Communication Requirements for Optimal Utilization of LV Power Distribution Systems

Koojana Kuladinithi[1(✉)], Helge Fielitz[2], Maciej Muehleisen[1], Christian Becker[2], and Andreas Timm-Giel[1]

[1] Institute of Communication Networks, Hamburg University of Technology, 21071 Hamburg, Germany
{koojana.kuladinithi,maciej.muehleisen, andreas.timm-giel}@tuhh.de

[2] Institute of Electrical Power and Energy Technology (IEET), Hamburg University of Technology, 21071 Hamburg, Germany
{helge.fielitz,c.becker}@tuhh.de

Abstract. Decentralised electric power generation using renewable energy sources are becoming increasingly popular. As a consequence, decentralised electrical energy sources such as photovoltaic (PV) are connected to the low voltage (LV) power grids. This raises the requirement of dedicated and coordinated control of loads and power generation to realize intelligent power management in order to guarantee the full use of the available power transmission capacity. In this paper, we have analyzed the communication requirements when coupling a communication network with the LV power grid to enhance the maximum utilization of the existing physical resources. This paper identifies the exact communication requirements needed in enhancing the utilization of the LV power grid. There are, mainly two requirements: Firstly, the necessity of a fast reaction time in the range of 10 ms up to 300 ms, when the power system operates closer to its maximum utilization. Secondly, the necessity of a very low synchronisation time that should be less than 5.6 µs (required for the phasor measurements). We further discuss the usability of existing communication technologies and architectures for the discussed scenario.

Keywords: CPN · LV power grid · Latency with ultra low jitter · Reliability · Time synchronisation · Communication networks

1 Introduction

Information and communication technologies penetrate more and more into our physical world. In production technology, this is referred to as ***Industry 4.0*** and, in more general as Cyber Physical Systems (CPS) or Cyber Physical Networks (CPN). In CPNs, the interaction between control of physical (embedded), often distributed, systems and communication networks is becoming increasingly more important. The control loops of physical systems can typically cope with constant or no delays. Because of variable and stochastic delays and packet losses in real communication networks, reliable control cannot be guaranteed.

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Following the increasing number of renewable energy generators (photovoltaics, wind power, solar power, etc.), generation of ***Electrical Energy (EE)*** is now much more decentralised than in traditional power grid setups. CPNs, such as ***EE Networks*** require a tight coupling between communication networks and physical objects, which might not be sufficiently provided by the standard TCP/IP based Internet protocol suite [1]. A number of research projects have identified different communication architectures to overcome some deficiencies in the current Internet such as dynamic service provisioning, scalability and changes in traffic patterns. Some of the prominent architectures are Information Centric Networking (ICN) [4], Netlet [2], Open Connectivity Services (OConS) [3, 5] and the Generic Path (GP) architecture [6]. These architectures, though widely discussed are primarily meant to address the requirements of human centered communications; they are not specifically made to standardize or to have any implementations for CPN applications. CPNs have a ***Command-Report*** [7] communication model, where the *Command* message is used to trigger a specific physical change of a certain node and the status of the change is observed in the next cycle through the *Report* message.

The main objective of this paper is to analyse the communication requirements for one of the CPN application areas in ***EE networks***, viz., LV power grids, and evaluate whether IP based technology can satisfy their communication requirements or, whether future network architectures are required to enhance the utilization of the grid by coupling the power system and the communication system.

Our motivation scenario, discussed in the next section, highlights two main requirements that help to enhance the utilization of the LV power grid, namely, the ***reliability and QoS of the communication channel*** and the ***time synchronisation in measurements***. Section 3 is devoted to highlighting the state of the art work done in power grids in general. We have done an initial investigation on how the identified requirements can be achieved with existing technologies. The results of this feasibility study will be discussed in Sect. 4. The last section concludes the paper highlighting the research challenges to achieve the optimum utilization of the LV power grid by integrating communication technologies.

2 Motivation Scenario

In this section, we discuss a CPN application scenario, which focuses on enhancing the utilization of the LV power grid. As the use of decentralized electric power generation by renewable energy sources becomes increasingly popular, the utilization of existing electrical power grids is shifting significantly from unidirectional to bidirectional power flows. This applies especially to the LV power grid to which a continuously increasing number of decentralized electrical energy sources as PV is being connected. This does not only lead to electric power flows from LV grids into overlaid medium voltage (MV) grids but also to a higher utilization of existing LV cables and lines. This is due to largely varying operating modes, which cover all possible combinations of high/low load and high/low generation. Existing LV grid infrastructures are typically designed to be very robust, allowing to transmit electrical currents occurring in maximum load scenarios. However, they are specifically dimensioned for transmission of electrical power from MV supply busbars to LV loads and not for transfers of decentrally generated electrical power. Significant increase of PV generation capacity installed in existing grids and corresponding operational scenarios may therefore lead to currents that are close to or beyond the allowed current limits of the installed lines, cables and transformers, if loads and generation units are operated without mutual coordination. Exceeding current limits of existing cables and lines leads to line trips initiated by protection devices. As shown in Fig. 1 reaction time of protection depends on current overshoot.

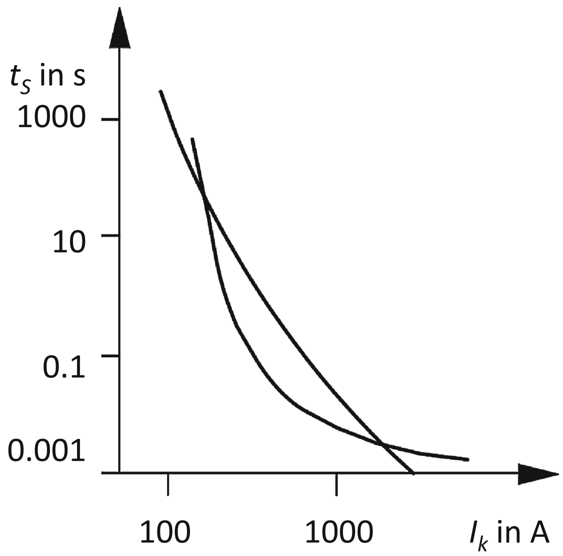

Fig. 1. Typical time-current-characteristics of line protection (t_s: reaction time in seconds, I_k”: current in mA) [12]

Dedicated coordinated control of loads and power generation units in these cases would allow intelligent power management of the whole system [15]. Its task would be on the one hand to guarantee full use of available power transmission capacity and on the other hand to safely keep each transmission device of the LV power grid below its allowed current limits. This could be accomplished for instance by switching on consumers connected to the same grid section as the generating PV systems when producing large amount of power in order to prevent electric power flowing into the overlaid MV grid and overloading the transmission lines of the LV grid section resp. transformer to the MV grid. When these possibilities have been fully exploited, PV generation can be commanded off or be limited in electric power output as a further measure to be initiated during high power generation scenarios. This leads to the same effect to relieve existing cables and lines of the LV or MV transmission devices of the surrounding grid. Hence, power management in LV grids can be used as described in order to optimize and increase the utilization of existing power transmission capacity when the number of decentralized generation units increases. By this, it can be avoided to reinforce given transmission capacity of the LV grid i.e. to install new stronger lines, cables and transformers.

Reliable bidirectional communication channels are a key enabler for realization of such kind of intelligent power management systems to increase the utilization of the LV power grid. In addition, controllability of generation units and loads, and their robust access through communication interfaces are necessary prerequisites for power management purposes.

- ***Reaction times of transmission line protection*** in case of currents exceeding the limits is typically realized to be quite fast, i.e., in the range of a few ***10 ms up to 300 ms*** (see Fig. 1). Power management activities that are designed to keep currents below their allowed limits are consequently required to operate within a significantly shorter timeframe in order to guarantee realization of corrective control actions before protection devices are triggered by high currents to trip lines. Hence, power management with a distributed set of decentralized power generations and loads generally needs to operate under time-critical circumstances with reliable communication channels and short delay times.
- Due to different time-criticality requirements of control actions, it must be also ensured that the communication network is able to prioritize messages for monitoring and control of loads and generation systems. In this context it is also necessary to enable ***capturing of status measurements in a time-synchronous manner*** to enable control and power management instances to consistently supervise the system state.

3 State of the Art: Preliminary Work for LV Power Grid

Large interconnected electrical power systems typically operate on different voltage levels, i.e. high, medium and low voltage, depending on the distance to be bridged. High voltage level systems are used to transmit electrical power from power plants to the substations over large distances. Therefore, this part of the grid is called transmission system. Medium and low voltage levels are used to distribute electrical energy to the consumers. This network is referred to as distribution system due to its functionality [11]. Fully automated measurement and control systems are common for transmission systems. Commands for control of system components and measurement data are transferred using specifically dedicated data networks that are independent from public communication systems. A so-called state estimator is an essential part of the power system control and monitoring system [11]. It receives physical measurements of power, currents and voltages in order to statistically estimate a consistent system state from the captured measurement data.

For protection of high-voltage systems, coordinated digital protection relays are typically applied to protect generators, transformers and transmission lines against overloads and short-circuits by automatically disconnecting faulty devices [13]. Thus, transmission systems Supervisory Control And Data Acquisition (SCADA), Energy

Management Systems (EMS) as well as protection systems are widely used. Standardized communication links and protocols for control and protection of high-voltage power systems are used, off the shelf solutions are available by many manufacturers.

For distribution grids, the situation is different. Usually there are no SCADA/EMS systems continuously implemented. Consequently, grid control and switching operations need to be executed manually in many distribution systems. This especially applies to LV grids, where additionally traditional fuses are used instead of digital protection relays [13]. Furthermore, methods like state estimation are typically not used due to the fact that measurement coverage of LV distribution systems is very low.

Due to the ongoing energy transition, there is a severe change in the use of electrical power grids. Following the increasing number of renewable energy generators (photovoltaics, wind power etc.) generation of electrical energy is now much more decentralized and connected to the low and medium voltage grid. This leads to a change of traditional power flows from top-down towards a bi-directional power flow over different grid voltage levels.

As a consequence, new challenges in the control of the grid are coming up. Mainly for currently uncontrolled distribution grids there is a strong demand of research towards empowering the traditional power grid to be able to integrate many decentralized renewable energy producers without extending its given structure, but by actively controlling and coordinating generation, loads and further intelligent controllable devices like energy storages [14].

The installation of smart meters has started in several areas; a large number of publications is available on the connection of a meter to a base station for billing purposes. Focus of this contribution is not on smart metering, as the update rates of the measurement results are too slow for real-time control and state estimation of the power grids [14].

Combining a fast and reliable data transmission system with the existing low voltage power distribution grid can solve today's challenges with the integration of decentralized renewable energy generators.

Figure 2 shows a proposal to combine an existing residential power distribution grid with a fast and reliable data communication network. The black lines represent the existing uncontrolled power infrastructure. A transformer feeds the grid that can be separated into busbars and connecting cables. To prevent the cables from thermal overload, protection devices are installed on each feeder of the system. With the installation of decentralized renewable power generators, here photovoltaic and wind power, the current flows in the power grid may change. A fast data network is foreseen to collect the data measured by Phasor Measurement Units (PMU) and to transfer it to a control system that is also to be newly established. This system calculates the loading of every device in the grid and controls the generators and possibly consumers accordingly. The current flows in the lines are calculated using the phase information at each busbar. In the next section, we have conducted an initial test in a very simple setup to show the importance of accurate measurements and also to identify characteristics of the communication system.

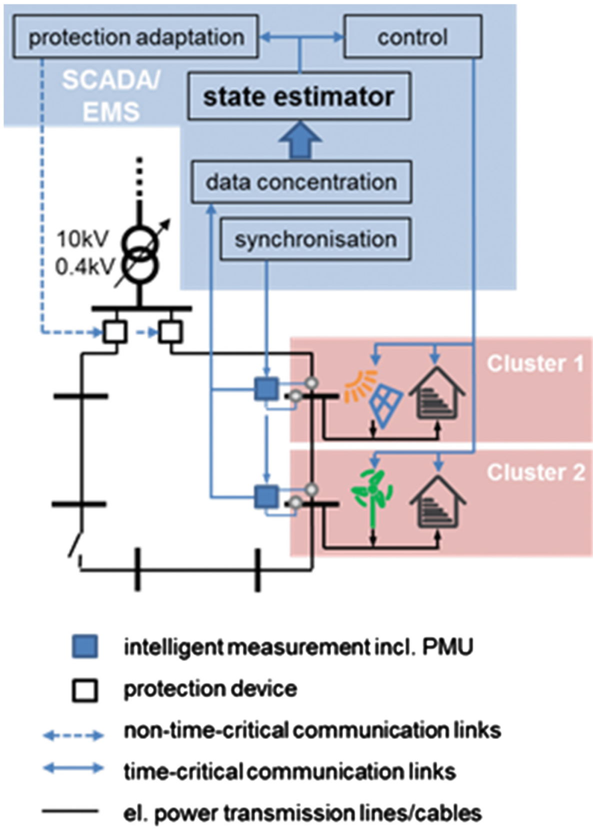

Fig. 2. Exemplary setup of a low voltage distribution system with intelligent measurement, state estimation and control, based on [15]

4 Feasibility Study

4.1 Scenario Setup

To show the effects of the communication system on the reliability of measurement data for load flow calculation of a power distribution grid, a generic power grid is created. It consists of three busbars that are interconnected to each other using cables. The cable lengths are 1 km each, the nominal voltage of the system is set to 0,4 kV, which is the normal residential voltage in most European countries [12]. Busbar 1 is fed by a static network, a so-called "infinite bus", that will not be part of the investigation in this paper. The cumulated loads at Busbars 1, 2, and 3 are set to 70 kVA each with a power factor of 0.9. These values represent a number of power consumers as typical cumulated loads for residential power distribution systems. For all connections, the cable type is the same with a thermal current limit of 165 A. Figure 3 shows the setup of the generic power grid that the simulations are based on. It can be understood as a very basic realization of a system as shown in Fig. 2.

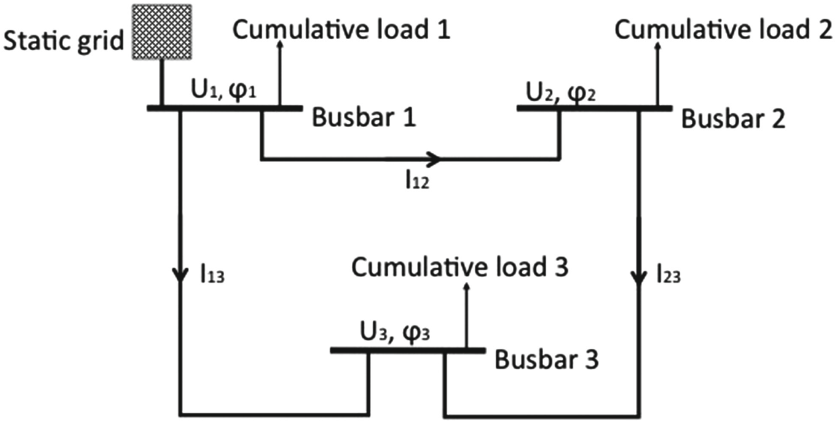

Fig. 3. Schematic of the generic power distribution grid used for the simulation

A commercial tool (NEPLAN(R) by ABB [19]) is used to calculate the currents in the cables and the voltages and phase angles at every busbar. In the further text, these results will be named as the "true" measurement results. The reason why a phasor measurement method is used instead of a current measurement to get the loading of each line is due to monetary and technical reasons: For current measurements additional equipment (current transducers, data converters) would be used. A phasor measurement can be performed by a residential smart meter. Additionally, including phasor measurements into state estimation algorithm can significantly improve state estimation results for power distribution grids [18].

For accurate phasor measurements of the voltages, a precise reference time is mandatory [16]. In the described model, the synchronous is achieved by a communication system. It is assumed that jitter in the time synchronisation is the only reason for errors in the phase measurement at every busbar.

4.2 Sensitivity Analysis of Time Synchronization and Reaction Time

In this sensitivity analysis, the effect of the time synchronisation delay on the estimated resp. calculated electrical line power flow is investigated. Inaccurate values of the voltage phasors lead to inaccurate line currents connecting the busbars which can be calculated according to Eq. (1), where $\underline{U}_i$ and $\underline{U}_j$ are voltage phasors at buses i resp. j, $\underline{Y}_{ij}$ and $\underline{Y}_{i0}$ the relevant elements of the nodal admittance matrix and $\underline{I}_{ij}$ the line current from bus i to bus j [12].

$$\underline{I}_{ij} = (\underline{U}_i - \underline{U}_j)\underline{Y}_{ij} + \underline{U}_i\underline{Y}_{i0} \tag{1}$$

The phase of the voltage at one busbar is varied in the range of 0.1° around the initial value. For a power distribution system running at 50 Hz a phase error of 0.1° corresponds to a timing jitter of 5.6 µs. Thus a very accurate time synchronisation is

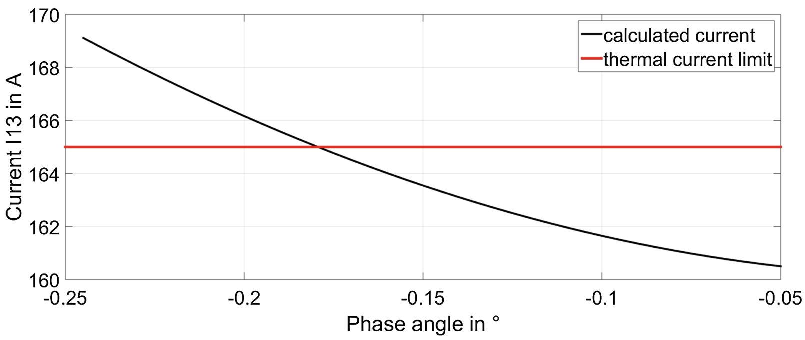

Fig. 4. Calculated current in the cable between Busbar 1 and 3 over measured phase angle φ_3 at Busbar 3

required for phasor measurements. The plots in Figs. 4 and 5 show the currents in the cables between busbars 1 and 3 resp. 2 and 3 to the corresponding phase. For Cable 13 the thermal current limit is also shown in the figure.

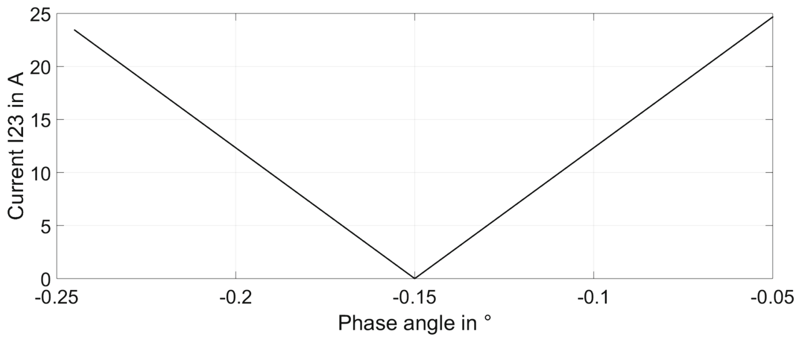

Fig. 5. Calculated current in the cable between Busbar 2 and 3 over measured phase angle φ_3 at Busbar 3

By monitoring the current flow in the power distribution grid the utilization of the lines should be increased. Today, as there is almost no information about the current values available, a large margin is used to prevent overloading of the cables. This unused power transfer capacity can be used for the connection of renewable energy. An overloading of the lines must be avoided to prevent the protection devices from tripping. Thus, a continuous reliable prediction of the line currents including information whether lines are overloaded or not is mandatory if the system is operated close to its thermal current limits.

As shown in Fig. 4, Cable 13 is operated close to its thermal limit. The true phase angle is $-0.14°$ which corresponds to a current of 163 A. A variation by $-0.1°$ due to timing jitter leads to a calculated current of 169 A instead. Hence, the calculation shows an overload although the true cable current is still below its thermal limit.

A small phase error leads to unwanted effects that might affect the reliability of the power distribution system: If the calculated current value is lower than the real line loading, the SCADA/EMS might increase the insertion of renewable energy into the grid leading to an increase of the line current. Although the calculated value is still below the limit, the line is in-fact overloaded and protection, which operates independently from these calculations, will disconnect the line due to overload. If the calculated value is higher than the real current, the SCADA/EMS system will perform countermeasures (e.g. disconnecting consumers or producers) although there is enough current transfer reserve. A similar sensitivity of the phasor measurement on the calculated line current of cable between Busbars 2 and 3 is depicted in Fig. 5.

This analysis shows that a reliable (precise) communication network is mandatory to enable proper and accurate state estimation including phasor measurements to facilitate the extension of current transfer capability of existing residential power distribution grids. Especially the knowledge of the delay of the communication link is mandatory. In summary, the following two requirements are the most critical for the scenario discussed in this paper.

- **Time synchronisation:** As shown in the above example sensitivity analysis, the error in the calculated line current is strongly dependent on the error of a synchronous time signal which is used for phasor measurement. To achieve an accuracy in the calculated line current of less than 4% in the shown example, a phasor measurement accuracy is needed in the range of 0,1° corresponding to a timing error of not more than 5.6 µs. Electrical power system control strategies that include processing information about existing delays in phasor measurements have already been proposed in [17]. Further research work on electrical power systems is needed to enable SCADA/EMS for LV grids including state estimation and phasor measurements [15].
- **Fast reaction time:** As already shown in Sect. 2, reaction time for closed-loop control actions is required in the range of a few 10 ms up to 300 ms, depending of time-current-characteristic of installed protection devices. Reaction time includes the time to activate further electrical consumers, re-estimate the network state, possibly a second iteration of activating consumers, re-estimate the network state and in worst case switching-off producers before the line protection fires. However, it can be expected that the overload is rather in the lower than in the higher end (see Fig. 1). This means an overall reaction time of 100 ms needs to be achieved. This includes three cycles of communication, two cycles of system state estimation, two cycles of activating consumers and one cycle to deactivate producers. If we assume 10 ms for each activation, deactivation and state estimation, we have 50 ms left for three cycles of communication. This results in around 15 ms for a complete protocol exchange.

4.3 Analysis on the Use of Existing Communication Technologies

Different kinds of communication technologies can be used to realise the communication between different components as depicted in Fig. 2. As discussed in Sects. 2 and 4.2, latency and reliability are critical factors that determine what kind of technologies

Table 1. Analysis of proposed interaction between the communication network and the LV power distribution systems (see Fig. 2)

Type of communication	Sections	Topology / number of devices	Distance/area	Target	Possible com. technologies
Time critical (fast reaction time - within 10 to 300 ms, reliable bi-directional communication)	within the cluster	star or ring topology /5−20 controlled devices	4 km^2	controlled devices	DSL, PLC, LTE, Fiber optic, WiFi 0r WPAN (with multi-hop), WiMAX/LTE 450 MHz
	SCADA/EMS to cluster	direct link	2−10 km	control, data concentrator, controlled devices	DSL, PLC, LTE, Fiber optic, WiFi 0r WPAN (with multi-hop), WiMAX/LTE 450 MHz
Time critical (time synchronisation accuracy of ca. 5-6 μs)	Cluster to SCADA/EMS	multi-point - 5 −20 devices (PMUs) to point (Data concentration unit)	2−10 km	intelligent measurements incl. PMU	DSL, PLC, LTE, Fiber optic, LTE 450 MHz
Non-time critical (reaction time within a couple of minutes)	SCADA/EMS to protection devices	point to multi-point (1 −10 devices)	2−6 km	triggering the protection devices	DSL, PLC, LTE, Fiber optic, WiFi 0r WPAN (with multi-hop), WiMAX/LTE 450 MHz

to use, specially when the power system is running close to the maximum utilization of the power lines in order to guarantee realization of corrective control actions. Table 1 shows possible communication technologies that can be used at different sections of the proposed architecture.

4.4 Communication Architectures

As shown from Tables 1 and 2, it is feasible to use different types of technologies at different places to realize the communications between different components in the LV power grid. However, it is not enough just to use the standard way of communication to fulfill the requirements identified in Sect. 4.1. Some of the specific characteristics that should be considered for our proposed CPN scenario are:

1. **Reliable networks with low latency and ultra low jitter:** Very reliable and low latency communications are a primary requirement as shown in Table 1, especially to achieve the fast reaction time. A TCP/IP based layered architecture may introduce additional overheads due to the use of different timers and different recovery mechanisms at different layers might lead to unpredictable delays. Unpredictable

Table 2. Properties of possible communication technologies [8] proposed in Table 1

Com. technology	Data rates	Coverage	Pros/cons
DSL	ADSL2 + : 24 Mbps down and 1.4 Mbps up VDSL2: up to 200 Mpbs down/up	up to 4 km up to 1.2 km	ADSL infrastructure is already established and most commonly deployed VDSL is not deployed everywhere
Optical fibers	IEEE 802.3ah: 100 Mbps	up to 10 km	Long distance, high bandwidth, robustness against electromagnetic and radio interference High cost, difficult to upgrade
PLC	NB-PLC: up to 500 Kbps BB-PLC: up to 200 Mbps	150 km 1.5 km	Infrastructure is already established, low operational cost Multiple non-interoperable technologies, difficult to support high bit rates
WiFi	IEEE 802.11e/s up to 54 Mbps IEEE 802.11n up to 600 Mbps IEEE 802.11p	up to 300 m up to 1 km (11p)	Low cost deployment, flexible Prone to interference, not very reliable, low coverage, multi-hop connections may degrade the quality of communications
WPAN	802.15.4 WirelessHART ISA 100.11A	up to 300 m	Flexible, low data rate, low power consumption Prone to interference Improved version of 802.15.4 guaranteed reliability and security, support mesh networks Support only start topology, guaranteed reliability
LTE with 450 MHz	Max. data rate per cell, 1 Gbps down, 350 Mbps up [10]	3 times more than std LTE with 800 MHz [10]	Guaranteed QoS, better cell range and coverage, specially suitable for indoor environments Not yet widely deployed
WiMAX	IEEE 802.16 128 Mbps down and 28 Mbps up	up to 10 km	Longer distance than WiFi, more sophisticated QoS Not widely deployed in Europe, network management is complex, use of licensed spectrum

delays and jitter (delay variation) make time synchronisation difficult. The mentioned interacting control loops with retransmissions are one point, another are unknown scheduling, queueing and processing delays in the different network elements. For the exchange of these delays, future network architectures allowing cross-layer information exchange might be more suitable, than the TCP/IP architecture with clear separation of layers. The communications architectures for CPN should have flexibility, adaptability and configurability in order to achieve the requirements of high reliability, low latency with almost zero jitter.

2. **Distributed functions:** In order to achieve the low latency and ultra low jitter (for example, the communication of synchronization signaling among PMUs), some of the areas need to function in a distributed manner. It is very important to have local optimisations while trading off other aspects. For example, low latency is typically more important than having higher throughput in the whole network. The flexibility in deploying different networking functions at different nodes that are able to operate independently may be suitable for this scenario to achieve the low latency with almost zero jitter.
3. **Resilient of the communications network:** As a result of the tight coupling required in communications and power systems, recovery from failures becomes an important aspect. For example, in case of a failure in the communication links, the power system should be functioning for a certain time and should also be capable of setting up communication links satisfying the minimum requirements. This is also valid in case of a failure of the power system.

In general, some of the future internet architectures such as OConS [3], GP [6] and Netlets [2] allow to orchestrate the protocol stack depending on the requirements. These architectures also cater for the deployment of distributed functions. However, further investigations should be done first to analyse how to optimise the protocol stack to achieve the identified requirements. This depends on many factors such as communication technology used, optimisation of parameters (e.g., retransmission timeouts), micro analysis of delays and jitter in different nodes and different components.

5 Conclusion

This paper shows how to enhance the utilization of the LV power grid by coupling the power system and the communication system. One of the CPN application areas in ***EE networks***, viz., LV power grids was selected due to the following reasons:

- Decentralized electric power generation using renewable energy sources becomes increasingly popular. As a consequence, electric power flows of existing electrical power grids are shifting significantly from unidirectional to bidirectional mode. This applies especially to the LV power grids to which a continuously increasing number of decentralized electrical energy sources such as photovoltaic is connected.
- Especially, existing LV cables and lines need to be utilized to a much larger extent and often need to be operated close to their thermal current limits.
- Dedicated coordinated control of loads and power generation is foreseen to realize intelligent power management in order to guarantee full use of available power transmission capacity and on the other hand to safely keep each transmission device of the LV power grid below its allowed current limits.

The realization of coupling the power system and the communication system is to be done by SCADA/EMS. This requires the use of state estimation to continuously capture the state of the system from a given set of measurements. The implementation of SCADA/EMS requires reliable bidirectional communication channels that enable execution times of 15 ms for iterative closed-loop control cycles. Additionally, time-synchronization of PMUs shall be realized to increase measurement coverage of LV power grids. Sufficiently accurate distributed phasor measurements require an error of the synchronizing time that is less than 5.6 μs. Based on the analysis of Sect. 4, these requirements need to be realized by the use of appropriate communication media and the communication architectures and protocol stacks.

5.1 Outlook

As discussed in Sect. 4.4, there are so many factors which influence the realization of our scenario. Therefore, as next steps, further investigations should be done to see the following aspects.

- ***Optimization of the protocol stack for reliable and low latency communications:*** In our scenario, this is not always required, but it is very important to have a reliable and low latency communication channel, when the power system operates closer to its maximum utilization.
- ***Low latencies with ultra low jitter for time synchronisation:*** This could be achieved by enabling distributed functions and reconfigurations of the protocol stack.

We plan to use a co-simulation platform for our future work. When simulating either the power system or the communication system separately, it is very difficult to capture the correct and exact behaviour. The research in the area of integrating event-driven network simulators with time based simulators for power systems is very challenging [9].

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