TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

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Aspects of Critical Communications in Disturbance Scenarios

Julkaisu 1467 • Publication 1467

Tampere 2017

Tampereen teknillinen yliopisto. Julkaisu 1467
Tampere University of Technology. Publication 1467

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Aspects of Critical Communications in Disturbance Scenarios

Thesis for the degree of Doctor of Science in Technology to be presented with due permission for public examination and criticism in Tietotalo Building, Auditorium TB109, at Tampere University of Technology, on the 28th of April 2017, at 12 noon.

Tampereen teknillinen yliopisto - Tampere University of Technology
Tampere 2017

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ISBN 978-952-15-3932-9 (printed)
ISBN 978-952-15-3933-6 (PDF)
ISSN 1459-2045

Abstract

INFRASTRUCTURES are the foundations of modern societies. The most important ones are the so-called critical infrastructures: mobile networks and electricity networks. If these networks are damaged or otherwise unavailable, the functionality of the whole society is at risk and can result even in public safety hazards. Furthermore, people expect all the time ubiquitous access to internet through mobile networks as many services rely on these wireless networks. The dependence is growing all the time as the number of worldwide subscriptions has already exceeded the world population and the amount of internet of things (IoT) and other connected devices continues to increase exponentially.

This thesis focuses on the critical communications aspects of mobile networks during disturbance scenarios. These are defined as situations where, e.g. there is a power blackout in the electricity network, which affects the functionality of the mobile network.

The contributions of this thesis can be divided into three main themes. The first one is the actual functionality of mobile networks during disturbance scenarios. This includes finding out how the behavior of subscribers changes when there is an uncommon disturbance scenario in the mobile network and how to prolong the disturbance time functionality of the existing networks. The results show that subscribers utilize mobile networks more than usual already before the power blackout starts when they try to find out information about the status of an upcoming storm. Immediately after the disturbance scenario starts, the subscribers within the blackout area are more active as the statistics show 73 % increase in the number of new calls and 84 % in the amount of short message service (SMS) messages. The results show also that the majority of mobile network availability is lost after 3–4 hours from the start of the incident. In order to prolong this availability time, simulations are performed to find out how utilizing only a portion of the available base station (BS) sites affects the service coverage. The results show that around 20 % of BS sites would be enough to cover 75 % of the original service coverage. Therefore, the operational time of the so-called mobile network backup coverage could be increased several times given that core network (CN) and backhaul network are also operational.

The second main theme in this thesis presents a new developed situation awareness system (SAS) that combines the outage information of both mobile and electricity networks. This is an important tool for monitoring the networks and performing disaster and disturbance management. The user interface of the developed SAS is a map view showing the outage information, i.e. the faults, in both networks. It utilizes operational data from both networks such as the coverage outage areas of the mobile network and the outages of transformers in the electricity network in near real-time. The developed SAS helps to prioritize maintenance and repair work to the most critical areas as well as help to form a better overall situation awareness that fire and rescue services and authorities could utilize for improving public safety actions.

The last main theme in the thesis considers innovative solutions in order to find out methods to improve the performance, i.e., to mitigate the outage of mobile networks in disturbance scenarios. The three different approaches presented are the indirect guidance of subscribers, the concept of a temporary low altitude platform (LAP) network with the help of drones, and the concept of a macro sensor network (MSN). First, the energy and capacity aspects of mobile networks can be improved when the subscribers are indirectly guided to self-optimize their location in the serving cell area. This can result in serving more user equipment (UEs) within a cell or to decrease the amount of energy needed for transmissions. Next, the coverage aspects of a LAP system are studied in order to find out the suitability of forming a temporary emergency coverage with a wireless local area network (WLAN) equipped drones. The results show that this kind of approach could provide a suitable emergency coverage for a limited area with a reasonable number of drones. Finally, a framework for MSN is studied to investigate the possibility of bringing wireless sensor network (WSN) functionalities into mobile networks. The results show that the concept of MSN could remarkably improve the resilience of mobile networks in situations where the backhaul connection is broken. However, implementing and further developing this kind of functionality will require changes in the 3rd Generation Partnership Project (3GPP) specifications and self-organizing network (SON) features within the network.

Overall, this thesis provides insight on how to develop the current and future mobile networks toward more resilient infrastructures. It highlights the importance of critical communications as a fundamental part of modern societies. Thus, securing the functionality and performance of mobile networks in all situations is crucial. As a result, the contributions in this thesis can be utilized as a starting point in the future research to develop new functionalities for mobile networks. One of such approaches can be a safety mode, which would improve the mobile network resiliency during disasters and disturbance scenarios.

Preface

This thesis is based on the research work carried out during the years 2013–2016 at the Department of Electronics and Communications Engineering, Tampere University of Technology, Tampere, Finland.

First, I gratefully acknowledge all the financial support received for enabling the research work required for writing this thesis. The majority of the funding was received from Finnish Funding Agency for Technology and Innovation (Tekes) under a project called "Cooperative planning and monitoring of mobile and electrical networks". I am also very pleased for the personal supportive grants from Tuula and Yrjö Neuvo Foundation, and Finnish Foundation for Technology Promotion (TES). I would also like to acknowledge doctoral training network in electronics, telecommunications and automation (DELTA) for financial support in the form of travel funds to conferences. Finally, the supplementary dissertation funding of Tampere University of Technology Graduate School in the Doctoral Programme of Computing and Electrical Engineering supported me in finalizing this dissertation.

I would like to express my deepest gratitude to my supervisor Prof. Jukka Lempiäinen. It has been a pleasure to work with him and to follow his vision of the research in the field of wireless communications and especially in the field of radio network planning and optimization. I would also like to thank Prof. Mikko Valkama and Prof. Markku Renfors for creating such a good and inspiring atmosphere over the years.

I am grateful to the thesis pre-examiners Prof. Riku Jäntti and Prof. Jouko Vankka for their valuable time and efforts in the review process. Furthermore, I wish to thank Prof. Mario Garcia-Lozano and Prof. Riku Jäntti for agreeing to act as the opponents in the public examination of my thesis.

I wish to dedicate special thanks to my friendly ex-roommate and one of the co-authors Syed Fahad Yunas. His constructive and encouraging feedback has been truly invaluable. I would also like to express my gratitude to my other co-authors Dipesh Paudel, Heidi Krohns-Välimäki, Jussi Haapanen and Prof. Pekka Verho for the enjoyable collaboration. Furthermore, I would like to thank Muhammad Usman Sheikh with whom I have had the pleasure to discuss research related topics and to write publications outside the topic of this thesis. Special thanks are also required for Hans Ahnlund who helped me with the simulations.

I have also had the joy of sharing our office with my other roommate Sharareh Naghdi with whom I have had a pleasure to discuss work and life in general. I wish to thank also Tero Isotalo, Panu Lähdekorpi, Jussi Turkka, Markus Allén, Jukka Talvitie, Toni Levanen and Ari Asp for first acting as great teachers during my bachelor's and master's studies and later as colleagues. The work in the department would have been too exhausting without relaxing breaks and events with the aforementioned people as well as with Aki Hakkarainen, Dani Korpi, Janis Werner, Mahmoud Abdelaziz, Matias Turunen, Mike Koivisto and Simran Singh who have always been there when it comes to coffee, lunch or sauna. Besides the previously mentioned activities, I wish to thank Pedro Figueiredo e Silva, Timo Huusari and Jaakko Marttila for accompanying me to the gym or other sports-related activities which have helped me to achieve "a healthy mind in a healthy body". I would also like to thank everyone else whom I had the pleasure of meeting and working in these years. I am grateful also to our helpful secretaries Heli Ahlfors, Tuija Grek, Sari Kinnari, Soile Lönnqvist and Päivi Oja-Nisula who have taken care of all the daily practicalities at work.

I would especially like to thank my parents Anja and Juha, my sisters Noora and Jenna, as well as my brother-in-law Mikko for encouraging me to push forward and for supporting me throughout my studies and life in every way. I also want to thank my wife's parents Elisa and Erkko, her siblings Erkka and Elina, as well as Ene and Sanni. Finally, and most of all, I want to thank my beloved wife Evita for all the love, patience and care over the years.

Tampere, March 2017
Joonas Säe

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List of Publications

This thesis is a compound thesis based on the following seven publications.

[P1] J. Säe and J. Lempiäinen, "Mobile Network Service Demand in case of Electricity Network Disturbance Situation," in *Proceedings of the 27th International Symposium on Personal, Indoor, and Mobile Radio Communication (PIMRC)*, Valencia, Spain, September 2016.

[P2] J. Säe and J. Lempiäinen, "Maintaining Mobile Network Coverage Availability in Disturbance Scenarios," in *Mobile Information Systems*, volume 2016, 10 pages, September 2016.

[P3] H. Krohns-Välimäki, J. Säe, J. Haapanen, P. Verho, and J. Lempiäinen, "Improving Disturbance Management with Combined Electricity and Mobile Network Situation Awareness System," in *International Review of Electrical Engineering*, volume 11, number 5, pages 542–553, October 2016.

[P4] H. Krohns-Välimäki, J. Haapanen, P. Verho, J. Säe, and J. Lempiäinen, "Combined electricity and mobile network situation awareness system for disturbance management," in *Proceedings of the IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA)*, Bangkok, Thailand, November 2015.

[P5] J. Säe and J. Lempiäinen, "User guided energy and capacity optimization in UMTS mobile networks," in *Proceedings of the 25th International Symposium on Personal, Indoor, and Mobile Radio Communication (PIMRC)*, Washington D.C., USA, September 2014.

[P6] J. Säe, S. F. Yunas, and J. Lempiäinen, "Coverage aspects of temporary LAP network," in *Proceedings of the 12th Annual Conference on Wireless On-demand Network Systems and Services (WONS)*, Cortina d'Ampezzo, Italy, January 2016.

[P7] D. Paudel, J. Säe, and J. Lempiäinen, "Applicability of macro sensor network in disaster scenarios," in *Proceedings of the 4th International Conference on Wireless Communications, Vehicular Technology, Information Theory and Aerospace & Electronic Systems (VITAE)*, Aalborg, Denmark, May 2014.

Abbreviations

2G	Second generation
3G	Third generation
3GPP	3rd Generation Partnership Project
4G	Fourth generation
5G	Fifth generation
AP	Access point
BS	Base station
CN	Core network
CPICH	Common pilot channel
CS	Circuit switching
DAD	Disaster area drone
DL	Downlink
DMS	Distribution management system
DPM	Dominant path model
DSO	Distribution system operator
E-UTRA	Evolved UMTS terrestrial radio access
EIRP	Effective isotropic radiated power
eNB	Evolved Node B
EPC	Evolved packet core
ETSI	European Telecommunications Standards Institude
FANET	Flying ad hoc network
FCC	Federal Communications Commission
FDD	Frequency domain duplex
FICORA	Finnish Communications Regulatory Authority
GD	Gateway drone
GSM	Global system for mobile communications
HAP	High-altitude platform
HO	Handover
HPBW	Half-power beamwidth

HTTP	Hypertext transfer protocol
HTTPS	Hypertext transfer protocol secure
ICT	Information and communication technology
IDD	Inter-drone distance
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of things
ISD	Inter-site distance
KPI	Key performance indicator
LAP	Low altitude platform
LOS	Line-of-sight
LTE	Long term evolution
MANET	Mobile ad hoc network
MEO	Medium-Earth Orbit
MNO	Mobile network operator
MPG	Mobile performance gaming
MSN	Macro sensor network
MySQL	Structured query language
NLOS	Non-LOS
OLOS	Obstacle LOS
PS	Packet switching
QoS	Quality of service
RAB	Radio access bearer
RAN	Radio access network
RSCP	Received signal code power
RSRP	Reference signal received power
SA	Situation awareness
SAS	Situation awareness system
SCADA	Supervisory control and data acquisition
SDCCH	Standalone dedicated control channel
SINR	Signal-to-interference-and-noise ratio
SMS	Short message service
SOAP	Simple object access protocol
SON	Self-organizing network
TRX	Transceiver
UAV	Unmanned aerial vehicle
UE	User equipment
UL	Uplink
UMTS	Universal mobile telecommunications system
WLAN	Wireless local area network
WSN	Wireless sensor network
XML	Extensible markup language

Symbols and Notations

A	Frequency dependent parameter for Okumura-Hata model
$a(\cdot)$	City size dependent function
B	Frequency dependent parameter for Okumura-Hata model
C	User-defined parameter for tuning the propagation slope
C_{m}	Area correction factor
d	Distance between transmitter and receiver
d_{km}	Distance between BS and UE [km]
$f(\cdot)$	Interaction loss function
f_{MHz}	Frequency [MHz]
g_{t}	Transmitting antenna gain
h_{BS}	BS antenna height
h_{UE}	UE antenna height
i	Interaction index
$\bar{i}_{\mathrm{DL}}$	Average other-to-own cell interference
K	Total number of users per cell
k	User index
L	Path loss
$\overline{L}$	Average path loss
l	Channel index
m	Number of busy channels
N	Maximum number of interactions
n	Path loss exponent
NF	Noise figure
N_{rf}	Noise spectral density
p_m	Blocking probability
R_k	Bit rate of the kth user
T	Temperature
t	Time of arriving call
v_k	Activity factor of the kth user

W	System chip rate
α_k	Orthogonality factor of the kth user
η_{DL}	Downlink load factor
λ	Wavelength
λ_{r}	Amount of inter-arrival incidents over time
μ	Amount of calls over time
ρ_k	SINR of the kth user
φ	Propagation direction angle
Ω	Amount of calls over time

CHAPTER 1

Introduction

All the time ubiquitous mobile networks are the foundation for wireless networks in modern societies. People expect that they can access the internet and other services from everywhere and at any time. Nowadays, many services such as subscriber services (phone calls, instant messaging, internet browsing, etc.), resilience infrastructure maintenance and repair work (mobile networks and electricity networks), and emergency services rely on wireless communications access provided by mobile networks. Thus, the majority of services within a society require a working wireless connection.

1.1 Background and motivation

The worldwide amount of mobile connections has already exceeded the population with over 7.4 billion subscriptions [27, 38]. Besides connecting people, the internet of things (IoT) will further increase the importance of cellular networks with the emergence of new fifth generation (5G) mobile networks within a few year, i.e. already before 2020 as expected in the industry [4, 27, 69]. Moreover, it is estimated that currently there are over 400 million IoT devices utilizing only mobile networks and it is forecast that by 2022 it will reach already 1.5 billion [27]. Thus, societies rely and continue to depend more and more on the availability and functionality of these networks.

The reliability of cellular networks has improved greatly during the 21st century, to some extend as a result of the *Tampere Convention on the Provision of Telecommunication Resources for Disaster Mitigation and Relief Operations* treaty [49] negotiated and adopted on June 18, 1998 [48], which officially came into force on January 8, 2005 [50]. Many countries have improved the resiliency of mobile networks to some extent, but few countries in the world have prepared for the worst possible outcome.

Since the majority of modern technologies utilize electricity as their power resource, the functionality of critical services is directly related to the availability of electricity. Without it, e.g. the whole communications network would not work. Thus, the resilience of mobile networks usually translates to how long it can maintain its functionality without electricity from the main grid by utilizing some other power resources. These include mostly backup batteries and aggregates or the utilization of renewable energy resources directly at the base station (BS) sites where they are needed (given they are sufficient enough, i.e. they are a suitable option for that particular location).

The main cause of not having electricity from the grid to power other infrastructures is a power blackout, which can result from a simple hardware failure or in the worst case some (natural) disaster scenario. Naturally, given a normal utilization of the communications networks, the backup energy resources are dimensioned to last some predefined time period. However, if the cellular network has to rely on backup power this usually means that a power blackout has also occurred, and that the behavior of mobile network subscribers has changed. This translates into more demand for mobile network services, which results in the lack of capacity and shorter time period for the backup batteries to maintain operation.

This thesis focuses on the problems that occur with disturbance scenarios in mobile networks. How do subscribers change their mobile network service behavior during disturbances? How to prolong the operational time of mobile network services during a disturbance scenario? How to improve disturbance management and the overall situation awareness? What kind of innovative methods could be utilized for critical communications in order to mitigate mobile network service outages?

1.2 Objectives and scope of the thesis

The main objective of the thesis is to investigate innovative methods to improve the performance and restoration of mobile networks in case of disturbance scenarios. This includes studying the effects of disturbance situations in mobile networks and their effect on the mobile network subscriber behavior, new methods to monitor the network functionality in order to improve the overall disaster management, and finding out different innovative approaches to improve the performance (i.e. to mitigate service outage) of mobile networks.

1.3 Thesis contributions and structure

In short, the main contributions of the thesis are the following.

- Providing information on the current mobile network subscriber behavior during disturbance scenarios by analyzing operative cellular network service demand caused by a power blackout in the electricity network [P1].
- Prolonging the “disturbance time availability” of mobile networks by utilizing only a portion of BS sites within a disturbance area during a power blackout [P2].
- Improving disaster management by developing and studying a combined situation awareness (SA) system for mobile and electricity networks [P3–P4].
- Proposal and analysis of indirectly optimizing mobile network energy and capacity usage with the help of mobile network subscribers [P5].
- Analyzing the coverage possibilities of a temporary low altitude platform (LAP) system deployed into a disaster area with the help of a wireless local area network (WLAN) equipped drones connected to a cellular network [P6].

- Investigating the applicability of a wireless sensor network (WSN) functionalities for cellular networks in disaster scenarios [P7].

Publications [P1–P7] provide more details and examples compared with what is discussed in this thesis summary. In order to provide a fluent reading experience, the notation of the thesis and the visual appearance of some figures differs slightly from the associated publications.

The thesis is organized into three different main parts. The first part includes Chapters 2 and 3. Chapter 2 provides insight into the background of critical infrastructures, whereas Chapter 3 presents the contributions of the thesis on how mobile network subscribers behave during a disturbance scenario and how to prolong the disturbance time availability of the networks. The second part discusses in detail the developed SA system in Chapter 4. The last part in Chapter 5 presents innovative approaches to improve the performance of mobile networks especially during disturbance and disaster scenarios. Finally, Chapter 6 concludes the thesis.

1.4 Author's contributions to the publications

The base for this thesis topic was formed in the context of a Tekes-funded project called "Joint planning and monitoring for mobile communication and electrical networks" (referred to as "TELE4SG" later on). This project inspired the author and Prof. Jukka Lempiäinen to device the actual topic together regarding the aspects of mobile networks as a critical infrastructure.

In general, Prof. Jukka Lempiäinen has contributed to all publications [P1–P7] by mainly initiating a discussion about a possible idea for a publication, providing support with discussions during the research phase, and giving feedback for the written manuscripts. The final topics of the publications were mainly finalized by the author, except for publications [P3–P4], which were formed together with M.Sc. Heidi Krohns-Välimäki and publication [P7], which was formed together with M.Sc. Dipesh Paudel.

The author is the main contributor to the majority of the publications [P1–P2, P5–P6]. In [P1–P2], the author performed all the simulations, analysis, and manuscript writing leading to publications. In [P5], Prof. Jukka Lempiäinen performed the required measurements and initiated the writing process, but the author did all of the analysis and the majority of the actual manuscript preparation. Likewise, the simulations in [P6] were performed by D.Sc. Syed Fahad Yunas, but all of the writing process and simulations scenarios planning with the analysis of the obtained results were prepared by the author.

Publications [P3–P4] were written in cooperation with M.Sc. Heidi Krohns-Välimäki as the first author, with co-authors M.Sc. Jussi Haapanen and Prof. Pekka Verho from the Department of Electrical Engineering in Tampere University of Technology. The topics for these publications came from the TELE4SG project, where the author was the main researcher for wireless communication field and H. Krohns-Välimäki, J. Haapanen and P. Verho were responsible for the topics related to electrical engineering. In practice, the author contributed to these publications by refining the ideas for the manuscripts, writing the parts of the publications related to wireless communications, performing the required simulations from the wireless communications part of the manuscripts, suggesting and applying changes to the manuscripts, and finalizing the papers. Prof. Pekka Verho provided similar support for these publications as Prof. Jukka Lempiäinen and J. Haapanen programmed the SA system. H. Krohns-Välimäki presented the work of [P4] in Bangkok, Thailand in 2015.

M.Sc. Dipesh Paudel is the first author of the last publication [P7]. The author of the thesis served as the supervisor and examiner for D. Paudel and gave him the topic initially for his master of science thesis. The author helped D. Paudel with the calculations, the writing process and the forming of the operational framework for the manuscript. The author also participated in the writing process and finalized the paper. D. Paudel and the author presented the work of [P7] in Aalborg, Denmark in 2014.

1.5 Methodology

This thesis utilizes several different methodologies, or more precisely methods, in order to study the topic of this thesis. Understanding the merits and limitations of these chosen methods help to evaluate the accuracy of the results and possible sources of error. The utilized methods in different publications are shortly described in the following.

Empirical methods (measurements) are utilized in [P1, P5]. Measurements provide data, which can be analyzed and utilized to draw a conclusion from the measured properties. Thus, existing measurable phenomena can be modeled with the help of empirical methods. Possible errors can occur e.g. due to errors in the accuracy of the measurements. As a result, the grade of possible errors should always be taken into account.

The situation awareness system (SAS) developed in [P3–P4] follows the proof of concept methodology. In other words, this methodology is a realization of a prototype and the target is to determine its feasibility. This method can present and verify that the suggested idea functions in real life. The limitations of this methodology are related in taking account all possible situations available. Therefore, the feasibility of, e.g., a tested system depends on how thoroughly the new system has been tested.

Computer simulations are the approach utilized in [P2, P6]. Simulations offer a relatively inexpensive way to test real-world processes with the help of models. Thus, e.g. the suitability of (expensive) complex systems are easier to implement and test. The drawbacks of utilizing simulation methods are the limitations related to models and accuracy. As such, the results are only as accurate as the models are and how well those models can match real-world characteristics.

The last utilized methodology is a type of constructive framework, an algorithm, in [P7]. It provides a logical array of connected elements as a self-contained sequence of operations to be performed. Like in (computer) simulations, the accuracy of algorithms or the actions they perform are limited to the elements included in the algorithm. Thus, all possible states and their interconnections in the algorithm should be defined precisely for it to function without any errors. As a result, the outcome of an algorithm is well-known.

CHAPTER 2

Critical Infrastructures

Societies depend heavily on infrastructures; the *technical structures* or the *underlying framework* that provides the foundation for a working nation. The design, construction and maintenance of infrastructures are usually categorized as tasks in civil engineering and moreover in municipal engineering. They are in charge e.g. of streets, sidewalks, bridges, water supply and sewer networks, and street lighting.

Modern societies, i.e. the majority of current societies, rely specifically on the so called *critical infrastructures.* These are the most important infrastructures, known as *level 1* infrastructures [60]:

- information and communication technology (ICT): mobile networks;
- electricity generation, transmission and distribution: electricity networks;
- water supply.

Thus, in order to maintain the functionalities of current societies, it is very important for any nation to secure the operation of these fields in all situations. This chapter introduces first disaster and disturbance scenarios and then shortly two of the most important critical infrastructures: *mobile networks* and *electricity networks* and the interdependencies existing between them.

2.1 Disaster and disturbance scenarios

Disaster scenarios usually occur without any warning. The cause of these incidents can be earthquakes, tsunamis, hurricanes or other (natural) weather-based storms or man-made disasters, such as accidents, cyber-attacks or sabotage. The effects can be devastating and prevent the normal utilization of the networks.

In recent years, there have been many cases of large disasters scenarios around the Earth. For example, a powerful earthquake struck off the Pacific coast of Tohoku, 400 km northeast of Tokyo, Japan, in March 2011. This caused a tsunami that damaged the infrastructure very seriously [8]. Another large example occurred in the United States of America when Hurricane Sandy caused widespread disaster scenarios in the East Coast from Florida to Maine in October 2012 [30]. The devastating earthquake that struck Nepal in April 2015 [37] also destroyed a large part of the existing infrastructure. These examples show that even modern societies are very vulnerable to extreme weather conditions and solutions to improve the resilience of the infrastructures have to be developed.

A milder version of a disaster scenario is a situation, where the functionality of the network is partly limited but not directly and immediately life-threatening. Disturbance scenarios can be considered to be e.g. electricity network blackouts from the mobile network point-of-view. These power blackouts are usually caused by strong weather phenomena, like storms and strong winds, which cut down trees that will break power lines. This will eventually stop the functionality of mobile networks and the whole society is at risk to be halted, which can eventually result in a public safety hazard.

2.2 Mobile networks

The current mobile networks, i.e. the widely existing second generation (2G), third generation (3G) and fourth generation (4G) networks, or ICT in general, are one of the key parts of societies. The societies depend more and more on mobile networks as everything starts to be connected to the internet and this dependence has grown fast in the past few decades especially with the remarkable growth in the number of connected devices like (smart) phones, tablets, and IoT equipment.

In fact, there are already regulations on how to prepare for disturbance scenarios and power blackouts. For example, Finnish Communications Regulatory Authority (FICORA) has instructed that cellular network BS sites in Finland must have backup power for at least two to four hours. This depends on the type and environment of the BS site, i.e. whether the equipment are located inside a private property in an urban area or a mast in a rural area [31]. This regulation should guarantee that mobile networks continue to operate at least few hours after a power blackout, but again it depends on the condition of the backup batteries or other reserve power at the BS sites and the service demand as high load translates to higher power consumption [62].

Mobile networks consist of a core network (CN), a backhaul network and BS sites. Mobile networks in this thesis concern mainly the BS sites and the actual service coverage they provide. Usually, mobile network operators (MNOs) have their own infrastructures although the majority of BS site locations and masts are shared among different operators. This thesis concentrates on providing service from only one MNO infrastructure in the studies.

2.3 Electricity networks

Electricity networks are also categorized as level 1 critical infrastructures. The reason for this is quite obvious: the majority of modern society's functionalities require electricity. Electrical networks consist of electricity generation, transmission and distribution. This thesis limits electricity networks to the distribution network: the network that delivers electric power to the end users. This is because the majority of the faults that end users experience occur at this part of the network.

Distribution system operators (DSOs) are roughly the electricity network equivalents of MNOs. They operate the electricity network distribution with the help of a distribution management system (DMS) and supervisory control and data acquisition (SCADA) control system. DMS is utilized to monitor and control the distribution network with SCADA, which provides means to remotely access a variety of control modules located e.g. in electricity network substations and transformers.

2.4 Interdependencies between mobile networks and electricity networks

Mobile networks, like any other electronic devices, require electricity in order to work. Thus, the operation of mobile networks depends heavily on electricity networks although reserve power resources and alternative sources of electricity like solar panels and wind turbines provide some alternative possibilities.

The operation of electricity networks would not first seem to depend on the availability of mobile network services. However, modern electricity networks begin to have more intelligence with them in a concept known as the smart grid. This means that the conventional operation of just distributing electricity from one place to another has changed so that electricity distribution can be guided in several directions, where ever it is needed. Besides this advanced delivery, smart grids have e.g. advanced metering and monitoring and is more closely dependent on different communication technologies [14]. For example, the so-called remote-controlled switches have been installed in the distribution networks in order to improve the restoration process. These remote-controlled switches utilize mobile networks for the communication part and if mobile networks stop working the repair teams need to be dispatched to close them manually, which will slow down the restoration process. In fact, remote-controlled switches can improve the reestablishment time with several hours [12, 23].

Nowadays, many parts of electricity networks utilize mobile networks as a mean to establish a connection to SCADA and DMS. The most critical connections are backed up with satellite connections, but e.g. connections from the remote-controlled switches in transformers utilize mostly mobile networks for the communication. Furthermore, not so critical, but still important part is the remote automatic meter reading meters, which send information about the electricity usage from the end customers to DSOs.

One more interdependence between these critical networks is the availability of mobile networks in the restoration process, i.e. after a disturbance has occurred. The repair teams need communication access to receive instructions, mostly by utilizing smart phones, tablets or laptops, on how to proceed with the situation. The teams need to change location without this information, i.e. drive to another area, in order to regain the connection. Thus, a lot of time is wasted without a connection. This further highlights the importance of backup power at the BS sites and the overall functionality of mobile networks during a disturbance scenario.

The authors in [45] have evaluated the interdependencies between mobile communication and electricity distribution networks in fault scenarios. They list also ensuring power supply to base stations as one of the most important solutions to improve the resiliency of both mobile and electricity networks.

CHAPTER 3

Mobile Networks in Disturbance Scenarios

This chapter is the first main part of the thesis and is based on the results provided in publications [P1–P2]. It focuses on the subscriber behavior and the functionality of mobile networks during disturbance scenarios. First, data from an actual operative network is analyzed [P1] to express how an up-to-date modern cellular network functions during a disturbance situation and what kind of impact it has on the behavior of subscribers. This chapter also analyzes how to maintain the cellular network *disturbance time functionality*, i.e. how long the network could function without electricity from the power grid by utilizing the existing, limited reserve power [P2].

3.1 Impact of disturbance scenario on mobile network service demand

Mobile network traffic follows a certain routine day after day. This includes normally: some high service demand hours, the so-called busy hours, that occur usually during lunch time or after work hours when people make calls to their friends and families; other mediocre network usage time periods during the day; and a very low network usage time period during the night. This daily routine repeats day after day and has a specific profile which can be noticed from the statistics for each of the evolved Node B (eNB) cell. The profiles for working days, i.e. from Monday to Friday, are very similar with each other, but the profiles are clearly different for the weekends.

These mobile network traffic profiles also tend to repeat similarly week after week. Moreover, the change of the season can be observed from the (weekly) traffic profiles, e.g. from spring to summer as people have summer vacations that break the normal routine. Major changes or uncommon events can also be noticed from the statistics. For example, a large gathering of people is visible in the statistics with increased traffic and blocking rates as the mobile network capacity is not dimensioned for such events. These can include, among others, music concerts, sports events or festivals that gather massive amounts of people. Thus, the network at these locations can not meet the demand requirements set by the temporarily increased number of subscribers. This results in the lack of service for the portion of the demand that exceeds the planned service capacity for that specific geographical area. However, usually information for these kind of events is available in advance. Therefor, mobile operators can set up temporary extra capacity with transferable BS trailers for these areas in order to increase the capacity to meet the expected service demand increase.

This is not the same for sudden, unexpected disturbances in the network or major disaster scenarios. These can include, among others, storms that eventually cause power outages. This relates back to mobile network BSs since their operation depends on the availability of electricity. Should a power blackout occur, the continuity of the cellular network service depends on the availability of reserve power, which in turn depends usually on national regulation and the preparedness of mobile operators. However, even reserve power does not guarantee the availability of mobile network services in disturbance areas. This is because the service demand usually changes as the subscriber behavior changes, which can result in the cellular network not being able to handle all the (increased) traffic, i.e. the capacity is not planned to cope with the extra traffic caused by the disturbance or disaster scenarios. It should be noted that the behavior of the subscribers can be dissimilar in different environments, i.e. the subscribers in rural areas might be more used to or prepared for power blackouts than users in urban or suburban areas. The cause of the disaster scenario also affects the behavior of the subscribers as large natural disasters will result in more panic among the citizen than an uncommon blackout, e.g. in the electricity network.

3.1.1 Random service access

The capacity dimensioning of cellular networks is based on the potential number of subscribers and the expected network resource utilization. This includes e.g. how often subscribers utilize services of a different kind and how much these services require capacity. In general, the target is to offer reasonable capacity to subscribers and still consider the overall costs. This way mobile operators can secure cost-efficient network operation.

The available mobile network capacity depends heavily on the subscriber behavior (e.g. data usage) and the offered services. In modern societies, subscribers are assumed to have freedom such that they may move around and utilize services independently and access the network anywhere and at any time. This kind of behavior is based on Poisson distribution, which can be utilized e.g. for traditional speech users. In a Poisson distribution, users have a *random* length of a call and follow the negative exponential curve [53], [13], i.e. the probability density function is defined as

$$p(t) = \mu e^{-\mu t}, \tag{3.1}$$

where t denotes the time of the arriving call and μ is the amount of calls over time, i.e. $1/\mu$ is the average call duration. In addition to the random length of a call, subscribers have *random* time between the calls, also following the negative exponential curve. The probability density function is likewise defined as

$$p(t) = \lambda_\mathrm{r} e^{-\lambda_\mathrm{r} t}, \tag{3.2}$$

where λ_r is the amount of inter-arrival incidents over time, or $1/\lambda_\mathrm{r}$ is the average inter-arrival time. When both the length of the calls and the arrival time of the calls are random, the most interesting value is the probability of a user not being able to make a call. Thus, the well-known Erlang-B formula (without queuing) [13] defines the blocking probability p_m as

$$p_m = \frac{\left(\frac{\lambda_\mathrm{r}}{\mu}\right)^m / m!}{\sum_{l=0}^{m} \left(\frac{\lambda_\mathrm{r}}{\mu}\right)^l / l!}, \tag{3.3}$$

where m is the number of busy channels and l is the channel index. Thus, with the help of (3.3) the (speech) traffic capacity can be defined for a know configuration with a predefined blocking probability target.

In [53], a comparison between operative network and equation 3.3 is shown for a traditional one transceiver (TRX) BS having 7 traffic channels (1 channel reserved for signaling, 8 channels in total) in global system for mobile communications (GSM). Equation 3.3 results in 2.0 Erl capacity with 0.3 % blocking probability and measurements from the real network give 2.0 Erl traffic and 0.4 % blocking probability, i.e. practical values follow the theoretical calculations quite well. The theoretical maximum capacity (7 traffic channels, without blocking) would be 7 Erl if callers are not able to access the network randomly and no gaps exist between calls. Thus, 4.5 Erl of capacity is missed in order to have freedom for users to make calls randomly and with random call lengths, and simultaneously to keep the blocking at the level of 1 %.

Erlang-B formula is a good way to approximate the normal capacity need in the network. However, when a sudden change, like a disturbance scenario, occurs the behavior of subscribers most likely changes. Usually, this means that the randomness of users accessing the network changes as well. During such events, it is more probable that arriving calls start to correlate, i.e. subscribers are more likely to access the network simultaneously and usually in batches. In queuing theory, this can be modeled with the so called batch arrivals model [13]. When comparing this ideology with the Erlang-B model, the capacity need will be greatly higher for batch arrivals model. Thus, if the mobile network capacity demand would be dimensioned based on this model, the operation of the networks would be far of from being cost-efficient as disturbance occasions are relatively rare in the networks. As a result, MNOs are not planning their networks with the help of the batch arrivals model. A more suitable option would be to try to influence and control how mobile network subscribers will behave during disturbance scenarios.

In order to increase the available capacity in disturbance or disaster scenarios, the randomness of call lengths and times could be temporarily disabled and specific time slots could be reserved for different users in the disturbance area. The randomness of call lengths is easy to control by forcing the ongoing calls to disconnect at desired call length, but the randomness of accessing the network will require strong guidelines for the subscribers. These could be sent beforehand to the subscribers and as a text message with short message service (SMS) at the beginning, or in some cases even before a possible disturbance scenario, to notify the users that the network is not able to handle normal operations at that moment and that call durations are e.g. fixed to a certain maximum duration with a predefined time slot. For example, in 1 TRX GSM case, capacity could be increased from 2.5 Erl theoretically up to 7 Erl (with 0 % blocking) meaning a notable capacity increase in this very limited configuration. The same 7 Erl capacity would be achieved with 24.9 % blocking if the randomness of accessing the network and the call length would remain the same as in normal scenarios. The emergency calls should be prioritized so that they will get through in all situations, but for the not-so-time-critical-calls this method should provide some fairness among the subscribers, e.g. subscribers can not reserve the channels for themselves for too long.

3.1.2 Measurement results and analysis from the real network

Description of the power blackout area

The analysis in publication [P1] was performed to a certain area in Finland with the statistics of one MNO. The geographical area was roughly 1500 km^2 with a population around 7000 people, in which the MNO had roughly 39 % market share. The GSM network of the MNO had a total number of 19 BS sites having 58 cells and correspondingly the total number of universal mobile telecommunications system (UMTS) sites was 14 with 62 cells. The raw data of the GSM and UMTS network consisted of key performance indicator (KPI) statistics. This data was gathered before, during and after a power blackout that lasted for several hours. As a result, the backup power ran out from most of the BS sites. The power blackout started at 15.30 on Thursday, when roughly half of the regional electricity network of the studied area went down, and at 15.55 already 87 % of the area was missing electricity as seen from Fig. 3.1. The effects of the blackout started to decrease after this as repair teams progressed in reconnecting the outage areas back online and around 1.00 in the next day, i.e. after nine and a half hours 50 % of the area had been reconnected to the electricity network. It then took 11 hours more to reach 90 % availability in the electricity network around 12.00 on Friday. The last remaining 10 % of the outage areas still took around 12 hours to fully restore the electricity network.

Besides electricity, also the outage of GSM and UMTS mobile network technologies are shown in Fig. 3.1. The shape follows that of the electricity network version as expected. One of the GSM mobile network BS sites did not manage to reboot itself automatically, thus a zero percentage outage for GSM network was not achieved even though electricity was restored. The time resolution for the electricity network data is five minutes, and one hour for mobile network data, correspondingly. Furthermore, in Fig. 3.1 the mobile network outage seems to start before the electrical network blackout, but this is indeed because of the time resolution and the way the performance data is collected and stored. Events in the mobile network, that have occurred e.g. between 15.00 and 15.59, are shown in the data at 15.00.

Mobile network outage analysis

Fig. 3.2 and Fig. 3.3 show the GSM and UMTS mobile network statistics before, during and after the blackout in the electrical network. The green, orange, and blue bars show

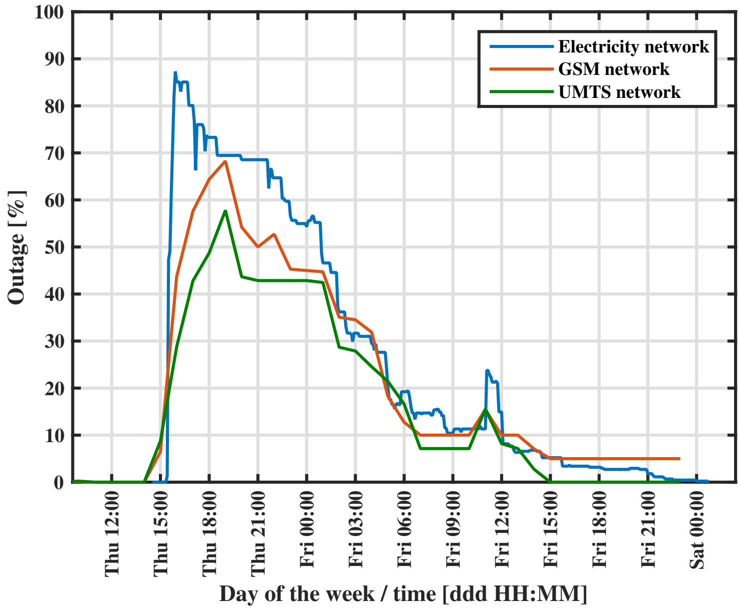


Figure 3.1: Outage percentage for both electricity and mobile networks. The time resolution is 5 min for the electricity network and 1 h for mobile networks. The date / time format is 'ddd' refering to the first three letters of a day and 'HH:MM' for a time presentation with two digits for both hours and minutes.

KPIs for Wednesday, Thursday, and Friday, respectively. The solid, dashed, and dotted lines present the *availability* of the electricity network for Wednesday, Thursday, and Friday. A numerical summary of the data is given in Table 3.1 after the figures.

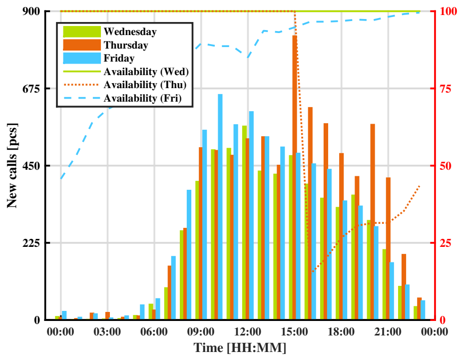
Fig. 3.2a shows the number of new calls. Normally, the KPI profile for each weekday is similar, but when the availability of the network drops at 15.00 on Thursday, there is a spike in the number of new calls. The increased amount of new calls continues for the whole Thursday evening, which indicates that the power blackout has activated subscribers to call more than usually. The same effect is visible in Fig. 3.2b; the number of new standalone dedicated control channel (SDCCH) seizures in uplink (UL) peaks when the electricity blackout began. This effect is also visible during the night between Thursday and Friday, i.e. in the early hours of Friday, most likely due to network maintenance workers. It should be noted that besides call setups SDCCH also includes location updates and SMS messages. The actual call traffic has increased when compared with the profile on Wednesday in Fig. 3.2c. Table 3.1 shows that the call traffic has increased from a total of 376 Erl to 471 Erl (from Wednesday to Thursday), resulting in a total traffic increase of 25 %. Finally, the packet switching (PS) data traffic allocated to GSM in Fig. 3.2d seems higher than the reference day (Wednesday), but this is partly because the availability of UMTS network had decreased, which results in part of the data traffic falling to GSM network. Overall, the KPIs values in GSM network have a noticeable change caused by the electrical network blackout.

Correspondingly, Fig. 3.3 shows the situation in UMTS network statistics. First, in Fig. 3.3a, the amount of circuit switching (CS) traffic is shown in Erlangs. This amount is slightly higher before and right at the time when the power blackout begins. The amount of CS traffic is reduced after this as the availability of the UMTS network degrades, however, the reduction is caused by the lack of service availability, not from the reduced CS traffic behavior, since the CS traffic increases notably as the availability increases. In Fig. 3.3b, the amount of downlink (DL) data is shown; a similar effect as in CS traffic is noticeable, i.e. the availability is reducing the amounts of data. On the other hand, the traffic amounts are greatly higher before the power blackout starts, most likely due to subscribers trying to search for information about the storm that eventually caused the electricity outage. Fig. 3.3c shows the number of SMS messages in UMTS network. The power blackout causes a clear spike in the chart and the amount of SMS messages in the entire Thursday evening is clearly higher than in the reference day. Finally, in Fig. 3.3d, the number of radio access bearers (RABs) has a very noticeable spike at the time when the power blackout started. RAB is used for information transfer between a user equipment (UE) and the CN.

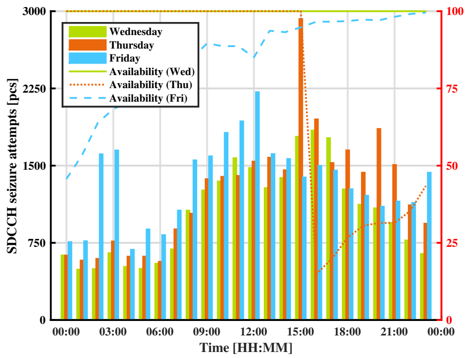
3.1.3 Discussion on subscriber behavior in disturbance scenarios

The observed results presented in the previous Section 3.1.2 show how the mobile network subscribers behave in the case of a small and uncommon disturbance scenario in the form of an electricity network blackout in rural area. The statistics from the GSM and UMTS networks show how the subscriber *mobile network service behavior* changes when a disturbance scenario occurs. This behavior can already be noticed before the actual disturbance began from the amount of DL data, as subscribers e.g. try to find information related to the possible upcoming storm. When the disturbance (i.e. the power blackout in this case) had finally occurred, especially the call traffic and the amount of SMS messages had a noticeable spike in the network statistics. These include 73 % increase in the number of new calls and an increase of 84 % in the number of SMS messages compared with the reference day (Wednesday) at the time when the disturbance situation started. This increased service demand trend continued through the majority of the power blackout, i.e. the subscribers continued to utilize the network more than usual despite the lack of mobile network availability. In addition, the results show that the largest mobile network outage occurred after 3–4 hours from the beginning of the outage, thus meeting the requirements set by FICORA although some BS sites run out of energy already before this.

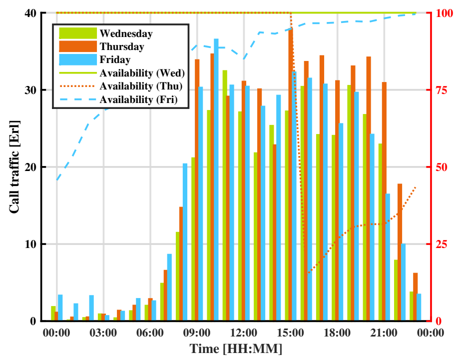
In order to cope with the lack of mobile network services caused by the outages in the electrical network, some possible solutions can be considered. One of these suggestions is partially restricting the ubiquitous cellular network experience, i.e. instead of using the network all the time and everywhere, some limitations for the services might be beneficial from the overall network functionality and also from the subscriber point of view. These limitations should not, however, prevent the real need in the case of life-threatening emergencies, but instead help to prevent the cellular network (service) congestion. A fairly simple solution would include guidelines, i.e. common rules, which would state that if a power blackout should occur, the subscribers should avoid making unnecessary



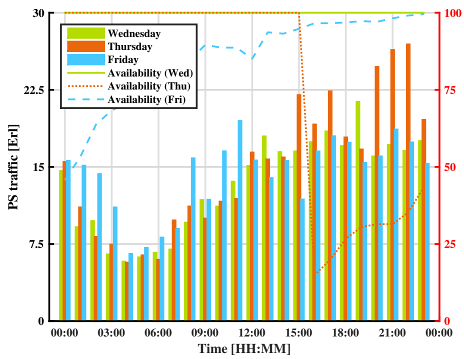
(a) The number of new calls.



(b) The number of new SDCCH seizures.

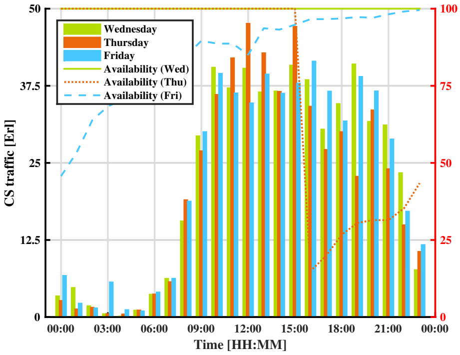


(c) The amount of call traffic.

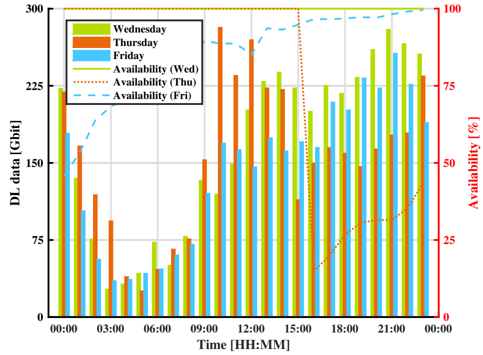


(d) The amount of PS traffic.

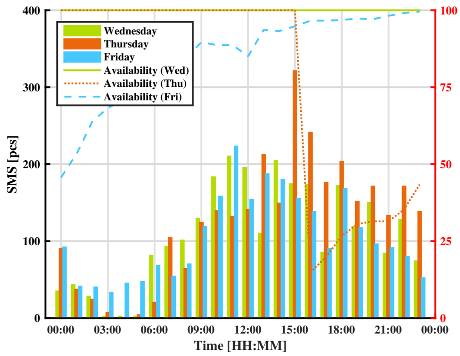
Figure 3.2: GSM network statistics from the electricity blackout. The bars present the KPI values and the lines the availability of electricity network. The time format is 'HH:MM' for a time presentation with two digits for both the hours and minutes.



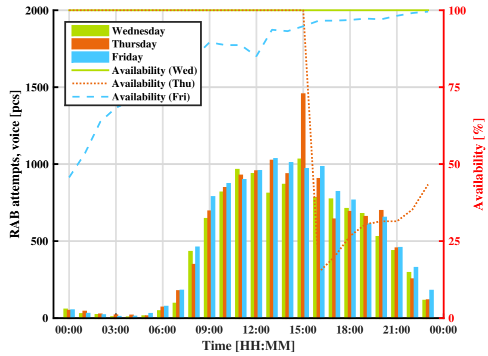
(a) The amount of CS traffic.



(b) The amount of DL data.



(c) The number of SMS.



(d) The number of RAB attempts for voice calls.

Figure 3.3: UMTS network statistics from the electricity blackout. The bars present the KPI values and the lines the availability of electricity network. The time format is 'HH:MM' for a time presentation with two digits for both the hours and minutes.

Table 3.1: GSM and UMTS network statistics before, during and after the electricity blackout. The mean and median values present the values for one hour.

	Key performance indicator	**Wednesday**				**Thursday**				**Friday**			
		total	*mean*	*median*	*std*	*total*	*mean*	*median*	*std*	*total*	*mean*	*median*	*std*
2G	The number of new calls [pcs]	5787	241	274	199	7652	319	415	254	6794	283	301	228
	The number of new SDCCH seizures [pcs]	25103	1046	1074	450	29890	1245	1380	566	32139	1339	1408	396
	Call traffic [Erl]	376	16	21	12	471	20	26	15	434	18	22	13
	PS traffic [Erl]	319	13	15	5	358	15	16	6	342	14	15	4
3G	CS traffic [Erl]	536	22	30	16	511	21	23	17	543	23	29	16
	The amount of DL data [Gbit]	3958	165	200	84	3714	155	161	72	3429	143	164	70
	The number of SMS [pcs]	2577	107	106	66	2952	123	136	82	2498	104	92	55
	The number of RAB attempts [pcs]	11088	462	482	372	12012	501	548	420	12188	508	535	394

calls and reduce the mobile network utilization in general. This solution, however, is not easy to control since it is only a guideline. Nevertheless, instructions and guidance in advance would increase the probability of unnecessary cellular network utilization. When the capacity requirement could be lowered, some of the cellular network technologies could be shut down immediately to spare more backup energy.

A more complex solution to increase the (speech) capacity during disturbance situations would be to restrict the randomness of the call lengths and the randomness of the subscribers to access the network by allowing only a certain set of subscribers within the area to access the network. If applied to the configuration of the example network analysis, an increase from 410 Erl (Erlang-B (3.3), 1 % blocking) to 435 Erl would be theoretically possible although in practice this would be somewhere between the normal and the theoretical value. This would need efficient algorithms to allocate mobile network subscribers to specific time slots to access the network beforehand and to restrict the customers to access the network outside this time slot. Emergency calls should always be prioritized in these situations.

It should be noted that the results in this study are based on one disturbance scenario and the reference day for the analysis is also from only one day, thus the generalization of these results would require several other study cases. Nevertheless, this study offers data from an operational mobile network operator, and shows how subscribers utilize the network during an uncommon power blackout situation.

3.2 Maintaining mobile network coverage availability

Disturbance and especially disaster scenarios can happen without a warning. Whether they are disasters caused by human, such as accidents or sabotages, or natural weather-based storms, the effects can be destructive, which can prevent the normal utilization of mobile networks. Typically, the major causes of blackouts in electrical grids are storms [77]. Furthermore, they affect commercial mobile networks and public services, thus yielding service and communication outages. Eventually, this can prevent emergency help requests in these areas. In addition, rescue and maintenance teams can not communicate through commercial mobile networks in these conditions and have to have a separate communication system.

Coverage outages in mobile networks are mainly caused by (storm-related) power outages. In order to maintain some service level in these cases, macro BS sites are typically supplied with backup batteries. These reserve energy resources provide power to keep BSs operational, but only for a very limited amount of time. For example, in Finland BSs have to be operational for 2–4 hours, as required by FICORA [31]. This helps to mitigate a majority of shorter power blackouts, however, the repair-work may take even several days to restore the networks especially after some strong weather phenomenon. This results in the unavailability of commercial cellular networks, which may also endanger rescue operations. One alternative is to have power aggregates at certain critical BS sites, to guarantee their electricity supply for a longer period of time. Aggregates are slightly costly to be supplied and used at every site, thus some optimization is needed in a similar way as in the case of battery backups, i.e. how many aggregates should be enough to enable sufficient cellular network coverage from the location point of view. Moreover, in case of longer-term electrical cut-offs (i.e. over one day), aggregates are eventually required to guarantee (cost-efficient) mobile network communications in disturbance scenarios, given that the backhaul and core network are also equipped such that the communication is still possible.

Besides coverage outage caused by power blackouts, other type of critical discontinuity in mobile networks may happen due to (major) malfunctions in the CN equipment or major damage in the core network elements. Besides pure technical malfunctions, these problems can be caused by a cyber-attack or sabotage, thus potentially paralyzing the whole mobile network. However, these are out of the scope of this study and the focus is on optimizing the backup energy utilization.

Some solutions for mobile communications have been proposed to manage especially disaster scenarios in order to improve the resilience of mobile networks. In Japan, the so-called critical sites have been implemented in urban areas to durable high-rise buildings [70] with at least 24 h backup batteries to give continuous service e.g. in case of disasters. High-altitude platforms (HAPs) [57] have been discussed earlier as a possible solution to provide service coverage in case the existing infrastructure has been destroyed e.g. as a result of an earthquake, a tsunami, or a hurricane. This idea has been taken further with Google's project Loon, which targets to provide worldwide Internet access through HAPs, which are implemented with balloon platforms [36]. Also Facebook has utilized the HAP approach in the internet.org project [51], where solar powered drones are utilized instead of balloons.

Nowadays, satellite communication services are also possible for disaster areas although these systems can be rather expensive. One example of these are the so-called Medium-Earth Orbit (MEO) satellite systems, which are able to provide global service although the service is limited to $\pm 62°$ latitude [47]. Moreover, temporary, movable networks, like mobile ad hoc networks (MANETs), are a popular research area for disaster scenarios as seen from many publications on the topic in [16, 55, 74, 75, 89]. Although MANET is a prominent technology for these occasions, they usually replace the existing infrastructure with a new one instead of trying to improve it. Thus, instead of implementing a new infrastructure, it would be more beneficial to enhance the existing one towards a resilient network, which would be able to maintain its functionality as long as possible.

In order to maintain even some services in a disturbance areas, publication [P2] analyzes the effect of reducing the number of active eNB sites to save energy with the remaining part of eNB sites. As a result, the cellular network will function longer than conventionally.

3.2.1 Energy saving concepts in cellular networks

The two most common energy-saving concepts in mobile networks are: the so-called *green* cellular networks and cellular networks with sleep mode techniques. The idea of green cellular networks originates from utilizing sustainable energy sources and taking into account environmental aspects in cellular networks. This usually relates to favoring renewable energy resources to reduce the carbon footprint of cellular network infrastructures or saving energy by reducing the energy consumption of base stations. Nowadays green cellular networks are studied widely, and e.g. the authors in [41] present a survey on the state of green cellular networks and the possible challenges they currently have. It is important to realize that the largest power consuming part of cellular network infrastructures are base stations, as presented in [40]. Furthermore, the largest part of base station power consumption comes from the power amplifiers (50 % to 80 %) [17].

The so-called sleep mode concept can be divided into three main approaches: saving energy through actions in time, frequency, and spatial domain [66]. Thus, switching off devices (BSs) for some period of time by taking into account the traffic amount helps to save energy. The traditional sleep mode concept has been studied e.g. in [64], where the effect of one or more base stations turned to sleep has been evaluated. A case study of dynamically switching off base station sites is presented in [71], where the authors show great energy saving in the cellular network during low traffic periods. One of the most recent wide surveys on these energy-efficient base stations, i.e. base station sites with sleep modes as well as green cellular networks, is presented in [94]. The authors present an extensive list of recent publications on these topics and discuss the assumptions and simplifications utilized in these papers to show the great effect they can have in the achievable benefits in actual networks.

Most of the conventional sleep mode techniques are applied to normal network utilization, i.e. the network is working normally without any disruptions or abnormalities. As a result, sleep mode techniques can be utilized during low-traffic time periods, i.e. certain times within a day and night, when the capacity demand is low. However, it should be highlighted that the traffic load increases during disturbance scenarios [P1] as subscribers access the mobile network in these areas to search for information regarding the cause of the disturbance situation and try to e.g. call other people from these areas (and vice versa) to make sure that they are ok. Therefore, sleep mode algorithms based on low-traffic network utilization could not be directly utilized in these events.

One way to enable sleep mode techniques during disturbance scenarios is to ignore the instantaneous traffic, i.e. to force BSs to sleep. As a result, energy is saved by utilizing only a portion of the BS sites to provide the so-called *backup coverage* for areas where the electricity supply from the power grid is (temporarily) cut off, because of the abnormal circumstances. Thus, a modified sleep mode concept in cellular networks is the main approach utilized in this study for the functionality of BS sites operating only with backup power (i.e. during a disturbance scenario). However, during this sleep mode BS sites only wait for their turn to power on, without broadcasting anything during this time. Therefore, power amplifiers and air conditioning are not needed and signal processing power requirements are very low as there is nothing to transmit or receive during the sleep time. As a result, the power consumption of these sleeping BS sites is very marginal. This is more effective in saving energy then having traditional sleep mode techniques, where the BSs wake up to check the situation every once in a while. The approach utilized in this study does not take into account traffic loads, instead the target is to find out what would be the effect of selecting only a portion of the available BS sites to the overall network performance it a specific area. Moreover, the study does not include algorithms in how to actually select the usable BS sites (although the selection of BS sites is based on choosing active BS sites evenly within a target area).

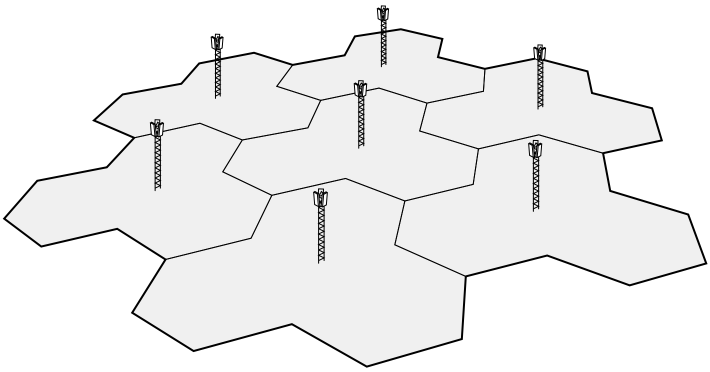


Figure 3.4: Cloverleaf tessellation (layout) with seven three-sectored BS sites.

3.2.2 Radio network planning

Radio network planning is a process to design (the best possible) wireless communication network such that coverage, capacity and the quality of service (QoS) meet (and exceed) the set requirements in a cost-efficient manner. The requirements refer to providing a certain level of service to the given amount of subscribers in a target geographical area. In order to maximize these aspects, a radio network planner needs to pay careful attention to some very important factors. These include the target area environment, which defines the propagation slope, the model used to calculate the maximum path loss to estimate the cell range, and the network layout in terms of base station locations with respect to other base stations.

Network layout

The performance of a mobile network depends on many factors and one of the important ones is the used network layout, also known as the tessellation. In the ideal case, it forms a continuous network with raster-like properties, i.e. the layout has symmetric shapes regarding the positions of the BS sites and the antenna directions. The half-power beamwidth (HPBW) of the antennas also affect the choice of tessellation, but the cloverleaf tessellation is the most optimal choice for a 65 degree HPBW antenna [54]. This is the most commonly utilized tessellation in Europe and an example of it with seven BS sites is presented in Fig. 3.4. It shows that every antenna in a BS site is pointed directly towards one of the neighbor BS sites. Thus, each beam from a directional antenna is not directed towards another beam resulting in lower interference from the neighbor BS cell.

Propagation model

Coverage of a mobile network generally defined as a geographical area, where a BS and a UE can still communicate with each other. The exact coverage area of a macro BS site would require perfect knowledge of the intended environment. Thus, coverage areas are estimated with path loss models to achieve reasonable accuracy for practical networks.

One of the most common practices is to utilize a well-known Okumura-Hata prediction model (and its extended version, the COST-Hata-Model) [15, 43, 58]:

$$\begin{aligned} L = {} & A + B\cdot\log_{10}(f_{\mathrm{MHz}}) - 13.82\cdot\log_{10}(h_{\mathrm{BS}}) \\ & - a(h_{\mathrm{UE}}) + [C - 6.55\cdot\log_{10}(h_{\mathrm{BS}})]\cdot\log_{10}(d_{\mathrm{km}}) \\ & + C_{\mathrm{m}}, \end{aligned} \tag{3.4}$$

where

L is path loss in [dB],
A and B are parameters set according to Table 3.2,
C is a user-defined parameter for tuning the propagation slope,
f_{MHz} is frequency in [MHz],
h_{BS} is BS antenna height in [m],
h_{UE} is UE antenna height in [m],
$a(\cdot)$ is a city size dependent function,
d_{km} is distance between BS and UE in [km], and
C_{m} is an area correction factor.

Table 3.2: Frequency dependent A and B parameters for the Okumura-Hata model.

	150–1500 MHz	**1500–2000 MHz**
A	69.55	46.3
B	26.16	33.9

When Okumura-Hata model (3.4) is utilized, it should be remembered that it requires tuning for different environments in order to achieve accurate results. For example, the area correction factor, C_{m}, has to be set with correct morphological values defined by the propagation environment. Correspondingly, the propagation slope, which is defined by $[C - 6.55\cdot\log_{10}(h_{\mathrm{BS}})]$, can be tuned with BS antenna height (during the initial radio network planning phase) and by tuning the C parameter to achieve the correct propagation path loss exponent. As seen from Table 3.2, there are some limitations to the utilization of Okumura-Hata model regarding the frequencies. However, these limitations do not prevent the utilization of this model with other values, it just means that the model will start to have some errors. Therefore, this has to be kept in mind when analyzing the results for the utilized 2600 MHz band. However, the nature of this study is to present the difference between utilizing a different, limited number of eNB sites, thus the absolute values are not highlighted. Other restricting parameters are the heights of the antennas [43, 58] although it is more important that the BS antenna is above the rooftop level then the absolute value.

Planning thresholds

Planning thresholds are also needed when calculating the maximum path loss with propagation models. One of the most important planning thresholds is the slow fading margin [59]. It can be calculated from the standard deviation of the slow fading, the propagation slope and the coverage probability target for the required services in a target area. Moreover, the values for slow fading margin are clearly different for indoor and outdoor locations. When the target is to design a radio network with indoor coverage, some additional planning thresholds are needed. First, the value for slow fading margin needs to be updated from the outdoor version and then the building penetration loss should be added to the link budget calculation.

Inter-site distance and coverage overlapping

The shortest distance (direct path) between the closest neighboring BS sites is usually referred to as inter-site distance (ISD). These distances are clearly different for rural and urban environments and for different type of cells, e.g. for macrocells and microcells. One example of the magnitude of these ISDs is 750 m for urban and 7500 m for rural environment, according to 3rd Generation Partnership Project (3GPP) [1].

Coverage overlapping occurs when one (geographical) location has service from two or more cells. Usually, the grade of coverage overlapping is smaller in rural areas compared with urban areas because of large ISDs. Vice versa, the coverage overlapping is higher in urban areas since BS sites are close to each other, i.e. the ISD is shorter. As a result, the probability to have a service coverage with a reduced number of BS sites is higher in urban areas compared with rural areas.

Practical capacity requirements

As mentioned before, mobile network (capacity) requirements depend on population density with the potential number of subscribers and the requested services for a given area. The serving mobile network cells for these areas are shared mediums, thus the available capacity per UE depends on the total number of simultaneous users within the same serving cell, the data throughput requests of each UE and the instantaneous channel conditions. To expand this limited capacity of one channel, more channels, i.e. additional frequency bands can be utilized. Thus, recent implementations include several frequency layers (bands) and technologies at one BS site [68]. An example of this would be a BS site, that has a GSM base station, a UMTS base station, and a long term evolution (LTE) base station (eNB) and each of these technologies would operate on at least two different frequency bands. These could be e.g. GSM operating at 900 MHz and 1800 MHz, UMTS operating at 900 MHz and 2100 MHz, and LTE operating at 800 MHz and 2600 MHz. In order to minimize the required power, several technologies, e.g. GSM and UMTS and several frequency layers could be switched off (e.g. only the lowest frequency band of the remaining technology is utilized for service, such as LTE 800 MHz), and still certain services such as short messages, speech, or limited data services should be maintained (depending on the available technology and its capabilities). This results in conserving backup power in crisis situations, but still enables services for a longer period of time compared with a situation where BS sites would continue to operate normally and quickly consume the available reserve energy. This approach, for example, is nowadays utilized in Finland.

3.2.3 Mobile network simulations

The analysis of prolonging mobile network availability was studied with link-level simulations implemented with commercially available radio network planning software called ICS Designer [10]. The chosen area was a randomly picked and relatively flat area in France, which had a 25 m resolution digital elevation map. After the simulation results were obtained, they were exported into MATLAB software [84] for further analysis.

Macrocellular cloverleaf tessellation with three-sectored eNB sites was utilized in the simulations. A conventional grid of 19 eNB sites was the base for the network layout, which has one eNB site in the middle and two tiers, first tier with six sites and second tier with twelve eNB sites, around it forming a hexagonal grid. All eNB sites in the original layout had an equal ISD of 500 m for urban and 4000 m for rural environment. Results were analyzed from a circular area with 1.25 km and 10 km radii from the center eNB site. Thus, the maximum amount of cells was 57 in normal situation. Three additional tiers of eNB sites were placed around the central grid in order to take into account the effect of eNB sites outside the target area. As a result, continuous coverage was formed such that the selection of eNB sites was repeated around the target area.

The Okumura-Hata model was used for calculating the path loss values in the simulations and the model itself is adjusted with topographical corrections. Moreover, fading was taken into account with log-normal distribution having zero mean and 9 dB standard deviation. LTE is utilized in the simulations with evolved UMTS terrestrial radio access (E-UTRA) bands 3 and 7 (1800 MHz and 2600 MHz) for urban environment. E-UTRA bands 20 and 3 (800 MHz and 1800 MHz) are utilized for rural environment. All of the considered frequency bands are frequency domain duplex (FDD) channels. All key parameters regarding the simulations are presented in Table 3.3 and additional simulation information is available in [P2]. The selection of antenna gain and the corresponding HPBW have been fixed in order to compare only the differences caused by the wireless channel.

In order to study the performance of a mobile network with a limited configuration, a set of eNB sites need to be selected from the total amount of 19 eNB sites in a grid. If all possible combinations would be considered, the maximum number of different sets (in any order), e.g. with nine eNB sites out of 19 eNB sites would be $\binom{19}{9} = 92\,378$, and with just three eNB sites out of 19 eNB sites result in $\binom{19}{3} = 969$ different sets. Because each set of selected eNB sites had to be defined manually for the commercial radio network planning tool, the number of different sets was reduced considerably, down to six different configurations per given amount of eNB sites. Nevertheless, this provides a trend on how the performance of the network behaves as a function of available eNB sites. In order to noticeably prolong the backup coverage time duration, the focus was in cases, where less than half of the eNB sites per studied area remained. Moreover, the selection of remaining eNB sites was chosen manually such that the coverage would be sufficient, i.e. the set of eNB sites was chosen evenly from the grid of 19 eNB sites.

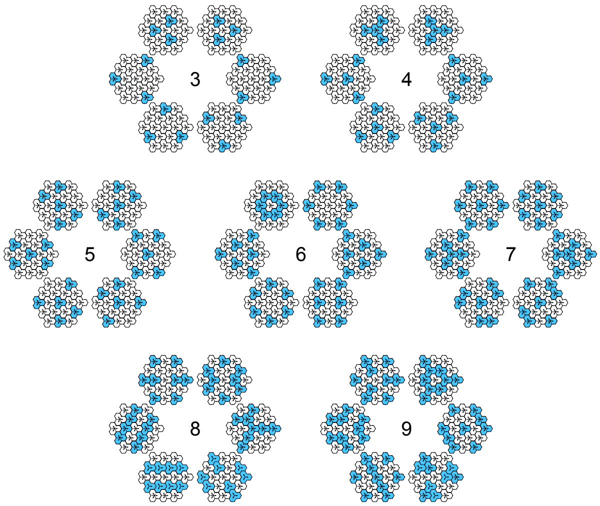


Figure 3.5: Selection of different three to nine eNB site configurations that were utilized in the simulations for a target area (and repeated in a similar way around this area to form a continuous coverage). The selected eNB sites out of a grid of 19 eNB sites are highlighted with blue color.

Table 3.3: Key simulation parameters.

	Parameter	**Value**
E-UTRA band	20 (FDD)	800 MHz
	3 (FDD)	1800 MHz
	7 (FDD)	2600 MHz
Spectrum resources	bandwidth	10 MHz
	number of usable resource blocks	50 pcs
	loading	75 %
Dimensions	calculation resolution	25 m
	building height	8 m
	ISD – urban	500 m
	ISD – rural	4000 m
eNB	antenna height (urban/rural)	20 m/40 m
	antenna gain	17.22 dBi
	antenna HPBW	65°
	additional losses	3 dB
	maximum transmission power	20 W
UE	antenna height	1.5 m
	antenna gain	0 dBi

3.2.4 Performance results with limited configuration

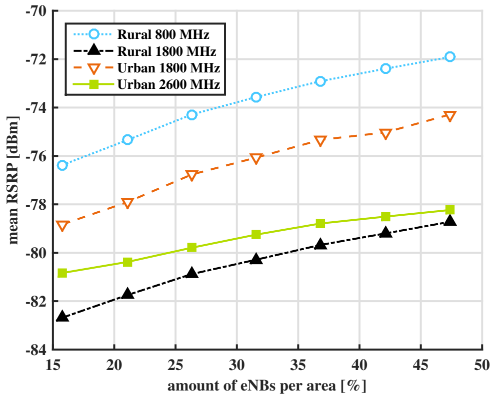
The performance of a limited network configuration is analyzed with a selection of KPI values. The most interesting values are the mean reference signal received power (RSRP) levels (Fig. 3.6a), the mean service probabilities (Fig. 3.6b), and the average signal-to-interference-and-noise ratio (SINR) (Fig. 3.6c) with respect to the number of eNB sites. The corresponding exact values are presented in Table 3.1.

Fig. 3.6a shows that when the number of eNB sites grows, the average RSRP levels increase, which is intuitively expected. Rural environment with E-UTRA band 20 (800 MHz) has the highest average RSRP values and correspondingly rural environment with E-UTRA band 3 (1800 MHz) has the lowest RSRP values. The environment type with different antenna heights for the rural and urban areas has a huge impact on the average RSRP values, because the antenna height for the rural area cases is two times the height of the antenna in urban area cases. Another important factor is the utilized frequency, i.e. for rural area the higher 1800 MHz frequency band is more than twice the lower 800 MHz frequency band. In the urban cases, the higher 2600 MHz frequency band is less then twice the lower 1800 MHz frequency band, thus the differences between the average RSRP values for two rural cases is more evident than the corresponding differences for the urban cases. It should not be forgotten that the urban cases are affected by buildings, thus there is some additional attenuation with respect to rural cases.

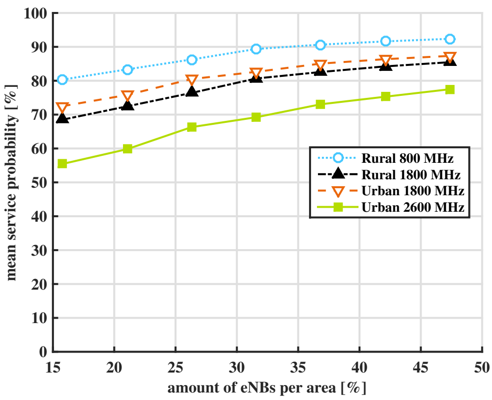
The average probability to have (backup) coverage in the different cases is shown in Fig. 3.6b. E-UTRA band 7 (2600 MHz) had the lowest average probability (55.44 %) to have service coverage in the urban environment. This occurs naturally when the amount of eNB sites is the smallest (15.79 %). Thus, although the urban area had a denser eNB site placement than the rural area, the coverage areas with a higher frequency band are quite limited, as well as the overlapping areas. This is mostly because the attenuation is higher in the urban environment (with buildings) as well as with a higher frequency band. When the same frequency band was utilized in both the urban and rural environment, the urban E-UTRA band 3 had slightly higher probability to have a service than its rural counterpart (rural E-UTRA band 3). The highest service availability was achieved with the lowest frequency, i.e. 800 MHz band in the rural case, where the probability to have a service was over 80 % even with the lowest amount of eNB sites (15.79 %). In order to have the same amount probability for (backup) coverage in other cases, E-UTRA band 3 cases (1800 MHz) would need around 26.32 % in urban and 31.58 % in rural scenarios and E-UTRA band 7 (2600 MHz) up to 50 % of the eNB sites in the urban environment.

In Fig. 3.6c, the average SINR values are presented. It can be noticed that in rural environment the achievable values are much higher than in urban cases, mostly because of low interference from less dense eNB site placements, i.e. the minimum ISD is 4000 m. When more eNB sites are available, the average SINR degrades because of the increased interference levels.

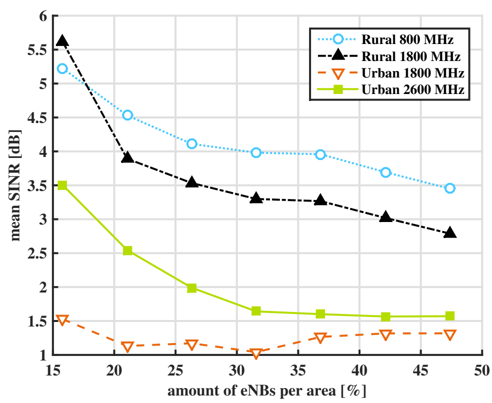
When the exact values are observed from Table 3.4 as a function of available eNB sites, the differences between different E-UTRA bands and environments are easy to compare. Intuitively thinking, each KPI (RSRP, service probability, and SINR) should have a better value as the percentage of eNB sites per area is increased, and in general this is observed in Table 3.4. The only difference is the utilized lower urban frequency



(a) Average RSRP level.



(b) Average service probability.



(c) Average SINR.

Figure 3.6: Visualizations of the simulation results.

band (1800 MHz), where the average SINR value is slightly increased when more than 31.58 % of eNB sites are utilized. However, this increase stops after more than 42.11 % of eNB sites are utilized.

3.2.5 Conclusions on maintaining mobile network coverage availability

Backup coverage is required when disasters or disturbance scenarios occur. As the name suggests, the mobile network can not have "normal" service availability in these cases as the goal is to provide acceptable or even some coverage to enable communications. When eNB sites are equipped with reserve power, the goal is to extent the availability of mobile network services as long as possible. Thus, instead of immediately utilizing the backup power in all eNB sites, one way to prolong the functionality of the sites is to utilize only a set of eNB sites at a time. This means that some areas would not have coverage at every time instant during the overall backup coverage time window. However, as the operating sets of eNB sites are cycled over time, all areas would have a certain time window when the mobile network services are available. Thus, in order to achieve e.g. approximately 75 % (area) availability only 20 % to 42 % of eNB sites in urban areas, and 15 % to 25 % of eNB sites in rural areas are needed according to the simulations. This would result in an increase of 100 % to 500 % on the operational time of backup coverage, correspondingly. As a result, this kind of operation can be considered as a different kind of state in the mobile networks called the "safety mode". Another way to interpret this is to observe that mediocre coverage would be possible for a longer period of time if only 20 % of eNB sites were equipped with aggregates or any other means of powering up eNB sites. This could be cheaper than having e.g. up to 24 h backup batteries deployed to these eNB sites as is the case in [70].

Traditional sleep mode techniques are designed to save energy mainly during the low traffic time periods and this is usually not the case during disturbance situations. Many studies such as [64, 71, 94] consider different sleep mode techniques with heterogeneous networks having eNB site layouts of a different kind. In order to get some idea about the effectiveness of the approach utilized within this paper, the authors in [6] present a comparable sleep mode technique, where part of the eNB sites remain active all the time and part of the eNB sites can switch to the sleep mode. The results in the study suggest that on average the power savings from an actual network implementation would range from 7.38 % to 27.72 % on a 24 h time period during normal network operation. Consequently, although still not directly comparable, the energy savings are only a part of the approach utilized in this study. This difference can be explained with high QoS, i.e. sleep mode techniques are designed to have high service availability. However, in this study the requirements for QoS are clearly lower because the idea is to lower QoS to enable even some (sufficient) level of service for a clearly longer period of time by aggressive energy saving.

The studied availability levels with a limited amount of active eNBs can be reached in existing networks by adding only controlling units. Moreover, the achieved results assume that backhauls and core networks are properly functioning (which is usually the case, at least in Finland, as the backhaul element backup power regulation is stricter for backhaul elements than for eNB sites by a factor of 2–6 [31]). Thus, more specific

Table 3.4: Simulation results with limited network configuration.

Percentage of eNB sites per area	**mean RSRP [dBm]**				**mean service probability [%]**				**mean SINR [dB]**			
	rural 800 MHz	rural 1800 MHz	urban 1800 MHz	urban 2600 MHz	rural 800 MHz	rural 1800 MHz	urban 1800 MHz	urban 2600 MHz	rural 800 MHz	rural 1800 MHz	urban 1800 MHz	urban 2600 MHz
15.79 %	−76.37	−82.68	−78.83	−80.83	80.35	68.52	72.50	55.44	5.22	5.62	1.53	3.51
21.05 %	−75.35	−81.75	−77.91	−80.38	83.35	72.44	75.81	59.81	4.53	3.89	1.13	2.55
26.32 %	−74.29	−80.88	−76.77	−79.79	86.28	76.41	80.50	66.32	4.11	3.53	1.17	1.99
31.58 %	−73.56	−80.29	−76.07	−79.25	89.37	80.66	82.62	69.23	3.98	3.30	1.04	1.64
36.84 %	−72.91	−79.67	−75.33	−78.79	90.66	82.58	85.06	73.05	3.96	3.27	1.27	1.60
42.11 %	−72.39	−79.20	−75.03	−78.51	91.61	84.24	86.36	75.29	3.69	3.02	1.32	1.57
47.37 %	−71.91	−78.72	−74.29	−78.23	92.38	85.47	87.33	77.49	3.45	2.79	1.32	1.57

solutions need to be proposed to maintain their availabilities in case of disconnections. It should be noted that in real operational networks the selection of eNB sites for backup coverage is not straightforward. The geographical distribution of eNB sites is first of all asymmetric and in practice only roughly follows the cloverleaf tessellation. Moreover, this study only showed how the network would perform if each eNB site was independent of another eNB site, i.e. the study did not take into account the possible backhaul connection limitations of (wirelessly) linked eNB sites. This can have more serious effects within rural environments if, for example, wireless microwave links are utilized more frequently compared with urban areas, where wireless links between eNB sites rarely exist.

CHAPTER 4

Situation Awareness System for Disturbance Management

Important part of restoring damaged infrastructures is disaster management. In this second main part of the thesis, a new developed SAS [P3–P4] is presented to improve and help the disaster management process. The new SAS is based on combining the outage information from two different infrastructures: mobile networks and electricity networks. This information is visualized for a quick and easy to comprehend view on a map, which e.g. helps to prioritize the restoration plans for the most critical areas in both networks.

4.1 Existing situation awareness systems

The concept of a situation awareness has a long history. In general, SA can be interpreted with many different kinds of contexts and is usually associated with decision making in complex systems containing huge amount of data, known as the concept of *big data* [63, 65]. Nowadays, some of these decisions are decided by machines, e.g. by automated computer programs, but usually the most critical decisions fall eventually to humans. For example, [26] lists different contexts for SA as follows: aircraft, air traffic control, large-systems operations, tactile and strategic systems, or even other ordinary activities like walking and driving a car. The SAS developed in this thesis can be listed as a tactile and strategic system: a tool helpful for deciding the best course of action that addresses critical information in widely varying situations. Thus, the developed SAS itself does not perform decisions, but it is helpful in determining the next move on how to improve the situation at hand.

Coverage area maps are usually freely available and accessible for the majority of MNOs around the globe. These coverage maps are convenient for checking whether a MNO has e.g. wide LTE coverage around the areas where the subscriber should need it. An example of these can be found e.g. from the services of MNOs in Finland [22, 25, 83], or MNOs in United Kingdom [46, 79, 90] to give a few examples. Thus, although modern cellular networks are advertised to have coverage all the time and everywhere, there can still be areas without mobile network coverage. For the majority of the subscribers, however, all the time ubiquitous connectivity is achieved through mobile networks.

Commercial or public mobile network SASs are not that common. From the MNOs point of view, these are systems that give more information than just the estimated coverage areas. These systems give up-to-date information from the status of the network and possibly even the estimated areas where they are likely to occur. This kind of information is well-known for MNOs themselves, but it has not been traditionally shown to the subscribers. There can be many reasons behind it, like showing a better status of the network than it actually is as the telecommunications field is very competitive, or the information is too critical for public, i.e. it could be utilized for backtracking e.g. the locations of BS antenna locations in order to sabotage them.

Nevertheless, some SASs for mobile networks exists. In Finland, for example, FICORA has launched a service called MONITORi already at the end of 2013, which currently provides up-to-date geographic information about a number of different services. At present these services include information in Finland such as broadband and telephone network availability, coverage areas of terrestrial television and radio, postal services and most importantly faults and disturbances of mobile networks [33–35]. The faults and disturbances service of MONITORi combines the fault information of all MNOs and visualizes the areas which are affected on a map. However, only severe and very severe disruptions are visualized, and this information is provided by MNOs on a regional accuracy after the incidents. Thus, the service provides only a delayed and rough geographical area of the mobile network disturbances. In other words, it is not a suitable tool for even near real-time SA, but only providing information about what had happened. More accurate and closer to real-time SASs are available e.g. on the websites of all MNOs in Finland [21, 24, 82]. It should be noted that FICORA has regulated how MNOs need to notify the faults in their networks to subscribers according to [32], but it does not require the visualization of these disturbances. Thus, each MNO has decided on their own how accurate information is visualized in their SAS in Finland.

Similar SASs can be found e.g. from Sweden [78, 80, 81], but other similar SASs are hard to find. In United Kingdom, there is one MNO, who visualizes problematic areas on an online map service, however, it only works after specifying an address and it shows only a symbol on the map and not the actual extent (geographical area) of the disturbances [90]. Another example of a similar approach can be found from Australia, where one MNO shows live outages on an online map after specifying an address to the system [88]. However, it presents just symbols to inform whether there is a problem at specific BS sites without actual estimated influence areas.

4.2 Situation awareness system implementation

The new implemented SAS combines the information from two different critical infrastructures: mobile networks and electricity networks. The information is visualized in an online map service, where the disturbances are shown in near real-time.

The information for the mobile network is based on the actual live network status of an operating MNO. This includes the configuration of the corresponding mobile network of the MNO and accurate pre-calculated simulations of the corresponding coverage areas (simulated with the Okumura-Hata model) of each cell in the network. Thus, when there is a problem in the network, e.g. a faulty BS, information about it will be sent to the system and the corresponding cells are visualized in the system. To be more precise, the system visualizes only coverage outages. This means that one faulty BS might not cause coverage outage, because other neighbor BSs are still able to provide coverage for these areas because of coverage overlapping.

The disturbance information for the electricity network part is provided by different DSOs through their DMS services. DMS generates the outage information data of the current status of electricity network, including details like the start and end time of disturbances, as we as the type and description of these events. This outage information is provided on two different levels: a transformer level and a customer level. The transformer level information data is generic and can not be utilized to identify a single customer. However, it contains a list of affected transformers and with the help of customer level information, which contains e.g. customer identification information, it can be used to identify a single customer. In the developed SAS systems case, the closest transformer of each BS indicates the availability of electricity of that specific BS. The information data is provided through extensible markup language (XML) format, which is fetched over hypertext transfer protocol secure (HTTPS) protocol. The data is further parsed and finally displayed in a browser-based user interface.

Furthermore, the system combines other beneficial information besides the status of the critical infrastructures. These include information on the current weather conditions, the status of fire and rescue service tasks, and traffic report, as shown in the structure of the system in Fig. 4.1. The weather information is fetched using hypertext transfer protocol (HTTP) from a web feature service interface provided by the Finnish Meteorology Institute. Correspondingly, the information from the fire and rescue service tasks is fetched over HTTP from an interface provided by the Finnish rescue services. Finally, the information about the traffic data can be fetched from the Finnish Transport Agency service with simple object access protocol (SOAP).

The system was also designed to include other critical information, such as the so-called critical customers. These can be, e.g. hospitals, water pumping stations, elderly people with safety phones or patients with special health care needs. The information of critical customers is a manually updated structured query language (MySQL) database, which can be updated by the users themselves. The SAS can then visualize different critical customers in the online map service.

The overall user interface is presented in Fig. 4.2, where a snapshot of the system is presented for one example case. The system highlights the borders of the corresponding municipality where there are problems in the networks. For example, a faulty transformer station in the network is visualized with a gray light bulb icon and additional information about that disturbance can be received by clicking the corresponding symbol. A faulty BS site is visualized with a BS icon.

4.3 Live demonstration - Case in Finland

The suitability of the developed SAS was tested in practice with a live demonstration. A real-life disturbance scenario is shown in Fig. 4.3, which occurred in a certain area in

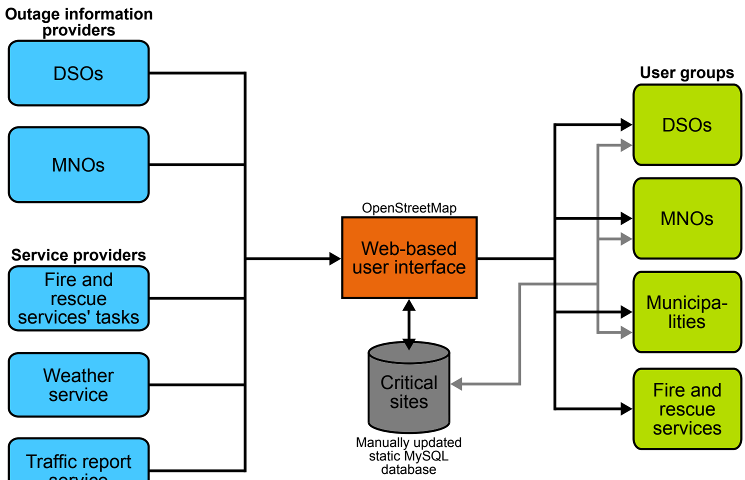


Figure 4.1: A diagram of the implemented SA system.

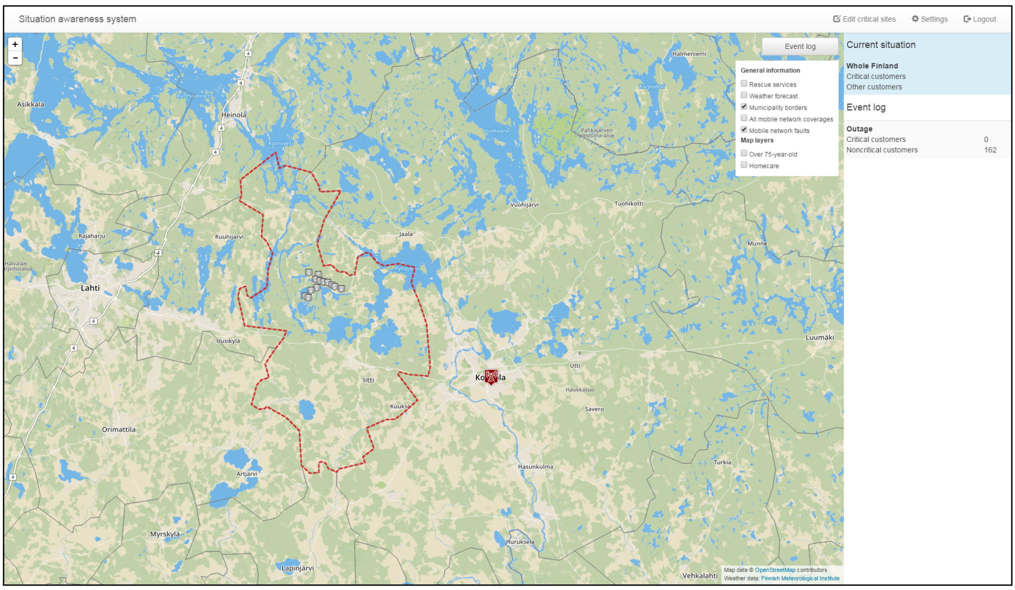


Figure 4.2: The user interface of the developed SA system.

Finland in 2015. For simplicity, only GSM network was analyzed. The red polygon ( ) represents the areas without GSM network coverage. Moreover, the symbols represent different points of interest in the map. First, the gray light bulb icon ( ) indicates the outage of a transformer in the electricity network. The blue, yellow and red symbols of a BS represent the status of it: normal BS operation ( ), BS operation with backup power

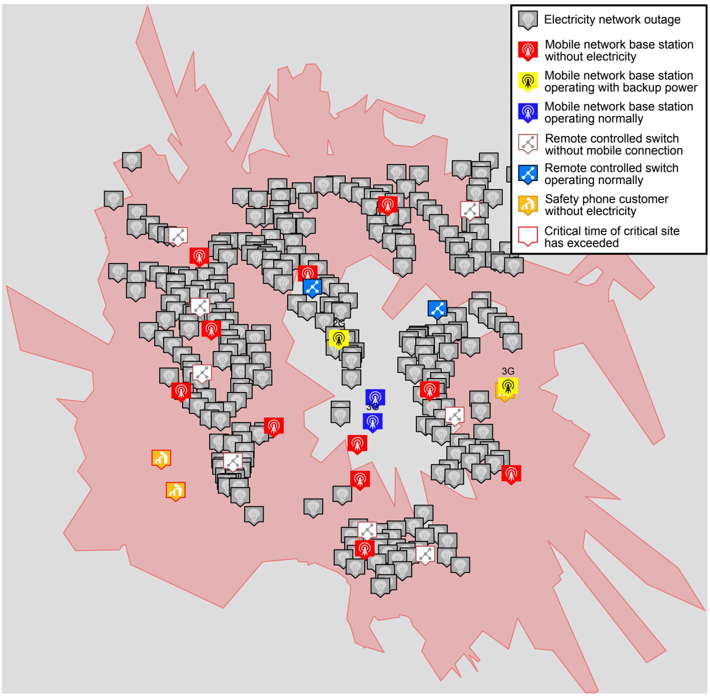


Figure 4.3: Detailed view of the user interface during a disturbance scenario with focus on GSM network outage.

(), and non-operational BS (), respectively. The status of additional information is also given with other symbols, as shown in the legend of Fig. 4.3. The information about the status of remote controlled switch is presented with two icons: on () and off (). Finally, critical customers, such as (elderly) people with safety phones, are presented in the map with orange icons () and when the predefined critical customer's critical time window has expired, the symbol will have a red edge ().

The effect of a disturbance scenario on the availability of cellular network coverage is clearly visible in Fig. 4.3, as the majority of BSs are without electricity after few hours from the start of the blackout, and only one area in the center of the figure has working BSs. The reason for this is that this area is a city center of a small town, thus the BS sites in this area have more reserve energy. This also indicates that these BSs are more critical than the other BSs in the surrounding area. The exact location and the map layer is removed because of a non-disclosure agreement with the cooperating MNO.

4.4 Situation awareness system conclusions

The most obvious benefit of using the developed SA system is the easy way to monitor both networks in the same service at the same time. Moreover, by utilizing this kind of service, the interoperabilities of the different infrastructures are easy to observe.

This information can then be e.g. utilized in prioritizing the restoration process after disturbance scenarios.

Besides MNOs and DSOs, also authorities and other parties are able to benefit from the system. For example, municipalities in Finland are responsible for the well-being of elderly citizens [5]. Thus, when the critical customers have been included in the system, the status of mobile network coverage (e.g. for safety phones) and the availability of electricity in that location are easy to monitor.

The most vulnerable parts of critical infrastructures can be found out over time by utilizing the SAS. This in turn is useful information in improving or even planning new networks. Over time, MNOs can also benefit from the system by detecting deteriorated backup power batteries. This is possible, since the duration of the backup batteries should be known and the system is able to provide information of the actual duration of the BS operation with reserve power. Correspondingly, DSOs can utilize the information about critical locations with degraded reserve power to prioritize the repair actions to such locations.

The main challenge in the functionality of existing SASs, which combine information from more than one critical infrastructure [72, 76], is the lack of interdependency information between different infrastructures. By utilizing this information, the overall SA view is easier to comprehend. Moreover, information is available for many different user groups, such as MNOs, DSOs, fire and rescue services, and authorities.

One crucial point, that has to be addressed when talking about SASs, is the actual implementation part. As the system is based on utilizing information from commercial networks, SASs can not be implemented without data directly from these companies. Thus, adopting this kind of system depends entirely on the willingness of stakeholders to participate in these kind of systems. As a result, developing SASs can be challenging unless there would exist e.g. legislation that would force different stakeholders to provide data for such systems, which would help authorities to improve the resiliency of society.

CHAPTER 5

Innovative Approaches for Mitigating Mobile Network Service Outage

This chapter is based on the work in [P5–P7]. It is the third main part of this thesis and presents different innovative methods in order to improve the functionality of mobile networks especially during disturbance scenarios.

5.1 User-guided energy and capacity optimization for mobile networks

Mobile network coverage is rather stable with a fixed configuration, however, the instantaneous state of the mobile network channel changes all the time. This channel state is related to the location of the receiver with respect to the transmitter, the surrounding environment, the actual time incident of the measurement, as well as the utilized frequency. Overall, it can be stated the wireless cellular channel is time-, frequency-, and space-variant. Thus, changes in any of these domains can alter the UE QoS of the serving cell connection.

One of the most intuitive ways to improve the connection between UE and BS antennas is to change the location of the UE. For example, simply moving a UE from an outage area to a location with coverage. This idea can be taken further by improving the connection between a UE and BS antennas by (indirectly) guiding the UE to a better location within service coverage. In practice, this means that a subscriber would change the location where he or she is making a phone call or otherwise utilizing the mobile phone. This change in the location can be from one room to another room or even different location within one room in indoor locations. The idea is the same: the change in location affects the channel conditions. [42]

In the majority of modern cellular networks, the indoor network coverage is provided from the outdoor network infrastructure. This raises severe problems in modern buildings:

the building penetration loss is very high as the building material has changed over the years as energy saving demands are stricter in the construction industry [20]. In practice this can be seen from reinforced walls with metallic surfaces and windows with the so-called low emission glasses [9]. This just emphasizes the importance of the location inside the building to utilize the mobile phone, i.e. to find the best possible position such that the channel conditions would be as good as possible.

In order to get some understanding about the channel conditions indoors, subscribers can e.g. see what the signal strength icon in their phones is showing and try to improve it by simply changing their location. The problem is that normally people are not interested in what the channel conditions are, thus they ignore the instantaneous signal strength and try to improve their location only when there is e.g. some problem with ongoing phone calls. In order to study the effects of slightly changing the UE location, a concept known as mobile performance gaming (MPG) was utilized in [P5]. The concept is simple: the properties of a game in mobile phone changes with respect to the instantaneous channel conditions and the information is sent for analysis. For example, the difficulty of a game is harder when the UE is located closer to the cell edge area. Because people are not playing all the time or are not interested in playing at all, the MPG concept was utilized with the help of the so-called live wallpapers for mobile phones. The properties of the wallpaper, i.e. the visualization, changed with respect to the instantaneous channel conditions. This way subscriber can pay more easily attention to the channel conditions.

5.1.1 Energy and capacity efficiency

The transmission powers of wireless networks are limited. In practice this means that there is a certain range of powers that can be utilized, e.g. to transmit (DL/UL) signals in mobile networks. Moreover, energy-efficiency is very important in order to save energy.

The same idea is valid for capacity: maximize the spectral efficiency in order to utilize resources more efficiently. Thus, a system which has a high value for successfully transmitted and received bits/second/Hertz is more efficient than a system having low value for the corresponding KPI with the same spectral resources (i.e. bandwidth). In practice this means that capacity is higher with a more spectrum-efficient system, which is the same as providing service to a higher number of UEs.

Because the measurements in this study were performed in UMTS network, the benefit of having a better channel condition is evaluated with the help of estimating the required average transmission power in BS to serve a number of users. The measurement UE saved the received DL power level, which corresponds to measuring the received signal code power (RSCP) from the common pilot channel (CPICH), which is transmitted with a constant power in UMTS network [2]. The CPICH power is typically between 5 % to 15 % of the total transmission power, e.g. 10 % out of 20 W equals to 2 W $\approx$ 33 dBm.

The actual average transmission power $P_{\mathrm{TX}}^{\mathrm{DL}}$ in UMTS can be approximated with the following equation [44]:

$$P_{\mathrm{TX}}^{\mathrm{DL}} = \frac{N_{\mathrm{rf}} \cdot W \cdot \overline{L} \cdot \sum_{k=1}^{K} (v_k \cdot \frac{\rho_k}{W/R_k})}{1 - \eta_{\mathrm{DL}}}. \tag{5.1}$$

Here, N_{rf} denotes the noise spectral density of the UE receiver front-end. It can be calculated with

$$N_{\mathrm{rf}} = \mathrm{k} \cdot T + NF, \tag{5.2}$$

where k is the Boltzmann's constant ($\approx 1.381 \cdot 10^{-23}$ J/K), T is temperature in Kelvins (normal assumption is $T = 290$ K), and NF is the UE noise figure. The other parameters in (5.1) are the following: W is the system chip rate, $\overline{L}$ is the average attenuation between a BS transmitter and UE receiver, i.e. the mean path loss, k is the user index, and K is the total number of users per cell. Moreover, v_k is the activity factor, ρ_k is the SINR, and R_k is the bit rate of the kth user. The DL load factor is denoted with η_{DL} and calculated as

$$\eta_{\mathrm{DL}} = \sum_{k=1}^{K} \frac{\rho_k \cdot R_k \cdot v_k}{W} \cdot [(1 - \alpha_k) + \bar{i}_{\mathrm{DL}}]. \tag{5.3}$$

Here, α_k is the orthogonality factor of kth user in the cell and $\bar{i}_{\mathrm{DL}}$ is the average other-to-own cell interference.

5.1.2 Measurement campaign

The effect of small-scale displacement in indoor mobile networks was studied with the help of commercial UMTS networks. LTE coverage was still limited at the time of the measurements in a normal urban residential apartment in downtown Helsinki, Finland in 2013, thus the data from UMTS network was utilized and collected with the help of MPG application in the measurement phone. It was a non-calibrated Samsung Galaxy S4 smart phone, thus the absolute values were not highlighted. The measurement UE was placed on different tables around the apartment (height approximately 50 cm to 120 cm) and left at one location for a few minutes in the measurements.

A rough blueprint of the measurement apartment (first floor) is shown in Fig. 5.1. It shows four different measurement scenarios:

1. UE placed around common areas in the apartment (all tables).
2. UE placed in a subset area of measurement scenario 1. The maximum location difference was 3 m to 6 m within the area (different tables).
3. UE placed in a subset area of measurement scenario 2. The maximum location difference was 1 m to 2 m within the area (different locations on one table).
4. UE fixed to one location within the area of measurement scenario 3.

The measurement UE did not have any body contact during the measurements, however, the measurement person was able to move around in the surroundings approximately 3 m to 5 m from the phone. All of the measurements were performed with the phone staying in idle mode, i.e. no data transmission or call was ongoing, and the phone was able to perform a handover (HO) to different available cells. The MPG application saved the measurements such that average values for every 10 s were recorded, thus data with a rate of 6 samples per minute was imported to the analysis.

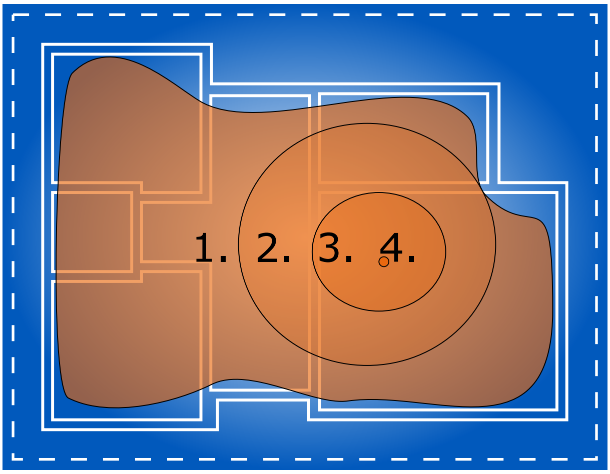


Figure 5.1: Blueprints of the measurement apartment with different areas for the measurement scenarios 1.–4.

5.1.3 Measurement results

All of the measurement results are visualized in Fig. 5.2. During the measurements, the measurement UE was connected to 3–7 different BS cells within four different scenarios inside an apartment in downtown Helsinki, Finland. As can be seen from the mean and standard deviation values in Table 5.1, the channel conditions are close to that of a typical indoor coverage values in a cell edge area.

As the measurement area is shrunk down, the standard deviation is smaller, meaning that there is less variation between the measurement data. Taking this into account and the fact that the overall measurement values ranged from −127 dBm to −95 dBm, it can be noted that the received signal power level can be improved easily 10 dB. Furthermore, it is possible to improve the received signal strength from 20 dB to 25 dB by moving from the worst location to the best location.

In practice, an improvement of 10 dB or 20 dB in the path loss is remarkable. For example, by utilizing (5.3) with 33 speech users ($R_k = 12.2$ kbit/s) and the following typical values: $\rho_k = 6$ dB, $v_k = 0.5$ $\alpha_k = 0.7$ and $\bar{i}_{\mathrm{DL}} = 0.5$, the DL load factor η_{DL} equals to 16.7 %. As a result, when this value is utilized in (5.1) with 7 dB UE noise figure and an average 150 dB path loss (e.g. measurement scenario 1: RSCP = −117 dBm, CPICH = 33 dBm, UE antenna gain = 0 dBi, BS antenna gain = 17 dBi, and building penetration loss = 17 dB), the required total transmission power is 42.9 dBm (≈ 20 W). An improvement of 10 dB in the path loss would result in total transmission power of 32.9 dBm (≈ 2 W) and 20 dB improvement into 22.9 dBm (≈ 0.2 W), respectively. This clearly shows the benefit of improving the average path loss from the energy point of view. Correspondingly, the theoretical capacity inspection shows that if the transmission power was fixed to 20 W, then an improvement of 10 dB in the path loss would result in increasing the number of speech users from 33 to theoretically up to 133 (downlink load factor would increase from 16.7 % to 67.3 %). The improvement would be even higher

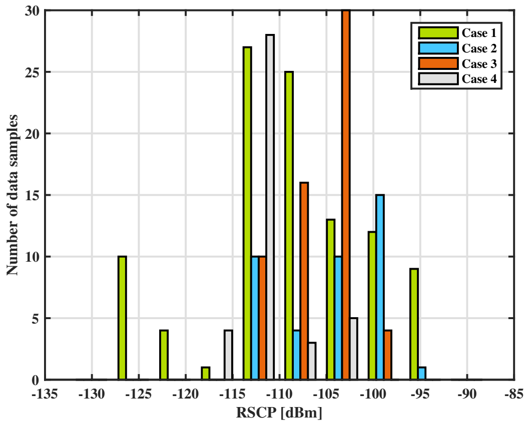


Figure 5.2: Histograms of the measurement scenarios 1.–4.

with 20 dB path loss gain, but the DL load factor would start to limit the number of additional users as well as the maximum number of simultaneous active users supported in one UMTS cell. Taking these into account, the improvement of 20 dB would result, e.g. theoretically up to 150 speech users causing 75.9 % load with only 34.9 dBm (less than 4 W) transmission power. Thus, improvements are practically seen with more simultaneous users (up to the system limit) and lower transmission powers.

Table 5.1: Mean and standard deviation values for measurement scenarios 1–4.

measurement scenario	**mean RSCP (dBm)**	**standard deviation (dB)**
scenario 1	−108.5	8.46
scenario 2	−104	5.54
scenario 3	−106	3
scenario 4	−111	3

5.1.4 User-guided energy and capacity optimization conclusions

The obtained measurements show that the DL signal power level (RSCP in UMTS) at the receiver (UE) could be increased up to 10 dB to 25 dB, when the UE location is optimized. This can significantly improve the mobile network energy-efficiency and capacity-efficiency when subscribers perform this kind of indirect mobile network optimization. However, it should be noted that in order to achieve high benefits from this kind of system, the majority of subscribers should improve their channel conditions if possible. Nevertheless, all improvements, especially from very bad channel conditions, will improve the overall situation and reduce the required transmission power of the UE.

Although the measurements were performed in a UMTS network, similar energy savings are possible to achieve in other cellular network technologies. The challenging part, however, is to motivate subscribers into actually optimize their location. During disturbance and disaster scenarios these kind of actions would help to save the BS backup energy, and eventually prolong the functionality of the network operating with reserve power.

5.2 Low altitude platforms for disaster scenarios

The existing mobile network infrastructure can be temporarily unavailable after disaster strikes. Assuming local backup power, the BS sites can maintain their operation only for a short period of time. Moreover, when repair and emergency teams are able to reach the disaster-hit area, the reserve power can already be finished. This would mean that the communications in that area would not work and that other methods for communications have to be utilized, besides the existing cellular network, as mentioned in Section 3.2.

The coverage aspects of LAP network are investigated in [P6] with the help of drones, or more generally known as unmanned aerial vehicles (UAVs). The idea is similar to that of HAP systems [36, 51, 57]: provide a (temporary) communication infrastructure for the so-called emergency coverage in disaster-hit areas. The idea is similar to the one presented in [39, 85, 86]: the utilization of UAVs to form a temporary network for disaster response. However, the authors in [39, 85, 86] focus on deploying only a very small-scale version of the idea.

The LAP concept proposed in [P6] is presented in Fig. 5.3 and it utilizes Institute of Electrical and Electronics Engineers (IEEE) 802.11 family standards to form a flying ad hoc network (FANET) as presented in [11]. The emergency coverage is provided through WLAN access points (APs) utilizing 2.4 GHz frequency band with 20 MHz bandwidth in the so-called disaster area drones (DADs). The backhaul connection between DADs is based on utilizing 5 GHz frequency band with 40 MHz bandwidth. The actual connection to the Internet in this concept is provided through gateway drones (GDs), i.e. UAVs equipped also with 3G/4G modems, which have to be placed in the border area between the disaster-hit and still unaffected areas.

It is assumed that the operation of drones is semi-automatic. Thus, the system is able to connect and provide a temporary network coverage for a desired location. This means that the emergency field team just need to launch the drones at a predefined suitable location, and that the drone would automatically take off to a suitable hover altitude. As such, the aim of this study is to focus on the coverage capabilities of the proposed LAP concept. In order to form an idea about these aspects, simulations were performed to find out how would e.g. different inter-drone distances (IDDs) and the hover altitudes of DADs affect the service coverage areas.

5.2.1 Service area simulations

The simulations in this study were performed with ProMan tool, which is software for wave propagation and radio network planning. It is a part of WinProp Software Suite [7]. The propagation model chosen for the simulations was the dominant path model (DPM) [7]. The model determines the dominant paths between UEs and BSs, as

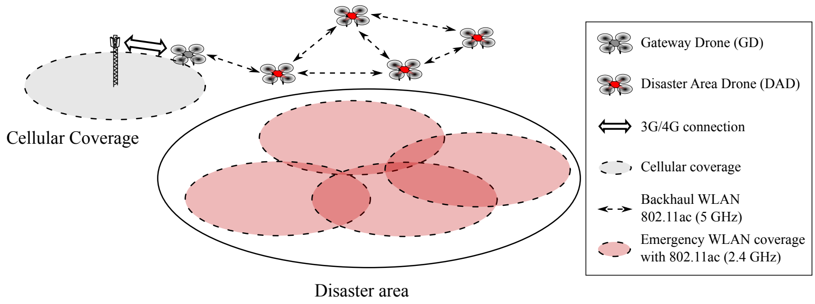


Figure 5.3: An example of the LAP network concept.

in most cases only two or three propagation paths contribute more than 90 % of the total energy [91, 92]. Thus, the heavy calculations of ray-tracing or ray-optical models can be simplified to consider only the main paths. As a result, the computation time of DPM is comparable to that of empirical models (such as Okumura-Hata or Walfisch-Ikegami), but the accuracy of the model is close to that of ray-tracing models. The DPM model to calculate the path loss L is defined as:

$$L = 20\cdot\log_{10}\left(\frac{4\pi}{\lambda}\right) + 10\cdot n\cdot\log_{10}(d) + \sum_{i=0}^{N} f(\varphi, i) + \Omega + g_{\mathrm{t}}, \tag{5.4}$$

where λ is the wavelength of the utilized frequency, n is the path loss exponent and d is the distance between the transmitter and receiver. Moreover, the sum of individual interaction loss function, $f(\varphi, i)$, is due to diffraction loss for interaction i up to maximum number of interactions N with φ as the angle between the former propagation direction and the new direction. The so-called tunneling effect, i.e. the wave-guiding effect of propagating signals is taken into account with Ω. It is empirically determined and described in detail in [7, 93]. The last parameter, g_{t} is the gain of the transmitting antenna.

All of the important simulation parameters are presented in Table 5.2. The simulation area consisted of 6 km × 6 km flat rural and dense urban (Manhattan) environments. The choice of IDD was set to 960 m for both environments, to be in line with test results provided in [73]. In addition, the effects of densification were studied with 480 m IDD for urban areas as well as increasing the number of DADs from one up to $11 \times 11 = 121$ drones in a square grid. The drones were set to hover in the altitudes from 50 m to 500 m. The path loss exponent n in line-of-sight (LOS) paths was set to 2 before and to 2.6 after the break point distance to match the measurement results in [61]. The path loss exponent for obstacle LOS (OLOS), or commonly known as non-LOS (NLOS), was set to 3.5 to match (dense) urban environment.

The detailed information for drone parameters is shown in Table 5.3. The effective isotropic radiated power (EIRP) for 2.4 GHz frequency band in WLAN is limited to 20 dBm in Europe according to European Telecommunications Standards Institute (ETSI) [28]. Correspondingly, the EIRP for 2.4 GHz frequency band in WLAN is limited to 36 dBm in the United States according to Federal Communications Commission (FCC) [29]. The minimum usable coverage threshold can be considered to be −82 dBm

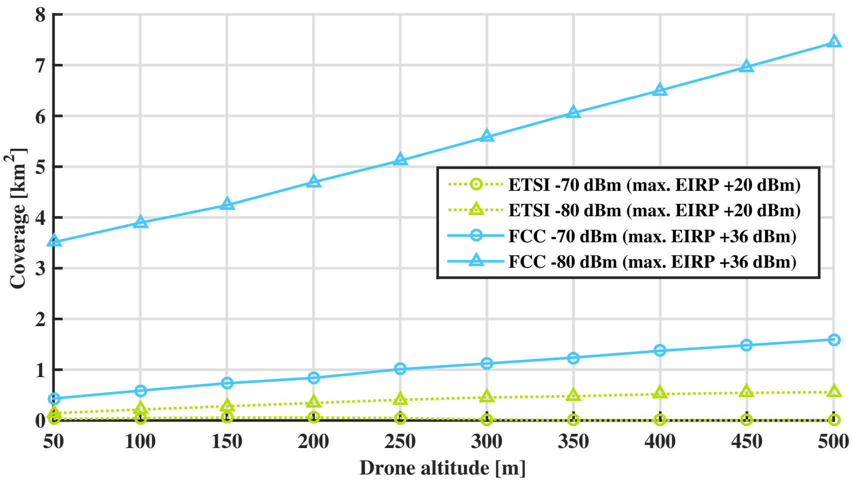


Figure 5.4: Emergency coverage area of a *single DAD* as a function of drone hover altitude in rural area.

for 20 MHz bandwidth according to [52, 67], thus with 2 dB margin the actual minimum threshold for the emergency coverage in the simulations was set to −80 dBm and a stricter value to −70 dBm for comparison.

5.2.2 Low altitude platform results

The results for the simulations in flat rural area are presented in Fig. 5.4. The results show that as the height of the antenna (the DAD hover altitude) is increased, the overall emergency coverage area is larger than with lower altitude, as expected. The difference in the actual coverage areas between different altitudes is little. The smallest service areas (with −80 dBm coverage threshold) of 0.14 km^2 (ETSI) and 3.51 km^2 (FCC) are achieved with the lowest drone altitude (50 m). Likewise, the largest coverage areas are the result of the highest DAD altitude (500 m) with 0.56 km^2 for ETSI and 7.4 km^2 for FCC.

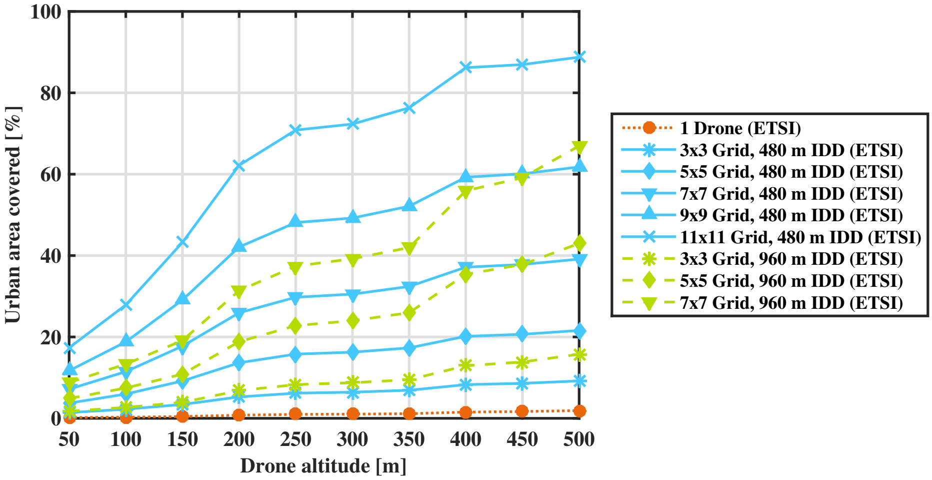
The results for urban areas with Manhattan grid are shown in Fig. 5.5. Instead of showing the absolute coverage areas, a percentage of the total outdoor area is shown to easily compare the effects of densification. The grid of DADs is centered at the simulation area. Fig. 5.5a presents the results for ETSI regulation and Fig. 5.5b for FCC regulation. Once again, the coverage area increases as the altitude of drones is larger, but also when the number of serving DADs is increased. The differences between IDD and the number of DADs are clearer with the FCC regulation. For example, 5×5 grid with 960 m IDD in the 150 m altitude is able to provide already slightly better coverage area than 5×5 grid with 480 m IDD in the same altitude.

Table 5.2: Simulation environment parameters.

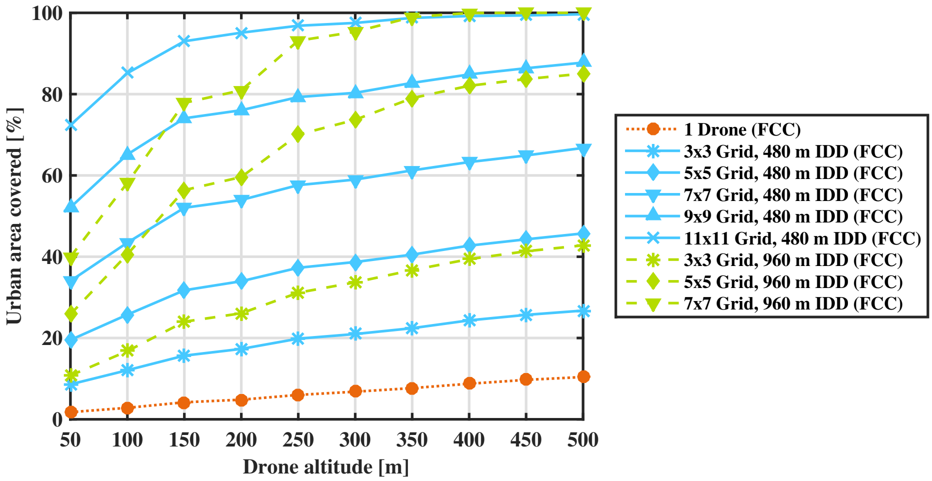
	Parameter	Value
Path loss	model	dominant path
	exponent (LOS)	2 / 2.6 (before / after break point)
	exponent (OLOS)	3.5
Calculation	area	6 km × 6 km
	resolution	20 m (rural) / 10 m (urban)
	environment	Flat (rural) / Manhattan (urban)
Dimensions	building size (urban)	100 m × 100 m
	building height (urban)	25 m
	street width (urban)	20 m
Drone	inter-drone distance	960 m (rural) 960 m, 480 m (urban)
UE	receiver (UE) antenna height	1.5 m

Table 5.3: Drone parameters.

	Parameter	Disaster Area Drone
WLAN	standard	IEEE 802.11 family [52]
	frequency band	2.4 GHz / 5.8 GHz
	bandwidth	20 MHz / 40 MHz
	max. EIRP (backhaul)	35 dBm
	max. EIRP (emergency coverage)	20 dBm (ETSI) / 36 dBm (FCC)
	additional losses	2 dB
Antenna	heights (drone altitudes)	50 m, 100 m, 150 m, 200 m, 250 m, 300 m 350 m, 400 m, 450 m, 500 m
	model (backhaul)	HVG-2458-05U [56]
	model (emergency)	NanoStation locoM2 [87]
	HPBW (backhaul)	360° × 45° (azimuth & zenith)
	HPBW (emergency)	60° × 60° (azimuth & zenith)
	tilting (backhaul)	-
	tilting (emergency)	90° (Facing downwards)
	gain (backhaul)	5 dBi
	gain (emergency)	8.5 dBi



(a) Maximum DAD emergency coverage EIRP = 20 dBm (ETSI).



(b) Maximum DAD emergency coverage EIRP = 36 dBm (FCC).

Figure 5.5: Dense urban environment outdoor coverage for the Manhattan grid. Coverage threshold limited to −80 dBm.

5.2.3 Low altitude platform conclusions

The coverage aspects of the proposed LAP concept show that the emergency coverage would be possible to implement with a reasonable number of drones. However, the energy of drones will present a problem, as the batteries will not last long. This problem can be partially solved with the so-called persistent drones, which can utilize a thin filament for providing energy from the ground up to $\approx 120\,\text{m}$ (400 ft) [18].

As the capacity aspects were out of the scope in [P6], the two most limiting factor for increasing the emergency coverage area were the maximum EIRP and the IDD. Changes in the EIRP would need permission from ETSI/FCC and more directive (high gain) antennas would be needed in order to increase IDD. However, this would require more precise alignment between the drone antennas.

5.3 Macro sensor network

Besides the availability of electricity, the functionality of cellular networks depends on the availability of backhaul connection to the CN. Thus, a large part of the mobile network can be temporary down if a (critical) connection is cut off. To improve the resilience of mobile networks in such occasions, [P7] suggests the concept of a *macro sensor network (MSN)*. The idea is to provide a WSN functionality for mobile networks in order to maintain some connectivity to CN.

When the conventional backhaul connection is cut off, BSs stop working, i.e. communication becomes impossible. However, the current mobile networks are very dense, i.e. there is a lot of overlapping between the serving cells. Furthermore, with high masts, LOS connections are possible between different BSs sites. One possibility to enable communication would be to relay data directly from one BS to another in the manner of multi-relay communication [19]. Multi-relay communication resembles also the so-called self-backhauling or in-band relaying concepts where the idea is quite the same: enable a connection from the UE to the network through more than one eNB. However, this ideology has not been taken to the macro level in the context of disaster scenarios. As already mentioned in Section 3.2, the usual approach to disaster-hit areas is to form a new temporary infrastructure with the help of MANETs. Instead, improving the existing network with the help of the proposed MSN concept would be more suitable.

5.3.1 Macro sensor network concept

The resilience of mobile networks can be increased by developing mobile network functionalities for coping disturbance or disaster scenarios. The MSN presented in this study is an example of such concepts.

In this study, a disaster scenario means a situation, where the link between the radio access network (RAN) and CN is broken. For LTE, this corresponds to a situation where the link between eNBs and the evolved packet core (EPC) is unavailable. When such incident occurs, the WSN functionality is activated within eNBs and EPC. This kind of automatic process can be considered to be close to that of a self-organizing network (SON). Eventually, the realization of WSN capabilities within LTE utilizes the X2 interface as defined by 3GPP [3]. The X2 interface is essentially a logical connection to enable direct connections between (neighbor) eNBs and the physical connection is not restricted into a wired connection. Thus, the implementation of the X2 connection between eNBs is eventually vendor-specific and can be implemented even over a wireless channel. This capability of LTE is utilized in this macro sensor network concept such that the wireless X2 connection is actually implemented with the help of reserving part of the resource blocks to communications between eNBs.

5.3.2 Macro sensor network operational framework

The framework for the proposed WSN concept is presented in Fig. 5.6. When the link between eNB and EPC is broken, the functionality of the eNBs and the EPC will switch to "WSN mode". The eNBs within the disturbance area will switch to WSN mode as soon as the connection to the EPC breaks. Next, eNBs will begin to search for neighbor eNBs by sending a discovery message. If the neighbor eNB site has a working backhaul connection, it sends back an acknowledgment message with "flag 1" to indicate that communication to the EPC is possible through it. If the neighbor eNB is missing the link to the EPC, it sends back an acknowledgment message with "flag 0" as well as information about its one hop neighbors.

EPC will also activate the WSN functionality of those eNBs which are geographically situated in the vicinity of the affected area as shown in Fig. 5.7. This is required in order to enable WSN functionality discovery message flow and finally the actual communication to the disaster area. When the disaster scenario is over, EPC can send a command to all MSN eNB sites to disable the WSN functionality and return to the normal operation mode.

5.3.3 Macro sensor network conclusions

A realization of a LTE network with WSN functionality, also known as MSN was suggested in [P7]. The node-to-node or eNB-to-eNB functionality in LTE for MSN would enable limited communication for disaster areas where the link between the eNB and EPC is broken, but the eNB sites still have power to maintain operation.

The concept proposed in this study falls to the category of SONs as this MSN functionality will need to be implemented as an automated service. This will bring flexibility to the networks to cope with disturbances in the backhaul connections, thus improving the resilience of the networks. Besides actual disaster or disturbance scenarios, this kind of functionality would also improve the network operations during backhaul maintenance. However, in order to realize and further develop this kind of functionality, some changes in the 3GPP specifications are eventually needed.

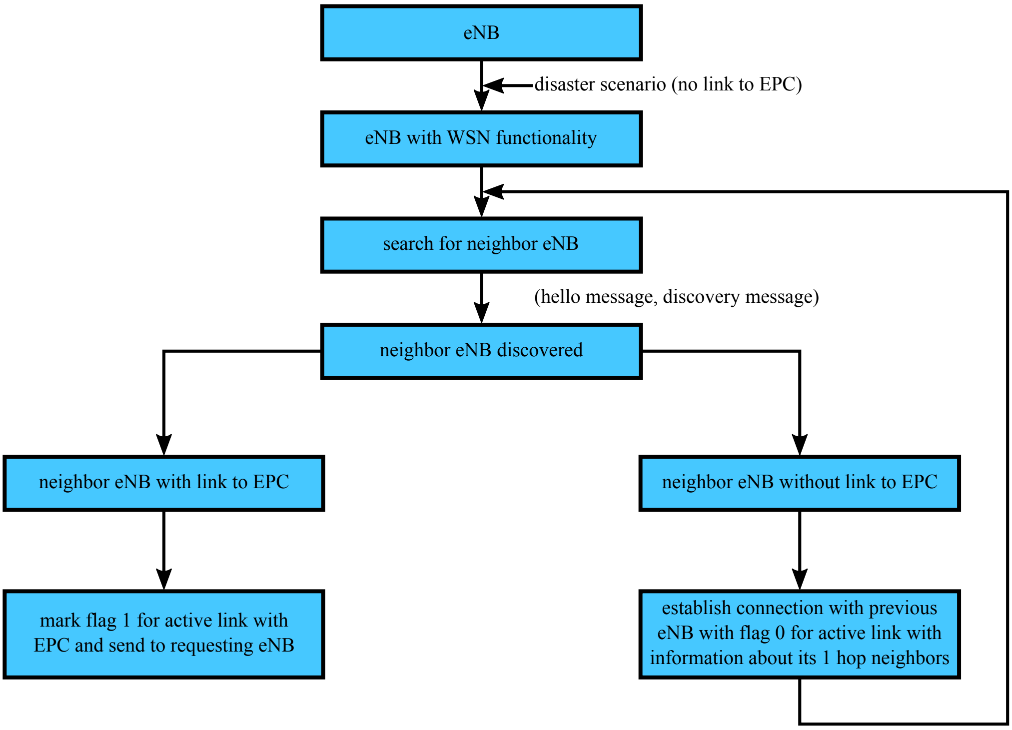


Figure 5.6: Node-to-node (eNB-to-eNB) communication flow chart.

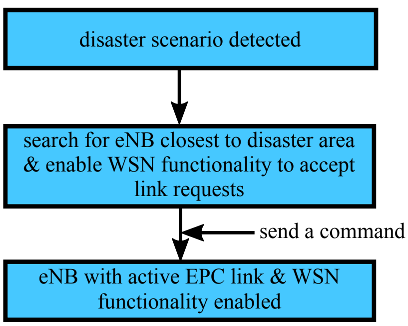


Figure 5.7: EPC events.

CHAPTER 6

Conclusions

Critical infrastructures are the foundations of modern societies. The most critical, known as level 1 infrastructures, are mobile networks and electricity networks. This thesis concentrated on the aspects of critical communications, thus the studies performed for this thesis were considered mainly from the wireless communications field. These include understanding the current “behavior” of subscribers when something partly unexpected occurs, how to improve the existing systems by utilizing the current equipment, how to improve the restoration of these networks by utilizing new SAS and other innovative approaches in order to mitigate service outages.

6.1 Summary

The behavior of modern cellular network subscribers in normal situations follows a similar, predictable, trend over time. However, when an uncommon disturbance scenario occurs, the particular behavior of subscribers change as was discussed in Section 3.1 [P1] in Chapter 3. In short, the subscribers within the disturbance area are more active than in normal situations. If the network is not capacity limited, as is usually the case in rural areas, the network can be expected to cope with the suddenly increased service demand. However, capacity related problems are expected to occur, when operating in high loaded areas, such as urban areas as the service demand is expected to increase up to 84 %, thus service blocking starts to limit the availability of mobile network services.

When a disturbance scenario occurs and results in the lack of electricity from the main grid, the disturbance time functionality of mobile networks is limited by the availability of reserve power. In modern mobile networks, this reserve power is usually backup batteries. Thus, the operational time of mobile network BSs is limited by the amount of energy within these batteries. Moreover, the network is configured to try to maintain normal operation with the help of this reserve power. One possible solution to prolong the mobile network operation utilizing backup batteries in disturbance scenarios was presented in Section 3.2 [P2] in Chapter 3. By utilizing only a portion of the existing BS sites at a time, and loosening service coverage requirements, around 20 % of BS sites would be enough to serve roughly 75 % of the disturbance area. Thus, the disturbance time functionality could be prolonged several times given that CN and backhaul network are also operational during this time period.

One of the most important parts of restoring the possibly damaged infrastructure is disaster management. It includes everything required in order to normalize the situation and one essential tool for it is a situation awareness system as developed and presented in Chapter 4 [P3–P4]. The new SAS developed for this purpose combines the information of two critical infrastructures: mobile networks and electricity networks. The user interface of the developed SAS is a map view, where the actual faults and the affected areas in the operative networks are visualized in near real-time. The most obvious benefit of this system is the combined view of both networks. Thus, information regarding both of them are easy to observe at the same time and e.g. the prioritization of maintenance and repair actions are more fluent by taking into account the interdependencies between these networks as provided in the SAS. Furthermore, the SAS helps to build a more accurate SA that e.g. authorities, and fire and rescue services can utilize for public safety actions.

The innovative approaches to mitigating mobile network service outage were presented in Chapter 5 with Sections 5.1–5.3 focusing on Publications [P5–P7]. First, in Section 5.1 [P5], the focus was on guiding mobile network subscribers indirectly to self-optimize their location such that the channel conditions were improved. Thus, the overall impact on the system level saves both energy and capacity within mobile networks. Next, the coverage possibilities of a temporary LAP network were investigated with the help of drones in Section 5.2 [P6]. The obtained results show that this kind of approach could be utilized for a limited area with a reasonable number of drones. Finally, the possibilities of bringing WSN capabilities into cellular networks were suggested in Section 5.3 [P7]. The MSN concept was based on reconnecting eNB sites without a link to EPC through other eNBs in a relay type of manner. The actual implementation of such system would require SON features and changes into 3GPP specifications, but the outcome of such system would remarkably improve the resilience of mobile networks.

6.2 Discussion and further development

It is well-known that after disaster scenarios mobile networks will either immediately stop working because of destroyed infrastructure or relatively fast after the incident as a result of a power blackout in the electricity network. If the cellular network retains its capability to function, the huge surge in cellular network service demand will most likely prevent the utilization of the network. However, the effects of disturbance scenarios, i.e. the “milder” versions of disaster scenarios and their effects on service demand are not usually studied. Thus, publications on the topic are hard to find. The results in this thesis provide this information, i.e. results from an uncommon disturbance scenario in modern society. This information provides insight on how to design the networks to withstand the capacity increase caused by disturbance scenarios. In order to deepen this knowledge and to keep up with the development of mobile networks, future studies are needed to generalize the achieved results and to observe the impact of the upcoming 5G networks e.g. on subscriber service behavior.

The so-called green or energy-efficient communications approach for cellular networks targets to save and reduce the energy these networks consume and the majority of energy consumption relates to BSs. The existing approaches in this field are mostly different strategies to shortly switching off BSs during low traffic time periods. The studies performed in this thesis are a state of the art for considering saving the energy of BSs in disturbance scenarios. Conventionally this kind of approach is not utilized in order to retain full mobile network service coverage after disturbances. However, it is more beneficial to prolong the availability of a mobile network at the expense of reducing the QoS than having full service coverage for a shorter period of time. As the results of this thesis are based on a theoretical BS site layout, a clear future topic in this area is to model an operative mobile network layout and apply the utilized approach to it.

The situation awareness system presented in this thesis is a state of the art tool for modern societies. Disturbance management is very important in order to recover from a disturbance scenario and the developed SAS provides a solution to handle it. The most obvious benefit of the developed system is the combination of both of the most critical infrastructures. The challenges in these kind of new systems are usually related to gaining access to the operative data of several different companies. Thus, in order to set up this kind of a system e.g. for a whole country requires a great deal of cooperation and means the be able to receive data from many different kinds of companies. As a result, successfully implementing this kind of a system for broad utilization requires most likely either a legislation or at least some sort of regulation.

Innovative methods are always needed in any (research) field. As the name suggests, the target is to find new perspectives to (improve) existing solutions. The studies in this thesis presented a few different possibilities related to finding innovative methods. By definition, these present state of the art approaches for mitigating mobile network outage or improving their resiliency. However, more studies are needed in these new approaches in order to eventually implement these features into existing mobile networks. Therefore, this is especially interesting and fruitful research area for future studies.

Altogether, this thesis emphasizes the importance of critical infrastructures and different approaches on how to improve the current mobile networks. The obtained results provide insight on how to develop the current and future mobile networks toward more resilient infrastructures in order to improve the critical communications part especially in disturbance (and disaster) scenarios. In addition, the contributions in this thesis can be utilized in the future, e.g., as a starting point to develop a new state for mobile networks called a *safety mode*. It could change the functionality of mobile networks such that the critical communication can be sustained better during disturbance or disaster scenarios.

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Publications

Publication 1

J. Säe and J. Lempiäinen, "Mobile Network Service Demand in case of Electricity Network Disturbance Situation," in *Proceedings of the IEEE 27th International Symposium on Personal, Indoor, and Mobile Radio Communication (PIMRC)*, Valencia, Spain, 4.-7. Sep. 2016. DOI: 10.1109/PIMRC.2016.7794961

Mobile Network Service Demand in case of Electricity Network Disturbance Situation

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***Abstract*—The aim of this study is to analyze how cellular network subscribers behave during an electricity network disturbance situation. Furthermore, removing the effect of randomly accessing the network could improve especially the speech capacity during these events. When part of the mobile network is unavailable, the availability of the cellular network services decreases. However, the subscribers have increased demand for services during disturbance scenarios since they fetch information from the Internet and try to contact their family and friends. The analysis in this paper shows that even an uncommon power blackout resulted in an increase of 73 % in new calls and 84 % in the number of short message service (SMS) demand for mobile network services in a rural area.**

***Index Terms*—Availability, mobile networks, disturbance, disaster, blackout, service demand, rural.**

I. Introduction

After any major incident, such as a natural disaster scenario, the service demand behavior of mobile network subscribers changes. Traditionally, the large-scale statistics of the mobile network traffic from any region, like a certain city or even a larger area of a municipality, follow a certain routine day after day. This includes normally: a very low network usage time period during the night; some high service demand hours, the so called busy hours, that occur usually during lunch time or after work hours when people make calls to their families and friends; and other mediocre network usage time periods during the day. This cycle repeats day after day and has a specific profile which can be noticed from the statistics. The profiles for working days, i.e. from Monday to Friday, are very similar, but the profiles for the weekends are slightly different. This can actually be already noticed on Friday evenings as subscribers tend to prepare for the weekend, thus usually increasing the service demand.

The mobile network traffic profiles tend to repeat similarly week after week. It is also normal to observe a change in the traffic profiles when the season changes, e.g. from spring to summer as people have holidays that break the normal cycle. If there are some major changes or uncommon events, their affect can also be noticed from the statistics. A large gathering of people can be noticed from the statistics with increased traffic and blocking rates as the mobile network capacity is not dimensioned for these events. They can include, among others, rock concerts, sports events or festivals that gather massive amounts of people. Thus, the network at these locations can not meet the demand requirements set by the temporarily increased number of subscribers and results to lack of service for the portion of the demand that exceeds the planned service capacity for that specific area. However, there is usually some information available in advance for these kind of events and mobile operators can set up some extra capacity with movable base stations (BSs) for these areas in order to temporarily increase the capacity to meet the expected service demand increase.

This is not the same for sudden, unexpected network disturbances or disaster scenarios. These can include, among others, storms that cause destruction to electricity networks resulting eventually in power outages. This relates back to mobile network BSs since their functionality depends on the availability of electricity. In Finland, the Finnish Communications Regulatory Authority (FICORA) has assigned that cellular network BSs sites must have backup power for two to four hours depending on the type and the environment of the BSs, i.e. whether the equipment is located inside a private property in urban area or a mast in rural area [1]. This should guarantee that mobile networks continue to operate (voice and data) at least few hours after a power blackout, but this again depends on the condition of the backup batteries or other reserve power at the BS sites with respect to the service demand. However, this does not guarantee the availability of mobile network services at those locations. This is because the service demand increases as the subscriber behavior changes, which results in the cellular network not being able to handle all the increased traffic, i.e. the capacity is not planned to cope with the extra traffic caused by disturbance or disaster scenarios. It should be noted that the behavior of the subscribers might be dissimilar in different environments, i.e. the users in rural areas might be more used to power blackouts than users in urban areas. The cause of the disaster scenario also affects the behavior of the subscribers as large natural disasters will result in more panic among the citizen than an uncommon blackout, e.g. in the electricity network.

This paper presents a study performed in Finland, where one regional electricity network power blackout (caused by a storm) was analyzed from the mobile network statistics point of view. *The target is to show how the cellular network traf-*

fic demand changes according to an unexpected, uncommon event. This helps to understand how the networks should be designed to prepare for possible disturbance scenarios or what are the possible problems that should be taken into account. Furthermore, the situation could be improved with guidelines on how to utilize the network in these disturbance situations with some modifications on the basic principles for accessing the network.

II. Background

Mobile network capacity dimensioning is initially based on the number of potential subscribers and some assumptions. These include e.g. how often calls are made and how long these calls should last or what other kind of services could be expected. Moreover, the target is to offer suitable capacity to subscribers with minimal costs, i.e. the network should be fully utilized in the busiest time periods. This way the operators do not have to invest in additional capacity and the network operation should be cost-efficient.

A. Random service access

Mobile network capacity depends heavily on the offered services and the user behavior. A general assumption is that users may move and utilize services freely and randomly anywhere and any time. For traditional speech users, a relatively accurate modeling based on Poisson process can be utilized. In a Poisson process, users have a *random* length of a call and follow the negative exponential curve [2], [3], i.e. the probability density function is defined as

$$p(T) = \mu e^{-\mu T}, \tag{1}$$

where T denotes the time of the arriving call and $1/\mu$ is the average call duration. In addition, users have *random* time between the calls, also following the negative exponential curve and the probability density function is, respectively

$$p(T) = \lambda e^{-\lambda T}, \tag{2}$$

and $1/\lambda$ is the average inter-arrival time. When both the length of the calls and the arrival time of the calls are random, the most interesting value is the probability of a user not being able to make a call. The well-known Erlang-B formula (without queuing) can be defined [3] and the blocking probability p_m is defined as

$$p_m = \frac{\left(\frac{\lambda}{\mu}\right)^m / m!}{\sum_{n=0}^{m} \left(\frac{\lambda}{\mu}\right)^n / n!}, \tag{3}$$

where m is the number of channels that are busy and n is the number of total channels in the system.

Erlang-B formula gives estimation about the available speech traffic of a certain configuration (the amount of channels) when certain blocking probability is expected, and when the subscriber call behavior is random. In [2], a comparison is shown for a traditional one transceiver (TRX) BS having 7 traffic channels (1 channel reserved for signaling) in global system for mobile communication (GSM). Erlang-B formula provides $2.5\,\mathrm{Erl}$ traffic in case of $1\,\%$ blocking probability. Measurements from the real network give $2.0\,\mathrm{Erl}$ traffic and $0.4\,\%$ blocking i.e. practical values follow the theoretical calculations quite well. The theoretical maximum capacity (7 traffic channels, without blocking) would be $7\,\mathrm{Erl}$ if callers have a certain allocated time slot for a service and no gaps exist between the channel allocation in the time domain. Thus, $4.5\,\mathrm{Erl}$ of capacity is missed in order to have freedom for users to make calls randomly, and simultaneously to keep the blocking at the level of $1\,\%$. Thus, *to increase the available capacity in disturbance or disaster scenarios, the randomness of call lengths and times could be temporarily disabled* and specific time slots could be reserved for different users in the disturbance area. For example, in 1 TRX GSM case, capacity can be increased from $2.5\,\mathrm{Erl}$ theoretically up to $7\,\mathrm{Erl}$ (with $0\,\%$ blocking) meaning a notable capacity increase in this very limited configuration. The same $7\,\mathrm{Erl}$ capacity would be achieved with $24.9\,\%$ blocking if randomness would remain. This will obviously need some algorithms to allocate "call slots" so that the subscribers in these areas know when they can make their calls. The emergency calls should get through in all situations, but for the not-so-time-critical-calls this method should provide some fairness among the subscribers, e.g. subscribers can not reserve the channels for too long. A system of this kind would need some method in order to call or notify the subscribers whose time slot to call is up so that the signaling still works without congesting too much.

B. Related work

The impact of disaster scenarios on mobile network traffic has been investigated *mostly after major* natural disasters. The authors in [4] show that the availability of mobile networks was lowered by $32\,\%$ in Hurricane Sandy in 2012. Likewise, the authors in [5] show that the cellular network call amount was increased 60 times the normal demand after the Tsunami had hit Japan in 2011, resulting in a blocking rate of $95\,\%$ for new calls. Thus, the service demand increase is huge in major disaster scenarios. This paper, however, studies the effect of a smaller, uncommon power blackout on the subscriber behaviour.

As a suggestion for these enormous service demands, the authors in [6] show that if the mobile network core is virtualized, the operation of such network can be improved during these events by reprioritizing the cellular network traffic services. They show that when the call traffic has a sudden 50-fold increase, the voice call acceptance rate is around $5\,\%$ without any modifications on the core network. When the core network resources are reallocated, the call acceptance is increased up to $25\,\%$, thus improving the overall situation only by changing the core services.

Some studies ([7], [8]) also suggest automatic algorithms and machine learning to discover anomalous patterns in network traffic to predict when a major event is about to emerge.

This information can be useful, when a sudden incident happens in the network to automatically react to the changed situation. Thus, any kind of uncommon event remarkably changes the subscriber behavior and authors in [9] also show through simulations that the network congestion is mainly caused by the dynamic changes in subscriber behavior.

C. Possible methods to increase the mobile network capacity in disturbance areas

Mobile network coverage is lost without electricity supply if BSs lack backup power. Thus, when a power blackout occurs in the power grid, the mobile network has to rely on backup power to enable mobile network services in the corresponding blackout area. This so called *backup coverage* continues until the backup power runs out, which usually takes up to few hours. The backup coverage should be utilized as efficiently as possible, and the required services should be balanced with the amount of users and the available capacity.

One possibility to maximize the available network capacity is to guide mobile users [10] away from the so called bad locations, i.e. areas where the cellular network environment is the most challenging. These locations include places where the received signal energy is very low and there is a possibility to improve it with small actions, e.g. moving from one room to another, where the received signal strength is higher. This option would indeed restrain the freedom of utilizing the mobile network from anywhere, but disaster scenarios require a different way of utilizing the network in order to maximize at least some availability of the network services.

Another solutions relate to studies like [6], i.e. reprioritizing some elements in the core network to enable more calls in the network. Also, like suggested in the conclusion in [9], the subscribers should be informed and advised to use the cellular network selectively to increase the odds of a successful call completion.

Finally, the solution presented in this paper relies on an idea of taking away the ability of subscribers to randomly access the mobile network. This means that the mobile network operators would have a predefined plan to restrict the normal calls from subscribers during disturbance situations in case the network starts to congest over a predefined threshold. At such event, the operators would send a broadcasting short message service (SMS) to the customers to notify about the change in the network functionality and that the customers should avoid performing calls if possible. The message would also remind the customers what would be the time slot within an hour they could try to make a call.

III. Measurement results and analysis from the real network

A. Description of the power blackout area

The analysis of this study was performed to a certain area in Finland for one mobile operator. The area was roughly $1500\,\mathrm{km}^2$ in size with a population around 7000 people, in which the mobile operator has roughly $39\,\%$ market share. The number of BS sites for GSM network was 19 with 58 cells and correspondingly the number of universal mobile telecommunications system (UMTS) sites was 14 with 62 cells. The raw data consist of GSM and UMTS network statistics gathered before, during and after a power blackout that lasted for several hours. This means that the backup power ran out from most of the BS sites. The power blackout started at 3.30 p.m. on Thursday when half of the regional electricity network of the specific area went down, and at 3.55 p.m. $87\,\%$ of the area was missing electricity as seen from Fig. 1. After this, the situation started to improve as repair teams progressed in reconnecting the outage areas back online and around 1.00 a.m. in the next day, i.e. after nine and a half hours from the beginning of the electricity disturbance situation, half of the area had electricity. It then took 11 hours more to around 12 p.m. to reach $90\,\%$ availability in the electricity network. The last remaining $10\,\%$ of outage areas still took around 12 hours to fully restore the electricity network.

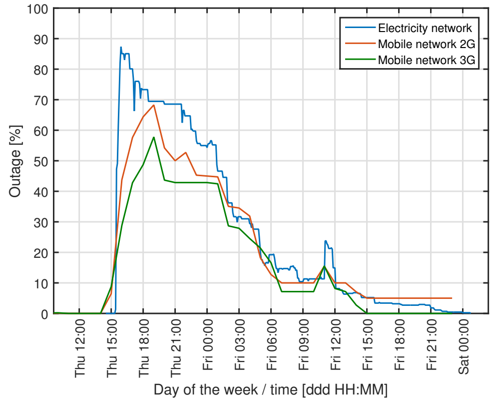


Fig. 1: Outage percentage for both electricity and mobile networks. The date / time format is 'ddd' refering to the first three letters of a day and 'HH:MM' for a time presentation with two digits for both hours and minutes.

Besides electricity, also the outage of 2G (GSM) and 3G (UMTS) mobile network technologies are shown in Fig. 1. The shape follows that of the electricity outage version, which was to be expected. The time resolution for the electricity network is five minutes, but for mobile networks it is one hour. The reason for not having a zero percentage outage for 2G mobile network after fully restored electricity network availability is that one of the mobile network BS sites did not manage to reboot itself automatically. Thus it had to be manually rebooted. It also seems that in Fig. 1 the mobile network outage starts before the electrical network, but this is because of the time resolution and the way the performance data is collected and stored. Events in the network that have occurred, e.g. between 3.00 p.m. and 3.59 p.m., are shown in the data at 3.00 p.m.

B. Mobile network statistics analysis

The figures on the following page, i.e. Fig. 2 and Fig. 3, show the 2G and 3G cellular network statistics before, during and after the disturbance in the electrical network. The green, orange, and blue bars show some selected key performance indicators (KPIs) for Wednesday, Thursday, and Friday, respectively. The solid, dashed, and dotted lines also show the availability of the electricity network for Wednesday, Thursday, and Friday. A numerical summary of the data is shown in Table I after the figures.

Fig. 2a shows how the number of new calls differ for each day. The KPI profile for each weekday is similar, but when the availability of the network drops at 3.00 p.m. on Thursday, there is a spike in the number of new calls. This trend continues for the whole Thursday evening, which indicates that the power blackout has activated subscribers to make more phone calls than usual. The same effect is visible in Fig. 2b; the number of new standalone dedicated control channel (SDCCH) seizures peaks when the electricity blackout begins. The effect is also visible during the night between Thursday and Friday, i.e. in the early hours of Friday, most likely due to repair workers. This is because besides call setups SDCCH also includes location updates and SMSs. In Fig. 2c, the actual call traffic has some increase compared with the call traffic on Wednesday. From Table I it can be seen that the call traffic increased from a total of 376 Erl on Wednesday to 471 Erl on Thursday, resulting in a total traffic increase of 25 %. Finally, in Fig. 2d, the data traffic allocated to 2G seems higher than the reference day (Wednesday), but this is mostly because the availability of 3G network is also lower than the normal situation, which results in part of the data traffic falling to 2G network. Besides SDCCH seizures, all other KPIs in 2G network have a noticeable increase in the values from Wednesday to Thursday followed by a decrease on Friday.

Correspondingly, Fig. 3 shows the situation in 3G network statistics. First, in Fig. 3a, the amount of circuit-switched (CS) traffic is shown in Erlangs. This amount is slightly higher before and right at the time when the power blackout starts. The amount of CS traffic is reduced after this as the availability of the 3G network degrades, however, the reduction is caused by the lack of service availability, not from the reduced CS traffic behaviour, since the CS traffic increases notably as the availability increases. In Fig. 3b, the amount of downlink (DL) data is shown. A similar effect as in CS traffic is noticeable, i.e. the availability is reducing the data amounts. On the other hand, the traffic amounts are greatly higher before the power blackout starts, most likely due to subscribers trying to search for information about the storm that eventually caused the electricity outage. Fig. 3c shows the number of SMSs in 3G network. The power blackout causes a clear spike in the chart and the amount of SMSs in the entire Thursday evening is clearly higher than in the reference day. Finally, in Fig. 3d, the number of radio access bearers (RABs) has a very noticeable spike at the time when the power blackout started.

C. Example of the capacity increase without random access

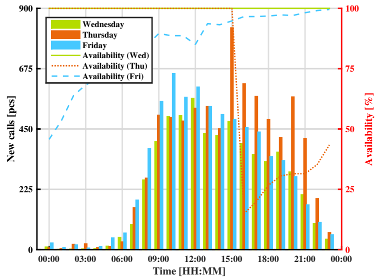
In the smallest GSM configuration case 1 TRX has 7 traffic channels meaning capacity of 2.5 Erl with 1 % blocking probability. With the assumption of one call lasting 90 s, which is 25 mErl, this corresponds to having 100 calls in one hour. The difference with regard to 7 Erl means that the number of calls could be increased theoretically up to 280, i.e. an increase of 180 % for the number of calls would be achieved. This assumes that there is no blocking because of the idea of preventing the users from calling randomly.

If this idea is applied to the given GSM configuration of the power blackout area, the following increase in the capacity can be noted. The area has 58 TRXs resulting to 464 channels in total, but actually 435 can only be utilized for calls since 29 channels are reserved for signalling purposes (one signaling channel per two TRX). Thus, 435 traffic channels can support roughly 410 Erl of traffic (16400 calls), whereas theoretically up to 435 Erl (17400 calls) could be supported. The difference is additional 1000 calls (6 %) in this configuration.

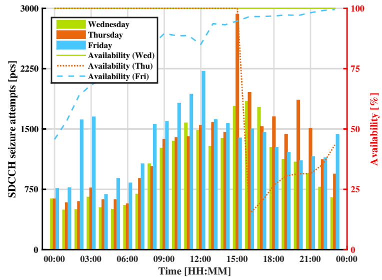
The significant relative difference in the improvement with 1 % blocking versus the theoretical case in these two examples are caused by lack of overlapping calls, i.e. the capability of calling randomly is removed and perfect call slot allocation is assumed. However, it would be more beneficial to reduce the available capacity in order to save energy to prolong the cellular network service during these electricity network disturbance scenarios. When this idea is combined with the pre-allocation of traffic channels to increase the capacity with no random access, the offered capacity is higher than conventionally and the backup coverage lasts longer.

IV. Conclusions and Discussion

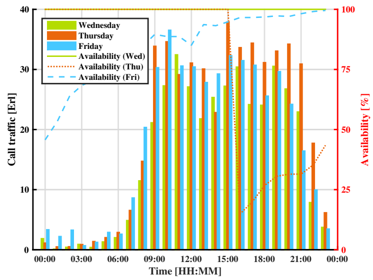
This paper provided statistics and analysis from an operational mobile network in Finland. The observed results show how the cellular network subscribers behave in the case of small and uncommon disturbance scenario in the form of electricity network blackout in rural area. The statistics from the GSM and UMTS networks showed how the subscriber *mobile network behavior* changes when it occurred. This behavior can already be noticed before the actual disturbance time, e.g. from the amount of DL data, as the subscribers try to find information related to the possible upcoming disturbance event. When the disturbance (i.e. the power blackout in this case) had finally occurred, especially the call traffic and the amount of SMSs had a noticeable spike in the network statistics. These include an increase of 73 % in the number of new calls and an increase of 84 % in the number of SMSs compared with the reference day at the time when the disturbance situation started. The increased service demand trend continued through the majority of the blackout, i.e. despite the lack of cellular network availability the subscribers continued to utilize the network more than usual. It should be noted that the results are based on one disturbance scenario and the reference day for the analysis is also from only one day, thus the generalization of these results would require several other study cases. Nevertheless, this study offers data



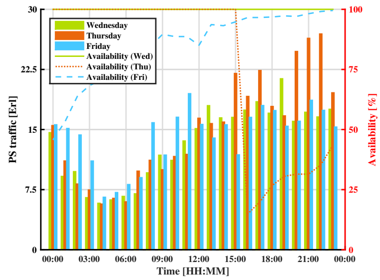
(a) The number of new calls.



(b) The number of new SDCCH seizures.

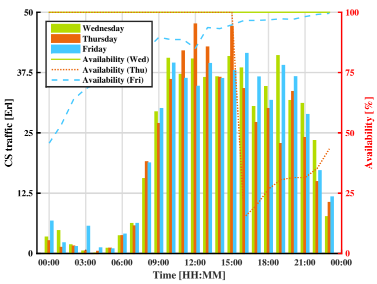


(c) Call traffic in Erl.

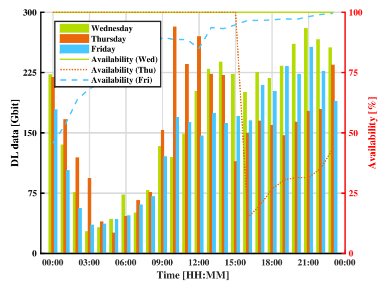


(d) PS traffic in Erl.

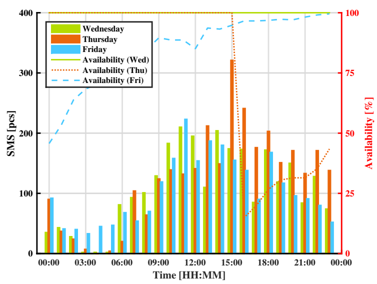
Fig. 2: 2G statistics from the electricity blackout. The time format is ’HH:MM’ for a time presentation with two digits for both the hours and minutes.



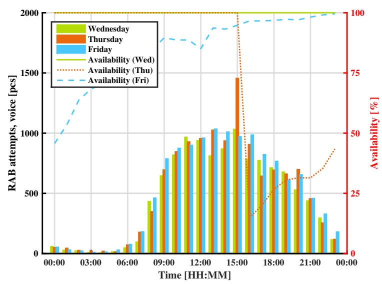
(a) CS traffic in Erl.



(b) The amount of DL data.



(c) The number of SMS.



(d) The number of RAB attempts for voice calls.

Fig. 3: 3G statistics from the electricity blackout. The time format is ’HH:MM’ for a time presentation with two digits for both the hours and minutes.

TABLE I: 2G and 3G network statistics before, during and after the electricity blackout. The mean and median values present the values for one hour.

	KPI	Wednesday				Thursday				Friday			
		total	*mean*	*median*	*std*	*total*	*mean*	*median*	*std*	*total*	*mean*	*median*	*std*
2G	The number of new calls [pcs]	5787	241	274	199	7652	319	415	254	6794	283	301	228
	The number of new SDCCH seizures [pcs]	25103	1046	1074	450	29890	1245	1380	566	32139	1339	1408	396
	Call traffic [Erl]	376	16	21	12	471	20	26	15	434	18	22	13
	PS traffic [Erl]	319	13	15	5	358	15	16	6	342	14	15	4
3G	CS traffic [Erl]	536	22	30	16	511	21	23	17	543	23	29	16
	The amount of DL data [Gbit]	3958	165	200	84	3714	155	161	72	3429	143	164	70
	The number of SMS [pcs]	2577	107	106	66	2952	123	136	82	2498	104	92	55
	The number of RAB attempts [pcs]	11088	462	482	372	12012	501	548	420	12188	508	535	394

from an operational mobile network operator, and shows how subscribers utilize the network during an uncommon blackout situation.

In order to cope with the lack of mobile network services caused by the outages in the electrical network, some possible solutions were considered. One of these solutions could be partially restricting the ubiquitous cellular network experience, i.e. instead of using the network all the time and everywhere, some limitations for the services might be beneficial from the overall network functionality point of view. These limitations should, however, not prevent the real need in the case of life-threatening emergencies, but instead bring some help to prevent the congestion of cellular networks. A fairly simple solution would include guidelines, i.e. common rules, which would state that if a power blackout should occur, the subscribers should avoid making unnecessary calls and reduce the cellular network utilization in general. This solution, however, is not easy to control since it is only a guideline. Nevertheless, instructions and guidance in advance would increase the probability of unnecessary cellular network utilization. When the capacity requirement could be lowered, some of the cellular network technologies could be shut down immediately to spare more backup energy.

A more complex solution to increase the (speech) capacity during disturbance situations would be to restrict the randomness of the subscribers to access the network. If applied to the configuration of the example network analysis, an increase from $410\,\mathrm{Erl}$ (Erlang-B, $1\,\%$ blocking) to $435\,\mathrm{Erl}$ would be theoretically possible. This would need efficient algorithms to allocate mobile network subscribers to specific time slots to access the network beforehand and to restrict the customers to access the network outside this time slot. Emergency calls should always be prioritized in these situations.

The future work will concentrate on studying how much longer mobile networks could operate in the case of disturbance scenarios while operating on backup power *and* applying some energy saving prospects. These include instructions and guidelines for the subscribers on how to utilize the network during disturbance scenarios. This in itself is an interesting research topic: how would this kind of preparedness affect the subscriber behaviour. It would enable a higher success rate on completed calls as the congestion would be much lower than in current solutions and enable more capacity, i.e. the available resources would be utilized more efficiently during these events. This should also lead to being able to operate on more restricted configuration resulting in more energy savings and prolonging the backup coverage time.

Acknowledgment

The authors would like to thank European Communications Engineering (ECE) ltd, the Finnish Funding Agency for Innovation (TEKES).

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Publication 2

J. Säe and J. Lempiäinen, "Maintaining Mobile Network Coverage Availability in Disturbance Scenarios," in *Mobile Information Systems*, volume 2016, 10 pages, Sep. 2016.
DOI: 10.1155/2016/4816325

Maintaining Mobile Network Coverage Availability in Disturbance Scenarios

Joonas Säe and Jukka Lempiäinen

***Abstract*—Disturbance and disaster scenarios prevent the normal utilization of mobile networks. The aim of this study is to maintain the availability of cellular networks in disturbance scenarios. In order to extend the disaster time functionality, energy usage optimization is needed to maintain reasonable coverage and capacity. Simulations performed with different network layouts show the effects of choosing only a portion of evolved node B (eNB) macro sites to operate at a time. Different sets of three to nine three-sectored eNB sites are selected to study how the network would perform with a limited number of eNB sites. Simulation results show how the mobile network availability duration can be sustained by selecting a set of eNB sites to operate at a time and still maintain a reasonable service level and availability in disturbance scenarios. An increase of 100 % to 500 % can be achieved in the duration of "backup coverage" in cellular networks with backup batteries when the percentage of active eNB sites is reduced down to 20 %.**

***Index Terms*—Availability, disaster, disturbance, mobile networks, macro sites, network-level simulation, energy conservation, resilience.**

I. Introduction

DISASTER and disturbance scenarios usually occur without a warning. Whether they are natural weather-based storms or disasters caused by human, such as accidents or sabotages, the effects can be devastating and usually prevent the normal utilization of mobile networks. Typically, storms are the cause of blackouts in electrical grids [1]; furthermore they have an impact on public safety and commercial mobile networks, thus yielding service and communication outages in urban and rural areas. This can eventually prevent citizens requesting emergency help in these outage areas. In addition, maintenance and rescue teams can not communicate through commercial mobile networks and have to have a separate communication system.

Service outages in mobile networks are mainly caused by (storm-related) power outages. In order to enable some service in these cases, evolved node B (eNB) macro sites are typically supplied with backup batteries. These reserve energy resources provide power to run eNBs, but only for a limited time period. In Finland, this corresponds to 2–4 hours, as required by the Finnish Communications Regulatory Authority [2]. After strong weather phenomenon, in the worst case the repair-work may take several days resulting in the unavailability of commercial cellular networks that may also endanger rescue operations. An alternative is to have aggregates over the network or at certain critical eNB sites, to guarantee their electricity supply for a longer period of time. Because aggregates are slightly costly to be supplied and used at every site, some optimization is needed in a similar way as in the case of battery backups, i.e. how many aggregates should be enough to enable sufficient cellular network coverage. Moreover, in case of longer-term electrical cut-offs (i.e. over one day), aggregates are eventually required to guarantee (cost-efficient) mobile network communications in disturbance scenarios.

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Another type of critical discontinuity in mobile networks may happen due to major malfunctions in the core transmission network, major damage in the core network elements, such as controllers, or in the switching functions. These malfunctions can also be caused by sabotage or a cyber-attack, which may cause very wide discontinuity in the whole mobile communications network. However, these are out of the scope of this study as this paper is concentrating more on optimizing the backup energy utilization.

Some solutions for mobile communications have been proposed to manage these disturbance and disaster scenarios to improve the resiliency of mobile networks. In Japan, the so called critical sites have been implemented in urban areas to durable high-rise buildings [3] with at least 24 h backup batteries to give continuous service e.g. in case of disasters. High altitude platforms (HAPs) [4] have been discussed earlier as a possible solution to provide service coverage in case of hurricanes and tornadoes have destroyed the existing infrastructure of a cellular network in the disaster area. This idea has been even taken further with Google's project Loon, which targets to provide worldwide Internet access through HAPs, implemented with balloon platforms [5]. Also Facebook has their HAPs approach in their internet.org project [6]. Instead of utilizing balloons, Facebook relies on solar powered drones.

There are also solutions to utilize satellite communication services for disaster areas although these systems are rather expensive and might not work inside buildings. Moreover, temporary movable networks, like mobile ad hoc networks (MANETs), are a popular research area for disaster scenarios as seen from publications on the topic in [7], [8] and [9]. Many of these solutions are replacing the existing infrastructure with a new one instead of trying to improve it.

In this paper, the aim is to utilize the traditional macro cellular network infrastructure and extent the availability of the network several times from the current backup time when the electrical grid is down and the mobile network relies on backup power. This is possible with an approach, where only a portion of the eNB sites are utilized at a time and switched to another set of sites when the first set runs out of energy. This differs from a traditional sleep mode technique such that the non-active eNBs are not utilized at all during the ”sleep time” to save as much energy as possible, which is important in disturbance situations. This will obviously degrade the coverage availability and capacity, but disturbance and disaster scenarios require exceptional methods to enable even some service as long as possible. Only macro sites are considered in this study because small cells are usually available only within cities and they are not equipped with backup power. Maintaining reasonable coverage for disturbance scenarios both in urban and rural areas are emphasized, i.e. the focus is on having more resilient mobile networks. Long term evolution (LTE) is utilized in the simulations with evolved UMTS terrestrial radio access (E-UTRA) operating bands 20 and 3 (800 MHz and 1800 MHz) for rural environment. E-UTRA bands 3 and 7 (1800 MHz and 2600 MHz) are utilized for urban environment. All of the considered frequency bands are frequency division duplex (FDD) channels.

II. Related Work

This work is related to at least two different energy-saving concepts: cellular networks with sleep modes and green cellular networks. However, the idea of these concepts is not utilized in the traditional way. This paper utilizes the idea of saving energy only in disturbance situations, i.e. in disaster scenarios in the following manner; saving energy by utilizing only a portion of the eNB sites to provide ”backup coverage” to areas where the electricity supply from the grid has been (temporarily) cut off, e.g. due to strong weather phenomenon. Thus, this study goes beyond the state of the art for utilizing mobile network backup energy as this kind of approach has not been proposed for disturbance situations.

The idea of green cellular networks is to have sustainable development in cellular networks towards utilizing sustainable energy sources and taking into account environmental aspects. This usually relates to favouring renewable energy resources to reduce the carbon footprint of cellular network infrastructure or saving energy by reducing the energy consumption of base stations in some manner. Green cellular networks are nowadays studied widely and several publications are available in this field. The authors in [10], e.g. present a survey on the state of green cellular networks and the possible challenges they currently have. The largest power consuming part of cellular networks are base stations, as presented in [11]. Furthermore, the largest part of base station power consumption comes from power amplifiers (50–80 %) [12].

The traditional sleep mode concept has been studied e.g. in [13], where the effect of one or more base stations turned to ”sleep” is studied. A case study of dynamically switching off base station sites is presented in [14], where the authors show great energy saving in the cellular network during low traffic periods. One of the most recent wide surveys on these energy-efficient base stations, i.e. base station sites with sleep modes as well as green cellular networks, is presented in [15]. The authors present an extensive list of recent publications on these topics and discuss the assumptions and simplifications utilized in these papers to show how great effect they can have in the achievable benefits in actual networks.

Most of the traditional sleep mode techniques consider only a ”normal” network utilization. This is because the idea behind most sleep mode techniques is based on saving energy in the low-traffic time periods during the day and usually the sleep modes are only considering these circumstances. This does not necessary mean that these techniques could not be utilized during disturbance scenarios. However, it should be highlighted that traffic load increases during disturbance scenarios as people try to contact other people from these areas (and vice versa) and utilize the mobile network to search for information regarding the cause of the disturbance situation. Thus, algorithms based on low-traffic network utilization would not work during these events.

A modified sleep mode concept in cellular networks is the main approach utilized in this paper for the functionality of eNB sites operating only with backup power (i.e. during a disturbance scenario). However, during this sleep mode the eNB sites just wait for their turn to power on, not to broadcast anything during this time. This way e.g. power amplifiers and air conditioning are not needed and signal processing power requirements are very low as there is nothing to transmit or receive during the sleep time. Thus, the power consumption of these ”sleeping eNB sites” is very marginal. This is more effective in saving energy then having traditional sleep mode techniques, where the eNBs ”wake up” to check the situation every now and then. The approach utilized in the paper does not take into account traffic loads, instead the target is to find out what would be the effect of selecting only a portion of the available eNB sites to the network performance. Moreover, the study does not include algorithms in how to actually select the usable eNB sites (although the selection of eNB sites is based on choosing some eNB sites evenly within a target area).

III. Radio Network Planning

Radio network planning is a process to design the best possible wireless communication network such that coverage, capacity and the quality of service meet (and exceed) the requirements set by the amount of subscribers in a target area. In order to maximize these aspects, a radio network planner needs to pay careful attention to some very important factors. These include the environment, which defines the propagation slope, the model used to calculate the maximum path losses with the help of a link budget resulting to estimate the cell ranges, and the network layout in terms of base station locations with respect to other base stations.

A. Network Layout

The performance of a cellular network depends on many factors and one of the important ones is the used network layout or more precisely the used tessellation. Ideally, tessellations form a continuous network that has raster-like properties. This means that the layout has symmetric shapes regarding the positions of the eNB sites and antenna directions. The half-power beamwidth (HPBW) of the used antennas also affect the choice of tessellation, but for a 65 degree HPBW antenna the cloverleaf tessellation is the most optimal choice [16]. It is the

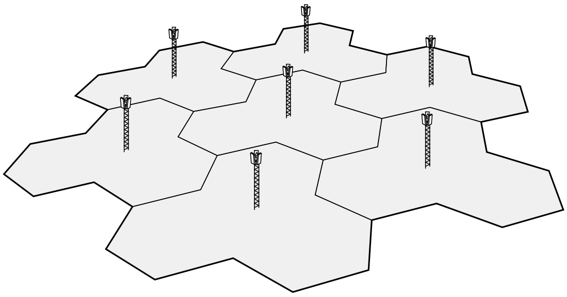

Fig. 1. Cloverleaf tessellation with seven three-sectored eNB sites.

most commonly used tessellation in Europe and an example of it with seven eNB sites is presented in Fig. 1.

Fig. 1 shows that every eNB site antenna is pointed directly towards one of the closest neighboring eNB sites. However, this is done in such a way that the antenna beams are pointed in between two other antenna beams thus reducing interference as much as possible.

B. Propagation Model

Coverage of a mobile network is defined as a geographical area, where the eNB and user equipment (UE) can still communicate between with each other. Coverage estimations can be calculated with reasonable accuracy, e.g. by using a well-known Okumura-Hata prediction model equation (or its extended version, the COST-Hata-Model) [17]:

$$\begin{aligned} L = {} & A + B \cdot \log_{10}(f_{\mathrm{MHz}}) - 13.82 \cdot \log_{10}(h_{\mathrm{eNB}}) \\ & - a(h_{\mathrm{UE}}) + (C - 6.55 \cdot \log_{10}(h_{\mathrm{eNB}})) \cdot \log_{10}(d_{\mathrm{km}}) \\ & + C_{\mathrm{m}}, \end{aligned} \quad (1)$$

where

L is path loss in [dB],

A, B and C are constants,

f_{MHz} is the used frequency in [MHz],

h_{eNB} is eNB antenna height in [m],

h_{UE} is UE antenna height in [m],

$a(h_{\mathrm{UE}})$ is a city size dependent function,

d_{km} is distance between eNB and UE in [km], and

C_{m} is an area correction factor.

Before the Okumura-Hata model can be used to get the maximum cell distance, some link budget calculations are needed to define the maximum path loss between the eNB and UE.

It should be noted, that the Okumura-Hata model (1) has to be tuned for every environment separately to get more accurate results. In addition, the area correction factor, C_{m}, has to be set regarding the propagation environment morphological values. Correspondingly, the propagation slope, which is defined by $(C - 6.55 \cdot \log_{10}(h_{\mathrm{eNB}}))$, has to be set regarding the eNB antenna height and the wanted propagation path loss exponent by tuning the C constant.

C. Planning Thresholds

Planning thresholds are used together with propagation prediction models to calculate the maximum path loss in the link budget. The main planning threshold value is the slow fading margin [18]. It is calculated from the standard deviation of the slow fading, the propagation slope and the coverage probability for the service.

It should also be addressed whether the radio network coverage is designed for outdoor or for indoor usage. When designing a radio network with outdoor macro cells, and there should also be some indoor coverage, some additional planning thresholds are needed. First, the value of slow fading margin should be increased and then the building penetration loss should be added to the link budget calculation in order to expect more realistic predictions.

One example of a typical average distance between neighboring eNB sites, i.e. intersite distance (ISD), is 750 m in urban and 7500 m in rural environment [19]. While maintaining the antenna height and moving eNB sites closer to each other, more coverage overlapping occurs. This means that areas with coverage from one eNB site have coverage also from other neighbor eNB sites. In rural areas, the coverage overlapping is minimized because of large ISDs and respectively in urban areas there is more coverage overlapping because of shorter ISDs, i.e. the eNB sites are close to each other. This means that the possibilities to decrease the number of eNB sites and still have available coverage should be greater in urban areas than in rural areas, but this depends heavily on the configuration of the network.

D. Practical Capacity Requirements

Mobile network capacity requirements depend on population density and the requested services. Since mobile network cells are shared mediums, the available capacity per UE depends on the total number of mobile network subscribers within the serving cell and the data throughput each UE requests. To expand this limited capacity, more channels, i.e. additional frequency bands can be utilized together with different technologies. Thus, recent implementations include several frequency layers (bands) and technologies at one eNB site [20]. An example of this would be a base station site, that has a GSM base station, a UMTS base station, and a LTE base station (eNB) and each of these technologies would operate on at least two different frequency bands. These could be e.g. GSM operating at 900 MHz and 1800 MHz, UMTS operating at 900 MHz and 2100 MHz, and LTE operating at 800 MHz and 2600 MHz. To maximize availability, and thus to minimize the required electrical power need, several technologies, e.g. GSM and UMTS and several frequency layers should be switched off (e.g. only the lowest frequency band of the remaining technology is utilized for service, such as LTE 800 MHz), and still certain services such as short messages, speech, or limited data services should be maintained (depending on the available technology and its capabilities). This results in conserving backup power in crisis situations, but still enables services for subscribers for a longer period of time compared with a situation where eNB sites

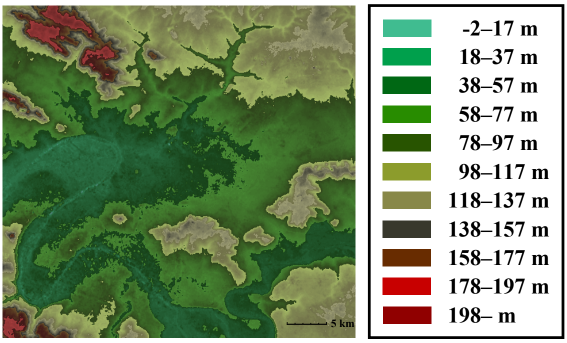

Fig. 2. Digital elevation map of the simulation area.

would continue to operate normally and quickly consume the available reserve energy.

IV. Simulations

Link-level simulations were implemented using commercially available radio network planning software called ICS Designer. The area was a randomly picked and relatively flat area in France, which had a 25 m resolution digital elevation map as shown in Fig. 2. After the simulation results were obtained, they were exported into Matlab software for further analysis and visualization.

A. Simulation Setup and Environment

All simulations were based on a macrocellular cloverleaf tessellation with eNB sites that had three sectors. A conventional eNB grid of 19 sites was used as a reference case, which has one eNB site in the middle and two tiers, first tier with six sites and second tier with twelve eNB sites, around it forming a hexagonal grid. All eNB sites in the original layout had an equal ISD of 500 m for urban and 4000 m for rural environment. Circular areas with 1.25 km and 10 km radii from the centre eNB site were the base "area of interest" for the analysis. In total 57 cells was the maximum amount of cells in one area. In order to take into account sites outside the target area, three more tiers of eNB sites were placed around the central grid of eNB sites. Thus, continuous coverage was formed such that the selection of eNB sites was repeated around the target area to avoid errors in the edge areas of the calculation area.

The antenna height values of 20 m and 40 m with five degree antenna tilting were used in the simulations. The horizontal antenna HPBW was 65 degrees with 17.22 dBi gain for eNB sites while UE antennas were omnidirectional antennas with 0 dBi gain.

Okumura-Hata model was used for calculating the path loss values in the simulations. Fading was taken into account with log-normal distribution having zero mean and 9 dB standard deviation. All key parameters regarding the simulations are presented in Table I. The distribution of transmit power to different LTE downlink physical channels is visible in Table II.

TABLE I
Key Simulation Parameters

Parameter	Value	Unit
operating frequency band 20 (FDD)	800	MHz
operating frequency band 3 (FDD)	1800	MHz
operating frequency band 7 (FDD)	2600	MHz
bandwidth	10	MHz
number of usable resource blocks	50	pcs
loading	75	%
calculation resolution	25	m
intersite distance – urban	500	m
intersite distance – rural	4000	m
antenna height – urban	20	m
antenna height – rural	40	m
building height	8	m
eNB antenna HPBW	65	°
eNB antenna gain	17.22	dBi
additional losses	3	dB
UE antenna height	1.5	m
UE antenna gain	0	dBi
max. eNB TX power	20	W

TABLE II
Distribution of Downlink Transmit Power to Different LTE Physical Channels

LTE physical channel	Share	Unit
reference signal	4.76	%
physical downlink shared channel (PDSCH)	74.33	%
physical downlink control channel (PDCCH)	20.24	%
physical broadcast channel (PBCH)	0.33	%
primary synchronization signal (P-SS)	0.17	%
secondary synchronization signal (S-SS)	0.17	%
Total	100	%

B. Simulation Scenarios

Simulation scenarios had a large number of different types of network layouts. The idea was to find suitable configurations to achieve good enough coverage for the simulation area and at the same time minimize the service outage. The cellular network can function an extended period of time when only a part of the network is working on backup energy at a time. In order to reduce the number of different possible combinations which would be possible for a set of eNB sites, the number of different kinds of sets out of all possible sets was reduced. If all possible combinations would be considered, the maximum number of different sets (in any order), e.g. with nine eNB sites out of 19 eNB sites would be $\binom{19}{9} = 92\,378$, and even three eNB sites out of 19 eNB sites would have $\binom{19}{3} = 969$ different sets. Thus, the number of different sets was set at a small amount, six in this paper, to study how the performance of the network behaves as a function of available eNB sites.

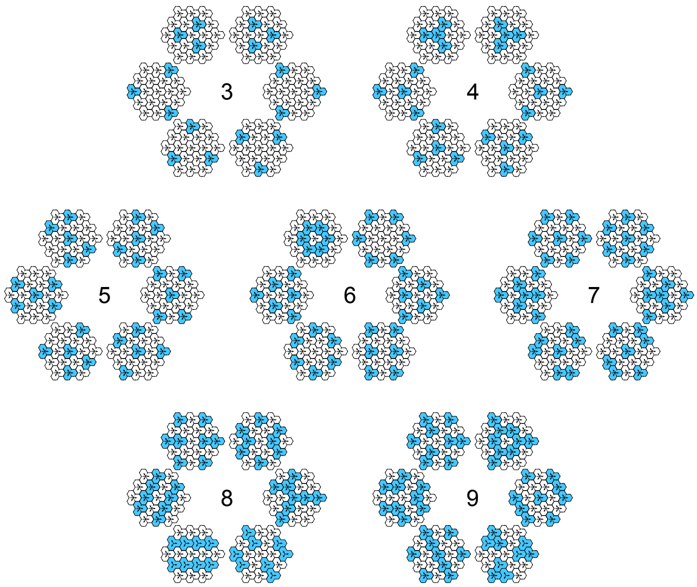

Fig. 3. Selection of different three to nine eNB site configurations that were utilized in the simulations for a target area (and repeated in a similar way around this area to form a continuous coverage). The selected eNB sites are highlighted with blue color.

The focus is especially to study having less than half of the eNB sites per studied area. The eNB sites chosen for a set were based on spreading the available sites as evenly as possible to the studied area, since e.g. choosing only the three closest eNB sites from one ”corner” of the grid would results in the uneven distribution of backup coverage in the target area of interest.

Fig. 3 shows how eNB sites were chosen for three to nine eNB site cases. As can be seen, the eNB sites were chosen in a way to be able to serve the target area as evenly as possibly. An example of service probability with two different sets of six eNB sites is visualized in Fig. 4.

V. Results

In the following, Fig. 5 shows the mean reference signal received power (RSRP) level, Fig. 6 the mean service probability, and Fig. 7 the average signal-to-interference-and-noise ratio (SINR) with respect to the number of eNB sites. Fig. 8 and Fig. 9 present the average area throughput to study the available capacity with respect to the amount of eNB sites. The corresponding exact values are presented in Table III and Table IV.

The mean RSRP values in Fig. 5 show that as the number of eNB sites grow the average RSRP increases, which is expected. Rural environment with E-UTRA band 3 (1800 MHz) has the lowest average RSRP values and correspondingly rural environment with E-UTRA band 20 (800 MHz) has the highest RSRP values. The average values of RSRP are clearly different for all cases. First of all, the environment type with different antenna heights for the rural and urban areas has a huge impact on the average RSRP values, since the antenna height for the rural area is two times the height of the urban area. Next, another important factor is the utilized frequency, i.e. for rural area the higher frequency band is more than twice the utilized lower frequency band. In the urban cases, the higher frequency band is less then twice the utilized lower frequency band, thus the differences between the average RSRP values for the two rural cases is more dramatic than the corresponding differences for the two urban cases. Finally, the urban case is also affected by the buildings, thus lowering the average RSRP values. In this study, the lowest value was −82.68 dBm with 15.79 % of eNB sites available.

Fig. 6 presents the average probability to have backup coverage in the different cases. The lowest probability to have service coverage was with E-UTRA band 7 (2600 MHz) in the urban environment. The lowest value was 55.44 % with 15.79 % of the eNB sites available. Thus, although the urban area had denser eNB site placement than the rural area, the coverage areas with a higher frequency band are quite limited, as well as overlapping areas. This is mostly because of the attenuation is higher in the urban environment (with buildings) as well as in a higher frequency band. When the same frequency band was utilized in both the urban and rural environment, the urban E-UTRA band 3 had slightly higher probability to have a service than its rural counterpart (rural E-UTRA band 3). The highest service availability was achieved with the lowest frequency, E-UTRA band 20 in the rural case, where the probability to have a service was over 80 % even with the lowest number of eNB sites (15.79 %). In order to have over 80 % probability for (backup) coverage in other cases, E-UTRA band 3 cases (1800 MHz) would need around 26.32 % in urban and 31.58 % in rural scenarios and E-UTRA band 7 (2600 MHz) around 50 % in the urban environment.

When the exact values are observed from Table III as a function of available eNB sites, the differences between different

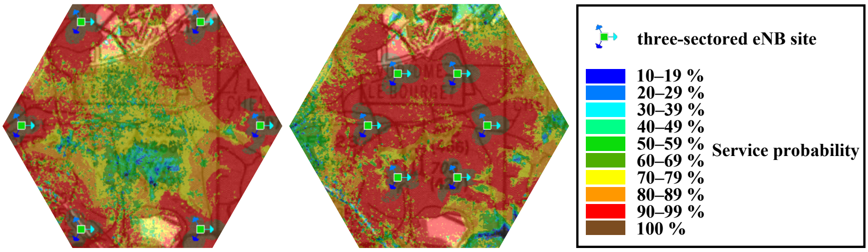

Fig. 4. An example of service availability with two different sets of six eNB sites.

TABLE III
SIMULATION RESULTS

Percentage of eNB sites per area	mean RSRP (dBm)				mean service probability (%)				mean SINR (dB)			
	rural 800 MHz	rural 1800 MHz	urban 1800 MHz	urban 2600 MHz	rural 800 MHz	rural 1800 MHz	urban 1800 MHz	urban 2600 MHz	rural 800 MHz	rural 1800 MHz	urban 1800 MHz	urban 2600 MHz
15.79 %	−76.37	−82.68	−78.83	−80.83	80.35	68.52	72.50	55.44	5.22	5.62	1.53	3.51
21.05 %	−75.35	−81.75	−77.91	−80.38	83.35	72.44	75.81	59.81	4.53	3.89	1.13	2.55
26.32 %	−74.29	−80.88	−76.77	−79.79	86.28	76.41	80.50	66.32	4.11	3.53	1.17	1.99
31.58 %	−73.56	−80.29	−76.07	−79.25	89.37	80.66	82.62	69.23	3.98	3.30	1.04	1.64
36.84 %	−72.91	−79.67	−75.33	−78.79	90.66	82.58	85.06	73.05	3.96	3.27	1.27	1.60
42.11 %	−72.39	−79.20	−75.03	−78.51	91.61	84.24	86.36	75.29	3.69	3.02	1.32	1.57
47.37 %	−71.91	−78.72	−74.29	−78.23	92.38	85.47	87.33	77.49	3.45	2.79	1.32	1.57

E-UTRA bands and environments are easy to compare as well as the differences between each parameter. Intuitively thinking, each parameter (RSRP, service probability, and SINR) should have a better value as the percentage of eNB sites per area is increased, and in general this is observed in Table III. The only difference is the utilized lower urban frequency band (1800 MHz), where the average SINR value is slightly increased when more than 31.58 % of eNB sites are utilized. However, this increase stops after more than 42.11 % of eNB sites are utilized.

In Fig. 7, the mean SINR values are presented. It can be noticed that in rural environment the achievable values are higher than in urban cases, mostly because of low interference from less dense eNB site placements, i.e. the minimum ISD is 4000 m. When more eNB sites are available, the average SINR degrades because of the increased interference levels.

Fig. 8 and Fig. 9 show the average throughput per area. As can be noted, the available average data rates are much higher in urban cases since the ISD is much lower, i.e. the network is much denser. Is should be remembered that the loading of the network was set to 75 %, thus only 37 resource blocks were available out of 50 resource block available in the 10 MHz bandwidth for LTE.

VI. CONCLUSIONS AND DISCUSSION

In this paper, the availability of mobile networks in disturbance scenarios was studied by simulating different network layouts for macro eNB sites. Thus, a solution for improving the cellular network functionality in disturbance situations was presented, which is a very important topic in the resilience of mobile networks. The target of the simulations was to find out how would a limited network configuration perform in

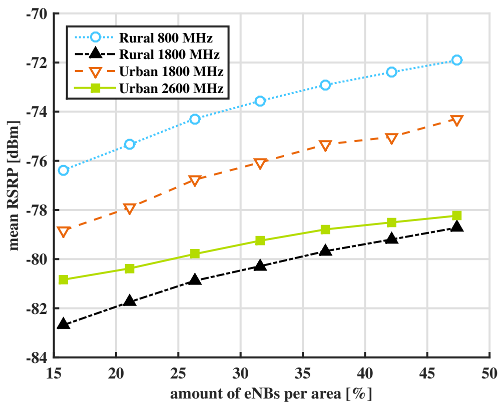

Fig. 5. Average RSRP level with respect to the amount of eNB sites per area.

TABLE IV
MEAN AREA THROUGHPUT

Percentage of eNB sites per area	mean area throughput (Mbps/km^2)			
	rural 800 MHz	rural 1800 MHz	urban 1800 MHz	urban 2600 MHz
15.79 %	0.23	0.24	9.07	11.79
21.05 %	0.28	0.26	11.44	13.88
26.32 %	0.33	0.31	14.38	16.11
31.58 %	0.39	0.36	16.94	18.43
36.84 %	0.46	0.42	20.40	21.38
42.11 %	0.50	0.46	23.49	24.32
47.37 %	0.55	0.50	26.43	27.37

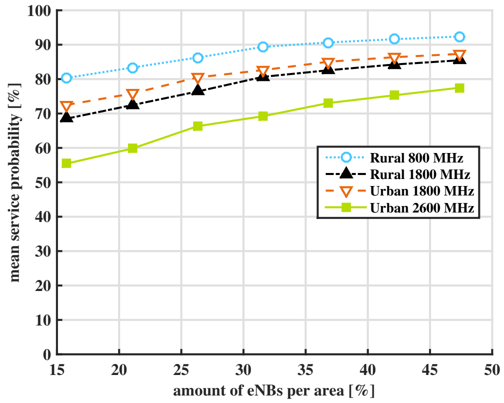

Fig. 6. Average service probability with respect to the amount of eNB sites per area.

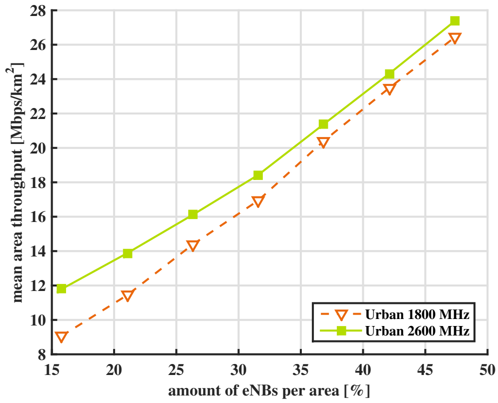

Fig. 9. Average area throughput with respect to the amount of eNB sites per area in urban environment.

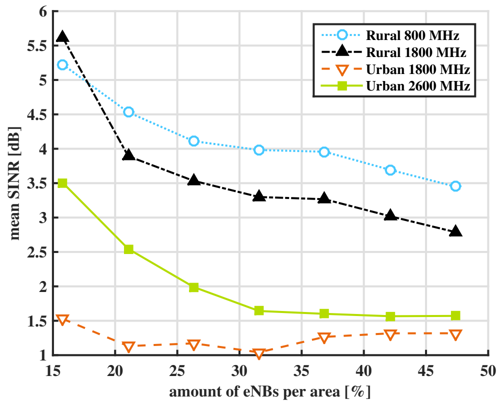

Fig. 7. Average SINR with respect to the amount of eNB sites per area.

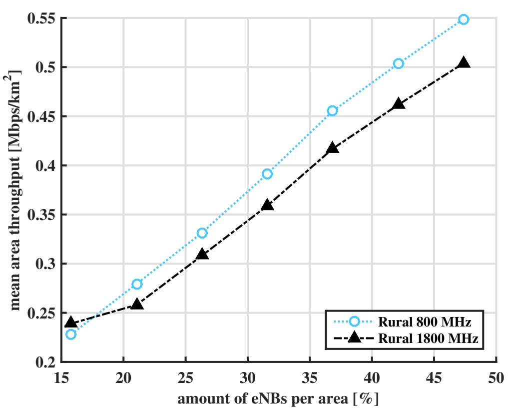

Fig. 8. Average area throughput with respect to the amount of eNB sites per area in rural environment.

terms of coverage and capacity with mobile network availability (without adding additional backup power sources). This minimum configuration can be utilized with battery backups to extend the network availability called backup coverage. As the name suggests, this exceptional state of the network can not have ”normal” service availability as the goal is to provide ”acceptable” or at least some coverage that would last much longer than initially. This would mean that some areas would not have coverage at every time instant during the backup coverage time window, but since the operating sets of eNB sites are cycled over time, all areas would have a certain time window when the service is still available. Thus, in order to achieve e.g. approximately 75 % availability only 20 % to 42 % of eNB sites in urban areas, and 15 % to 25 % of eNB sites in rural areas are needed. This means that *an increase of 100 % to 500 % could be achieved on the operational time* of backup coverage, correspondingly. This also translates to having mediocre coverage for a longer period of time if approximately 20 % of eNB sites would be equipped with aggregates or any other means of powering up eNB sites, which would be cheaper than having e.g. 24 h backup batteries deployed to every possible eNB site.

The comparison of the achieved results to other sleep mode techniques is not that straight forward. First of all, the traditional sleep mode techniques are designed to save energy during low traffic time periods and this is not the case during disturbance situations. Second, many studies such as [13]–[15], all consider different sleep mode techniques with different kind of eNB site layouts with heterogeneous networks (besides macro sites, there can also be micro and small cell sites). In order to get some idea about the effectiveness of the approach utilized within this paper, the authors in [21] present a comparable sleep mode technique, where part of the eNB sites remain active all the time and part of the eNB sites can switch to sleep mode. The results in the study suggests that on average the power savings from an actual network implementation would be from 7.38 % to 27.72 % on a 24 h time period. Thus, although still not directly comparable, the energy savings are clearly a lot less than in the approach utilized in this study. The difference is mostly explained with the fact that the sleep mode technique is designed to keep high quality of service (QoS), i.e. high service availability. In this paper the requirements for QoS are clearly lower since the idea is lower QoS to enable even some sufficient service level for a clearly longer period of time by aggressively saving energy.

Although it seems that there would be more overlapping in the rural areas, it should be noticed that the service availability is higher in urban areas when the same E-UTRA frequency bands are utilized (band 3). This indicates that the operational time of the backup coverage in urban areas would last somewhat longer. Thus, the achievable gain is strongly related to the overlapping rate of neighbouring cells which is also defined by the utilized frequency band as well as the configuration of the eNB sites.

The studied availability can be reached in existing networks by utilizing existing configurations and resources by adding only controlling units. Moreover, the achieved results assume that transmission lines and core networks are properly functioning (which is usually the case, at least in Finland, as the backhaul element backup power regulation is stricter than for eNB sites by a factor of 2–6 [2]), and thus more specific solutions need to be proposed to maintain their availabilities in case of disconnections. It should be noted that in real operational networks the selection of eNB sites is not so straightforward. The geographical distribution of eNB sites is not symmetrical and only roughly follows the cloverleaf tessellation. Moreover, this study only showed how would the network perform if each eNB site was independent of another eNB site, i.e. the study did not take into account the possible backhaul connection limitations of linked eNB sites. This would have more serious effects within rural environments where wireless microwave links are utilized more frequently compared with urban areas, where wireless links between eNB sites rarely exist. The results are valid only for the given configuration, however, they were chosen such that they represent possible real-life implementations and provide insight on the level of service availability with a limited cellular network configuration.

The future work on this topic will consider more practical eNB site layouts, i.e. the distribution of sites will be closer to real-life implementations with more clustered locations of eNB sites. Moreover, the effect of wireless microwave links, i.e. the backhaul connection will also be taken into account based on an operational cellular network operator.

ACKNOWLEDGMENT

Author J. Säe would like to thank Tuula and Yrjö Neuvo Fund and Finnish Foundation for Technology Promotion for supporting the research work. The authors would also like to thank European Communications Engineering (ECE) ltd and the Finnish Funding Agency for Innovation (TEKES) for funding the research work.

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Publication 3

H. Krohns-Välimäki, J. Säe, J. Haapanen, P. Verho, and J. Lempiäinen, "Improving Disturbance Management with Combined Electricity and Mobile Network Situation Awareness System," in *International Review of Electrical Engineering*, volume 11, number 5, pages 542–553, October 2016. DOI: 10.15866/iree.v11i5.10175

Improving Disturbance Management with Combined Electricity and Mobile Network Situation Awareness System

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Abstract – *This paper presents a new method to improve the disturbance management of electricity networks and mobile networks with a situation awareness system that was developed in this study. The system is based on combining the disturbance information from electricity and mobile networks. Both of the networks provide useful information for disturbance management: electricity outage areas from the electricity network systems and coverage outage areas from the cellular network operators. The outage information from an electricity network is received through the Distribution Management System (DMS) service and combined with customer identification codes to find out whether mobile network base stations lack electricity. This information is combined with operational mobile network coverage areas calculated beforehand with an empirical Okumura-Hata path loss model in order to visualize coverage outage areas. A situation awareness system that combines these parts provides new disturbance management insights and shows the disturbances of both networks with one glance. Thus, the restoration plans for both networks can be sped up and critical areas can be more easily prioritized since a clear visual presentation of the situation is easy to comprehend. Therefore, this new method improves the resilience of society, especially during major disturbances.*

***Keywords**: Disturbance management, Electricity network, Mobile network, Situation Awareness System*

Nomenclature

A	frequency-dependent constant
$a(h_{MS})$	city size -dependent function
B	frequency-dependent constant
C_m	area correction factor
d_{km}	distance
f_{MHz}	frequency
h_{BS}	effective base station antenna height
h_{MS}	effective mobile station antenna height
L	path loss

I. Introduction

Storms such as Valio in 2015, the Tapani storm at Christmas 2011, four storms in the summer of 2010 in Finland and the storms Per 2006 and Gudrun 2005 in Sweden caused widespread and long-lasting disturbances in the supply of electric power. In these storms, some individual customers were without electricity even for several weeks. In January 2011 and January 2015, the snow load on trees caused widespread disturbances in Finland. In addition to storms that affect rural areas, e.g., Hurricane Sandy caused widespread disturbances in urban areas in the eastern USA in October 2012. There were, e.g., floods that caused an outage to Manhattan in New York. Most of these disturbances caused problems for mobile networks, water supply, residential heating and the conditions of farm animals. In July 2014 and January 2015 in Finland, the disturbances of the electricity network caused notable outage regions for mobile networks. Some areas were left without mobile network coverage for almost a day, which greatly influenced the resilience of society. [1]-[10]

A situation where both the electricity and mobile networks have a disturbance at the same time is complex to manage. Nowadays the electricity network has a lot of remote-controlled devices such as switches. Some of these devices use a mobile network to communicate with Supervisory Control and Data Acquisition (SCADA). Meanwhile, mobile network base stations need electricity to operate. The Finnish Communications Regulatory Authority (FICORA) has determined that base stations in Finland must have backup power batteries or some other form of reserve power to maintain the transmission for at least three hours in the event of a disturbance in the electricity network [11]. However, an electricity disturbance can last longer than the reserve backup power, e.g., if a storm delays the beginning of the repair process for a certain time. In addition to remote-controlled devices, the Distribution System Operator (DSO) relies on mobile networks to contact and follow repair teams and contractors during disturbances. If both stakeholders receive information from each other’s networks, their recovery processes could be executed more efficiently.

In addition to the recovery of both networks, information about disturbances can be crucial to public authorities such as fire and rescue services or municipalities. For example, municipalities are responsible for home care patients with safety phones or emergency buttons. If the electricity or mobile network service is lacking, the safety buttons will not function. The disturbance information from both networks would help fire and rescue services and municipalities to target their activities. [2]-[12]

In this study, a new method was developed to improve the disturbance management of electricity networks and mobile networks with a situation awareness system. The system improves information exchange between different stakeholders in disturbances. The method was tested with an implemented live demonstration of the system. The system presented here is an extension of an earlier demonstration developed for electricity network disturbances [2]-[5]. The development process of the system that is demonstrated was iterative and is based on workshops and user need interviews organized during this study. In addition, a case study of a disturbance situation of both electricity and mobile networks in Finland, presented in [1], was carried out with a demonstration to test and improve the method. This paper focuses on one main feature of this system, which combines both electricity and mobile network outages in the same view. This information will help the DSO to focus their restoration planning in order to recover the mobile networks they need for their remote-controlled devices. Meanwhile, it will also help mobile network operators to plan their need for extra deployable reserve power.

The demonstration example was constructed on the basis of information from multiple operative networks: four from the electricity networks and one from the mobile network. These network elements were modeled accurately in the situation awareness system that was developed in order to correspond to the actual infrastructure of a certain area in Finland.

The main contribution of this paper is to improve the restoration process in electricity supply disturbances by taking into account the effect of the interdependencies between electricity and mobile networks. Section 2 describes the interdependencies between electricity and mobile networks. The present sources of situation awareness in major disturbances are discussed in Section 3, and Section 4 presents the new method for information exchange in the event of a disturbance. Section 5 describes the implementation of the situation awareness system. This implementation is then demonstrated in a case study as presented in Section 6. The benefits of the system are discussed in Section 7, and finally conclusions and discussion of the study are given in Section 8.

II. Interdependencies Between Electricity and Mobile Networks

The development of electricity networks towards a smart grid has increased their dependency on mobile networks. In previous studies, it has been noticed that there are significant interdependencies between electricity and mobile networks. In the Tapani 2011 storm in Finland, the mobile network coverage was reduced by 25% as a result of outages and it took four days to restore it almost fully. On the other hand, a wide disruption of the mobile network can affect the electricity network if the public mobile networks are congested. [12]-[17]

In recent years, the restoration process of electricity networks has been improved by increasing the number of remote-controlled switches. The reestablishment time can be improved by several hours with these. However, some of these switches use the Global System for Mobile Communications (GSM) network to communicate. If there is no communication between the remote-controlled switches and substations, a repair team has to be dispatched to close the switches manually and this will slow down the restoration process. [18], [19]

In addition, there are communication links between substations and SCADA. Often, the mobile network is utilized for their communication because the price is fair for data transfer with adequate speed. Secondary substations can monitor and control the electricity network remotely. This function is important for power system restoration because it helps to locate faults. [16], [20]

The number of Automatic Meter Reading (AMR) meters in electricity networks has increased. Smart metering devices are utilized for reading and recording signals related to power quality and failure detection. Usually, they utilize mobile networks for communication. The data are typically transmitted either via Short Message Service (SMS) or the circuit-switched non-transparent GSM data service. [21]

Remote-controlled devices are not the only thing in the electricity network restoration process that is dependent on mobile networks. The DSO’s work management is heavily dependent on mobile networks in disturbances. The repair teams move around while restoring the network. They need communication access to communicate with the control center to locate faults and to receive permission to fix them. In addition, the teams need information about their next tasks. Most of the communication with the DSO’s operator is handled via mobile phones or tablet computers using the Distribution Management System (DMS) service, which also relies on the mobile network. If cellular network coverage is missing, the contractor remains unaware of how to proceed. In addition, some DSOs utilize a work management system that locates their team with the Global Positioning System (GPS) to help with the task allocation. [22]

Some of the above-mentioned communication methods are secured by using services from two different mobile network operators. However, in many cases mobile network operators share the same masts. Thus, a power blackout at one mast location results in the unavailability of more than one mobile network operator's service availability in that particular area. In addition, it is expected that, e.g., in Sweden the total energy consumption of mobile networks will increase by 20 percent, from 108 TWh in 2015 to 132 TWh in 2021 [23]. Thus, as the need for electricity in mobile networks continues to increase, it is even more important to improve the recovery process of the electricity supply to these networks in disaster scenarios.

The functionality of mobile networks depends on the availability of electricity networks. When there is a power blackout, the mobile network is not able to provide any coverage without any backup power. However, e.g., in Finland, the mobile networks should still continue to operate, because FICORA has issued a regulation [11] stipulating that mobile network base station sites should have backup power for three hours in the event of a disturbance in the electricity network. This is usually implemented with backup batteries, since, e.g., the availability of renewable energy devices, such as solar panels and wind turbines, is a rare sight at base station sites in Finland, mostly because of their low efficiency rate. Thus, base stations commonly rely on battery backup power during electricity disturbances.

The backhaul connections in mobile networks, i.e., the connections from the mobile operators' core network to the base station sites, are mostly implemented with fiber connections. These connections also rely on the electricity network in order to function. The devices in the backhaul transmission lines usually have a longer backup power reserve than the base stations, at least from six to twelve hours [11]. The most critical sites are equipped with aggregates to enable operation for longer periods of time, together with ready-made contracts with different companies to deliver more fuel to these sites when needed.

III. Existing Situation Awareness Systems for Major Disturbances

At present, in disturbances, the DSO creates the awareness of the disturbance, mainly on the basis of DMS and SCADA, which show the outage situation of an electricity network. In addition, the DSO utilizes a Work Management System (WMS), which reveals the situation of repairers and resources. In most cases, the DSO decides the fixing order on the basis of the locations of customers with high consumption or the faults that cause the most trouble with electricity supply [2]. The present sources of situation awareness in electricity supply disturbances were compared in a previous study [3]. In this study, the comparison was extended to include the sources of situation awareness in mobile network disturbances.

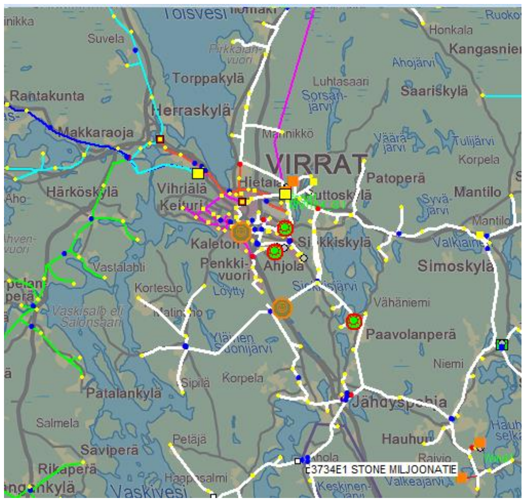

Fig. 1. A view of the DMS service.

In Finland, most of the DSOs display information about outages on their web pages, e.g., on transformer-level maps. In addition, some DSOs offer DMS services (Fig. 1) to their contractors and to local fire and rescue services in Finland. These services give access to the DMS view for the authority during disturbance scenarios. A common factor for all of these systems is that there are only a few bidirectional functions on these systems and they are not usually personalized to different user groups. At present, mobile network operators rarely utilize these systems. [2], [3]

There are some Situation Awareness (SA) systems available for electricity supply disturbances. Some of them are designed for common emergency situations and some especially for disturbances of the electricity supply. In Germany, there are a few situation awareness systems that have been developed for disturbances. One DSO has developed a system which delivers information about outages to the authorities. The system filters the needed information about planned and unplanned outages from the network control system. This information is transmitted to the rescue coordination centers via email. The data from the email can be integrated into the systems of the rescue coordination centers. In addition, municipalities receive information about outages via an SMS which includes the phone number of the DSO. [24]

In Canada, the Multi-Agency Situational Awareness System (MASAS) has been developed for exchanging emergency management incident-relevant information between multiple stakeholders. The system has been designed for exchanging information in non-ordinary situations, e.g., in a flood season. The system is based on a map where information about weather, earthquakes, fires and electricity outages can be presented. The MASAS can be used for sharing information about disturbances of the electricity supply even though it is not designed specifically for that. [25], [26]

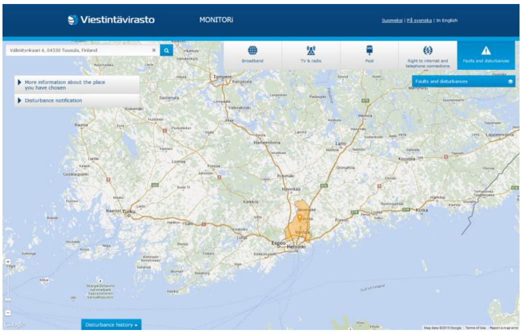

Fig. 2. An example of a disturbance visualization from FICORA's service for severe and very severe disruptions to mobile networks.

Generally, the DSO does not know the locations of mobile network base stations. In Finland, some DSOs cooperate with their mobile network operators so that they have information about the location of the most significant base stations.

Nowadays in Finland, different mobile network operators provide their own services for informing subscribers about disturbances of their own network. There are three main mobile network operators in Finland, which have their own infrastructure, and correspondingly there are three different services for informing the customers. The level of accuracy differs greatly in terms of how precisely, e.g., any disturbance is visualized on a map. FICORA has set minimum requirements for this [27], but even more accurate information can be given. For example, operators can show coverage outages even on a single base station level. In addition, FICORA has a web service which combines the disturbance information of different operators. An example of this kind of disturbance visualization is shown in Fig. 2. The information is usually presented at the municipality level, as can be seen from the figure. However, it is generated only after severe or very severe disruptions to the network and shows only the rough area where the disturbance affects the coverage of the mobile network.

One mobile operator in Finland shows the mobile network service problems in considerable detail, together with the expected coverage area of the outage. This is more accurate than is required by FICORA, but illustrates the disturbance situations quite well.

In the United Kingdom, e.g., one operator offers a service that can show the coverage areas and some unexpected issues or planned maintenance on a map. However, the problems are shown on the map only after a specific area is searched, and even after an area has been specified, the problems are shown with symbols on the map without a clear influence area. Thus, only rough estimates of the affected coverage areas are shown. Another operator in the UK has a similar kind of service, but rather than the problem areas being shown on a map, the problems are only listed without specific information on the locations on the map. In Australia, a similar kind of approach is presented as in the UK. In their service, after an address has been defined, a map shows the specific area with the symbols of the base station towers. These symbols also represent whether the service is OK, there is some planned work or there is some live outage at a specific base station site. Moreover, the map only shows the symbols when an address is defined, and thus the service status map does not show the status of any other regions without a new address being searched for.

The mobile network operators receive fault information from the base stations directly to the system. These include, among others, information about any problems related to the functionality of the equipment or warnings about service- or transmission-related misbehavior. Thus, operators should know whether base station site equipment is not able to access an electricity supply and is forced to utilize the backup power. Additionally, the mobile network operators in Finland have some agreements with the electricity companies to receive information about the status of electricity networks. This helps in following the operational status of electricity networks, but a direct combination of the relations between these networks is not available.

Mobile network operators are also prepared for major disturbances. Cooperation with electricity companies is important to coordinate the distribution of backup power to critical areas. However, there is no common system, e.g., a common map service, to show disturbances of both networks that is available for this purpose. The mobile network operators also follow weather forecasts in order to prepare for possible disaster scenarios caused by storms or other extreme weather phenomena.

In Finland, State Security Networks Ltd. has developed a situation awareness system, KRIVAT, that combines information from different stakeholders such as DSOs and telecommunication operators. They offer a map-based view that presents disturbances of electricity networks and mobile networks. However, the system does not present accurate coverage areas of mobile networks. In addition, the service includes a discussion forum for all stakeholders and with meteorology. The main difference from other existing services is that in addition to a situation awareness system they offer a secured telecommunication connection to their customers.

One form of preparedness for major disturbances is a real-life exercise in cooperation with electricity companies and the authorities. Thus, mobile network operators practice in advance the situations in which major disturbances could happen. This improves their ability to react to these events and helps to speed up the recovery process in times of actual disaster scenarios.

IV. The Method for Information Exchange in Disturbances

In this study, a new method was developed to improve information exchange between stakeholders in electricity and mobile network disturbance cases. This method is based on a concept of a situation awareness system that benefits all stakeholders. [1]-[5]. The method is tested with a developed demonstration of a situation awareness system that specifically combines the information from both the electricity and mobile network. The demonstration illustrates how the exchange of information between stakeholders could be executed by using the situation awareness system.

IV.1. *A demonstration of a situation awareness system*

The developed demonstration illustrates disturbances of electricity and mobile networks in a web-based user interface. In addition, it illustrates customers who are heavily dependent on the electricity or mobile network, the so-called critical customers. The critical customers can be, e.g., patients who need special healthcare, elderly people or critical infrastructure sites such as water pumping stations. Information about critical customers is stored in a manually updated database which users can update by themselves. The structure of the system is presented in Fig. 3.

The demonstration combines information from multiple DSOs and mobile network operators as seen from Fig. 3. This information can be combined with information about weather conditions, e.g. lightning strikes, the status of fire and rescue service tasks and traffic report. The main users (customers) are distribution system operators and mobile operators. In addition, municipalities, authorities and fire and rescue services can benefit from the system. The demonstration can be personalized for different organizations.

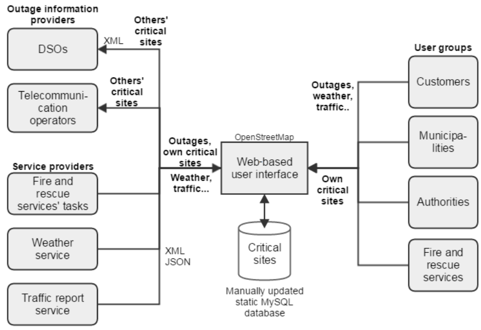

Fig. 3. A diagram of the demonstration.

IV.2. *The user interface of the demonstration*

The demonstration presents combined information from both electricity and mobile networks on a map. The user interface of the demonstration consists of a map part to which different information layers can be added and an event log where the amount of the electricity network outages can be seen with one view (Fig 4).

Fig. 5 shows a closer view of the user interface (the map has been stripped away from the figure because of a non-disclosure agreement). The gray light bulb symbol indicates the transformer station which has an outage and the red polygon indicates the lack of mobile network coverage. In addition, mobile network base stations have their own symbol. The color of the base station symbol shows whether the base station does not have electricity or if it is running on batteries. It is marked with a blue symbol when the situation is normal. If a base station has to rely on batteries, the color of the symbol is yellow, and if it does not have any electricity the color of the symbol is red.

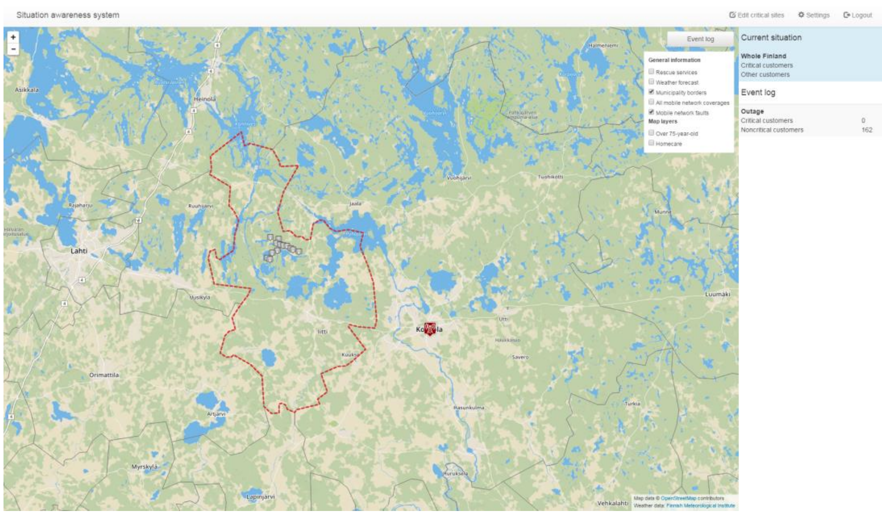

Fig. 4. The user interface of the demonstration.

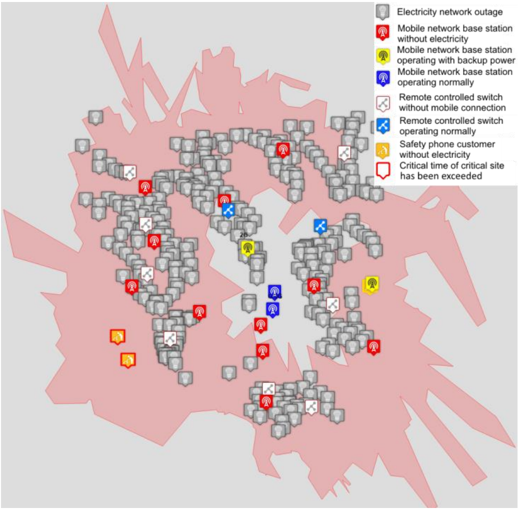

Fig. 5. Detailed view of the user interface during a disturbance.

V. The Implementation of the Demonstration

V.1. *Electricity network*

The electricity network part of the situation awareness system is based on existing systems and methods used by the DSOs to inform customers about outages and maintenances. The main source of the information is the DMS. The DMS maintains the distribution network state and signals related systems whenever a change of state occurs. Currently, this method is utilized by the DSOs in order to provide an outage information web page to customers. The web page shows the current state of the network, information on when outages started and the approximate ending time of these outages. This is also used for providing an SMS service in which the DSO informs its users about future maintenance and possible outages as soon as the information about them has been confirmed. When a change of state happens, the DMS generates outage information data about the current state of the network. The data contain important information about the outage, such as the start time, the end time and the type and a description of each outage. These data are sent to the situation awareness system using the Simple Object Access Protocol (SOAP) or by sending the data as an Extensible Markup Language (XML) formatted file. The data are sent over Hypertext Transfer Protocol Secure (HTTPS). If the data are sent using the SOAP, the DMS implements a SOAP client that connects to the SOAP server implemented by the situation awareness system. The DMS pushes the changes to the situation awareness system whenever a change of state occurs. If a simple file transfer is used, the situation awareness system polls the server changes in the file.

The DMS generates outage information on two different levels; a transformer level and a customer level. The transformer-level outage information contains the outage information and a list of affected transformers. The information is generic and cannot be utilized to identify any single customer unless the customer's transformer code is known. The customer-level outage information contains the same outage information as the transformer-level outage information. It also contains more information about the outage, such as a list of affected customers' identification numbers, the certainty of the outage and the state of the outage, meaning whether it is a new outage or recurring outage or the supply is temporarily restored. These data can be used to identify a single customer.

Once the data are received, the system saves the data into a relational database (such as MySQL or PostgreSQL). As the data are sent on two different levels (the transformer and the customer level) the data are first parsed and combined together. Each outage has a unique identifier that can be used to combine the two levels of outage information together.

Users connect to the system with a web-based user interface. The user interface works on all modern browsers. Once a user connects to the system the user requests data from it. The outage information which the user is interested in is sent to the user on the basis of previously set organizational information and user settings. The data that are received are further parsed on the user's browser and displayed to the user. The data can be further filtered by the user in the browser-based user interface. The user interface keeps on polling the server for changes in the network in order to keep the user interface up to date.

V.2. *Mobile network*

The implementation of the mobile network part of the system was based on the existing infrastructure of a mobile network operator and accurate configuration data available for a certain area in Finland. The individual coverage areas were accurately simulated with a mobile network simulation tool in which all the necessary configuration parameters had been taken into account. These included base station locations, antenna heights, antenna directions, antenna tilting levels, antenna models and their gains, transmission powers and any additional losses, as well as the frequencies used for GSM and the Universal Mobile Telecommunications System (UMTS), i.e., the second-generation (2G) and the third-generation (3G) cellular networks. In addition, the simulations required information about the elevation data of the area in the form of Digital Elevation Maps (DEMs), together with the type of environment the area had. The environment is taken into account with different morphographic corrections, which cause different attenuations for the propagating signal.

The simulations then used the Okumura-Hata [28] path loss model to calculate the final coverage areas for every

GSM and UMTS cell. This is based on calculating the maximum distance that the signal between the base station antennas and the user equipment can propagate. The Okumura-Hata path loss model or its extension, the COST-231-Hata model (for higher frequencies), is defined as:

$$L = A + B \cdot \log_{10}(f_{\mathrm{MHz}}) - 13.82 \cdot \log_{10}(h_{\mathrm{BS}}) - a(h_{\mathrm{MS}}) + (44.9 - 6.55 \cdot \log_{10}(h_{\mathrm{BS}})) \cdot \log_{10}(d_{\mathrm{km}}) + C_{\mathrm{m}}, \quad (1)$$

where L is the path loss in [dB],

A, B are frequency-dependent constants,

f_{MHz} is the frequency used in [MHz],

h_{BS} is the effective base station antenna height in [m],

h_{MS} is the mobile station antenna height in [m],

$a(h_{\mathrm{MS}})$ is a city size-dependent function,

d_{km} is the distance between the base station and mobile station in [km],

and C_{m} is an area correction factor.

The constants A and B are defined separately for different frequencies according to Table I [28].

TABLE I
COST-231-HATA PROPAGATION MODEL CONSTANTS

	150-1500 MHz	1500-2000 MHz
A	69.55	46.3
B	26.15	33.9

The city size-dependent function $a(h_{\mathrm{MS}})$ is defined as:

$$a(h_{\mathrm{MS}}) = 3.2 \cdot (\log_{10}(11.75 \cdot h_{\mathrm{MS}}))^2 - 4.97 \quad (2)$$

$$a(h_{\mathrm{MS}}) = (1.1 \cdot \log_{10}(f_{\mathrm{MHz}}) - 0.7) \cdot h_{\mathrm{MS}} - (1.56 \cdot \log_{10}(f_{\mathrm{MHz}}) - 0.8) \cdot h_{\mathrm{MS}} \quad (3)$$

Equation (2) is defined for large-sized cities with frequencies greater than or equal to 300 MHz and (3) for small to medium-sized cities for all the valid frequencies presented in Table I. The area correction factor, C_{m}, is also defined separately for different-sized cities. For large-sized cities C_{m} is 3 dB and for medium-sized cities it is 0 dB [28]. It should be noted that there are some limitations on how to use the COST-231-Hata propagation model. The model is valid for frequencies between 150 and 1000 MHz and 1500 and 2000 MHz for ranges between 1 km and 20 km. In addition, the effective base station antenna height is limited to between 30 and 200 meters, while the mobile station antenna height is limited to between 1 and 10 meters. Nevertheless, all of the values used in the simulations for the simulated area are within the limitations.

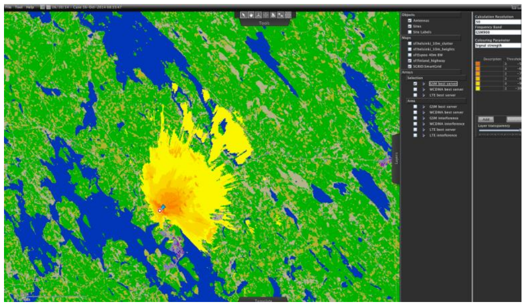

Fig. 6. An example of the coverage simulation for one cell.

Another aspect that defines the behaviour of the Okumura-Hata model is the propagation slope, which is the $(44.9 - 6.55 \cdot \log_{10}(h_{\mathrm{BS}}))$ part in (1). As can be seen, the only variable in defining the propagation slope is the effective base station antenna height, h_{BS}. However, the propagation slope defines the way the signal attenuates while propagating through the environment. Thus, with a fixed h_{BS}, the only way to change it is to change either the value 44.9 or the multiplier 6.55. The simulation tool fine-tunes the value 44.9 with respect to the environment to get the correct propagation slope for the correct areas.

The simulation results are exported separately for each base station site as images in order to visualize the cell coverage areas. An example of the coverage simulation for one cell is shown in Fig. 6. It should be noted that the coverage area follows the differences in elevation and the effect of different types of environments.

On the basis of the customer identification code or the transformer code, the base stations can be combined with the outage information. The result of the connection is utilized to find out whether the base station does not have an electricity supply from the network.

Other fault information can also be imported into the situation awareness system. Besides the fault information about the lack of a power supply from the electricity network, the information about the status of cells is also imported into the system. This enables the system to visualize the lack of coverage, e.g., in the case of maintenance work.

V.3. *Other information*

Other information is needed for the system to be operational. Critically electricity-dependent site information is important to the system. The data are received from the users of the system and can be imported into the system in two ways. Users can utilize the web-based user interface to add new sites manually. This is viable in cases where the number of sites is low, as in the case of a small water utility. In cases where the stakeholder has a high number of critical sites (such as a municipality), integrating the stakeholder's database is also possible. The critical site database is then automatically updated once a site is added to the stakeholder's own database.

The weather information in the system is fetched from an interface provided by the Finnish Meteorology Institute (FMI). FMI provides a Web Feature Service (WFS) compatible interface for fetching the weather information. FMI provides forecasts, current weather information and history information. The data are fetched using Hypertext Transfer Protocol (HTTP).

The Finnish rescue services provide an interface for media and other users to get information about the current activities of the rescue services. These data are also fetched from the interface using HTTP.

Furthermore, other information can be implemented into the system; e.g., the Finnish Transport Agency (FTA) provides information about the current traffic situation. These data can be fetched from the SOAP interface provided by FTA. In addition, the system can be integrated with DSOs' work management systems to follow the location of the repair teams.

VI. The Live Demonstration – Case in Finland

The demonstration was tested in two different cases. In the previous study the system was tested on the basis of history data from a disturbance case in Finland that affected both the electricity and mobile networks [1]. In this study, the system was tested with live operational networks.

A live version of the demonstration was developed to test how the SA system could be implemented. The demonstration combines information from four DSOs and one mobile network operator. The demonstration presents the lack of coverage areas in the mobile network and outages of the electricity networks on the transformer level on a map view. The area that is studied is the operating area of the chosen DSOs. In addition to mobile network coverage, the base stations that have faults are also shown on the map.

The information on the outages is combined with the information about the location of the critical customers. Customers can be added to the system on the basis of their transformer number. The system gives a warning when a critical customer has an electricity network outage.

In order to implement this functionality in (near) real time, an interface between the mobile network system and the situation awareness system was developed. In the system, the mobile network fault information is collected every 10 minutes from a file that has been generated by the mobile network operator and sent to the situation awareness system. The system then extracts the information and visualizes the possible changes that have happened after the previous fault information update. This enables a near real-time presentation which is still relatively light to compute. The data from the DSOs is collected every five minutes from the DSOs' web page interface. At present, the outages of the electricity networks are observed on the transformer level.

The live demonstration was tested for two months in this study. The disturbances that occurred during the testing time were observed with it. During the testing period there were no major disturbances to any of the networks. Smaller outages occurred once or twice per week. Once a small electricity network outage resulted in just one mobile network base station blackout (Fig. 7). In this case the outage did not have an effect on mobile network coverage because the other base stations nearby covered the missing area.

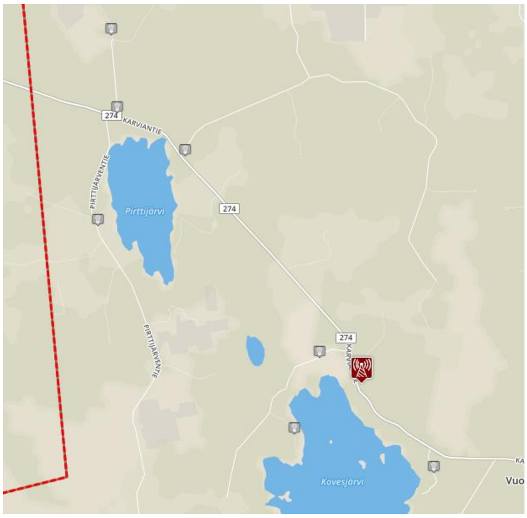

Fig. 7. Outage of electricity network and faulted base station of mobile network illustrated in the demonstration.

VII. Benefits of the method for situation awareness system

The combined electricity and mobile network situation awareness system helps to monitor the electricity and mobile networks, especially in the event of major disturbances. It improves the restoration process as a result of the added value from the interoperability of these networks. In addition, the resilience of the society during disturbance situations improves when the authorities have information as to whether their critical customers or critical sites lack electricity or mobile service. This information can then be utilized to prioritize the restoration process of the networks for the most critical areas. Thus, repair teams are able to concentrate more on the most critical areas, and if the situation changes it will be visible in the system and changes to the repair order can be decided fluently and effectively. The improvements in terms of information exchange and benefits to the system are illustrated in Table II.

As shown in the case study [1], the situation awareness system can be utilized to find out the vulnerabilities and the interdependencies of critical infrastructures. This information can be highly useful when planning an electricity or mobile network. In addition, the information can be utilized in a restoration planning process. Illustrated situation awareness improvements help DSOs to plan their restoration processes more effectively. The repair order of the electricity network faults can be changed so that the most important base stations utilized by DSOs' remote-controlled devices are restored first. In addition, the fault repair order can take into account the most disturbance-vulnerable electricity consumer sites, which are important to the resilience of society. This can also improve DSOs' network planning by recognizing existing problematic areas, which could be prevented in the planning process of new areas. If the DSOs know the location of the important base stations, they can plan the network so that those areas are more resilient, e.g., with ground cabling. Furthermore, the DSOs can consider changing the communication media in those areas where mobile network coverage is most vulnerable to disturbances.

TABLE II
SITUATION AWARENESS BENEFITS

	PRESENT	WITH SITUATION AWARENESS SYSTEM	BENEFITS OF THE SYSTEM
DSOs	customers with high consumption of electricity	customers who are heavily dependent on electricity	DSOs can take these sites into account when planning the network or the restoration plan
	no or some important base stations of mobile network	all faulted base stations of mobile network	base stations most important to DSOs' operation can be detected and secured
	inaccurate awareness of mobile network coverage	detailed awareness of mobile network coverage	predict the possible disturbances in own network caused by mobile network
	location of repair teams	information if repair team does not have mobile network service	repair team can be informed beforehand where to proceed when they need to find some coverage
	location of remote-controlled devices	warning if remote-controlled device does not have mobile network coverage	prediction if this can affect DSOs' own restoration process
Mobile network operators	warning if base station does not have electricity supply from the electricity network	estimation of the end time of the outage	prediction if more backup power is needed
	inaccurate information about the running time of the back-up power of the base stations	prediction of how long the mobile network will operate with backup power after the first outage	mobile network operators can utilize this information to renew poorly functional batteries
	inaccurate awareness of disturbances of electricity supply	detailed awareness of disturbances of electricity supply	predict the possibility of disturbance situation in own network
	base stations that are the most important for mobile network coverage	base stations that would be most important to the restoration of the electricity network	mobile network operators can improve their backup for the most important base stations to expedite the coverage restoration process of the mobile networks
	no information about critical customers that are highly dependent on mobile coverage, e.g., home care patients, retirement homes	which base stations are most important to the critical customers, e.g., retirement homes	the sites can be taken into account when placing the backup power
Authorities & Municipalities	inaccurate awareness of disturbances of electricity network	detailed awareness of disturbances of electricity supply from one view	authorities and municipalities can improve the planning of their own duties
	inaccurate awareness of mobile network coverage	detailed awareness of mobile network coverage	authorities and municipalities can improve the planning of their own duties
	location of customer whose life is dependent on electricity supply or mobile network coverage	warning if critical customer does not have electricity supply or mobile network coverage	prediction of whether residents need to be evacuated or otherwise helped
	location of own critical sites, e.g., water pumping stations	warning if critical site does not have electricity supply or mobile network coverage	municipalities can plan which sites need backup and which can be substituted, e.g., sharing water among residents instead of providing the backup to a water pumping station

One benefit of the system is that the DSOs and the mobile network operators can find out how their recovery process is working. They can detect if everything went as planned. Likewise, they can find out whether the processes of the other stakeholders caused the problems or if the problems were in their own processes.

In addition, the demonstration can extend the DSOs' work management with the information about repair teams which do not have mobile network coverage. It can also be utilized to warn the teams before they move to an area without coverage or to inform them beforehand where to proceed when they need to find some coverage.

With the information received from the demonstration, mobile network operators could plan their backup power batteries or reserve power more precisely. They can recognize the base stations that are the most important to the resilience of the electricity network and improve their backups. This can expedite the coverage restoration process of the mobile networks. Further, the information about disturbance areas of electricity networks can be used to find the most vulnerable base stations from the operators' own network and increase their backup power batteries or other reserve power. While cooperating in the network planning process, DSOs and mobile network operators can detect the most vulnerable areas for the operations of both networks and plan the backup power together.

In the long run, the SA system makes it possible to detect deteriorated mobile network base station backup batteries. The DSOs can use this information to, e.g., plan their restoration process so that the electricity will be restored first at those locations. The mobile network operators can utilize this information to renew poorly functional batteries.

The information feed to the system can be processed further; e.g., when the customer number of the base station is known, it is possible to detect if it does not have electricity feed from the network at the moment. Further, knowing that the base station is still working means it is possible to find out that it is working on batteries. In this case, how long the batteries will work can be determined. The information can then be saved into the system for later utilization. DSOs can utilize this information to predict how long their devices will have a mobile connection. In addition, the mobile network operators can utilize this information in the maintenance planning process.

Besides improving the recovery of the electricity and mobile networks, the system can improve the resilience of society in disturbances. Municipalities are able to recognize the customers who have safety phones or safety buttons in areas which are temporarily lacking mobile network coverage or an electricity supply. Municipalities can utilize the information to send help to customers or to plan their evacuation. The warnings of critical sites help municipalities to plan the placement of movable reserve power or to plan whether the site can be substituted, e.g., sharing water among residents instead of providing backup power to a water pumping station.

For authorities such as the fire and rescue services the awareness of the disturbance area plays an essential role for their operation. Thus, they can prepare for an increasing amount of work and summon more officers to duty. The combination of the information of multiple DSOs reduces the number of information sources and the workload of the authorities. With the situation awareness system, the fire and rescue services can increase their help to the municipalities, e.g., it will improve evacuation planning together with municipalities.

VIII. Conclusion

In this study, a new method to improve the disturbance management of electricity and mobile networks was presented. The method is based on a situation awareness system which combines the information from both the electricity and the mobile network. During the study a demonstration of the system was implemented utilizing the existing systems. To test the method a live demonstration was performed in Finland. The demonstration combines information from multiple DSOs and one mobile network operator.

The main problem with the present situation awareness systems utilized in disturbances of electricity and mobile networks is that the interdependencies of different infrastructures are not taken into account and the information presented in the system is not further processed as is the case in the MASAS system [25], [26]. In addition, some of the systems are still limited to presenting information from only one stakeholder. This can hamper the restoration process of the networks.

The authorities and the operators of both networks can benefit from the situation awareness system and not only the authorities as in the system presented in [24]. The DSOs and network operators can utilize the system in restoration planning, e.g., the mobile network operators can place more backup power at the base stations that are most important for the operation of the electricity network. In addition, the information from the system can be utilized to improve the network planning, e.g., DSOs can ensure the electricity supply for the most important mobile network base stations by ground cabling. For the authorities the most beneficial functionality is the information about the status of the critical sites. With this information they can focus their actions on the right residents, e.g., safety phone customers.

There can be problems in adopting the new method if it depends on a commercial system, where the data are produced by customers themselves. Some of the existing systems have had problems acquiring customers because the variety of the input data is dependent on the number of customers that produce the data. In that case, the amount of information received for first users is limited and the benefits of the system stay low. The best situation in which to adopt the method is if there is legislation or regulation that forces the stakeholders to add data to the system. In that case, the system could utilize all the data at the same time.

IX. Further Studies

The future research should relate to analyzing the performance of the real-time system and its impact on the overall time needed to manage disturbance situations. The testing of the live demonstration will continue further. The main goal is to test the demonstration in the event of a major disturbance that affects multiple electricity networks and mobile networks. In addition, more users will be added to the system, e.g., DSOs and municipalities, for testing purposes.

The future research around this new method should also include developing additional algorithms, e.g., automatic warnings on top of the system that has been developed. In addition, e.g., machine learning algorithms could highlight interesting information from the operational networks, especially about the interdependencies between the networks.

Acknowledgements

The authors would like to thank the Finnish Funding Agency for Innovation (TEKES) for funding and supporting the research work.

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Publication 4

H. Krohns-Välimäki, J. Haapanen, P. Verho, J. Säe, and J. Lempiäinen, "Combined electricity and mobile network situation awareness system for disturbance management," in *Proceedings of the IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA)*, Bangkok, Thailand, 3.–6. Nov. 2015. DOI: `10.1109/ISGT-Asia.2015.7387099`

Combined Electricity and Mobile Network Situation Awareness System for Disturbance Management

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***Abstract*—In this research, a demonstration of a situation awareness system is presented. A real case of the disturbance of the electricity network was illustrated with the demonstration. The state of the remote controlled switches was simulated based on the model of the mobile network coverage and compared with the real state information from the online remote field service provider. The case study confirmed that there are interdependencies between both networks. The main contribution of this research is a new method to improve the disturbance management of electricity and mobile networks and to improve the resilience of the society in disturbances by a combined situation awareness system.**

***Index Terms*—Disturbance, Situation awareness, Co-operation, Mobile network, Remote controlled switch.**

I. Introduction

There have been several problems in the information exchange between organizations in disturbances of electricity supply. Interdependencies between electricity and mobile networks have been noticed. The situation where both electricity and mobile network have an interruption at the same time is complex to manage.

Storms like Pyry and Janika in Finland in 2001, Gudrun 2005 and Per 2006 in Sweden, four storms in the summer of 2010, storms at Christmas of 2011and two storms in autumn of 2013 in Finland caused widespread and long lasting disturbances in the supply of electric power. In those storms, some individual customers were without electricity for a few weeks. In January of 2011 snow load on trees caused widespread disturbances in Finland. In addition to storms that affect the rural area, the hurricane Sandy caused widespread disturbances in Eastern parts of the USA in October of 2012 including some cities. There were e.g. floods that caused outages in Manhattan, New York. [1]-[7]

Many of the long lasting and wide spread disturbances, the so called major disturbances, are induced by storms and other severe weather conditions. However there have also been major disturbances that have not been especially long lasting but extremely wide spread, like the disturbances in the transmission systems in the USA and Canada in 2003 and in Central Europe in 2006. Both of these caused negative societal consequences. [1]-[7]

Typically, the disturbances caused problems in telecommunication, water supply, animals' conditions in farms and with the coldness in private houses. The coldness of the houses has even resulted in some evacuations. The problems with telecommunication also affected safety phones and safety buttons. [1]-[7]

Electricity distribution and mobile networks are interdependent. Mobile network base stations require electricity to operate. The base stations should have backup power batteries or other reserve power to maintain the transmission for at least three hours assigned by The Finnish Communications Regulatory Authority (FICORA). However, the electricity disturbance can last longer than the reserve backup power, e.g. because of storms. [8]-[10]

While the electricity network can operate without telecommunications for the operation of the distribution automation (DA) it is necessary. Traditionally most of the communication was done using proprietary communication methods and protocols. Nowadays the mobile network is utilized in multiple ways in distribution networks such as DA and communication with repair groups. [11], [12]

The electricity network is developing towards the Smart Grid, thus the amount of DA devices in the distribution network has increased in recent years. DA devices improve the outage recover times. Previously, a telecommunication link was only established to critical parts of the network such as substations. After a remote connection to substations, the utilization of remote controlled disconnecters started. Nowadays in addition to these devices a connection is also needed for automatic meter reading (AMR). The connection between control center and DA devices is often based on mobile network technologies. Powerline communication

The authors would like to thank the Finnish Funding Agency for Innovation (TEKES) for funding and supporting the research work

(PLC) is also used together with a mobile network (e.g. for AMR meters). These connections also depend on the mobile network as part of the communication link to the control center is implemented using a mobile network. [12], [13]

In addition to remotely controlled devices, Distribution System Operator (DSO) relies on mobile networks to contact and follow repair teams and subcontractors during disturbances. If both actors receive information about these disturbances, their recovery processes could be executed more efficiently.

After the storms in Finland in December 2011 the Finnish Electricity Market act was changed to improve the reliability of the electricity networks. The new addition to the legislation requires DSO to prepare a contingency plan for disturbances. Further, it was added to the legislation that the maximum duration to outage will be six hours in urban areas and 36 hours in rural areas concerning all of the customers from the beginning of 2029. DSOs must prepare development plans to describe how these limits will be achieved and how the electricity supply for the sites that are important to the resilience of the society are ensured. Further, the new legislation requires that the DSOs should participate in the formation of a situational awareness and supply any information relevant to this purpose to the responsible authorities. [14]

This paper presents the demonstration of a situation awareness system that combines information about interruptions of electricity and mobile networks. This system can be utilized to improve the resilience of both networks. Further, a case in which an interruption occurred in both networks has been studied.

II. METHODS

A demonstration of inter-organizational situation awareness system to disturbances of electricity supply has been developed in this research. The developing process has been iterative. The present situation has been studied by literature review and in several cooperative workshops of this research. These results are presented in [1]-[3]. Methods of the usability and user-centered design have been utilized in the design process to improve the demonstration e.g. semi-structured interviews for user needs [14], [15].

In this paper, the main focus is in instrumental case study approach [16]. The case has been simulated with the developed demonstration and compared with the real life case. The results of the comparison were analyzed for studying the capability to utilize the demonstration to improve the restoration process of the electricity networks and mobile networks.

III. THE SOURCES OF THE SITUATION AWARENESS IN DISTURBANCES

Endsley's theory of the three levelled situation awareness is utilized in design process of the system. The theory defines the situation awareness (SA) as the triad of "perception", "comprehension" and "projection". The first level consists of perception of the status, attributes and dynamics relevant elements in the environment of the situation. At the second, level the comprehension of the situation is formed based on the information received at the first level. At the third level, the perception and comprehension are utilized to form a projection of the future happenings in the situation. [15], [17], [18]

DSO's situation awareness can be divided into two categories; internal and external (Fig 1). At present, the studies of DSO's SA are focused internal SA. Thus, the information systems that DSO utilizes are focused to support mainly on that. These systems are SCADA, Distribution Management System (DMS), work management system (WMS) and customer information system (CIS). All of these are designed to support the everyday actions of DSO. [19]-[21]

SCADA collects the status and measurement data from the network. This information is used to control the network. DMS connects data from SCADA and customer information system to map-based user interface. With DMS the overall picture about the network can be seen. It can be used to plan and remake the connections in the network. At disturbance situation DMS is important tool to locate the outages and to get an overall awareness of the situation. In addition, the WMS is an important tool in disturbances, thus it is utilized to locate the repairer teams and to communicate with them. It can be utilized to share tasks and send teams to right places to fix faults. [21]

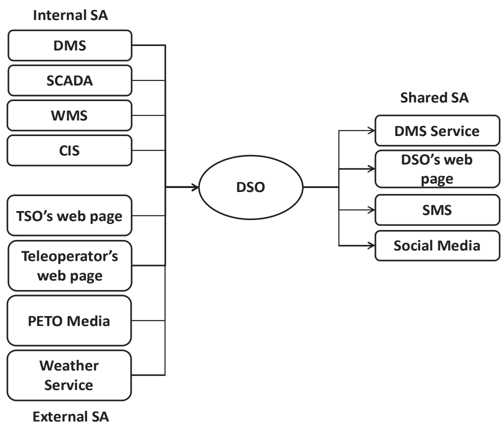

Figure 1. The DSO's situation awareness.

The external situation awareness of DSO can be divided to the information that DSO delivers to other actors and customers and to the information that DSO receives from others. The main information that DSO needs is the situation of transmission network, because the issues in transmission network can affect the distribution network. Some of the DSOs want to follow the outages of their neighbour DSOs' networks. By following that information, DSO can predict if storm is coming to their operating area. However, public web pages are the only way to follow the other DSOs. In addition to their systems DSO gets weather forecast and warnings from local meteorological institute. Other information that DSO receives can be e.g. tasks of fire and rescue services. [1]

Some DSOs are co-operating with their local mobile network operators and they may have information about the locations of the important mobile network base stations. In addition, they may follow the coverage information of the mobile network from operator's public web page. In Finland, the mobile network operators are offering information about their interruptions on a digital map. There are no restrictions about how accurate level the information has to be illustrated, thus some operators are offering information in municipality level while others are offering it in more detailed level. For the purpose of the DSO this information is often too inaccurate.

Some DSOs are maintaining a database about customers that are highly dependent on electricity. However, this information is usually outdated because there are no established practices. [1], [2]

At present, the information that DSO shares to others is focused mainly on their web pages. Most of the DSOs in Finland have an outage map on their web page. Users can utilize the outage map to see which areas the outage affects (in transformer level accuracy), when it has started, when it is estimated to end and how many customers it affects. This information comes from DSO's DMS. Some DSOs utilizes DMS also to share more detailed information to repairers, subcontractors and fire and rescue services. This so called DMS service was originally designed to share information to subcontractors and it is a direct view to DMS. Technical language is used in the interface and can be difficult to use by the fire and rescue service. In addition, some DSOs have SMS services that send the outage start time, estimated duration and the estimated end time information to the customer. [22], [23]

In Finland, there are three main mobile network operators who have their own infrastructure. Their operating areas are wider than DSO's, i.e. nationwide. There are multiple DSOs in area of one mobile network operator. The mobile network operators are not offered any additional services i.e. DMS service by DSOs, thus they are relaying on public web pages of DSOs. Consequence of this is that the information that mobile network operators achieve from the disturbances of the electricity network is shattered to multiple systems.

There are some Situation Awareness (SA) systems available for the disturbances of electricity supply. Some of them are designed especially for disturbances of electricity supply and some for common emergency situations. Common for those systems are that they are focused on level 1 and 2 SA and do not process different information to give the projection to future. [20]-[26]

IV. THE DEMONSTRATION OF SITUATION AWARENESS SYSTEM

The problem with present sources of the situation awareness is that the interdependency between electricity and mobile network has not been taken into consideration. None of the systems combines information of the both networks. Furthermore, the devices that are dependent on both networks are not included in present systems. [1], [2]

In this study, the demonstration of a situation awareness system to disturbances of electricity supply has been developed. This demonstration consists of two parts; 1) first part illustrates the mobile network coverage and base stations, 2) the second part illustrates the information from different actors related in disturbance e.g. fire and rescue services tasks. The demonstration combines information from multiple DSOs and mobile network operators to web based user interface. In addition, information about remote controlled devices can be added to the system. The system structure is presented in Fig. 2.

The main users are distribution system operators and mobile operators. In addition, municipalities, authorities and fire and rescue services can benefit on it. The demonstration can be personalized by organizations.

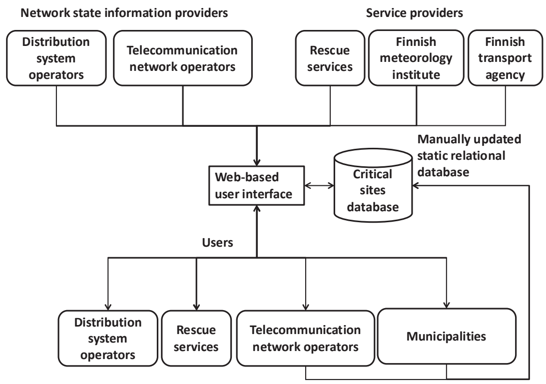

Figure 2. The diagram of the demonstration.

This demonstration presents combined information from both networks (Fig. 3). The gray symbol indicates the transformer station which has an outage and the red polygon indicates the lack of mobile network coverage. In addition, mobile network base stations have their own symbol. The color of the base station symbol informs if the base station does not have electricity or if it runs on batteries. It is marked with a blue symbol when the situation is normal. If a base station has to rely on batteries, the color of the symbol is yellow, and if it does not have any electricity supply the color of the symbol is red.

In addition, there is a symbol for the repair team and remote controlled switches. The location information of the repair team can be combined with coverage information to achieve information if the repair team is approaching an area without coverage. Remote controlled switches are presented with a white symbol if they do not have mobile network coverage. Otherwise they have light blue symbols.

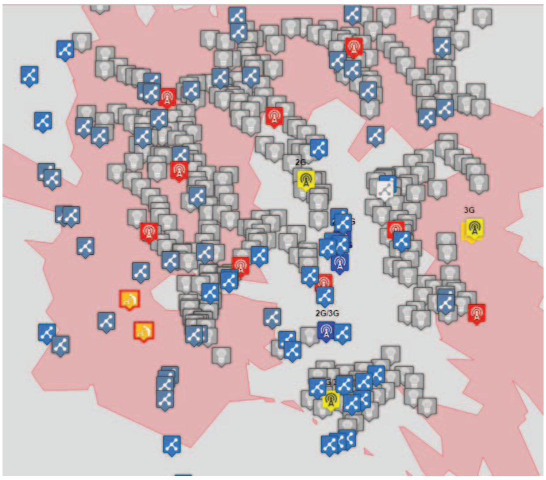

Figure 3. A view of the system.

The public authorities can add information about their own critical sites such as people with safety phones to the system. These sites are presented with their own symbols (orange symbol in Fig. 3). The symbol of such critical site will show if there is no electricity or mobile network coverage.

V. THE CASE STUDY - THE REMOTE CONTROLLED SWITCHES

An outage case that occurred in Finland was studied in this research. Information about the case was received from multiple organizations. The DSO provided transformer status information about the area. The mobile network operator provided configuration and status information about the mobile network base stations. An online remote field service provider provided information about the communication link statuses of the switches in the electricity network.

The provided base station configuration data was used to simulate the coverage areas of each base station. The coverage areas have been accurately simulated with a mobile network simulation taking into account all necessary configuration parameters. These parameters include base station locations, antenna heights, antenna directions, antenna tilting, antenna models and their gains, transmission powers and any additional losses as well as the used frequencies for Global System for Mobile Communications (GSM) and Universal Mobile Telecommunications System (UMTS) systems. In addition, Okumura-Hata path loss model was used to calculate the overall signal power loss of the propagated signal from a transmitter to receiver, also taking into account the effect of the elevation differences in the area. The simulation results were exported separately for each base station site as images to visualize the coverage areas.

The base station data has been visualized on the map with the coverage areas and the status information. The mobile network operator provided the information whether the base station was active or not. No information was provided on whether the station is supplied by the network or by the backup battery. A simple model is used: whenever the nearest transformer is affected by the outage, the base station is being supplied by the backup battery.

In addition third party remote controlled switch statuses were displayed on the map. The status of a switch is either on or off. The switch mainly used the network of the mobile network operator that provided the mobile network data. If the switch is on, the packet loss is 0 %. If the switch is off, the packet loss is 100 %. The modelled coverage areas are used to calculate a modelled status for each switch based on their location in the coverage area. Both the modelled and the actual status are then displayed on the view.

The example of the system's view is shown in figure 3. The blue symbols present mobile network base stations that are being supplied by the network. The yellow symbols present mobile network base stations that are possibly being supplied by a backup battery. The red symbols present mobile network base stations that are down. The bright blue symbols present remote controlled switch that have a working telecommunication link. Similar white symbols present remote controlled switch without a working telecommunication link. Similar grey symbols present remote switch that are modelled to not have a working telecommunication link but actually have one. The differences in the model and the real state are discussed in the next chapter.

VI. THE RESULTS OF THE CASE STUDY

In the studied case, the storm caused interruption to electricity network. Because of the storm, the interruption in electricity network expanded gradually. The base stations of the mobile network have backup power, thus the interruption did not effect on mobile network and switches immediately. Based on the modelled situation of the mobile network, the first switches (grey symbol in Fig. 4) became unreachable 2 hours earlier than in the real case

When the worst situation occurred in the mobile network, the worst situation from the switch point of view began. There were 103 switches in the studied interruption area. In the worst case 12 switches were unreachable (Fig. 4). This happened approximately 4 hours after the first failure in the electricity network. After this the situation was improving when the base station in south-west of the observed area was restored. However, 9 hours after the beginning of the interruption, more switches started to become unreachable even though the mobile network was already operating in the area. In this case, the dropped switches were located to the edge of the studied area. Approximately 12 hours after the beginning of the interruption all switches were fully functioning.

In the model, the amount of the switches that did not function was bigger than in real case. 63 switches were unreachable in the worst case in the model. In addition, the timing of the worst situation did not match to real case. In the last drop of the switches, the modelled values resembled the real data.

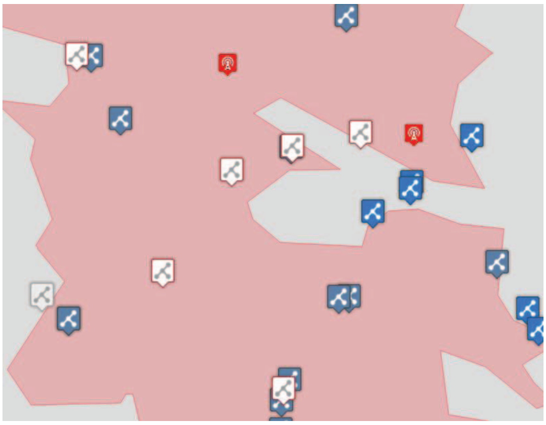

Figure 4. The worst situation in the observed case.

VII. Discussion

The data about remote controlled devices illustrated in the system, was analyzed to utilize the demonstration to improve the restoration process of the both network was studied. Information about the modelled status of the switches and the real status of the switches were compared. There are some differences in the statuses especially in the edges of the observed area.

There were some issues with the information as the observed areas were slightly different. Some of the differences between modelled and real status can be caused by the 10 minute status polling time of switches.

If the data is observed only from the mobile network coverage point of view, it can be said that the modelled and measured statuses do not match. There can be several reasons for that. First, the coverage area has only been generated from a specific area and does not include the coverages of the surrounding base stations. The coverages usually overlap and can improve the service in the edges of the current observed area. Second, the switches could utilize two operators' mobile networks. However, in this case all the switches were using the same mobile network. If the comparison is made in the middle of the modelled area, the model and the real data resemble each other. The most probable reason for this is that that modelled mobile network area is too small. A larger area should have been modelled.

9 hours after the beginning of the disturbances 10 switches became unreachable while there was mobile network coverage in the area. There is a small chance that the devices do not have electricity and their backup power was lost. However, the chance is quite small, because the backup batteries are designed to last at least 24 hours. The other option is that the mobile network coverage simulations are incorrect on that location. However, the switches are located in the area where everything else is working.

The studied remote controlled switches utilize the network of one mobile operator. Their resilience could be improved by utilizing networks of multiple operators. However, in Finland mobile operators are using common masts often, thus if the interruption in electricity network is affecting one mobile network it is most likely affecting the others too.

Based on the analysis of the case, the situation awareness system can be utilized to find the interdependencies between electricity network and mobile network. Further, this information can be utilized in the restoration planning of both networks. With the system the DSO and the mobile network operator can locate the most important base stations in the electricity network. The DSO can utilize the information to restore the electricity first to those base stations, thus achieving communication to their own remote controlled devices. The mobile network operator can utilize the information to locate the transferable backup generation to the base stations that are most important for DSO's communication. In addition, if the interruption information is combined with the information of how long the base station has backup power it can be utilized to project the future events of both networks.

The DSO can utilize the information about the coverage area of the mobile network to inform their repair teams about the problems in communication, e.g. the repair team can be warned if they are approaching an area with no coverage.

Further, the system can be utilized when developing both networks. The DSO can ensure the supply to the most important base stations e.g. by cabling. Likewise, the mobile network operator can improve the backup of the important base stations.

The public authorities can utilize the system to follow their own sites that are critically dependent on electricity or mobile network e.g. safety phone customers. With this information they can focus their actions better. In addition, the simulation part of the system can be utilized for training purpose.

For further development the methods utilized in the demonstration will be applied into a live demonstration. The demonstration presented above is an offline demonstration of a previous disturbance. In the live demonstration the mobile and electricity network data is gathered in real time, the data is combined and the current situation is shown on the web based user interface. Users such as the mobile network operator, the DSO and municipalities can use the system during the live demonstration to gain information about the current situation in the electricity and mobile networks. Different situation awareness rating and testing methods can be utilized to study the suitability of the demonstrated system to disturbance management when the live demonstration is own use.

Conclusion

Major interdependencies exist between electricity networks and mobile networks. The sources of the situation awareness of the DSO consist of internal and external sources. Present methods are focused mainly on DSO's internal situation awareness. There are some situation awareness systems to information exchange in disturbances and some of the DSOs are co-operating with their local mobile network operator to locate the most important base stations. However, any processed information about the interdependencies of the both networks is not supported. Further, the authorities are using multiple web pages and DMS services to achieve the information about both networks.

In this research, a demonstration of a situation awareness system was developed. This system illustrates the interruptions of electricity and mobile networks on a map. Information about the sites and devices that are dependent on either of these networks e.g. remote controlled switches or elderly residents can be added to map. This information can be utilized to improve the restoration process of the electricity networks or mobile network and to improve the resilience of the society in disturbances.

It was noticed from the analysis of the disturbance case, that the remote controlled switches are highly dependent on the mobile network. In the studied case, some contradiction between the modelled state of the switches and the real state appeared, because the effect on base stations outside the observed area could not be taken into account while modelling the mobile network coverage. Otherwise, the modelled area resembled the real case.

Based on the case it is not possible to make a conclusion how the unreachable switches effected on the restoration process of the electricity network. To make these conclusions, the information of the manually controlled switches would be needed in addition to information how long the manual opening process took.

The demonstrated situation awareness system could help the authorities to plan their actions better, e.g. to evacuate only the residents whose life is dependent on one or both of the networks. In addition, the resilience of the society can be improved by using the demonstration to plan the placement of the backup power.

The DSO and the mobile network operator can utilize the system to improve their restoration process after the situation, e.g. the mobile network operator can improve the backup of the base station which is important to the electricity network. Likewise, the DSO can plan the cabling to ensure the electricity supply to important base stations.

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Publication 5

J. Säe and J. Lempiäinen, "User Guided Energy and Capacity Optimization in UMTS Mobile Networks," in *Proceedings of the 25th International Symposium on Personal, Indoor, and Mobile Radio Communication (PIMRC)*, Washington D.C., USA, 2.–5. Sep. 2014. DOI: 10.1109/PIMRC.2014.7136290

User Guided Energy and Capacity Optimization in UMTS Mobile Networks

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***Abstract*—The power levels of cellular network User Equipment (UE) may vary considerably in both the receiver and the transmitter side, especially in indoor locations. With an indirect guidance method, the users are self-optimizing their UE to a better location with the help of an application. Thus, the user distribution is weighted more on high quality connection areas, which results in saving the UE batteries and reducing the overall radiation. This power reduction can also be understood as a capacity increase, especially in radio networks based on Code Division Multiple Access (CDMA), such as the Universal Mobile Telecommunications System (UMTS) technology.**

The aim of this paper is to show the possibility and the opportunity to save energy or to increase the capacity in cellular networks when the users are indirectly guided to optimize their UE locations. In this study, energy and capacity optimization is verified for residential indoor users in the measurements where the users are served by signals coming from several outdoor Base Stations (BSs) in a typical urban environment. The results obtained show that a path loss (PL) improvement of up to 10–25 dB can be achieved when the user locations are optimized and the signals are coming from the outdoor BSs.

Keywords—Indoor, user location, energy, optimization

I. Introduction

Currently, mobile network users expect a ubiquitous and very high quality service. However, since the users are frequently located indoors, one of the most difficult challenges is to offer good coverage and signal quality to these locations. Therefore, implementation of outdoor BSs and separate indoor systems (indoor BSs) is required in order to cover indoor areas. In both approaches, the typical target is to guarantee a predefined minimum signal power level for a user with a good signal quality and data throughput. The distribution of dense outdoor BSs or, in particular, indoor antenna distribution in indoor systems is required to achieve this minimum power requirement at the majority of the indoor locations. As a result, several very high-power signal level locations can also be achieved indoors.

Mobile networks are very densely deployed in urban areas, and BS sites still include several technologies from Global System for Mobile Communications (GSM) to UMTS and Long Term Evolution (LTE) due to the speech and data throughput requirements. This automatically yields to high-energy consumption due to the low efficiency of the transmitters (especially in CDMA) and to the needs of air conditioning requirements. Hence, high radio frequency radiation results naturally in the substantial amount of transmitters.

Despite this very dense multi-technology deployment, the distribution of the received power levels may still vary, especially in indoor locations within a small area of few meters depending on the BS and UE locations [1]. This is typical for a time and space variant indoor propagation channel, especially when the UE is served by one BS, and when the environment is active. The received power level deviations are neither measured nor reported in residential apartments nor even in the offices when the indoor coverage is served by several outdoor BSs in an urban area, and when the power levels of interest are clearly better than the coverage threshold.

Typically, radio network planning guidance targets to offer minimally acceptable received power levels everywhere, resulting in higher received power level than needed in several indoor locations [2]. Similar aspects can be noted when UEs are located in vehicles. Moreover, these high-quality planning guidelines are controversial, because it is expected that the UE locations are homogenously distributed and the users are not trying to – or do not need to – optimize their terminal location.

If it is assumed that the behavior of mobile users could be influenced in indoor or in-vehicle locations, the received power level could be significantly improved by moving the terminals just a little. These movements could be guided by some behavior rules, or by new approaches like Mobile Performance Gaming (MPG), which would continuously guide the user to locate his or hers terminal optimally and send statistics e.g. to an operator. The target of the guidance is not to limit the mobility, but instead to avoid bad locations, and guide users to better connections whenever easily possible.

In case of optimal or even partially optimally located indoor terminals, the required energy consumption, as well as the amount of radiated power, could decrease dramatically. Moreover, the changed user distribution would have impacts on channel modeling and to other research areas.

A practical measurement campaign is carried out in a typical residential apartment environment to show the impact of user behavior on the received power levels and the reductions in the required energy consumption. Measurements are carried out in an urban area in a commercial 3GPP networks including several serving BSs. A key target of the measurements is to show the deviation of the measured signal power levels above the minimum acceptable power level, that is values better than a certain threshold. This shows the opportunity to improve the mobile connection with small-scale terminal movements.

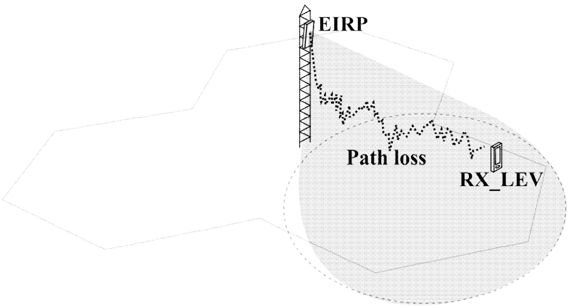

Fig. 1. Coverage of macro BS site: a PL between the BS and MS antennas.

II. THEORY

Mobile networks are deployed based on the Cellular Concept approach where recently 3-sectored macro BS sites are mostly built [3] at a certain distance by giving coverage over a certain geographical area as shown in Fig.1.

A. Transmission Power at BS

A BS antenna at each sector (Fig. 1) transmits effective isotropic radiated power (EIRP) to a radio propagation channel, and a mobile station (MS) antenna receives a power level RX_LEV at a reception location. When the EIRP and the RX_LEV are known, the PL between the BS and MS antennas can be theoretically calculated, or practically measured, for example, by using a constant transmission power such as the Pilot Signal (Common Pilot Channel, CPICH) in downlink direction in the UMTS system [4].

PL between BS and MS antennas (downlink) in UMTS indicates directly the required average transmission power $P_{\mathrm{TX}}^{\mathrm{DL}}$ to get a connection, that also includes interference, as defined in [5]:

$$P_{\mathrm{TX}}^{\mathrm{DL}} = \frac{N_{\mathrm{rf}} \cdot W \cdot \overline{L} \cdot \sum_{k=1}^{K} v_k \cdot \frac{\rho_k}{W / R_k}}{1 - \eta_{\mathrm{DL}}}, \tag{1}$$

where N_{rf} is the noise spectral density of the mobile receiver front end in watts per hertz or watt-seconds. Value for N_{rf} can be calculated as the sum of the thermal noise density N_0 in watt-seconds, and the dimensionless mobile receiver noise figure *NF*. The system chip rate *W* is in chips per second, $\overline{L}$ is the average dimensionless PL of the mobiles in a cell, and *K* is the number of all active mobiles in a cell. The dimensionless service activity of the *k*th user is v_k, ρ_k is the dimensionless E_b/N_0 requirement of the *k*th user, and R_k is the bitrate of the *k*th user in bits per second. The dimensionless downlink load factor is denoted by η_{DL}.

Especially in UMTS, the PL and thus also the required power per connection should be optimized because it has a direct link to the network capacity as indicated in the downlink load equation

$$\eta_{\mathrm{DL}} = \sum_{k=1}^{K} \frac{\rho_k \cdot R_k \cdot v_k}{W} \cdot \left((1 - \alpha_k) + i_{\mathrm{DL}} \right), \tag{2}$$

where α_k is the dimensionless orthogonality of the *k*th user, and i_{DL} is the average dimensionless other-to-own cell interference.

B. Radio Propagation in Outdoor and Indoor Locations

The variation in the received power level RX_LEV means directly variation in the required transmission level equivalent to the EIRP.

The received power level in indoor locations is time and space dependent [1] meaning that the received power level is changing when the receiver moves, or when the environment changes as people are moving, or closing and opening doors near the receiver. These deviations in the received power levels are caused by Rayleigh fading (fast fading), but also by slow fading (the average of fast fading is varying) because of the indoor walls. This special effect of the time and space variant indoor environment has to be taken into account when measurement results are analyzed.

When outdoor BSs are used to cover indoor locations, the propagation between a BS and MS antennas can be predicted by using, for example, a well-known Okumura-Hata (COST-Hata-Model) equation [6].

$$\begin{aligned} L = {} & A + B \cdot \log_{10}(f_{\mathrm{MHz}}) - 13.82 \cdot \log_{10}(h_{\mathrm{BS}}) - a(h_{\mathrm{MS}}) \\ & + (C - 6.55 \cdot \log_{10}(h_{\mathrm{BS}})) \cdot \log_{10}(d_{\mathrm{km}}) + C_{\mathrm{m}}, \end{aligned} \tag{3}$$

where L is the PL in dB,

A, B and C are varying constants,

f_{MHz} is the used frequency in MHz,

h_{BS} is the BS effective antenna height in m,

h_{MS} is the MS antenna height in m,

$a(h_{\mathrm{MS}})$ is a city size dependent function,

d_{km} is the distance between BS and MS in km, and C_{m} is an area correction factor.

In (3), it has to be remembered that the equation needs to be tuned for every environment separately to get accurate results. The area correction factor, C_{m}, has to be set regarding the propagation environment. Correspondingly, the propagation slope, defined as $(C - 6.55 \cdot \log_{10}(h_{\mathrm{BS}}))$, has to be adjusted regarding the BS antenna height.

The Okumura-Hata equation gives predictions of the received power level at outdoor locations, and thus indoor penetration loss of 10–30 dB has to be added depending on the building materials and types [7] to have prediction results in indoor locations. Moreover, the coverage planning of outdoor BSs is typically based on Okumura-Hata type of predictions, which means that BS coverage needs to overlap enough with neighbor BSs to have a continuous coverage and service in indoor locations (Fig. 2).

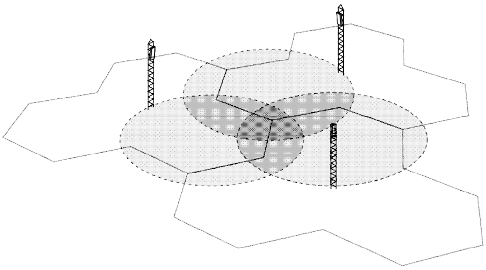

Fig. 2. Coverage overlapping of multiple BSs.

C. Multiple Coverage in Cellular Mobile Networks

In mobile cellular networks, the received power level may vary also because the signal power is coming from several BS sites, or cells as indicated in Fig. 2. Depending on the exact terminal location, one carrier may be superior compared to the others. One carrier is offering better received power at one location, and other carrier in the next location because of the slow fading, and because of the different materials like glass windows or concrete through a propagation path between the BS and MS antennas.

In coverage overlapping areas of multiple serving BSs, the typical radio planning target of location or service probability of 90–99% should be well achieved. Moreover, if the coverage planning criteria is expecting to get 90–99% connection probability from one BS, and simultaneously several BSs are covering the same location as typically in a densely deployed urban areas, the received power level may have much higher values [3].

III. Measurement Campaign

A. Measurement Environment

A practical measurement campaign was carried out at one main location in a normal urban residential apartment in downtown Helsinki, Finland. Thus, indoor locations of typical residential users were measured in a high density BS coverage and capacity area. The measurement location as well as the measurement timing was selected randomly. Two different carriers (Network 1, Network 2) were measured.

All measurements represent results in configuration where signals propagate to indoor locations from the implemented outdoor BSs. Network 1 and Network 2 have different network configurations.

Normal commercial non-calibrated mobile terminal was used in all measurements, and thus absolute values are not highlighted but relative received power levels are the most interesting ones. The data was collected with a help of an application that utilizes MPG, which sends the measured data to a server, where it can be accessed.

B. Measurement Scenarios

Four different measurement Scenarios were repeated for Network 1, and only Scenario 1 for Network 2 (Fig. 3 represents the blueprints of the measurement apartment and the measurement areas):

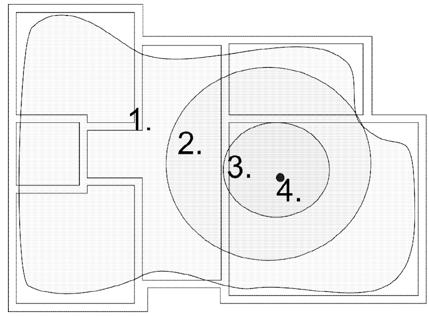

Fig. 3. Measurement Scenarios 1–4 in the apartment.

1. Mobile terminal on different tables around common areas in the apartment.
2. Mobile terminal at a certain small area of 3–6 m maximum difference in location. This subarea was selected based on the measurement Scenario 1.
3. Mobile terminal at a very small area of 1–2 m maximum difference in location (different parts of a table); this measurement is carried in the subarea of measurement Scenario 2.
4. Mobile terminal is constantly at one location on the table inside the area of measurement Scenario 3.

All measurements were carried such that the mobile terminal is on a table approximately 50–120 cm from the floor, and in all measurements the mobile is not having a body contact but measurement person is able to walk or stay in the surroundings of the mobile i.e. sitting, standing, or walking approximately 3–5 meters around the mobile. The measurement Scenario 4 is especially showing variations of the received power level due to these environmental changes.

All measurements were carried in the apartment on the first floor from the street level.

Measurements are carried in two commercial 3GPP networks (Network 1, Network 2) i.e. the mobile terminal is measuring received power level from all technologies: GSM, UMTS, and LTE. Measurements are done in IDLE mode i.e. the mobile terminal is not connected to the network, and thus measurement happens in the downlink direction where a BS transmits and the mobile terminal receives the signal power. In GSM, the Broadcast Control Channel (BCCH) is measured because it has a constant transmission power in downlink direction as well as the Common Pilot Channel (CPICH) has in UMTS technology. In LTE, a reference signal was measured to have a similar effect of the constant transmission power.

Typically, in 3GPP technologies, 32 neighbor BSs (or cells) can be measured, but only six bests are reported by a mobile terminal [8].

In IDLE mode, mobile terminal measures continuously, and reported samples are averages over certain seconds. Averages were recorded every 10 s meaning 6 averaged samples per minute, and 60 averaged samples in 10 minutes.

In IDLE mode in 3GPP, a mobile terminal is selecting the technology based on radio parameters. One technology can have priority given by parameter settings. This means that mobile terminal is staying in the priority technology as long as the coverage ends, or the coverage is very bad even if other technology offers better power level.

In measurements, it was noted that UMTS technology was highlighted i.e. mobile terminal tried to stay in UMTS network as long as possible due to much better data communication compared to GSM technology. At the same time, LTE coverage was still limited, and thus results of LTE technology are not significant. Thus, the highest priority and reliability of measurements and results is in UMTS technology.

IV. MEASUREMENT RESULTS AND ENERGY SAVING

In a typical radio network planning, location or service probability of 90% is calculated for a certain coverage threshold. Fig. 4 shows a cumulative curve of the received power samples in Scenario 1 (Network 1). Fig. 4 shows that 90% coverage threshold corresponds to the received power level of –125 dBm. This coverage level does not correspond to a reasonable speech quality in UMTS technology and approximately corresponds to a maximum throughput level of 0.3–1 Mbit/s when Dual Carrier technology is implemented in HSPA, and when only one user is served by one BS.

Fig. 5 shows the obtained results of the measurement Scenario 1. In Fig. 5 it can be seen that the received power levels vary 25–30 dB for both networks in different parts of the apartment even if 3–7 BS cells are offering indoor coverage at different locations inside of the apartment. It has to be highlighted, that every sample in the results represents the best received power level at each terminal location inside the apartment. Moreover, the terminal had enough time at each measurement point to change to the best serving BS cell. The mean values (μ) of the received power levels for the Networks 1 and 2 were μ_1 = –108.5 dBm and μ_2 = –114 dBm with standard deviations (σ) of σ_1 = 8.46 dB and σ_2 = 6.39 dB, respectively.

A specific small area of Network 1 was selected (Scenario 2) because the received power level was changing rapidly in this certain area. Fig. 6 shows 15 dB variation in the received power level even if the terminal was moved only 3–6 meters between the measurement points. The mean signal level was μ_3 = –104 dBm with standard deviation of σ_3 = 5.54 dB. Moreover, in Fig. 7, the obtained results show power variations when the mobile terminal has different locations at one 2 m x 1.5 m size house table (Scenario 3).

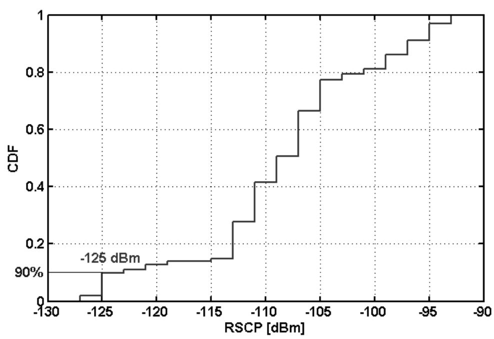

Fig. 4. Scenario 1, Network 1: the coverage threshold for 90% location probability.

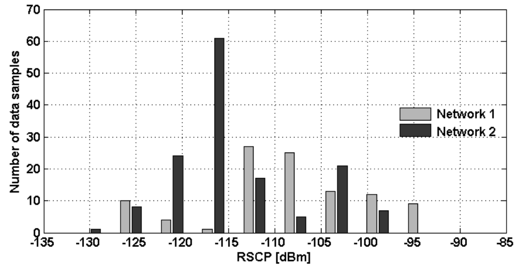

Fig. 5. Scenario 1: the received power levels of two different networks.

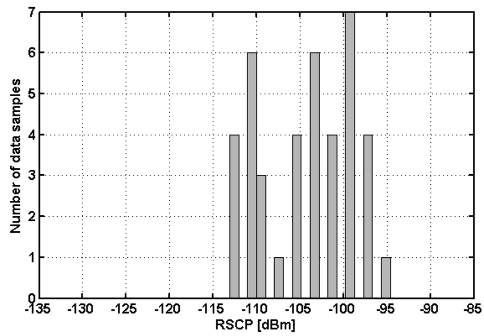

Fig. 6. Scenario 2 (Network 1): the smaller measurement area inside the measurement area in Scenario 1.

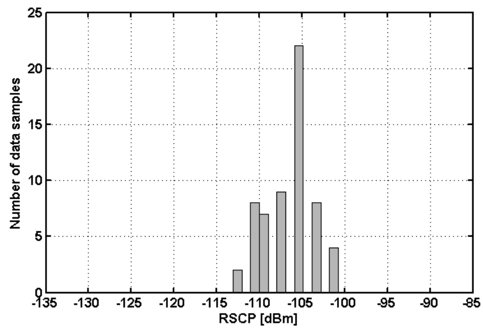

Fig. 7. Scenario 3 (Network 1): the very small measurement area inside the measurement area in Scenario 2.

Despite of only small movements, power level variations of around 10 dB can still be noted, while having μ_4 = –106 dBm and σ_4 = 3 dB.

Finally, the results of measurement Scenario 4 in Fig. 8 show the received power level variations of environmental changes that happen when the mobile terminal is at one constant measurement location (one measurement point of Scenario 3). It can be noted that the received power level vary 6–10 dB when the measurement engineer is in the surroundings of the terminal. This corresponds to a case where the user is at home and reasonably close to the mobile. The mean power level and the corresponding variance of the stationary mobile is μ_5 = –111 dBm and σ_5 = 3 dB.

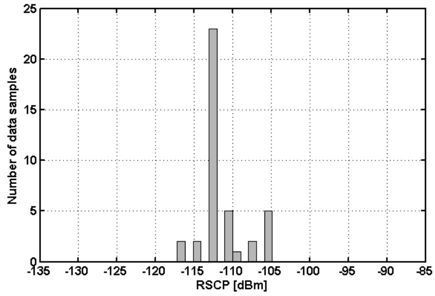

Fig. 8. Scenario 4 (Network 1): only one measurement point inside of the measurement area in Scenario 3.

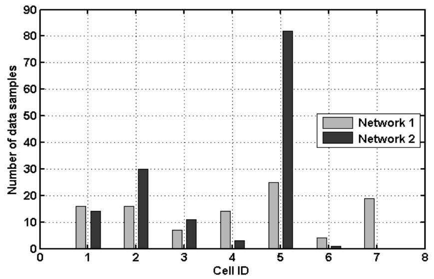

Fig. 9. Amount of samples from different BSs in Scenario 1.

The results presented in Fig. 5–8 include measurement samples from 3–7 BSs from Network 1 and Network 2, because the apartment is covered by several BSs as typically happens in an urban area where BSs are implemented densely to have enough capacity and indoor coverage. Fig. 9 shows the deviation of the samples between different BSs in Scenario 1.

As a conclusion of Fig. 5–8, it can be noted that the received power level may be improved easily 10 dB and even up to 20–25 dB in downlink direction when the mobile terminal location is optimized in small-scale movements in a residential apartment. These improvement levels already exclude variation of environment that was 6–10 dB. Moreover, improvement of 10–25 dB at the reception can be used to reduce the transmission power levels to keep constant quality, and simultaneously to increase capacity, to reduce radiation, and to reduce battery consumption of mobile terminals. Finally, similar energy savings happen also in the uplink channel, because propagation channel is reciprocal, and thus the reception level can be improved also at the BS receiving end.

Improvement of the reception power level means also improvement of PL, and capacity increase can be estimated by using equation (2).

An example calculation using equation (2) with 33 speech users (R_v = 12.2 kbit/s and E_b/N_0 = 6.0 dB), and typical values v_k = 0.5, α_k = 0.7 and i = 0.5 results in load η_{DL} = 16.7%. Using this load value in (1) with receiver noise figure of 7 dB and average PL of 150 dB (Scenario 1: RX_LEV = –117dBm, CPICH_TX_Power = 33 dBm), the required transmission power is 42.90 dBm (= app. 20W).

When 20 dB PL improvement is considered (RX_LEV = –97 dBm) in (1), the amount of speech users can be increased up to 150 users (354% increase) still using only power of 34.86 dBm (< 4W) but causing load η_{DL} = 75.9%.

V. Conclusions and Discussion

In this paper, it was first introduced the possibility to guide users to optimize their terminal locations based on the connection quality. Moreover, this optimization directly reduces radio energy consumption at the BSs and MSs, and thus reduces costs, increases capacity, saves mobile batteries, and reduces unnecessary radiation. The user behavior at residential indoor locations was highlighted, and the practical measurement campaign in UMTS network was done to show the impact of energy reduction in indoor locations.

The obtained results show that the reception level of each location optimized mobile terminal can be increased 10–25 dB when short-term environmental changes of 6–10 dB due to moving persons in apartments are excluded. These kinds of reception improvements can cause high capacity increase in mobile networks, thus yielding to excessive capacity optimization and cost savings in the infrastructure. The results can also show a way to new possibilities in radio link budget by presenting a new variable called *UE location optimization gain* to account for possible improvements coming from optimized UE locations.

Similar results about PL improvements can be found also in other technologies, like in GSM and LTE. In addition, it can be noted that PL improvements might help significantly in disaster scenarios where only part of the BSs are operating, for example, due to lack of electricity.

Acknowledgements

Authors would like to thank the Finnish Funding Agency for Innovation, European Communications Engineering Ltd and Greatest Heroes Ltd for funding and supporting the research work.

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Publication 6

J. Säe, S. F. Yunas, and J. Lempiäinen, "Coverage aspects of temporary LAP network," in *Proceedings of the 12th Annual Conference on Wireless On-demand Network Systems and Services (WONS)*, Cortina d'Ampezzo, Italy, 20.–22. Jan. 2016.

Coverage Aspects of Temporary LAP Network

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***Abstract*—This paper studies the coverage aspects of a low altitude platform (LAP) system that can form a temporary communication network. The system consists of multiple autonomous drones equipped with dual-band Wi-Fi access points (APs) with ad hoc capabilities to form a mesh network. The suitability of the LAP system is evaluated from the coverage point of view with calculations and simulations. The results show that more drones are needed to cover (dense) urban than rural environment and the drone altitude should also be higher in urban areas compared with the rural areas.**

***Index Terms*—low-altitude platform, drone, UAV, Wi-Fi, mesh network, Ad Hoc, disaster scenarios, temporary network, emergency coverage.**

I. INTRODUCTION

Cellular networks should maintain their operational status even after (mild) disaster scenarios, however, a major problem arises when a key part of the network infrastructure is destroyed or unavailable. One such problem can be a damaged power grid or broken power lines (e.g. because of fallen trees) which supply electricity to the base station (BS) sites. The lack of electricity from the network is not a problem at first, since nowadays many operators around the world have equipped their BS sites with backup power. However, this just extends the operational time of the mobile network for a couple of hours after the electricity blackout.

Repair and emergency teams move to disaster (or blackout) areas usually as fast as possible. When they arrive at these areas, in the best case scenario, the mobile network might still be operational for a while with backup power. However, in the worst case, the cellular network might not be operational or the infrastructure might be damaged to the point that it can not function.

The emergency teams have usually their own way of communicating, e.g. through terrestrial trunked radio (TETRA) system, which is commonly used in public safety networks. However, cellular and electricity network repair teams have no possibility to use these systems. Thus, they have to rely on the existing network and pre-planned processes on how to start the repair actions. As a result, this means that there is no way to communicate between these repair teams and a lot of time is spent on moving around in the disaster-hit area in order to contact other teams for prioritizing important or critical areas.

In order to enable the use of conventional user equipment (UEs), like smart phones with Wi-Fi, a new temporary mobile network could be easily formed. There has been a lot of research around high altitude platform (HAP) systems for providing emergency coverage and recently Google's project Loon has brought this subject back on the hot topics of future networks with their HAP balloons [1]. To compete with Google's project Loon, Facebook has also invested in HAP systems with their own high-altitude long-endurance planes combined with their Internet.org project [2].

This paper studies the coverage possibilities of a temporary low altitude platform (LAP) network with the use of drones, or more generally known as unmanned aerial devices (UAVs). The idea of a temporary LAP network is based on a simple design principle: *a quick and easily deployable communication infrastructure for emergency coverage in disaster-hit areas with relatively low costs and fairly simple maintenance*.

In this study, it has been assumed that the temporary LAP network can be deployed such that the operation of LAP drones is semi-automatic. This means that field teams in the disaster areas only need to launch a drone, after which the drone will automatically take off to a predefined altitude from its take off location and form a mesh network with other drones.

The aim of this paper is to study the coverage aspects of temporary LAP systems as an emergency network for disaster areas, mainly intended for repair teams and as a backup network for rescue teams. Simulations are performed to dimension the coverage capabilities of different configurations, including the inter-drone distances (IDDs) and the operation altitude of the drones. The study also investigates the coverage aspects in two different environments: flat rural environment and (dense) urban environment with the Manhattan grid, i.e. with a dense building layer.

II. RELATED WORK

The suitability of a disaster network has been studied from many perspectives in the literature. The authors in [3] have presented the idea of providing emergency broadband coverage with the utilization of LAPs. Their idea is based on utilizing balloons as the platforms for LAPs, like with the majority of other authors in the field, and Wi-Fi for the transmission. A similar idea is refined in [4], where TETRA and worldwide interoperability for microwave access (WiMAX) systems were also tested as the candidates for a temporary wireless network. The authors in [5] have expanded the idea and considered the use of drones with Wi-Fi to form resilient networks in order to communicate to isolated disaster areas. However, their implementation involves a moving drone in very low altitudes and needs to be in the close proximity of any client to collect data.

In this study, the drone altitudes of few hundred meters are considered together with mesh networking as a base for the LAP concept. It has the similar kind of idea as presented in [6], [7]: the use of unmanned aerial vehicles to form a temporal network for a disaster response. However, in [6] the authors are focusing on the localization, navigation and coordination of these devices and not the possible size of the service coverage areas, which could be possible with UAVs. In [7] some service area related aspects are taken into account, however, the authors have simulated an area of 100 m × 100 m with 50 nodes, and a fixed transmission radius of 20 m. Obviously, this kind of dense drone network would not be realistic in a rural area because the number of drones to deploy would be huge.

The authors in [8] explain the concept of flying ad hoc networks (FANETs), which is the ideology utilized in this study. The authors in [9] have also implemented an experimental study utilizing this concept. Although, they have performed the study with only two drones, they manage to establish communication for a distance of 1000 m in between the drones. The altitude of the drones in [9] is set to 10 m, so the coverage area of one drone is quite limited.

III. LAP CONCEPT

A. Propagation modeling for simulations

In order to simulate wireless communication systems, a proper radio wave propagation model is required. The basic free space path loss model would suit well with the scenarios, where mostly line-of-sight (LOS) connections are simulated. The initial IDD was calculated with the logarithmic free space model [10]. However, in order to achieve more realistic results, a deterministic propagation model was chosen for the actual simulations.

The outdoor radio channels are modeled using a deterministic radio propagation model called the dominant path prediction model (DPM) [11]. The DPM model makes the path loss prediction based on the premise that in most propagation scenarios, there are only one or two paths that contribute 90 % of the total received signal energy, hence the model determines the dominant path(s) between a transmitter and receiver for the received power estimation. As such, the accuracy of the DPM model has been reported to have accuracy similar to (and in some cases better than) the ray tracing models, while the computation time is comparable to that of empirical models (e.g. COST-231 Hata model and Walfisch-Ikegami model) [11].

The computation of the path loss in DPM is based on the following equation [11]:

$$L = 20\log_{10}\left(\frac{4\pi}{\lambda}\right) + 10n\log_{10}(d) + \sum_{i=0}^{k} f(\varphi, i) + \Omega + g_{\mathrm{t}} \quad (1)$$

where d is the distance between a transmitter and receiver, n is the path loss exponent, and λ is the wave length. The sum of individual interaction losses function, $\sum_{i=0}^{k} f(\varphi, i)$, is due to diffraction for each interaction i of all k with φ as the angle between the former direction and the new direction of propagation. The wave-guiding (tunneling) effect, Ω, considers the effects of reflections (and scattering). It is empirically determined and described in detail in [11]. Finally, g_{t} is the gain of the transmitting antenna in the receiver's direction.

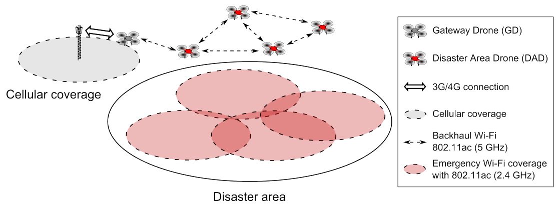


Fig. 1: An example of the temporary LAP network concept.

The recommended value for the path loss exponent, n, depends on the propagation environment (rural, suburban, urban, indoor) and the height of the transmitter. The authors in [12] have performed field tests with 2.4 GHz Wi-Fi and compared the path loss exponent with the existing ones for several propagation models. They found that the values for n in LOS range from 2.54 to 2.76. Thus, in this paper the value was chosen to be 2.6.

B. Temporary LAP network concept

The LAP concept considered in this study is shown in Fig. 1. It consists of utilizing dual band Wi-Fi equipped drones that will form an ad hoc network with IEEE 802.11 family wireless local area network (WLAN) technology utilizing 5 GHz frequency band with 40 MHz bandwidth as the backhaul connection between the disaster area drones (DADs). The actual emergency coverage is then formed with access points (APs) utilizing 2.4 GHz frequency band with 20 MHz bandwidth. In order to connect the emergency network to the Internet, some drones have to be equipped e.g. with a third generation (3G) or fourth generation (4G) cellular network modems. These drones, called the gateway drones (GDs), have to be placed in between the disaster areas and the unaffected operational cellular network area next to it.

IV. SERVICE AREA SIMULATIONS

The coverage aspects of the LAP concept were studied with the help of simulations. Different deployment cases were implemented with the help of simulation software called WinProp Software Suite with its ProMan tool for simulating wave propagation and radio network planning. The simulation results were then visualized with Matlab software.

A. Simulation setup

The rural environment simulations were implemented on a 6 km × 6 km flat terrain. The calculation resolution was set at 20 m and all other general parameters are presented in Table I.

The maximum inter-drone distances, where the communication should still be possible, were calculated with free space

TABLE I: Simulation environment parameters.

Parameter	*Value*
Simulation area	6 km × 6 km
Path loss model	Dominant path model
LOS Path loss exponent	2 (free space), 2.6 (after break point)
OLOS Path loss exponent	3.5
Calculation resolution	20 m (rural), 10 m (urban)
Calculation environment	Flat (rural) / Manhattan (urban)
Building dimensions (urban)	100 m × 100 m
Building height (urban)	25 m
Street width (urban)	20 m
Inter-drone distance	960 m (rural) 960 m, 480 m (urban)
Receiver (UE) antenna height	1.5 m

TABLE II: Drone parameters.

Parameter	*Disaster Area Drone*
Standard	802.11ac/n/g/b/a
Wi-Fi frequency band	2.4 GHz / 5.8 GHz
Bandwidth	20 MHz / 40 MHz
max. EIRP (backhaul)	35 dBm
max. EIRP (emergency coverage)	20 dBm (ETSI) / 36 dBm (FCC)
Antenna heights (Drone altitudes)	50 m, 100 m, 150 m, 200 m, 250 m, 300 m 350 m, 400 m, 450 m, 500 m,
Antenna HPBW (backhaul)	360° × 45° (azimuth & zenith)
Antenna HPBW (emergency)	60° × 60° (azimuth & zenith)
Antenna model (backhaul)	HVG-2458-05U [13]
Antenna model (emergency)	NanoStation locoM2 [14]
Antenna tilting (backhaul)	-
Antenna tilting (emergency)	90° (Facing downwards)
Antenna gain (backhaul)	5 dBi
Antenna gain (emergency)	8.5 dBi

loss model [10]. Based on the calculations, in the simulations the DADs were placed 960 m apart from each other to hover in the following altitudes: from 50 m to 500 m. The path loss exponent was assumed to match free space before the break point distance and after it the exponent was set to 2.6 according to Table I to match the values in [12] for LOS connections. For non line-of-sight (NLOS) regions, the obstacle line-of-sight (OLOS) path loss exponent was utilized and set to 3.5 to match the path loss exponent value for (dense) urban environment.

The key drone parameters for the simulations are presented in Table II. In Europe, the effective isotropic radiated power (EIRP) of Wi-Fi is limited to 20 dBm for 2.4 GHz frequency band and 36 dBm for 5.8 GHz frequency band by European Telecommunications Standards Institute (ETSI). The corresponding values set by Federal Communications Commission (FCC) in the United States are 36 dBm for 2.4 GHz frequency band and 35 dBm for 5.8 GHz frequency band. In this study, 5 GHz frequency band EIRP is 35 dBm when a 5 dBi omnidirectional antenna is utilized. 2.4 GHz Wi-Fi EIRP was set to 20 dBm (ETSI) and 36 dBm (FCC) when a 60° × 60° (azimuth & zenith) half-power beamwidth (HPBW) antenna was utilized. This antenna was faced downwards (tilted 90°) and mounted below the drone in order to form a *spotlight* or *data-shower* coverage on the terrain below.

In order to have some urban environment comparison, the next simulation rounds were set up also with 6 km × 6 km area and the IDD was kept the same at first (960 m) to be in line with the values used in [15]. Next, the IDD was reduced to 480 m to study the effect of densification of these drones. These urban simulations had the Manhattan grid to see the effect of dense urban environment and the calculation resolution was set at 10 m. Table I shows the parameters for the Manhattan grid (the dimensions of the buildings and the width of the streets).

The simulation of gateway drones was not included with the simulation of the mesh network, since the implementation of a 3G or 4G cellular network modem to the system was not possible. However, this was not relevant from the coverage point of view, and in this study it has been assumed that the GD has enough capacity to the existing cellular network that it would not be a bottleneck for the functionality of the mesh network. The mesh network capabilities were only considered in the idea level, so practical equipment related to them were not studied.

B. Results

The emergency coverage area of one DAD is larger with higher altitude as expected. However, the difference in the actual coverage areas between the different altitudes is not large. The lowest coverage is achieved with the lowest drone altitude of 50 m resulting in a service area (−80 dBm) of 0.14 km^2 (ETSI) and 3.51 km^2 (FCC). Correspondingly, the highest emergency coverage was simulated to be 0.56 km^2 (ETSI) and 7.4 km^2 (FCC) with a drone altitude of 500 m. The results for different drone coverage areas with respect to the altitude are shown in Fig. 2.

Fig. 3 shows results for the urban environment with the Manhattan grid. It shows the total (outdoor) area coverage percentage (the area where the minimum received signal power level is greater than or equal to −80 dBm with respect to the simulation area of 36 km^2) as a function of drone altitude for different configurations. Fig. 3a shows the results for the ETSI regulations and Fig. 3b for the FCC regulations. The coverage increases when the number of drones and the drone altitude increases, as expected. However, longer IDD with a lower number of drones is able to provide as good or better coverage than shorter IDD with a higher number of drones. It should also be noted that the coverage of the outdoor urban environment depends strongly on the dimensions of the buildings and the orientations of the streets with respect to the locations of the drones.

V. Conclusions and Future Work

The coverage study performed in this paper for the LAP concept shows that the emergency coverage for a disaster area would be possible to implement with a reasonable number of drones. The LAP concept can utilize the existing cellular infrastructure that is still functional next to disaster areas, thus

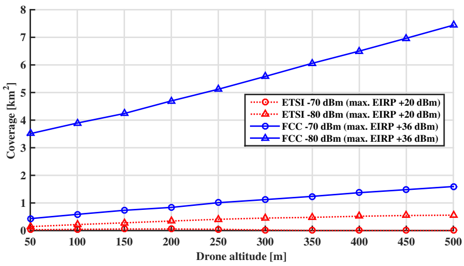
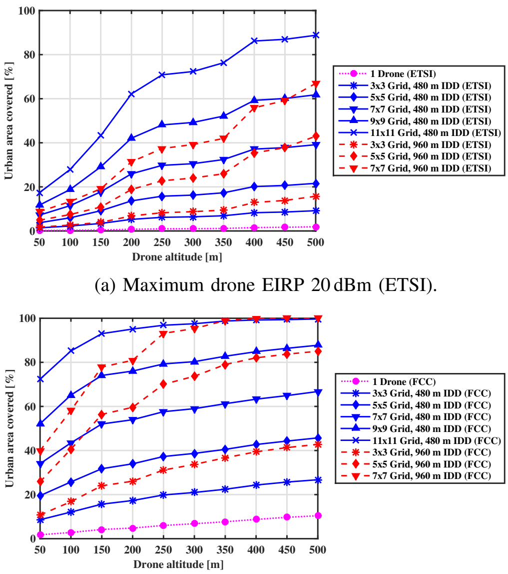


Fig. 2: Emergency coverage area of *one drone* as a function of drone altitude in rural area.



(a) Maximum drone EIRP 20 dBm (ETSI).

(b) Maximum drone EIRP 36 dBm (FCC).

Fig. 3: Dense urban environment outdoor coverage for the Manhattan Grid. Coverage limited to −80 dBm.

enabling cost-efficient solution to provide Internet connection to the disturbance area.

It should be noted that the altitude of the drones does not provide much gain for coverage, i.e. the coverage area for higher drone hovering altitudes is not significantly larger in rural environment. As a result, the drone hovering altitudes should be kept rather low. Therefore, the biggest limiting factor for larger coverage areas is IDD, but in order to extend it, some highly directive antennas would be needed.

The flight and hover time of the drones will not be a problem, since nowadays there exist drones [16] that can stay in the air with a microfilament system providing energy from the ground-level up to 150 m for as long as needed. Thus, the results are implementable at least to 150 m altitude. However, results for the higher altitudes provide insight on how much coverage could be possible to achieve without height restrictions.

The results of this paper relied on simulation scenarios and their accuracy might not correspond entirely with real life implementations although the utilized models are rather accurate. Thus, the future work on this topic will concentrate on more complex scenarios. The focus will also be on the capacity aspects, and eventually the target is to implement the proposed system.

Acknowledgment

The authors would like to thank the Finnish funding agency for innovation (Tekes) for funding the research work.

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Publication 7

D. Paudel, J. Säe, and J. Lempiäinen, "Applicability of macro sensor network in disaster scenarios," in *Proceedings of the 4th International Conference on Wireless Communications, Vehicular Technology, Information Theory and Aerospace & Electronic Systems (VITAE)*, Aalborg, Denmark, 11.–14. May 2014. DOI: 10.1109/VITAE.2014.6934480

Applicability of Macro Sensor Network in Disaster Scenarios

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***Abstract*—The efficient use of communication technologies during disaster scenarios is vital for the relief and rescue works as well as for the disaster affected people. During the disaster scenarios, links between the Radio Access Network (RAN) and the Core Network (CN) might be broken. If the link between such affected nodes can be re-established via node-to-node communication, the data from the users can be transported to the network. Thus, this utilization of node-to-node communication can be a key technological achievement for cellular networks during such scenarios. The aim of this paper is to present the possible realization of a macro site node-to-node sensor network functionality for cellular networks during disaster scenarios. The merits of 3GPP LTE technology have been utilized in this paper to present a framework for this node-to-node communication in 3GPP LTE technology.**

***Keywords*—disaster scenarios, LTE, node-to-node communication, WSN.**

I. Introduction

Communication has played a vital role during different disaster scenarios from its early development to the present day. Communication techniques have been used for providing early information about the disaster and during the emergency rescue and relief operation for disaster affected people. Thus, during crisis events, communication is critical for disaster management. The use of wireless communication for the disaster management backs to events surrounding the sinking of "Titanic" in the night of April 13–14, 1912. The radio communication system was vital communicating with nearby ships because of which they changed their course for rescue of the passengers onboard in the "Titanic" [1]. Moreover, the Tsunami of 2004 at Indian Ocean was an alert for the world on the need for efficient communication system during an emergency for disaster management. Public Land Mobile Network (PLMN) can be an effective communication technology in the disaster scenarios to transfer the data from the sensors, establish communication between relief teams or with the victims. The Tampere Convention, organized by joint effort of UN and ITU in 1998 in Tampere, Finland, facilitates the use of telecommunication for humanitarian aid, removing regulatory barriers and in the use of frequencies [2].

When disaster strikes, various communication links might be interrupted and the communication network becomes non-functional. Various research works have been done to provide a prompt communication service to the relief works and people in disaster affected areas. Reference [3] presents the Wireless Sensor Network (WSN) for the disaster management and [4] shows the use of Ad hoc Networks for the rescue operation and disaster survivor detection. High Altitude Platform (HAP) system has been proposed in [5] for replacing UMTS coverage in disaster scenarios. However, HAP faces the challenge of stationary allotment of its stations due to wind and the supply of the energy. HAP system is expensive as well. The combination of cellular mobile network and the ad hoc networks leading to the Multi-hop Cellular Network (MCN) is proposed in [6] which combine the benefits of fixed infrastructure of cellular mobile networks and the flexibility of ad hoc networks. However, MCN does not scale well and it is difficult to provide uninterrupted high bandwidth connectivity to a large number of users with these networks [6].

In this paper, it has been focused on a disaster scenario, where the link between the RAN and CN is broken and thus transmission between network elements is affected. For LTE network this is the link between eNodeB and the Evolved Packet Core (EPC). The possible solution proposed in this paper is the realization of surrounded eNodeBs sites as WSN nodes to establish the relay network for transmission purpose between the affected nodes. The nodes should sense the disaster scenario and switch to sensor mode. The communication between these nodes is at the macro level and thus is termed as macro sensor network. This functionality can be realized as a "Safety Mode" and the communication blackout can be eliminated and transmission network can be re-established. The established link can provide limited services such as SMS, speech or limited data services. Thus, by utilizing the pre-existing infrastructure of 3GPP technology, an effective communication can be achieved during disaster scenarios.

II. Theory

For the efficient node-to-node communication, the occurrence of interference from other sources should be analyzed. This section introduces the theory behind the node-to-node communication. It is assumed that the eNodeB antennas are organized into three sector sites and the network layout is clover-leaf.

A. Frequency Reuse Pattern

Reference [7] shows the frequency reuse scheme where the available frequency band is divided into several sub-bands. A set of frequencies are allocated for cell edge users in a cell with full downlink transmission power. Users in the inner cell are served with reduced power. The frequency reuse pattern for the node-to-node communication is realized such that the reused pattern proposed for the cell edge users in [7] is used for the communication between the antennas as shown in Fig. 1.

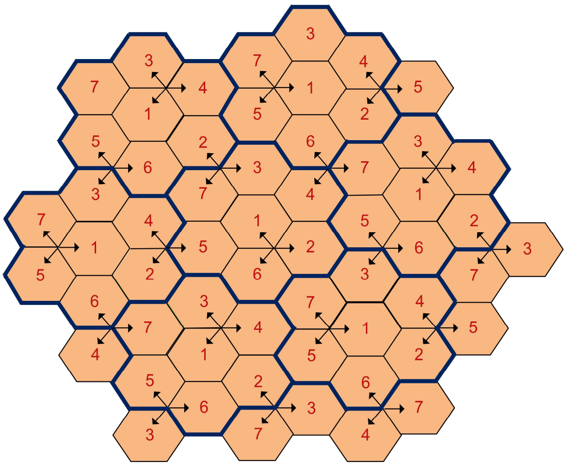

Fig. 1. Frequency Reuse Pattern.

The reuse pattern in Fig. 1 can now be used for the node-to-node communication during the disaster scenarios. The thick color boundary line shows the size of a single cluster. The reused cells are organized such that the interference from the cells with same frequency is minimized.

B. Inter-cell Interference

The effective use of resources in a cellular system can highly enhance the capacity of the system. In a cellular network employing frequency reuse across different cells, inter-cell interference occurs when neighboring cells use the same frequency band for communication. Reference [8] and [9] show a general approach of frequency reuse for inter-cell interference reduction. As shown in Fig. 2, transmitter T1 transmits a signal to its desired receiver R1. At the same time transmitter T2 also transmits a signal. Then, R1 receive a signal from T1 as well as from T2. At the receiver R1, the signals from T1 and T2 are superimposed and the signal from T2 is interference for R1. Moreover, higher interference leads to low Signal to Interference and Noise Ratio (SINR) value which finally implies low quality of the wanted signal.

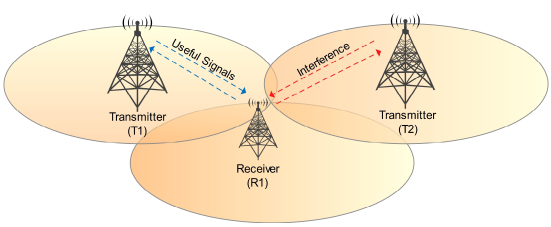

Fig. 2. Radio Communication System.

In order to calculate the inter-cell interference, the following equations are needed. First, the SINR is defined as

$$SINR = \frac{P_{\mathrm{r}}}{P_{\mathrm{inter-cell}} + P_{\mathrm{intra-cell}} + P_{\mathrm{n}}}, \quad (1)$$

where P_{r} is the received power, $P_{\mathrm{inter\text{-}cell}}$ is the other-cell interference power, $P_{\mathrm{intra\text{-}cell}}$ is the inner-cell interference power and P_{n} is the noise power.

The signal power S of the desired transmitted signal received by the receiver can be calculated as

$$S = P_{\mathrm{td}} + G_{\mathrm{td}} + G_{\mathrm{r}} - PL, \quad (2)$$

where P_{td} is the transmitted power, G_{td} is the antenna gain of the transmitted station, G_{r} is the antenna gain of the desired receiver station and PL is the path loss. The interference power of the neighbor co-channels received at the same receiver can be calculated as

$$I = P_{\mathrm{ti}} + G_{\mathrm{ti}} + G_{\mathrm{rd}} - PL. \quad (3)$$

Here P_{ti} is the transmit power from interfering station, G_{ti} is the antenna gain of interfering transmit station, G_{rd} is the antenna gain of the desired receiver station measured at the angle of arrival of the interfering station.

C. Path loss

The proposed node-to-node communication is at the macro site layer, i.e. the base station antennas are at towers, and thus the assumption is that the antennas have Line-of-Sight (LOS) visibility between each other and the Fresnel zone is free. Hence, free space path loss model can be utilized to predict the signal strength at the receiver. The equation can be expressed as

$$PL(\mathrm{dB}) = 32.45 + 20 \cdot \log_{10}(D) + 20 \cdot \log_{10}(f), \quad (4)$$

where D is the distance in km and f is the frequency in MHz. Free space path loss model predicts that the received power declines as a function of the distance between the transmitter and the receiver.

D. Wireless sensor network

The role of WSN can be vital for the disaster management during the disaster scenarios. WSN can be used for object tracking, monitoring and transmitting environmental information and for object detection as well. The sensor node sends its data to the sink or the fusion center, which is responsible for processing and extracting the sensor data. This delivery of data from the node to the sink may follow multiple-hops. In this paper, the functionality of sensing and the multi-hop routing approach of WSN are used to deliver the data to the desired destination, which can be from an eNodeB to the EPC, or vice versa. Moreover, the sensor network which is ad hoc in nature has the capability of minimum dependence on network planning and the capability of nodes to self-organize and self-configure without the involvement of the central controller. Hence, an operational ad hoc network should cope with the dynamic restructuring of the link. Thus, in ad hoc network, two different nodes can communicate with each other via other intermediate nodes.

The topology management is a key issue in WSN. Reference [10] states the topology management procedure including the topology discovery algorithms. In this paper, the WSN that is formed during disaster scenarios consists of a various number of sensor nodes communicating over the wireless links using a fixed network infrastructure. Thus, the routing protocol for WSN has to ensure a reliable multi-hop communication. References [11–13] describe various routing protocols which can be used in WSN, but this study is not limited to a specific routing protocol.

III. Example Scenarios

The example scenarios are based on the frequency reuse scheme designed for the node-to-node communication during disaster scenarios in rural areas but are not limited to them. The results were calculated for the 800 MHz bandwidth.

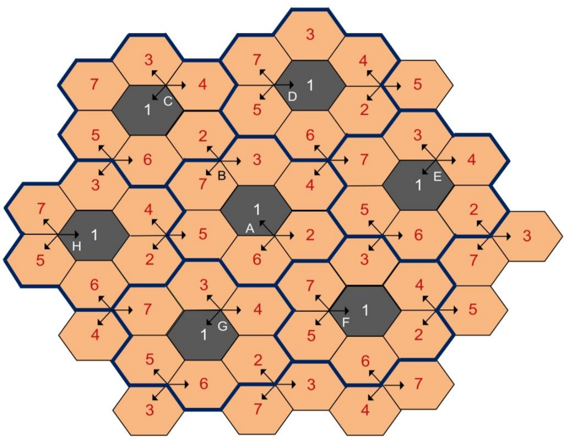

Fig. 3. Frequency reuse pattern with 1. tier of interfering nodes.

Fig. 3 shows the frequency reuse pattern with the first tier of interfering nodes. This study considers only the first tier of interfering nodes, since they are causing the majority of the interference. The cells with the frequency reuse of frequency number 1 are shown by dark grey color. Node A is the transmitting node, B is the receiving node and nodes C, D, E, F, G and H are the interfering nodes. The effective gain of the transmitting, receiving and the interfering antennas are included in the calculation. The angle of reception of the signal at the receiver antenna varies according to the location and the transmission from the interfering nodes. The inter-site distance (ISD) between neighbor eNodeBs is assumed to be equal. The carrier power and the interference power is calculated from the transmit power, the gain of the antennas and the path loss between them. Then, the SINR value is calculated.

The capacity of the resulting node-to-node link is determined from the calculated SINR values. The bandwidth scalability of the LTE network is utilized for the frequency reuse planning and for the capacity analysis.

IV. Results

LTE technology with OFDMA radio access scheme is selected for the downlink transmission. This study considers OFDMA for both uplink and downlink in node-to-node transmissions. OFDMA yields to a frequency structure which divides the data over a number of sub-carriers. The spacing between two sub-carriers is fixed at 15 kHz. One Resource Block (RB) has 12 sub-carriers in frequency and 14 continuous symbols in time. Thus, one RB is 180 kHz in frequency and 1ms in time. The bandwidth scalability property of LTE allows 1.25, 2.5, 5, 10, 15, 20 MHz frequency band to provide the service. Fig. 1 shows the reuse pattern with 7 different frequencies in a transmission cluster. In this paper, it is assumed that each frequency band assigned is 2.5 MHz from the total of 20 MHz LTE band. Thus, 17.5 MHz is assigned for the node-to-node communication and remaining 2.5 is assigned for the users. These frequencies can be utilized both in the uplink and downlink directions. User band of 2.5 MHz is reused in every cell based on 1/1 reuse concept assuming high quality scheduler in LTE technology. Correspondingly, if 1.25 MHz is used, 8.75 MHz could be reserved for transmission and 11.25 MHz for the users.

The SINR was calculated with (1)–(4) and the resulting SINR equals to 5.92 dB. Table I shows that the calculated SINR values are the same because the ratio between the carrier power and the interference power is approximately the same for different inter-site distances. Comparing these result values with the recommended value of SINR presented in [14], it can be noted that the implementation of QPSK modulation technique with 3/4 or 4/5 coding rate is possible.

TABLE I
SINR values for different ISD.

Inter-site Distance (m)	2000	3000	6000
SINR (dB)	5.920	5.919	5.917

3GPP specification TS 36.213 specifies the MCS and TBS for LTE. Reference [15] gives the mapping between MCS Index, Modulation Order and the TBS Index. The antenna of LTE assigns the MCS Index and the RB on the basis of CQI for the downlink transmission. This CQI value depends upon the SINR. Reference [15] also specifies the mapping between TBS index, the number of RB and the corresponding TBS value. From this mapping, the possible peak data rate that QPSK can provide, based on the calculated SNIR value, was determined to be 1864 kbps. Moreover, the peak rate of 3728 kbps can be achieved for 2x2 MIMO, and 7456 kbps for 4x4 MIMO systems.

V. Operational Framework

The framework has been developed for the various events associated with the node-to-node communication during the disaster scenarios. These events include the detection of the disaster scenarios by the nodes, the events related to the establishment of the path between the nodes and the events that should be triggered from the CN.

A. *Disaster Detection and Link Establishment*

In this paper, the disaster scenario corresponds to a situation where the link between the eNodeB and the CN is broken. This corresponds to situations, where the link is physically broken, but it can also be considered in situations where the logical connection is temporarily unavailable.

Fig. 4 shows the flow chart for the detection of the disaster scenario. When the link between the eNodeB and the EPC is broken, eNodeB should detect this event and then it should switch its functionality to macro sensor mode. In macro sensor mode, eNodeB should work with LTE functionality as well as with sensor node functionality. With this functionality, node should detect the disaster events, should perform route establishment with neighbor node and should act as relay hop.

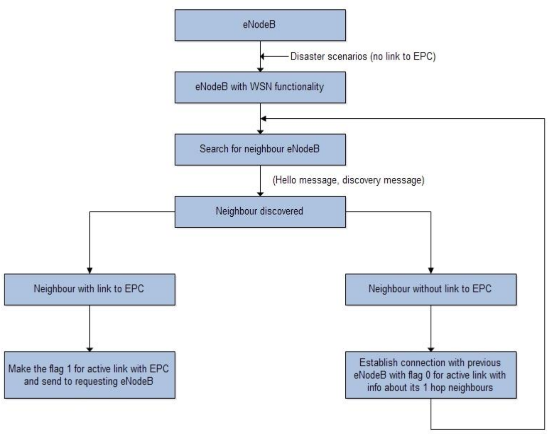

Fig. 4. Node-to-node communication flow chart.

The link establishment procedure uses an efficient protocol to establish the link with the most preferred neighbor node. A node sends the discovery message (hello message) to the neighbor nodes. The receiver can reply with the positive or negative response. If the response is positive, then in the reply message, the QOS information is also sent to the transmitting node. The receiver node can be the node with the active link or with the inactive link with the EPC. If the receiving node has active link to EPC, then this is the final hop. Otherwise, this node searches for another neighbor node with active link to EPC. All the route information can be stored in the cache in each node.

B. *Events from CN*

The sensor mode functionality is activated at the nodes which are affected by the disaster. But to transport the data from such nodes to the CN, certain number of eNodeBs with the active link to the CN should also be initialized with the sensor network functionality.

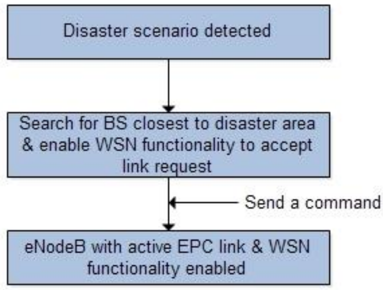

Fig. 5. EPC events.

Fig. 5 shows the operation and maintenance entity of EPC that should detect this fault situation and should locate the nodes in the geographical areas. Then, EPC should send a command to the unaffected nodes in the vicinity of the disaster area to enable the sensor mode functionality. These nodes at the vicinity will act as nodes between the EPC and the affected nodes to facilitate the delivery of the data to and from the network.

C. *Network Restoration*

The maintenance of the network can re-establish a communication link between the affected eNodeBs with the EPC. Then, the repaired node should act as a last hop for providing the relay function to the EPC. Once, role of the repaired node in the node-to-node communication is over, it can notify EPC and should switch back to the normal state.

VI. Conclusions and Future work

This paper presented the new functionality of node-to-node communication to facilitate the communication during the disaster scenarios. To enable the node-to-node communication during the link outage of RAN and CN, the realization of LTE radio network as a macro sensor network is proposed to maintain the communication.

The results presented in this paper show that a node-to-node communication can be established in LTE during the disaster scenarios. Furthermore, this type of backup node-to-node communication would be strongly limited in UMTS due to the frequency constrains. Correspondingly, node-to-node approach could be implemented in GSM with reduced capacity also due to frequency constrains.

The device-to-device communication is considered as the key technology for the future evolution of the LTE technology. The study of proximity-detection functionality for device-to-device communication is shown in [16–17]. Further, the LTE-Advanced has introduced the concept of Relay Nodes for the efficient heterogeneous network planning. The Relay Node is connected to the Donor eNodeB via radio interface [18]. The future work should take these approaches into account.

The node-to-node communication for the cellular network has opened a new research area in the field of communication. The SON technology is also required to implement the sensor mode functionality, and thus even extends this new research area. The complexity and bottle neck from the volume of data generated by the users to the node-to-node communication should also be studied. The use of maximum ratio combining or the switched combining can be a good research area to study the signal reception through two different antenna links.

ACKNOWLEDGMENT

The authors would like to thank the Finnish Funding Agency for Innovation and the European Communications Engineering for funding and supporting the research work.

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ISBN 978-952-15-3932-9
ISSN 1459-2045