# Cellular Network Coverage Analysis and Optimization in Challenging Smart Grid Environments

Stefan Monhof, Stefan Böcker, Janis Tiemann, Christian Wietfeld Communication Networks Institute (CNI) TU Dortmund University, 44227 Dortmund, Germany Email: {Stefan.Monhof, Stefan.Boecker, Janis.Tiemann, Christian.Wietfeld}@tu-dortmund.de

Abstract-Smart grid services require reliable and efficient communication, which can be provided by modern cellular networks. However, smart grid components are often installed in environments that are challenging for radio networks, like energy meters in basements. While grid operators need to know the availability of cellular networks before installing components, current methods for evaluating mobile network coverage in such environment usually require lengthy tests or expensive and complicated measurement equipment. In this paper, we introduce the Mobile Network Analyzer (MNA), which is an easy to use device for fast coverage analyses and network quality assessment. It can be used by grid operators to check the network coverage before deploying smart grid components. We show the applicability of the MNA in an exemplary case study on the cellular network coverage at electricity meter cabinets at 168 locations and in a six month long-term field campaign in a wind farm. We determined that the communication availability can be improved by up to 29 % by leveraging the networks of multiple cellular network operators with the help of global SIM cards or national roaming. Additionally, we examined specific smart meter gateway installations, focusing on deep indoor coverage.

### I. INTRODUCTION

For the operation of smart grid services, a reliable, secure and efficient communication infrastructure is required. The communication capabilities of critical smart grid components have to be maintained even, or especially, in challenging situations, like electricity blackouts, natural disasters or cyber attacks [1]. Since modern cellular network technologies, like Long Term Evolution (LTE), offer high data rates and support

for guaranteed Quality of Service (QoS), they are promising solutions to interconnect smart grid components, like Distributed Energy Resources (DERs) or smart meters, either as a fail-over or as the primary link. Particularly, when devices need to be upgraded in the smart grid roll-out, cellular technologies offer the benefit of lower deployment costs compared to wired solutions. For example, smart meters can be integrated into the smart grid by equipping them with a cellular modem, without the need to install new wired lines. However, the cellular technology has to be highly-available to meet the requirements of smart grid applications and the most benefits could be achieved by using existing commercial cellular networks. The general availability and reliability of smart grids can be increased by means of Software-Defined Networking (SDN) [2], but in the specific case of mobile communications, the availability of the wireless last mile is crucial. It can be increased by leveraging multiple commercial networks by means of national roaming [3] or a global Subscriber Identiy Module (SIM) card. Since national roaming is not available in Germany, a global SIM card that is able to use all networks was used. The potentials of national roaming, which could be made available with 5G, or the use of a global SIM card are analyzed in this paper. Nevertheless, cellular communication cannot be used in all locations, because of energy grid components, like energy meters, that are often located in challenging environments, like in basements of buildings. For smart grid operators, it is important to know if cellular technologies are an adequate



Figure 1. Mobile Network Analyzer at different measurement locations: outdoor, at a meter cabinet, inside of a closed meter cabinet, at the foot of a wind turbine generator equipped with an outdoor antenna for long-term analyses (from left to right)

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choice for a certain location before installing new components. This requires an easy to use, cheap and fast method to evaluate the cellular network coverage at those locations. In this paper, a new concept for assessing mobile network coverage and quality in challenging environments is presented and an implementation, called *MNA*, is introduced. It is an easy to use device that allows fast discovery of mobile network coverage at the specific measurement location. Results of field measurement campaigns, which were performed using the MNAs, are presented for a smart metering application and for a smart grid application in this paper.

The rest of this paper is structured as follows: In Section II relevant state-of-the-art work and analyses on basement attenuation are presented. Afterward, the concept of the MNA and its implementation, as well as national roaming, are introduced in Section III. Results of exemplary field measurement campaigns, which were performed using the MNAs, are presented for a smart metering application in Section IV, which includes an analysis of basement and indoor attenuation (Section V), and for a six-month long-term smart grid application in Section VI in a wind farm. This includes gains that can be achieved by leveraging multiple operators and an analysis of the network switching latency when using a global SIM card. Finally, the paper is concluded in Section VII.

#### II. RELATED WORK

There is work on mobile network coverage and quality evaluation. Yet, it is often either simulative, expensive or not considering challenging environments like basements or even meter cabinets. A survey on literature related to the evolution of cellular communications for operations of smart grid networks is given in [4]. The authors identified that there are only a few studies using field measurements to analyze the reliability of smart grid applications and support network planning. First measurements on building attenuations were performed in [5] using an expensive set-up that requires signal generation outside of a building. The authors of [6] conducted coverage and latency analyses of commercial mobile network operators at different locations. The coverage analysis was done at two different locations and the authors conclude, that while the outdoor LTE coverage is adequate, it is problematic in basements of especially old buildings. In [7] we examined the use of mobile communication systems for distribution grids by means of simulation. The building penetration capabilities of wireless technologies were analyzed in a line-of-sight scenario and the attenuation of radio signals in basements was quantified for different frequency bands. In [8] the authors present an analysis of the spectral capacity of LTE and Code-Division Multiple Access (CDMA) in the 450 MHz band. For this purpose, they also performed measurements of basement attenuation, in the frequency bands 800 MHz and 1900 MHz, and compared the results to [7]. In [9] we introduced a solution for stress testing smart grid communication systems. For this, measurement devices were placed at different locations in the tested network. By sending test data, it was evaluated if the required QoS levels can be achieved. It was intended that the measurement devices are installed in the tested network for a longer period in time, so the operator of the communication network can use it to tune its network. [10] evaluates the quality of the German mobile networks. For this purpose extensive drive and walk test are performed all over Germany with different devices and SIM cards. This test includes assessments of voice quality and quality of data transmissions for different use cases. Smart grid specific environments are not yet covered in this study. Other papers focus on aspects like latency [11] under the condition that cellular network coverage is available. The advantages in indoor coverage of recent advances in Machine-Type Communication (MTC) technologies Narrow Band Internet-of-Things (NB-IoT) and LTE for Machines (LTE-M) are analyzed in [12].

#### III. CELLULAR NETWORK ANALYSIS USING A MNA

In this section, the developed Mobile Network Analyzer (MNA) is presented. First, its concept in terms of goals and performance indicators is described. Afterward, details on usage and implementation are given.

#### A. Goals and Performance Indicators

The MNA provides an easy to use and fast way to determine the mobile network coverage at a certain measurement location. Network coverage in this context means that a complete list of available mobile network cells is generated as measurement result. We define a cell as *available* if its broad-casted radio signals can be received with a power that exceeds a certain threshold. The indicators used to determine the received power and the exact power levels depend on the considered technology. For LTE the Reference Signal Received Power (RSRP) [13] and in Global System for Mobile Communications (GSM) the Received Signal Strength Indication (RSSI) is used to quantify the received power level at a device. The list of available cells includes the received power levels, so the number of cells per operator or frequency band and their corresponding power levels can be used to assess the quality of network coverage. The list of available cells can be determined fast, in usually 1 min to 2 min, because the MNA does not need to attach to any network in this process. Therefore, it does not even require a SIM card and is cheap to perform. Furthermore, the MNA is able to evaluate the quality of a certain cell at measurement time, by means of throughput and latency measurements. For this, a SIM card for the analyzed network is required and it requires additional time, in exchange it gives more detailed performance indicators.

#### **B.** Implementation and Measurement Process

The MNA is implemented in a custom build User Equipment (UE), based on an embedded PC and a Huawei ME909s-120 modem. This module supports GSM, Universal Mobile Telecommunications System (UMTS) and LTE (category 4) and is controlled using a virtual serial interface. In this way, obtaining detailed information on the active and other available mobile networks, as well as precise control over technologies, frequency bands and operators that are used, is allowed. To

 Table I

 MEASUREMENT PARAMETERS OF A NETWORK SCAN FOR EACH CELL

Parameter	Description	
arfcn	Radio Channel Number	
band	Frequency Band	
lac	Location (GSM) / Tracking (LTE) Area Code	
mcc	Country Code of Operator	
mnc	Network Code of Operator	
bsic	Base Station Identification Code (GSM only)	
rxlevel	RSSI (GSM) / RSRP (LTE)	
cid	Cell Identity	
pci	Physical Cell ID (LTE only)	

perform measurements in networks of different operators, the MNA can be equipped with up to three SIM cards. The measurement software on the UE is developed in the Python programming language and runs on the Linux distribution armbian. The handling of the device is straightforward. There is just one button that triggers a measurement. The configuration of the device and collection of results is done by an external server, which is contacted after the measurement if LTE coverage is available. A display indicates the current state of the device. Figure 1 shows a picture of our MNA and its application in different measurement locations. The duration of a measurement run depends on configuration details but lies in the range of 1.5 min to 7.5 min. The MNA can be used for a single measurement at a specific location or for long-term measurements. In cases of single measurements, the device powers off afterward. When performing long-term measurements, the device stays on and performs the configured measurements frequently, for example, once an hour. A network scan can be used to obtain a list of available cells as described above for a specified technology and optionally frequency band. It captures all cells in reception range with a minimum power level of  $-110 \,\mathrm{dBm}$ . Therefore, for the rest of this paper, no reception means that the received power of a cell is lower than  $-110 \,\mathrm{dBm}$ . For LTE this power level corresponds to the RSRP, for GSM to the RSSI respectively. Table I gives an overview of the parameters that are obtained for each GSM/LTE cell when performing a network scan. Since the modem does not attach to a cell within the network scan process, it will be called *passive measurement* in this paper. A network scan can be executed in a multistaged measurement process that consists of *passive* network scans and active measurements (i.e., data rate and latency measurements). In the first stage, a network scan for LTE cells is performed. If at least one LTE cell was found for each Mobile Network Operators (MNOs), the passive part of the process is finished and the active part is started for the best cell (in terms of highest received power) of each MNO. If for at least one operator no LTE cell is available, a GSM scan is performed, too. This allows determining the best available technology for each operator while reducing the measurement duration. Active measurements could be used for further quality evaluation of the discovered networks, but are not considered further in this paper.

## C. Coverage Gain through Global SIM Card

Availability of mobile communication can be increased by leveraging multiple commercial cellular networks of different operators. This can be either achieved by using multiple SIM cards of different operators, by using a global SIM card, or by means of *national roaming*. In both cases, roaming is required. Roaming means that a UE connects to the Radio Access Network (RAN) of an operator (visited operator) that did not issue the used SIM card (home operator). Usually, roaming is used to get telephony or data services in foreign countries, but may, under certain circumstances, also be used within the home country. In this case, the term national roaming is used, but from a technical point of view, it is not different from roaming in foreign countries. Whether roaming is possible depends on the roaming agreements between relevant operators, which define the terms under that roaming is allowed. These agreements may also include guarantees regarding the provided QoS. The users themselves only have an agreement with their home operator, but not with the visited operators. A global SIM card has the benefit that multiple networks can be used with just one contract with one operator and a single SIM card. Therefore, a single modem is sufficient and no logic to switch between SIM cards has to be implemented. Mobile network operators offer global SIM cards with rate plans that specifically focus on MTC communications, like for smart metering or smart grid applications. They allow to leverage all available cellular technologies and networks, but usually include little data volume, as for monitoring and control applications high data volumes are not required.

## IV. MNA-ENABLED COVERAGE ANALYSIS WITH FOCUS ON SMART METERING

For the mobile network coverage and reliability analyses, two measurement campaigns were performed in North-Rhine Westphalia, Germany. The first campaign evaluates the network coverage at the location of electricity meters at 168 different addresses. A GSM network scan was performed at 139 different locations only, because of the multi-staged measurement process, which does not perform a GSM network scan if LTE coverage of all three German MNOs is available. This was the case for 29 locations. Each measurement was performed at the location of a meter point cabinet, which may be located on different floors for different addresses. Because of re-farming of GSM frequencies, it can be assumed that the LTE coverage will replace GSM eventually [14]. Therefore, it is not distinguished between different technologies in these analyses. Instead, the analyses are separated for the comparable frequency bands 800/900 MHz and 1800 MHz, since path loss and attenuation depend on the frequency. In Figure 2 the empirical mobile network coverage at the meter point locations (a) and achievable gains by using a global SIM card (b) are plotted for each operator. The error bars indicate confidence intervals of 95 %, which means that the percentage of other locations with network coverage lies within these intervals with a probability of 95%. Since network coverage at one location is either present or not, it can be represented by a



(a) Coverage of each operator and combined coverages with a confidence (b) Coverage gains through the use of a interval of 95%

Figure 2. Empirical mobile network coverage of each operator (168 locations) and combined coverage of multiple operators at 800/900 MHz and 1800 MHz and achieved coverage gains through the use of a global SIM

Bernoulli distribution with probabilities based on measured values. To calculate the confidence interval, the distribution was approximated with a normal distribution using the central limit theorem. The coverage in the 800/900 MHz frequency bands ranges between 82% (Operator 1) and 95% (Operator 3). As it would be expected, the coverage of 1800 MHz cells is less compared to 800/900 MHz cells inside of buildings, due to higher attenuation. Operator 2 does not operate any cells in the 1800 MHz band in the measurement region and due to lower samples, the uncertainty of the measurement values are higher for 1800 MHz than for 800/900 MHz. The reliability of available cellular networks in the measurement region was analyzed to evaluate if mobile communication could be an adequate way to monitor and control smart grid equipment. For this purpose, the mobile network coverage was not only examined for each operator separately, but also for combinations of two or more operators. The application of mobile networks of more than one operator can increase the reliability of communication by switching to a different network in situations of cell outages or overload if no other cell of the same operator is available. Figure 2b shows the achievable gain for each operator in detail. For 800/900 MHz, the coverage can be increased to >97% by combining two operators or even to 99% by combining all three operators. For Operator 1 this corresponds to a gain of about 15%. In the 1800 MHz frequency band, the coverage can be increased to 85% with gains up to 29%.

Since this study is limited to a small region and time, one should be careful when drawing conclusions from these results. Especially a rating of operators should not be concluded. The operators are still in the middle of rolling out LTE, therefore coverage improvements are expected. However, the results show the potential of a global SIM card or national roaming to increase and ensure coverage in challenging environment, especially in times of technology roll-outs, and harsh situations.

## V. DEEP INDOOR COVERAGE

Electricity meters are often installed in challenging environments, like inside of metal meter cabinets in basements. Therefore, we performed a study on the additional attenuation



Figure 3. Probability density of basement and indoor attenuations at 800/900 MHz

 Table II

 Comparison of measured and simulated basement attenuations

Approach	800/900 MHz	1800 MHz
Simulated [dB] ([7])	$24.2(\pm 8.9)$	29.7(±10.4)
Measured [dB] ([8])	$17.5(\pm 6)$	22.5(±6) (at 1900 MHz)
Measured [dB]	$15.03(\pm 8.69)$	19.5(±8.15)

of Radio Frequency (RF) signals in basements. Figure 3a shows the probability density of the measured attenuation in basements. The data is based on measurements at 32 locations and contains the attenuations of the signals of 199 cells in the frequency ranges of 800/900 MHz. 41 cells in the frequency bands of 1800 MHz were captured at a total of 16 locations. The received power of the cells was measured once in front of the building and once at the meter's cabinet. Only locations with outdoor and deep indoor measurement results can be taken into account in the evaluation in order to determine a certain attenuation/deviation. The measured basement attenuations are in the range of  $-8 \,\mathrm{dB}$  to  $44 \,\mathrm{dB}$ (800/900 MHz) and 5 dB to 43 dB (1800 MHz). A negative attenuation (i.e., a power gain) may be the result of shadowing effects if the building is located between the UE and the base station. It may also occur because of different orientation of the antennas of the UE or multi-path propagation. The measured mean attenuation is  $\mu = 15.03 \,\mathrm{dB}$  with standard deviation  $\sigma = 8.77$  for  $800/900 \,\mathrm{MHz}$  and  $\mu = 19.50 \,\mathrm{dB}$ with standard deviation  $\sigma = 8.15$  for 1800 MHz respectively. Table II summarizes the attenuations from the simulations [7], measurements performed in [8] and the results presented in this paper. According to simulations in [7], the expected basement attenuation is 24.2 dB with a standard deviation of 8.9 in the 800 MHz band and 29.7 dB with a standard deviation of 10.4 in the 1800 MHz band. In comparison, Figure 3b shows the empirical probability density of the indoor attenuation on the ground floor or higher based on measurements at 17 different locations. The mean attenuation is lower than in basements, because of simpler conditions, like fewer walls and ground to penetrate, bigger windows, etc. This also results in a smaller standard deviation. The simulation results in [7] show a similar behavior. These simulations were performed in a Line-of-sight (LOS) scenario, assuming closed basements without any windows or doors. Therefore, it is expected that the empirical basement attenuation is lower than the values from the simulation. While there is a difference of about 9 dB between measurements and simulations for 800/900 MHz, the shape and standard deviation match good. This shows, that the model in [7] represents a simplified worst-case analysis, but in practice propagation benefits from non-line-of-sight (NLOS) through windows.

## VI. MNA-ENABLED LONG-TERM AVAILABILITY ANALYSIS WITH FOCUS ON SMART GRID

The second field campaign aims to analyze the long-term availability and quality of cellular networks. For this purpose, three MNAs were installed at the foot of wind turbine generators in a wind farm. They performed a network scan



Figure 4. Results of a six-month long-term field campaign: Received power of the strongest cell of Operator 1, Operators 2+3 (roaming candidates) and all operators at measurement location 1 of the long-term measurement campaign

each hour for six consecutive months. Figure 4 shows the RSRP variation of the strongest received cell of Operator 1 at location 1 (no roaming) as exemplary results from all performed long-term measurements. The results show that the RSRP value fluctuates over time in the magnitude of  $\pm 3 \,\mathrm{dBm}$ . The median of  $-79 \,\mathrm{dBm}$  of the strongest cell of Operator 1 displays valid and reliable network coverage. The outliers around  $-101 \, dBm$  correspond to the received power of the second strongest cell of Operator 1 at this location and indicate single cell outages (e.g., for maintenance) of the strongest cell. In this case, LTE cells with an RSRP of  $-95 \,\mathrm{dBm}$  (roaming boundary) or higher should be preferred to ensure a stable connection, even though these particular outages could be completely handled within the network of Operator 1. The cells of other operators (roaming candidates) are available by means of roaming. The RSRPs of these cells and the strongest cells of Operator 1, which are above the roaming boundary, are plotted as Operator 1 + X. So cell outages may have degraded the communication service of Operator 1 at this location, while the overall availability of Operator 1 was still 100% because the second available cell of Operator 1 has an RSRP value in a range that potentially does not allow a stable connection ( $< -95 \, dBm$ ). In cases like this, roaming enables to obtain a stable connection with a higher probability. Therefore, (national) roaming is able to prevent complete connection losses in times of cell outages while improving the reliability compared to the application of a single operator's network. While a global SIM card can increase the availability of cellular communication in general, it comes at the price of additional latency to switch networks. For this purpose, the time to attach to a network and to switch between networks was measured in the lab with three different SIM cards. A local SIM acts as a reference. It has a rate plan for business customers from a German provider and is therefore not capable to attach to the networks of other German operators. Additionally, two global SIM cards (global SIM A/B) that are able to roam into all German networks were used. All measurements were performed with one SIM card at



Figure 5. Network switch latency for each operator and three SIM cards

a time. Network attach (local SIM) and network switch (global SIM A & B) procedures were triggered in the lab in varying intervals, while measuring the execution times. A total of 14,000 measurements were performed for each combination of SIM card and operator. Figure 5 shows the distribution of the time that was required for attaching to our home network (local SIM) and foreign networks as roaming candidates (global SIM A & B) for each operator and SIM card. The required time depends on different criteria, like load in the eNodeB and the core networks, communication performance between the different operators, or roaming agreements that may prioritize some users on the cost of other user's performance. Also, the standardized attachment and error handling procedures [15] use timers and waiting periods in the magnitude of 10 s, which can lead to high delays. To measure the latency, the time from manually issuing a network attach command to the point in time where it is possible to use a data connection was measured using the MNAs. While even for the home network the attachment duration can take up to 9 s, the durations using roaming SIM cards are much worse and it can take up to 100 s to switch a network. For time-critical applications, this means that it may be required to use multiple modems that are attached to different mobile networks for faster switching between operators.

#### VII. CONCLUSION

In this paper, we presented an easy to use and fast methodology to analyze and improve the mobile network coverage for smart grid applications. The capabilities of the developed Mobile Network Analyzer (MNA) for easy and quick coverage and quality analyses were demonstrated in field campaigns in the contexts of smart metering and DER. It was shown that the MNA can be used to analyze the cellular network coverage in challenging environments, like basements or recultivated areas. The results on the distribution of basement attenuation from the field campaign confirm literature results based on simulations and therefore, could be used for prediction of basement coverage for smart metering applications. Particularly in challenging environments, the use of multiple networks offers a great potential to improve mobile network coverage and reliability, but the time that is required for switching between networks has to be taken into account when planning the application of cellular technologies for critical applications. Since the use of multiple networks is a general concept, it can be applied for various applications. The presented measurement approach is not limited to smart grid or smart metering applications, but can also be used for any other critical infrastructure or any application that requires reliable mobile network connections. The MNA is suited for fast determination of network coverage as well as for longterm monitoring.

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