8 Conclusion and Future Work

This chapter concludes this thesis and provides an outlook on future work in the area of mobile ad hoc networks and peer-to-peer overlay networks

8.1 Conclusion

Due to the continuing proliferation of ever more powerful mobile devices, it becomes increasingly interesting to build large-scale and complex distributed network applications that one is accustomed to from the Internet such as name services, messaging systems or storage systems for mobile ad hoc networks as well. As peer-to-peer networks share key characteristics with MANETs such as resilience to dynamic network topologies, the lack of any central infrastructure, or the need for self-organization, the convergence of mobile ad hoc networks and peer-to-peer overlay networks appears to be a very promising way to build such distributed applications in mobile environments.

Unstructured, broadcast-based peer-to-peer networks generally suffer from severe scalability problems with increasing numbers of participating nodes, which especially limits their general applicability in MANETs with their scarce resources. To overcome the scalability issues of such unstructured P2P networks, Distributed Hash Tables have been introduced. These DHTs have been used as efficient general-purpose building blocks for large-scale distributed network applications in the Internet. Although intuitive, the direct deployment of conventional DHTs in order to equally serve as efficient building blocks for distributed applications in MANETs is not a practicable approach. This is mainly due to three reasons: the overlay stretch, physical route discovery and overlay routing table maintenance (see Section 1.1).

Therefore, in order to provide the powerful primitive of key-based routing in MANETs, the characteristics of such networks have to be taken into consideration. This has been the design goal of MADPastry. MADPastry combines the functionality of the popular DHT Pastry and the popular reactive ad hoc routing protocol AODV at the network layer to provide reliable indirect, key-based routing in MANETs. MADPastry has a number of key characteristics that makes it especially suitable for mobile ad hoc networks. First of all, MADPastry explicitly considers physical locality by using Random Landmarking to form overlay clusters so that nodes that are physically close to each other will also quite likely be close to each other in the overlay ID space. By using RLM, MADPastry can exploit physical locality without the need for any specialized hardware requirements such as GPS. Secondly, MADPastry explicitly considers physical routes during its overlay routing. In order to avoid expensive network-wide route discoveries whenever possible, MADPastry will deviate from an optimal overlay routing if the physical route for the current overlay hop is unknown and favor a less optimal overlay destination for which the physical route is known. Even if a physical route discovery does become unavoidable, due to its overlay clusters, physical route requests can often be limited to such a cluster instead of flooding the entire network. Furthermore, MADPastry nodes heavily exploit packet overhearing for implicit table maintenance in order to reduce the costly table maintenance. In fact, a MADPastry node only needs to periodically contact its "left" and "right" leaf, both of which will likely be in its physical vicinity due to MADPastry's clusters. Finally, by providing standard DHT functionality, MADPastry can be used as a general-purpose building block for distributed applications.

Our simulation results have shown that MADPastry provides very efficient key-based routing in a wide variety of different network settings. It generally achieved comparable or better success rates while producing significantly less network traffic compared to a reference broadcast-based routing agent as well as a DHT-based routing agent without explicit consideration of physical locality. Especially in networks with high request rates, MADPastry benefits strongly from its locality awareness with its short and mainly up-to-date routes. These results support the above mentioned design goals of MADPastry. Additionally, the results presented in this thesis have also shown the limitations of Distributed Hash Tables in MANETs. In volatile networks, i.e. in networks with high node velocities and/or high churn rates, it is quite difficult to maintain valid routing structures. In such environments, one might indeed be well advised to resort to a structure-less broadcast approach.

With its efficient key-based routing for MANETs, MADPastry can be used as a general-purpose building block for distributed network applications in mobile environments. MADPastry's general applicability has been demonstrated in this thesis through two concrete applications. First of all, it has been described how to build a straight-forward and reliable name service for MANETs on top of MADPastry. Furthermore, it has been shown how MADPastry can be employed not only to provide key-based routing but also efficiently for direct unicasting between a given source and a given destination. Therefore, using MADPastry as the DHT substrate, the porting of many existing DHT-based applications from the domain of the Internet for a deployment in MANETs can be expected to be much simplified. Nonetheless, it still remains to be seen how DHT-based applications that store huge amounts of data and use large quantities of keys (such as ePOST [34]) would perform on top of MADPastry and whether they are applicable for MANETs at all.

In section 3.5, related approaches were compared against each other according to various performance parameters. That table will now be extended to also include MADPastry for an overall comparison. Again, the following parameters are used for the comparison:

Scalability. This is a measure of how well a given approach is expected to scale to large network sizes. One of the central questions is whether the employed discovery mechanisms will only work adequately in small networks because they would generate too much overhead in larger networks, or whether they could also be used efficiently in larger networks (Excellent/++ → Very poor/--).

Topological Adaptability. This measure tries to estimate how well a given approach can be expected to cope with topological changes in the physical network – for example induced by node mobility. The central issue here is whether the data structure(s) used for service/object discovery can adapt adequately to topological changes (Excellent/++ → Very poor/--).

Maintenance Complexity. This is a measure of how much maintenance overhead will be generated in order to keep the data structure(s) of the respective approaches up-to-date. Complex maintenance procedures will generate significant traffic, which will clearly influence the overall scalability as well (Very low/++ → Very high/--).

General Applicability. General applicability refers to the range of applications for which a given approach could be used as a building block. For example, some approaches are solely designed for broadcast-based file-sharing, while others can be used for name resolution but lack a generic key-to-node mapping functionality so that they cannot be used efficiently for service discovery, etc (Excellent/++ → Very low/--).

Hardware Prerequisites. This parameter indicates what assumptions concerning the hardware, that it runs on, a given approach makes. For example, a question is whether a given approach could be employed on regular devices or whether the presence of specialized hardware such as a GPS receiver is required (None/0 → many/--).

The general assessment parameters described above are weighed using the following symbols in the table below:

++ : Excellent, very low

+ : Good, low

0 : N/a, medium, none

- : Poor, high, some

-- : Very poor, very high, many

Table 8.1 Comparison of MADPastry and related approaches

	Scalability	Topological Adaptability	Maintenance Complexity	General Applic-ability	Hardware Prerequisites
Conventional DHTs	--	--	--	++	0

Broadcast-based P2P / Service Discovery	--	++	++	--	0
Unstructured Key Lookup (KELOP)	-	0	+	--	0
Zone-based P2P	--	+	+	-	0
ISPRP / SSR	--	-	+	++	0
VRR	--	+	+	++	0
Ekta	0	+	0	++	0
Multicast-based Service Discovery	0	-	-	0	0
Cluster-based Service Discovery	0	0	+	0	0
Hierarchical Service Discovery	0	-	0	++	0
Geographic Service Discovery without Location Information	+	-	-	++	0
Geographic Service Discovery	++	++	0	++	--
MADPastry	**+**	**0**	**+**	**++**	**0**

8.2 Future Work

MADPastry's performance has been evaluated in various network settings. To gain an even deeper understanding of the behavior of Distributed Hash Tables in

MANETs, it would be interesting to investigate the impact of further network settings such as different node densities or node mobility patterns. Moreover, the experiments in this thesis have considered random traffic patterns where requests were uniformly distributed. It would, therefore, also be worthwhile investigating different traffic patterns such as traffic bursts or Zipf distributions for the requests.

Another technical issue that was not considered in this work is node heterogeneity. For the experiments presented here, all nodes were considered to be equal in terms of computation power, transmission power and uptime (in the churn experiments, uptime was uniformly assigned). Due to the large variety of available mobile devices, mobile ad hoc networks will likely consist of quite heterogeneous nodes. Thus, it would be interesting to examine how such node heterogeneity could be exploited to further increase the performance of MADPastry. Part of this future work would need to address the question of how to realistically model such heterogeneity, – whether one should assume uniformly distributed computation power or, instead, whether there would be relatively few very powerful nodes with the remaining nodes being largely similar.

MADPastry combines Pastry overlay routing and AODV ad hoc routing to provide efficient key-based routing for MANETs. Another interesting question would be how other DHTs such as CAN or Chord would fare if combined with ad hoc routing protocols. [30] investigates the combination of Chord and AODV.

In this thesis, MADPastry has been used to build two concrete applications. It will be interesting to see how other complex DHT-based applications from the Internet will perform on top of MADPastry. As DHT substrates such as MADPastry do not provide any transport layer functionality, a more general question will be whether conventional DHT-based Internet applications can be ported directly for a deployment in MANETs using, for example, MADPastry, or whether such applications would have to be adapted to account for the inherently less reliable communication in MANETs.

Another significant question to study would be how mobile nodes could dynamically adapt their peer-to-peer strategies to changing network environments. For example, if nodes had a notion of how quickly the network topology is changing or a notion of the network load, they could choose between a DHT-based strategy and an unstructured broadcast-based strategy depending on the situation. One promising approach, here, could be the combination of MADPastry and a cross-layer architecture as presented in [62].