Accepted for presentation in: IEEE International Conference on Smart Grid Communications (SmartGridComm)

Performance Evaluation of an IEEE 802.11 Mesh-based Smart Market and Smart Grid Communication System

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***Abstract*—An increased level of volatile renewable Distributed Energy Resources (DER) constitutes the need of continuous monitoring and active power coordination to ensure the short-term and long-term stability of future distribution grids. These Smart Grid functionalities present lots of new challenges, but at the same time facilitate the opportunities for Smart Market ancillary services. For this purpose, this paper presents an evaluation of an IEEE 802.11 Mesh-based network architecture, which is based on standardized Cigré benchmark distribution grids and specified Smart Grid traffic. Performance results depict that the considered mesh network is a suitable solution for currently specified traffic requirements, but assumption on increased future traffic requirements results in about a four times worse scalability in terms of number of supported devices, which needs to be considered for current and future Smart Market deployments.**

I. Introduction

Conventional energy grids with centralized generation are changing towards decentralized power supply based on volatile renewable DER. An increased number of dynamic energy consumer units (e.g. Electric Vehicles (EVs)) intensifies the effect of more fluctuating, bidirectional power flows on all voltage levels and thus constitutes the need of active power coordination to ensure the short-term and long-term stability of our electricity systems.

Thus, new concepts to facilitate distributed energy flow management are foreseen, which imply a transition from passive to active grids. A progressive smart meter rollout and an increased installation of intelligent substations provide means for Active Distribution Grid (ADG) wide monitoring, as well as energy flow control management. In order to cope with such arising challenges and capabilities of Smart Market and Smart Grids, the implementation of holistic Information and Communication Technologies (ICT) are an essential requirement. The great diversity of possible technology and networking options offer many approaches to the planning and operation of Smart Grids and characterize various problems of current research. In this context, the authors in [1] introduce several wired and wireless technologies covering several Key Performance Indicator (KPI) such as data rate, coverage or reliability. This paper focuses on a local, wireless ICT solution for Low Voltage (LV) network parts of the distribution grid, in order to provide monitoring and control capabilities for a huge amount of single, volatile DERs located very close to each other. For this purpose, an IEEE 802.11 Mesh-based architecture for Neighborhood Area Networks (NAN) is proposed and explained in detail (see Section III). Section IV introduces the simulation environment and its underlying models and scenarios as fundamental basis for the performance evaluation followed in Section V. Based on a scalability analysis, this paper ends with a case study for exemplary Smart Market and Grid requirements providing ICT network planning relevant results for different communication unit densities. Finally, major findings are summarized including an outlook on further work.

II. Related Work

There are several wired and wireless technology solutions to connect DERs within a NAN. In particular narrow-band, as well as broad-band Power Line Communication (PLC) technologies, especially in combination with Long Term Evolution (LTE) (450 MHz) as backbone link, are widely discussed wired and mobile cellular network combinations [2]. This paper proposes a wireless IEEE 802.11 Mesh-based communication system, in contrast to wired PLC solutions for local communication issues, while at the same time the backhaul link is not focused in this work.

In this context authors of [3] present a system architecture and performance evaluation of a Radio Frequency (RF) mesh based system for smart energy management applications in the NAN. A comparable technology approach is discussed in [4], whereby the focus is put on evaluation of currently deployed and design of new systems. Both RF mesh approaches operate in the 902 to 928 MHz band, which is regulated by the FCC in the United States, but licensed to mobile cellular networks in Europe. Alternative approaches leverage the 2.4 GHz Industrial, Scientific and Medical (ISM) band and are based on IEEE 802.11s, which provides higher scalability and flexibility while ensuring low installation and management costs [5]. Authors in [6] compared the performance of the default IEEE 802.11s Hybrid Wireless Mesh Protocol (HWMP) with an adapted Optimised Link State Routing (OLSR) in a NAN based ad hoc network and determine that adapted routing protocols also address routing challenges in a NAN based Smart Grid mesh network.

III. Mesh-based Neighborhood Area Network for Smart Market and Grid Control Systems

Mesh technology is a suitable solution for variable propagation conditions typically encountered in NANs.

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The communication range can be increased by performing multiple hops using other mesh nodes as a repeater until a final destination is reached. Consequently mesh systems are dynamically able to find alternative paths through the mesh network in case performance parameters of the initial route get worse, e.g. due to a parked truck in front of a house.
This work proposes an IEEE 802.11 Mesh-based network architecture for a NAN, assuming that every Smart Meter entity in a NAN, further referred to as Smart Market and Smart Meter Communication Unit (SMCU), is equipped with an outdoor antenna. European wide successful community networks illustrate that this assumption is feasible [7], amplified by an increasing penetration of photovoltaic systems in typical NANs, that easily enable the outdoor antenna roof mounting. The proposed mesh architecture is illustrated in Figure 1, whereby selected mesh points can serve as a mesh gateway, which is connected to a high speed backbone link to the Smart Market and Smart Grid management system.

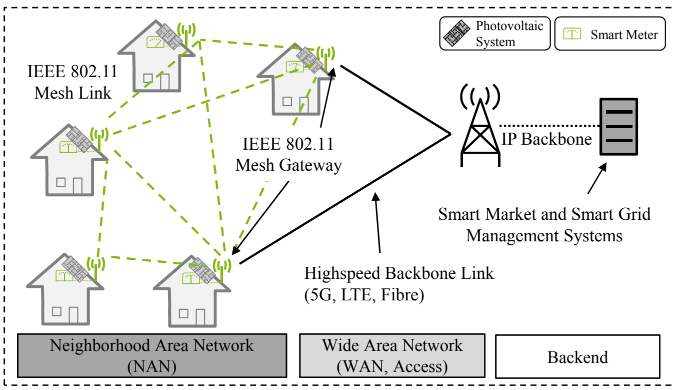

Fig. 1: Smart Market and Smart Grid Neighborhood Mesh Network Architecture

The proposed IEEE 802.11 mesh technology is based on IEEE 802.11n, operated in the 2.4 GHz band, limited to modulation and coding scheme zero (MCS0), which is robust and offers the highest achievable coverage, but still provides a sufficient data rate of 6.5 Mbit/s. The IEEE 802.11n is implemented in ad-hoc mode, which enables the mesh functionality, extended by *Mobile Ad Hoc Network* (MANET) routing protocols. This work implements the *Ad-Hoc On-Demand Distance Vector* (AODV) routing protocol, whereby the reactive AODV parameters are significantly adapted to requirements of NAN environments. The active route timeout defines the lifetime of a route and is initially set to 5 s, but adapted to 3600 s in order to consider the reduced NAN mobility, which is limited to minor environment changes, e.g. parked trucks. Additionally, the hello interval is extended in order to avoid insufficient overhead due to dynamic environment changes smaller than 60 s. As a summary all relevant network parameters are listed in Table I.

IV. Modeling and Scenario Generation

The performance analysis is performed with help of Riverbed Modeler (previously known as OPNET), which is capable of design and evaluation of various communication networks. It provides IEEE 802.11 PHY and MAC, as well as higher ISO/OSI layers, and thus provides the basis of for a performance analysis of the proposed Smart Market and Smart Grid Mesh architecture for NAN scenarios. In that regard, the authors design extensive and reliable simulation models and scenarios to achieve nearby realistic performance results that allow distribution network operators to transfer presented results to already deployed scenarios, as well as to support planning phases of future deployments.

TABLE I: Parameter settings of the IEEE 802.11n Mesh-based network

Parameter	Value
Frequency	2.4 GHz
Transmit Power (W)	0.1000
Transceiver Sensitivity (dBm)	-82
Modulation Scheme	6.5 Mbit/s (MCS0)
Ad-Hoc Routing Protocol	AODV
Route Request Retries	5
Active Route Timeout (s)	3600
Hello Interval (s)	uniform(60,120)
Allowed Hello Loss	2

A. *Smart Grid Traffic Modeling*

The implemented traffic model is based on [8], defines ICT requirements for Automated Meter Reading (AMR) purposes and is further referred to as FNN traffic. FNN traffic requirements are defined, considering packet size, arrival rate, required latency and service priority. Considering these requirements various use cases are grouped in four different scenario classes (A,B,C,D), whereby scenario class D aggregates the most challenging requirements. Furthermore, the minimum data rate R_i that needs to be provided by each use case i is derived based on packet size and required latency. Using these input parameters, worst case traffic modeling is performed, delivering the minimum data rate, required by each SMCU in the worst case of all active *non-priority* and *priority* use cases. To determine worst case load of priority services the sum of minimum data rate requirements of all corresponding use cases is calculated.

$$R_{prio} = \sum_i R_{i,prio} \tag{1}$$

Worst-case load of non-priority use cases is equivalent to the highest data rate requirement of a single use case among all non priority use cases, assuming sufficiently short transmission times and low frequency of occurrence, so that no more than one non priority use case service is active simultaneously.

$$R_{non-prio} = \max_i(R_{i,non-prio}) \tag{2}$$

In case of a communication channel supporting Quality of Service (QoS), the minimum data rate requirement is the maximum of the data rate requirement of priority R_{prio} and non-priority use cases $R_{non-prio}$.

$$R_{min,QoS} = \max(R_{prio}, R_{non-prio}) \tag{3}$$

If no QoS (nQoS) is supported the overall minimum data rate requirement is the sum of data rate requirements of priority R_{prio} and non-priority use cases $R_{non-prio}$.

$$R_{min,nQoS} = R_{prio} + R_{non-prio} \tag{4}$$

In order to consider the worst case traffic scenario during our performance analysis, the traffic model used during simulation is restricted to scenario class D and nQoS resulting in the most challenging requirements.
According to our above presented traffic model, the considered data rate requirements are summarized per SMCU and use case group in Table II.

TABLE II: Minimum data rate requirement per Smart Market/Grid Communication Unit (SMCU) [8]

Use Case Group	**Minimum data rate requirement [kbit/s]**			
	With QoS		**Without QoS**	
	Download	Upload	Download	Upload
A	1,33	3,20	1,76	3,80
B	1,33	3,20	1,76	3,80
C	1,33	3,20	1,78	3,82
D	1,33	3,20	2,02	4,07

B. Empirical Path Loss Modeling

In order to cover path loss, shadowing, and multipath effects of the wireless communication channel the empirical *WinnerII* [9] path loss propagation model for frequencies between 2 GHz up to 6 GHz enhances the simulation environment. The *WinnerII* channel model provides a huge variety and contains 17 specific profiles, covering Line-of-Sight (LOS), Non-LOS (NLOS), indoor and outdoor scenarios, as well as different topology types like urban, suburban and rural. The path loss modeling extension in this work is focused on relevant NLOS path loss profiles for urban (C2), suburban (C1) and rural (D1) scenarios. The minimum receiver sensitivity (MCS0, see Table I) is $P_{Rx} = -82\ dBm$ and the maximum allowed transmit power in Europe is limited to $P_{Tx} = 20\ dBm$. Thus, the maximum permissible path loss results in $P_{Tx} - P_{Rx} = 102\ dB$, leading to maximum coverage ranges for NLOS scenarios as presented in Table III.

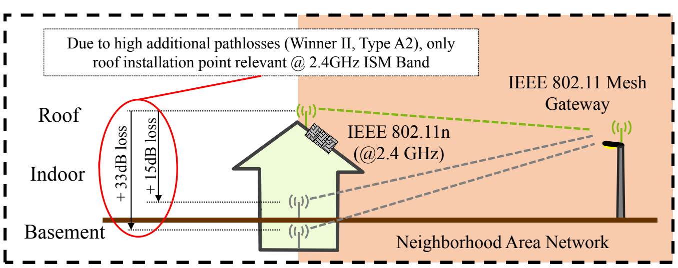

Fig. 2: Suitable Smart Market/Grid communication unit antenna installation points in the 2.4 GHz ISM band [9]

Due to the reason that the 2.4 GHz frequency band causes too much additional path loss for indoor antenna installation points (see Figure 2), this work assumes that all DERs are equipped with an outdoor antenna. This assumption is feasible for a NAN, due to the reason that the current penetration of photovoltaics, which could be easily enhanced by an antenna, is still very high and will increase rapidly in future. These additional path loss values illustrated in Figure 2 are comparable with results achieved with a Ray Tracing analysis presented in [10].

C. Noise Modeling

The simulation environment is extended by a noise model part, which enables the consideration of dynamic noise models derived from [11], [12]. These noise measurements evaluate typical man made noise with regard to 1 MHz. The implemented noise model in this work quantifies this input with regard to IEEE 802.11n 20 MHz channel bandwidths. Thus, the noise model provides noise levels starting from -114 dBm (thermal noise) up to -75 dBm. Within the simulation environment additional noise affects the Signal-to-Noise-Ratio (SNR), whereby successful packet delivery is possible starting with a SNR threshold of 2,9 dB [13].

D. Cigre Benchmark Scenarios

This work is based on Cigré benchmark networks for European distribution grids [14]. These benchmark networks serve as a reference for the integration of renewable energy sources in conventional grids and represent an average of all distribution grid voltage levels. Thus, the Cigré benchmark network data is used to generate reliable, transferable simulation scenarios as illustrated in Figure 3. The basis for geographical positions of considered communication units (SMCU) within the simulation scenario is the Mid Voltage (MV) Cigré benchmark network. This MV benchmark network is transferred to a Cartesian coordinate system and thus enables a topology derivation based on MV substation density (topology layer). The topology information of urban, suburban and rural areas is merged with Low Volatge (LV) Cigré benchmark network data, whereby each MV substation serves as a transformer for one LV network. The density and quantity of SMCUs per MV substation depends on the topology layer data, whereby the distance between LV network entities varies as a subject of the topology type (see Table III). In order to consider statistically relevant varieties within our LV benchmark grids, final SMCU positions are randomly chosen per topology type as a subject of a normal distribution.
This scenario modeling approach guarantees transferable simulation scenarios to realistic deployments, but also considers varieties of SMCU positions in the topology layer in order to provide statistically relevant results.

V. Performance Evaluation

The performance evaluation starts with a scalability analysis based on simulation scenarios that rely on simulation parameters listed in Table III (see Section IV). The derived SMCU positions in the communication layer are the basis for IEEE 802.11n mesh stations, whereby each scenario is equipped with one mesh gateway in order to determine limits of reliability and delay. In this context each simulation run evaluates the performance of n SMCUs, whereby n is sequentially iterated from 1 up to 300 SMCUs per mesh gateway. First off, reliability of the mesh network is analyzed based on the packet success rate (PSR).

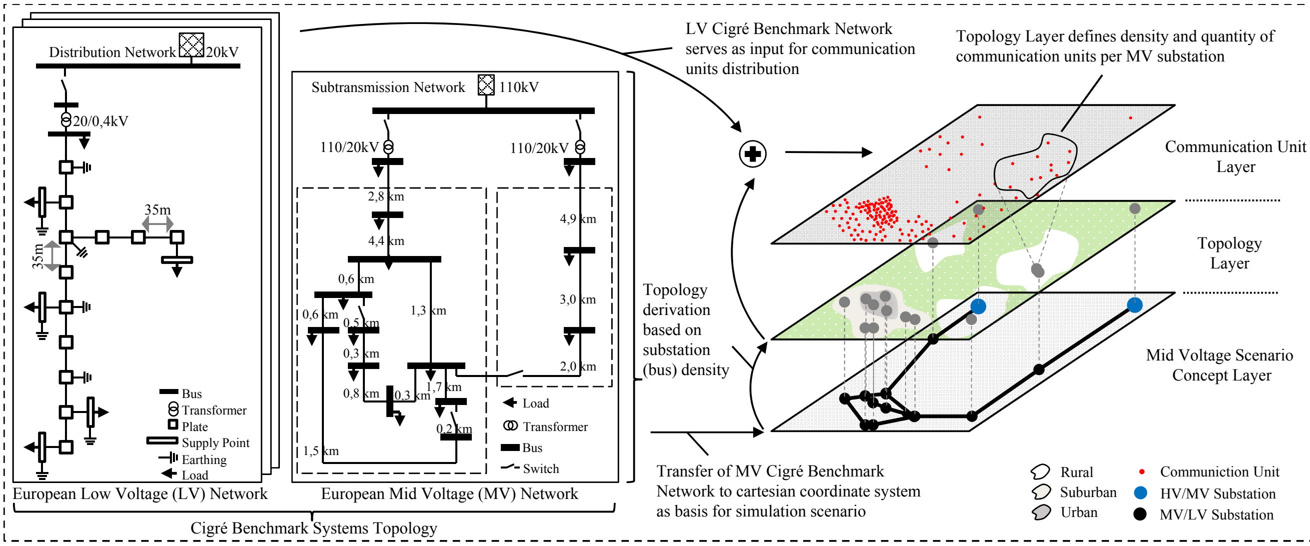

Fig. 3: Scenario generation based on topology of Cigré benchmark networks for European distribution grids [14]

For this purpose a PSR of 98 % is set as threshold, whereby network constellations with PSRs lower than this threshold are assessed as not functional for Smart Market and Smart Grid purposes. Figure 4 presents the PSR for increasing traffic demands in a fixed urban scenario.

TABLE III: Scenario parameter for NLOS simulation runs (f=2.4 GHz, h_{MS}=h_{BS}=10 m, P_{Tx} = 20 dBm)

Topology Type	Coverage Range	Population Density	Entity Distance
Rural	270.3 m	2/hectare	35 m
Suburban	75.6 m	6/hectare	20 m
Urban	63.1 m	12/hectare	10 m

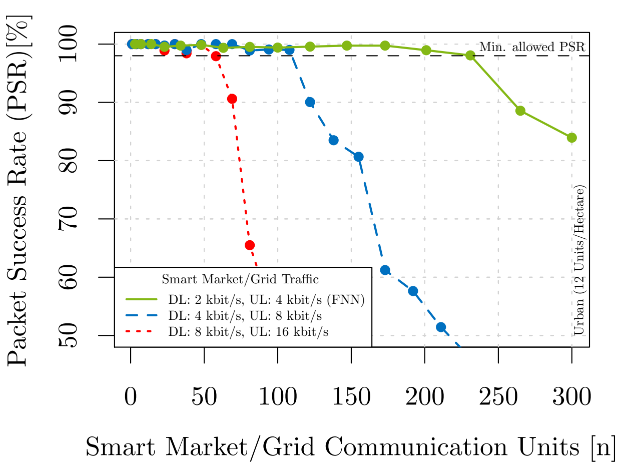

Fig. 4: Packet Success Rate for increasing traffic demands

Traffic classes vary from worst case FNN traffic (see Section IV-A) up to FNN traffic increased by a factor of 2, respectively 4, in order to consider additional traffic demands of future Smart Market ancillary services. Considering FNN traffic, it can be shown that more than 200 SMCUs per gateway are feasible. Only scenarios with more than 200 SMCUs result in a lower PSR than 98 %. At this point the communication channel is saturated and the IEEE 802.11n channel access reaches its limits. Thus, deployments with more than 200 SMCUs need to be planned with a second mesh gateway to relieve the communication channel.In addition, Figure 5 illustrates PSR results for fixed FNN traffic and different topology area types.

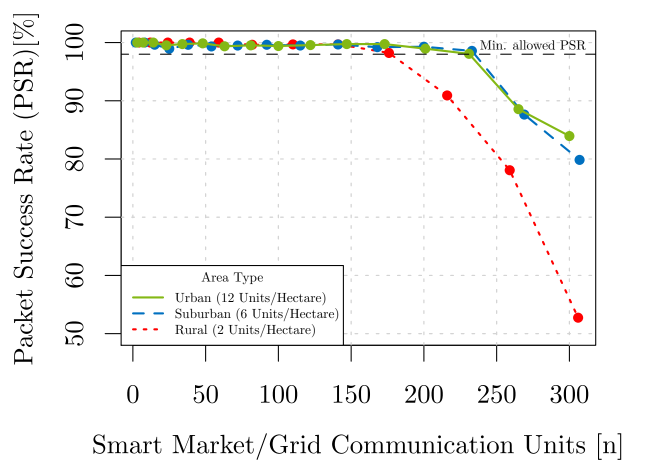

Fig. 5: Packet Success Rate for different unit densities considering FNN [8] traffic demand

It is shown that the previously described limit of more than 200 SMCUs can only be achieved for urban and suburban topology areas. Despite the fact that the SMCU density in suburban scenarios is half of density considered in urban scenarios, both show comparable performance characteristics.This can be explained by the fact that a lower SMCU density of suburban scenarios is compensated by a bigger coverage range, so that performance results show related progressions. Rather, PSR of rural scenarios

reaches the threshold earlier (approx. 170), because of a significantly better propagation characteristic, leading to higher coverage ranges, results in less hops, but increase the co-channel interferer at the same time.
A further indicator for the scalability analysis of the proposed system is the mean End-to-End delay τ_{SMCU} per SMCU. The delay is initially analyzed for a fixed urban scenario and increasing traffic demands (see Figure 6).

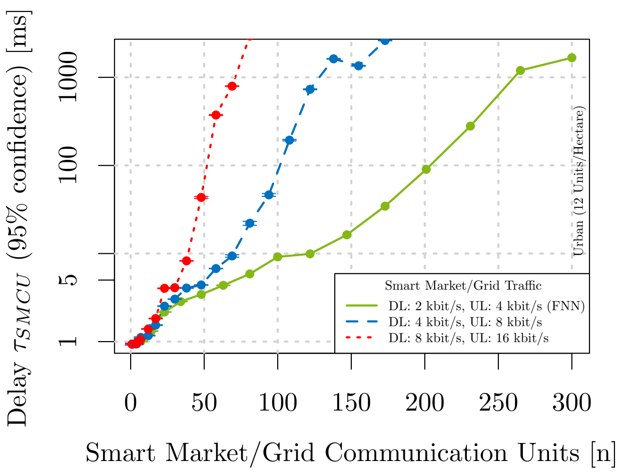

Fig. 6: End-to-end delay for increasing traffic demands

In general, the delay is increasing as function of the related traffic class with growing number of SMCUs. This is explained by additional traffic load that is generated by more SMCUs, hence corresponding channel access time increases as well and results in higher delay times.

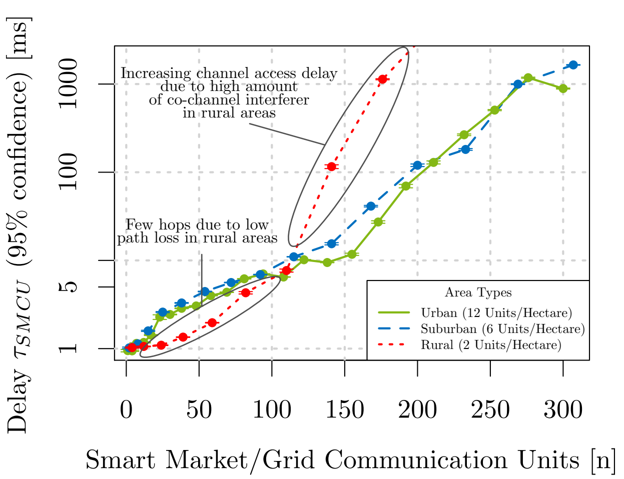

Fig. 7: End-to-end delay for different unit densities with FNN [8] traffic demand

Figure 7 illustrates mean end-to-end delay τ_{SMCU} per SMCU for fixed FNN traffic demand, but different topology area types and corresponding SMCU densities. In general, the scalability analysis shows that the assumed PSR threshold of 98 % results in case of FNN traffic demand for a sufficient mesh network size of less than 170 SMCUs per gateway even in rural scenarios. A future traffic demand that is four times higher than FNN traffic results in about a four times smaller cell sizes (SMCUs per mesh gateway), which needs to be considered for future Smart Market deployments. In case of the mean end-to-end delay per SMCU all scenarios fulfill explicitly the FNN requirements, where the maximum allowed latency is defined with 20 s. As above, suburban and urban scenarios show comparable performance results. Delay results for rural scenarios can be divided into two areas. First, the range from 0 up to 100 SMCUs provides smaller delays than urban and suburban scenarios, due to less hops based on better propagation characteristics. At a certain point of about 100 SMCUs, this effect is reverted, because as previously described rural propagation characteristics are much better and cause additional co-channel interferer.

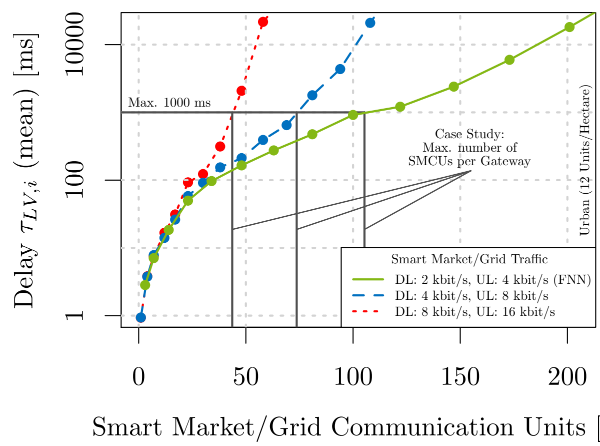

Fig. 8: *Case Study:* Maximum end-to-end delay for overall Mid Voltage network monitoring and control scenarios

These scalability results are consequently used for a case study analysis that depicts the impact of mean End-to-End delay τ_{SMCU} per SMCU for Smart Market services that are managed from higher voltage levels. For this purpose, we assume that in the worst case a LV/MV substation needs to communicate iteratively with all SMCUs belonging to one LV grid. In this case the delay per LV grid $\tau_{LV,i}$ is calculated as a sum of n SMCUs belonging to the $i-th$ LV grid, $\tau_{LV,i} = \sum_{i=0}^{n} \tau_{SMCU}$. Due to the reason that communication processes are parallelized, the total End-to-End delay τ_{tot} for an overall MV grid is defined as maximum of m individual LV grids, $\tau_{tot} = \max_m \tau_{LV,i}$. In this context, Figure 8 presents the results of this case study for a fixed urban scenario and increasing traffic demand. Corresponding results can be used for deployment planning of IEEE 802.11n Mesh-based networks for the purpose of Smart Market and Smart Grid services. In case of assuming a maximum allowed delay of 1000 ms τ_{tot}, the maximum number of SMCUs per mesh gateways can be derived and varies from 105 SMCUs (single FNN traffic) down to 45 SMCUs for four times FNN traffic demand.
In addition to this case study, Figure 9 analysis the

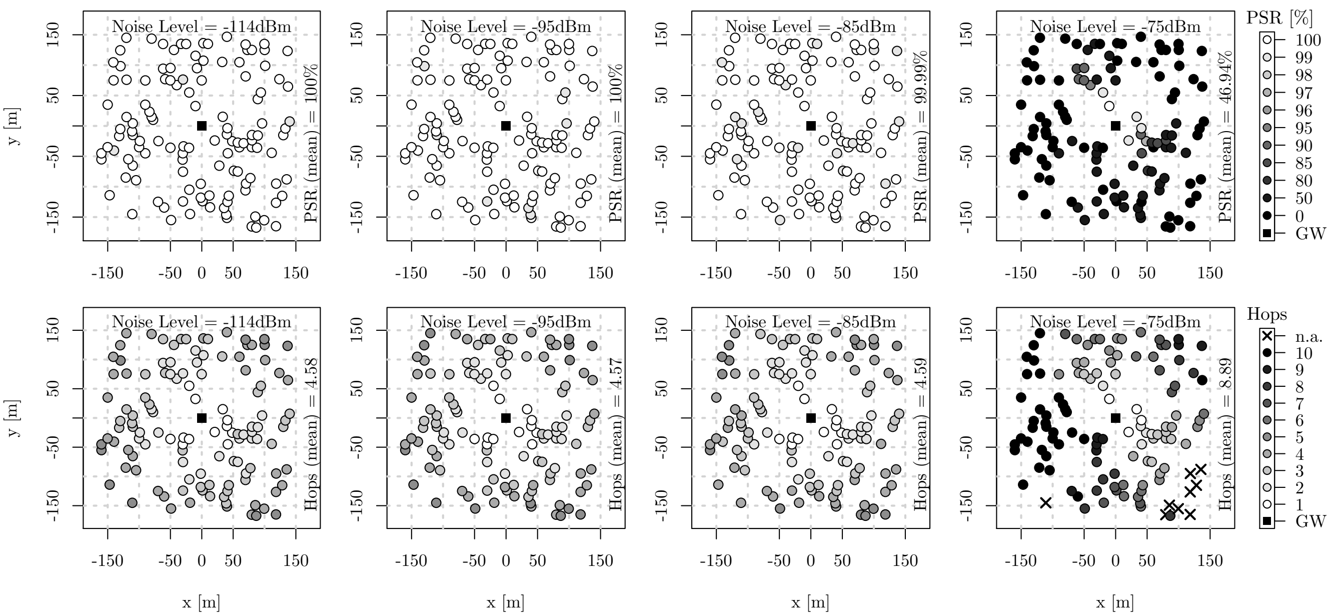

Fig. 9: Reliability Analysis for FNN traffic in urban scenario and different noise levels

reliability of FNN traffic demand in an urban scenario for the previously analyzed fixed number of 105 SCMUs per gateway and different noise levels. Corresponding results for PSR and the number of hops from source to destination show that due to the implemented coding scheme (MCS0, IEEE 802.11n) the system's performance is robust against increasing noise levels. Up to a noise level of -85 dBm performance results are nearby constant and only collapse at a noise of -75 dBm, whereby the related PSR decreases to 47 % and the number of hops doubles up to 9 hops.

VI. Conclusion

In this paper we present a scalability and case study analysis for an IEEE 802.11n Mesh-based neighborhood network. The performance analysis is performed on the basis of extensive simulation models that allow distribution network operators to transfer key results to future deployments. Performance results shows that the proposed network is feasible for European distribution grids and current traffic requirements, but performance is significantly reduced for assumed future demands. In future work, we aim at replacing the IEEE 802.11n mesh technology by Low Power Wide Area Network (LPWAN) technologies that also provide mesh functionality, but operate in lower frequency bands and allow the mounting of indoor and basement antennas.

Acknowledgment

This work has been carried out in the course of research unit 1511 "Protection and control systems for reliable and secure operations of electrical transmission systems", funded by the German Research Foundation (DFG) and the Ideal project, funded by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant agreement no. 03ET7557A.

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