Ns-2 [3] is running for more than a day [8].

Other design focus points are flexibility and extensibility. All crucial parts that can influence the simulation are designed as exchangeable models. First of all is the commu-

nication model that defines whether two nodes in the network can in principle communicate with each other. Next is the edge model that is responsible for neighborhood representation. It provides access to links between nodes in a graph structure, using the communication model to decide whether there is a link between any two nodes. There is a very simple edge model with no memory overhead, but wasting computation time, up to a very fast model that requires much memory. Finally, there is the transmission model that is used to transmit messages. It uses the edge model to select potential receivers of a sent message. There are several models available that can also be put into a chain of multiple models. Beginning with a reliable model that simply transmits every message, there are also models for simulating message loss and delay, as well as CSMA and TDMA. All of these models can be arbitrary combined, which leads to very flexible and powerful options in simulation behavior. Also, models can easily be exchanged to run an algorithm in different scenarios without any additional effort.

The simulation controller manages the process of simulation, and provides access to the simulated world with all available nodes. This allows for an easy development of centralized algorithms. It is possible to write a task that is executed once and has access to the whole simulation via the controller. However, Shawn has been primarily designed for simulating distributed algorithms. Each node in the network can contain multiple independent processors, whereby each processor may implement an individual algorithm. These algorithms may either run independently from each other, or interact over common variables that are appended in a type-safe way to the nodes.

The design with processors, tasks, and the previously presented models enables a rapid algorithm engineering with short development cycles per algorithm. This makes Shawn an attractive choice, especially for implementing and evaluating high-level algorithms.

iSense [5] is a hardware and software platform. Its modular approach allows adapting the hardware and software used for a specific application exactly to the required functionality.

A fundamental design guideline is to use only languages and tools that are well understood by a large user community. Consequently, the object oriented C++ programming language and popular tools such as the Gnu Compiler Collection [7] (GCC) and the Eclipse [6] development framework are used. iSense includes a tiny STL-like implementation. Thus, implementations for standard containers such as lists, maps and sets are already part of iSense. Hence, the learning curve for many system designers and solution developers is extremely flat.

iShell is a tool that is provided by iSense. It provides an easy way for the communication between sensor networks and PCs. Functionalities like serial and over-the-air programming are supported, as well as a serial terminal and a plug-in system to facilitate the supplementation of individual desired functionality as monitoring or analyzing the network.

Application code that has been developed with the iSense framework is ready to run on any platform that supports an implementation of the iSense API. Primarily it is available for the iSense hardware platform, as well as for the simulation environment Shawn. Thus, system designers and solution developers are able to test their implemented applications in the simulator before transferring them onto the iSense hardware. That way time will be saved for the overall development process.

Thus, there are three options given to practically evaluate implemented protocols or algorithms:

(1) Simulating with Shawn.

(2) Testing on real hardware with iSense.

(3) Testing on a common centralized sensor node testbed.

When implementing algorithms, protocols, or applications for either of these three options, it is trivial to switch to one of the others afterwards. This is because of the compatibility between Shawn and iSense. This expands the possibilities for evaluating and validating, and reduces the overall time of development processes in addition to all the other technologies' features and advantages mentioned above.

4. CONCLUSION

We introduced the European project FRONTS. The main objectives of the project are to get a fundamental understanding of the properties of wireless sensor networks, to develop algorithms, design rules for algorithms and applications, and to form a unifying framework for adaptive wireless sensor networks.

One of the next steps will be to build up the Experiments Repository. This contains the aim of establishing a repository of applications for simulation, as well as building up a testbed composed of real sensor nodes. Further, the testbed shall be connected to the Internet via the tool iShell that is provided by iSense. That way all project partners will be able to test their algorithms on a common hardware platform.

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