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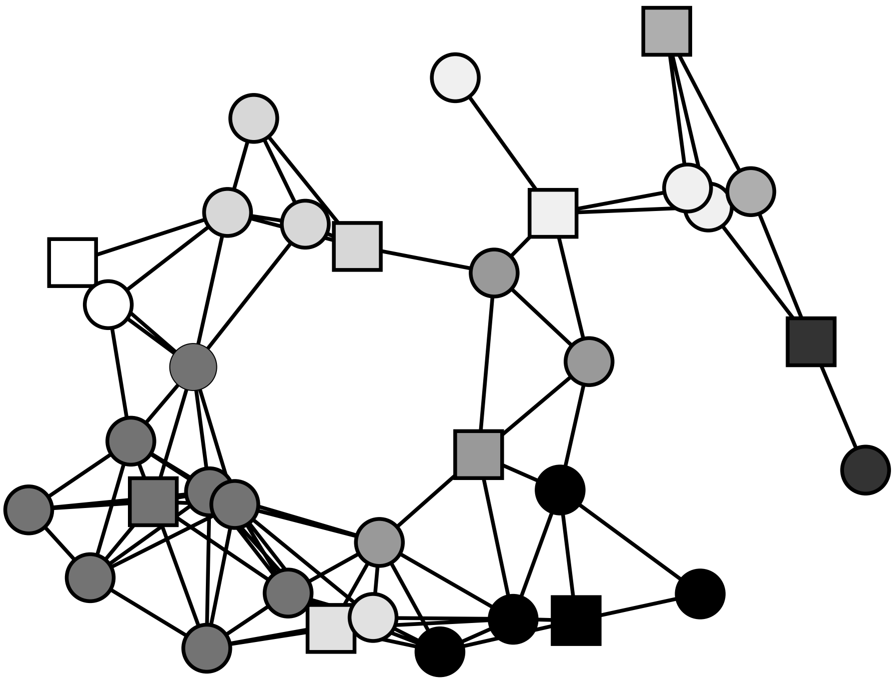
Mobility Modeling, Connectivity, and Adaptive Clustering in Ad Hoc Networks



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1 Introduction

The last 10 years have seen a tremendous boom in the mobile communications market. People have become accustomed to the convenience of making calls with mobile phones and browsing the Internet with notebooks via wireless connections. Two prime examples of this development are the great success of the Global System for Mobile Communication (GSM) and the recent deployment of Wireless Local Area Networks (WLANs). In the future, more and more mobile devices will become networked, following the trend toward ubiquitous networking. One of the main goals in current research is to design new wireless networks that are flexible, low–cost, and require little administration.

In this context, the principle of *ad hoc networking* received much interest during the past five years. In an ad hoc network, mobile devices communicate with each other in a peer–to–peer fashion (see Fig. 1.1); they establish a self–organizing wireless network without the need for base stations or any other pre–existing network infrastructure. An outstanding feature of this emerging technology is *wireless multihop communication*: If two devices cannot establish a direct wireless link (because they are too far away from each other), devices in between act as relays to forward the data from the source to the destination. In other words, each device acts as both a mobile terminal and a node of the network. This feature is not supported in current systems for mobile communications. In this way, ad hoc networking creates a new paradigm for mobile communications, where

Figure 1.1: A small ad hoc network

networks can be established in a spontaneous manner ("on the fly") without any cost or effort of building up and maintaining a network infrastructure.

There are various application scenarios both for stand–alone ad hoc networks and wireless multihop extensions to existing, infrastructure–based networks. Examples include spontaneous networks among mobile computers at conferences, networks among vehicles, and wireless sensor networks.

The particular characteristics of ad hoc networks impose significant challenges in the design of transmission schemes, communication protocols, algorithms, and system architectures. Ad hoc networks do not have dedicated, central network control entities or databases. Thus, functions like location management, medium access, power control, or security support must be accomplished in a distributed manner. Moreover, the fact that *all* nodes may be mobile — along with the changing properties of the radio channel — results in a very dynamic network topology. Thus, all network functions must have a high degree of adaptability with respect to mobility and outage of nodes.

Although the basic idea of wireless multihop networks goes back to at least the 1970s, there are still several open issues. Existing solutions from cellular networks and the Internet cannot be mapped in a straightforward manner to ad hoc networks; in many cases, completely new approaches are needed. The last few years have therefore seen a huge amount of research and development in this area. For example, the Internet Engineering Task Force (IETF) established a working group with the aim of standardizing new routing protocols that will be suitable for mobile ad hoc networks. This effort started in 1997 and is still in progress. In addition to protocol aspects, several theoretical issues are under investigation. For example, a comprehensive analytical treatment of capacity, connectivity, scalability, and fairness in wireless multihop networks is needed. Last but not least, methods to model and simulate such networks must be rethought. All these research activities are essential to understand and deploy large–scale ad hoc networks and to operate them in an efficient manner.

This thesis makes contributions to three significant research areas in the field of ad hoc networking. These areas are:

- **Mobility Modeling:** For the simulation of ad hoc networks, we must describe the movement behavior of the mobile nodes. As real movement patterns are difficult to obtain, a common approach is to use synthetic *mobility models*, which resemble the behavior of real "mobile entities." These models must be designed, and their impact on simulation results must be understood.

- **Connectivity and Other Topology Properties:** The random and dynamic nature of ad hoc networks creates a network topology that shows certain characteristics. The difference between a topology of an ad hoc network and that of a conventional network is especially apparent considering the connectivity among the devices. While a mobile device in a cellular system is "connected" if it has a wireless link to at least one base station, the situation in a decentralized wireless multihop network is more complicated. Since nodes also act as relays (routers) for other devices, each single mobile node contributes to the connectivity of the entire network. If a node fails, the connectivity between two other nodes might be destroyed. If the spatial node density is too low, the multihop principle for communication does not work at all. In other words, the communication among nodes in an ad hoc network is not guaranteed; only probabilistic measures can be given. This raises a number of theoretical questions.

- **Distributed Adaptive Clustering:** Algorithms and respective protocols are needed to separate the network nodes into logical groups, so–called clusters. Such a cluster structure enables us to set up hierarchies that can be used for address assignment, hierarchical routing, and resource control, to give three examples. Clustering algorithms need to be designed, and their behavior and performance needs to be evaluated.

The remainder of this thesis is organized as follows: Chapter 2 explains the basic principles and challenges of ad hoc networking in more detail. We give some potential applications, describe enabling technologies and open research issues, and outline aspects related to modeling and simulation.

Chapter 3 investigates mobility modeling. We first give a survey and classification of mobility models found in the literature. Examples include random movement on plain areas, scenario–based models with obstacles, and vehicular models on predefined streets. The most commonly used model in the research community on ad hoc networks is a quite simple model denoted as *random waypoint model*. Despite the popularity of this model, we observe that its behavior and impact on simulation results are not well understood. This is the motivation for us to investigate its stochastic properties in detail; we study, for example, the resulting spatial node distribution and the average speed of a node. Next, we analyze an alternative model denoted as *random direction model*. We discover that it avoids some of the disadvantages of the random waypoint model. Finally, we present a completely new model that describes the movement behavior of nodes in a more realistic manner. Throughout the chapter we outline pitfalls that might occur when using mobility models without knowing their properties. The results are of interest for researchers to understand the impact of mobility models on the network performance and to conduct meaningful simulations.

Chapter 4 presents a detailed study of topology properties of ad hoc networks. As mentioned above, we are especially interested in properties related to the network connectivity. For a given random spatial node distribution and a simple radio channel model, we address questions such as: What is the probability that a node is isolated, i.e., it has no link to any other node? Which node density is required to enable multihop communication between any two nodes in the network? What is the expected number of intermediate nodes from a source to a destination? How does mobility affect the connectivity? These and other questions are addressed by employing probabilistic methods from spatial statistics and random graph theory. We solve some previously unsolved theoretical problems in an analytical manner. For example, we derive the node density that is required to achieve an almost surely connected network with random waypoint mobility.

Chapter 5 is about distributed, mobility–adaptive clustering algorithms for ad hoc networks. After discussing the basic functionality and design choices of clustering, we take an approach to the question "What is a good clustering algorithm?". Here, we define a set of criteria that can be used for performance evaluation. In the main part of the chapter, we investigate a promising clustering algorithm in detail. We study basic attributes such as the number of nodes per cluster and performance attributes such as the number of signaling messages required to maintain a cluster structure. From the basic understanding of these results, we give some rules on how to design good clustering algorithms. Most important, we show how the performance can be improved by introducing a hysteresis parameter and making the algorithm more adaptive to mobility.

Finally, Chapter 6 summarizes our contributions and gives some directions for further research. Appendix A contains a brief description of the developed simulation tools. Appendix B lists the used symbols, mathematical notation, and abbreviations.

Parts of the material treated in this thesis were previously published in [Bet01a, Bet01b, BK01a, BK01b, BX01, KBS+01, Bet02a, Bet02b, BHPC02, BK02, BW02, BZ02, JB02, KSB02, XB02, Bet03d, BE03, BF03, BH03, BM03, BRS03], have been accepted for publication in [Bet03c, BHPC03], and are currently under review in [Bet03a]. At the same time, new and unpublished results are presented.