An Insight Into Communication Technologies Utilized in Smart Metering Systems

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***Abstract*—This paper presents an insight into the smart metering field. The paper address specifics of different network hierarchy structures (wide area networks, neighborhood area networks, and home area networks) and topologies used for this purpose (mesh, point-to-point, virtual point-to-point, or broadcast networks). Next, we focus on listing and describing some of the most commonly used communication technologies (both wired and wireless, such as power line communication, public switched telephone network, digital subscriber line, radiofrequency, in-home radio frequency, wireless local area network, or mobile network communications), their characteristics, advantages, and disadvantages utilized for remote and smart metering.**

***Keywords*—Smart metering; Communication technologies; Advanced metering infrastructure**

I. Introduction

Smart metering implies implementation of the Advanced Metering Infrastructure (AMI), replacing the old, classical type of electromechanical electricity meters with new, technologically more advanced, smart meters [1]. In opposition to old electromechanical meters, smart meters can actively participate in home energy management. Thus, offering additional functionality compared to old meters, such as two-way communication between the utility company and the customer's smart meter. This brings numerous benefits both for customers and Distribution Network Operator (DNO). For example, DNO can remotely (for example, via GPRS) switch off the customer in case of its unpaid electricity bills, which were, until recently, handled on-site. Furthermore, smart meters enable the data acquisition and measurement of electrical parameters for local power production, for instance, solar power systems [2], [3]. Smart meters also allow for remote reading of the energy consumed in several intervals during the day, thus allowing for time-based pricing and billing with multiple tariffs for the consumed electrical energy. In this way, a customer can actively participate in the electricity market as opposed to the monthly, semi-yearly, or per-request readouts with a fixed energy price and two tariffs performed on-site by a worker or some via some Automatic Meter Reading (AMR) system [4]. Also, customers can have the data displayed on the smart meter itself or in some other way (e.g., mobile applications) to better assess electricity consumption, reduce it, or reschedule consumption for periods with lower electrical energy prices. This is best represented during peak consumption intervals when the customers know that the electricity and the grid load would be higher than usual and thus can reschedule their unnecessary consumption to a different time of day. Also, this leads to some customers reducing their consumption and, hence, also reducing the emissions that would be generated as a result of increased consumption [5]. This, in addition, greatly improves overall grid stability by reducing the demand during the peak time [2], and of course, locally unburdens supplying transformers located in substations. Furthermore, since the smart meters give real-time readouts to the utilities, it is possible to better monitor and plan for the appropriate energy generation to keep the grid parameters stable and in the acceptable range, ensuring that supply matches demand. Smart meters can also notify of particular grid failures, informing the utility company on the exact location of the fault. Likewise, they automatically report the restored grid power to each customer that is equipped with a smart meter. Additionally, there is a remote control capability where the utility company can temporarily remotely switch off the electricity supply in case of reaching load limits [6]. Likewise, it is possible to have a smart home setup where the smart meter can command certain appliances to turn off. However, this functionality requires additional equipment [7]. This is usually done if a local energy hub (transformer station) is nearing its thermal power limit and a blackout is imminent. Smart meters can also help the utility companies to make cost savings by being able to more efficiently detect energy thefts and provide better maintenance by monitoring power quality and thus giving a better insight into the power grid state in real-time [1], [5]. When talking about smart metering, electricity is the main focus, but there are other consumptions to monitor, such as water and gas. However, those measurements are also mostly relayed through the smart electricity meters, since they have to be battery powered if they cannot be powered from the source they monitor [8]. The smart meter installation at the customer premises (AMI infrastructure, as well as the smart meters themselves) have a somewhat high cost, so there are projects and scheduled roll-outs being conducted to make the transition to intelligent metering easier and more cost-effective [9]. The rest of the paper is structured as follows. Section II briefly presents network hierarchy structures in smart metering systems, with topologies of communication networks addressed in Section III. Utilized communication technologies are described in Section IV. Conclusion remarks are given in Section V.

II. Network hierarchy structures

For the smart meter to communicate with the utility provider company through the AMI, it has to establish communication through a hierarchy of structured networks [3]. There are three networks often used in the AMI, depending on the distance of the devices and the area that the networks cover. These three network hierarchies are Wide Area Network (WAN), Neighborhood Area Network (NAN), and Home Area Network (HAN).

A. Wide Area Network (WAN)

WAN is a type of Local Area Network (LAN) that covers a large geographic area (thousands of square kilometers). It connects with a number of data concentrators that collect the data from smart meters and send it to the utility company control center [10]. The WAN allows for real-time monitoring of the grid, ensures the long-distance communication requirements, and acts as the AMI backbone [11]. The amount of needed data throughput is high since numerous devices are sending metering data through the network, requiring large transfer speeds and reliability of the network [3].

B. Neighborhood Area Network (NAN)

NAN is a type of LAN that consists of neighboring devices, in this case, smart meters or households. It usually spans across the area of a neighborhood or several square kilometers. It can be implemented in a wired or wireless manner, and the end nodes are data collectors that collect and aggregate data from smart meters. This aggregated data is forwarded to data concentrators, which send the data to the utility company over a secure connection [3], [12].

C. Home Area Network (HAN)

HAN is a type of LAN where, most often, the smart meter is the core of the network acting as a gateway towards the utility company [13]. Household appliances that possess an option to connect to the network [10], other metering devices, as well as the smart meter itself, can connect through a wired or wireless connection depending on the system being implemented. This network exists inside and in the vicinity of the home, in an area up to 200 square meters. It can provide monitoring and control of the energy used and display it on an In-Home Display (IHD) [9], a smartphone app, a web interface via web browser, or a smart TV [14]. If the household appliances possess such an option, or with the use of smart plug-ins for classic appliances, there is also a possibility to turn the appliances on or off through the HAN, thus creating a home automation system.

III. Communication network topologies

Smart metering systems may use several network topologies, where the communication technologies used depend on the topology. Of course, the implemented topology influences the system's reliability and robustness. Usually, it is recommended to use a hybrid model topology, which combines different topologies based on the level of hierarchy in the network. In most cases, an in-home metering gateway is commonly used as a device that provides communication and handles traffic of the smart metering devices in the HAN and towards the NAN or WAN. The gateway can be a separate device or can be integrated into the smart meter itself, depending on the system [15].

A. Mesh network topology

Mesh network topology consists of devices, often referred to as nodes, that can connect to multiple neighboring nodes, thus making the network flexible due to the possibility for the data to take different routes dynamically. The route can change depending on the conditions of the network, and the optimal one is selected. The nodes connect to a data concentrator, which sends the data to the utility control center. However, in this topology, each node can be connected to more than one data concentrator, making this type of topology more reliable and robust. Without the mesh topology, it is usually necessary to have two gateways, one for the NAN and one for the HAN. However, with the mesh topology, the data concentrators can directly communicate with all in-home devices with no gateway for the HAN devices. The advantages are its self-healing properties, each node can act as an independent router or repeater, extending the total coverage, self-organization and configuration, high scalability, and good coverage due to multi-hop routing [13]. The disadvantages are its short range of communication since it uses Radio Frequency (RF) communication that is limited by power, distance, physical obstructions, interferences, as well as the increased need for encryption and security [16].

B. Point-to-point concentrated network topology

Point-to-point concentrated network topology has nodes connecting to a central data concentrator that does the routing of the data to the utility control center. This topology has a better range because the nodes can connect to the data concentrator using different technologies (both wired and wireless). It is possible to use different topology structures such as the star, tree, ring, and bus structures [17]. Where the bus structure is used, the nodes are usually connected by a wired connection and close together, and the failure of one node does not affect the other nodes unless the master node fails. A star structure is used inside the home, where a single gateway acts as the central hub and is used to connect all the devices, usually wirelessly. However, direct communication between the nodes is not possible, so the network cannot work without the master node. The ring structure is a closed loop where the messages are transmitted from node to node in a single direction, and any node can be the master node, but if one node fails, the whole network fails as well. The advantages are simplicity and different available technologies which may be used. The disadvantages are more complex management of the gateway and the reduced performance of using a single intermediary device and data concentrator for the whole communication, having only one possible route [15].

C. Virtual point-to-point network topology

Virtual point-to-point network topology uses third-party owned, managed, and maintained infrastructure for the communication network, for instance, telecom company infrastructure. In that way, a virtual point-to-point network is established between the metering devices and the control center, depending on the technology that is chosen. Some examples of the technologies used for this topology are the Global System for Mobile communications (GSM) with the Short Message Service (SMS) or the General Packet Radio Service (GPRS), which are commonly used in the field. The advantage of this topology is the simplicity of network access to the field devices. The disadvantages are the dependence on the third-party infrastructure and a single route of communication (however, these can be mitigated by having a backup communication technology available) [15].

D. Broadcast network topology

The broadcast network topology is similar to point-to-point networks but with a much greater range of operation. The examples are RF controlled systems where signals are transmitted to receivers across the country and ripple controlled systems where a low-frequency signal is injected into the medium voltage grid and thus received by specialized receivers or meters with integrated receiving capability. This topology has been used in history to change the meters' tariff rate, control field load management, or switch public lighting. These networks mostly provided one-way communication, but with the advancement in technology now possess two-way communication capability. The advantage of this topology is the reduced cost of maintenance and deployment. On the other hand, the disadvantage is low transfer speeds due to the type of technology used [15], [17].

IV. Communication technologies

Communication is the most critical aspect of smart metering, and today it is often required to have two-way communication between the smart meter, AMI, and AMR [16], [18]. In this way, it is possible to perform instant readings of data remotely from the smart meter (such as electricity consumption, number and type of detected failures, power quality information, etc.), as well as to conduct billing and grid management according to the received data. With numerous smart meters deployed, a reliable and high capacity transfer network is required to be able to provide the service needed to operate the smart metering systems [5]. Each of the meters has to be able to record and transmit data reliably and securely through the selected communication channel towards the utility control center and receive remote operation commands and act upon them. There are different communication technologies available for communication between the AMI and the smart meters, which can be divided into two categories: wired and wireless networks. Additionally, some technologies are optimized for only indoor or outdoor use, while others can cover both applications depending on their technical requirements. The utility companies have to define their communication requirements of reliability, security, and sufficient transmission speeds - these are the main inputs for designing communication infrastructure and selecting appropriate communication technology through which to provide their services. Note also that the technology used is subject to local regulatory authorities and must comply with laws, regulations, and standards [15]. In most cases, it is advised to have a hybrid communication system where different customers can have different products that use different communication technologies, as well as to ensure a backup communication technology.

A. Wired technologies

1) Power Line Communication (PLC): allows for data exchange between devices connected to the same power line, and this is done by injecting a higher frequency signal in the power lines [15], [17]. PLC is one of the older and simpler technologies used for communication with the smart meter. The communication is achieved over the power lines already directly connected to the smart meters. Albeit, the addition of some devices such as repeater, coupling devices, and transformer bypass bridges might be needed [10], [16]. There are two types of PLC systems: narrowband PLC and broadband PLC. The PLC represents a low-cost solution due to using already existing infrastructure with minimum modifications to the existing system, making it suitable for industry and home automation proposes [19].

a) Narrow-Band PLC (NB-PLC): is mainly used for automation inside the home or utility company services, and it uses medium to low frequency signals injected in the power lines. There are different versions of this technology depending on the type of modulation. It is possible to achieve different transmission speeds, which can be further optimized by data compression techniques [15]. Necessary components in this technology are the data concentrators, which receive data at the substation level or, rather, at the distribution transformer and send it to the DNO. Also, there is a possibility to use the PLC technology on both the low-voltage and medium-voltage power grid systems. However, for the medium-voltage application, special capacitive or inductive coupler devices need to be installed to bypass the transformers [20].

b) Broadband PLC (BB-PLC): delivers greater transmission speeds by injecting high-frequency signals in the power lines, which enables home networking, but it also can be used outside the home [10]. One of the standard applications is for the utility company to offer internet services to their customers via the in-home smart meter. This is useful in areas with weak signal coverage and poor telecommunication infrastructures. However, this kind of service takes a toll on the grid and requires investing in equipment to be able to provide broadband internet services with PLC over the grid, which makes the system more costly and more challenging to maintain [15]. The advantages are the use of existing infrastructure in every home, eliminating additional infrastructural expenses and making the installation easier. Also, it is directly powered from the grid, while maintenance is relatively easy and inexpensive. The disadvantages are connection over a grid which may result in loss of communication [21], as well as limited working range and limited frequency range available for communication. This is because power lines can contain higher harmonics present because of electrical converters on the load side. The latter can cause interference with the communication, and also, there is a possibility that PLC interferes with some more high-tech appliances in the home. The PLC technology is sensitive to disturbances, and it depends on the signal quality, making it less suited for data transmissions. However, there is a possibility of using a hybrid solution where PLC is combined with other technologies, for example, a mobile network, in order to fix the shortcomings of PLC [16].

2) Public Switched Telephone Network (PSTN): uses modems or similar devices to connect to the remote meter, where data is transmitted to the utility company via a modem-to-modem connection using one or multiple twisted-pairs [22]. There is a possibility of using the existing customer phone line if so needed, where the communication is done in predefined time windows a few times a day (not to occupy the phone line constantly) and frees the phone line if it needs to be used, or there can be a dedicated phone line just for the utility company [17]. The disadvantages are the number of modems needed to be installed, interruptions and potential absence of communication due to line problems, possibly occupied phone line. However, the advantage is its coverage, which is relatively good even in remote areas [10], [15].

3) Digital Subscriber Line (DSL): and other similar technologies, such as coaxial cable, optical fiber, and satellite based internet, can be used to provide a connection of the smart metering systems to the WAN by using third-party infrastructure already available in the customer's home, making it an alternative communication system [10]. This can be achieved by using a wired connection directly with the router, using in-home broadband PLC or dongle bridge devices that connect using a wired connection and generate a wireless network to which the metering devices link [15]. The advantage is using the existing technology which is readily available, it is low cost with high transfer speeds; while disadvantages are that it is third-party owned, it can have lower reliability and potential downtimes, and a possible lack of coverage in rural areas [16]. Table I gives frequency ranges, data rates, and distances covered by the wired technologies in smart metering.

Table I
WIRED COMMUNICATION TECHNOLOGY COMPARISON

Type	Frequency	Data rate	Distance
NB-PLC	3-500 kHz	10-500 kbps	3-150 km
BB-PLC	1.8-250 MHz	14-200 Mbps	200 m-1.5 km
PSTN	300 Hz-3.4 kHz	56-128 kbps	5 km
DSL	25 kHz-1.5 MHz	1-100 Mbps	1.5-5 km

B. Wireless technologies

1) Radio Frequency (RF):

a) Low-power RF: can use different RF bands that are usually unlicensed, but still need to comply with the local laws and regulations. They normally require data concentrators, although the number of data concentrators vary depending on the system used, and are usually organized as a star or mesh topology. The service location evaluation defines which technology will work best for the given location. The advantages are the ability to replace the in-home metering getaway and its HAN due to the possibility of direct communication with the in-home devices. Also, using the mesh topology reduces dependence on data concentrators, and an expansion of the network coverage area can be achieved. The disadvantages are the higher cost of data concentrators for rural areas because of fewer customers. When using a star topology, it is harder to provide equal coverage for all the customers or data concentrators, while the use of the mesh topology can reduce the performance of the network [15].

b) Licensed RF: is an RF broadcast technology with higher power, making it effective at a longer range, providing a larger coverage area. There are various RFs available depending on the location, some examples being Very High Frequency (VHF) and Ultra High Frequency (UHF) technologies which can be used as point-to-point, point-to-multi-point, or trunked radio systems [17]. These used to be one-way communication technologies, but new versions are offering two-way communication with faster data transfer rates. The advantages of this technology are good coverage since, with relatively little infrastructure, it is possible to cover a large area. This technology can also be used for HAN, NAN, and WAN networks. In addition, in some cases, it can eliminate the use of an in-home gateway and can even interface other measuring systems directly, such as water consumption meters. However, there is a chance of incompatibility with gas meters, and other home appliances since the required transmission power is relatively high, driving up the consumption of the devices. Additionally, because of the frequency used, there is a possibility of the antenna size being relatively large in comparison to the device, and thus those devices may still need to use a gateway device. A licensed RF network offers less interference because of the licensed frequency band and can be shared with other utility providers. However, the management is more complex and needs more specialized personnel to maintain it [15].

2) In-home RF: There are several technologies for in-home RF communication purposes, some of which will be described in the sequel. In-home RF should be able to reach on the outside and in the vicinity of the home too, since the smart meter can be located outside the home or be in a metal cabinet that can block the signal. Also, interferences with other household appliances and wireless technologies may be an issue, so it is important to ensure coexistence with the technologies used. Some solutions to those problems are low-noise amplifiers, mesh networking, and automatic frequency channel switching. For example, one of the benefits is using an already owned device able to connect to the in-home RF network, for instance, a smartphone, smart TV, or a computer, and use them as an IHD with no additional cost [15].

a) ZigBee: is a wireless communication technology used for energy monitoring, wireless sensors, home or industrial automation, and other similar tasks [16]. It is based on the IEEE 802.15.4 standard and best suited for transferring a single signal transmission from an input device or sensor periodically or intermittently, making it suitable for smart metering communication [18]. The advantages are low deployment cost, low-energy consumption for battery-operated devices, mobility, simplicity, robustness, relatively small data usage, up to 60000 devices in one network [18], and also self-configuring and self-healing properties [17], [22]. It supports star, mesh, and tree topology, making it a flexible solution for smart metering systems. The disadvantages are limited data rate, small memory size, low processing capability, low security, and small battery capacity for battery-operated devices, which impose some constraints to the practical implementations of the technology. Furthermore, ZigBee is susceptible to interference with other technologies and devices such as Wi-Fi, Bluetooth, and microwave signals. However, there is a similar technology called Z-Wave, which eliminates the interference sensitivity that ZigBee has. There is also ZigBee Smart Energy Profile (SEP) which allows for the integration of smart meters in a wireless sensor network with other devices, where the smart meters can collect data from other devices and control them. Furthermore, the customers can monitor their energy consumption in real-time, thus making better use of the consumed energy [18].

b) Bluetooth: is a low-power wireless technology used for short-range data exchange between devices that create a Personal Area Network (PAN) [22]. The advantages are low cost, the possibility of connecting multiple devices without synchronization problems, and low-power consumption. However, its disadvantages are low data rates, short range, and low security, thus making Bluetooth a satisfactory solution only for AMR applications and in-home communications.

c) Wireless Local Area Network (WLAN): is a technology that allows for linking multiple devices through wireless connection within a limited area in a way that they form a Local Area Network (LAN) [17]. Usually, it also provides access to the internet, acting as an Access Point (AP). It is based on the IEEE 802.11 standard, most commonly known under the marketed brand name Wi-Fi [18]. The advantages are easy installation due to the plug-and-play option, low cost, and the fact that it is a vastly deployed and mature technology, making it easier to integrate it into smart metering systems. The disadvantages are relatively high-power consumption and the high possibility of interference with other technologies that communicate on the same or close frequency bands, although the newer 5 GHz WLAN eliminates the 2.4 GHz WLAN interference problems.

3) Mobile network communications: Mobile networks, also known as cellular networks, have been deployed in most of the inhabited areas providing readily available services, thus making this infrastructure practical for multiple applications, including smart metering [22]. There are several types of mobile communication technologies with regard to the data being transmitted, with new generations of mobile technologies being developed continuously improving the previous ones. The most common technology in smart metering thus far is GSM; however, the energy utility can choose the one that best suits their application [15]. Mobile networks are able to provide direct access to the utility WAN for the metering devices, eliminating the need for additional infrastructure since it is owned and maintained by the telecom provider rather than the utility company [23]. Also, the already existing telecom infrastructure makes it easier and quicker to install new devices on the network. However, coverage can be an issue in some locations, so there is a possibility of installing external antennas for the smart meters to improve the signal. The devices contain a Subscriber Identity Module (SIM) card, and thus they can be susceptible to the mobile service provider failing. To solve this vulnerability, there is a possibility to use multi-operator SIM cards. Adding the AMI to a mobile network can cause it to become congested. However, the AMI can be scheduled in such a way that task execution occurs in off-peak periods (for example, at night). Finally, this technology can be used in conjunction with a different technology, for example, PLC up to the data concentrator and then mobile network from the data concentrator to the utility company. This is the reason many pilot projects select this technology to start with [15]. As mentioned, there have been several generations of mobile networks. GSM / GPRS (2G) was the second and digital generation of wireless mobile communications technology, and in the case of smart metering, it typically transmitted data via Short Message Service (SMS) or the Circuit Switched Data (CSD) [22]. 3G was the third generation technology enabling faster data transfer providing data-only services for telemetry in smart metering purposes, and was commonly used for connecting the data concentrators to the control center [24]. Long-Term Evolution (LTE) is a wireless broadband communication standard that is an evolution on 3G technology [24], while the 4G denotes the fourth generation of mobile communications which, instead of supporting traditional circuit-switched telephony services, relies on an Internet Protocol (IP) based voice communication. Worldwide Interoperability for Microwave Access (WiMAX) is a wireless broadband access technology based on the IEEE 802.16 series standard. It supports two-way point-to-point and point-to-multi-point network topologies and has good coverage range [13]. With the commercial availability of the newly developed fifth-generation (5G) mobile technology, it is certain that in the near future, 5G will make its way into the smart metering field [25]. The advantages of mobile network communications are reducing costs and time of building a communication infrastructure for remote metering, already implemented security algorithms, fast and easy installation, low maintenance costs and power consumption, high rates of data transfer, and wider coverage. The disadvantages of mobile network communication for this purpose is that the network is not exclusively used by the utility company but shared with others, thereby lowering its security. It can lead to network congestion and decreased performance, especially in emergencies [16]. Table II gives frequency ranges, data rates, and distances covered by the wireless technologies in smart metering.

Table II
WIRELESS COMMUNICATION TECHNOLOGY COMPARISON

Type	Frequency	Data rate	Distance
RF	54-862 MHz	18-24 Mbps	10-100 km
ZigBee	868/915/2400 MHz	20-250 kbps	10 m-1.6 km
Bluetooth	2.4 GHz	0.721-1 Mbps	10-100 m
WLAN	2.4/5 GHz	2-600 Mbps	100 m-1 km
2G	900-1800 MHz	14.4-144 kbps	10 km
3G	1.9/2.1 GHz	2-14 Mbps	10 km
4G	700-2500 MHz	100-300 Mbps	10-30 km
LTE	400-3800 MHz	300 Mbps	30 km
WiMAX	1.8-3.65 GHz	30-75 Mbps	5-50 km

V. CONCLUSION

This paper provides an insight into smart metering technologies, detailing different network hierarchy structures and network topologies used in this field. Also, the paper lists and describes some of the most commonly used communication technologies for remote metering, their characteristics, advantages, and disadvantages. Selection of appropriate technology for specific smart metering should be made by utility companies based on the service locations and other system requirements (like reliability, security, and sufficient transmission speeds) and limitations that may occur. Finally, it is possible to implement multiple coexisting communication technologies, either as a combined system or as backup communication options.

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