1 Introduction

Wireless communication is a key technology in today's society. It started in 1864 as Maxwell postulated the existence of electromagnetic waves and Hertz gave a few years later an experimental confirmation. Henceforth wireless technology started its triumphal march, from the first radios to modern satellite communication. Nowadays, Germany's Federal Network Agency earns several billions by auctions of UMTS licenses and there is hardly a point in urban areas that is not within the range of a WLAN access point. The advantages of wireless communication in comparison to wired technology are the support of mobility and the possibility to cover large, partly inaccessible areas. On this basis, a multitude of new technologies, standards and applications have emerged over the last years.

An example are wireless mesh networks (WMN) that are used in the area of control, monitoring, and sensing. In such networks, radio nodes, more precisely resource-constrained devices equipped with low-energy radio transceivers, are organized in a mesh topology. Direct communication between all nodes may not be possible and, if necessary, data must be routed through intermediate nodes. However, a high interconnection between nodes is assumed, thus the network provides a high resilience. This kind of redundancy is important since wireless communication is highly error-prone due to the unreliability of the radio channel. WMNs open up new applications, e.g. the monitoring of phenomena in inaccessible or harsh environments. Furthermore, they are competing with established wired bus systems in automation and control systems.

During the last years, many communication protocols for wireless mesh networks were developed such as 6LoWPAN, ZigBee, IEEE 802.11s, or WirelessHART. They all proved to be robust in small, multi-hop networks. But, what if a certain application does require the deployment of several thousand nodes? Most protocols have physical limits of tens of thousands nodes, i.e. due to the used address space. However, the actual network size for which a regular operation is possible is much smaller. For example, ZigBee uses 16-Bit network addresses and a stochastic address allocation scheme, i.e. a device joining the network picks a random address. Conflict handling is becoming a serious problem in large-scale networks (birthday paradox). Moreover, many communication protocols maintain tables of destination nodes for routing purposes. Storing such a table might exceed the memory space of resource-constrained nodes.

Networks of high density are an even bigger challenge than large-scale deployments. If a node has several hundred or even thousands of neighbors within communication range, most communication protocols are no longer applicable.

On the one hand, the periodic exchange of control information, which is essential for most protocols, congests the wireless channel. On the other hand, resource-constrained devices are not capable to store and process data of hundreds of adjacent nodes.

Up to now, only challenges of large-scale and dense WMNs, abbreviated in the following as LD-WMN, have been outlined. Are there meaningful application fields or is the study of such networks merely of academic nature? In fact, research projects to monitor and control distributed, large-scale industrial processes motivate this work. The following list gives possible application fields for LD-WMN:

solar power plants In these systems several thousands, movable flat mirrors (heliostats) focus sunlight on a receiver tower. The resulting thermal energy is used to produce electricity. Recent plants use wired field buses to control the individual heliostats. Disadvantages, such as the need of a comprehensive wiring or the vulnerability to lightning strikes, are overcome by the use of a wireless field bus.

smart meter Since 1. January 2010 all new buildings in Germany have to be equipped with smart meters to measure the energy consumption (German Energy Industry Act §21d). Furthermore, the consumption data have to be stored and read out with a rate of 15 minutes. Instead of wired technologies, wireless communication can be applied to reduce installation and maintenance cost.

lightning control An active research area in the industry is the use of wireless communication in the control of light. For example, self-sufficient streetlights need a reliable wireless bus system that works in dense and large deployments.

In addition to the above, other applications are conceivable, e.g. in the area of home automation or inventory management. Hence, a significant rise in demand of wireless technologies working in large-scale, dense networks is expected in the future.

Unfortunately, the scalability of recent protocols may not be sufficient to meet the requirements of certain applications. This leads to the more general question, to what extent specific requirements can be met, e.g. in terms of throughput or end-to-end delay. Is it even possible to establish wireless communication in LD-WMN, especially when using resource-constrained devices?

The main goals of this dissertation are to assess the possibility of using wireless communication in large-scale, high dense mesh networks as well as to develop methodologies and protocols for these environments. Starting point and motivation of the dissertation was the HelioMesh project that was funded by the German government and carried out by the German Aerospace Center (DLR), TRINAMIC Motion Control, and the Hamburg University of Technology. For the HelioMesh project, the author developed and investigated protocols for wireless communication in large-scale, self-organizing heliostat fields optimized for time-critical applications.

The subject of communication in LD-WMN is widely studied so that several contributions are done ranging from topics of network planning up to the concrete realization of services for controlling plants. The dissertation gives a definition of large-scale, mesh networks. Here, the following two assumptions are made: devices are resource-constrained and equipped with IEEE 802.15.4 transceivers; nodes are deployed very densely and equally, thus the network provides a high connectivity. General requirements of LD-WMN are defined. Of practical importance is the compliance to certain service level agreements and government regulations, e.g. a reliable shutdown of devices in an emergency situation. In respect to the defined requirements, the author reveals shortcomings of recent communication protocols.

In order to cope with the challenging conditions of LD-WMN, the dissertation provides several novel communication protocols. Concepts for splitting the network into smaller subnetworks are elaborated. This provides a viable basis for running communication protocols. Next to this, scalable broadcasting and routing protocols are defined that are optimized to the conditions of LD-WMN. Here, the idea of self-stabilization has highly influenced the design of the protocols in order to provide fault-tolerance. On application level, dedicated protocols for specific purposes such as a reliable emergency shutdown and over the air programming are given. The evaluation of protocols is mainly done in simulations and in a testbed deployment of 90 wireless nodes in the solar power plant Jülich.

Since the software development for embedded and distributed systems is challenging, the dissertation proposes tools to facilitate the development process. An important outcome of this is the CometOS framework, which was the base of most experiments done in this work. CometOS provides a convenient programming interface for the implementation of network protocols as well as extensive testing capabilities. This work gives a thorough introduction to this tool.

This dissertation is structured as follows: Chapter 2 provides an overview of the HelioMesh project. The application field of solar power tower plants serves as motivation for the introduction of LD-WMN in general. The chapter closes with a definition of used models and provides the necessary knowledge for understanding this work. In Chap. 3 the topic of programming software for LD-WMN is addressed. This includes a thorough introduction of the OMNeT++ simulation tool as well as the CometOS framework, which enables rapid software development of communication protocols for resource-constrained devices. Several examples and a study for a seamless transition from simulation to real-world scenarios are given. The first algorithmic approaches for coping with LD-WMN are given in Chap. 4. By using the concepts multi-channel communication, multi-gateway deployment, and clustering, the virtual size of the network is drastically reduced. This provides a promising base for running communication protocols. Hence, Chap. 5 shows the usage of connected dominating sets as viable base for broadcasting. In this context a reliable and scalable broadcasting scheme is proposed and evaluated. Afterwards the topic of routing in LD-WMN is addressed in Chap. 6. Existing protocols are examined for their applicability in LD-WMN. Also new protocols are proposed that are optimized for the intended scenario. The chapter closes with an extensive evaluation based on simulations. A case study is done in Chap. 7. Here also solutions for common network services are presented such as an emergency shutdown and over-the-air programming. Finally, a conclusion is drawn in Chap. 8.

2 Problem Domain

A novel application scenario for wireless networks is the monitor and control of distributed, large-scale industrial processes. An example is the control of a solar tower plant consisting of thousands of heliostats. The possibility of using wireless communication in such environments was analyzed in the HelioMesh project. In general, the scale and density of these networks require new concepts for reliable wireless communication.

Section 2.1 introduces the HelioMesh project, which is the motivation for this dissertation. A subsequent generalization of large-scale, dense wireless mesh networks (LD-WMN) is presented in Sect. 2.2. Next to the specification of these networks, general requirements on the communication protocols are derived. Afterwards, the goal of the dissertation is substantiated: the development of methodologies and protocols for wireless communication in large-scale, dense mesh networks. Finally, a brief introduction to the mathematical background of this work, e.g. terminology, graph theory, self-stabilization, and statistics, is given (Sect. 2.3).

2.1 Motivation: The HelioMesh Project

This thesis originates from results of the HelioMesh project. Goal was to develop a self-sustaining and autonomous heliostat and to investigate the use of short-range radio technologies for the control of solar power plants. The HelioMesh project was funded by the German government and carried out by the German Aerospace Center (DLR), TRINAMIC Motion Control, and the Hamburg University of Technology. In the following an introduction to the HelioMesh project is given. This will later serve as an example application for LD-WMN.

2.1.1 Wireless Communication in Solar Power Plants

To become independent of fossil fuels and to contribute to the climate protection, current research focuses on renewable energy. In the field of solar thermal energy collectors, solar power plants show great potential for future use because of their high efficiency in transforming solar into electrical energy combined with lower investment than comparable technologies like parabolic trough power plants. In solar power plants several thousands heliostats, which are movable mirrors tracking the sun, focus sunlight on one receiver tower. There, a steam turbine generator produces electricity. Figure 2.1 shows an example of solar power plant.

Figure 2.1: Example of a solar power plant. *Author: Work of the United States Department of Energy - Public Domain*

Recent plants use wired field buses and power cables to control and supply each heliostat. In conjunction with the concept of the autonomous and self-sufficient heliostat that obtains energy from an additional photovoltaic cell, wireless communication is highly beneficial: High installation costs due to extensive wiring are avoided. The plant manufacturer or operator also gains great flexibility in installing or replacing heliostats.

An example of an infrastructure for the wireless control of heliostat fields is sketched in Fig. 2.2. The whole system is controlled by a central unit called base station, which manages the entire network and provides an interface for the plant control to access the heliostats. The base station is connected to gateways (red lines), e.g. via Ethernet. The gateways are equipped with wireless transceivers and communicate with the heliostats. If no direct wireless communication is possible, routing techniques will have to be applied (blue lines).

2.1.2 Objectives

Next to the use of wireless communication, further aspects were examined in the HelioMesh project. The project contained the following three working packages:

Wireless Mesh Communication (TUHH) Goal was to evaluate and validate the feasibility of a wireless mesh network as control technology for a field of self-powered, autonomous heliostats, thus eliminating the need for cabling.

Auto-Calibration System (DLR) A precise alignment of the heliostats to the receiver tower is mandatory for the process control. To enhance precision and to reduce the network traffic, an auto-calibration method for the heliostats had to be developed.

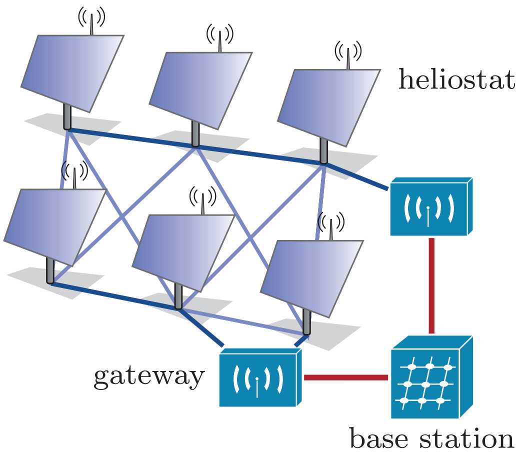

Figure 2.2: Basic communication infrastructure of the HelioMesh project

Optimized drive system and local power management (TRINAMIC) To avoid any cabling, the energy consumption of the drive system had to be optimized in order to run the heliostat self-sufficiently powered by a photovoltaic panel and a supercapacitor.

The author's role in the HelioMesh project was the conception and development of protocols for the wireless mesh communication. A challenge was the enormous size of a solar power plant with up to thousands of heliostats and the high density of the heliostat deployment within such a plant. This requires a communication system of highest scalability. Further design goals are fault-tolerance, minimal latency for time-critical operations, safety and reliability, security, use of low-cost hardware, and low power consumption.

2.1.3 Use Cases

This section defines typical use cases of a solar power plant. Later on, general requirements and traffic patterns for communication in LD-WMN are derived from this. The communication infrastructure of the HelioMesh project had to support the following use cases:

- After the initial deployment, a configuration of the heliostats is necessary. For this, the base station needs to know the existence of available heliostats in order to build up a secure connection to them.

- After the initial deployment as well as after long-term usage a calibration of a heliostat becomes necessary. For this purpose, a heliostat focus sunlight to a special target surface below the absorber of the receiver tower. The plant control evaluates the image data from a camera in order to get