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Wireless Communication Technologies for Smart Grid Distribution Networks †

Juan Carlos Rodriguez [1,*,‡,§], Felipe Grijalva [2,‡], Marcelo García [3,‡], Diana Estefanía Chérrez Barragán [4,‡], Byron Alejandro Acuña Acurio [4,‡] and Henry Carvajal [5,‡]

1 Analog Devices, Inc., Wilmington, MA 01887, USA
2 Colegio de Ciencias e Ingenierías "El Politécnico", Universidad San Francisco de Quito USFQ, Quito 170157, Ecuador; fgrijalva@usfq.edu.ec
3 Facultad de Ciencias Técnicas, Ingeniería Mecatrónica, Universidad Internacional del Ecuador UIDE, Quito 170411, Ecuador; margarciasaq@uide.edu.ec
4 School of Electrical and Computer Engineering (FEEC), University of Campinas (UNICAMP), Campinas 13083-852, SP, Brazil; diana.cherrez@gmail.com (D.E.C.B.); byronacunia@gmail.com (B.A.A.A.)
5 Faculty of Engineering and Applied Sciences (FICA), Telecommunications Engineering, Universidad de Las Américas (UDLA), Quito 170503, Ecuador; henry.carvajal@udla.edu.ec
* Correspondence: juancarlos.rodriguez@analog.com
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‡ These authors contributed equally to this work.
§ The opinions expressed in this publication are those of the authors. They do not purport to reflect the opinions or views of the Analog Devices Inc. (ADI), its subsidiaries or employees.

Abstract: The modernization of the current electric power grid into a smart grid requires the integration of advanced instrumentation, automation, and communication technologies to optimize efficiency, safety, and reliability. In traditional power grids, communication and control tasks are concentrated in substations, limiting their coverage to high-power equipment. As distributed energy resources increase in different sections of the grid, power flow becomes bi-directional. This requires monitoring and control at the Transmission and Distribution (T&D) level, which forms the largest portion of the power grid. To achieve efficient energy flow management and enable consumer participation in demand management, the integration of information and communication technologies (ICTs) is essential. Wireless sensor networks (WSNs) have been identified as a suitable solution for communications within the distribution network. An ongoing challenge, however, is the definition of the best candidates to solve this problem, among the currently available wireless technologies. This paper reviews different wireless communication technologies that provide robustness, reliability, speed, scalability, and cost-effectiveness for monitoring distribution lines. An outline of the architecture for smart grid communications, the definition of sensor network requirements for power line environments, and an overview of specific studies focusing on technology comparisons are the main contributions of this paper. The purpose of this review is to delineate current technologies in order to establish potential future research directions within the field.

Keywords: smart grid; wireless communication; distribution networks; energy management; wireless sensor networks; IoT

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1. Introduction

The smart grid can be defined as the modernization of the existing electric power grid infrastructure, with the aim of optimizing efficiency, safety, and reliability. This modernization facilitates the gradual integration of renewable energy resources through the use of advanced instrumentation, automation, and communication technologies [1].

In the current paradigm of the electricity network, control and communication operations are mainly limited to substations, where transmission lines and distribution feeders

are connected via busbars and transformers. Measurement and control equipment in these sections of the grid is usually bulky and has high investment costs. Reliable communication links are always readily available between these high-power appliances, such as power cabinets, transformers, and power stations [2].

The gradual introduction of different distributed generation resources in the future grid will cause the direction of the power flow (which has been historically conceived as "one-way") to be considered "bi-directional" instead. In that situation, to keep security and reliability, the monitoring and control tasks must focus on the lowest sections of the grid. In the new paradigm of the smart grid, generation, Transmission and Distribution (T&D), and customer levels are considered. While the deployment of technologies at the generation and customer levels has already started, at the T&D level, there is still a requirement to develop the infrastructure for power management tasks. The key to accurate power management is monitoring the conditions of the grid over a broad range. Only real-time sensing and data communication technologies at this level will make this possible. As T&D infrastructures are the largest within the power grid, the range to cover is vast, and it has become an urgent issue to identify reliable and cost-effective solutions for these tasks.

To enable the management of energy flow at the T&D level and provide consumers at the customer level with a voice in demand management tasks, the integration of information and communication technologies (ICTs) is going to play a fundamental role in the progress of the smart grid. Currently, research efforts in the field of ICTs for the smart grid are extensive, and there is an ongoing discussion about the best technologies at different levels. Wireless sensor networks (WSNs) are widely considered the most suitable solution for communication nodes that perform sensing functions at different sections of the distribution network. This review paper summarizes the investigations on wireless communication technologies that may offer adequate robustness, reliability, speed, and the ability to scale into large-scale and low-cost networks, to monitor distribution lines (typically of 22 kV). Section 2 presents a brief introduction to the communications architecture in the smart grid, including an overview of the most popular technologies available for the task of smart grid monitoring. Section 3 explores the requirements of sensor networks in the power line environment. Section 4 outlines past studies on the performance of the different available technologies in practical applications and their comparison. Section 5 presents a summary and conclusions, along with recommended potential future research work in this area.

2. Available Wireless Technologies for Smart Grid Communications

The communication system is the key component for monitoring and control tasks in the smart grid infrastructure [3]. Different communication technologies, either wired or wireless, are available for the electric utilities that comprise the different sections of the grid. The smart grid paradigm proposes three main sections: generation, T&D, and customer levels. The development of standardized communication structures has begun at the customer level, where developed countries are gradually modernizing energy metering equipment. The communication between smart meters and the backhaul utility is known as the Advanced Metering Infrastructure (AMI).

The AMI is an advanced instrumentation technology enabled by real-time sensing and data communication to gather and convey raw measurements. Communication technologies must be chosen to address various requirements in the different parts of the AMI. The AMI's communication architecture is depicted in Figure 1.

The Neighborhood Area Networks (NANs) and Home Area Networks (HANs) of the AMI infrastructure are suitable for wireless deployment, as distances are relatively short. Information is concentrated in data aggregation points (DAPs). The backhaul network connecting the AMI head end and the DAPs can either be wireless or wired. The link between the DAPs and consumers requires NANs with coverage of a larger distance. Each DAP can connect to hundreds of smart meters (SMs).

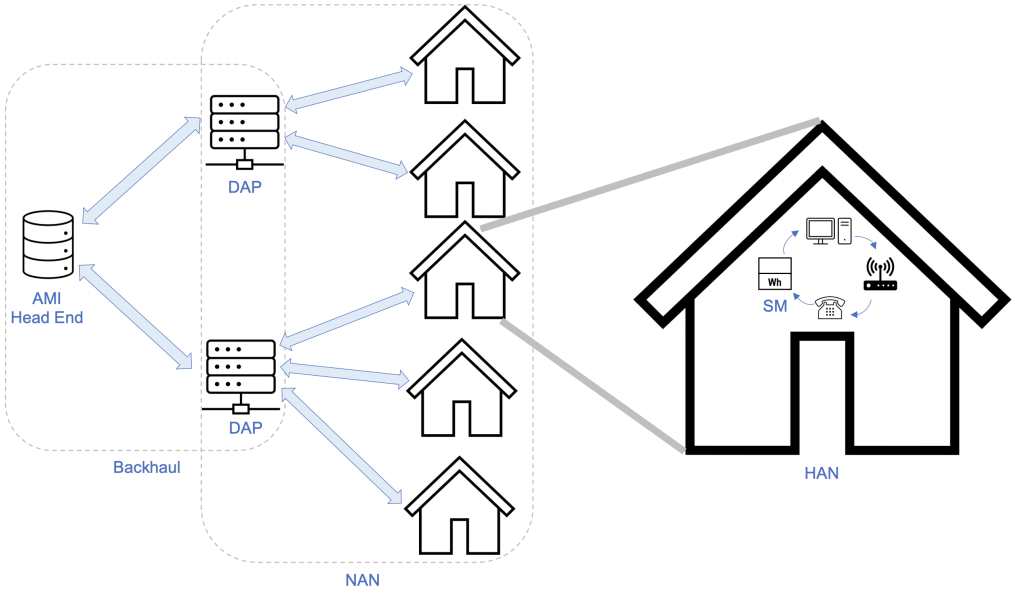


Figure 1. Architecture of the AMI (re-drawn from Ziming et al. [4]).

Elements responsible for sensing the parameters of power lines are usually referred to as sensor nodes. The projected locations of these sensor nodes (i.e., on utility poles in overhead distributed lines and on outer conductor surfaces in underground lines) suggest that the standards of both HANs and NANs may be adequate for defining their communication technologies roadmap. Many communication protocols have been proposed for the composition of NANs and HANs, as well as for other sections of the smart grid (such as the backhaul). A list of the most popular communication technologies considered adequate for different smart grid sections is shown in Table 1.

Table 1. Overview of communication technologies for the smart grid [5].

Technology	Spectrum	Data Rate	Coverage Rate	Limitations
GSM	900–1800 MHz	Up to 14.4 kbps	1–10 km	Low data rates
GPRS	900–1800 MHz	Up to 170 kbps	1–10 km	Low data rates
3G	1.92–1.98 GHz 2.11–2.17 GHz (licensed)	384 Kbps–2 Mbps	1–10 km	Costly spectrum fees
5G	3 to 90 GHz	5–10 Gbps	20–40 km	Costly spectrum fees
WiMAX	2.5 GHz, 3.5 GHz, 5.8 GHz	Up to 75 kbps	10–50 km 1–5 km	Not widespread
PLC	1–30 MHz	2–3 Mbps	1–3 km	Harsh, noisy channel environment
ZigBee	2.4 GHz–868–915 MHz	250 kbps	30–50 m	Low data rates, short range

Technologies for NANs have to provide a radius of coverage in the range of thousands of meters. The reliability of the communication channels between DAPs and smart meters (SMs) dictates that the spectrum used will have to be exclusive or interference-free. Consequently, the most suitable candidates need to be either licensed or leased wireless solutions. HANs have requirements that are not as stringent as those of NANs. In general, the message arrival rate within a customer premise is not as high as that between SMs and DAPs. They have been recognized with the generic name of "last-inch access". A comparison of the desired characteristics of different NAN and HAN communication technologies can be found in Table 2.

Table 2. Comparison of wireless communication technology candidates from the perspective of their suitability for NANs and HANs [4].

Coverage	Technology	Range	Latency	Reliability	Cost and Ease of Deployment
HAN	WiMAX	30 km	Low	High	Medium/Medium
	UMTS/LTE	30 km	Low	High	Medium/Low
	802.22	30 km	Medium	Medium/Low	High/Medium
NAN	WiFi	200 m	Medium–High	Low–Medium	Low
	ZigBee	100 m	Low–Medium	Medium	Low
	Bluetooth	100 m	Low	Medium	Low

In the literature, the preferred topology for smart grid applications at the level that has been discussed is wireless mesh. This technology enables any node in a network with routing capabilities to perform self-healing functions in a smart grid. It is suitable for home energy management and advanced metering infrastructures. Its disadvantages include coverage, the need for encryption techniques due to the information passing through every access point, and loop problems causing a reduction in bandwidth. A summary of the features, strengths, and challenges of each of the communication technologies is presented in Tables 1 and 2, including whether they incorporate deployment in a wireless mesh technology [5].

2.1. ZigBee

ZigBee is recognized as the most suitable technology for smart grid Home Area Networks (HANs) and is preferred by most AMI vendors and metering and energy management systems. It operates in the 2.4 GHz band, with a maximum radio output power of 1 mW, covering up to 100 m at 240 Kbps, using OQPSK modulation. It offers low development and operating costs within an unlicensed spectrum. It is based on the IEEE 802.15.4 standard [6]. Its disadvantages include concerns about low processing and memory capabilities and, mainly, susceptibility to interference from other 802.11 LAN [7] appliances. Interference avoidance schemes and energy-efficient routing protocols are challenges to be overcome.

2.2. WiFi

The IEEE suite of standards for wireless LANs, IEEE 802.11, is the most commonly deployed wireless standard within homes. As such, the devices and integrated circuits (ICs) are relatively cheap, making it an attractive solution. Amendments to the standard incorporate mesh networking capability, which is used in HANs. The data rate of WiFi ranges from 11 Mbps to 54 Mbps. It operates in the 2.4 GHz band, and it has a range of 30–46 m.

2.3. Bluetooth

The Bluetooth specification was designed for personal area networks (PANs) and is, therefore, suitable for HANs. The specification supports functions such as mesh networking. Furthermore, the specification ensures less latency compared to the two previously mentioned standards through the use of a time division multiple access (TDMA) scheme. Similar to ZigBee, it uses CSMA, which can result in large latency if many devices are in operation. It has a very short range of approximately 10 m and a low data rate of 1.5 Mbps. It operates in the 2.4 GHz band.

2.4. IEEE 802.22

The wireless regional area network is an alternative to mainstream broadband wireless that uses the white spaces in the television spectrum. It proposes to use cognitive radio technologies to exploit the unused spectrum in the frequency range allocated to television

broadcasting. As the spectrum used is not dedicated, the latency in data transmission could be higher than other solutions for HANs.

Cellular networks are a good option for communication between smart meter nodes and utility far nodes, i.e., in NANs. The cellular communication technologies available to utilities for smart metering deployments include 2G, 2.5G, 3G, WiMAX, and LTE. A data transfer interval of 15 min between the meter and the utility produces a large amount of information, which requires a high data rate connection. GSM and GPRS are currently being used to enable communication between smart meters and the backhaul utility. GPRS is used for data, with a typical rate of 30–80 kbps, whereas EDGE provides 160 to 236 kbps. These ranges are those of cell phones, so coverage is not a concern with these technologies. Other wireless technologies being used for smart grid projects include CDMA, WCDMA, and UMTS, even in the backbone of smart grid communications, as in the case of Verizon's 3G CDMA. SP AusNet in Australia chose WiMAX as the technology for dedicated communication between smart meters and the central system of SP AusNet. Another technology that is being used for this kind of task is 4G. Relaying functionality has also been incorporated into 3GPP Release 10 (commonly known as LTE Advanced), which will allow extended coverage using relay/repeater stations. Since cellular network infrastructure is already built, it presents a cost-effective feature. Cellular networks provide sufficient bandwidth for intermittent applications, security control, and wide coverage. The big drawback of these technologies is their reliability because the services are shared by customers, resulting in network congestion or a decrease in performance under emergency or abnormal situations. This is not acceptable in power utilities. One option for addressing these issues is the implementation of private cellular networks.

From these solutions, WiMAX, which implements IEEE's 802.16 standard for metropolitan networks, is a leading candidate for providing connectivity between DAPs and SMs. It is based on orthogonal division multiplexing access (OFDMA), which assigns slices of the frequency spectrum to different users, avoiding interference among the users and increasing the spectral efficiency of the system. WiMAX is an attractive solution in the sense that its structure is much less sophisticated compared to rival cellular standards such as Long-Term Evolution (LTE). It has a minimum range of 8 km and data rates ranging from 45 to 75 Mbps.

Up to this point, wireless technologies for smart grids have been outlined. They share some common disadvantages, which can be summarized as follows:

- Poor performance in electrically noisy and harsh environments.
- Concerns about security.
- Limited transmission range (except for cell phone technologies) and low data rates.
- Non-industrial-level reliability.
- Standards that are not robust.

Even though wireless technologies are the principal candidates for the deployment of communication among sensor nodes at the distribution level, it is worth mentioning the features that wired technologies can offer in the same context. The two options described below are considered in this summary.

2.5. Power Line Communication (PLC)

PLC uses existing power lines to transmit data at rates of up to 2–3 Mbps. It was the first choice in the implementation of AMIs, where it was used for data communication between smart meters and the data concentrator, whereas GPRS technology was used for transferring the data from the data concentrator to the utility's data center. The utilization of existing infrastructure reduces installation costs, making PLC an attractive solution for urban area applications. However, due to the harsh and noisy nature of power line networks, there are technical challenges. The channel is difficult to model. Also, the low-bandwidth characteristic of 20 kbps and sensitivity to disturbances make PLC unsuitable for data transmission. Medium-Voltage Broadband Power Line Communication (MV-BPLC) technology is considered an important candidate for communication with primary

and secondary substations, and [8] proved that MV-PLC is effective in supporting grid management. However, it also suffers from deficiencies like cable length, PV DGs, industrial loads introducing high-frequency noise, and a lack of reliability with faults. Future work includes designing a hybrid model (wireless with MV-BPLC).

2.6. Digital Subscriber Lines (DSLs)

DSL offers an already-built infrastructure with high-speed data transmission that has previously been exploited in smart grid projects. Its disadvantages are reliability, potential downtime, and the expense of installing and constantly maintaining communication cables.

In general, wired technologies, such as DSL, PLC, and even optical fiber, are costly for wide-area development, but they offer the most robust communication capabilities. On the other hand, wireless technologies reduce installation costs but have constraints in terms of bandwidth and security options.

2.7. Fifth-Generation Wireless Networks

The amalgamation of 5G architecture and smart grids presents significant opportunities in Transmission and Distribution. The introduction of 5G slicing adds intricate layers across user and utility domains, impacting energy dynamics and load balancing. The dynamic deployment paradigm aligns network functions with service needs. With end-to-end agreements covering communication service administration and network management for efficiency [9], 5G slicing ensures minimal latency.

The 5G grid segregates networks, which are shared with telecom systems. Industrial control achieves precision through 5G. Adaptable slicing enhances agility, reinforcing security. This approach reduces expenses and manages network velocity [9].

Technical 5G network services unfold through multi-layered slicing. Feeder automation requires intelligent orchestration for latency and bandwidth. Grid integration involves virtualized infrastructure. Wireless communication and power transmission promise progress, but costs and weather vulnerabilities pose challenges. Mobile radio and microwave transmission are alternatives. Cognitive radio supports smart grid wireless communication. The integration of 5G meets energy needs, aiding in forecasting and maintaining balance. Tailored strategies empower cities, and observability ensures distribution stability.

3. Requirements of Sensor Networks Implemented in the Power Line

The basic unit performing measurement tasks at a specific point on a distribution line was previously defined as a sensor node. The concept of the Sensor Network (SN) refers to the gathering of sensor nodes located in different sections of a power line through an appropriate communication link. This concept arises from the necessity of coordinating a large number of sensors for real-time monitoring in different parts of the power grid. It is motivated by the availability of modern low-cost sensing and communication technologies.

Among the challenges that the implementation of reliable SNs presents are the harsh, uncertain, and dynamic operating environments, as well as energy concerns. There are three main technologies that currently need development within the topic of SNs: sensing, networking, and information processing. The challenges, difficulties, and available technologies are discussed by Chen et al. [10,11], from which the following main requirements can be highlighted:

- The need for simple network protocols and algorithms for sensor nodes with limited computational and memory capacities.
- The self-healing capacity of the networking strategy, as sensor nodes are prone to failure in hostile environments.

Wireless communications offer the most flexible and straightforward interconnection between nodes. However, their use in power system environments presents security and reliability concerns, such as EMI, fading signals, bandwidth overloading, and security.

Despite this, wireless networks are still considered the most attractive technology for this development. These technologies are known as wireless sensor networks (WSNs).

The Institute of Electrical and Electronics Engineers (IEEE) has produced several standards related to communication in power systems. Notable standards include IEEE 802.16 (WiMAX), IEEE 802.11 (WiFi), and IEEE 802.15 (wireless personal area networks). These standards may not be specific to power systems but are often used in various applications, including power systems [12].

In [13,14], the authors recognized the four major challenges of WSNs in smart grid applications:

- Harsh environmental conditions: The connectivity of networks can vary due to link failures, and sensors are susceptible to RF interference.
- Reliability and latency: Due to the time sensitivity of sensors, the controller has to receive information in a timely manner.
- Link capacity: The bandwidth of each wireless link depends on the interference level at the receiver, leading to high bit-error rates (BER) ranging from 1×10^{-2} to 1×10^{-6}. The latency at each link varies continuously, so it is hard to meet QoS requirements.
- Design and implementation resources: Energy, memory, and processing resources are limited, so the protocols for WSNs are tailored to ensure high energy efficiency.

Finally, among the most important capabilities that any communication technology developed for a smart grid application should provide are the following:

- Security, as initial experiences in smart meter installations in households have already shown that public concerns about new smart grid technologies should not be ignored.
- Reliability, robustness, and availability, which are provided by most wired technologies. However, hybrid solutions using wireless and wired technologies might be used for the whole infrastructure. For wireless solutions in NANs, wide coverage is needed. Therefore, reliability is important, with latency low enough not only to satisfy demand-side management (DSM) requirements but also to serve all other AMI applications. This translates to a minimum reliability of 99.5% and a latency requirement of less than 1 s, which is a relatively relaxed figure compared to commercial broadband requirements [15]. HANs require a minimum reliability of 99.5% and a latency of less than 5 s, as they are shorter in reach and easier to access within the AMI.
- Scalability through the integration of web services, protocols, instruments, and configurations of the grid.
- Quality of Service (QoS). Quality, in this context, is defined in terms of performance degradation, like delays or outages. Requirements can be defined based on the power price. The impact of delays or outages on a reward system for a house appliance, based on the price, makes it possible to optimize the reward as a means to measure the QoS. Routing methodologies are used to meet the previously defined QoS requirements. This leads to concepts such as dynamic pricing and distributed energy resources management, which are presented in [15].

4. Previous Studies on Selecting Suitable Technologies for Power Line Monitoring

Although the field of WNSs is currently highly developed, there are few works that address the issue of wireless link quality or the experimental performance of different WSN technologies at the Transmission and Distribution (T&D) level [13]. The most significant efforts in applying previous theoretical frameworks of WSNs to practical scenarios are summarized in this section.

Toma et al. [16] introduced a self-powered WSN for underground HV power lines. The authors addressed one of the challenges in developing WSNs for power lines and presented the design of a protocol and network. The main objective of this work involved measuring temperatures and currents in underground conductors, as well as monitoring and controlling the capacity of transmissions (overall ampacity). Wireless sensors were deployed due to the large gaps that the information must travel to reach the gateway. The

second challenge of the project was the necessity of finding a way to encapsulate the data from the sensor to transmit them in a minimal number of packages.

Each sensor node consisted of an XBee-PRO 802.15.4 module, including an MC9S08GT60 MCU and an MC13193 RF chip. The backend server was connected to the last node through a GPRS module. The energy harvesting device was magnetic, but the sensor also incorporated a battery. The proposed protocol for communications was based on the Freescale Simple Media Access Controller (SMAC). The WSN used a 10 ms time slot for communication between two consecutive nodes, as well as Time Division Multiple Access (TDMA). The limit of transmission was 123 B, encapsulated according to the HDLC standard protocol, to be added to the 802.15.4 package. Each node's frame of data had a length of 12 B. To maintain accurate clock synchronization and minimize power consumption, the protocol was based on the IEEE 1588 standard. As network reliability was a concern, the protocol provided redundancy, where each node was required to communicate with at least two consecutive nodes. Under normal conditions and at a sampling rate of 10 s, the WSN achieved synchronization after 5 min; after 10 min, all odd nodes disconnected. The power consumption of the battery, in case the line was off, allowed for a duration of 2 weeks for each node.

Yang et al. [17] designed a sensor net for overhead transmission lines to transmit the local information of sensor modules peer-to-peer back to a master node, far away from local sensors, which is powered via a magnetic harvesting device clamped onto the power line. Digi's ZigBee-PRO RF module is used, implementing 802.15.4. It was noted that the protocol specifies Direct Sequence Spread Spectrum(DSSS) and Offset Quadrature Phase-Shift Keying (O-QPSK) to modulate the RF carrier, which helps enhance communication immunity to ambient noises, especially those with wide frequency bandwidth, such as impulse noises commonly observed in high-voltage power line environments. The topology is a cluster tree, along with a central coordinator RF module to provide synchronization services and end routers to connect to the higher subnet. It uses 128-bit encryption. The module is complemented with a TMS320F2812 DSP. The results show an outdoor range of 1.6 km, a data rate of 250 kbps, and a packet transmission rate of 50 packets per second (20 ms per packet), each containing 100 bytes of data.

The device was tested on a power line conductor. It was shown to be autonomously powered by a primary-side current ranging from 100 to 1000 A. To test the communication performance, a host PC was used to continuously transmit a data stream (32 bytes/packet) to the module, and the communication performance was evaluated by receiving the same data stream looped back from the remote PLS module. For the communication performance, two criteria were evaluated: the Received Signal-Strength Indicator (RSSI) and the Percentage of Successful Reception (PSR). In a second experiment, the communication performance was evaluated at a distance of up to 700 m between two nodes in outdoor conditions. The results of both experiments are shown in Tables 3 and 4.

Table 3. Performance of IEEE 802.15.4 in indoor environments from the study by Gupta et al. [17,18].

Current (A)	Range (m)	RSSI (dBm)	PSR
1000	50	−70 to −75	100%
	100	−92	∼45%
500	10	−45 to −50	100%
	50	−73	100%
	100	−93	∼45%

Table 4. Performance of IEEE 802.15.4 in outdoor environments from the study by Gupta et al. [17,18].

Range (m)	RSSI (dBm)	PSR	Conditions
200	∼−76	∼95%	Close to line of sight
400	∼−83	∼80%	Trees
500	−92	∼35%	Trees and buildings

The test results showed that the high current did not affect the communication performance. However, the obstacles between the two communication nodes significantly affected the performance. Even though the communication performance was degraded, outdoor transmission at a distance of up to 400 m was achieved with a transmission success rate of up to 80%. The effect of high voltage, mainly due to the corona effect, will be validated in the future.

State-of-the-art sensor communication technology for sensing nodes on power lines, as discussed in [19,20], was implemented usingZigBee technology based on IEEE 802.15.4 in the TI's CC2530 SOC solution. It should be mentioned that this technology is comparable to Bluetooth but with the added advantage of very low latency. The sensor uses an 8051 MCU, 256 KB flash, 8 KB RAM, 12-bit ADC, and eight channels. It takes 400 ms to communicate and go back to sleep. At 100 A, the operational frequency is as high as once every minute. Energy storage ensures 13 cycles of operation after an outage.

As previously mentioned, review studies on smart grid communication technologies, such as [3], have recognized that a big challenge in this area is the difficult estimation of the instantaneous value of the wireless link quality. From all the real-world studies on WSNs where different sensor platforms have been used, the common observations are:

- The recognition of three distinct reception regions in a wireless link: connected, transitional, and disconnected.
- Wireless link quality varies over space and time, unlike standard models often used in simulation tools. The coverage area of sensor radios is neither circular nor convex, and packet losses are common at a wide range of distances, varying over time.
- Link asymmetry (one-way communication) occurs when the transmit power is low.

A measurement of the link quality was performed by Gungor et al. [14], using sensors implementing IEEE 802.15.4. They used a packet length of 30 B and a buffer size of 64 packets. The experiments were conducted in three locations: an outdoor environment near a 500 kV substation, inside a power control room, and in an underground transformer vault. The channel was modeled as a log-normal shadowing path loss, where the Signal-to-Noise Ratio (SNR) γ in dB, was expressed as

$$\gamma(d)_{dB} = P_t - PL(d_0) - 10\eta\left(\frac{d}{d_0}\right) - X_\sigma - P_\eta \quad (1)$$

where P_t is the transmit power in dBm, $PL(d_0)$ is the path loss at the reference distance (d_0), η is the path-loss exponent, X_σ is a zero-mean Gaussian random variable with a standard deviation of σ, and P_η is the noise power in dBm. For different propagation environments, the values of η and σ were calculated from the measured data using linear regression. The results for these parameters are presented in Table 5. Two links for communications were also considered: line of sight (LOS), and non-LOS (NLOS).

Table 5. Mean power loss and shadowing deviation in different electric power environments, as measured by Gungor et al. [14].

Propagation Environment	Path Loss (η)	Shadowing Deviation (σ)
500 kV substation (LOS)	2.42	3.12
500 kV substation (NLOS)	3.51	2.96
Underground transformer vault (LOS)	1.45	2.45
Underground transformer vault (NLOS)	3.15	3.19
Main power room (LOS)	1.64	3.29
Main power room (NLOS)	2.38	2.25

Noise and interference were measured using a TinyOS application that samples RF energy at 62.5 Hz by reading the Received Signal-Strength Indicator (RSSI) on a CC2420 radio in the various aforementioned environments. The noise measurements on an 802.15.4

network indicated an average noise level of around −90 dBm for indoor environments and −105 dBm (of constantly changing) background noise for outdoor environments. The results also showed that a previously existing microwave signal (from a microwave in the study), led to 15 dBm interference in the 2.4 GHz band. Also, interference of 802.11 b was caused by the overlapping band.

The final link-quality measurements were determined using three metrics: the Packet Reception Rate (PRR), RSSI, and Link-Quality Indicator (LQI). The latter is also known as the chip error rate. The distance from receiver to sender varied from 1 to 20 m. The power level of each sensor was −25 dBm and the packet size was 30 B, sending 200 data packets at a rate of 2 packets per second. The results showed that the PRR (ratio of the number of successful packets to the total number of packets transmitted over a certain number of transmissions) strongly correlated with the LQI. Hence, the LQI is a good indicator of the packet reception probability in this kind of experiment. The LQI ranged from 50 to 110.

Comparison of Technologies

Wireless sensor networks are built from nodes that must be low cost and have very low power consumption. At least one of these two requirements is met by the available technologies presented in this summary, such as IEEE 802.15.1 (Bluetooth) and IEEE 802.15.4 (ZigBee). There will be cases where one technology will be preferred over the other, depending on the application type, environment, sensor node technology, and network configuration requirements. Therefore, there is a clear need to analyze different technologies with respect to each other in order to be able to decide which one would be more suitable for a given application, with certain constraints and requirements.

Buratti et al. [21,22] numerically addressed the issue of the lifetime of a WSN to compare Bluetooth and ZigBee in a particular application. This was the first study to compare such technologies in the context of WSNs. The authors used the EMORANS scenario as a framework for the comparison. EMORANS defines the test conditions for wireless communications, as follows:

- The geometry of a square layout of a side is set to 100 m.
- A node density of either 100 or 500 nodes is used with a uniform distribution over the square.
- A sink is required for periodically collecting the measurements performed over the sensed area by nodes.
- The initial battery charge is set to 1 Joule to facilitate shorter simulations. The channel model loss in logarithmic scale should be $k_0 + k_1 ln(d) + s$, where d is the distance, k_0 = 40 dB, k_1 = 13.03 (obtained through experimental measurements made in the field in a rural environment), and s is a Gaussian random variable, with a mean of zero and a standard deviation of σ, modeling channel fluctuations. The capture packet model used states that a packet is correctly received in case the loss is smaller than a given threshold, Lm, which depends on the technology used.
- The three definitions of network lifetime are as follows, where a round is the time elapsed between two consecutive measurements:
  - The interval of time (measured in rounds) from the first transmission in the wireless network to the point when the percentage of nodes with remaining energy drops to zero.
  - The average percentage of nodes that remain reachable within the network over a specified time window.
  - The average percentage of reports sent from nodes to the sink over a defined time window.

If in any of these definitions, the lifetime falls below a specific threshold, which is set according to the type of application, the quality of the lifetime is considered low. The first definition takes into account only energy consumption issues, whereas the second takes into account both energy consumption and connectivity issues. The third definition refers to energy consumption, connectivity, and MAC failures. In Figure 2, a comparison of

Bluetooth and IEEE802.15.4 is provided, considering two networks composed of 500 and 100 nodes.

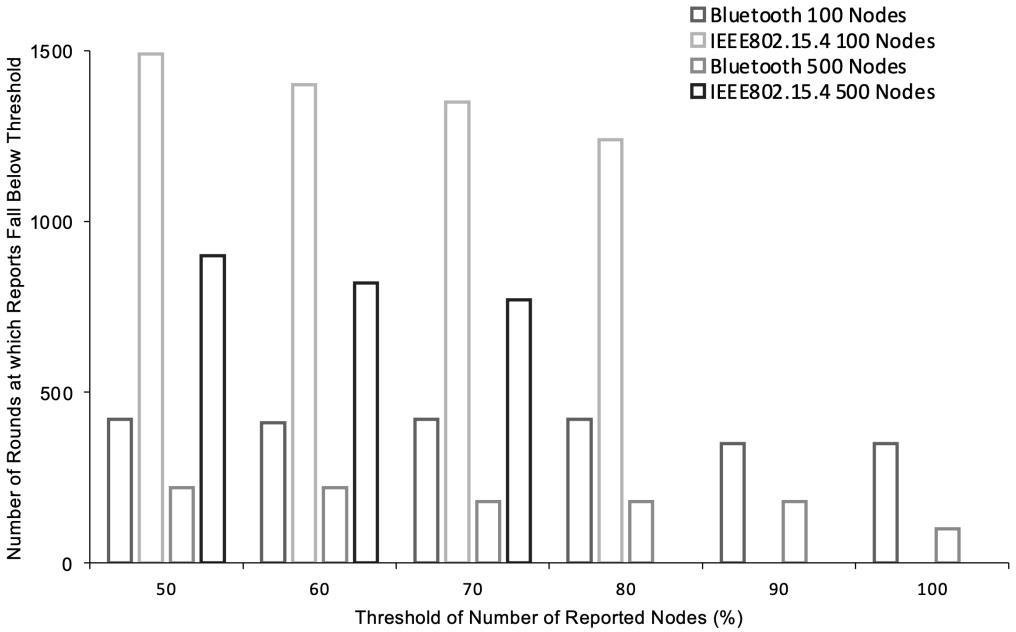


Figure 2. Network lifetime comparison of Bluetooth and ZigBee (taken from Buratti et al. [21]).

Figure 2 shows the rounds at which the number of reports arriving at the sink from the nodes started to fall below a certain percentage (a threshold), indicated on the x-axis. ZigBee exhibited a longer lifetime compared to Bluetooth, supporting up to 80 nodes. However, beyond 80 nodes, the lifetime of ZigBee is not shown because in the first round, more than 10% of packets in the 100-node case were lost. The choice of technology depends on the application requirements. If, in fact, one considers a network composed of 100 nodes and an application that requires that the sink receives 100% or 90% of the packets, one would choose Bluetooth because IEEE802.15.4 cannot attain these percentages. In the case where the application can tolerate a loss of more than 10% of the packets, IEEE802.15.4 is better because it establishes a more energy-efficient network.

Gupta and Malvika [18] presented a comparison of the major characteristics of the two main protocols for short-range terrestrial communications: WiFi and Bluetooth. The study did not focus on WSNs but provided interesting information, which is summarized in Table 6.

As shown in Table 6, the power requirements of Bluetooth devices are significantly lower compared to those of WiFi n/abg devices. However, the data rates of WiFi are higher. Additional considerations about the signal rate and channel characteristics might be useful for considering similar patterns in other WSN technologies.

Finally, Sharman et al. [23,24] briefly evaluated different technologies using standards for synchrophasors. The authors concluded that wired technologies such as ADSL2 and FTTC are the best last-mile possible candidates for smart grid operations. Among wireless technologies, WiMAX is the best witha packet loss of 0.0322, a latency of around 9 ms, and a throughput of 20 Mbps (<2 ms for required protections).

Table 6. A comparison of Bluetooth and WiFi n/abg protocols [21].

	Bluetooth	**WiFi**
Frequency band	2.4 GHz	2.4 GHz, 5 GHz
Coexistence mechanism	Adaptive frequency hopping	Dynamic frequency selection, Adaptive power control
Multiplexing	FH55	DSSS, CCK, OFDM
Future multiplexing	UWB	MIMO
Noise adaptation	Link layer	Physical layer
Typical output power	1–10 mW (1–10 dBm)	30–100 mW (15–20 dBm)
Nominal range	10 m	100 m
Maximum one-way data rate	732 kb/s	31.4 Mb/s
Basic cell	Piconet	BSS
Extension of the basic cell	Scatternet	ESS
Topologies	Various analogies: see Subsection Network Topologies	
Maximum number of devices in the basic cell	8 active devices; 255 in park mode	Unlimited in ad hoc networks (IBSS)
Maximum signal rate	1 Mb/s	54 Mb/S
Channel access method	Centralized: polling	Distributed: CSMA/CA
Channel efficiency	Constant	Decreasing with offered traffic
Spatial capacity	From 0. 1 to 400 Kb/s $\cdot m^2$	About 15 kb/s$\cdot m^2$
Data protection	16-bit CRC (ACL links only)	32-bit CRC
Procedures used for the network setup	Inquiry, Page	Ad hoc networks: Scan, Authentication Infrastructured Scan
Average speed in the network setup without external interference	$5s + n - 1.28s$, where n is the number of Slaves in the piconet, ranging from 1 to 7	n.c. 1.35 ms for an unsaturated network, c probed channels
Authentication	Shared secret, pairing	Shared secret challenge-response
Encryption	Eo stream cipher	RC4 stream cipher RES
QoS mechanism	Link types	Coordination functions
Typical current absorbed	1–35 mA	100–350 mA
Power-save modes	Sniff, hold park, standby	Doze

5. Summary and Conclusions

This report has presented an overview of the candidate technologies for the task of communication for sensing devices located in different sections of the future electricity distribution network, also known as the smart grid. The new paradigm of smart grid communications defines, at the customer level, a communication architecture known as the Advanced Metering Infrastructure (AMI), which includes Home Area Networks (HANs) to facilitate communication among different elements within customer households, including smart meters (SMs). It also includes Neighborhood Area Networks (NANs) to facilitate communication between SMs and concentration points. On the other hand, devices in charge of measuring tasks in distribution lines are known as sensor nodes (SNs). The concept of the AMI is adequate for SNs due to their location. Hence, technologies that are used in NANs and HANs are suitable for use in SNs. Wireless mesh topologies are the most suitable within that paradigm.

Among the suitable wireless technologies for this kind of development are 802.15.4 (ZigBee), IEEE 802.11 (WiFi), and Bluetooth, which are common technologies in HANs. Among them, ZigBee provides the longest coverage range (100 m) but at the smallest data rate (240 kbps). Cellular networks and 802.22 are employed in HANs, as the coverage area can extend up to thousands of meters. Cellular networks have the advantage of wide coverage and have been used as the backbone of smart grid deployments. Their disadvantage is their low reliability for real-time tasks in sensing and power management applications. WiMAX (802.16 implementation) is another candidate that does not encounter the problem of interference issues from other technologies. It has a practical range of up to

8 km and speeds in the order of Mbps. Wired technologies that have been considered in smart grid deployments include Power Line Communication (PLC), which provides data rates in the order of several Mbps and has been used in SM applications. However, the difficulty of channel modeling is a big disadvantage. Digital Subscriber Line (DSL) and fiber optic communication have also been considered, but these wired technologies are costly for wide-area deployment. Correspondingly, wireless technologies reduce installation costs but have constraints in terms of bandwidth and security options.

A large number of sensors are installed along the distribution power line in a wireless sensor network (WSN). WSNs have punctual challenges and requirements, which have been identified in the literature. To address the main bandwidth and energy concerns, WSNs should implement protocols and algorithms designed for limited computational and memory capacities. In addition, the self-healing capacity is important in the environment of a power line. The future IEEE P1777 standard will define the precise requirements and challenges of different technologies. The main challenges for WSNs are the harsh environmental conditions and the energy required to power them. More specifically, the main requirements of WSNs are the security of information, robustness in terms of wide coverage, and reliability to keep the information flowing continuously. This latter feature is very important, as time delays and outages are critical in the power utility grid. Scalability, as the possibility of integrating protocols and grid configurations, is also an important feature in the context of the sensor nodes of different instrumentation and communication technologies. Wireless technologies must address issues such as performance in noisy grid environments, security concerns, the limited range of transmission, low data rates, non-industrial-level availability, and the lack of robust standards for WSNs.

The experimental performance of different WSNs in the environment of power lines has not often been addressed in the literature. Some studies have presented the design of protocols for WSNs. ZigBee technology is a very popular technology. The challenge of maintaining accurate clock synchronization between sensors has been clearly identified. In one study, this was accomplished with the IEEE 1588 standard. Apart from measurements of the coverage range, data rate, and latency, the quality of the channel is an important indicator of communication performance. Metrics for achieving this are not yet standardized, but the Received Signal-Strength Indicator (RSSI) in the nodes, Percentage of Successful Reception (PSR), and Packet Reception Rate (PRR) have been used in some studies. Ultimately, a parameter called the Link-Quality Indicator (LQI) (known as the chip error rate) has proven to be a good indicator of the packet reception probability in WSNs. In outdoor environments, 802.15.4 can achieve a transmission success rate of 80% at 400 m, with physical obstacles as the main drawback. Power line currents of 500 A do not affect communication according to the experiments conducted. The complexity of the WSN's communication channel in power system environments has been addressed using mathematical models like the log-normal shadowing path loss. The gathering of data for this model is dependent on the specific communication environment. ZigBee has been tested using this model, showing around -105 dBm of noise in outdoor environments and interference with 802.11 signals in the 2.4 GHz band.

Future Research Work

While a limited number of studies have analyzed the performance of the various communication technologies in high-voltage distribution line environments, there is scope for future research in this domain. Some promising research directions include:

- Simulation-Based Performance Analysis: To address the dearth of studies on high-voltage distribution lines, conducting simulations of different communication protocols under such conditions is a crucial step. Evaluating the performance of the following prominent wireless sensor network (WSN) technologies will provide insights into the suitability and efficiency of these technologies in the context of high-voltage distribution lines: ZigBee (802.15.4 standard), WiMax, Bluetooth, WiFi, and 5G.

- Mathematical Modeling of Communication Channels: The development of mathematical models for the communication channels within the grid infrastructure, specifically in high-voltage (HV) power lines, is a valuable avenue of research. Techniques such as Finite Element Analysis (FEA) using software like ANSYS Maxwell can be employed. Such models can be informed by the findings from the literature review in this paper, enabling a more comprehensive understanding of the communication channels' behavior in HV environments.
- Performance Evaluation Using the Link-Quality Indicator (LQI): To extend the analysis, an evaluation of the technologies reviewed in this paper, particularly in HV distribution line scenarios, using metrics like the Link Quality Indicator (LQI) is necessary. The methodology for these assessments can draw inspiration from the approaches detailed in the referenced articles. Utilizing network simulation tools like OpNET can facilitate these evaluations.
- Defining WSN Performance in Power System Environments: A significant contribution would be the definition of WSN performance in power system environments, a knowledge gap that currently exists in the literature. Providing insights into the strengths and weaknesses of different WSN technologies within this context can aid in informed decision making for smart grid deployments.
- Development of Protocols and Strategies: Based on the insights gained from initial experiments and performance evaluations, there is potential for the development of new protocols and strategies for smart grid communication. These innovations can be shaped by real-world findings and may lead to advancements in the reliability and efficiency of communication systems within the smart grid.

By exploring these research avenues, we can contribute valuable knowledge to the field of smart grid communication, address existing gaps, and pave the way for more robust, reliable, and efficient energy distribution systems.

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References

1. Goudarzi, A.; Ghayoor, F.; Waseem, M.; Fahad, S.; Traore, I. A Survey on IoT-Enabled Smart Grids: Emerging, Applications, Challenges, and Outlook. *Energies* **2022**, *15*, 6984. [CrossRef]
2. Çelık, D.; Meral, M.E.; Waseem, M. A new area towards to digitalization of energy systems: Enables, challenges and solutions. In Proceedings of the 2022 14th International Conference on Electronics, Computers and Artificial Intelligence (ECAI), Ploiesti, Romania, 30 June–1 July 2022; pp. 1–6.
3. Butt, O.M.; Zulqarnain, M.; Butt, T.M. Recent advancement in smart grid technology: Future prospects in the electrical power network. *Ain Shams Eng. J.* **2021**, *12*, 687–695. [CrossRef]
4. Zhu, Z.; Lambotharan, S.; Chin, W.H.; Fan, Z. Overview of demand management in smart grid and enabling wireless communication technologies. *IEEE Wirel. Commun.* **2012**, *19*, 48–56.
5. Gungor, V.C.; Sahin, D.; Kocak, T.; Ergut, S.; Buccella, C.; Cecati, C.; Hancke, G.P. Smart grid technologies: Communication technologies and standards. *IEEE Trans. Ind. Inform.* **2011**, *7*, 529–539. [CrossRef]
6. IEEE 802.15 WPAN Task Group 4. Available online: https://www.ieee802.org/15/pub/TG4.html (accessed on 5 November 2023).
7. IEEE 802.11 Wireless Local Area Networks Standard. Available online: https://www.ieee802.org/11/ (accessed on 5 November 2023).
8. Lopez, G.; Matanza, J.; De La Vega, D.; Castro, M.; Arrinda, A.; Moreno, J.I.; Sendin, A. The role of power line communications in the smart grid revisited: Applications, challenges, and research initiatives. *IEEE Access* **2019**, *7*, 117346–117368. [CrossRef]

9. Dragičević, T.; Siano, P.; Prabaharan, S.S. Future generation 5G wireless networks for smart grid: A comprehensive review. *Energies* **2019**, *12*, 2140.
10. Chen, Z.; Amani, A.M.; Yu, X.; Jalili, M. Control and Optimisation of Power Grids Using Smart Meter Data: A Review. *Sensors* **2023**, *23*, 2118. [CrossRef] [PubMed]
11. Yang, Y.; Lambert, F.; Divan, D. A survey on technologies for implementing sensor networks for power delivery systems. In Proceedings of the 2007 IEEE Power Engineering Society General Meeting, Tampa, FL, USA, 24–28 June 2007; pp. 1–8.
12. Chamana, M.; Bhatta, R.; Schmitt, K.; Shrestha, R.; Bayne, S. An Integrated Testbed for Power System Cyber-Physical Operations Training. *Appl. Sci.* **2023**, *13*, 9451. [CrossRef]
13. Abujubbeh, M.; Al-Turjman, F.; Fahrioglu, M. Software-defined wireless sensor networks in smart grids: An overview. *Sustain. Cities Soc.* **2019**, *51*, 101754. [CrossRef]
14. Gungor, V.C.; Lu, B.; Hancke, G.P. Opportunities and challenges of wireless sensor networks in smart grid. *IEEE Trans. Ind. Electron.* **2010**, *57*, 3557–3564. [CrossRef]
15. Abrahamsen, F.E.; Ai, Y.; Cheffena, M. Communication technologies for smart grid: A comprehensive survey. *Sensors* **2021**, *21*, 8087. [CrossRef] [PubMed]
16. Toma, D.M.; del Rio, J.; Mànuel-Làzaro, A. Self-powered high-rate wireless sensor network for underground high voltage power lines. In Proceedings of the 2012 IEEE International Instrumentation and Measurement Technology Conference Proceedings, Graz, Austria, 13–16 May 2012; pp. 1881–1885.
17. Yang, Y.; Divan, D.; Harley, R.G.; Habetler, T.G. Design and implementation of power line sensornet for overhead transmission lines. In Proceedings of the 2009 IEEE Power & Energy Society General Meeting, Calgary, AB, Canada, 26–30 July 2009; pp. 1–8.
18. Gupta, M.; Singh, S. A survey on the zigbee protocol, it's security in internet of things (iot) and comparison of zigbee with bluetooth and wi-fi. In *Proceedings of the Applications of Artificial Intelligence in Engineering: Proceedings of the First Global Conference on Artificial Intelligence and Applications (GCAIA 2020)*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 473–482.
19. Riba, J.R.; Moreno-Eguilaz, M.; Bogarra, S. Energy Harvesting Methods for Transmission Lines: A Comprehensive Review. *Appl. Sci.* **2022**, *12*, 10699. [CrossRef]
20. Moghe, R.; Yang, Y.; Lambert, F.; Divan, D. Design of a low cost self powered "Stick-on" current and temperature wireless sensor for utility assets. In Proceedings of the 2010 IEEE Energy Conversion Congress and Exposition, Atlanta, GA, USA, 12–16 September 2010; pp. 4453–4460.
21. Buratti, C.; Korpeoglu, I.; Karasan, E.; Verdone, R. Bluetooth or 802.15. 4 technologies to optimise lifetime of wireless sensor networks: Numerical comparison under a common framework. In Proceedings of the 2008 6th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks and Workshops, Berlin, Germany, 1–3 April 2008; pp. 539–543.
22. Gupta, S.K.; Singh, S. Survey on energy efficient dynamic sink optimum routing for wireless sensor network and communication technologies. *Int. J. Commun. Syst.* **2022**, *35*, e5194. [CrossRef]
23. Sharma, D.K.; Rapaka, G.K.; Pasupulla, A.P.; Jaiswal, S.; Abadar, K.; Kaur, H. A review on smart grid telecommunication system. *Mater. Today Proc.* **2022**, *51*, 470–474. [CrossRef]
24. Laverty, D.M.; O'Raw, J.; Morrow, D.J.; Cregan, M.; Best, R. Practical evaluation of telecoms for smart grid measurements, control and protection. In Proceedings of the 2011 2nd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies, Manchester, UK, 5–7 December 2011; pp. 1–5.

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