Swarm Grids for a decentralized power grid control

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ABSTRACT

A decarbonized power supply requires not only a significant higher amount of electrical energy generation from renewable energy sources but also a higher power demand of carbon neutral loads. To limit the necessary extension of the power grid a smart control of controllable loads, storages and renewable power sources is necessary. We propose a decentralized power grid control, where participating devices organize themselves to avoid an overload of the power grid. The devices will communicate to each other and exchange information about their power needs and about measurements. With this, they can derive further information about the grid state and avoid an overload. The requirements for the communication are derived and examples for communication implementations are shown. As an example, an application for charging boxes for electric vehicles is presented.

KEYWORDS

Power grid control, controllable load, decentralized control, swarm grid, grid state estimation, charging of electric vehicles, power grid communication

INTRODUCTION

The electrical power system will soon exhibit significantly more loads. However, to most of them load management can be applied. A centralized control requires a significant amount of effort and investments for grid operators. Thus, a distributed control may well be suited to cope with the complexity of the control task. Furthermore, the distributed electricity generation with renewable energies benefits from distributed control of the electricity distribution.

First, an overview of distributed grid control methods is given. Then our approach of a swarm grid control is presented. In the second part, communication requirements for the swarm grid approach are derived and possible communication technologies are presented.

Decentralized Load Management

Flexibilities in the power grid can be used in a variety of ways in an electrical energy supply system and can be useful in different applications. It makes a significant contribution to market integration, supports secure grid operation and helps to restore supply after disruptions [2]. It also makes it possible to reduce load and feed-in peaks, which in turn improves grid utilisation and increases the stability of the system [3]. In order to utilise flexibility effectively, its specific

characteristics must be taken into account. A basic distinction can be made between negative and positive flexibility. These systems can be categorised as generators, loads and storage systems, with each of these categories offering different flexibility potential [1][2][4]. Flexibility is called up either market-driven or through direct incentivisation. In an incentive-based approach, consumers adjust their load behaviour on the basis of economic signals. This contrasts with demand side management, in which a centralised authority intervenes directly in the control of loads [6]. In the heating and mobility sectors in particular, it is not always possible to utilise flexibility solely in accordance with grid requirements, as the energy demand is primarily determined by the intended use. This emphasises the need for intelligent control systems that enable optimal coordination between grid requirements and user needs [7].

Cellular power grids

The decentralized nature of renewable power generation and the large number of upcoming flexibilities make a decentralized approach for the control reasonable. This is reflected in the proposal for a cellular gid system (see Figure 1), which as be worked out by a working group of the Association of German Electrical Engineers (VDE) [8]. It is based on an hierarchically organised grid structure. The concept ensures that control deviations and grid problems are first resolved at a local level before they escalate and involve higher grid levels. At the heart of this approach is the introduction of cell managers who are responsible for the operation of individual grid cells. These cell managers control and coordinate a limited, locally linked infrastructure comprising generators, consumers, storage facilities and energy converters. They take on important tasks such as grid protection, voltage regulation, provision of system services, grid security management and grid monitoring. For the control different stages of urgency are considered according to the traffic light concept [5]. The concept of cellular grids lacks concrete realisations. Only single aspects are shown in practise, such as operating cells in islanding mode [9].

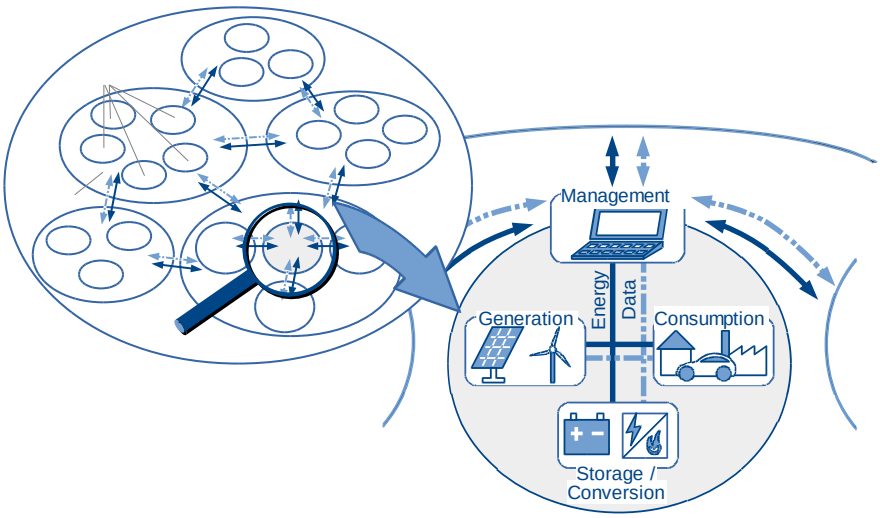

Figure 1. Illustration of a cellular power system.

Agent-based modelling and simulation

An advanced approach to a decentralized control is the use of energy agents. Armin Waffenschmidt [40] works out such an approach and gives an overview of different proposals. The following information is derived from his work.

Agent-based modelling and simulation (ABMS) refers to the simulation of dynamic processes through the repeated interaction of individual software agents over a period of time in discrete

time steps. Accordingly, an agent-based model refers to the modelling environment in which this interaction takes place [11].

An individual agent is characterised by several basic properties [11]:

- Autonomy: An agent acts autonomously and self-directed in the model environment. The possible actions are limited and are orientated towards the respective purpose of the model.

- Modularity: As part of the model, an agent is self-contained and uniquely identifiable. An agent-based model is therefore scalable. In addition, each agent can have different attributes, functions or behaviours as well as the ability to make its own decisions.

- Interaction: Agents have the ability to interact with other agents. This takes place via mechanisms defined in the model.

In contrast to other modelling approaches, ABMS makes it possible to model heterogeneous and complex systems from the perspective of the individual agents that play a role in them [12]. Macal and North [11] describe in a seminal work on ABMS that it has become widespread and successful in an increasingly complex world.

ABMS has already been used in various studies to map processes and the behaviour of individual stakeholders as well as market mechanisms in the area of energy communities. Akhatova et al [13] differentiate between the clusters ‘Diffusion ABMs’ and ‘Exploratory ABMs’ based on the objective of the modelling. Vuthi et al [14] emphasise that many existing ABMS deal with individual, very specific aspects in energy communities, e.g. in the areas of local energy markets, RE, microgrids, heat supply, mobility or regulation.

Mengelkamp et al [15] use an ABMS to compare market designs and bidding strategies of a local energy market. The modelling compares a peer-to-peer market and a market based on the merit order principle with so-called ‘zero-intelligence agents’ (agents without a bidding strategy) [16] and ‘intelligently bidding agents’ (learning agents with a bidding strategy). In connection with this theoretical modelling, a local energy market with a total of 20 households was also implemented in practice as part of the ‘Landau Microgrid Project (LAMP)’ [17, 18].

Zhou et al [19] also created an agent-based framework to simulate energy sharing between prosumers. In addition to agents representing consumers and prosumers, a ‘retailer’ agent, which acts as a passive buy-er or seller, and an ‘energy sharing coordinator’ were introduced. Heendeniya [20] also presents an agent-based model for simulating energy sharing in energy communities, but without the option of comparing different market models. Based on a one-sided merit order auction process, energy can be exchanged via a central coordinator.

In the PEAK research project [21], ABMS is also used to simulate local energy sharing, whereby the higher-level electricity grid and the market-based use of flexibility are also taken into account. The PEAK platform introduced here, represented in the model by a platform agent, "enables prosumers to sell surplus energy to neighbours and, conversely, to buy energy from neighbours if there is an existing demand. In addition, prosumers can offer their flexibility to the grid operator in order to actively manage bottlenecks in the grid." [22] In addition to the prosumer agents, which represent the market participants, the modelling also includes a market agent, which coordinates both the local energy and flexibility markets on the PEAK platform, as well as a grid agent, which represents a grid operator and carries out grid status forecasts. In a paper linked to this project, Regener et al [23] use ABMS to compare different models of how peer-to-peer markets can be implemented in energy communities with active network management, i.e. with the inclusion of network information as in the PEAK project.

The work of Monroe et al. [24] is also relevant, in which an agent-based model of decentralised peer-to-peer trading was compared with real data from an associated research project in Perth, Australia.

Easy Smart Grid

A special sort of agent is offered as software controller by Easy Smart Grid [10]. Contrary to many other energy agents, which use price information, it uses physical grid state variables, from which a kind of pseudo price information as indicators is derived. Furthermore, it allows a hierarchical structure according the cellular power grid approach. The indicators can be used to continuously monitor the grid state of a grid cell. In isolated grid areas, such as microgrids or island grids, the energy balance can be determined by the grid frequency. A low frequency indicates an energy bottleneck, while a high frequency indicates an energy surplus. This enables a physics-based real-time pricing, which allows a fast market reaction without the need for complex ex-ante or ex-post market mechanisms. Vincent Brüggemann has recently shown the functionality in a meshed grid with three different connected power grid cells [39]. In his thesis, he gives a comprehensive overview of the literature on distributed grid control, which has been used here in the first chapter.

SWARM GRID PROPOSAL

Grid agents typically react on soft parameters like price information. This usually corresponds to the yellow range of the grid traffic light concept [5], where hard switching operations are avoided, but market mechanisms are used to avoid grid overload. The red traffic light state requires hard switching to prevent damage. Here, we present a distributed control solution to cover his case.

A proposal is made here for the control of such a cellular electricity grid structure, which the authors call a ‘swarm grid’. The name refers to the swarm-like control structure, which does not require a higher-level control system to coordinate the grid components.

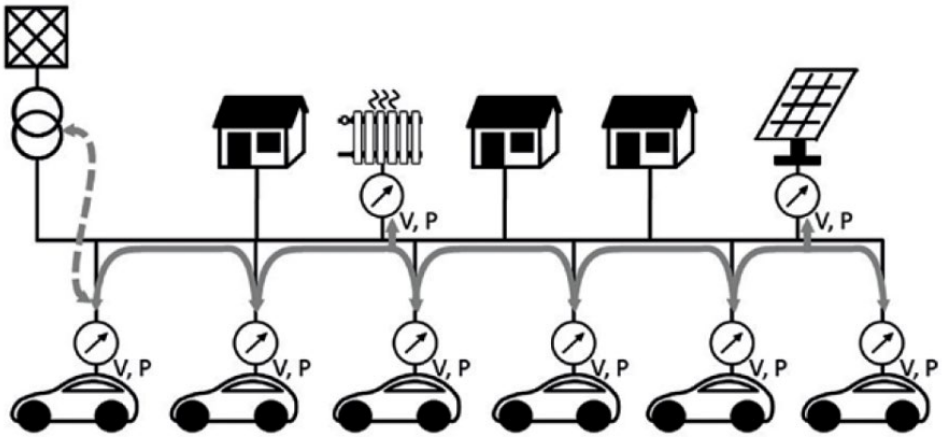

Figure 2. Illustration of a decentralized grid control according to the swarm principle.

In a swarm (e.g. a school of fish), the members are able to measure (e.g. fish can see), know or communicate about the others (e.g. keep an eye on each other), decide and react (e.g. change swimming direction). The components in a swarm grid should also be able to measure, communicate with each other, process the information and react. Specifically, the concept presented includes the following:

The components are able to measure the voltage at the connection point and the power or current of the device connected to this point. In a more advanced environment, the devices are able to measure the voltage angle or even the grid impedance. The components communicate with each other by exchanging the measured information (see illustration in Figure 2). In this way, each component can obtain an overview of a much larger part of the network than just the connection

point. Preferably, the communication is limited only to components in the same network branch to communicate with each other.

Taking the measured values into account, each grid component is able to calculate a detailed picture of the current grid status. This is done by a grid state estimation [25] [26].

The procedure may include methods for estimating the grid topology from the measurements and the subsequent calculation of voltage and current states in the determined power grid [27]. This enables components to automatically adapt to possible topology changes on a regular basis and seamlessly integrate them into the network when additional components are added.

If the topology is known, it is then possible to calculate line currents from the voltage measurements at the known nodes and thus gain an overview of the load situation

From these calculations, the components can make decisions about their behaviour, e.g. power management to avoid overload, using an optimization algorithm. A possible method is described in [28]

Naturally, this only applies to controllable loads whose power can be modulated without significantly impairing their function. This can apply to components such as charging boxes for electric vehicles, electric heat pumps, air conditioning controls, batteries or combined heat and power (CHP) systems. Such components will dominate future distribution grids in a society with 100 % renewable energy.

This publication presents details of the communication concept. First the requirements are derived and then communication methods are proposed.

REQUIREMENTS FOR DATA COMMUNICATION

To specify the required data rate for the communication, the amount of data, which has to be transmitted must be specified. One has to distinguish between initialization information and operational information.

Initialization data

Initialization information is transmitted between the devices, when the system is set up the first time or when a device is added to the system or device parameters have changed. This may include information about the grid topology and general data of the connected devices like device type, maximum power capability or capacity (if available). The transmission of this information is not time critical and the communication has no critical specifications. It is not further considered here.

Real time data

Operational information includes e.g. measurement data and is necessary for the devices to react to grid situations. This data needs to be transmitted in real time and is thus time critical. Table 1 lists a proposal for a data set to be transmitted as operational information.

Phase voltage: Laboratory measurements revealed that precise voltage measurements are crucial for a reliable grid state estimation. A precision of less than 0.1% is required, as learned from experience. Thus at least 2 bytes are necessary to describe one voltage measurement, which results in 6 bytes for a three-phase measurement.

Phase currents: The precision of the phase currents has been experienced to be less critical. However, they might exhibit a wide range. To ensure a suitable precision in this case, also 2 bytes per measurement are assumed as appropriate. Again, this adds up to 6 bytes for three phases.

Power Factor: 2 bytes per phase are used here as well to maintain the precisions, when calculating real and imaginary parts of the current.

Voltage phasor: The voltage phasor cannot be measured as absolute value, but only relatively against other devices. The time between a reference time signal and the next zero crossing of the voltage slope is used as measurement value for each device. As reference time signal e.g. the time signal of the global positioning system (GPS) can be used. By calculating the difference between two of these times, the time shift of the two voltage signals of two devices can be calculated and thus the voltage phasor relative to each other. Since the final signal is the difference of the two measured values, each measured value needs a high precision and therefore 2 bytes are reserved for each phase.

Not all measurement units are able to measure the voltage phasor. In this case, an estimation error for the line currents may appear. However, it has been shown that for typical use cases the error ´calculating line currents remains below 10%, if the voltage phasor is not considered [1].

Table 1. Message content and length.

Item	Bytes
Phase voltages	6
Phase currents	6
Power factors	6
Voltage phasors	6
Required energy	2
Required ending time	2
Station ID	2
Status	1
Check sum	1
SUM	32

Required energy: The required energy is the amount of energy the device needs until the ending time, e.g. to charge an electric vehicle until a desired final time or to operate a heat pump to maintain the temperature in a house. This value and the required ending time are transferred such that all devices can use them for their decision on power reduction, if the grid is detected to be overloaded. To maintain a reasonable precision over a wide range of values, two bytes are used.

Required ending time: Specifies the time until a device needs the specified amount of required energy. The resolution should be at least 1 min, which leads to 1440 values per day. Therefore 2 bytes are necessary.

Station ID: The station ID identifies the device. The further estimations are based on maximum 256 devices per power grid (see below), which would require only one byte. However, it might be the case that neighboured grid areas need to communicate in the future. Therefore, two bytes are reserved for the station ID.

Status: The status byte may indicate the status, warnings or errors of the devices. It will be defined later. However, it is assumed that 256 states, which is 1 byte, will be sufficient for the application.

Check sum: The information will be broadcasted by the devices to all other devices at once. Then the protocol does not include confirmation of the received information (**see below**). Therefore, a 1 byte check sum is provided to allow a check of the received information.

In total 32 bytes are required for the real time data transmission.

Number of devices

The require capability of the data transmissions also dependent on the number of connected devices. To determine, how many devices can be expected, exemplary power grids are investigated. First, exemplary low voltage reference grids derived by Jörg Scheffler [36] are analysed. He shows exemplary power grids for different types of settlement areas. For each of the given power grids, the number of connected houses is counted, sorted by the power lines connected to the transformer.

Table 2. Number of connected buildings in different exemplary low voltage power grids by Scheffler [36]

Line No.	Rental houses	Sub-Urban	City centre	Rural village
1	1	18	8	20
2	1	22		34
3	1	35		1
4	1		8	10
5	1	16	8	
6	1	35	6	
7	1		6	
8		24		
Sum	7	150	36	65
Max per line	1	35	8	34

Table 3. Number of connected buildings in different exemplary low voltage power grids in the Ahrtal valley.

Settlement area	Rental houses	Sub-Urban	City centre	Rural village		
Line No.	Trafo 1	Trafo 1	Trafo 1	Trafo 1	Trafo 2	Trafo 3
1	28	3	2	7	2	13
2	9	10	6	5	13	19
3	7	22	9	20	18	16
4	3	16	2	2	27	28
5		16	4	9	10	
6		17	4	8	5	
7		8	4			
8		13				
Sum	47	105	31	51	75	76
Max. per line	28	22	9	20	27	28

The results are listed in Table 2. Here, a maximum number of 35 houses per line and 150 houses per grid area are counted. To verify, whether this would be realistic, real existing low voltage

grids are analysed. They are in the Ahrtal valley and the grid data was provided by the local grid operator to the authors. The results listed in

Table 3 show results in a similar range. For both, the sub-urban are shows the highest amount of houses per grid area.

To derive the number of expected devices it is assumed that each house will have one energy management system according to our proposal, which will manage multiple devices within one house. To have some margin, further considerations will assume a maximum of 256 (corresponds to 1 byte) devices, which are connected in one power grid. The final solution will not be limited to this amount. However, if there will be more devices connected, some of the specifications might degrade.

Data rate and protocol

In our concept, each device gets the operational data of each other device. If each device would communicate individually with each other device, $n \cdot (n\text{-}1)$ transmission operations (n = number of devices) would be necessary. In order to significantly reduce the number of transmission operations, each device broadcasts its information to all other devices simultaneously. Then only n transmission operations are necessary. Unfortunately, then the TCP/IP protocol cannot be used, because it does not allow broadcasting. Instead, the UDP/IP protocol is used. However, broadcasting with UDP does not include a confirmation, if the information is correctly received. Therefore, data integrity has to be checked "by hand" in the upper level of the communication stack.

Using a broadcast protocol, the total number of transmitted bytes N_{transm} are:

$$N_{transm} = N_{messg} \cdot N_{dev} \tag{1}$$

N_{messg} is the number of bytes in one message and N_{dev} is the number of devices.

In this considered case it is N_{transm} = 32 Bytes · 256 Stations = 8192 Bytes.

To achieve a real time communication, all operational data should be exchanged within 1 s. Thus, the required minimal data rate is 8.192 kBytes/s for the net data payload. Since the UDP protocol and the different physical layers may add additional information to the data packages, this value is to be considered as the theoretical minimal data rate, which must be higher in practice.

COMMUNICATION METHODS

The following communication methods are considered up to now:

- Powerline communication (PL)
- Broadband Powerline Communication (BPL)
- Lora
- 5G

These methods have been tested either in our laboratory test setup or in real life environments.

Powerline communication (PL)

Powerline transmission technology transmits data information using the power cables. It can be classically divided into in-house and access technology. In the area of in-house communication, PLC adapters are based on the Homeplug AV standard, for example, using modulation frequencies of up to 68 MHz and thus enabling data rates of typically up to 500 Mbit/s (single in single out, SISO) and 1200 Mbit/s (multiple input multiple output, MIMO) under ideal

laboratory conditions. In reality, measurable powerline transmission rates in the in-house sector are around 200 Mbit/s.

In the access PLC area, i.e. for communication outside buildings (the classic last mile), two different powerline technologies are commercially available (see also illustration in Figure 3).

As narrow band powerline communication (NPL) the G3-PLC technology is traditionally used in Germany up to 500 kHz. This technology can be connected both 1-phase and 3-phase. However, due to the chip availability and specification, it only allows operation in SISO mode and not in MIMO mode. Although very long ranges of up to several kilometres can be achieved due to the frequency range used, the data rates of up to 80 kbit/s on the IP layer are limited at the same time. In principle, G3 technology is not limited to the frequency range of 150 kHz to 500 kHz.

The second PLC technology available in the access sector is broadband powerline (BPL) technology. It operates in the frequency range from 2 to 30 MHz and enables data rates of up to 200 Mbit/s on the physical layer. This technology also only uses the SISO mode. Due to the frequencies involved, BPL technology achieves higher data rates than G3-PLC technology, but suffers from a shorter range. This means that more repeaters have to be used, which in turn reduces the effective data rate and drives up investment costs.

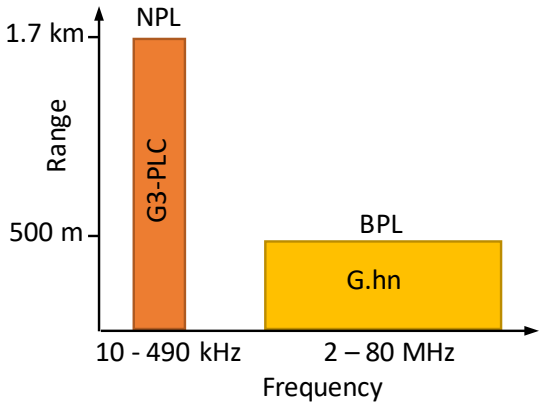

Figure 3. Powerline communication methods.

Broadband Powerline Communication (BPL)

Broadband Powerline Communication (BPL) has been tested with devices “Magic 2 LAN DINrail” by company Devolo. The chipset consists of the 88LX5152 and 88LX2720 models from MaxLinear. The chip uses the G.hn standard and is therefore compatible with other devices of the same standard, regardless of manufacturer. The adapter works in the BPL range at a frequency of 2 to 30 MHz and uses multiple-input multiple-output (MIMO) technology. With MIMO, signals can also be transmitted and received in parallel on multiple paths. This increases the data rate.

It has been tested in our laboratory environment, where we have 6 racks, where each rack consists of a battery and three single power converters to charge and discharge the batteries (see Figure 4). The transmitted spectra were measured with a broadband spectrum analyser as shown in Figure 5. It turned out that BPL transmission was very sensitive against the disturbances generated by the power converters. As soon as they were operating in a reasonable power range, no communication was possible. Since this may also happen in a real power grid, it was concluded that BPL would be too sensitive to be use in a real power grid. Furthermore, its distance range is principle smaller than the range of narrow band powerline communication and

the possible high bandwidth of up to 200 Mbit/s is not needed for the application. Therefore, further experiments were abandoned.

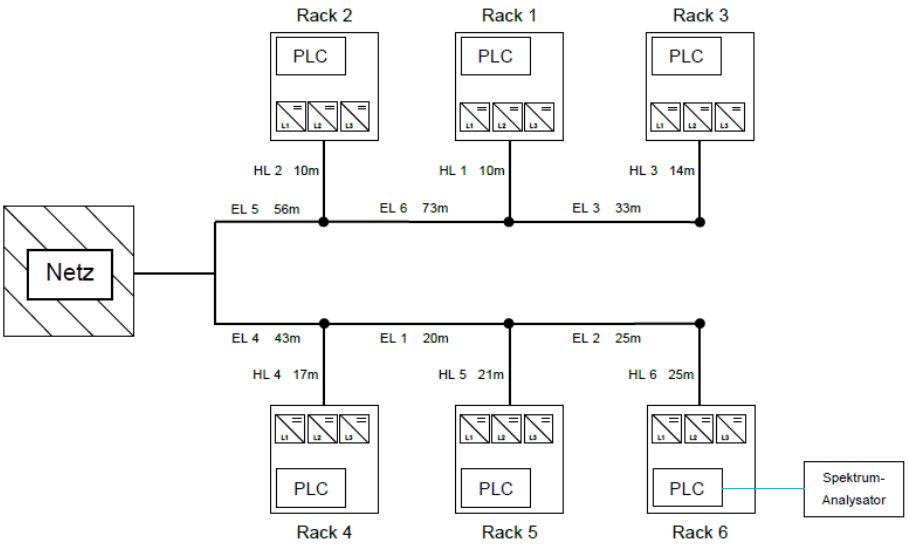

Figure 4. Laboratory grid topology used for Broadband Powerline (BPL) Communication investigations.

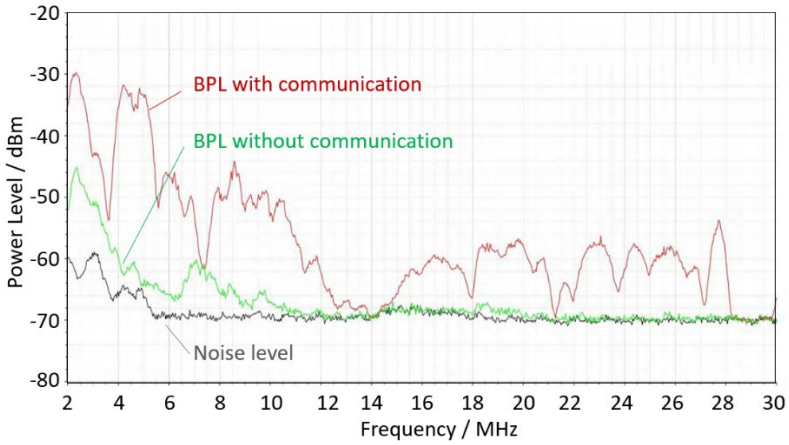

Figure 5. Measured BPL Spectra.

Narrow band powerline communication (NPL)

To test the narrow band powerline communication (NPL), also referred to as powerline communication (PLC), devices by company devolo are used. We used the adapter devolo G3-PLC Modem 500k. These devices support a range of up to 600 meters of cable length and operate within a transmission frequency of 100 to 500 kHz [30]. One advantage of lower frequencies is that they extend the range of the PLC network. Previous research has also demonstrated that lower frequencies are less susceptible to temperature variations [31].

They use G3-PLC standard (according to ITU-T G.9903), which is a standard developed for Access Powerline Communication (Access-PLC) for exchanging meter data between consumers and energy producers within the smart grid (intelligent power network). The Access-PLC technology works in the frequency range of 150 to 500 kHz. Here some of their parameters are listed:

- Gross data rate of up to 240 kbit/s, which corresponds to 65 kbit/s (net) for TCP/IP data transmission
- Operating frequency 150 kHz to 500 kHz
- OFDM modulation method
- Dynamic routing mechanism supports mesh networking and automatic selection of the optimal transmission path
- Automatic Repeat Request (ARQ) improves error detection and data reliability
- Dynamic connection adjustment to select the optimal data rate based on channel conditions

The available net data rate of 65 kbit/s just matches for the required data rate of 8.192 kBytes/s.

This technology has been tested by Lukas Alexander Mischker [41]. The results presented here are taken from his report.

PLC is commonly used for point-to-point connections and employs IPv4 for connecting and addressing devices. To implement the broadcast function we implemented IPv4 multicast. This multicast allows a source to communicate with a group of destination members within the network, effectively reducing network load [2918].

For our data, we chosed to send packets of 32 bytes as derived before, such that the available data rate does not present any issues. This work will therefore concentrate on the reliable delivery of the packets. Since IP multicast is implemented on top of the UDP protocol, the host cannot verify whether all destinations have received the transmitted packets. As a result, packet loss becomes the key performance metric in our analysis.

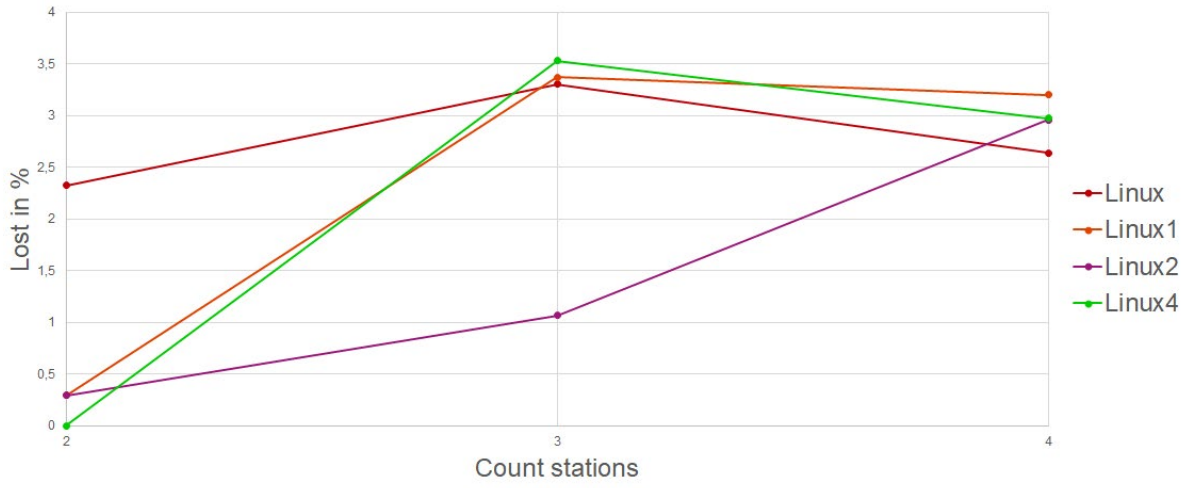

Figure 6. Package loss with update time of 2 s

Powerline test setup. The test environment was the 9th floor of the Cologne University of Applied Sciences building. Connections to other floors or buildings could not be established due to the building's cable topology and missing documentation. Four Raspberry Pi 4s were connected via the Devolo devices to form the network. One device was placed on a different phase to determine whether this would significantly affect the connection's reliability. All stations experienced a ping delay of approximately 200 ms when communicating with other stations. Throughout the tests, all stations continually checked for new packets from the other stations. Each test lasted 15 minutes. The update wait times tested were 0.5, 1, 2, and 5 seconds, with two to four stations participating in each scenario

Powerline results. It turned out that the update wait time is a crucial parameter, which determines the loss rate. With a update wait time of 2 s, package loss of 3.5% could appear (see

Figure 6). The station connected on a different phase, which relies on capacitive coupling between the phases, experienced the highest packet loss at 4%. Due to the lack of documentation on the building's electrical wiring, it is not possible to determine whether this is caused by the phase coupling or the additional cable length. Additionally, this could be a result of fewer packets being sent, meaning a longer test might result in decreased packet loss.

Further analysis of the data **Fehler! Verweisquelle konnte nicht gefunden werden.**revealed that the powerline modules began resending the same packets multiple times when a certain volume of data was transmitted within a specific time frame.

Additionally, we placed one device on a different electrical phase from the other three stations. This did not result in noticeably higher packet loss for that station, further supporting the idea that the packet loss is due more to how powerline technology allocates transmission intervals and the fact that data is being transmitted faster than the protocol allows.

LoRa

LoRa is a broadcast technology and operates as a frequency-based network, using small chirps to encode its data. It was developed by the LoRa Alliance to reliably transmit small amounts of data over long distances while maintaining low power consumption. LoRa can operate on different frequency bands, notably 169 MHz and 430 MHz in Asia, 433 MHz and 868 MHz in Europe, and 915 MHz in America [32]. It is essential that the antenna used is capable of transmitting within these frequency ranges. LoRaWAN is designed for a star topology, with a central access point connecting the network to the internet. However, in a LoRa network, all smart meters with the same LoRa configuration can transmit information, meaning that they automatically form a mesh network without additional setup.

Previous scientific studies have shown that LoRa's range can be significantly reduced if the line of sight is obstructed. For example, in [32], the maximum range was found to be 250 meters with a stationary sender and 120 meters with a mobile sender in a heavily obstructed area. The connection failed when the sender was moved inside a building. On the other hand, [33] concluded that a LoRaWAN gateway could potentially reach around 80% of all end devices within a 1.5 km range in an urban environment.

This study aims to investigate whether the range can be significantly extended by adjusting the transmission power and spreading factor. Therefore, the primary parameters measured in this work are packet loss and the maximum range. Two separate tests were conducted: the first was a short-term analysis to determine if a successful connection could be achieved between four senders. The second was a long-term test over five consecutive days to assess whether external factors impact the measurements. The long-term was run within only station 2 and 3 as for security reasons the other stations could not be used without supervision.

LoRa test setup. The test setup is described in Figure 7. Each station was equipped with a Raspberry Pi 4 connected to a RAK3276 module via UART. During the test, 32-byte packets with an identifier and a rolling number were sent every 52 seconds, with a spreading factor of 10. This resulted in a duty cycle of 1%. Since the test was conducted in Germany, the regulations of the Federal Network Agency, as outlined in [8], were applied. This required the use of frequencies between 869.40 MHz and 869.65 MHz, which allow a duty cycle of 10% and a maximum output power of 500 mW. Our stations transmitted at around 163 mW, as this was the hardware's physical limit. The test was conducted between two buildings at the Cologne University of Applied Sciences. Figure 2 shows an approximate layout of the distances between the stations. Attempts to connect other buildings on campus over longer distances were unsuccessful.

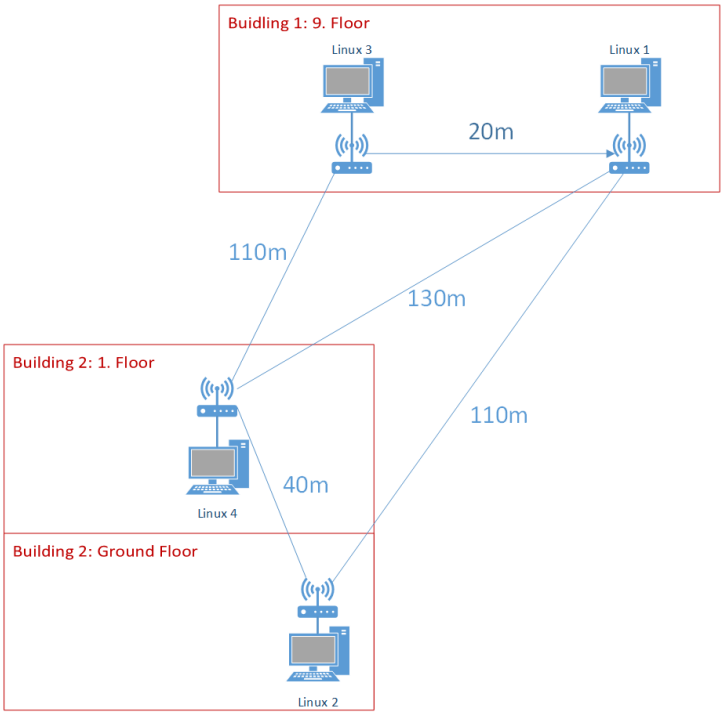

Figure 7. (Fig. 2.) Test setup for Lora

LoRa results. During testing, the first noticeable effect was that the placement of the stations had a significant impact on network reliability. An antenna placed closer to a window was much more likely to establish a stable connection with the other stations. Among the stations shown in Figure 7, stations 1, 2, and 3 had stable connections with high package receiving rates. Station 4 could only connect reliably to station 2 with a reduced receiving rate between 60% and 705 (see Figure 8). This was probably due to the concrete walls between station 4 and the others.

Figure 11 demonstrates sporadically throughout the entire test period failures occurred. These connection losses lasted for about half an hour, during which no packets were received. The cause of this issue could not be identified.

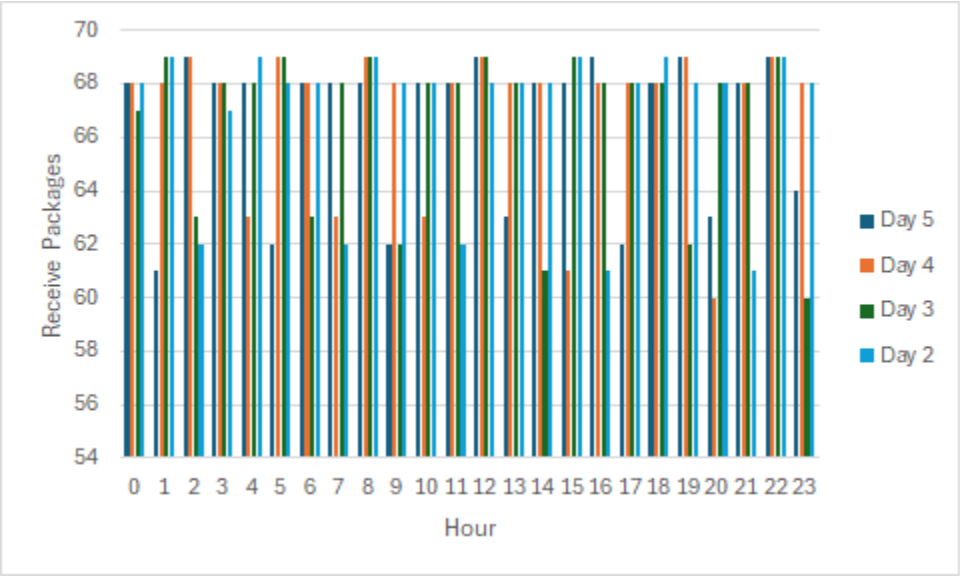

Figure 8. Received packages of Station 3 from station 2

5G Standard

The investigations about the 5G-satndard are performed by Leif Terstegen [46]. His results are presented here.

5G is a framework for various technologies and protocols that together enable the next generation of mobile communication. It was primarily developed for mobile devices and includes a variety of standards designed for different applications.

One standard that supports local communication via mesh networks is DECT-2020 NR (NR+). All other standards rely exclusively on cellular communication and are therefore not suitable for mesh operation. Nordic Semiconductor is currently the only company that manufactures chips with an integrated DECT NR+ modem. To support this research project, Nordic Semiconductor provided several nRF9151-DK boards.

NR+ is a modern standard of the DECT family and represents a further development of the previous DECT standard, which was primarily used for cordless telephones. This standard was developed specifically for applications in the Internet of Things (IoT), smart home and smart metering sectors [34].

5G Tests. In the first test, free-field communication was tested in direct line of sight. Measurements were taken at 5-meter intervals over a distance of 270 meters. Each measurement consisted of 3660 messages, which included all combinations of TXP, MCS and different message lengths.

The messages received were analyzed in terms of packet loss as a function of TXP (Figure 1) or MCS (Figure 2). As the results showed strong fluctuations, a moving average with a width of seven measurements was applied to visualize the overall trend. The analysis showed that the transmission power had a significant influence on the packet loss. Already at a transmission power of TXP1 (-40 dBm), considerable packet losses occurred from about 5 meters, while at higher transmission powers (from TXP10, 10 dBm) hardly any significant losses were detected even at 270 meters. In addition, it became evident that more complex modulation types led to higher packet losses, particularly as the distance between transmitter and receiver increased.

These results make it clear that both modulation and transmission power are decisive for transmission quality. Higher transmission power and simpler modulation types enable more reliable data transmission.

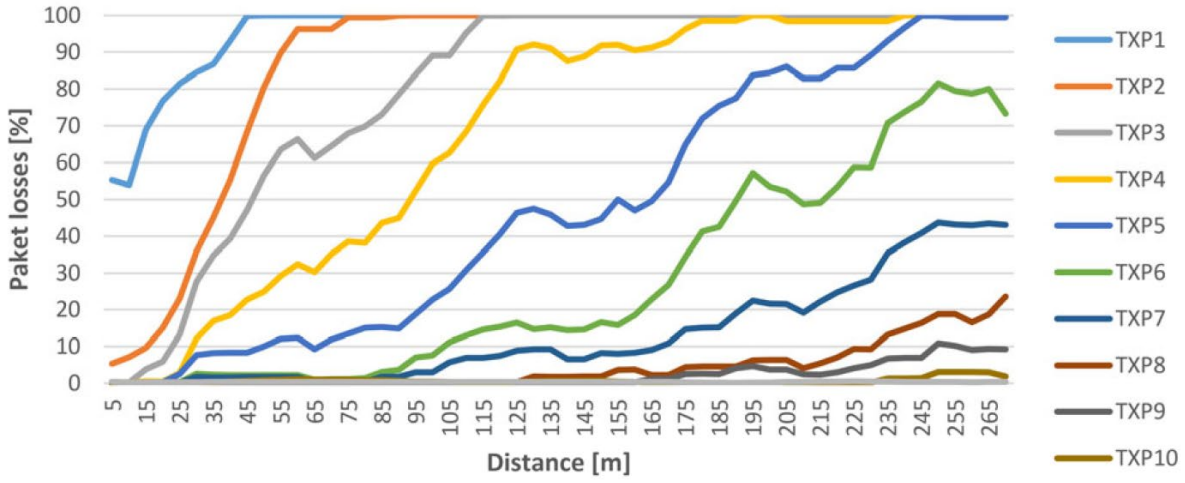

Figure 9. (Figure 1:) Packet losses per TXP.

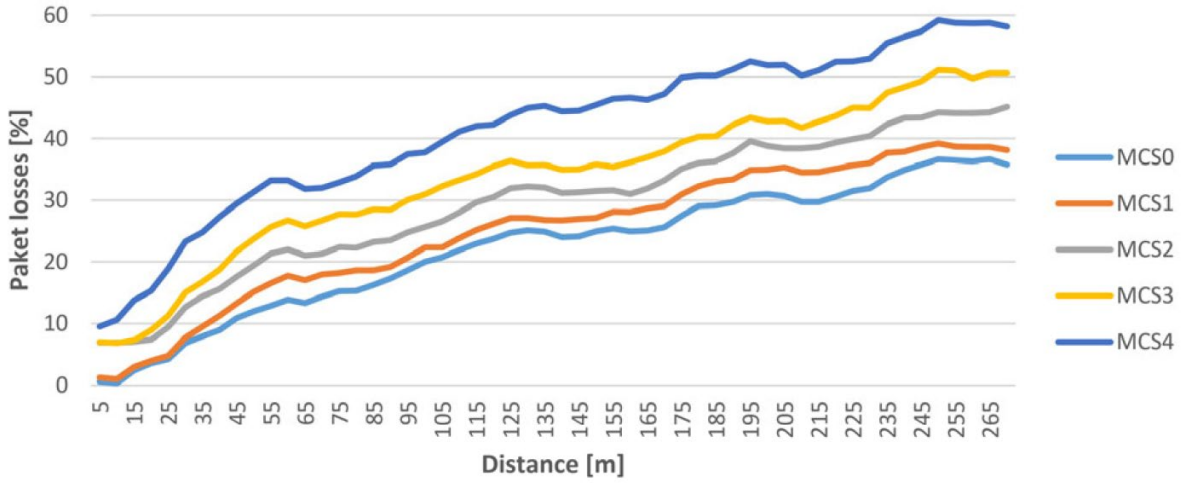

Figure 10.(Figure 2:) Packet losses per MCS.

A second test is performed as an extension of the first test. Here, only messages with the highest transmission power and the simplest type of modulation were transmitted in order to determine the maximum possible transmission range. The evaluation of the results showed that even over a distance of 760 meters, most messages were successfully received without packet loss. The average packet loss over all measurements was only 0.3%.

Further tests wee performed in a living are environment. It included setups with transmitter in the basement of buildings, which lead to poor results.

Despite these challenges, the results clearly indicate that the placement of devices is crucial for maintaining stable connections. The network's capability to achieve high throughput could be significantly enhanced if devices are placed in elevated areas such as outer building walls, balconies, or roofs.

Summary on result 5G. The 5G standard uses DECT NR+ as a robust radio protocol that meets the requirements for mesh operation for local communication. By using license-free frequency bands, very high data rates can be achieved, which are more than sufficient for the transmission of small measurement data. Even if the frequency range is subject to restrictions and parallel transmissions are missing, stable data rates of around 1 Mbit/s were achieved. For measurement data with a size of 100 bytes and a disrupted connection with 99% packet loss, around 6000 messages per minute could still be transmitted.

The transmission works reliably with a direct line of sight even over distances of more than 760 meters. However, obstacles such as walls or other barriers significantly impair the transmission quality. In urban areas and in dense mesh networks, the nRF9151-DK with NR+ is suitable for data transmission between smart meter gateways. The efficiency of this transmission can be increased even further if the standard is fully implemented, including the data link layer, MIMO operations and the use of multiple frequency bands.

CONCLUSIONS

In summary, 5G (using DECT NR+), Powerline Communication (PLC) and LoRa each offer unique advantages and limitations for communication between smart meter gateways. 5G shows strong performance with high data rates, long range in line-of-sight conditions, and suitability for dense mesh networks, especially if the advanced features of the protocol are fully exploited. PLC, while leveraging existing infrastructure, exhibits significant packet loss even at modest data rates, raising concerns about its scalability and reliability in larger, more complex networks. LoRa, while advantageous for long-range communications on licence-free spectrum,

suffers from high packet loss due to interference and regulatory constraints, making it less suitable for the frequent, multi-hop transmissions typical of smart meter mesh networks. Overall, 5G is the most promising solution, especially in urban environments, while PLC and LoRa may be relegated to niche or complementary roles.

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