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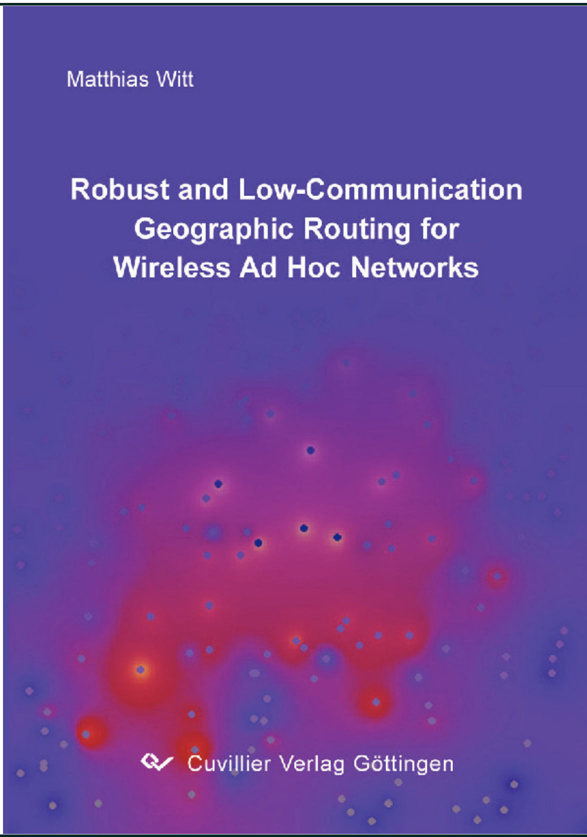
Robust and Low-Communication Geographic Routing for Wireless Ad Hoc Networks



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1 Introduction

Wireless ad hoc networks are decentralized networks of computer devices called *nodes* that communicate over wireless links and make dynamic forwarding decisions. They are classified into wireless sensor networks and mobile ad hoc networks (MANETs). The former consist of small-scale sensor nodes monitoring environmental data, typically deployed arbitrarily over an area with minimal configuration; the nodes in MANETs are portable devices like laptops, PDAs, or cellular phones. Applications for sensor networks include habitat monitoring, environmental surveillance, and healthcare applications; MANETs can be used for disaster relief operations where no communication infrastructure is available, or car-to-car communication.

Wireless ad hoc networks impose new challenges on routing algorithms for various reasons. A major problem is that topology changes caused by node failures, node removal or addition, and mobility are common. This is a big issue for routing algorithms that are based on neighborhood tables. Another point is that communication failures are likely. Anisotropic signal propagation and varying transmission ranges lead to unidirectional links, which affect unicast schemes based on neighborhood tables. Another important issue especially for sensor networks is energy efficiency, because energy is a limited resource and often battery replacement is virtually impossible. This demands for algorithms with low communication overhead, since the radio hardware is one of the most power-consuming units of the nodes.

In a wireless network where the nodes have information about their own locations, geographic routing can be performed, i. e., messages are forwarded toward the destination location using this positional information. Several geographic routing algorithms have been proposed in the literature. Most of them are beacon-based, i. e., the nodes exchange information about their neighborhood via beacon messages including ID and position. Forwarding decisions are made using this neighborhood information; the next hop is chosen from the neighborhood table, and the message is forwarded to the next hop via unicast. Apart from relying on bidirectional links (unless sophisticated neighborhood table management is performed), beacon-based routing algorithms suffer from inherent problems in case of frequent topology changes or high mobility caused by outdated neighborhood tables. In contrast to that, beacon-less algorithms, which operate with broadcast transmissions, do not face these problems, as they do not rely on static topologies.

The main goal of the thesis is the design and evaluation of a robust beacon-less geographic routing algorithm for wireless ad hoc networks called BGR (Blind Geographic Routing) that operates with as little communication overhead as possible and performs well under realistic conditions. Like other beacon-less algorithms, BGR does not use neighborhood tables, but forwards messages via broadcast. The general idea is that all nodes which receive this broadcast and are located within a designated forwarding area (determined by the forwarding node and oriented toward the destination) compete for becoming the next hop by starting a timer. The time is chosen dependent on the Euclidean distance of the node to the destination; the timer of the node closest to the destination expires first; this node forwards the message again. The other competing nodes notice this forwarding and cancel their timers.

This is the general scheme of beacon-less routing algorithms. BGR provides several significant improvements not found in previous algorithms. Like some other algorithms, BGR supports different recovery strategies in case of an empty forwarding area. In contrast to recovery strategies of other algorithms, the strategies of BGR neither have high communication overhead nor depend on regular communication models like the unit disk graph model. BGR also includes a novel strategy to avoid problems that arise when two or more nodes forward the message almost simultaneously. Furthermore, BGR is the first beacon-less geographic routing algorithm to support three-dimensional topologies. This is achieved by utilizing forwarding volumes instead of areas.

Additionally, the thesis proposes various delivery semantics for geographic routing, a topic that has not been addressed in the literature before. These semantics are *closeness* (how close must a node be located to the destination in order to consume the message), *multiplicity* (how many nodes may consume the message), and *accept-outside* (may a node where a message got stuck consume the message when the node is within transmission range from the destination).

BGR has been designed to tolerate location errors; simulation experiments confirmed a delivery ratio of over 95 % even for location errors in the order of magnitude of the transmission range. The width of the forwarding areas/volumes is adjusted according to the estimation of the standard deviation of the location error. Calculations of the estimated distance between nodes as a function of the real distance are presented in the thesis.

Furthermore, an analytical model for calculating the delivery probability of BGR is developed. An approximation of the delivery probability under the unit disk graph model (unit ball graph model in 3D) is calculated dependent on source-destination distance, transmission range, and network density.

Finally, extensive simulation studies show that the performance of BGR is over 95 % even in the case of mobility, radio irregularity, and location errors, while communication overhead is minimal. The results are directly compared with Greedy Perimeter Stateless Routing (GPSR), a well-elaborated beacon-based routing algorithm. Several recent variants of GPSR are investigated that were introduced partly in the literature and partly in this thesis. The goal of the variants was to improve the performance of GPSR for realistic scenarios. The simulations, however, show that BGR is still clearly superior.

In mobile networks, the delivery ratio of BGR even increases at higher node speeds. Although GPSR, in contrast to BGR, guarantees delivery under the unit disk graph model if the neighborhood graph is connected, GPSR shows significant deficiencies even under low mobility or radio irregularity. Small location errors do not degrade the performance of GPSR much; high location errors, however, lead to significantly worse delivery rates compared to BGR.

The thesis is organized as follows: Chapter 2 gives an introduction to wireless ad hoc networks. Chapter 3 provides an overview on geographic routing algorithms with a special focus on beacon-less algorithms. Additionally, a general framework for beacon-less geographic routing algorithms is developed. Novel delivery semantics for geographic routing are proposed and discussed in Chapter 4. The main contribution of the thesis is presented in Chapter 5, which gives a detailed description of the BGR algorithm. In Chapter 6, the influence of location errors on geographic routing algorithms is discussed. After presenting related work, improvements for BGR and GPSR are introduced on the basis of stochastic computations. An analytical model for calculating an approximation of the delivery probability of BGR is developed in Chapter 7. In Chapter 8, simulation results for BGR and GPSR are presented and evaluated. Finally, Chapter 9 gives a summary of the thesis and discusses future perspectives.