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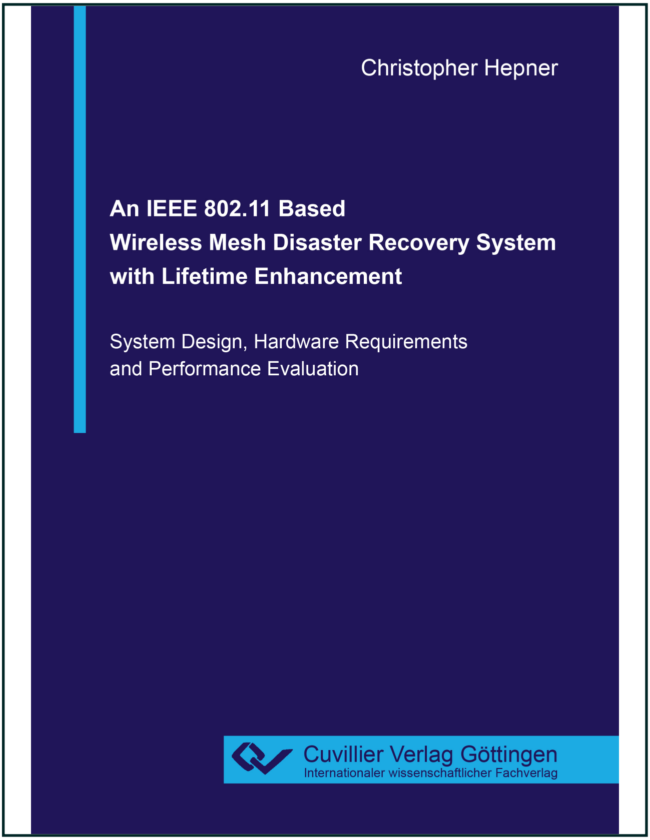
An IEEE 802.11 Based Wireless Mesh Disaster Recovery System with Lifetime Enhancement

System Design, Hardware Requirements and Performance Evaluation



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Chapter 1

Introduction

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1.1 Motivation

After the occurrence of a disaster such as an earthquake, tsunami, hurricane or flood most of the communication infrastructure is usually destroyed or not working due to the loss of power. However, providing a suitable communication network in disaster areas – called a Disaster Recovery System (DRS) throughout this work – as quickly as possible is one of the most essential needs for rescue managers or people in need in order to organize help. This importance is growing also in view of the increasing number of natural disasters over the last 40 years. Figure 1.1 shows the accumulated increase of geophysical (e. g. earthquake, mass movement, volcanic activity), hydrological (e. g. flood, landslide) and meteorological (e. g. storm) disasters sorted by continents since 1975 according to the International Disaster Database of the Centre for Research on the Epidemiology of Disasters (CRED) [1]. Some of the biggest natural disasters to be mentioned in the last years are the floodings during 2010/2011 in China with up to 134 million affected people, the flooding during 2010 in Pakistan with over 20 million people affected and 1985 deaths, Typhoon Haiyan in 2013 which affected over 16 million people in the Philippines and caused 7354 deaths, further the Haiti 2010 earthquake which affected about

3.7 million people and caused 222.570 deaths, the great earthquake in Japan during 2011 which affected 368.820 people and caused 19.846 deaths and the Nepal 2015 earthquake which affected over 5 million people and caused 8831 deaths. Recently hurricanes passed in late 2017, e. g. Harvey, Irma and Maria in central America and earthquakes, e. g. in Mexico strengthen the need for appropriate disaster recovery systems.

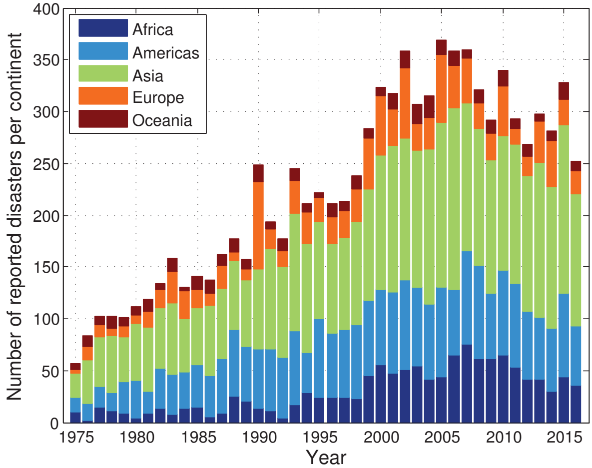

Figure 1.1: Total number of reported natural disasters between 1975 and 2016 [1]

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While nowadays help usually arrives within a few days it still happens that some regions are isolated for weeks after natural disasters. However, the great earthquake in East Japan (2011) or the Pakistan flood (2010) showed that the rescue teams are composed only of very few trained professionals, but of hundreds of disorganized volunteers during the first hours. Therefore it has been proposed, e. g. in [2], [3], [4], [5], [6], [7] and [8], to use the infrastructure which is still working or to use devices carried by the rescue teams and volunteers themselves or a combination of both to set up a communication system.
Because of the so called "golden 72 hours" [3] – which are the most important ones for successful rescue operations – a communication system for the rescue volunteers and rescue teams should instantaneously be available without any deployment. Almost immediate availability and a sufficient lifetime of a communication infrastructure after occurrence of a disaster can thus be considered as key elements of successful operations of search and rescue and is the key subject of this research work.

Additionally, during the last years internet and social media became more and more important in the aftermath of natural disasters. Volunteers at the East Japan great earthquake (2011) used the internet to organize their activities [9]. A study of NetHope [10] shows that spontaneous local volunteers were using internet-based social media on mobile devices to reach out for help during the 2010 Pakistan flood. Humanity Road Analytics details that the most commonly searched terms used by the public when viewing their website were the need for “shelters” followed by “find hospital” [10]. Google engineers built the “Google Person Finder” in response to the January 2010 Haiti earthquake in order to help those affected by the earthquake to connect with their relatives [11]. It is an open source web application that allows individuals to post and search for the status of relatives or friends affected by a disaster. Since then the software was used e. g. in the February 2010 Chile earthquake, July 2010 Pakistan floods (where it didn’t work well because people in the affected area had no internet access [12]), February 2011 Christchurch earthquake, March 2011 Tohoku earthquake and tsunami, October 2011 Van earthquake, April 2013 Ya’an earthquake, October 2013 cyclone Phailin, November 2013 typhoon Haiyan and April 2015 Nepal earthquake. Recently Google has also activated the Person Finder service in the aftermath of hurricane Maria in 2017.

Recently the Federal Office of Civil Protection and Disaster Assistance – Bundesamt für Bevölkerungsschutz und Katastrophenhilfe (BBK) – in Germany has also published a guide for emergency preparedness and correct action in emergency situations. The document focuses on personal preparedness of each individual ([13], 2016). In general it is said: Germany is well prepared. A number of organizations such as fire brigades, the police and rescue services are there for everyday aid. However, it is also stated that even the best assistance is not always on the spot immediately and in the event of a large-scale and very serious disaster the rescue workers cannot be everywhere. Everyone is encouraged to be able to help themselves. The BBK has also developed an Emergency Information and Warning App called NINA (Notfall-Informations- und Nachrichten-App). The App is intended to warn users about emergencies and hazards all over Germany, such as severe weather, floods and other relevant events. The push functionality calls the attention of the users always to current threats. However, it has to be emphasized that during an electric power breakdown, mobile phones will only continue to work for a short time and these services are no longer available [13].

In 2015 the BKK has started a collaborative research project with the Technical University of Darmstadt and the University of Kassel, called “smarter”. “smarter” stands for Smartphone-based Communication Networks for Emergency Response and allows, by the help of a smart phone App that was developed during the project, the direct communication from smart phone to smart phone via a Wi-Fi based ad-hoc network. The research partners thereby examined different areas covering the technical feasibility, the legal framework or the behavior and needs of people in crises and disasters. In the smarter project the BBK looked at the behavior of the population in crises and catastrophes. To this end a field test was carried out during the project in order to examine how the participants used the App and which functions they considered to be of particular importance. The preliminary evaluation of the data in [14] showed that it was most important for the participants to exchange messages, to call for help and to receive valuable information. [14]

1.2 Objective

For the immediate needs of communication after the occurrence of a disaster, approaches that use the infrastructure which is still available ([3], [5], [8]) seem to be most suitable. In this work a new approach for this kind of DRS is proposed based on the mesh network amendment for Wireless Local Area Networks (WLANs) IEEE[1] 802.11s [15]. The focus thereby is on enhancing the lifetime of the DRS in order to bridge the time until professional rescue teams with their communication equipment will arrive while still keeping a network connectivity that provides essential communication needs, especially Voice over IP (VoIP) and low-rate data services. It is assumed that WLAN interfaces will be available in many systems in the future such as smart phones, laptops, cars and home appliances where most of them are battery powered or at least have an auxiliary battery. All these WLAN devices in the disaster area are assumed to have mesh functionalities and therefore are called Mesh Stations (MSTAs). Because of the number of devices available in disaster areas and the ease of networking without the need of additional infrastructure a wireless mesh network built from the devices that are still functional after the occurrence of a disaster may provide a very attractive way to set up a communication network in a disaster area already during the first hours.

Currently, WLAN based mesh networks have their primary usage scenario in the domain of public wireless access where the wireless mesh network provides a flexible backhaul for WLAN access points, which are distributed throughout cities or university and company campuses. In the future, however, it seems quite probable that the mesh network capability might be available in a high number of WLAN devices, e. g. through its availability in open source implementations such as OpenWrt [16]. In order to protect owners of the MSTAs from illegal usage and law infringements by unwanted establishment of a DRS a mechanism such as an emergency mode for the MSTAs ([5], [17]) has to be used. During an emergency situation the wireless stations will leave their usual mode of operation and will switch into the emergency mode and thus can be used by the rescue teams or people in need. Let us remark that the activation of this mode is out of the scope of this work.

Objectives of this work are to propose a Wireless Mesh Network (WMN) based DRS using legacy IEEE 802.11s, to develop a suitable algorithm for lifetime enhancement of the DRS and to investigate the achievable network performance of such a DRS.
The system coverage of the DRS will be investigated by system simulations carried out in Matlab and the achievable network performance will be analyzed by network simulations with the network simulator ns-3. In order to get more reliable results from the network simulations which additionally account for constraints introduced by the underlying hardware, the ns-3 network simulator is further extended by including hardware parameters which are obtained by small testbed measurements in a laboratory environment.

[1]Institute of Electrical and Electronics Engineers (IEEE).

Let us make the proposed DRS more explicit by giving a simple example. Figure 1.2 shows a sketch of a disaster recovery situation after an earthquake with connected Mesh Stations in home appliances (e. g. Access Points (APs) with Mesh capability) and cars. All MSTAs which are within the transmission range of each other establish peer links in between them and thus allow the routing of data throughout the mesh network formed by them. The communication is routed from handheld devices (e. g. smart phones, laptops) of the rescuers through an essentially static network formed by the remaining devices (e. g. battery powered MSTAs in cars, Access Points with mesh functionality and smart home devices) that are still working. One or more MSTAs in the mesh network may also act as a gateway to another network. Figure 1.2 shows the communication between two users by their smart phones over the mesh network as an example.

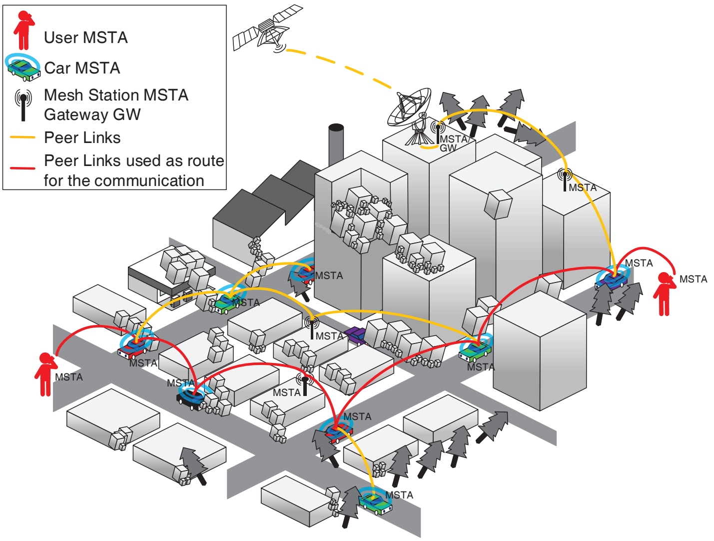

Figure 1.2: Sketch of Disaster Recovery System (DRS) after an earthquake built from connected Mesh Stations (some of them with gateway capability to other networks) in home appliances and cars.

Smart phones and laptops are assumed to have a relatively low battery lifetime between zero and 24 hours. This also holds for currently available battery powered travel routers. On the other hand, WLAN interfaces available in cars or in some other types of battery powered electrical devices may have much longer battery lifetimes of several days because of the powerful batteries in these devices. It is assumed that the number of such devices will be strongly increasing throughout the coming years by the idea of the “internet of things” and the “connected car”. A WMN serving as DRS could thus be set up by the MSTAs available in numerous devices which are not destroyed. Volunteers as well as victims using their own smart phones or laptops may use this WMN and communicate within the covered area. Several services such as voice over IP, push to talk, video streaming or a map of the disaster area can be kept in mind as useful services for the rescue teams. Even an injured person who is located under rubble could set up an emergency call over the WMN.

The solution proposed in this work covers the following requirements that a disaster recovery system will have to fulfill:

1. System requirements:
   - Instantaneous availability of the system within the first hours after the occurrence of a disaster.
   - Formation of the system by standard user equipment.
   - Access to the system with standard user equipment.
   - Enhancement of the lifetime of the DRS while still providing sufficient coverage and network performance.
2. Service requirements:
   - Possible communication of rescuers and victims by a VoIP connection.
   - Possible exchange of text or voice messages.
   - Internet connection, if MSTAs with network access and gateway capability are still available.

These requirements have to be provided over a maximum period of time. Therefore a distributed algorithm is proposed which enhances the lifetime of such a system by an approach which allows to shut down non necessary nodes in order to save their battery capacity for later usage while still keeping network connectivity.
The difficulty thereby is to validate the functionality of such an algorithm with a huge number of MSTAs which are distributed in the disaster area. Testbed measurements of such a network with a large number of MSTAs would be time-consuming, expensive and rather difficult to set up. Network simulation on the other hand allows the relatively fast assessment even of complex scenarios with reproducible results and relatively simple change of settings, protocols and environment. However, it may provide unrealistic results if hardware aspects are not properly considered. In order to overcome these challenges an incremental approach, by successively increasing the complexity of the model and successively taking hardware influences into account is proposed, finally leading to a realistic modeling of the system, covering the most relevant parameters.

Figure 1.3 summarizes the methodology developed in this thesis and how it is used to develop a DRS which is capable of achieving the proposed requirements. Further the tool chain, which is used in this work is briefly outlined in Fig. 1.3.
First, the question of how many MSTAs are needed to achieve a connected network in a disaster area of given size is investigated based on state-of-the-art analytical calculations assuming toroidal boundary conditions and thus allowing to neglect boundary effects (Fig. 1.3 a).
In order to additionally account for boundary effects the achievable connectivity will be further calculated by Monte Carlo simulations carried out in Matlab for a dedicated amount of nodes N within finite rectangular areas. Of specific interest for what follows is the covered area which can be reached by the largest subset of connected nodes $n_1, \ldots, n_{N_c(t=0)}$ and its associated probability which will be called the coverage of the DRS. These quantities will be evaluated by Monte Carlo simulations on system level carried out in Matlab (Fig. 1.3 b).
The achievable lifetime of the network can be calculated by extending the simulation approach in Matlab to cover the finite lifetime of the individual nodes (Fig. 1.3 c). This is achieved by adding a certain lifetime to each node and calculating the coverage of the remaining nodes $n_1, \ldots, n_{N_a(t_j)}$ for dedicated time instances $t_1, \cdots, t_m$. Coverage thereby again is characterized by the area covered by the largest subset of connected nodes $n_1, \ldots, n_{N_{a,c}(t_j)}$ still available at a given time instance t_j and its associated probability.
In order to enhance the lifetime of the system a distributed algorithm will be developed. This algorithm denoted as Lifetime Enhancement Algorithm (LEA) allows to shut down redundant nodes and reactivate them later when needed (Fig. 1.3 d). The algorithm works on basis of the IEEE 802.11s Mesh Peering Management (MPM) protocol by developing an appropriate metric for the decision of when to shut down and when to reactivate an individual node. Again the coverage of the remaining active nodes which are still working and not shut down $n_1, \ldots, n_{N_a(t_j)}$ for dedicated time instances $t_1, \cdots, t_m$ can be calculated demonstrating the achievable extension of system lifetime at given coverage requirements.
In order to evaluate the network performance that can be achieved by the DRS, the protocol stack for the WMN has to be taken into account. The statistical network performance thereby is evaluated on basis of VoIP connections between two randomly placed nodes (e. g. two rescuers) using network simulations within the network simulator ns-3. As a first step (Fig. 1.3 e) the network performance at a given time instance t_j is investigated by using the distribution and positions of the active nodes $n_1, \ldots, n_{N_a(t_j)}$ as calculated by the implementation of the Lifetime Enhancement Algorithm (LEA) in the Matlab based system simulation. This type of network simulation in ns-3, which does not provide for an implementation of LEA within the network simulator itself we will call the so called static simulation. The static simulation thereby allows to analyze the achievable network performance of LEA without the additional influences of the protocol stack and physical layer during the execution of the LEA itself. Thus the static network simulation provides information on the network performance of the thinned out network that is established by LEA under the idealized assumption that LEA itself is not affected by the network protocol and wireless channel performance.

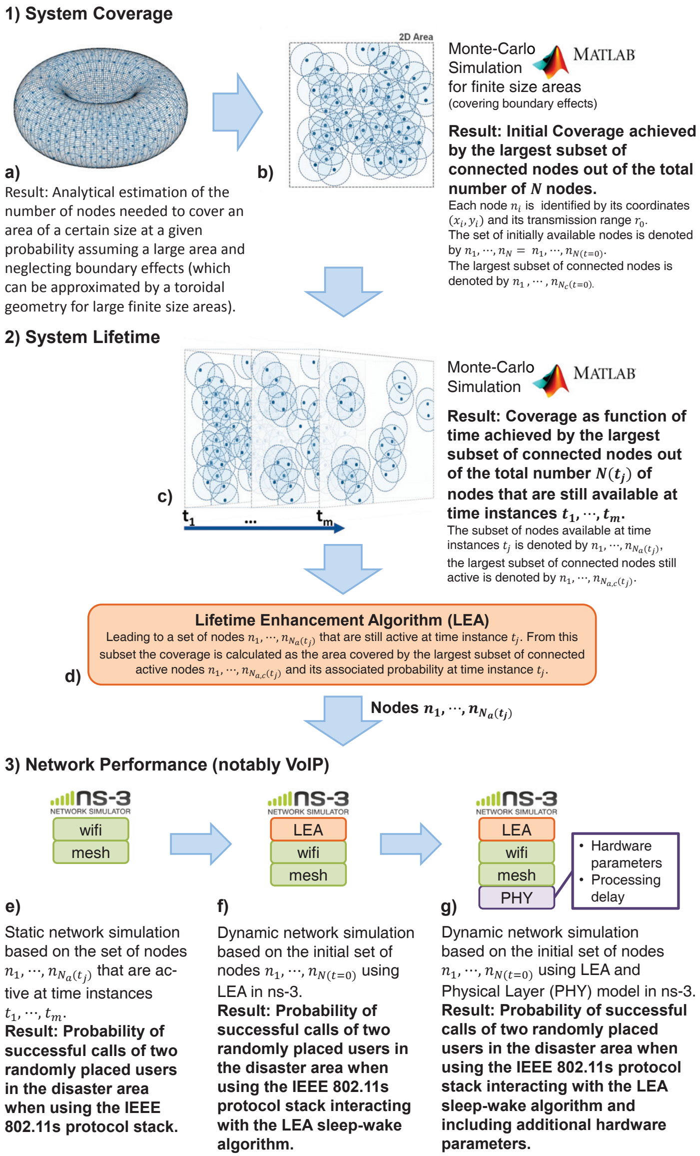

Figure 1.3: Overview on the methodology and toolchain used throughout the thesis in order to achieve the objectives of this work.

The key result of the static network simulation will be the probability for successful calls that can be achieved between two randomly placed users and is obtained by carrying out a sufficiently large amount of Monte Carlo simulation runs.
Second (Fig. 1.3 f), the DRS network performance will be evaluated by using a full implementation of the distributed algorithm within the network simulation itself which is based on alternating sleep and awake states for each individual node. In that way the algorithm can be analyzed in conjunction with the whole protocol stack. This type of simulation we will call the dynamic network simulation. Again the key result is the probability of successful VoIP calls between two users randomly placed in the disaster area and again it is obtained by carrying out a sufficiently large amount of Monte Carlo simulation runs.
Finally (Fig. 1.3 g), the network performance will be analyzed under the additional influence of an appropriate physical layer model which is based on explicit hardware parameters obtained from test network measurements with appropriate hardware modules. Key hardware parameters to be determined thereby are processing delays and packet error rates. Both parameters are investigated by measurement setups requiring only a small number of MSTAs, e. g. in small testbed arrangements. Using appropriate testbed arrangements it will be possible to measure the delay which is added by each hop in a multihop scenario. In that way the processing delays which are added in each MSTA due to the software execution time and scheduling mechanism of tasks in the CPU can be reliably estimated. In the framework of appropriate testbed setups the error rate performance of IEEE 802.11s hardware modules is evaluated and correlated with the physical layer model employed in ns-3. The ns-3 physical layer model is based on the calculation of Bit Error Rates (BERs) taking into account the forward error correction present in IEEE 802.11 and will be compared with hardware measurements.
The final results including these additional hardware parameters (i. e. an appropriate physical layer model based on the BER-model, hardware parameters as well as an appropriate processing delay model) will indicate the feasibility and possible lifetime of a IEEE 802.11s based DRS and the achievable network performance assuming a VoIP connection of two rescuers.

Part of this work has been published throughout the last years by the author. The influence of processing delays on the VoIP performance for IEEE 802.11s multihop wireless mesh networks and further the comparison of ns-3 network simulations with hardware measurements has been published in [18]. The Lifetime enhancement of Disaster Recovery Systems based on IEEE 802.11s Wireless Mesh Networks and further the enhancement by using a sleep-wake algorithm with a minimum number of neighbors has been published in [19] and [20]. The analysis of the ns-3 physical layer abstraction for WLAN systems and evaluation of its influences on network simulation results has been published in [21] and [22]. A validation of the ns-3 802.11s model finally has been published in [23].

1.3 Outline

This thesis is structured as follows:

Before developing the DRS system design in Part I of this thesis, some fundamental considerations are presented in Chapters 2 and 3.
Chapter 2 thereby gives an overview on the state-of-the-art of research on Disaster Recovery Systems and the IEEE 802.11 Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications.
Chapter 3 provides evaluation methods for coverage, connectivity and network performance of Wireless Mesh Networks. Specifically an appropriate method for the calculation of the coverage of a DRS is developed.
For a successful usage of the ns-3 network simulator in order to evaluate the performance of IEEE 802.11s WMNs based DRS a number of modifications and amendments had to be developed throughout this thesis. The second part of Chapter 3 is dedicated to a presentation of these modifications including a validation of the resulting MAC and PHY implementations in ns-3 based on both analytical calculations and simulation.

The thesis is then organized in two main parts. Part I discusses the system design. First the system concept of the DRS based on the requirements is shown in Chapter 4. The system coverage will be analyzed by analytical and simulative approaches and the system lifetime will be investigated based on Monte Carlo simulations.
Chapter 5 then presents the algorithm for the lifetime enhancement (LEA) of the DRS, carries out a proof of concept and finally develops the distributed sleep-wake algorithm acting on each individual MSTA.

Part II presents the system implementation and validation. First the network performance of the distributed lifetime enhancement algorithm is evaluated in Chapter 6.
Chapter 7 details the additional hardware requirements on the air interface. In particular the rerouting performance evaluation and the influence of processing delays on the VoIP-performance will be shown.
Chapter 8 shows the final system performance of the DRS including additional hardware parameters which will indicate the feasibility and possible lifetime of a IEEE 802.11s based DRS as well as the achievable network performance assuming a VoIP connection between two rescuers.

Chapter 9 concludes the thesis work and presents suggestions for future work.