State-of-the-Art of Distributed Channel Assignment

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Acronyms

4G Fourth Generation. 9

AODV Ad hoc On-Demand Distance Vector Routing. 9

BIR Broadcast Interference Ratio. 15

CAL Channel Abstraction Layer. 35

CAS Channel Assignment Server. 1, 11

CCA Cluster Channel Assignment. 26

CG Conflict Graph. 10, 29

CHH Head of Clusterhead. 26

CLICA Connected Low Interference Channel Assignment. 22, 27

DES Distributed Embedded Systems. 2, 8, 39

DGA Distributed Greedy Algorithm. 22, 23

DSR Dynamic Source Routing. 24

EETT Exclusive Expected Transmission Time. 20

ESSID Extended Service Set Identifier. 35

ETSI European Telecommunications Standards Institute. 8

ETT Expected Transmission Time. 17, 19, 20

ETX Expected Transmission Count. 17–20, 37, 42

FCC The Federal Communications Commission. 8

FNI Fractional Network Interference. 13, 16, 27, 29

HCC Highest Connectivity Cluster. 26

iAware Interference-Aware. 20

IBSS Independent Basic Service Set. 35

IEEE Institute of Electrical and Electronics Engineers. 1–4, 7–11, 17, 20, 21, 29, 30, 35, 36, 39, 40, 42

ISM Industrial, Scientific and Medical. 8

KMCR Kernel Multi-Channel Routing. 35

LIR Link Interference Ratio. 15, 41

LTE Long-Term Evolution. 9

MBSS Mesh Basic Service Set. 9

MCG Multi-Radio Conflict Graph. 10

MCR Multi-Channel Routing. 19, 24

MIMO Multiple Input, Multiple Output. 8

MR-LQSR Multi-Radio Link Quality Source Routing. 22

MST Minimal Spanning Tree. 24, 25

NNCQ Neighborhood Nodes Collaboration to support QoS. 26, 27

OFDM Orthogonal Frequency Division Multiplexing. 8

OLPC One Laptop per Child. 9

RSSI Received Signal Strength Indicator. 15

SAFE Skeleton Assisted Partition Free. 24

SINR Signal-to-Interference plus Noise Ratio. 15, 20

SIR Signal-to-Interference Ratio. 15

SNR Signal-to-Noise Ratio. 20

U-NII Unlicensed National Information Infrastructure. 8

WCETT Weighted Cumulative Expected Transmission Time. 19, 20, 22

WiMAX Worldwide Interoperability for Microwave Access. 9

WLAN Wireless Local Area Network. 8, 30

WMN Wireless Mesh Network. 1, 3–5, 7–10, 21, 39

WNIC Wireless Network Interface Card. 35, 37, 39, 41, 44

WSN Wireless Sensor Network. 39

Abstract

Channel assignment for Wireless Mesh Networks (WMNs) attempts to increase the network performance by decreasing the interference of simultaneous transmissions. The reduction of interference is achieved by exploiting the availability of fully or partially non-overlapping channels.

Although it is still a young research area, many different approaches have already been developed. These approaches can be distinguished into *centralized* and *distributed*. Centralized algorithms rely on a central entity, usually called Channel Assignment Server (CAS), which calculates the channel assignment and sends the result to the mesh routers. In distributed approaches, each mesh router calculates its channel assignment decision based on local information. Distributed approaches can react faster to topology changes due to node failures or mobility and usually introduce less protocol overhead since communication with the CAS is not necessary. As a result, distributed approaches are more suitable once the network is operational and running. Distributed approaches can further be classified into *static* and *dynamic*, in regard to the modus of channel switching. In dynamic approaches, channels can be switched on a per-packet basis, whereas in static approaches radios stay on a specific channel for a longer period of time. Static assignments have been more in focus, since the channel switching time for current Institute of Electrical and Electronics Engineers (IEEE) 802.11 hardware is in the order of milliseconds which is two orders higher than the packet transmission time.

Recently, surveys of channel assignment algorithms have been presented which cover certain aspects of the research field. The survey in [1] introduces the problem and presents a couple of distributed algorithms and [2] gives a broad introduction to centralized and distributed approaches. The survey herein is focused on distributed approaches for peer-to-peer network architectures.

This report describes the problem formulation for channel assignment in WMNs and the fundamental concepts and challenges of this research area. We present different distributed channel assignment algorithms and characterize them according to a set of classification keys. Since channel assignment algorithms may change the connectivity and therefore the network topology, they may have a high impact on routing. Therefore, we present routing metrics that consider channel diversity and adapt better to the multi-radio multi-channel scenario than traditional routing metrics designed for single channel networks. The presented algorithms are discussed and compared focusing on practical evaluations in testbed and network environments. The implementation for real networks is a hard and labor-intensive task because the researcher has to deal with the complexity of the hardware, operating system, and wireless network interface drivers. As a result, frameworks emerged in order to simplify the implementation process. We describe these frameworks and the mechanisms used to help researchers implementing their algorithms and show their limitations and restrictions.

We briefly describe the Distributed Embedded Systems (DES)-Testbed for which the DES-Chan framework was initially implemented. Basic measurements performed on the DES-Testbed are presented which work as a benchmark and reference for the evaluation of future channel assignment algorithms. Among these measurements is the impact of interference in respect to the channel distance using IEEE 802.11 hardware.

The report concludes with an outlook of current and future trends in this research area. We discuss the significance of the emerging frameworks for channel assignment in experimental network environments for future research.

CHAPTER 1

Introduction

1.1 Motivation

1.1.1 The Channel Assignment Challenge

Interference is an important factor that may limit the network performance in Wireless Mesh Networks (WMNs) [3]. Commonly used wireless network technologies, such as Institute of Electrical and Electronics Engineers (IEEE) 802.11, allow the usage of multiple non-overlapping channels. The idea of channel assignment is to minimize the network-wide interference by utilizing non-overlapping channels for interfering wireless transmissions. The key challenge of the problem is how to assign the available channels in a way, that interference is minimized and the network performance in regard of the network capacity is maximized while ensuring the network connectivity.

Channel assignment using different non-interfering channels can decrease interference but also alter the network topology. When the network interfaces of two neighboring network nodes operate on non-interfering channels they do not interfere with each other but also the nodes can not communicate directly. Thus, there is a trade-off between the channel diversity that may reduce interference and the network connectivity.

A simple scenario with a single-channel network and an optimal channel assignment is depicted in Figure 1.1.

1.2 Fundamentals

1.2.1 Wireless Mesh Networks

In WMNs, nodes may relay packets for other nodes [4]. The architecture of WMNs is depicted in Figure 1.2. The network architecture comprises three tiers: *gateways*, *backbone mesh routers*, and *mesh clients*. The backbone mesh routers are usually stationary and function as base stations for the mesh clients. They communicate over wireless links with each other and with mesh clients. Some of them may have wired connections to other networks and can thus function as gateways to different networks, such as the Internet. Mesh clients can be stationary or mobile and may function as routers by forwarding traffic for other mesh clients.

Further on, WMNs can be classified regarding the availability of the number of radios on each mesh router. In *single-radio* networks, every node is equipped with exactly

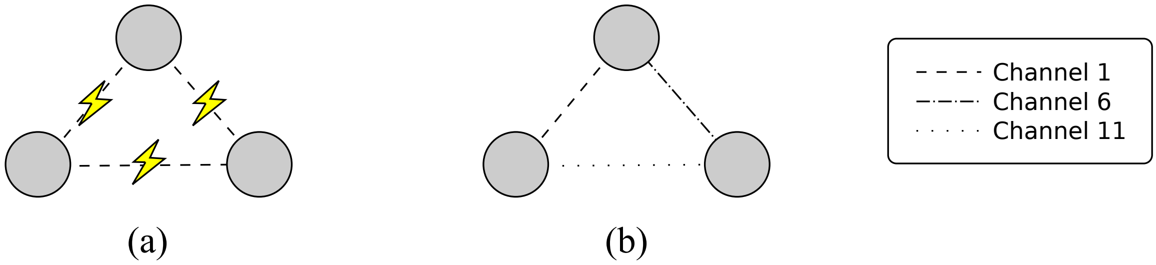


Figure 1.1: Channel assignment in single- and multi-channel networks. In (a), channel 1 is assigned to all links with the consequence that all links interfere with each other. An optimal channel assignment for this simple scenario can be achieved with the utilization of three non-interfering channels as depicted in (b). The links do not interfere with each other and the connectivity of the network has been prevailed. Still, at least two wireless network interfaces for each node are required to establish the links permanently.

one radio. In order to avoid network partitioning, the radios have to be tuned to a network-wide common channel. With this setup, single radio networks are prone to *intra-* and *inter-flow* interference as described in Section 1.2.5. In *multi-radio* networks, every node is equipped with more than one radio. These radios may be tuned to different non-overlapping channels, which allows to receive and transmit at the same time and to communicate simultaneously with different neighbors. Due to the low cost of commodity IEEE 802.11 hardware, multi-radio networks are the most common scenario for channel assignment in WMNs.

Many fields of commercial and non-commercial applications for WMNs evolved in the last decade. They are typically used for providing Internet access in dense city areas as well as in rural areas, university and business networks. Several companies offer hard- and software to set-up WMNs for business clients and consumers [5, 6, 7, 8]. Voluntary communities, such as the Freifunk community in Berlin [9], set up WMNs to provide Internet access in dense city areas for the participants.

1.2.2 Terminology and Network Model

Different terms and models have been used in the various problem formulations and algorithm descriptions for channel assignment. Therefore, we define a terminology and use it throughout the report.

The *unit disk graph* model [10] has been developed and used for WMNs. With this model the network is represented by an undirected Graph $G = (V, E)$, where V is the set of network nodes and $E \subseteq V \times V$ is the set of wireless links. The graph is undirected, since bidirectional links are required for communication using IEEE 802.11 because of the ACK-mechanism on the link layer. For simplicity, it is considered that all wireless interfaces have the same transmission radius r_t and interference radius r_i, with $r_i > r_t$. It is usually assumed that $r_i = \alpha \cdot r_t$ with $2 < \alpha < 3$, see [3].

A link exists between two nodes $u, v \in V$ if their distance $d_{u,v}$ is smaller than their transmission radius r_t, more formally $d_{u,v} \leqslant r_t$. If such a link exists, it is denoted with $l_{u,v}$. Two links $l_{u,v}$ and $l_{x,y}$ interfere with each other if they utilize overlapping channels and at least one of the following distances $d_{u,x}, d_{u,y}, d_{v,x}, d_{v,y}$ is smaller than the interference radius r_i [11].

It has to be taken into account, that the unit disk graph model comprises all virtual communication links in the network, regardless of a particular interface configuration. To

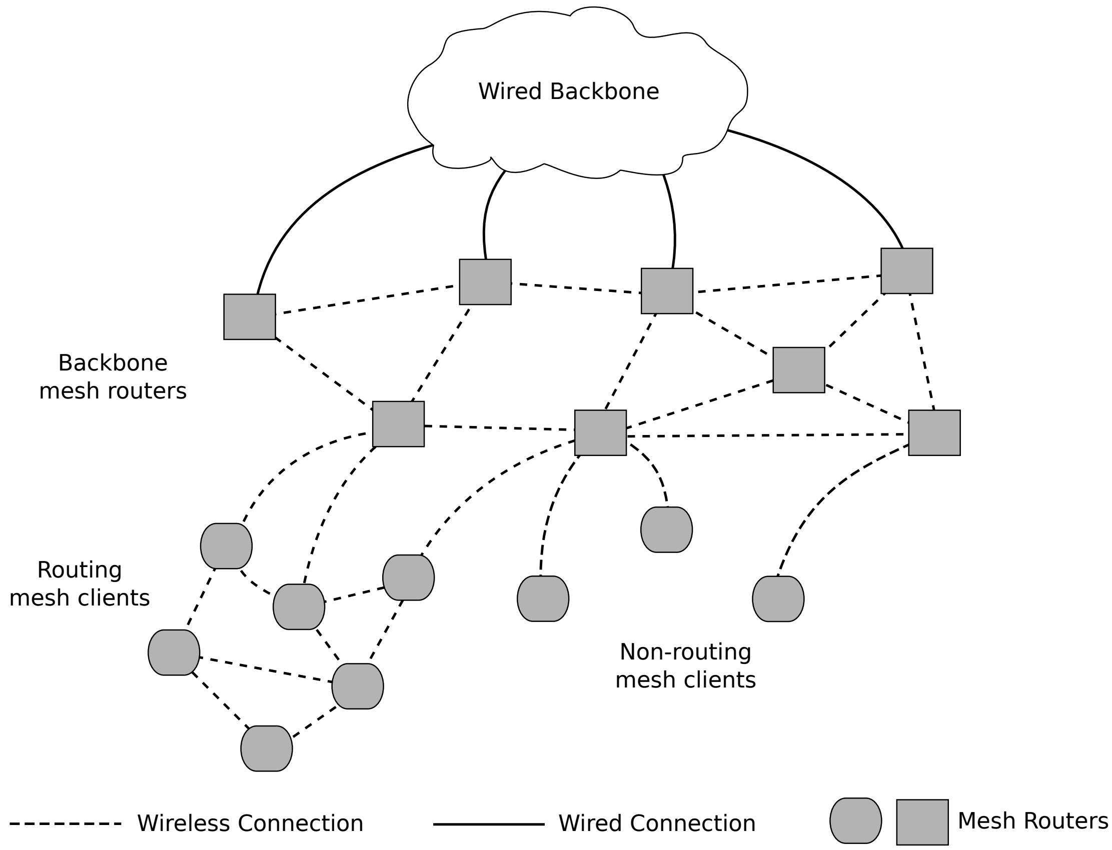


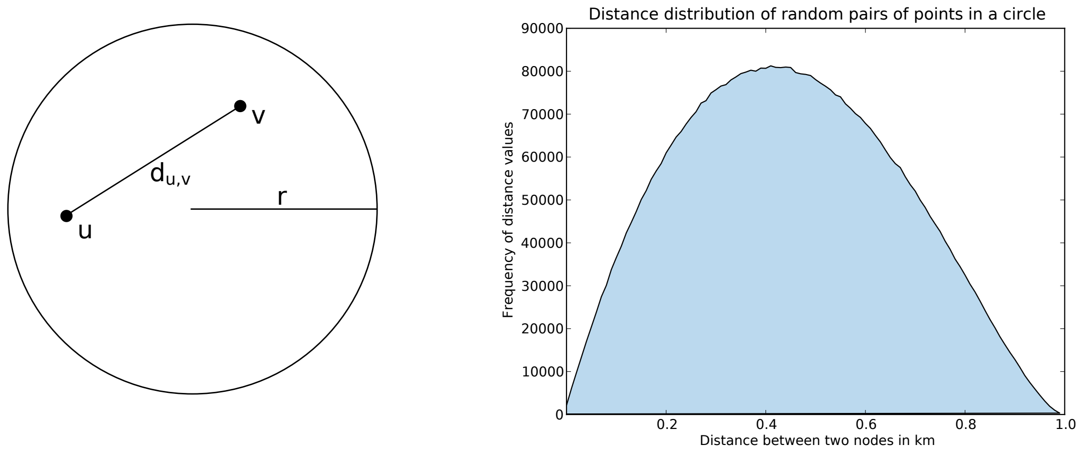
Figure 1.2: The stationary *backbone mesh routers* communicate over the wireless links with each other and with the mesh clients. Backbone mesh routers may have wired connections to another backbone network and can thus function as *gateways* to different networks, such as the Internet. The *mesh clients* may be stationary or mobile and may also function as routers by forwarding traffic for other mesh clients.

model the channel utilization, in the *network topology* model, a link between $v, u \in V$ exists only if $d_{u,v} \leqslant r_t$ and at least one interface on each node is tuned to the same channel. A link between the two nodes $u, v \in V$ on channel c in the network model is therefore given with $l^c_{u,v}$. Whereas the unit disk graph model describes the possible links in a WMN, the network topology model only comprises the links that can actually be used for communication.

1.2.3 Random Network Topologies

An interesting observation regarding the expected distance between uniformly distributed network nodes in a circle area has been stated in [12, 13]. The expected distance of two nodes $u, v \in V$ is given with $d^e = \frac{128}{45 \cdot \pi} \cdot r$, see Figure 1.3 (a).

The formula for the expected distance d^e allows us to derive characteristics of random topologies when the nodes are uniformly distributed. With the radius of the network area r, the transmission radius r_t, and the interference radius r_i we are able to control the network connectivity and the network-wide interference. With the distribution of the node distance, as depicted in Figure 1.3 (b), we can derive the probability p_{r_t} that the distance for any pair of nodes $u, v \in V$ is smaller than their transmission radius meaning that they can communicate with each other $p_{r_t} = p(d_{u,v} \leqslant r_t)$. Therefore, we can also



(a) The nodes u and v are distributed uniformly in a circle area

(b) Distance distribution of 5,000,000 random pairs of nodes in a circle with r = 0.5km

Figure 1.3: In (a), two nodes $u, v \in V$ are placed in a circle area with the radius r. The expected distance d^e between uniformly distributed nodes is given by $d^e = \frac{128}{45 \cdot \pi} \cdot r$. In (b) the distribution of the node distance of 5,000,000 pairs of nodes is depicted. The mean distance of the 5,000,000 samples is $d_m \approx 0.452740$ km and close to $d^e = \frac{128}{45 \cdot \pi} \cdot r \approx 0.452707$ km.

easily predict the expected mean node degree since all nodes are placed independently of each other. The expected mean node degree K is therefore $K = p_{r_t} \cdot N$, with N being the total number of network nodes.

The observation of the expected connectivity of the network can also be applied to the expected interference of two arbitrary links $l_{u,v}$ and $l_{x,y}$ with $u, v, x, y \in V$. For this we derive the probability p_{r_i} that the distance $d_{u,v}$ is smaller than the interference radius meaning that $l_{u,v}$ and $l_{x,y}$ interfere with each other $p_{r_i} = p(d_{u,x} \leqslant r_i)$.

We can calculate the probability $p_{r_i}(l_{u,v} \leftrightarrow l_{x,y})$ that two links interfere with each other using the definition that $l_{u,v}$ and $l_{x,y}$ interfere with each other if at least one of the following distances $d_{u,x}, d_{u,y}, d_{v,x}, d_{v,y}$ is smaller than the interference radius r_i [11]. Therefore, $p_{r_i}(l_{u,v} \leftrightarrow l_{x,y})$ is defined as follows

$$p_{r_i}(l_{u,v} \leftrightarrow l_{x,y}) = (p_{r_i,(u,x)} \bigvee p_{r_i,(u,y)} \bigvee p_{r_i,(v,x)} \bigvee p_{r_i,(v,y)})$$

For the probabilities it holds that $\{p_{r_i,(u,x)}, p_{r_i,(u,y)}, p_{r_i,(v,x)}, p_{r_i,(v,y)}\} \leqslant p_{r_i}$, because four nodes are placed in the circle area and each placement decreases the area in which the subsequent node can be placed so that all conditions hold, which means that none of the four distances is smaller than the interference radius. Therefore we can estimate the probability $p_{r_i,(u,v)(x,y)}$ that two links *do not* interfere with each other with

$$p_{r_i}(l_{u,v} \leftrightarrow l_{x,y}) \leqslant (1 - p_{r_i}) \cdot (1 - p_{r_i}) \cdot (1 - p_{r_i}) \cdot (1 - p_{r_i}) = (1 - p_{r_i})^4$$

In the following, we calculate the derived probabilities for two examples. First, we use $r = 0.5$ km as the radius of the circle network area, $r_t = 0.1$ km as the transmission radius, and $r_i = 0.25$ km as the interference radius. With this value for r, the expected distance between two nodes is $d^e \approx 0.453$ km. In Figure 1.4 the distribution of the distance between two nodes is depicted with the quantiles for the transmission and interference radius. With the quantiles, we derive the values for the probabilities $p_{r_t} = 0.04$ and $p_{r_i} = 0.2$

The node degree K is then expected to be $K = 0.04 \cdot N$. The probability that $l_{u,v}$ and $l_{x,y}$ do not interfere with each other is calculated as follows

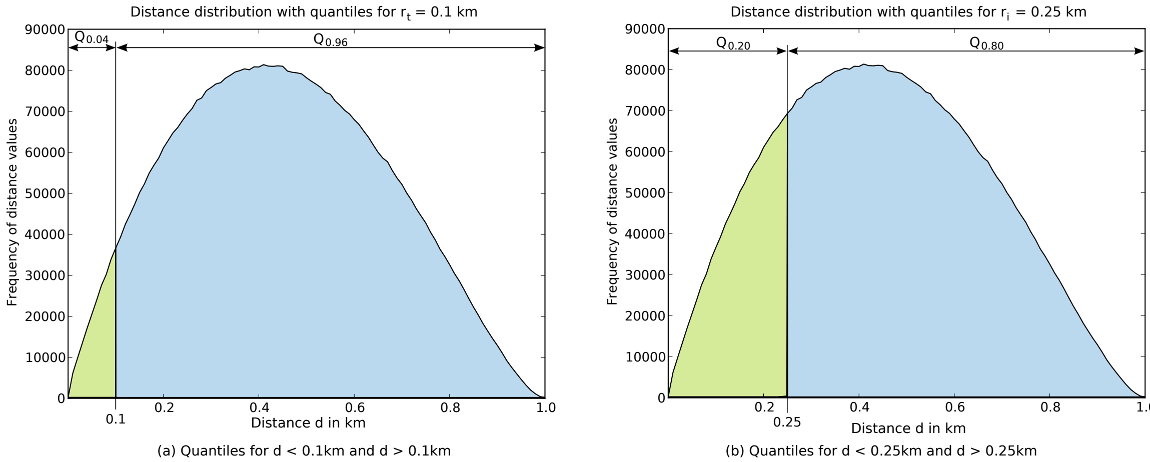


Figure 1.4: Node distance distribution with quantiles for $r = 0.5$ km, $r_t = 0.1$ km and $r_i = 0.25$ km. In (a) the quantiles for an transmission radius $r_t = 0.1$ km show that in 4% of the samples the expected distance is smaller than the transmission radius, $d \leqslant r_t$, therefore $p_{r_t} = 0.04$. In (b) the quantiles for the interference radius $r_i = 2.5 \cdot r_t = 0.25$ km show that in 20% of the samples the expected distance is smaller than the interference radius, $d \leqslant r_i$, therefore $p_{r_i} = 0.2$.

$$p_{r_i}(l_{u,v} \leftrightarrow l_{x,y}) \leqslant (1 - p_{r_i})^4 = 0.8^4 \approx 0.41$$

This means that in $\approx 59\%$ of all cases two links interfere with each other. Although rather small values have been chosen for the transmission and interference range, the chance that two links interfere with each other is therfore above 50%, which results in an estimation of high network-wide interference.

In a second experiment, we calculate the probabilities for $r = 0.5$ km , $r_t = 0.25$ km, and $r_i = 0.5$ km. In Figure 1.5 the distribution of the distance between two nodes is depicted with the quantiles for the transmission and interference radius. With the quantiles, we derive the values for the probabilities $p_{r_t} = 0.2$ and $p_{r_i} = 0.59$.

Therefore, the node degree K is expected to be $K = 0.2 \cdot N$. The probability that $l_{u,v}$ and $l_{x,y}$ do not interfere with each other is calculated as follows

$$p_{r_i}(l_{u,v} \leftrightarrow l_{x,y}) \leqslant (1 - p_{r_i})^4 = 0.41^4 \approx 0.028$$

This means that in $\approx 97\%$ of all cases two links interfere with each other. This value is very high, but still, the chosen values for the input parameters r, r_t, r_i are common in current simulation studies.

The observations show, that characteristics of a random network topology can already be derived from the choice of the input parameters. Still, networking experiments with simulation environments usually do not analyze their input parameters but instead calculate the characteristics of a particular scenario after it has been created. The choice of the parameters can ensure to create random scenarios with an average node degree and interference effects close to what is to be expected in real network deployments.

1.2.4 Technologies for Wireless Networks

Extensive research has already been performed in the area of channel assignment for cellular networks [14], which is usually referred to as *frequency assignment* in this domain. The problem formulation for this network type is different to IEEE 802.11 based WMNs

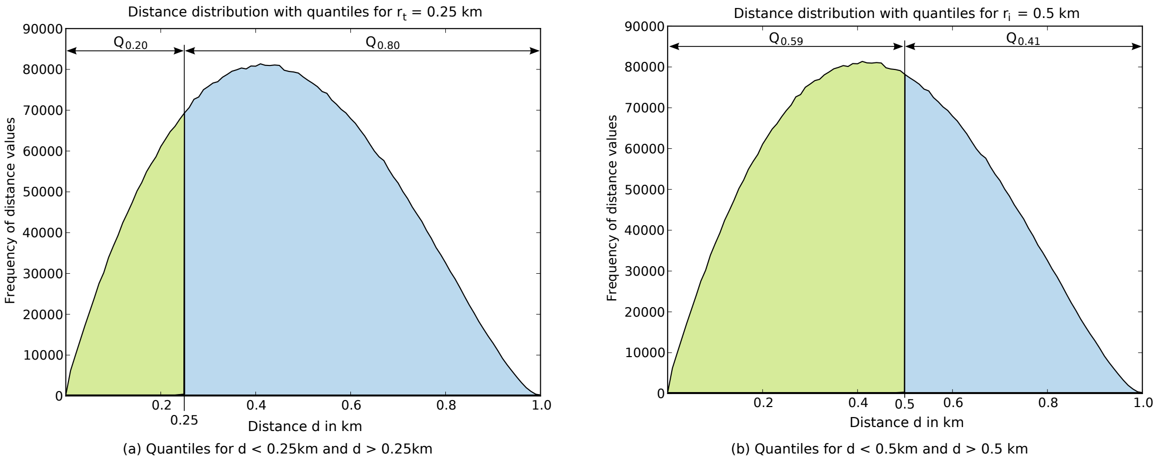


Figure 1.5: Node distance distribution with quantiles for $r = 0.5$ km, $r_t = 0.25$ km and $r_i = 0.5$ km. In (a) the quantiles for an transmission radius $r_t = 0.25$ km show that in 20% of the samples the expected distance is smaller than the transmission radius, $d \leqslant r_t$, therefore $p_{r_t} = 0.2$. In (b) the quantiles for the interference radius $r_i = 2 \cdot r_t = 0.5$ km show that in 59% of the samples the expected distance is smaller than the interference radius, $d \leqslant r_i$, therefore $p_{r_i} = 0.59$.

because in cellular networks, neighboring base stations are connected over wired networks, whereas in WMNs the router are usually connected over the wireless medium. In cellular networks it is common practice to assign non-overlapping channels to neighboring cells in order to minimize the interference. In contrast, it is required that mesh routers share a common channel in order to ensure the connectivity of the mesh network. Therefore, the solution of assigning the least used channel to a network node can not be transferred directly to WMNs.

Due to the wide availability and low cost of IEEE 802.11 devices, many WMNs rely on this technology. IEEE 802.11b/g supports up to 14 different channels on the unlicensed Industrial, Scientific and Medical (ISM) radio band at 2.4 GHz [15]. The distance of the center frequency of two adjacent channels is 5 MHz with a channel width of 22 MHz as depicted in Figure 1.6. Available data rates range from 1 Mbit/s to 11 Mbit/s for IEEE 802.11b and up to 54 Mbit/s for IEEE 802.11g. The standard provides three non-overlapping channels, for example the subset $\{1, 6, 11\}$. However, studies have shown that in reality those channels are interfering [16], we describe a similar study on the Distributed Embedded Systems (DES)-Testbed in Section 5.3. Political regulations restrict the number of usable channels in particular regions, for instance the European Telecommunications Standards Institute (ETSI) allows the usage of channels 1-13 [17], while The Federal Communications Commission (FCC) allows the usage of the channels 1-11 in the United States [18].

The IEEE 802.11a standard, intended for the United States, defines 12 non-overlapping channels on the 5 GHz Unlicensed National Information Infrastructure (U-NII) band. The IEEE 802.11h standard evolved to open the 5 GHz radio band for Wireless Local Area Network (WLAN) devices in Europe. It defines additional restrictions because of the coexistence of military and radar stations that utilize the same frequency band. Available data rates range from 1 Mbit/s to 54 Mbit/s.

The IEEE 802.11n standard offers data rates of up to 600 Mbit/s using Multiple Input, Multiple Output (MIMO) technology with Orthogonal Frequency Division Multiplexing (OFDM). The high data rate is achieved with the spacial diversity due to multiple anten-

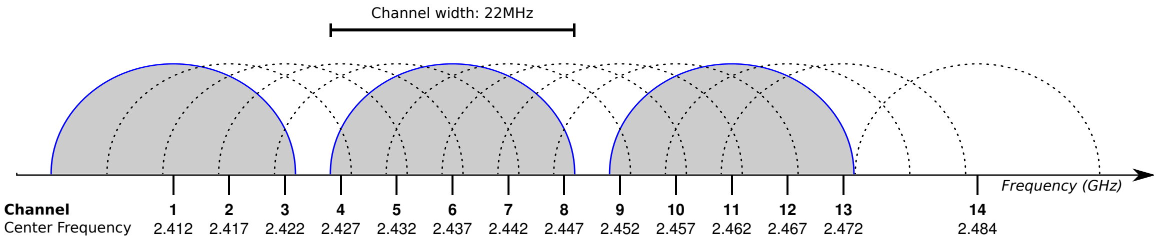


Figure 1.6: Available channels and their center frequency for IEEE 802.11b/g. Due to regulatory constraints, channel 14 is only available in Japan. A possible set of three theoretically non-overlapping channels $\{1, 6, 11\}$ is emphasized.

nas which allow to transmit data streams on the frequency at the same time. IEEE 802.11n operates on the 2.4 GHz as well as on the 5 GHz frequency band. The standard specifies a legacy mode, which ensures downward compatibility to IEEE 802.11a/g.

The IEEE 802.11n standard allows channel-bonding on the physical layer, which means that two non-interfering 20 MHz wide channels can be used simultaneously. This way, the available data rate can be doubled. This feature, also referred to as 40 MHz mode, decreases the amount of available non-interfering channels for IEEE 802.11n. Nevertheless, multiple non-interfering channels are supported so that channel assignment may increase the network performance.

The IEEE 802.11s draft addresses WMNs and specifies standard protocols, such as an routing protocol based on Ad hoc On-Demand Distance Vector Routing (AODV), for mesh devices in order to create a WMN. Work on the standard has started in 2003 and currently draft D4 is being processed. A reference implementation for the Linux kernel exists in the `mac80211` module that has been distributed with the One Laptop per Child (OLPC) initiative.

Of interest for channel assignment procedures is, that the standard specifies a protocol for channel switching. The procedure is primarily defined to satisfy regulatory requirements. A channel switch may be carried out to avoid interference with a radar signal or to ensure the connectivity of the Mesh Basic Service Set (MBSS).

The IEEE 802.16 Worldwide Interoperability for Microwave Access (WiMAX) standard also supports multiple non-interfering channels [19]. The standard operates on the unlicensed radio band from 2 GHz to 66 GHz with a flexible channel width, thus theoretically supporting many more non-overlapping channels than IEEE 802.11a/b/g. However, the future of IEEE 802.16 is unclear since big manufacturers have ceased the development of hardware due to the approach of Long-Term Evolution (LTE) as another Fourth Generation (4G) mobile technology for IP-based networks [20].

1.2.5 Interference

In WMNs, three different sources of interferences can affect the network performance as depicted in Figure 1.7. *Intra-flow* interference occurs when multiple hops on the path of a single flow utilize an overlapping channel and are in each others interference radius. Especially single channel networks are prone to this kind of interference. *Inter-flow* interference results when two links of different flows interfere with each other. As a third source, *external* interference results when devices which are not under control of the network operator utilize the same frequency band.

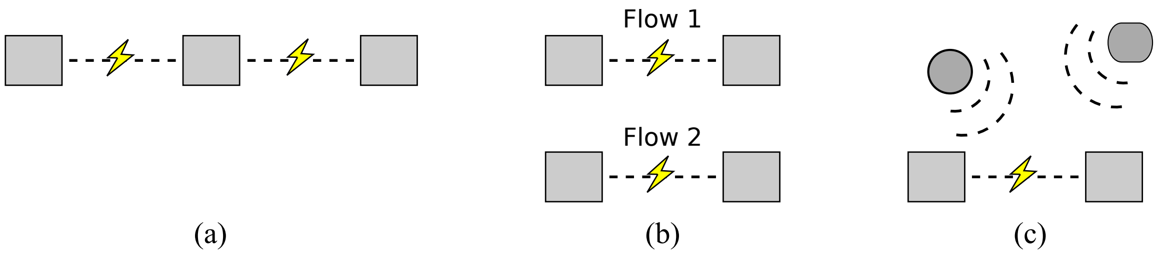


Figure 1.7: Intra-flow, inter-flow, and external interferences. Intra-flow interference may occur when two hops on a path utilize the same channel (a). Inter-flow interference results when two hops of two different flows interfere with each other (b). External interference is exerted form devices which are not under control by the network operator. This is often the case with co-located IEEE 802.11-based networks (c).

Usually, channel assignment algorithms try to reduce inter- and intra-flow interference and leave external interference aside, since it can not be controlled. Still, due to the large number of WMN deployments, it is likely that networks co-exist and therefore interfere with each other. It is therefore desirable to also consider the external interference during channel assignment. Since interference may change over time, the external interference has to be measured or estimated periodically, which can be very time- and resource-expensive.

1.2.6 Conflict Graphs

Conflict Graphs (CGs) or *interference graphs* model the interference between all links in a network [14]. The conflict graph G_C is given with $G_C = (V_C, E_C)$, where V_C corresponds to the edges E of the network graph $G = (V, E)$. An edge in E_C denotes, that the two corresponding edges in V_C interfere with each other.

The CG has been extended to the Multi-Radio Conflict Graph (MCG) in [21] in order to model multi-radio nodes. The difference is, that the MCG G_M is given with $G_M = (V_M, E_M)$, where V_M is the number of links between wireless interfaces instead of network nodes as in the original CG. The edges E_M are then created in the same way as in the CG, whereas two vertices in V_M are connected with an edge, when the two links between the wireless interfaces interfere with each other. The concepts of the conflict and multi-radio conflict graph are depicted in Figure 1.8.

It is important to notice that the conflict graph is not an interference model. An interference model, as described in Section 2.2, estimates the degree of interference two links may exert on each other, taking a particular interference metric into account. The conflict graph described the interference relationship between the network links estimated with such an underlying interference model. Usually, the underlying interference model is exchangeable for the conflict graph generation. The channel assignment problem can be formulated with a conflict graph, such as the goal of the algorithm is to minimize the number of the edges of the conflict graph.

1.3 Channel Assignment for Wireless Mesh Networks

1.3.1 Classifications

Over the last decade, many channel assignment algorithms have been developed for different scenarios. This resulted in a wide range of different approaches in regard to the

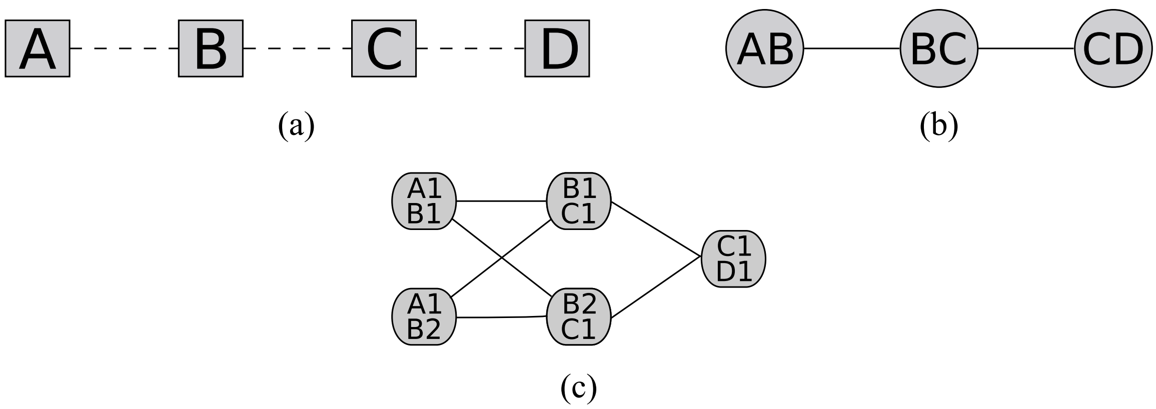


Figure 1.8: Conflict graph and multi-radio conflict graph. (a) The network topology consists of four mesh nodes each operating on the same channel. The network graph $G = (V, E)$ with $V = \{A, B, C, D\}$ and $E = \{(A, B), (B, C), (C, D)\}$. The resulting conflict graph is depicted in (b) with the corresponding graph structure $G_C = (V_C, E_C)$ with $V_C = \{AB, BC, CD\}$ and $E_C = \{(AB, BC), (BC, CD)\}$. In (c) the multi-radio graph is depicted when node B is equipped with two wireless interfaces and all remaining nodes with only one wireless interface. The graph structure for the multi-conflict graph is given with $G_{MC} = (V_{MC}, E_{MC})$ with $V_{MC} = \{A1B1, A1B2, B1C1, B2C1, C1D1\}$ and $E_{MC} = \{(A1B1, B1C1), (A1B1, B2C1), (A1B2, B1C1), (A1B2, B2C1), (B1C1, C1D1), (B2C1, C1D1)\}$.

network technology, application scenario, and network architecture. Because of the variety, the algorithms can be classified according to different key properties.

First, channel assignment algorithms can be considered *centralized* or *distributed*. Centralized channel assignment approaches rely on a central control instance that calculates the channel assignment for the whole network. This entity is often referred to as Channel Assignment Server (CAS) [21]. The CAS gathers network topology information, calculates the channel assignment based on the global network view, and notifies the network nodes about the result to adjust their channel assignment accordingly. In distributed channel assignment approaches, the algorithm runs on every network node and executes channel assignment decisions taking only local information into account. The communication overhead for a CAS does not exist in distributed approaches. Still, communication among the nodes is necessary to exchange local information and notify neighbors of changes in channel assignment. Distributed algorithms are considered to be less prone to node failures because they do not rely on a CAS which may constitute a *single point of failure*. Also they are usually more adaptive to a dynamic network topology in regard to node mobility and node failures because the corresponding topology changes can be handled locally. Still, distributed algorithms lack the advantage of using a global network view for the channel assignment calculations. This may lead to suboptimal results for network-wide channel assignment.

Another classification considers the frequency of channel switches on a network node. In literature, channel assignment approaches are classified into *dynamic* and *static* ones. In *dynamic* approaches, channel switches may occur frequently, in the extreme for every subsequent packet a different channel is chosen. The limiting factor for dynamic algorithms is the relative long channel switching time with commodity IEEE 802.11 hardware, which is in the order of milli seconds. *Static* approaches in contrast, switch the interfaces to a particular channel for a longer period, usually in the order of minutes or hours. Throughout this report, we will use the terms *fast* and *slow channel switching* for the two classes because the describe the methods more accurately. *Hybrid* approaches combine both methods.

1.3.2 Challenges in Distributed Channel Assignment

Distributed approaches must solve challenges concerning the retrieval of the channel usage in their neighborhood and the propagation of channel switches. Usually neighborhood information is exchanged periodically, which also allows to adapt to topology changes due to node mobility and node failures. In order to ensure that channel switches are noticed and do not result in dead interfaces or channel oscillation, channel switches are usually propagated in the neighborhood with simple handshake protocol mechanisms.

Channel oscillation describes the situation in which two links periodically switch channels because the channel switch for the first link leads to sub-optimal channel assignment on the second link and vice versa. This situation can be avoided with a 3-way handshake mechanism preceding the channel switches.

Another undesirable phenomenon is the *ripple effect* which describes the situation in which a channel switch is followed by several subsequent channel switches [22]. This happens when the channel of the first hop of an $\mathfrak{m}$-hop path is changed, and in consequence the channel assignment is not optimal anymore on the second hop. Therefore, the channel is switched on the second hop as well, and the situation repeats for all $\mathfrak{m}$-hops on the path.

The described phenomena may prevent the stabilization and convergence of distributed channel assignment algorithms. Therefore, it is important to develop appropriate countermeasures, such as handshake mechanisms for the prevention of channel oscillation. Some algorithms also introduce restrictions regarding the channel assignment choices, such that each channel-link combination may only be assigned once [23, 11]. While this helps guaranteeing the convergence and stabilization of the algorithm, it may lead to sub-optimal channel assignment and render the algorithm unadaptive to topology changes.

CHAPTER 2

Methodology and Metrics

The goal of this chapter is to describe metrics for channel assignment and develop a methodology to evaluate and analyze channel assignment algorithms that ensures comparability. Finding a universal methodology is complicated because algorithms may use different network and interference models, rely on different assumptions about the network behavior, and are evaluated in different experimentation environments.

Let us take a look at the Fractional Network Interference (FNI) metric to demonstrate the challenge [23]. The FNI is defined as the ratio of the number of edges in the conflict graph after channel assignment to the number of edges in a single channel network. On first sight, this metric seems adequate for evaluation since it represents how much the interference was reduced with the particular algorithm compared to the single channel network. Still, there are some limitations.

- This metric may only be used, if the channel assignment problem was formulated such that the number of edges in a conflict graph shall be minimized. This limits the comparability of the results to this particular class of algorithms.
- Even if the conflict graph is used, the underlying interference model may not be the same for different algorithms. For example, one algorithm applies the simple 2-hop neighborhood as interference model whereas another relies on a measurement-based interference approximation for a specific network.
- The metric reflects the decrease of interference only in regard to the used interference model which only approximates the interference to be expected in an arbitrary real network. This is especially interesting when the performance of the algorithms is evaluated in testbeds or real networks to validate the interference model.

This example shows the difficulty to find universally valid methods for the evaluation and analysis of channel assignment algorithms. We will first describe different classes of channel assignment metrics and eventually conclude how these metrics can be applied to analyze and evaluate a wide range of channel assignment approaches.

2.1 Metrics and Channel Assignment

In general, metrics are an essential part of all algorithms that make decisions based on variable input parameters. For these decisions metrics are needed in order to allow the comparison of the available choices. In channel assignment, metrics are used on different

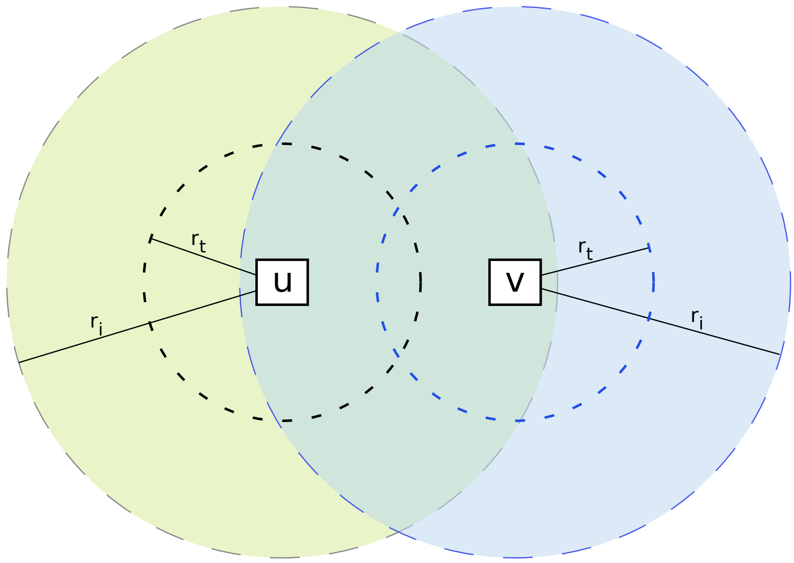


Figure 2.1: Transmission and interference radius. The nodes u, v are not in their transmission radius but in their interference radius. According to the protocol model, the nodes can not communicate with each other but when one of the stations transmits, it interferes with possible other signals received by the other station.

layers. First, *interference metrics* are required to define the level of interference itself that two links may exert on each other. In order to decrease the interference, a channel has to be selected which minimizes the interference with other links according to this metric. For the evaluation of the algorithm *performance metrics* are needed so that the results can be compared to other algorithms or single channel networks. These metrics can take the used interference model into account and express the decrease of interference achieved by the algorithm. They can also indirectly estimate this decrease by measuring the network performance which is usually measured with throughput and end-to-end delay. Finally, in order to exploit the channel diversity, *interference-aware routing metrics* are required.

2.2 Interference Metrics and Models

The goal of every channel assignment algorithm is to reduce the network-wide interference in order to increase the network performance. Therefore, the interference has to be measured or approximated, which is a complicated task in unshielded wireless networks. It is also likely that the interference in a real network changes over time because of dynamic environmental factors, such as moving objects and people. For these reasons, several interference models have been developed.

Simple models define for each node (or more precisely radio when nodes are equipped with multiple radios) a transmission radius r_t and an interference radius r_i, with $r_t < r_i$ as depicted in Figure 2.1. A transmission is correctly received at node u when only one node of all the nodes in which interference radius u resides, transmits at the time. Models based on this assumption usually approximate the m-hop neighborhood of a node u as the interference set which consists of all nodes whose transmissions may interfere at u. This model has been first described in [3] as *protocol model* and similar heuristics are still widely used due to their simplicity.

The same authors proposed the *physical model*, which takes the Signal-to-Interference

Ratio (SIR) and the background noise into account (the combination is coined as Signal-to-Interference plus Noise Ratio (SINR)), which is simplified as

$$\mathsf{SINR} = \frac{P_T}{N + \sum_{i \in I} P_i}$$

where P_T is the signal power of the transmission, N is the background noise and P_i is the signal strength of an interfering co-channel transmission.

The model assumes that the radio transmission power decays with distance r as $\frac{1}{r^\alpha}$ with $\alpha \geqslant 2$ and a background noise N. A transmission is correctly received if the SINR value at the receiver is above a particular level. This model is more complicated than the protocol model and is in its original form tailored to shielded, obstacle-free environments.

Due to the complexity of modeling radio signal propagation measurement-based approaches to study interference have been developed. In [24], simple heuristics based on the protocol model in a testbed environment are evaluated with the conclusion that they do not accurately estimate the interference. A new interference model is proposed based on throughput measurements in a static testbed. The Link Interference Ratio (LIR) is defined as the aggregate of the throughput on two links when transmitting simultaneously divided by the aggregate throughput when transmitting individually. For two links $l_{u,v}$ and $l_{x,y}$ the LIR is defined as

$$\mathsf{LIR}_{l_{u,v},l_{x,y}} = \frac{T_{l_{u,v}}^{l_{u,v},l_{x,y}} + T_{l_{x,y}}^{l_{u,v},l_{x,y}}}{T_{l_{u,v}} + T_{l_{x,y}}}$$

where $T_{l_{u,v}}$ is the unicast throughput for link $l_{u,v}$ when only this link is active and $T_{l_{u,v}}^{l_{u,v},l_{x,y}}$ is the unicast throughput for the link when the link $l_{x,y}$ is active simultaneously. Therefore, a LIR value of 1 indicates that two links do not interfere and a LIR of 0.5 indicates a maximum interference, resulting in that the two transmissions share the medium. This approach estimates the interference more accurately than simple heuristics but with an increasing network size, the measurements for every link pair are very time-intensive. The measurements are also only valid for static network topologies and have to be measured individually for every topology. For this reason, the authors approximate LIR with a Broadcast Interference Ratio (BIR) which relies on simultaneous broadcast transmissions on two network nodes. Therefore the complexity of the measurements is $\mathcal{O}(N^2)$ with N network nodes (instead of $\mathcal{O}(N^4)$, if all network link pairs are measured individually).

Measurement-based interference estimations have also been studied in [25]. Interference models are created based on Received Signal Strength Indicator (RSSI) values and pair-wise packet delivery counts for broadcast frames measured experimentally in a testbed. The measurements can function as seeds to the models in order to predict the interference in larger networks in which measuring the interference pair-wise is not feasible anymore.

As described, current research shows that simple heuristics for estimating interference are not accurate enough to be transferred to real network scenarios. Still, due to their simple nature they are the models most used in current research on channel assignment [26, 23, 11, 27, 28, 29, 30, 21, 31]. Measurement-based methods exist and promise a higher accuracy but are more complicated and time-consuming.

2.3 Performance Metrics

For the evaluation of channel assignment algorithms different performance metrics have been developed. These metrics can be classified into metrics that measure the *decrease of interference* and those that measure the *increase of network performance*. The former metrics are used to measure the decrease of interference achieved by the particular algorithm according to the used interference model. Usually, the overall network interference is measured after the application of the channel assignment algorithm and compared to a single channel network and random channel assignment. While it is a good approach to take the cause of the problem into account, it has to be kept in mind that the interference model is just a model and is limited in representing the possibly dynamic interference effects in real networks. Also, these metrics limit the comparison of algorithms to the ones that have a similar problem formulation. Therefore, these metrics can be used as a first step but an evaluation in an experimental environment is necessary to validate the interference model itself.

The latter metrics address this problem by analyzing the performance of the algorithms indirectly by measuring the network performance. The network performance is usually expressed using the throughput and end-to-end delay, which are measured with benchmark experiments. Throughput can be measured with `iperf` by sending sequential and simultaneous traffic flows through the network to quantify the aggregate network throughput. The `ping` tool can be used to measure the end-to-end delay. In the following, metrics of the described classes are introduced.

2.3.1 Fractional Network Interference

The Fractional Network Interference (FNI) metric measures the decrease of interference It has been defined in [23] and used for further approaches [31]. It is defined as the ratio of the number of edges in the conflict graph after channel assignment to the number of edges in a single channel network. In a single channel network, all network interfaces are tuned to the same channel. It is useful to compare the efficiency of the algorithm to a random channel assignment and the single channel case. As stated before, the FNI can only be used, if the channel assignment problem was formulated such that the number of edges in a conflict graph shall be minimized. With such a problem formulation the approximation of lower bounds using for example linear programming methods is possible to which the algorithm can be compared to. The main drawback of this metric is, that its significance depends on the underlying interference model, which may not be very accurate as described above.

2.3.2 Saturation Throughput

The *saturation throughput* is described as the maximum load that the system can carry in stable conditions [32]. It can be determined by increasing the traffic load on the system until the limit is reached. This metric can directly show an increase of the network performance and can be used as a benchmark test after the channel assignment procedure.

2.3.3 End-to-End Delay

The end-to-end delay defines the delay that a traffic flow in the network might experience. The goal of channel assignment is to minimize the total delay over all network-wide traffic flows. This metric is especially important in dynamic channel assignment algorithms because the channel switching time is much higher with current IEEE 802.11 hardware than the packet transmission time. This observation is reflected in several routing metrics for channel assignment, such as the routing metrics based on Expected Transmission Time (ETT), which consider the expected channel switching time for a given path.

2.4 Routing Metrics

Alongside the channel assignment algorithms, new routing metrics have been developed in order to better exploit the physical network characteristics. Since the channel assignment decisions may alter the network topology, the routing instance needs to adapt to these changes. Also, to fully exploit the benefits of a channel diverse path, this diversity has to be taken into account at the routing instance. Routing metrics considering channel assignment try to take advantage of the channel assignment decisions and promise a higher network performance in regard to throughput and delay. Routing metrics usually define a link metric, which estimates the quality of a particular link, and a path metric, which takes all links on a particular path into account.

2.4.1 Hop-Count

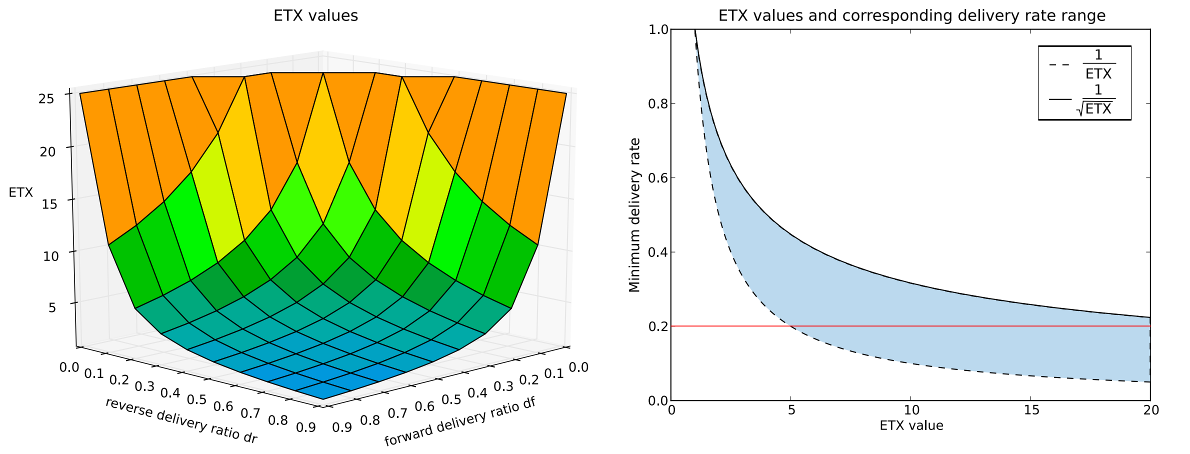
The hop-count metric specifies the minimum number of links, which have to be traversed in order to reach a destination. The link metric is 1 for each existing link regardless of its quality and the path metric is the number of hops of the shortest path to the destination. For wireless networks this metric has several drawbacks concerning the link quality. The minimum hop-count yields a minimum path length and therefore attempts to maximize the distance of each link on the path. But links with a relative high distance usually have a low signal strength and a high packet loss ratio. Therefore this metric is suitable for wireless networks only to a certain degree, but it is still incorporated into many routing metrics for wireless networks in order to avoid loops.

2.4.2 ETX

The Expected Transmission Count (ETX) link metric estimates how many transmissions for a packet are required so that it is successfully received [33]. The ETX value of a given path is defined as the sum of all ETX values of all links of this particular path. ETX values are calculated by each node sending broadcast probes and logging how many probes from their neighbors were successfully received. The forward and reverse delivery ratio are then used for the calculation of ETX, because for unicast communication an ACK frame has to be successfully received at the sender. The ETX value for a link is then calculated with

$$\mathsf{ETX} = \frac{1}{\mathtt{d_f} \cdot \mathtt{d_r}}$$

where $\mathtt{d_f}$ is the forward delivery ratio and $\mathtt{d_r}$ the reverse delivery ratio.



(a) ETX values for reverse and forward delivery rates

(b) Range of minimum delivery rates for particular ETX values

Figure 2.2: In (a) the ETX values for $d_f, d_r \in [0, 1]$ are shown, with $d_f \to 0$ or $d_r \to 0$ results in $\mathsf{ETX} \to \infty$. In (b) the consequences of ETX being a bi-directional metric for a particular link are shown. For a particular ETX value, the possible range for the minimum delivery rate can be quite big. Considering that a link with a delivery ratio of 20% is likely to be not usable for data transmission, we can derive that such a link quality may already occur at an ETX value of 5. Therefore, all ETX values above 5 have to be treated carefully.

It has to be kept in mind that ETX estimates the bidirectional link quality, so the same ETX value is used for transmissions in both directions of a link. This means that ETX does not consider link asymmetry. The corresponding ETX values for $d_f, d_r \in [0, 1]$ are depicted in Figure 2.2.

To show the bidirectional characteristic of ETX, we take a closer look at the example with $\mathsf{ETX} = 4$. Possible solutions for (d_f, d_r) are $(0.5, 0.5)$, $(0.3, 0.83)$, and $(0.25, 1)$. The first solution describes the situation in which the link quality of the forward and reverse direction of the link are the same. For a symmetric link d_f and d_r are equal with $d_f, d_r = \frac{1}{\sqrt{\mathsf{ETX}}}$. When the link is most asymmetric, we have a perfect link into one direction, for example with a forward delivery ratio of $d_f = 1$, and a reverse delivery ratio of $d_r = \frac{1}{\mathsf{ETX}}$. This means that we can conclude from an ETX value that

$$\min(d_f, d_r) \in [\tfrac{1}{\mathsf{ETX}}, \tfrac{1}{\sqrt{\mathsf{ETX}}}]$$

In wireless networks, the link asymmetry can have a big effect on the bidirectional link performance. In our example of $\mathsf{ETX} = 4$ with $(d_f, d_r) = (0.25, 1)$ the link may work very well in the reverse direction, when only short ACK frames are sent in the forward direction. However, the link may be useless for transferring large data frames in the forward direction because of the low link quality. In Figure 2.2 (b), the range for the minimum delivery rate for particular ETX values is shown.

An interesting aspect is the accuracy of the estimation in regard to the packet size. In the original specification of ETX, probe packets have a fixed size of 134 Bytes. In wireless networks, smaller packets are not as affected by lossy links as are larger packets. Therefore, the number of retransmissions for large packets is usually underestimated while it is over-estimated for smaller packets such as ACK packets. Besides varying packet sizes, ETX also does not consider the available bandwidth for a link.

2.4.3 ETT

The Expected Transmission Time (ETT) link metric is an extension of ETX [34]. It stands for the expected time to send a frame over a wireless link taking the available bandwidth into account. The ETT value of a given path is defined as the sum of all ETT values for all links of this particular path. The motivation to create ETT is to address shortcomings of ETX, such as that ETX considers only the loss rate of a link and neither takes the packet size nor the available bandwidth for a link into account. The ETT values are calculated as follows:

$$\mathsf{ETT} = \mathsf{ETX} \cdot \tfrac{S}{B}[s]$$

with S being the frame size and B the bandwidth for the particular link. In order to estimate the bandwidth over a specific link, packet pair probing can be used link-wise.

2.4.4 WCETT

The Weighted Cumulative Expected Transmission Time (WCETT) path metric is based on ETT and additionally considers the channel diversity on a given path [34]. The WCETT value for a path $r_{uy} = \{l_{u,v}, l_{v,w}, .., l_{x,y}\}$ with $|r_{uy}| = n$ is calculated with

$$WCETT_r = (1-\beta) \cdot \sum_{i=1}^{n} ETT_i + \beta \cdot \max_{1 \leqslant j \leqslant k} X_j$$

$$\text{with } X_j = \sum_{Hop\ i\ on\ chan\ j} ETT_i,\ 1 \leqslant j \leqslant k$$

where k is the number of available channels and β is a tunable parameter with $0 \leqslant \beta \leqslant 1$.

The first term constitutes the sum of all ETT values along the links on the path r_{uy}. The second term defines the bottleneck channel on a given path, which is defined as the maximum of the sum of the ETT values for a channel. The first part of the function ensures that a higher hop-count on a path increases the WCETT value and the second part favors channel diverse paths. The tunable parameter β allows to find a trade-off between the two components.

The WCETT values are the sum of all ETTs on a path plus the ETT of the bottleneck channel on a path (the channel with the largest aggregated ETT). With this consideration WCETT favors channel diverse paths over single channel paths. This way, intra-flow interference can be decreased, which leads to a higher throughput in multi-radio networks, if the radios operate on non-interfering channels.

2.4.5 MCR

The Multi-Channel Routing (MCR) metric is a modification of WCETT [29]. MCR additionally considers the channel switching time for each hop, which is an important factor for dynamic or fast channel switching algorithms. The switching time is estimated by periodically measuring which part of a second an interface stays on a particular channel. The less time it spends transmitting on channels other than a particular channel c, the lower is the switching cost for c.

2.4.6 EETT

The Exclusive Expected Transmission Time (EETT) metric is based on ETT and considers the inter- and intra-flow interference [35]. For each link $l_{i,j}$ the interference set $I_{l_{i,j}}$ is specified. It comprises all links that can interfere with $l_{i,j}$ including $l_{i,j}$ itself. The EETT value for $l_{i,j}$ is then the sum of the ETT values of all links in the interference set $I_{l_{i,j}}$. The EETT for a path is defined as the sum of the EETT values of all links on that particular path.

2.4.7 iAware

The Interference-Aware (iAware) metric is also a modification of the WCETT metric [36]. It additionally takes the Signal-to-Noise Ratio (SNR) and SINR values at the endpoints for a particular link as *interference ratio* into account. While the consideration of the signal strength promises more accurate results for the interference approximation, these values have to be measured and updated periodically which introduces a significant overhead.

2.5 Channel Assignment Evaluation

From the aforementioned metrics, some guidelines can be derived for the design and analysis of channel assignment algorithms. Up to today, most algorithms use simple heuristics to model the network interference which fail to accurately estimate the actual interference in real networks [24]. Algorithms usually allow the exchange of the interference model but it has to be kept in mind, that more accurate models require more complicated calculations and rely on results of measurements which can be very time-consuming in large networks. Still, such measurement-based interference approaches promise a more accurate approximation and therefore are a better choice than simple heuristics as interference models. As shown in [25] it is also possible to transfer measurement-based results to other network topologies.

Testbed experiments are required for the performance analysis of a channel assignment algorithm. The allow to measure the network performance under real conditions and validate the underlying interference model. Benchmarks consisting of basic throughput and end-to-end delay experiments are an adequate tool, to measure network performance. Comparing the results to single and random channel assignment would give a first insight into the performance of the channel assignment algorithm. Also, previously unnoticed hardware, operating system, and driver issues in the numerical analysis or simulator can occur in a testbed environment which have a high impact on the performance on the algorithm. One example is the channel switching time which depends on all of the three factors.

The presented routing metrics for channel assignment have been developed to exploit the channel diversity of a multi-channel network. All of these metrics are based on ETT, which addresses shortcomings of ETX. Still, ETX only considers bidirectional links, although asymmetric links are common in real IEEE 802.11 network deployments. It would be interesting to use a simple routing metric similar to ETX that considers unidirectional link quality. If a more reliable and accurate routing metric for unicast transmission can be derived, routing metrics for multi-channel networks based on this metric may produce better results than the presented ones.

CHAPTER 3

Distributed Channel Assignment Algorithms

In contrast to centralized channel assignment algorithms, distributed channel assignment algorithms lack a central control instance and perform channel assignment on each node considering only local information. Distributed channel assignment algorithms can be classified taking the underlying network architecture and the resulting traffic pattern into consideration. In WMNs, gateway nodes may exist that have a wired connection to a different network such as the Internet. Depending on the application scenario, the traffic pattern in this kind of networks may be restricted to flows from mesh nodes to gateways and vice versa and does not consider direct communication between two non-gateway mesh routers. In contrast, in peer-to-peer scenarios all mesh routers may communicate with each other. This approach is more applicable when the network offers different services which are located on different mesh routers. Peer-to-peer approaches are not restricted to particular traffic patterns, which makes them suitable for a wider range of application scenarios.

The algorithms described in this section make some common assumptions, for example that a number of non-overlapping channels C are available and that the number of interfaces K on every node is smaller than C ($\mathsf{C} \gg \mathsf{K}$). Usually the algorithms consider the mesh network as a stationary backbone, meaning that the mesh routers are immobile, although some algorithms consider node failures and low mobility, which makes them adaptive to topology changes. Also, all surveyed algorithms consider only bi-directional links because of the ACK-mechanism of IEEE 802.11 unicast transmissions. After a description of the different approaches, we introduce a classification for a conclusive discussion.

3.1 Distributed Algorithms

3.1.1 Ko - 2007

The distributed, greedy channel assignment algorithm was designed for scenarios with low or none mobility [26]. The algorithm considers the physical topology of the network and not the dynamic network conditions for the channel assignment. The used interference model consists of the interference set which is approximated with the 3-hop neighborhood. An interference cost function calculates the spectral distance between two channels and may be tuned with a single parameter resembling the degree of overlap between adjacent channels.

One wireless interface of each node is switched to a common channel in order to preserve the network topology and ensure basic connectivity. For the additional interfaces, a greedy algorithm selects the least interfering channel in the interference set using the interference cost function. As an additional constraint, at least one neighbor must have a radio tuned to the same channel in order to avoid dead interfaces. Channel changes are communicated with a 3-way handshake, in order to avoid channel oscillation. The authors prove the convergence of the algorithm in a static scenario by showing that the overall network interference decreases monotonically with each channel switch.

The algorithm is evaluated on a 14 nodes testbed with two wireless interfaces per node. Results are compared to the single channel case and a random channel assignment. The Multi-Radio Link Quality Source Routing (MR-LQSR) routing algorithm with the WCETT metric [34] is used.

The advantage of the algorithm is its simple greedy nature and the proven convergence. The algorithm can detect and adapt to network topology changes by the usage of a default channel. However, this has the trade-off that one interface per node is dedicated to control traffic on the default channel and can not be used to transfer data. The interference cost function is simple to calculate but only relies on the spectral distance of the available channels. Spatial distance between nodes, obstacles, and external interferences which have an impact on the interference and link quality in real networks are not considered.

3.1.2 DGA - 2008

The Distributed Greedy Algorithm (DGA) assigns channels to links instead of interfaces and is therefore topology presevering, meaning that all links are sustained during the channel assignment procedure [23]. This renders the approach independent of the overlaying routing algorithm. A binary interference model, which specifies an interference range of m hops is used. Suggestions to modify the approach to support fractional interference are given. A conflict graph is used to formulate the problem so that the number of edges in the conflict graph shall be minimized. This optimization problem is proven to be NP-hard and linear and semidefinite programming approaches are presented to obtain lower bounds for the minimum network-wide interference.

In the distributed algorithm a network link between two nodes is owned by the node with the higher node id and only this node may assign a channel to the link. At the network initialization, all links are assigned to the same channel. Each node then iterates over all owned links and changes the channel of the link which results in the largest decrease of interference in the local neighborhood. The largest decrease is achieved with the channel switch that removes the highest numbers of edges in the local conflict graph. The interface constraint has to be respected, which means that no more channels can be assigned to a node than it has interfaces. The channel switch is carried out using a 3-way handshake and update information message for the interference set (m-hop neighborhood). In order to avoid oscillation, each vertex and channel combination can only be changed once. This ensures the convergence of the algorithm but may lead to suboptimal results, especially when changes in the network topology occur.

For the evaluation, the algorithm is compared to a single and random channel assignment and the centralized Connected Low Interference Channel Assignment (CLICA) channel assignment algorithm [37]. Additionally, simulation studies measuring the saturation throughput were performed with ns-2 and networks with up to 750 nodes.

As the main advantage due to the link-based channel assignment, routing algorithms can operate independently on top of the channel assignment. The interference model is exchangeable with other models that allow the creation of the conflict graph. The main weakness of the algorithm is the restriction that each link and channel combination can only be changed once, which is especially inefficient when topology changes occur.

3.1.3 Sridhar - 2009

The link-based channel assignment approach is very similar to DGA with the difference that it additionally takes the expected traffic-load on the nodes into account [11]. Interference is modeled with a fixed interference range for all nodes and a weighted conflict graph is used to estimate the network-wide interference. The weights for the edges in the conflict graph are specified using a load-matrix that takes the expected traffic for each link into account. The channel assignment problem is then defined as minimizing the sum of the weighted edges of the conflict graph. The problem is proven to be NP-hard and the Lagrangian relaxation method is used as an approximation approach to obtain lower bounds for the minimum network-wide interference.

Besides a centralized genetic algorithm, a greedy distributed algorithm is presented, which works as follows. As input, each node knows its interference set that comprises the links that interfere with all links of this node according to the weighted conflict graph, the current channel assignment of all nodes in the interference set, and the radio usage matrix of all neighbors. For every link the owner is specified as the node with the higher cumulative expected traffic, and only this node may assign a channel to this link. The algorithm then works very similar to the previously described approach. A nodes starts with the *SELECT-Channel* phase, in which it picks one of its owned links and assigns the channel which provides the largest decrease of interference. This is defined as the channel switch which has the largest decrease of numbers of edges in the local conflict graph. Additionally, the interface constraint has to be respected, which means that no more channels may be assigned to a node than it has interfaces. The channel switch for this particular link is done in the following *ASSIGN-Channel* phase with a 3-way handshake. All nodes of the interference set are then informed of the new channel assignment. In order to ensure convergence and avoid channel oscillation, each channel may be assigned to a link only once, which may lead to suboptimal results.

Simulation studies of scenarios with different numbers of nodes are performed and the interference is measured after the convergence of the distributed algorithm. It is not mentioned which simulation environment was used and what values were used for the interference range.

Due to the strong similarity the same advantages and weaknesses account for this algorithm as to the previous one. The main difference is the extension with a load-matrix of expected traffic for every link, which enables this approach to perform load-aware channel assignment.

3.1.4 Net-X - 2006

A MAC-layer protocol as a joint solution of channel assignment and routing is proposed in [38, 29]. In the original algorithm, the 2-hop neighborhood is used as interference model.

The set of network interfaces on each node are divided into *fixed* interfaces, which stay on a fixed channel, and *switchable* interfaces, which can be switched dynamically to particular channels. If a node wants to communicate with a neighbor, it tunes one of the switchable interfaces to a channel of a fixed interface of the receiving node. The crucial part of this approach is the way how channels are assigned to the fixed interfaces. The authors present two different algorithms for this task. For a simple solution, a well-known function may be used which calculates the channel for a fixed interface based on the node id. As an alternative, neighborhood information is considered for the channel selection. For this, HELLO-packets with the assignment of fixed radios are exchanged periodically, which allows each node to learn about the channel assignment in the 2-hop neighborhood. Each node selects the least used channel for its fixed radio. While the former approach is only feasible in a static and known network topology, the latter introduces more overhead but can adapt to topology changes.

Additionally, the challenge of broadcasting in a multi-channel network is addressed. The presented solution is to send a broadcast packet once for each channel. The idea of using one packet queue for each link is presented in order to reduce the channel switching frequency by considering the current queue size for each channel. By defining minimum and maximum periods for a switchable interface to stay on one channel, fairness can be introduced with this algorithm. The NET-X framework implements this approach in a testbed environment which is presented in detail in Section 4.2.

An evaluation is performed with simulation studies with Qualnet 3.6 using Dynamic Source Routing (DSR) as routing algorithm with MCR. In the experiments the algorithm is compared to a single channel network. Currently, further research is performed on the algorithms to assign channels to the fixed radios [39].

The advantages of this approach are, that no default channel has to be used to ensure the network connectivity and that fairness is addressed with the queue management. A weakness constitutes the high implementation effort to ensure an efficient dynamic channel assignment. As described in the NET-X framework, changes in the kernel space have been necessary to reduce the channel switching time and implement the different channel-based packet queues.

3.1.5 SAFE - 2006

The Skeleton Assisted Partition Free (SAFE) algorithm uses Minimal Spanning Trees (MSTs) to preserve the network connectivity [28]. As the interference model, two links interfere with each other if their distance is 2-hops or less. A conflict graph is used and the goal of the algorithm is to minimize the number of edges in the conflict graph.

The channel assignment algorithm consists of two components. A random channel assignment is applied if $\mathsf{C} < 2{\cdot}\mathsf{K}$, where K is the number of wireless network cards on every node and C the number of non-overlapping channels. Due to the pigeonhole principle, two nodes will share a common channel altough they are assigned randomly, thus preserving the network connectivity. If the constraint does not hold, two nodes that are in each others transmission radius may choose disjunct channel sets and thus may not be able to communicate. This algorithm is very simple and preserves the network connectivity, but due to the random assignment it does not guarantee a decrease of interference.

The second component of the algorithm introduces the condition that all edges of a MST, the *skeleton*, of the network have to be preserved when $\mathsf{C} \geqslant 2{\cdot}\mathsf{K}$. For this, every node randomly chooses a channel set with $\mathsf{K}-1$ channels, leaving one interface unassigned. The node broadcasts its chosen channel set, and if links to all skeleton neighbors are already established it assigns a random channel to the unassigned interface. Otherwise it tries to establish links with the not connected skeleton neighbors by assigning a channel which is in the channel set of all skeleton neighbors. If there is such a channel, it is assigned to the interface, if not, a global common channel is used for these links. The algorithm may be executed periodically in order to adapt to changes in the network topology due to node failures or mobility.

The evaluation is carried out using simulation studies with network performance metrics for throughput and delay. The approach is compared to the centralized algorithm described in [40]. Fairness is considered by introducing a parameter which expresses the minimum throughput requirement that has to be met on all nodes.

The advantage of this algorithm is that it ensures the connectivity of the network using a MST of the virtual network links. Still, the algorithm is prone to node failures since this loss of a skeleton edge may partition the network. Also the random algorithm does not guarantee a decrease of interference.

3.1.6 Superimposed Code - 2007

The channel assignment approach [30] is based on the properties of superimposed codes [41]. An *channel code* vector is introduced, which is a binary vector with the same numbers of elements as non-overlapping channels are available. By definition a binary codeword Y covers a binary codeword Z if the Boolean sum $\mathsf{Y} \vee \mathsf{Z} = \mathsf{Y}$. A *s-disjunct-code* denotes a binary matrix X, with the property that the Boolean sum of any s codewords does not cover any other codeword in the matrix. By definition an s-disjunct-code is also a superimposed $(\mathsf{s}, 1, \mathsf{N})$-code [41].

For using the s-disjunct-code, the available non-overlapping channels are divided into *primary* and *secondary* channels for each node. Each node has a binary *channel code* vector, in which 1 denotes a primary channel and 0 a secondary. All channel code vectors form an s-disjunct-code, which implies that each node has at least one primary channel, which it does not share with s other nodes.

With this background, the authors design a channel assignment algorithm for broadcasts and unicasts. For the definition of the interference set of a node, the 2-hop neighborhood is used but any other binary model suffices. The idea of the designed algorithms is based on the assumption that every node knows the channel code vectors of the nodes in its interference set.

The steps of the algorithm are sketched as follows. A node should use one of its primary channels if it is secondary to all nodes in its interference set. If no such channel exists, it should use its secondary channel that is not primary to all nodes in the interference set. If this fails, the node chooses its primary channel, which is primary to the least number of nodes in its interference set. The authors prove, that if the number of nodes in the interference set is smaller than s the algorithm can guarantee network-wide interference free channel assignment. Under these circumstances, all nodes can select one of their primary channels which is secondary to all nodes of the interference set.

The evaluation is performed with simulation studies but lacks a comparison to single and random channel assignments as well as to other algorithms.

As advantage, this algorithm can prove network-wide interference free channel assignment in sparse networks. Still, the algorithm faces the problem that the channel code vectors have to be distributed among the nodes before the network initialization. Also, the radio-based assignment does not necessarily preserve network connectivity, which is not very practical for real network deployments.

3.1.7 NNCQ - 2007

The Neighborhood Nodes Collaboration to support QoS (NNCQ) algorithm for channel assignment is presented in [27]. As interference model and channel switching metric the packet loss ratio of a particular link is used, which is calculated periodically by monitoring sent and received packets. This approach is the only one which uses a dynamic metric for interference estimation. All nodes have a connectivity matrix that marks all the available links in the network. This matrix is available at the network initialization and is never updated.

The algorithm consists of two phases:

1. *Monitoring phase*: The nodes monitor the packet loss ratio for all their links.

2. *Channel switching phase*: If the packet loss rate for a link reaches a certain threshold, the channel switching phase is executed. In this phase, the sending node searches a different node-disjoint path using the connectivity matrix. If a new path is found, the sender initiates a channel switch with the next hop on the path. The least used channel for the link is chosen.

After the successful channel switch, multiple routes for the same destination are available. Therefore, a route selection process has to be executed. A source routing is used on top of NNCQ and either the best route is chosen for all transmission or the routes are used round-robin like. The latter method results in frequent channel switches and relatively long delays because of the channel switching time.

The algorithm is evaluated with simulation studies using ns-2. The perfomance in form of packet loss and throughput are compared to a single channel network.

The advantage of this approach is the consideration of the link quality which also incorporates external interference and allows nodes to quickly react to link quality changes. As a weakness, each node relies on a global connectivity matrix that is never updated and thus renders the approach unable to cope with network topology changes.

3.1.8 Cluster Channel Assignment - 2008

The Cluster Channel Assignment (CCA) approach divides the network nodes into clusters before the channel assignment procedure [31]. The Highest Connectivity Cluster (HCC) algorithm is used for clustering [42]. The HCC algorithm denotes a cluster head for each cluster, which is the node with the highest number of neighbors. For the interference model, it is assumed that links interfere which use the same channel in the 2-hop cluster neighborhood. A conflict graph is used to formulate the problem so that the number of edges in the conflict graph shall be minimized. Lower bounds for minimum network interference are obtained with a linear programming approach.

The CCA algorithm is divided into the following three steps.

1. *Channel division and selection for neighbor clusters*: One cluster is elected as Head of Clusterhead (CHH) and distributes the available channels into disjoint sub-sets and then assigns such a set to each neighboring cluster.

2. *Channel re-assignment*: In order to minimize interference, the same disjoint set of channels may only be reused in a cluster distance of 2. Therefore, channels have to be re-assigned if this constraint is violated.

3. *Assigning channels within the cluster*: A common channel is used by all nodes in the cluster in order to ensure reliable control communication. The remaining channels are assigned similar to the NNCQ approach in Section 3.1.7.

For the evaluation the approach is compared to the mathematically obtained lower bounds and the centralized CLICA channel assignment algorithm [37]. As performance metric the FNI and the saturation throughput are used in simulation studies with ns-2.

The algorithm introduces a hierarchical channel assignment procedure by partitioning the network into clusters. Still, the overhead for clustering is large and the algorithm can not adapt to topology changes.

3.2 Summary

3.2.1 Classification Keys

We use the following classification keys to characterize the presented channel assignment algorithms.

- Channel Switching Frequency (CSF): Defines the frequency of channel switching. In *dynamic* or *fast channel switching* approaches, channel switches may occur frequently, up to for every packet. In *static* or *slow channel switching* approaches interfaces are switched to a particular channel for a longer period. *Hybrid* approaches combine both methods.
- Link Connectivity Preserved (LCP): Defines if all virtual links of the network are preserved after channel assignment.
- Conflict Graph Minimization (CGM): Defines if the problem is formulated such that the number of edges in the conflict graph shall be minimized.
- Interference Model (IM): Defines on which interference model the algorithm is based.
- Failure / Mobility (FM): Defines the degree of adaptivity of the algorithm. Node failures and node mobility lead to network topology changes, which result in nodes joining and leaving the neighborhood of other nodes.
- Fairness (FA): Defines if the approach considers fairness in regard to network resources.
- Testbed Evaluation (TE): Defines if the approach was implemented and evaluated in a testbed environment.
- Traffic Load (TL): Defines if the traffic load is considered in the algorithm.
- Channel Oscillation (CO): Defines if the channel oscillation problem is addressed by the algorithm
- Routing Metric (RM): Defines if a routing metric is used that considers channel diversity in order to exploit channel diverse paths.
- External Interference Considered (EIC): Defines if external interference is considered by the algorithm. This may be adressed directly by controlling sources of external interference or indirectly by measuring the quality of a particular link.
- TX Power Control (TPC): Defines if the transmission power is considered and modified in order to decrease the exerted interference.

3.2.2 Discussion

The following discussion compares the different channel assignment algorithms considering the introduced classification keys. The characteristics of each algorithm are summarized in Table 3.1.

Of the surveyed approaches, all but two [27, 29] use slow channel switching for channel assignment. One reason for this is the relative long channel switching time, which is in the order of milliseconds for current IEEE 802.11 hardware. Also the implementation of dynamic channel assignment is more complex. For instance, the approach in [29] requires changes to the linux kernel and the drivers of the wireless interface in order to reduce the channel switching time [38]. New hardware is likely to reduce the channel switching time, thus making dynamic schemes more attractive for future approaches.

All surveyed approaches preserve the network connectivity in order to avoid network partitions caused by channel assignment. All approaches but [28, 30] also preserve the link-based connectivity. This means that all virtual network links are preserved, with the advantage that the overlaying routing is independent of the channel assignment. Still, new routing metrics have been designed alongside the channel assignment algorithm to exploit the channel diversity [26, 29]. The approach in [26] tunes an network interface on each node to a global common channel to preserve the connectivity. This interface is dedicated to network control traffic and is not used for data traffic.

All surveyed approaches use simple interference models based on the protocol model and define the interference set as the m-hop neighborhood, with $2 \leqslant m \leqslant 3$. Although these models intuitively reflect the interference of wireless networks to a certain degree and are simple to calculate, they are not validated with results from real networks. More sophisticated models exist, which rely on more input parameters and promise interference estimations with a higher accuracy as described in Section 2.2. Most approaches are evaluated on how well they decrease the interference according to the used model, but due to the lack of implementations for real networks, there is no validation of the models. Therefore, it would be interesting to exchange the simple interference model with more complex models and compare the obtained results.

More than half of the approaches formulate the channel assignment problem as minimizing the number of the edges in the Conflict Graph (CG) [23, 11, 28, 27, 31]. Only two of these algorithms are evaluated with the Fractional Network Interference (FNI) metric [23, 31] as described in Section 2.3.1. The fractional network interference is a useful metric to measure the decrease in interference according to the used interference model. Nevertheless, measurements in a real network or testbed environment are necessary in order to validate the interference model.

Adaptivity to topology changes caused by node failures and mobility is not of a high concern of the presented approaches. Two approaches are not adaptive because they prevent the re-assignment of a channel-interface combination in order to ensure the convergence of the algorithm [23, 11]. Adaptivity is also addressed by running the algorithm periodically as suggested in [28]. One reason why it is not considered an important feature is the assumed network architecture which is a stationary mesh backbone. Still, adaptivity may increase the network performance in case of mobile nodes and node failures.

Three of the presented algorithms consider fairness among the nodes for the channel assignment decisions [28, 29, 30]. The fair distribution of network resources is of higher concern in gateway-oriented network architectures [21, 43, 22], in which traffic patterns are more predictable and are usually limited to flows from mesh router to gateway and vice versa. In the presented approaches the expected traffic load is only considered in [27, 30]. This can be credited to that most approaches are targeted at peer-to-peer scenarios.

Most approaches prevent channel oscillation by using a three-way handshake to announce channel changes [26, 23, 11, 27].

None of the approaches explicitly takes external interferences into account for the channel assignment calculations. Of the presented approaches, only one considers external interference implicitly by periodically measuring the packet loss ratio of all links [27]. This is surprising, since due to the wide-spread and still increasing number of commercial and non-commercial IEEE 802.11 based network deployments, they are often co-located to each other. Especially if a network makes use of more than one channel, these co-located deployments are likely to interfere with each other. There is one centralized channel assignment approach which measures the external interference by monitoring IEEE 802.11 frames of external nodes [21].

Also, the surveyed approaches do not consider the possibility to reduce the interference by adjusting the transmission power on the nodes. This mechanism is briefly mentioned in [29]. For instance, it might be feasible to reduce the transmission power of a wireless interface after channel assignment until a specific threshold for the packet loss ratio on the links to all neighbors is reached. If the transmission power could be decreased this way, the interference range would be decreased. However, all the applied interference models for the algorithms are not able to estimate the change in interference this mechanism may have.

3.2.3 Outlook - DES-Channel Assignment

Based on the discussion of the algorithms and classification keys we try to predict the trends for future research in channel assignment.

Since most WLAN deployments are co-located with other wireless networks, the consideration of external interference becomes more important. Therefore, it is desirable to take measurements or estimations of the external interferences into account for the channel assignment. Regardless of the underlying interference model, it should be exchangeable to allow comparisons of different models. It is also desirable to support a measurement-based interference model during the evaluation phase. Closely related to this is the TX power control mechanism which has not been used so far in channel assignment algorithms. It would be interesting to define simple regulation mechanism in order to investigate their impact of the network-wide interference.

A channel assignment algorithm should also be adaptive, so that it can react to node failures and node mobility and optimize the channel assignment accordingly. A simple protocol for channel switches is needed, to avoid channel oscillation. The algorithm should allow to support fairness mechanisms and traffic load estimations if available.

The testing and evaluation of channel assignment algorithms should embrace a testbed environment in order to validate the feasibility of the approach. To decrease the effort to integrate the channel assignment algorithm into existing network deployments, it is desirable that the channel assignment is transparant to the routing protocol. To meet this requirement, the channel assignment has to be either link-preserving or channel switches have to be carried out in a static manner, so that the routing protocol can adapt to the changes in topology. Routing metrics should be developed and used for the evaluation, which consider channel diversity in order to exploit the decrease of interference due to the channel assignment.

We aspire to derive an algorithm that is able to meet many of these features. The approach is coind as DES-CA and the features are summarized in Table 3.1.

Algorithm	CSF	LCP	IM	CGM	FM	FA	TE	TL	CO	RM	EIC	TPC
Ko	static	Preserverd	3-hop NH	–	–	–	•	–	•	WCETT	–	–
DGA	static	Preserved	m-hop NH	•	–	–	–	–	•	–	–	–
Sridhar	static	Preserved	Fixed range	•	–	–	–	•	•	–	–	–
Net-X	hybrid	Preserved	2-hop NH	–	–	•	•	–	•	MCR	–	Mentioned
SAFE	static	No	2-hop NH	•	•	•	–	–	–	–	–	–
Superimposed Code	static	No	2-hop NH	–	–	•	–	–	–	–	–	–
NNCQ	hybrid	Preserved	Packet loss	•	–	–	–	•	–	–	Indirect	–
CCA	static	Preserved	2-hop Cluster	•	–	–	–	–	•	–	–	–
DES-CA	static	Preserved	Measurement	?	•	•	•	•	•	•	•	•

Table 3.1: Overview of distributed channel assignment approaches with the corresponding classification keys: CFS: Channel Switching Frequency, LCP: Link Connectivity Preserved, CGM: Conflict Graph Minimization, IM: Interference Model, FM: Failure / Mobility, FA: Fairness, TE: Testbed Evaluation, TL: Traffic Load, CO: Channel Oscillation, RM: Routing Metric, EIC: External Interference Considered, TPC: TX Power Control

CHAPTER 4

Frameworks for Channel Assignment

4.1 Motivation

Many challenges arise in the implementation process of channel assignment algorithms in a testbed environment. Among them, common operating systems are not designed to support channel assignment algorithms out of the box. Thus, the programmer has to deal with operating system specifics, drivers for the wireless interfaces and the capabilities and limitations of the particular hardware. If more than one particular algorithm should be implemented, the same problems and sevices have to be addressed multiple times.

A development framework for channel assignment algorithms can simplify the implementation effort in many ways. First, the framework can introduce an abstraction layer by providing a set of common functions, for instance for the configuration of the wireless interfaces. Additionally, a framework shall provide a basic set of interference models and common data structures such as conflict graphs. This way, the researcher can rely on already implemented components. By providing functions which abstract from low-level and operating system specific tasks, the researcher can focus on the logic of the algorithm instead.

In contrast to the implementation of one specific channel assignment algorithm, a framework should be as universal as possible in order to allow the implementation of a wide range of different algorithms. This ensures a better comparability of the different algorithms. In the remainder of the chapter two frameworks for channel assignment algorithms are described and discussed.

4.2 NET-X

The NET-X framework [38] was initially created to implement the channel assignment algorithm described in [29] for a wireless testbed environment based on the 2.4 Linux kernel. The algorithm divides the available wireless network interfaces on each node into *switchable* interfaces, which can be dynamically switched to different channels, and *fixed* interfaces, which stay on a single channel. The algorithm requires that if node v wants to send data to a neighboring node u, node v has to switch one of its switchable interfaces to the channel of the fixed interface at node u. Due to the possible communication with many neighbors in a short time window, the channel switching time and packet scheduling are critical factors for the performance of the algorithm. A detailed description of the algorithm is available in Section 3.1.4.

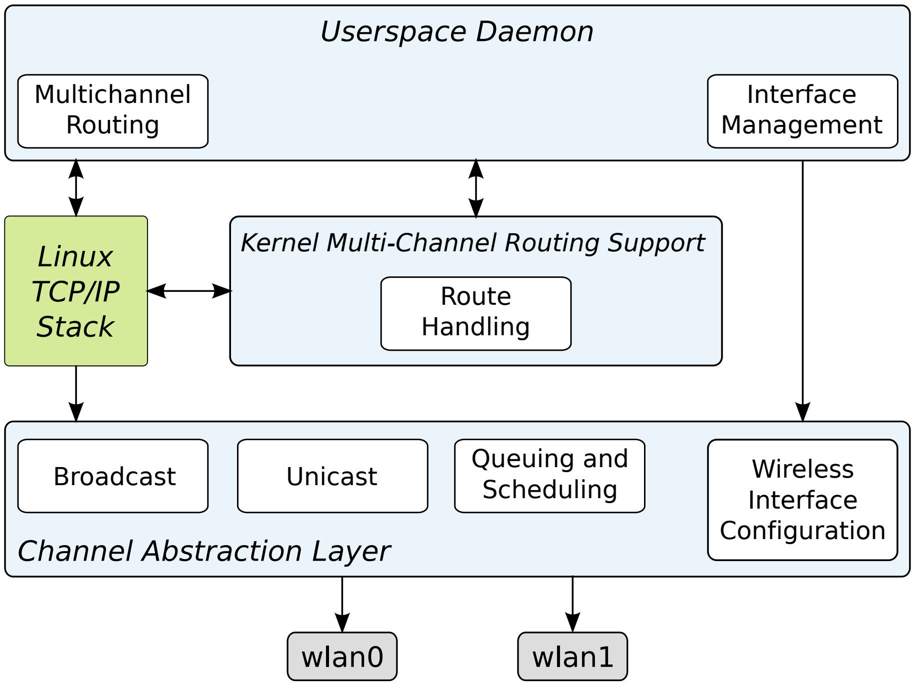


Figure 4.1: Architecture of NET-X. The Userspace Daemon comprises a multi-channel routing protocol and functions to manage the wireless network interfaces. The Kernel Multi-Channel Routing (KMCR) provides the necessary functionality to support reactive routing protocols, such as packet buffering during the route discovery procedure. The Channel Abstraction Layer (CAL) comprises broadcast and unicasts components, queuing and scheduling mechanisms for the channel queues, and implements the configuration of the wireless network interfaces through the Userspace Daemon.

The implementation of this particular algorithm requires several changes to the Linux network stack and to the driver of the wireless network interfaces. Linux routing tables only allow to specify the interface with which a particular neighbor can be reached but not the channel. This leads to the problem that the channel can not be specified in case the same interface is intended to communicate with different neighbors on different channels. Also, the broadcast mechanism has to be modified in order to ensure that all neighbors are able to receive broadcast frames. In single channel networks, it is sufficient to send a broadcast message once using the current network-wide channel. If many channels are available, broadcast frames can be transmitted on all network-wide utilized channels to ensure that all neighbors receive the frames. In order to avoid channel switching for every subsequent packet, distinct queues for each channel have to be provided. With this, a mechanism is needed which decides when and how channel switches are carried out. Also, memory management is required to append packets to the particular queue for channels, which are currently not utilized.

4.2.1 Architecture

The NET-X framework addresses these issues and also provides functions to control the *interface capabilities*. The interface capabilities are defined as all available resources and their parameters, that affect the network performance. This includes for example the utilized channel and transmission power. The NET-X framework comprises three components, the architecture of the framework is depicted in Figure 4.1.

Channel Abstraction Layer

The Channel Abstraction Layer (CAL) allows the configuration of the wireless interfaces and is implemented as a module between the network layer and the device drivers. With interface bonding, the wireless interfaces are presented as one virtual interface to the network layer. The CAL consists of the following three components.

- The *unicast component* allows to specify the wireless network interface and the channel to use for a particular neighbor for unicast communication. For this, a table is used in which the interface-channel information is stored for each neighbor.
- The *broadcast component* supports broadcasting on all channels that are currently used to reach neighbors.
- The *scheduling and queuing component* provides mechanisms for the queue management of the different channels and takes care of buffering packets when necessary. Because channel switches require a long period of time compared to the packet transmission time, channel switches on a per-packet basis are avoided by introducing a minimal duration T_{min} for which an interface stays on the same channel. In order to ensure a basic fairness, an interface may be switched to the same channel only for the duration T_{max} if all other queues are not empty.

Further on, the authors modified the device driver for the wireless interfaces in order to reduce the channel switching time. The channel switching time with commodity IEEE 802.11 hardware is in the order of milli-seconds [22, 38]. In addition to the hardware channel switching time, the actual time period until the interface can send on the new channel may be much longer. This is due to the protocol specification of the IEEE 802.11 ad hoc mode. According to the protocol, a wireless interface waits after initialization for Independent Basic Service Set (IBSS) (or cell id) advertisements by other stations in ad-hoc mode with the same Extended Service Set Identifier (ESSID). If no beacons are received for a specific duration, the node advertises a new IBSS via this particular interface. This procedure can take up to 100 milli-seconds in total [38]. In order to reduce the channel switching time, this mechanism was replaced in the driver with a hardcoded IBSS, allowing to save the waiting time period for IBSS advertisements.

Kernel Multi-Channel Routing

The Kernel Multi-Channel Routing (KMCR) addresses the special requirements of reactive routing protocols. For instance, if no route is available for a particular destination, packets have to be buffered during a route discovery procedure. The KMCR is implemented as a kernel module in order to avoid the reinjection of packets into the kernel and reduce context switches between the kernel and user space.

Userspace Daemon

The Userspace Daemon provides the interface for the routing protocol and the configuration of the Wireless Network Interface Card (WNIC) to the researcher. The number of wireless interfaces and the available channels for each interface can be specified in a configuration file, which is used by the Userspace Daemon to configures the CAL accordingly. The Userspace Daemon constitutes the interface between the CAL and KMCR components for tasks such as route discovery and route maintenance.

4.2.2 Current Research

Experiments with the NET-X framework are performed to evaluate different algorithms for choosing the channel of the fixed interfaces in the described channel assignment approach [39]. In order to allow research on QoS-provisioning, extensions to the framework have been developed for queue management [44], since in the original version a round-robin scheduler is used for all interfaces. The framework is available in a version of 2007 for the Linux kernel 2.4.26 at [45].

4.3 DES-Chan

The DES-Chan framework has been developed to facilitate the implementation of channel assignment algorithms for the DES-Testbed [46, 47, 48]. The DES-Testbed comprises a stationary wireless mesh backbone with currently more than 100 indoor and outdoor DES-Nodes. Every mesh router is equipped with three IEEE 802.11a/b/g wireless network interfaces. The motivation of DES-Chan is to gain practical experience with different distributed channel assignment algorithms in the DES-Testbed. Therefore, we defined common requirements of existing channel assignment algorithms as derived from the related work study in Chapter 3. With this information we defined the particular services that the DES-Chan framework should provide.

4.3.1 Requirements

First, a channel assignment framework must provide functions to configure the wireless network interfaces, primarily to set the channels according to the channel assignment decisions. Since all distributed algorithms take the local network topology into account, a neighborhood discovery service is needed. The neighborhood discovery service should allow to update the neighborhood information periodically by monitoring the state and quality of each node's links to its neighbors. Thereby, the algorithm can take notice of network state changes and handle them adaptively.

Also, because many algorithms rely on a graph-based network model, appropriate data structures for graph representations are required. Besides data structures for the network and conflict graphs, common operations on these data structures should be provided. Interference metrics and models are required in a way that it is possible to define new metrics or extend existing ones, since most algorithms usually allow to exchange their underlying interference model. For the propagation of changes in channel assignment, a communication component is needed that allows the network nodes to communicate with each other. This is also helpful to prevent channel oscillation and may be used to ensure the convergence of the algorithm.

4.3.2 Architecture

The DES-Chan framework comprises the following two components, the architecture is also depicted in Figure 4.2.

DES-Chan Core

DES-Chan-Core is a Python library that provides common functions and data structures for channel assignment algorithms. The library uses the `Python WiFi` project [49] for

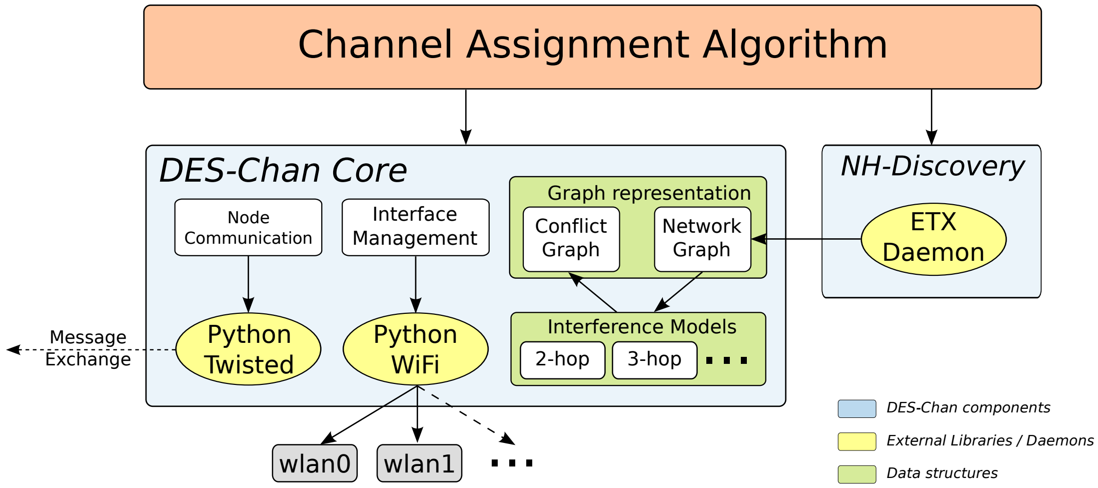


Figure 4.2: The DES-Chan framework for channel assignment comprises the DES-Chan core and the Neighborhood Discovery service. The DES-Chan Core comprises the wrapper functions to configure the wireless network interfaces and the message exchange with neighboring nodes. The component also comprises common data structures for channel assignment and multiple interference metrics and models. The Neighborhood Discovery service allows to periodically retrieve the local network information and measures the quality of all discovered links using the ETX metric.

the configuration of the WNICs by providing wrapper functions for the Linux Wireless Extensions. The library also provides functions to retrieve the status of the wireless interface, set them up and down, and get information of unconfigured wireless network interfaces.

Data structures for graph representation have been defined which provide functions for commonly used operations such as shortest path algorithms. As many of the presented channel assignment algorithms use conflict graphs as described in Section 1.2.6, a corresponding data structure is provided.

The `Python Twisted` library has been used into DES-Chan [50] in order to provide a way for node-to-node communication. The library provides an asynchronous networking engine and hides technical details like creating sockets and establishing connections from the developer. With this library, the researcher can quickly develop the required protocol implementation for exchanging messages among the network nodes and propagate changes in channel assignment.

Simple interference models have been implemented for DES-Chan, such as the 2-hop interference model with a binary interference metric. Also, the fractional interference model in respect to the spectral difference of two channels is provided. The architecture allows to add additional interference models or extend the existing ones. Thus, it enables to exchange interference models and metrics, which allows meaningful experimental comparisons in a testbed environment.

Neighborhood-Discovery

The *Neighborhood-Discovery* module provides a basic service for each node to get information about all nodes in their m-hop neighborhood, where m can be chosen by the particular algorithm. For all links in this neighborhood, periodic link quality measurements are carried out relying on the ETX metric. With the periodic updates of their neighborhood information, the network nodes are capable of reacting to topology changes due to node failures or mobility.

4.3.3 Current Research

The research focus of DES-Chan is to implement a wide range of different distributed channel assignment algorithms to enable their comparison. As reference implementations, a random link-based channel assignment algorithm and the DGA algorithm [23] as presented in Section 3.1.2 have been implemented. We will implement further algorithms and evaluate their performance in a testbed environment. We aspire to develop a novel channel assignment approach which considers the gained practical experience and the requirements of distributed channel assignment as derived from the discussion in Table 3.1.

4.4 Discussion

The presented channel assignment frameworks have been developed to simplify the implementation process in Linux-based wireless mesh networks. The focus of the NET-X framework is on dynamic channel assignment, which requires fast channel switching. The decrease of the channel switching duration has been achieved by modifying the Linux kernel and the wireless drivers. Still, these changes to the kernel increase the effort for the installation in other networks. The unicast component allows to specify a channel over which a particular neighbor can be reached. Therefore, existing routing protocol implementations have to be modified to make use of this feature, such as the reactive routing protocol implementation provided as part of the Userspace Daemon of the framework.

Static channel assignment approaches can also be realized with NET-X, although it is not in the focus and to the best of our knowledge, none has been implemented so far. A pure static approach would make the introduced improvements for fast channel switching as well as the queue management and fairness component useless and would introduce unnecessary overhead. Still, the broadcast component would also be useful for static approaches. The current research focus is put on the development and evaluation of different algorithms for choosing the channel of the fixed interfaces.

The focus of the DES-Chan framework is to provide services and data structures which are commonly used in distributed channel assignment algorithms. The framework allows to implement a wide range of different algorithms in order to perform a comparison of the different approaches. DES-Chan does not require any changes of the Linux kernel or the wireless network interface drivers. It is therefore easy to integrate into existing wireless mesh network testbeds. However, the framework does not allow fast channel switching which limits the framework to static channel assignment algorithms.

The DES-Chan framework allows to perform research on different aspects of the channel assignment challenge. Next to the algorithms for the channel assignment decisions, the underlying metrics and models can be exchanged and evaluated. New interference metrics and models can be defined and compared when utilized by different algorithms.

CHAPTER 5

DES-Testbed Measurements

This chapter documents several experiments that have been carried out on the Distributed Embedded Systems (DES)-Testbed in order to validate common assumptions of Wireless Mesh Networks (WMNs) with results on a real multi-radio mesh network. The experimentally determined channel characteristics are an important input for channel assignment algorithms. For instance, co-channel interference can be measured and thus the existence of possible non-interfering channels can be validated. Additionally, the results of the experiments can be used to specify upper bounds for the expected performance increase by applying channel assignment algorithms. These may differ from theoretical upper bounds because they usually rely on simplified interference models.

5.1 DES-Testbed

The DES-Testbed is a multi-radio WMN located on the campus of the Freie Universität Berlin. Currently it consists of more than 100 indoor and outdoor nodes, as depicted in Figure 5.2, with future plans to upgrade to a total of at least 125. The hybrid DES-Nodes consist of a *mesh router* and a *sensor node* in the same enclosure, thus forming an overlapping WMN and Wireless Sensor Network (WSN). The DES-Nodes are deployed in an irregular topology across several buildings on the campus as depicted in Figure 5.1. Besides the DES-Testbed, several in-parallel IEEE 802.11 networks exist to provide network access to students and staff members on our campus. These networks are not under our control and thus contribute to the external interference We treat this as a condition that is also likely to be expected in a real world scenario. For a description of the architecture of the DES-Testbed in full detail we refer to our technical reports [47, 48] and for the experimentation framework to [51, 52, 53].

Each DES-Node in the DES-Testbed is equipped with three IEEE 802.11 WNICs. One of the interfaces is a Ralink RT2501 USB stick and the other two are Mini PCI cards with an Atheros AR5413 chipset. The cards use the *rt73usb* and *ath5k* drivers, which are part of the Linux kernel. For the experiments presented in this chapter the Linux kernel 2.6.34 was used. While the Ralink WNICs are IEEE 802.11b/g devices using the 2.4GHz band, the Atheros WNICs additionally support the IEEE 802.11a standard on 5GHz.

Although the 5GHz band theoretically offers 19 non-overlapping channels, only four of these can be used per default in the DES-Testbed. The reason is, that the Atheros cards only support IEEE 802.11a and not the IEEE 802.11h extension which adapts the standard to the European regulatory requirements. Since we are interested in the channel

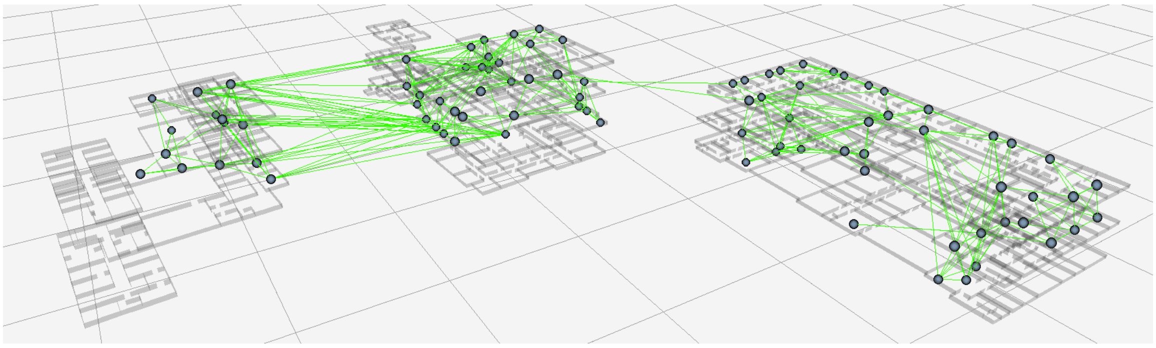


Figure 5.1: Snapshot of the DES-Testbed topology. The DES-Nodes are distributed over three buildings on the campus of the Freie Universität Berlin. Currently, outdoor DES-Nodes are deployed to improve the connectivity between the adjacent buildings.

Figure 5.2: Indoor and outdoor DES-Nodes of the DES-Testbed. The left picture shows the DES-Node version 2. The multi-radio mesh router consists of an Alix2d2 board with three IEEE 802.11a/b/g Ralink- and Atheros-based radios. An additional sensor node is connected to the DES-Node via USB. The outdoor node comprises the same components as the indoor node, but uses the Alix3d2 board to fit into the certified enclosure.

characteristics regardless of a specific regulatory domain, we configured a static regulatory domain database for the Linux kernel and removed all restrictions. Unfortunately, the ath5k driver has a hard-coded limitation for the ad-hoc mode in the upper 5 GHz band which had to be removed as well. As a result, all available 19 channels of IEEE 802.11a can be used for the following experiments on the DES-Testbed.

5.2 Network Topology and Link Quality in the DES-Testbed

As a first experiment, we assess the network topology of the DES-Testbed by determining the number of existing links and their corresponding quality. We estimate the link quality based on the measurements provided by the broadcast ETX daemon of the DES-Chan framework (see Section 4.3). We also investigate the impact of the radio frequency on the network topology. For this, we determine the number of links and their respective ETX values separately on each channel of the 2.4 GHz and 5 GHz frequency band of

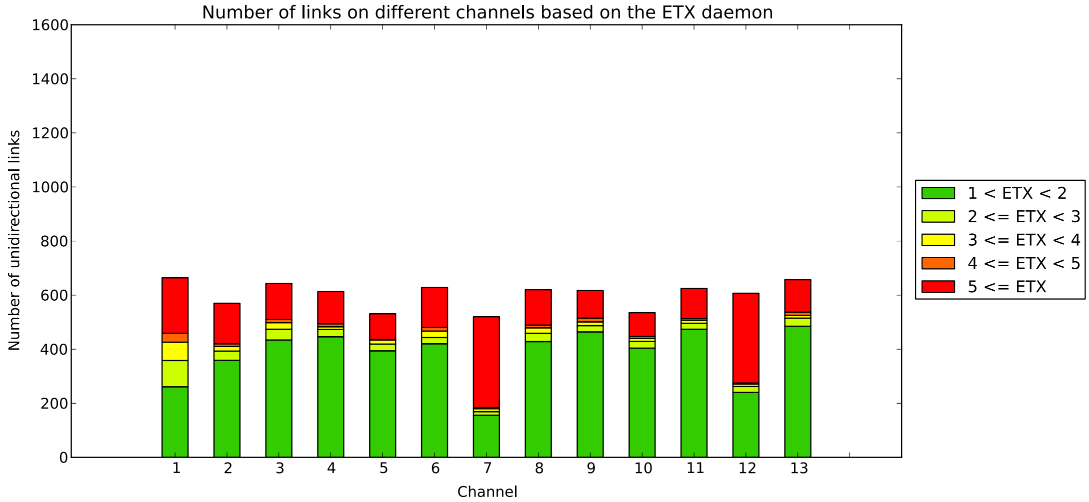


Figure 5.3: Number of links and their quality on the 2.4 GHz frequency band using the Ralink USB WNIC. On almost all channels, the majority of links are of high quality with $\mathsf{ETX} < 2$.

IEEE 802.11.

For the experiments we tuned one wireless network interface on each mesh router to the same channel. We started the ETX daemon to determine the amount of links and the corresponding link quality for each network node. The ETX values were measured periodically for 3 minutes on each channel.

It is expected that with a higher frequency, the signal range decreases. Therefore, the quality of links being present on channels at 2.4 GHz is likely to decrease when the channel is switched to 5 GHz [23]. The experimental validation is important since a link that exists when using a channel on the 2.4 GHz band may not exist when the corresponding wireless network cards are tuned to a channel of the 5 GHz spectrum. If a channel assignment algorithm does not consider this constraint, the network connectivity may be affected after the channel assignment procedure.

Figure 5.3 shows the results using the Ralink WNIC on 2.4 GHz. The majority of the links are of high quality, expressed by $\mathsf{ETX} < 2$. Surprisingly, the number of medium quality links for which $2 \leqslant \mathsf{ETX} < 5$ is very low. Low quality links expressed by $\mathsf{ETX} > 5$ have been observed more often.

Figure 5.4 shows the results of the same experiment using the Atheros WNIC. The results are similar in that they also show a large number of high quality links and a high amount of links with poor quality. Again, medium quality links for which $2 \leqslant \mathsf{ETX} < 5$ are rare. However, the absolute number of links is about three times higher compared to the results with the Ralink network adapter. This is credited to the higher transmission power of the Atheros Mini PCI network adapter which allows to reach nodes that are farther away. As a result, many more links exist, but the additional links have a poor quality and the ETX daemon uses only small broadcast packets. Therefore, it is questionable if they can actually be used for unicast data traffic.

Figure 5.5 shows the results using the Atheros WNIC on 5 GHz. Again, the majority of the links are of high quality, whereas the number of medium quality links is very small. The amount of links and their quality does not vary a lot among the particular channels of the 5 GHz spectrum. We expected a decrease of links for the higher frequencies which could not be observed. However, the ETX experiment delivers just a first impression

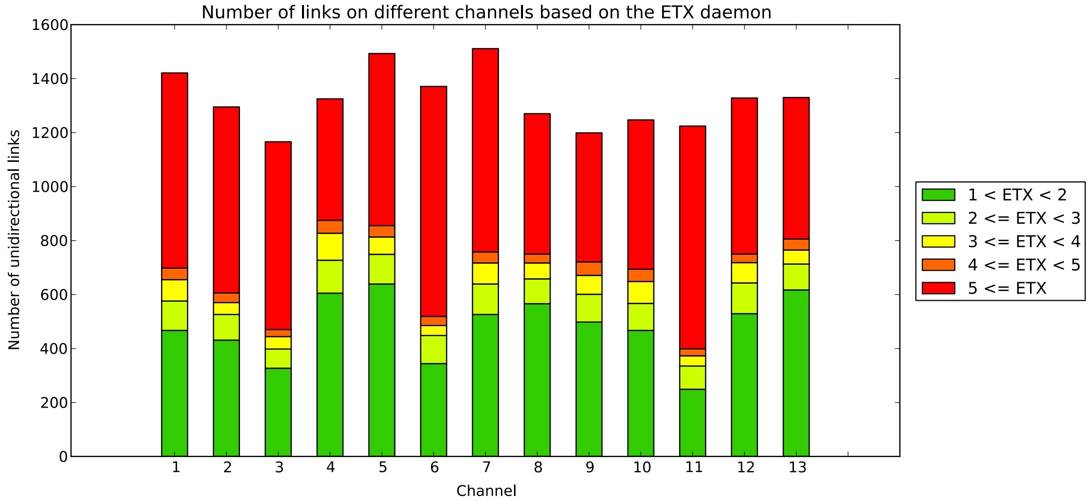


Figure 5.4: Links and their quality on the 2.4 GHz frequency band using the Atheros Mini PCI WNIC. There is a high amount of high quality links with ETX < 2 and also very low quality links with ETX $\geqslant 5$ on each channel.

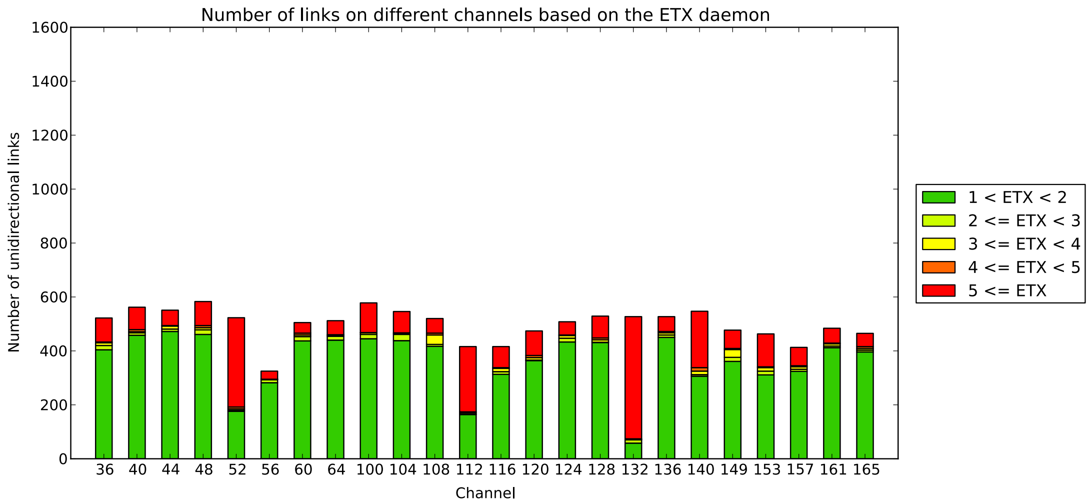


Figure 5.5: Number of links and their quality on the 5 GHz frequency band. Most links are of high quality with ETX < 2.

of the channel characteristics and a more detailed analysis using unicast traffic flows is required in future work.

In order to investigate the effects of the channel usage to the network topology, we take a closer look at the high quality links with ETX < 2 throughout all three experiments. The average number of high quality links of three experiment repetitions is 382 using the Ralink card on 2.4 GHz, 479 for the Atheros Mini PCI card on 2.4 GHz, and 365 for the Atheros Mini PCI card on 5 GHz. Thus, there are about 25% more high quality links on the 2.4 GHz channels using the Atheros network adapter compared to the other two experiment setups. This validates the assumption that the network topology is dependent on the particular frequency band in use and also on the particular wireless network adapter. Therefore, it can not be assumed that the link quality or even the network connectivity stays the same if channels are switched on demand on the available network interfaces.

5.3 Co-Channel Interference Measurements

IEEE 802.11b/g offers three non-overlapping channels, for instance {1, 6, 11}, and all available channels in IEEE 802.11a use non-overlapping frequency spectrums. This means in theory, that concurrent transmissions on these channels should not interfere with each other. In practice, experiments and measurement on different experimental platforms have shown, that the non-interfering characteristics do not hold for many reasons [16, 23, 34]. The causes for this effect are board crosstalk, radiation leakage and a small distance between antennas of simultaneously active radios. Among them, antenna distance can have the most severe effect on the performance [54]. To avoid the near-antenna effect, the experimentally specified minimum distance between two antennas is about 1 m. Since mesh routers are usually more compact, it is almost impossible to design a multi-radio mesh router with sufficient antenna distance. This is also the case with DES-Nodes, on which the three WiFi antennas are mounted with a distance of about 30 cm. Therefore, we also expect to experience side-effects on the theoretical non-interfering channels, which are subject to experimentation in this chapter.

One of the proposed measurement-based interference estimation schemes is the Link Interference Ratio (LIR) as introduced in [24]. For two links $l_{u,v}$ and $l_{x,y}$ the LIR is defined as

$$\mathsf{LIR}_{l_{u,v},l_{x,y}} = \frac{T_{l_{u,v}}^{l_{u,v},l_{x,y}} + T_{l_{x,y}}^{l_{u,v},l_{x,y}}}{T_{l_{u,v}} + T_{l_{x,y}}}$$

where $T_{l_{u,v}}$ is the unicast throughput for link $l_{u,v}$ when only this link is active and $T_{l_{u,v}}^{l_{u,v},l_{x,y}}$ is the unicast throughput for the link when the link $l_{x,y}$ is active simultaneously. As described in Section 2.2, the LIR expresses the interference of two links by relating the aggregate throughput of both links when they are active individually to the aggregate throughput when they are active simultaneously. A LIR value of 1 indicates that the two links do not interfere at all, whereas a LIR value of 0.5 means that the aggregate throughput is halved when both links are active at the same time.

The LIR is suitable to investigate the impact of the channel distance on two simultaneous transmissions. Therefore, in a first experiment we measure the LIR of two links being adjacent to the same node for a varying distance to investigate the effect of *intra-path* interference. In a second experiment, two links with different sender and receiver pairs which are in each others interference range were chosen. This experiment will give insights on *inter-path* interference.

For both experiments we use two Atheros MiniPCI cards with the `ath5k` driver. The auto-data-rate algorithm is used and RTS/CTS disabled. The channels of the links are sequentially set to all possible combinations on each frequency band.

We perform the experiment for all channel combinations of the 2.4 GHz and frequency band, the 5 GHz frequency band, and finally using both bands simultaneously. We repeated the experiment so that we have at least 40 measurements for each channel distance.

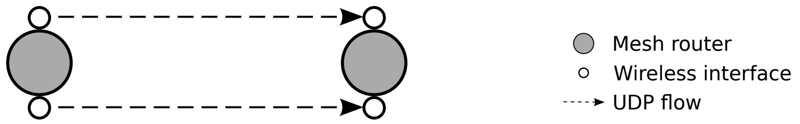


Figure 5.6: Experiment setup for measuring the effect of spectral channel distance to the LIR with adjacent traffic flows. 5 node pairs of the DES-Testbed are selected to measure the LIR of their corresponding links.

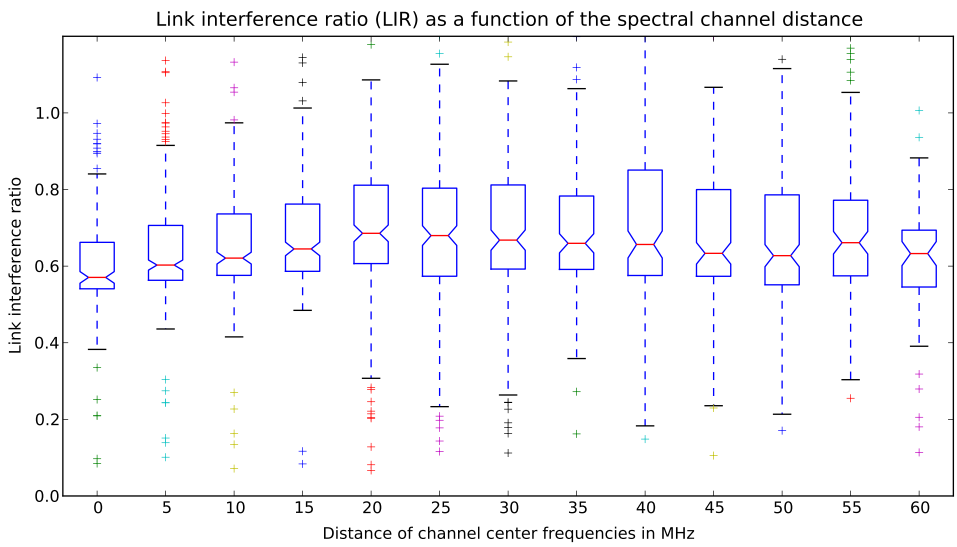


Figure 5.7: Results of the LIR of adjacent flows for channel combinations on the 2.4 GHz band. The LIR of two links in respect to their spectral distance is shown. The median for all channel combinations is about 0.6.

5.3.1 Adjacent Traffic Flows

First, we need to select a subset of the links between the mesh routers of the DES-Testbed. For this, we used the ETX daemon of the DES-Chan framework to identify high quality links in our testbed with an ETX value of 1. We then selected 5 node pairs which are connected by such high quality links. For each node pair, we selected one node as sender and the other as receiver, as depicted in Figure 5.6.

In order to measure the LIR we generate two UDP unicast flows from one of the routers (sender) to the other (receiver). Each flow is generated with `iperf` using 54 MBit/s for 30 seconds. After the flows, we start both flows another time simultaneously. We measure the individual and aggregate throughput and compute the LIR.

We chose this scenario because it is common in multi-hop WMN where a node on a path forwards traffic to a destination. For simpilicity, we reduced the set up to only two nodes, in which the sender and receiver utilize two radios each. Also, the advantage of multi-radio nodes lies in the capabilities to utlize more than one radio at the time and thus increase the throughput.

The results for the channel combinations on the 2.4 GHz band are depicted in Figure 5.7. Unfortunately, they show that in the DES-Testbed none of the channels of the 2.4 GHz band are non-interfering. The median of the LIR values is about 0.6 regardless of the used channel combination, which means that the aggregate throughput is almost halved when the two links are active simultaneously. Concluding from the results, a

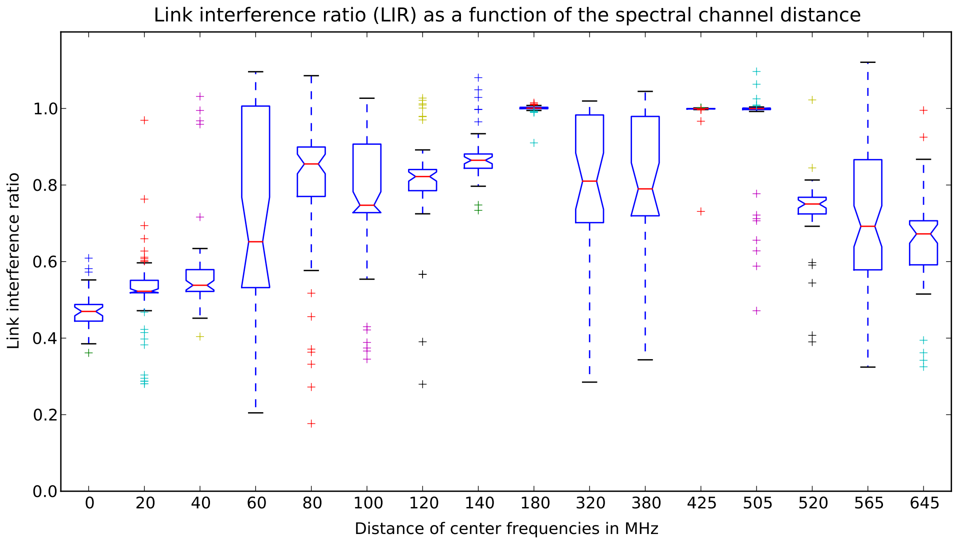


Figure 5.8: Results of the LIR of adjacent flows for channel combinations on the 5 GHz band. The median of the LIR value increases with channel distances of up to 180 MHz and then decreases again.

channel assignment with the highest possible spectral distance would only lead to a minor increase of the throughput. As already mentioned, we credit these results to the near-antenna effect of the DES-Nodes.

The results for a subset of all possible spectral channel distances of the 5 GHz band are depicted in Figure 5.8. It can be observed that the median of the LIR value increases with channel distances of up to 180 MHz. This rise of the LIR is much slower than expected, but the results show that the median is about 0.8 for a channel distance of at least 80 MHz.

For a channel distance of 320 MHz and more the LIR decreases again, which we did not expect. In a first investigation, this seems to be related to the link quality. For the UDP flows, we used `tcpdump` to monitor the RSSI values for each correctly received frame. We observed that the lower the RSSI values are, the lower the LIR values are for a increasing channel distance.

To display the results, we included the measured LIR values of two different node pairs u, v and j, k in Figure 5.9 and Figure 5.10. For the first node pair, the measured LIR values increase with a rising channel distance, which is as expected. With `tcpdump` we measured an average of about -65 dbm for all received frames. For the second node pair, the measured LIR values behave unexpectedly and start to drop already at a channel distance of 100 MHz below 0.5. With `tcpdump` we measured an average of about -89 dbm for all received frames, which is close to the threshold of the WNIC being able to receive a frame correctly. As a conclusion of this observation, we suspect that the huge difference in the RSSI values does hint at a very different link quality of these two link pairs. Unfortunately, the broadcast-based ETX-daemon does not seem to be appropriate to estimate link quality for unicast transmissions. We will investigate this observation in future work.

In the last set of experiments for adjacent flows, we selected only channel combinations from both available 2.4 GHz and 5 GHz frequency bands. One sender/receiver pair of WNICs is tuned to channel $c_1 \in \{1, 13\}$ whereas the other is tuned to channel $c_2 \in$

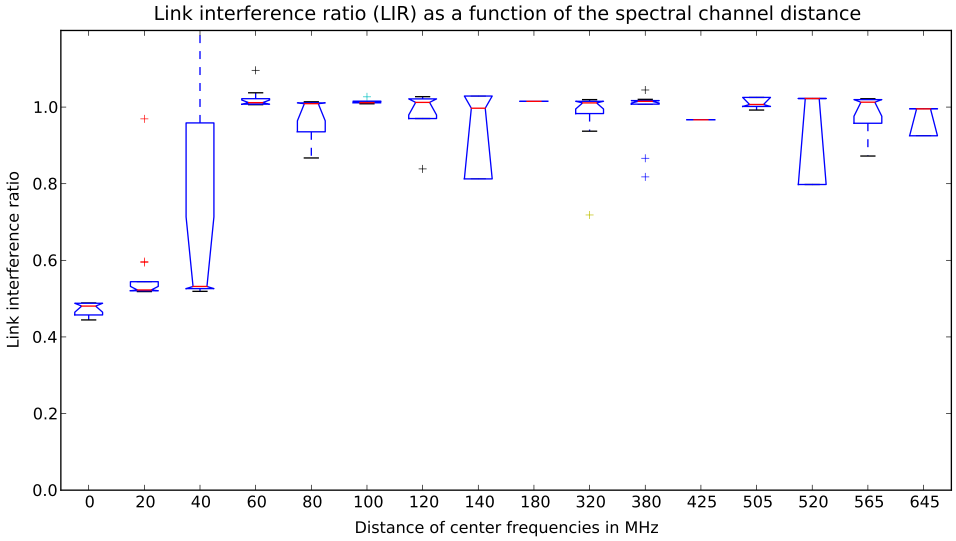


Figure 5.9: Results of the LIR of adjacent flows on links with a high RSSI value for channel combinations on the 5 GHz band. The average RSSI value for received frames was about -65 dBm. The LIR is close to 1 with a spectral distance of at least 60 MHz, which is as expected.

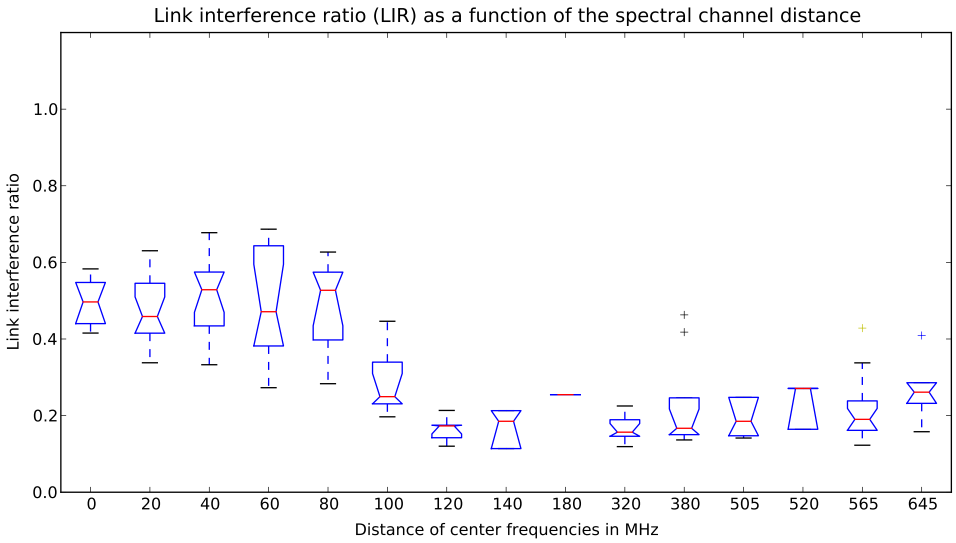


Figure 5.10: Results of the LIR of adjacent flows on links with a low RSSI value for channel combinations on the 5 GHz band. The average RSSI value for received frames was about -89 dBm. The LIR is less than .5 for channel combinations with a spectral distance of more than 100 MHz. We assume the low RSSI values to cause this effect, which we will further investigate in future work.

$\{36, 64, 100, 140, 149, 165\}$. The results, as depicted in Figure 5.11, show that the median of the LIR is between 0.8 and 1 and therefore only a small decrease of performance can be observed.

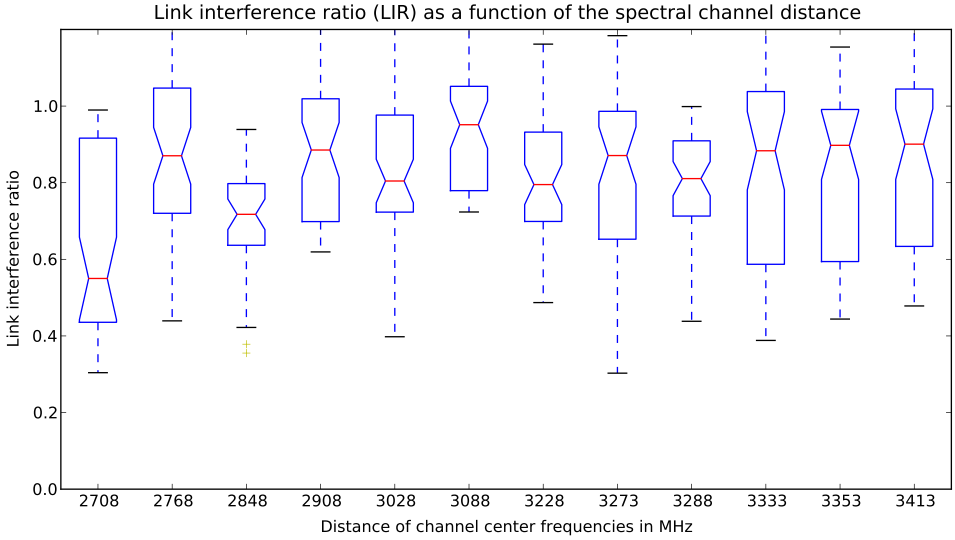


Figure 5.11: Results of the LIR of adjacent flows for channel combinations on the 2.4 GHz and 5 GHz band. The median of the LIR for all channel combinations is about 0.8. This means that the links only exert minor interference effects on each other.

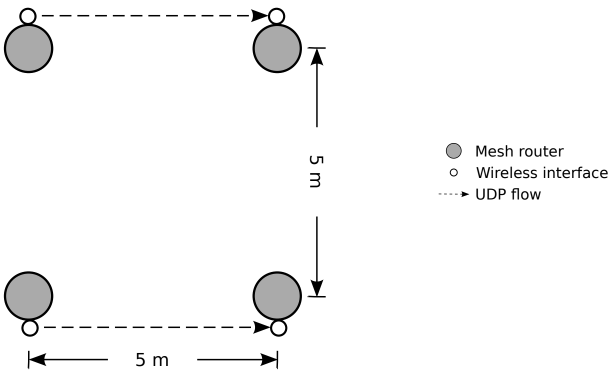


Figure 5.12: Experiment setup for measuring the effect of spectral channel distance to the LIR with non-adjacent traffic flows. Two node pairs are selected which are located in the same room. The LIR of the two links between the node pairs is measured.

Discussion of the results

Unfortunately, the results of the experiments differ vastly from the theoretical assumptions. For all channel combinations using only the 2.4 GHz band a LIR of about 0.6 was measured, which is only a minor improvement to the single channel network scenario. Minor interference effects are only observed with a channel distance of at least 80 MHz on the 5 GHz band. Therefore, two simultaneously active flows should make use of both frequency bands, where a LIR of about 0.8 was measured.

5.3.2 Non-Adjacent Traffic Flows

In the second experiment we measure the LIR for two non-adjacent flows. For this, two pairs of DES-Nodes located in a single room are used. The experiment setup is depicted in Figure 5.12.

The results for the channel combinations on the 2.4 GHz band are depicted in Fig-

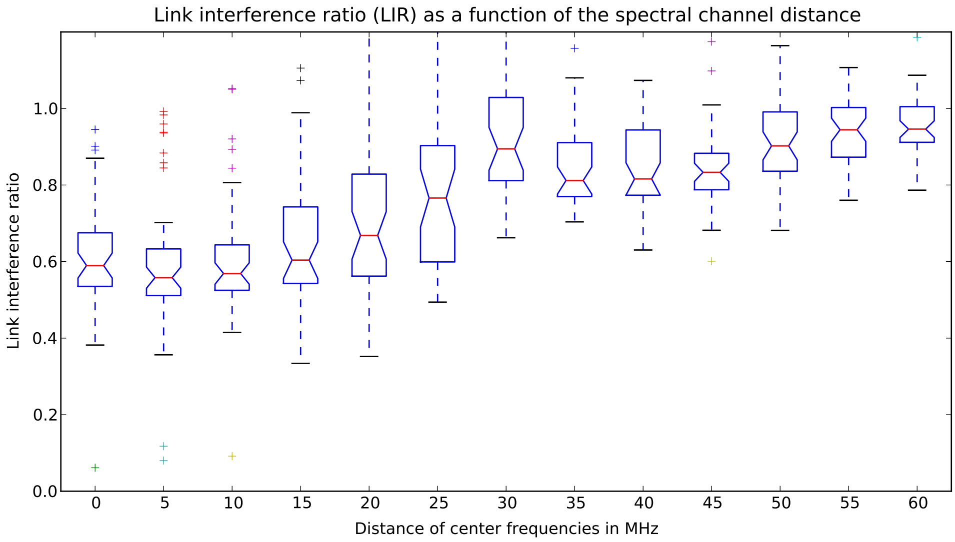


Figure 5.13: Results of the LIR of non-adjacent flows for channel combinations on the 2.4 GHz band. With a channel distance of 30 MHz, the median of the LIR is usually above 0.8 which implicates that a significant higher throughput can be achieved.

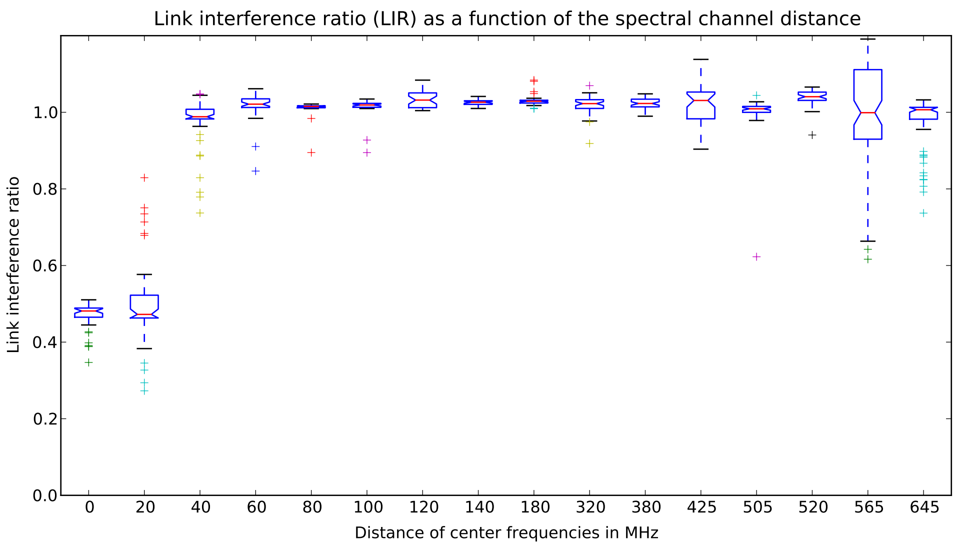


Figure 5.14: Results of the LIR of non-adjacent flows for channel combinations on the 5 GHz band. From a channel distance of 60 MHz, the median of the LIR is close to 1, which means that there are hardly any interference effects.

ure 5.13. With a channel distance of 30 MHz and more, the median of the LIR is usually above 0.8 which implies that a significant higher throughput can be achieved with at least that distance.

The results for the 5 GHz band are depicted in Figure 5.14. From a channel distance of 40 MHz, the median of the LIR is close to 1, which means that there are hardly any interference effects.

For the last experiment, we selected only channel combinations from both available 2.4 GHz and 5 GHz frequency bands. The results, as depicted in Figure 5.15, show that the median of the LIR is close to 1 for all channel combinations and therefore no

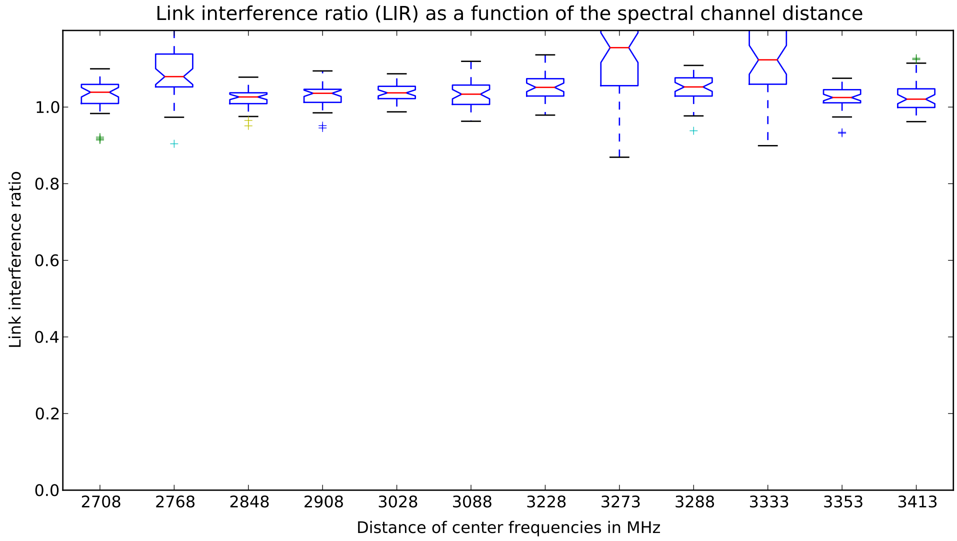


Figure 5.15: Results of the LIR of non-adjacent flows for channel combinations using the 2.4 GHz and 5 GHz band. The median of the LIR is close to 1 for all channel combinations and therefore no interference effect is observed

interference effects are observed.

Discussion of the results

Although none of the channel combinations in the 2.4 GHz allow completely non-interfering transmissions, a minimum channel distance of 30 MHz should be used for simultaneously active flows in order to achieve the highest possible throughput. This results in three possible channels $\{1, 7, 13\}$ for an efficient channel assignment. On the 5 GHz band a minimum spectral channel distance of 40 MHz is sufficient to experience only neglectable interference effects. Using both bands simultaneously, hardly any interference effects could be measured with the median of the LIR being close to 1.

The results for non-adjacent flows show fewer impact of interference as the corresponding experiments with adjacent flows. We assume the main causes for these results being the bigger antenna distance for the experiments with non-adjacent flows (5 m to 0.3 m). To validate the assumption, we will perform experiments with adjacent flows and longer antenna cables therefore increasing the inter-antenna distance in future work.

5.4 Multi-hop Path Interference

In this experiment, we validate the gained knowledge about the channel characteristics on the DES-Testbed with a manual channel assignment. For this we create a chain topology of five mesh routers, on which we can start traffic flows over up to four hops. First, we apply the same channel to all links in the chain topology, thus creating a single channel network scenario as depicted in Figure 5.16 (a). We then start an UDP flow with `iperf` from the first node of the chain to the second node. Afterwards we start an UDP flow from the first node to the third and so on, until the last node in the chain. We configured the WNICs with the fixed data rate of 6 Mbit/s and send the UDP flow for 30 s with the same data rate. We repeat the experiment for each hop 40 times.

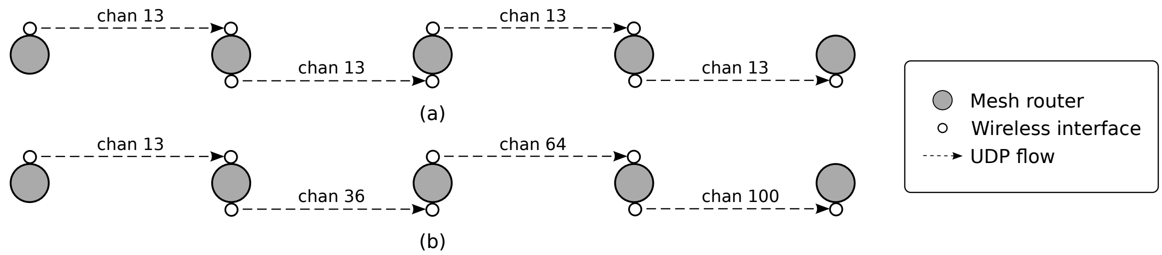


Figure 5.16: Experiment setup to measure throughput in a single- and multi-channel network. A subset of the mesh routers is selected to create a chain topology. In (a), we apply the same channel to all wireless links, thus creating a single channel network scenario. Based on the results of the previous experiments, we manually apply channels to the links which promise an increase of throughput compared to the single network scenario in (b).

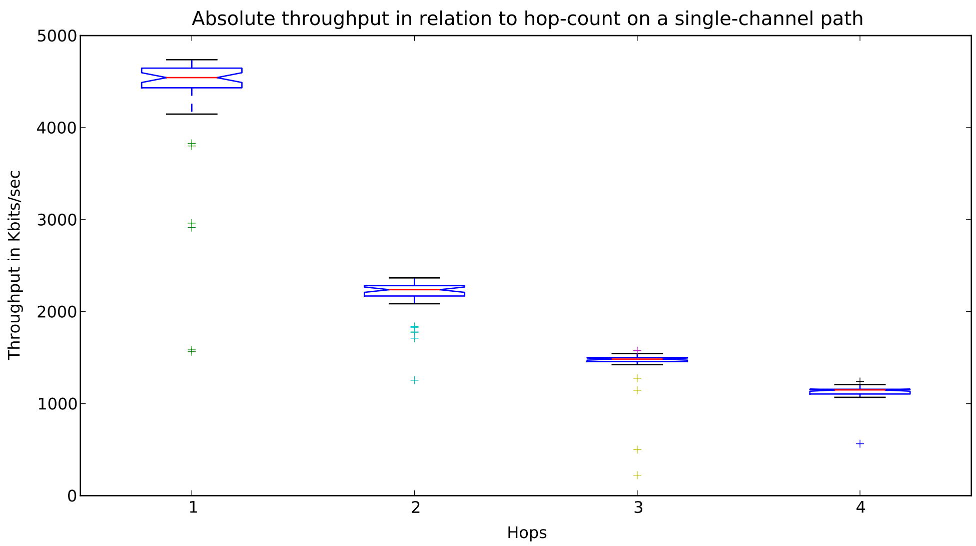


Figure 5.17: Results for the single-channel path experiment. As expected for the single channel network case, the throughput is more then halved on the first hop and keeps dropping with an increasing hop-count.

The results for the single channel network scenario for the throughput in relation to the hop count are depicted in Figure 5.17. As expected for the single channel network case, the throughput is more then halved on the first hop and keeps dropping with an increasing hop-count.

Based on the results of the channel characteristics experiments, we then manually assign channels to the chain topology in a way, that promises the biggest decrease of interference effects. As observed from the experiments on adjacent flows, both frequency bands should be used for the respective WNICs. We expect the throughput to be significantly higher compared to the single channel network. We apply the channels $\{13, 36, 64, 100\}$ to the links as depicted in Figure 5.16 (b) with which we expect to exhibit only minor interference.

The results for the multi-channel network scenario are depicted in Figure 5.18. As expected, the manual channel assignment leads to a higher throughput if the hop-count is bigger than 1. It only drops slightly with the increasing hop-count which implicates that the interference effects have been reduced significantly with the chosen channel assignment. These results show that the experimentally determined channel characteristics

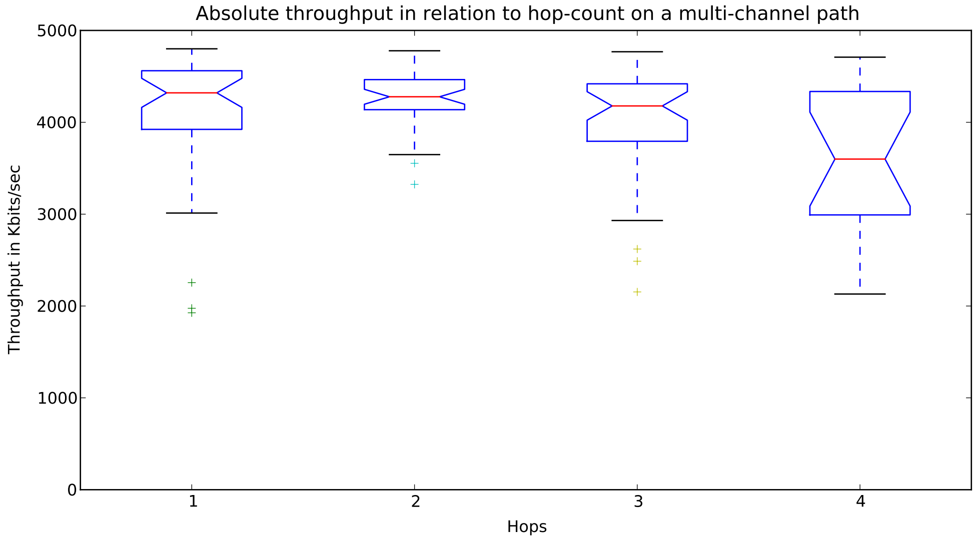


Figure 5.18: Results for the multi-channel path experiment. As expected, the manual channel assignment lead to a higher throughput if the hop-count is bigger than 1. It only drops slightly with the increasing hop-count which implicates that the interference effects have been reduced significantly with the chosen channel assignment.

also hold in multi-hop scenarios and underline the potential performance gain that can be achieved by proper channel assignment.

5.5 Discussion

The basic experiments and measurements were performed in order to gain insights on the network topology and the channel characteristics in the DES-Testbed. We first showed, that the network topology and the quality of particular network links is dependent of the utilized WNIC and the frequency band.

In a second series of experiments, the effects of the co-channel interference have been investigated. The LIR of two links is significantly lower for adjacent than for non-adjacent traffic flows. Nevertheless, using channels on both frequency bands also promises a higher throughput for adjacent traffic flows.

The results of the experiments have been validated with a manual channel assignment in a chain topology spanning 4 hops. The throughput has been significantly higher using the manual channel assignment compared to the single channel network scenario.

A comparison of the experiment results to the common assumptions of channel assignment algorithms as described in Chapter 3 yields some interesting deviations. First, the assumption of orthogonal channels as theoretically offered by IEEE 802.11 and considered in many channel assignment algorithms does not hold in practice. In contrast, if the experimental results are transferred to the channel assignment algorithms, the actual number of available channels is significantly reduced which may affect the performance of the algorithms.

Second, channel assignment either assume that a link between two nodes or radios exist or not. However, the experiments have shown, that the link quality may depend also on the WNIC characteristic and on the used frequency band. Therefore, when designing channel assignment algorithms, it should be considered that channel switches may alter the link quality or even the network connectivity.

Finally, the experiment results for adjacent and non-adjacent flows show different characteristics. Therefore, channel assignment algorithms should distinguish between adjacent and non-adjacent flows in order to optimally assign the available channels.

CHAPTER 6

Future Work

In future work we will focus on the practical issues of distributed channel assignment in wireless mesh networks. The performed experiments revealed several different research subjects which have to be furhter investigated to pave the way for an efficient distributed channel assignment.

One focus will be on measurement-based interference estimation which will be an important input for channel assignment algorithms. Since simple metrics are usually very inaccurate [24], we will investigate further measurement-based approaches for the DES-Testbed. The first experiments with the Link Interference Ratio (LIR) could be validated in a simple multi-hop path experiment and we will further investigate the metric (see Section 5.4).

Also, the ETX link metric proved not appropriate to determine the link quality for unicast transmissions since a low data-rate is utilized and the exchanged messages are of a small size (see Section 2.4.2 and Section 5.3). As a conclusion of this observation, we will investigate other link metrics which are better suited to estimate the link quality for unicast communication with variable packet sizes.

Based on DES-Chan, a wide range of different distributed channel assignment algorithms will be implemented to enable their comparison. A random link-based channel assignment algorithm and the DGA algorithm [23] as presented in Section 3.1.2 already exist. In future work, we will design and implement distributed channel assignment algorithms with the focus on scalability and adaptivity. The algorithms will consider the channel characteristics and measurement-based interference models, which have been experimentally determined in Section 5.3, and the requirements of distributed channel assignment as derived from the discussion in Table 3.1.

The DES-Testbed with more than 100 indoor and outdoor network nodes provides a great opportunity to evaluate the algorithms in a real-world multi-transceiver mesh network.

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