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A survey on wireless sensor networks for smart grid

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ABSTRACT

The traditional power grid in many countries suffers from high maintenance costs and scalability issues along with the huge expense of building new power stations, and lack of efficient system monitoring that could increase the overall performance by acting proactively in preventing potential failures. To address these problems, a next-generation electric power system, called the smart grid (SG), has been proposed as an evolutionary system for power generation, transmission, and distribution. To this end, the SGs utilize renewable energy generation, smart meters and modern sensing and communication technologies for effective power system management, and hence, succeeding in addressing many of the requirements of a modern power grid system while significantly increase its performance. Recently, wireless sensor networks (WSNs) have been recognized as a promising technology to achieve seamless, energy efficient, reliable, and low-cost remote monitoring and control in SG applications. In these systems, the required information can be provided to electric utilities by wireless sensor systems to enable them to achieve high system efficiency. The real-time information gathered from these sensors can be analyzed to diagnose problems early and serve as a basis for taking remedial action. In this paper, first WSN-based SG applications have been explored along with their technical challenges. Then, design challenges and protocol objectives have been discussed for WSN-based SG applications. After exploring applications and design challenges, communication protocols for WSN-based SG applications have been explained in detail. Here, our goal is to elaborate on the role of WSNs for smart grid applications and to provide an overview of the most recent advances in MAC and routing protocols for WSNs in this timely and exciting field.

1. Introduction

Electricity, one of the most popular and important forms of energy that impacts human lives, economics and politics, is produced in a very critical infrastructure known as power grid. A power grid is populated by a large number of components that are interconnected, while spreading in various geographic locations. Until recently, a centralized approach was used to develop the existing power grid infrastructure in which a few very high-power AC plants were interconnected with many substations by a large number of distribution lines that supplied (usually after a voltage reduction) uni-directionally the residential loads. In addition, recently, new renewable energy generators (e.g., photovoltaic systems, wind turbines) have been used to provide an alternate way for electricity production. These small-scale electric generators can be located near customer premises and are able to relieve the load from the power grid while helping in balancing the power demand and electricity supply.

The connection of these renewable solutions to the existing power system transformed it in a very large-scale, highly distributed generation system which incorporates a large number of generators, generally characterized by different topologies which combine different technologies with various current, voltage and power levels. With the addition of these new solutions, the existing power grid managed to partially serve the globally increasing demand for electricity, but still had to deal with problems such as: equipment failures, blackouts, poor communication and lack of effective monitoring of the infrastructure. Those challenges, along with production instabilities caused by structural or operational characteristics, can easily lead to huge economic losses, inefficient electricity usage, customer dissatisfaction and pollution from a huge amount of CO_2 emissions. Because of the costly maintenance of the existing aged infrastructures along

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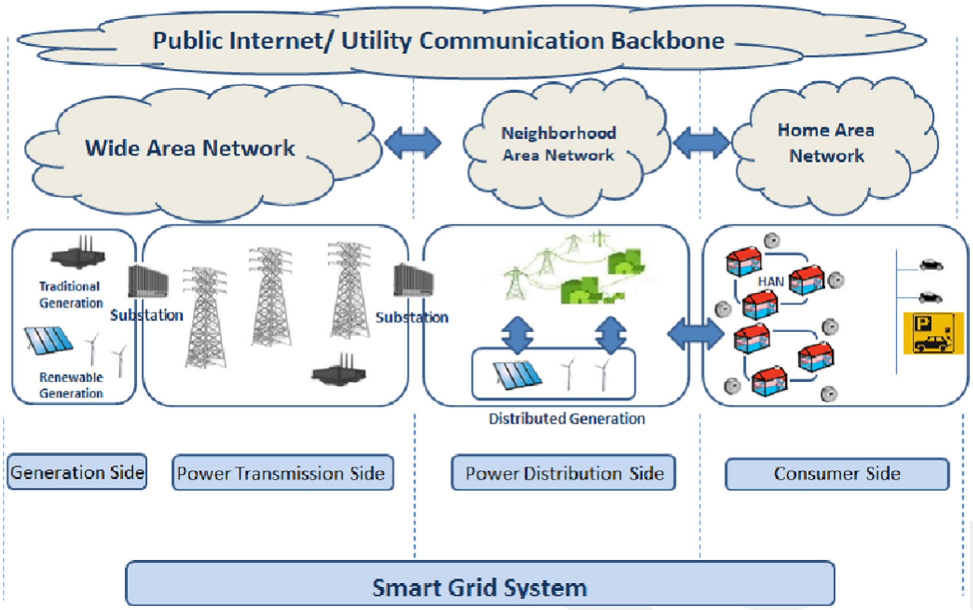

Fig. 1. An illustrative architecture of smart grid from generation to consumer sides.

with the rising costs for building new ones and the declining number of skilled personnel, the need for more dynamic and efficient operation of the system has become inevitable.

To this end, the power grid's efficiency can be improved by the use of various sensors. This approach allows collecting real-time data from various sensor devices in a power grid and communicating the collected data along the infrastructure. In this way, a problem in the system's functionality can be diagnosed proactively and timely generated remedial actions can be taken in order to prevent any failures that might affect the grid's performance. In these monitoring systems, the sensors can be installed on the critical power grid equipment and can be used to monitor essential grid components such as voltage, current, temperature, system frequency and power quality disturbances [1–4]. This way, a next-generation electric power system is created, the *smart grid (SG).*

To this end, the SG is a modernized power transmission and distribution (T&D) network, which uses two-way data communications, distributed computing technologies and smart sensors to improve safety, reliability and efficiency of power delivery and use. Using a sophisticated *information processing* and *communication* technology infrastructure, the SG will be able to fully use and benefit from its *distributed power generation* system, while maximizing the whole system's energy efficiency. Consequently, SG is also considered as a *data communication* network which, by supporting many power management devices, achieves seamless and flexible inter-operational abilities among different advanced system components that leads to an efficient performance [7–11,16]. Basically, the SG network can be divided into three segments; home area networks (HANs), neighborhood area networks (NANs) and wide area networks (WANs) as depicted in Fig. 1:

- ***HAN*** creates a communication path among smart meters, home appliances and plug-in electric vehicles. The HAN enables consumers to collect information about their consumption behaviors and the electricity usage costs via in-home display devices. Due to the low-bandwidth requirements of HAN applications, it needs cost-effective communication technologies, such as HomePlug, Wi-Fi, Bluetooth and ZigBee.
- ***NAN*** is established between data collectors and smart meters in a neighborhood area. To this end, short-range communication technologies, such as Wi-Fi and RF mesh technologies, can be used to collect the measured data from smart meters and transmit them to the data concentrator.
- ***WAN*** creates a communication path between service provider's data center and data concentrators. It is a high bandwidth and robust two-way communication network, which can handle long-distance data transmissions for SG monitoring and control applications. In general, the communication technology providing the best coverage with the lowest cost, such as LTE, cellular networks (2G–3G systems), fiber, power line communication networks, are widely adopted for WAN networks [7–11].

Recently, the *wireless sensor networks* (*WSNs*) have been widely recognized as a technology promising to improve various aspects of SGs, especially those that deal with power generation, bidirectional delivery, utilization and seamless monitoring, providing an energy efficient, reliable and low-cost solution for control management [1,5,6,14]. The existing and potential WSN applications for SG include advanced metering, demand response and dynamic pricing, equipment fault diagnostics, fault detection, load control, distribution automation and remote power system monitoring and control. SG is also considered as a data communications network; therefore the communication capabilities among the elements of an electrical power system will play a huge role on the efficient performance of any WSN-based SG application. However, the selection for the most appropriate communication technology varies depending on the requirements of WSN-based smart grid applications. For example, distributed feeder automation applications require low-latency and high-data-rate communications among substations and intelligent electronic devices in order to timely detect and isolate faults. On the other hand, smart metering applications require latency-tolerant information exchange between the meters and utility management center.

Importantly, Fig. 2 summarizes the evolution from the early automatic meter reading (Phase I), characterized by one-way communication, to the advanced metering infrastructure (AMI) (Phase II), incorporating two-way communications, and to the smart grid (Phase III) with intelligent applications and communication infrastructure via advanced sensor networking technologies. Here, it is crucial to note that the envisioned WSN applications for SG will be realized in the near future with the help of distribution automation, load and outage control, advanced energy management and smart sensors. Therefore,

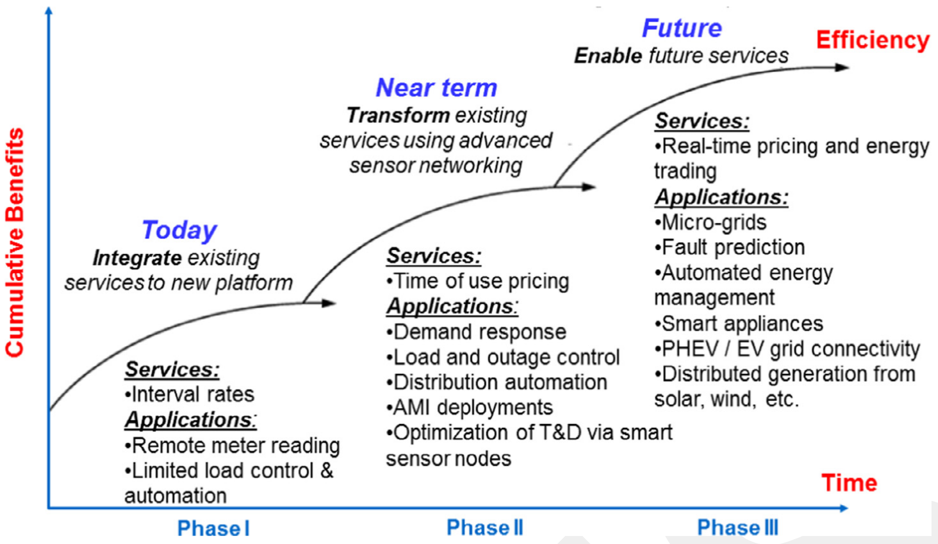

Fig. 2. Smart grid applications and services road map.

in many countries, the SG roadmaps have been created to draw a global path with recommendations and action plans for further sensor network technology improvements. In the revolution process of an SG, interoperable WSN and SG technologies still need to be developed with the collaboration of different industrial and government organization groups.

A number of surveys have been published to address SG challenges from different perspectives. In [108], the focus is on utilizing SG technologies in green information and communication technologies (ICTs). Another survey in [109] discusses the SG technology and its potentials. In addition, that study presents wireless communications for HANs and NANs providing a comparative study for each one. The overview of SG and its communication and security challenges have been presented in [110]. Also, the study in [111] provides the reference architecture of the SG communication system and its major components. In addition, that survey discusses the four major SG applications, which are used to identify the key requirements for smart grid communication systems. Furthermore, a bottom-up approach has been followed to describe the main approaches proposed in the literature to build communication and middleware solutions suitable for SG applications. The study in [1] also provides a wireless channel model for smart grid propagation environments and guides design decisions for SG applications.

Different from existing studies, in this paper, first WSN-based SG applications have been explored along with their technical challenges. Then, design challenges and protocol objectives have been discussed for WSN-based SG applications. After exploring applications and design challenges, communication protocols for WSN-based SG applications have been explained in detail. The main objective of this paper is to elaborate on the role of WSNs for smart grid applications and to provide an overview of the most recent advances in MAC and routing protocols for WSNs in this timely and exciting field.

The rest of the paper is organized as follows. In Section 2, WSN-based SG applications are divided in three main categories and presented in detail. The protocol design objectives for SG applications are covered in Section 3. In Section 4, MAC and routing layer protocols for SG are explained. In Section 5, the communication technologies for wireless sensor networks are covered. Finally, the survey is concluded in Section 6.

2. Wireless sensor network applications in smart grid

The evolution in WSN, especially on the problems related to energy exhaustion, energy harvesting, mobility and communication, has open new perspectives for their usage in a SG environment. Various, diverse range power grid applications from home area networks (HANs) to power T&D monitoring have been developed and used [1,5,7,8,17–23] allowing for robust and energy-efficient monitoring and control in a SG [24,86,88]. In general, the WSN applications for SGs can be divided in three main categories: generation side, T&D side and consumer side applications. In Table 1, a summary of WSN-based SG applications is given [85,107]. In the following, WSN applications in SG are described in detail.

Table 1
Wireless sensor network (WSN) applications in smart grid (SG) environments.

WSN-based SG applications	Power grid segment
Remote monitoring of wind or solar farms Power quality monitoring Distributed generation	Generation side
Equipment fault diagnostics Overhead transmission line monitoring Outage detection Underground cable-system monitoring Conductor temperature and dynamic thermal rating systems Overhead and underground fault circuit indicators Cable, conductor, and lattice theft Conductor temperature and low-hanging conductors Insulators Fault detection and location Animals and vegetation control	T&D side
Wireless automatic meter reading (WAMR) Residential energy-management (REM) Automated panels management Building automation Demand-side load management Power grid equipment monitoring and control	Consumer side

2.1. Generation side applications

Monitoring is the most crucial characteristic of the generation side applications. There are many different applications for WSN monitoring in a SG environment: remote monitoring of wind or solar farms, distributed generation, real-time generation monitoring and power quality monitoring.

- *Remote monitoring of wind or solar farms:* Wind or solar farms are an important resource of renewable energy that has gained popularity lately. Since the performance of a wind farm is affected by environmental or external conditions (e.g., wind's orientation, bird collisions, outdoor pressure and temperature) cost-effective audio and video data captured, from sensors in a WSN, can contribute to identify the external parameters that might affect the farm's performance [14]. Precautionary measures to maintain the farm's functionality can, then, be organized accordingly. Solar farms are another example of a renewable energy resource. Like in wind farms, WSN applications can monitor critical values of various external parameters, which can affect the solar farms performance (e.g., radiation and temperature values, DC voltage and weather conditions). WSNs can evaluate these values and can help to take the necessary measures to improve the farm's overall performance.

- *Distributed generation:* It allows for small-scale electric generation from renewable energy resources including solar and wind and aids in balancing the demand and supply of power. For the grid's continuity, various system parameters including power quality, frequency and voltage stability need to be measured regularly. For the integrity and security of the distributed generation system, WSN can be used for reliable communication. WSN are suitable because of their low cost and the ease of installation. In [14], an application for a distributed generation network is proposed, that is based on IPv6 and is of low cost. In this application, the sensors can communicate seamlessly with other IP-based devices using IEEE 8012.15.4-based link layer technology. The main focus of this application is to manage and correct the reference signal of the distribution generation in order to improve the overall process for power management.
- *Power quality monitoring:* Monitoring the power quality, by collecting the voltage and the current data and using them at remote control centers to make real-time decisions can increase the system's performance by protecting the secure operation of the system's electrical appliances along with the deregulation of the power market. Since WSNs are considered as a robust, reliable and low-cost system, they can be very efficient to be used by a power quality monitoring application.

2.2. Transmission and distribution side applications

WSN applications in this category deal with power transmission issues and distribution monitoring and are in the heart of the SG's functionality and performance. There are applications that deal with: outage detection, overhead and underground fault circuit indicators, cable, conductor and lattice theft, overhead transmission line monitoring, conductor temperature and dynamic thermal rating systems, fault detection and location, equipment fault diagnostics, underground cable system monitoring, insulators, animals and vegetation control [85,86]. Those applications are briefly presented in this subsection.

- *Outage detection:* Modern societies heavily depend on electricity, not only for economic but also for (simple) social reasons (e.g. street lights). Therefore, any outage will have big consequences in all these aspects of human life. As an example of economic loss, the power outage in US in 2002 had cost in the order of 79 billion dollars (i.e. a third of the total electricity retail revenue [25]). Lack of automated analysis, lack of skilled personnel, poor visibility and distant locations contribute to poor outage detection at the current facilities. Advanced sensors and monitoring systems, like the ones used in a WSN, are needed to deal with the detection of failures and, potentially, increase the stability of the power system.
- *Overhead and underground fault circuit indicators (FCI):* FCIs are used to identify any fault on the circuits of the deployed equipment, allowing the timely restoration of the power and, thus, maintaining the system's performance in an efficient manner. The exact location of the malfunction is crucial so as to reduce the needed time for repairs. Therefore, close examination of certain system variables that might cause false readings is necessary. Those system variables can be inrush current, proximity effect, cable discharge, back-feed voltages and currents. WSNs can cooperate for this purpose with the FCI products and their communication capabilities can lead to efficient and accurate system performance.
- *Cable, conductor and lattice theft:* The theft of power and communication cables has become very frequent globally. The challenge of combating theft is very important since it is very difficult to keep under close surveillance all the ground that is covered by the transmission lines due to its large distance and, at the same time, to protect it from such attacks. WSNs can provide help with their monitoring capabilities and the reliable dissemination of data in the network.
- *Overhead transmission line monitoring*: The transmission lines are very important for the efficient functionality of a SG. Unfortunately, there are many threats that can influence their work, damaging the grid and, even, jeopardize human lives in case an accident happens inside urban areas. Some of these potential hazards include lightning strikes, landslides, earthquakes, icing, hurricanes, bird damage and overheating. Furthermore, the high distribution and length of the grid's power lines creates difficulties in maintaining them. For these reasons, an intelligent, reliable monitoring system is required in order to cover the network continuously and efficiently. WSNs can provide the necessary low-cost technology, by the use of smart sensors and meters, that will not only provide power lines monitoring but also availability of real-time decision taking with the applications that are available in them [26]. The sensors will be connected to a relay node that will be responsible to disseminate the information to the SG's control centers.
- *Conductor temperature and dynamic thermal rating systems:* Cable's temperature plays an important role on succeeding optimal cable use. Hence, measurements of thermal cable ratings need to take place dynamically and continuously. The temperature of a conductor rises as electrical current runs through; therefore a rise on the cable's temperature can be explained as an increase on the conductor's load, which needs to be monitored with the use of sensors and smart meters available in WSNs, effectively and reliably.
- *Fault detection and location:* The traditional way for locating short-circuits faults involves trial and error methods. Unfortunately, the traditional method, apart from being time consuming, requires travelling to each location on-site in order to conduct the necessary operations which can be difficult depending on the SG's size. WSNs implement automated management functions for fault handling that efficiently prevent power outages [27–31].
- *Equipment fault diagnostics:* The reliable performance of the power's grid transformers is crucial to maintain continuous and efficient system functionality [32]. Discontinuity of power flow or unavailability of equipment because of failures must be prevented with the use of modern diagnostics that integrated digital information technology and intelligent techniques. These solutions, when combined with the effectiveness and low-cost of the WSN's communication and technology, will provide a reliable and highly efficient SG performance.
- *Underground cable system monitoring:* Known cable problems include failures in joints and in terminations. The monitoring, maintenance and repair of these problems has become more difficult in the case where those cable systems are deployed underground. The use of WSNs, once again, succeeds in providing automated control and visibility of the system to provide more accurate information about the condition of the power line status and performance.

- *Insulators:* Insulator's crucial role in the system performance is endangered by two very common and serious problems that can cause a breakdown of the cable's insulation cover and, therefore, damage on the system. The first such potential hazard is called *partial discharge (PD)* that causes a localized dielectric breakdown of a small portion of the cable's insulation. Real-time PD filed measurements, conducted by sensors in WSNs, are non-destructive, non-intrusive and relatively inexpensive, especially when compared to off-line testing. Most importantly, such measurements can find the exact location [33], of the PD on-time to schedule for a quick repair [34,35]. The second hazard for the insulators is *the leakage current*; leakage current is the current that flows through the insulator's body or over its surface which may lead to flashover of the insulation. Constant monitoring, with smart WSN's meters, of its value can lead to proactive maintenance of the insulator, preventing any further system damages that will deteriorate its performance [36–38].
- *Animals and vegetation control:* Preventing animals from damaging the system's cables is important to maintain the system's performance. WSN can be used to detect animal and avian interactions and allow for precautionary measures to take place. Predictive maintenance measures can also be applied [39].

2.3. Consumer side applications

Consumer side WSN-based applications are directly related to the end-users. Applications for wireless automatic metering, automated panel management, residential energy management, building automation, demand side load management, power grid equipment monitoring and control are some examples of applications that belong to the consumer side.

- *Wireless automatic metering:* Currently, in order to make any decision the user needed to have physical access to a meter or to a visual meter reading. With the use of WSN, in a SG environment, and the integration of smart wireless meters along with proper applications, access to real-time measurements is possible by web applications. That way, decisions like dynamic pricing, which provides different charging techniques during the peak hours, can be made easily and instantly, while the need for human readers is eliminated and prevention from meter tempering is given.
- *Automated panel management:* The capture of the sun rays in modern solar panels can take place in a more efficient way with the help of the sensor nodes, because of their tracking of the sun [40]. In this way, the generation of the solar energy from these panels will increase and benefit by the use of WSNs.
- *Residential energy management:* Many WSN-based applications are created regarding real-time power consumption monitoring. The reason for this is to allow the customer to schedule and shift power demanding residential operations in times were the system does not have a peak in demand. Those energy-related applications apart from being very popular and useful, contribute to optimize the system's overall performance by providing a dynamic balance between supply and demand [40–43].
- *Building automation:* This term describes the creation of a communication network between smart residential appliances, like lighting, heating, ventilation and air conditioning (HVAC), whose main purpose is to better control their energy consumption and reduce the energy waste. It is measured that saving up to 30% can be achieved with the use of smart residential appliances [42]. For communication between the residential appliances WSNs can be used due to their distinct advantages in terms of costs and installation complexity.
- *Demand side load management:* Demand side load management is a key parameter of a sustainable system which can provide various energy services from low-risk energy sources. By achieving load management, the energy-demand can be reduced along with its cost. In this regard, WSNs can play a significant role in the use of renewable energy sources [14].
- *Power grid equipment monitoring and control:* The advanced capabilities of the sensors in a WSN are used for measuring of various metrics that can give signs about the health of the power grid equipment and signal for maintenance actions. Such measurements may include voltage, current, temperature, pressure, or vibration values of the power grid equipment.

3. Protocol design objectives for WSN-based SG applications

As discussed above, WSNs have increasingly been considered as a promising technology to achieve seamless, energy efficient, reliable and low-cost remote monitoring and control in SG applications. However, the realization of these WSN-based SG applications directly depends on efficient communication capabilities among electric power system elements [88]. In Table 2, a summary of protocol challenges and design objectives for WSN-based SG applications is given. In the following, communication protocol challenges and design objectives are briefly discussed for WSN-based SG applications. A summary of protocol challenges and related design objectives are also summarized in Table 2 [85,86].

- *Reliability of wireless network:* Wireless nature of WSN-based SG also makes it unreliable due to asymmetry of wireless links, interference, non-uniform radio signal strength, fading, and multipath effects [13]. Various protocols and solutions are provided for WSNs in ideal conditions [14,44]. However, they are not well suited in the harsh environment of SGs. Variable link quality in WSNs, utilization of links and limited battery is very challenging task and this provides motivation to researchers to propose efficient and effective protocol for this environment [45]. This proposed protocol should be capable enough to provide real time processing and on time packet delivery within the demanded latency [14]. Hence, MAC and routing protocol should be implemented wisely for WSN-based SG applications. For example, to meet the high reliability requirements of the SG applications, the MAC layer can support reliable communication by controlling the retransmission of lost packets using techniques, such as automatic repeat request (ARQ), or by adding some redundant bits to the original packet using techniques, such as forward error correction (FEC).
- *Memory management:* In WSNs, sensor nodes have limited battery, memory, and processing power so, the limited memory is responsible to perform hassle free operations in the SG. Effective memory management can provide faster, reliable, and efficient communication in a SG environment, therefore lightweight protocols need to be designed to reduce the memory consumption.
- *QoS requirements:* WSN-based applications in SGs have different QoS specifications and requirements with respect to the delay and reliability. Consider the example of dynamic pricing notifications and alarm conditions; it is very essential to collect the data from various places in timely manner. Outdated data may suffer from inconsistency and unreliability and may give wrong decision in pricing and monitoring. Hence, a QoS-aware protocol is required to adopt the nature of SG application [1].
- *Power consumption:* In WSNs, all nodes are equipped with battery which makes power management very challenging. Optimal use of this limited battery power is very important while performing various operations in SG's communication environment. Those operations include sensing, computation, routing, and communication to other nodes, etc. that clearly demand for an energy efficient protocol for the WSN.
- *Heterogeneous environmental conditions:* Due to complex and dynamic nature of WSN-based SG applications, single communication technique is not sufficient enough to provide flexible, secure,

Table 2
Protocol design objectives for WSN-based SG applications.

Protocol challenges	Protocol design objectives
Reliability of wireless network	Link-quality-aware routing and MAC protocols, error control techniques
Power consumption	Energy-efficient protocols and energy harvesting solutions
Memory management	Low-overhead and simple protocols
QoS requirements	QoS-aware protocols and cross-layer designs
Heterogeneous environmental conditions	Hybrid protocols and cross-layer design
Security	Secure design and protocols
Interoperability	Standard-based WSN protocols and products

resilient, cost-effective, and reliable communication [46]. Hence, combination or mixed technology may be incorporated over the SG for better interoperability. This requirement may be fulfilled by the hybrid protocol of WSN-based SG application.

- *Security:* Wireless nature of WSN also makes the system vulnerable to various external denial of service (DoS) attacks [47,48], physical and cyber threats. SGs deal with sensitive, reliable and confidential data, so they should be securely transmitted from the smart meters and smart home appliances to the data collection centers to prevent from the theft and to prevent any unauthorized access. Hence, secure and reliable end-to-end protocol needs to be implemented on WSN-based SG application. Apart from these attacks and threats, WSNs may also be affected from the node platform deployment strategy, underlying communication infrastructure, system architecture, and nature of the application.
- *Interoperability:* Various important parts of SG, i.e., energy consumers, distribution networks, and energy generation units, exchange their data with other for different purposes. Hence, a standard-based and interoperable communication protocols are needed in this WSN-based SG environment [47].

4. MAC and routing layer protocols for WSN-based smart grid communications

Recently, various protocols and communication solutions for WSN-based SG system have been proposed [88]. In the following section, various existing MAC and routing layer protocols for WSN-based SG are briefly summarized.

4.1. MAC layer protocols for WSN-based smart grid applications

In general, the MAC layer is responsible for controlling the access to the shared wireless medium and thus, manages RF interference between data transmissions and aims to mitigate the impacts of packet collisions. In addition, it controls the duty cycling of the sensor radios in order to conserve energy. Error control is also one of the main functionalities of the MAC layer. Joint consideration of the RF interference management, error control, resource limitations of sensor nodes and application-specific quality of service (QoS) requirements is a challenging issue. As for WSN-based SG applications, varying channel conditions and high packet error rates in SG environments exacerbate all these above mentioned challenges [85,86]. Moreover, network performance degradation due to co-existing networks sharing the same RF spectrum in SG environments can be prevented at the MAC layer by utilizing different (or multiple) operating RF channels [87,104]. Additionally, the MAC layer can adaptively control the transmission power of sensor nodes to reduce energy consumption [85].

To meet the requirements of the SG applications, the MAC layer plays a critical role. For example, the MAC layer can support reliable communication by controlling the retransmission of lost packets using techniques, such as automatic repeat request (ARQ), or by adding some redundant bits to the original packet using techniques, such as forward error correction (FEC). A third approach to achieve reliability is hybrid ARQ where, the advantages of both FEC and ARQ schemes are utilized by incrementally increasing the error resiliency of a packet through retransmissions [106]. In a brief Comparison between FEC techniques and ARQ mechanisms; the later technique uses bandwidth efficiently at the cost of additional latency. However, while carefully designed ARQ schemes may be of some interest, naive use of ARQ techniques may not be feasible for applications requiring real-time delivery in harsh smart grid environments [105]. In [106], the FEC and hybrid ARQ schemes are shown to improve the error resiliency compared to ARQ techniques. The FEC schemes rely on transmitting redundant bits through the wireless channel to provide lower signal to noise ratio (SNR) values achieving the same error rate as the schemes not using redundancy. This advantage is utilized in a multi-hop network by constructing longer hop through channel-aware routing protocols or by reducing the transmission power. The analysis in [105,106] reveals that, for certain FEC codes, hop length extension decreases both the energy consumption and the end-to-end latency (subject to a target packet error rate) compared to ARQ. Thus, the appropriate FEC codes can be preferred for delay-sensitive traffic in smart grid [105,106].

Without any loss of generality, three types of MAC schemes, such as contention-based, reservation-based, and hybrid solutions, have been proposed for WSN-based SG applications. These solutions are based on two fundamental multiple access schemes: carrier sense multiple access (CSMA) and time division multiple access (TDMA). Here, it is important to note that other medium access techniques, such as frequency division multiple access (FDMA), code division multiple access (CDMA), and orthogonal frequency division multiple access (OFDMA), are generally not employed in WSN-based SG applications for various reasons, such as their high complexity, high processing and memory requirements, and low energy efficiency [85].

In contention-based MAC protocols, such as CSMA, to reduce communication latency, they can utilize adaptive contention windows and dynamic backoff schemes based on traffic types and application requirements of SG. For instance, the CSMA-based protocol CoSenS (Collect then Send burst Scheme) proposed in [65] considers the service variations to provide scalability, versatility, and simplicity. Moreover, the authors have also highlighted the weaknesses of CSMA protocol.

In addition, in contention-based MAC protocols, sensor nodes compete to access the channel, which may cause communication delay due to network contention in SG environments. To reduce this delay, the RT-MAC protocol is proposed in [89]. Although the RT-MAC protocol prevents the false blocking problem of RTS/CTS exchange, it cannot mitigate RF interference of multi-stream communications. The MaxMAC protocol utilizes additional wake-ups to achieve low latency and high reliability based on the traffic rates [90]. However, additional wake-ups in the MaxMAC protocol lead to extra power consumption for sensor nodes, which may not be tolerated in resource-constrained SG applications. The DRX and FDRX protocols are other MAC protocols proposed in [91] for SG applications. These protocols utilize application layer prioritization and tune MAC layer parameters to meet delay requirements of SG applications. A QoS-Aware MAC protocol based on the IEEE 802.15.4 standard is also proposed in [92]. This protocol utilizes service differentiation according to traffic types having different priorities.

In general, contention-based random access MAC protocols are known to be more scalable compared to schedule-based MAC protocols [87]. This is because sensor nodes do not require time synchronization among themselves in contention-based random access MAC protocols. In case of MAC protocols supporting reservation-based access, such as TDMA, transmission schedules can be planned to reduce communication delay [87]. A tree-based TDMA protocol has been presented for home area networks in SG [93]. Although TDMA-based protocols are efficient when there is time synchronization among the sensor nodes, they are not adaptive to respond to different traffic loads and requirements. A rate allocation algorithm based on schedule-based MAC protocol has also been proposed in [94]. This algorithm assigns different data rates to the nodes based on their delay requirements. However, this protocol may suffer heavily from the abundant data exchange causing extra overhead for providing QoS.

Recently, hybrid MAC protocols combining multiple MAC schemes have also been proposed to overcome shortcomings of using single MAC scheme. The IEEE 802.15.4 standard utilizes a hybrid scheme combining CSMA/CA and TDMA schemes [95]. However, this hybrid MAC may not be efficient for time-critical SG applications due to limited number of available slots and high network congestion and contention under high traffic loads. Another hybrid MAC protocol, called EQ-MAC, has been proposed for SG applications [96]. It uses contention-based medium access for sending messages and therefore, it can suffer from network contention and may not be suitable for delay-sensitive SG applications. Another hybrid MAC protocol, i.e., Z-MAC, also combines TDMA and CSMA protocols to reach high channel utilization and low communication latency [97]. When the Z-MAC protocol cannot provide time-synchronization in the network, it uses the CSMA protocol. In [98], the performance of the state-of-the-art WSN medium access control (MAC) protocols, such as IEEE 802.15.4, IEEE 802.11, CSMA, TDMA, and Z-MAC [97], has been compared to better understand the advantages and disadvantages of evaluated MAC protocols in harsh SG spectrum environments. Importantly, the MAC layer can adapt its operation based on smart grid application requirements, varying wireless link qualities and traffic requirements and can fine tune its operation parameters, such as transmission power, contention window size and duty cycle, properly.

In Table 3, a comparison of existing MAC protocols for WSN-based SG applications has been illustrated. Overall, resource limitations (in terms of memory, processing and communication) and application-specific QoS requirements of sensor networks are exacerbated by spatially and temporally varying channel conditions in smart grid.

Furthermore, when looking at multi-hop WSNs, all layers of the communication-protocol stack influence the performance of each other [85,86]. For example, the physical layer has a direct impact on multiple access of sensor nodes in wireless channels by affecting the RF interference levels at the receiver nodes. The MAC layer determines the communication of each transmitter node, which also influences the performance of the physical layer in terms of successfully detecting the RF signals. Furthermore, routing path decisions change the number of nodes to be scheduled, and thus, affect the performance of the MAC layer [85,86]. To this end, recent research efforts have focused on the cross-layer optimization and design methodologies, including the combination of the functionalities of two or more layers in a single coherent communication framework.

In summary, there are many MAC protocols designed for sensor networks in the related literature, none of these protocols meets diverse application requirements of SG and shows high communication performance in harsh SG environments. Hence, the MAC layer-related open research issues for SG can be briefly outlined below:

- Although there exist a number of error control techniques to achieve reliability in SG communication, yet improvements are required to achieve higher level of reliability and to operate in WSN that utilize spectrum-aware, cross-layer protocols. Therefore, cooperative schemes based on FEC or hybrid ARQ may prevent packet losses caused by electromagnetic interference and noise, and multi-path fading in SG environments. Thus, spectrum-aware energy-efficient error control mechanisms need to be designed in the MAC layer.
- The spatial correlation of sensed SG events, which typically occurs when utilizing sensor networks and network contention due to retransmissions should be addressed to provide both reliability and network efficiency.
- In smart grid environments, there are time- and location-dependent capacity variations of wireless links due to electromagnetic interference, equipment noise, and fading. To overcome varying link conditions in time and space domains, sensor nodes needs to have dynamic and opportunistic MAC protocols preventing adverse wireless channel effects. As for dynamic and opportunistic MAC protocols, the coordination of spectrum sensing with adaptive sleeping schedules needs to be also considered to provide connectivity to a sensor node after it wakes up.
- Considering limited resources of sensor networks in terms of processing, memory, communication, the new required MAC layer protocols should not rely on additional transceivers, needs to be developed.
- While designing MAC protocols, consideration of both spectrum sensing and duty cycling is necessary to balance the trade-off between spectrum efficiency and energy efficiency. Here, it is required to allow a node to search for a free channel and sleep for a specific amount of time to conserve energy.

4.2. Routing layer protocols for WSN-based smart grid applications

The increasing attention on WSN-based SG applications has lead the academia to study the designing of reliable and secure routing protocols for SG environments. There are different QoS requirements for WSN-based applications in SGs, since the SG spectrum environment is affected from low quality links, fading, interference, and obstacles.

Recently, different types of routing protocols, such as on-demand (AODV [50,51] and DYMO [53–54]), table-driven (DSDV [52]) and QoS-aware (TUQR) [55,56] routing protocols, have been evaluated in terms of packet delivery ratio, end-to-end delay, and energy consumption in different SG spectrum environments [49]. This study shows that none of the abovementioned routing protocols give satisfactory performance results for WSN-based SG applications.

In WSN-based SG applications, link-quality estimation is an important issue because robust estimations improve the performance of the higher layer communication protocols. Specifically, the routing layer protocols use the findings of link-quality estimators to choose the optimal routing path. In [99], the performance of the state-of-the-art link-quality estimation methods, such as PRR [100], RNP [100], WMEWMA [101], ETX [102], four-bit [103], have been evaluated in different SG spectrum environments. This study shows that the ETX [102] and four-bit [103] link-quality estimation methods show the best performance in SG spectrum environments. This is because these methods consider the link asymmetry, including uplink both and downlink qualities. Therefore, they can quickly respond to the changes in the smart grid propagation environments.

To overcome the adverse effects of SG spectrum environments, various dynamic QoS-based solutions have also been proposed to minimize the impacts of harsh SG spectrum environments [15,56]. Gungor et al. propose a resource-aware and link quality based routing metric (RLQ) adapting to varying wireless channel conditions and exploiting the heterogeneous capabilities in WSNs [17]. The proposed metric considers both the residual energy levels of sensor nodes and link quality statistics of communication links.

Table 3
Comparison of existing MAC protocols for WSN-based smart grid applications.

Protocol	Objective	Type	Energy awareness	Complexity	Evaluation method
RT-MAC [89]	Supporting real-time data streaming	CSMA contention-based	Yes	High	Simulations
MaxMAC [90]	Providing high throughput and low latency	CSMA contention-based	No	High	Simulations
DRX and FDRX [91]	Supporting delay and service requirements of smart grid applications	CSMA/CA contention-based	No	Low	Simulations
QoS-MAC [92]	Providing QoS support based on IEEE 802.15.4	CSMA/CA contention-based	No	Low	Simulations
Tree-based TDMA-MAC [93]	Supporting home area network (HAN) applications	TDMA reservation-based	Yes	Low	Simulations
Rate-allocation-based MAC [94]	Reducing average delay	TDMA reservation-based	No	High	Theoretical analysis and simulations
IEEE 802.15.4 [95]	Providing QoS support based on IEEE 802.15.4	TDMA/CSMA hybrid MAC protocols	No	Low	Simulations
EQ-MAC [96]	Providing QoS support for single-hop sensor networks	TDMA/CSMA hybrid MAC protocols	Yes	High	Simulations
Z-MAC [97]	Providing QoS support	TDMA/CSMA hybrid MAC protocols	No	High	Test-bed, simulations

In [57], Lai et al. propose energy-constrained routing protocol. In this protocol, wireless LQ is measured, utilized, and characterized by the design parameters, which decide the cost metric of the routing. This cost metric will allow the cost which has less energy consumption of WSNs. Reliability-based routing is proposed by Shin et al. in [13]. This protocol considers the interference due to the hidden terminal problem, fading and multi-path effects. Additionally, the authors have suggested some reliability-based parameters for better packet delivery. In [58], sensitivity of the protocols to the LQ estimations (LQEs) errors and error propagation are considered jointly with the LQ.

In addition, Chen et al. propose quality estimation based routing protocol (LQER) in [59] for better link connectivity and minimizing the retransmission cost. This protocol increases the life-time and reliability of the WSNs. It estimates the LQ before performing the routing operations by making a connected graph with number of hops. This protocol only provides the energy efficiency but does not guarantee about the end-to-end deadline. Reliability-oriented routing protocol is proposed by Daabaj et al. in [60]. This protocol considered the probability network connectivity and per-hop energy balancing which gives less energy consumption and high success rate of data packets.

In [61], the RPA scheme is proposed to support real-time communication for large-scale WSNs. Moreover, it also provides end-to-end deadlines by minimizing the processing and communication overhead. However, this protocol does not guarantee about the reliability. Another QoS aware routing protocol is proposed by Akkaya and Younis in [62]. This protocol considers multiple routes and class-based queuing system based on the error rates, energy levels, and distance. Real-time traffic and best-effort service can be accomplished by this protocol.

In [63], routing protocol for various levels of QoS, such as reliability, fault tolerance, low latency, and energy-efficiency is proposed. Moreover, it is claimed that the protocol is also well suited for various applications without redeployment and reconfiguration of sensor nodes. He et al. propose SPEED in [64], which is a reactive routing protocol that considers real-time traffic by reducing the end-to-end delay. In this routing protocol, each node performs local routing decision and controls the packet transmission speed based on delay and distance. It maintains a relay ratio to calculate whether a packet is forwarded or dropped, when target speed is not provided. Similarly, InRout protocol is proposed for industrial monitoring applications with typical QoS requirements [66]. This protocol not only provides best route but also considers the QoS while utilizing the resources in WSNs.

In addition to single-path routing algorithms, there are also various multipath routing protocols for WSN-based SG communication systems. Different from single-path routing protocols, multi-path routing protocols provide multiple paths between the source and the sink to provide load balancing and fault tolerance. On the other hand, multi-path routing protocols may lead to high delay and network load.

ReInForM, multi-path forwarding protocol, is proposed in [67]. This protocol gives high level of the reliability to WSN by transmitting multiple copies of the packets to sink node in the multiple routes. It uses information, such as neighborhood of each node, out-degree, hops to sink, channel error, and local knowledge of sensor conditions for better reliability. However, this protocol does not provide service differentiation.

In [68] Shin et al. propose an important multi-path routing protocol called REAR (reliable energy aware routing). This protocol uses the remaining energy capacity of sensor nodes, before performing the routing operation. In REAR, source broadcasts the packets to search out best multipath with high energy level to send the packet. Higher energy level node replied to broadcast packet and chosen as a relay node. REAR extends the life time of network, but it suffers from end-to-end deadline mechanism.

Furthermore, the MMSPEED protocol, QoS differentiation based protocol, is proposed by Felemban et al. in [12], which considers QoS in both timeliness and reliability domains. By integrating speed options with multiple packet delivery, QoS level can be achieve in the timeliness domain. MMSPEED also provides reliability to various applications by probabilistic multi-path forwarding [69]. This protocol uses localized geographic packet forwarding augmented with dynamic compensation which makes it, adaptable and scalable. EAMMSPEED protocol is also proposed in [70] which incorporated energy efficiency and MMSPEED protocol. This protocol employs energy aware packet forwarding scheme for QoS. It also makes energy level of sensor nodes into account at the time of performing routing decision. Poojary and Pai also propose MDPT multipath routing protocol in [71]. This protocol provides simultaneous multiple route between any pair of nodes. It not only increases lifetime of network but also protects the network to some specific attacks.

A real time multipath routing protocol is proposed by Krogmann et al. in [72]. This protocol employs a time constraint on the routing at wireless sensor and actuator networks (WSANs). It provides better QoS by parallel transmissions, and as a result reduces the delay in WSAN. Another energy-efficient and QoS aware multi-path routing protocol, EQSR, is presented in [73] which selects best next hop from the energy level of nodes. It also increases the lifetime of network and

Table 4
A comparison of selected routing protocols based on reliability, delay and energy efficiency.

Protocol	Description	Reliability sensitive	Delay sensitive	Energy aware
RAP [61]	Real-time communication protocol	No	Yes	NA
ReInForM [67]	Reliable information forwarding protocol	Yes	No	NA
EARQ [59]	Energy aware routing for industrial control applications	Yes	Yes	Yes
REAR [68]	Reliable energy aware routing	Yes	No	Yes
LQER [59]	LQ estimation based routing protocol	Yes	No	Yes
InRout [84]	Adaptive protocol for industrial control applications	Yes	Yes	Yes
EARA [57]	Energy-aware routing algorithm	Yes	No	Yes
RLQ [13]	Resource-aware and LQ based routing algorithm	Yes	No	Yes

reachability using redundant data. Moreover, it also provides service differentiation in timeliness domain.

In Table 4, a comparison of existing routing protocols for WSN-based SG applications has been illustrated. Due to the harsh communication characteristics of SG environments, such as background noise, high attenuation, the existing routing protocols suffer from volatile links and intermittent connectivity when deploying multi-hop networks in SG environments. Since existing multi-hop routing protocols cannot deliver adequate performance, novel routing design solutions for the SG has to be re-visited. Open research issues in SG for routing layer are stated below:

- For the SG environments, where connectivity and mobility are low, but the nodes may not have enough resources in terms of memory and processing, a more reliable packet forwarding scheme is necessary. Instead of deploying a classic “store-and-forward” scheme, a more opportunistic scheme of the “store-carry-and-forward” can be deployed for WSN-based SG applications. In this type of forwarding scheme, nodes will decide whether to forward a packet immediately or keep it for a while in order to be able to eventually deliver the packets from source to destination [49].
- Spectrum-aware routing algorithms need to be developed to maximize spectrum usage efficiency in harsh smart grid environments. In addition, multi-path routing techniques should be developed to benefit from path diversity for RF interference mitigation.
- While developing spectrum-aware routing protocols, RF spectrum decisions needs to be performed. This is required to make the decision either to change the channel to the located gap or continue with the same one based on its condition.
- Efficient routing metrics balancing protocol overhead and network performance should be developed. To this end, the routing metric should take into account channel conditions, RF interference and link-quality in SG environments with minimum protocol overhead.

5. Communication technologies for wireless sensor networks in smart grid

Promoting standards for SG environments and meeting specific international and national regulations is the main duty of a specific task group called “IEEE 802.15 Smart Utility Networks (SUN) Task Group 4g” which has reviewed the IEEE 802.15.4 standards and accordingly proposed some amendments designed for geographically diverse utility networks [5,74,75]. This was an urgent issue since, at the beginning, the IEEE802.15.4 standard, which offers speeds up to 250 kbps in the 2.4 GHz frequency band had been designed to provide low-power wireless PHY and MAC layers [75].

IEEE 802.15.4g amendment developed by the task group added new PHY support and defined MAC modifications. With these amendments, the PHY can support multiple data rates ranging from 5 to 400 kbps in bands with frequencies ranging from 450 MHz to 2450 MHz frequency bands [74,75]. In addition to this task group, to facilitate a large number of low-power widely dispersed communication end points for large scale critical monitoring applications, the IEEE 802.15 Low Energy Critical Infrastructure (LECIM) Task Group 4k (TG4k) was formed [76,77]. Mainly, the amendment enables trigger-driven and schedule-driven modes and supports data rates of up to 40 kbps while supporting low power operation for longer battery life [5]. In Table 5, the main features of different communication technologies for wireless sensor networks are given. The remainder of this section briefly introduces the main features of existing communication technologies for WSNs that might be used in smart grid.

- *6LoWPAN:* It was developed by the IETF IPv6 over Low Power Wireless PAN (6LoWPAN) Working Group. It offers important features such as address auto-configuration, neighbor discovery, header compression and fragmentation [5]. For routing, both mesh under and route over schemes are supported in the mesh topology. IEEE802.15.4 addresses are used in the mesh under scheme. In contrast, routing is performed at the IP layer in the route over scheme.
- *ZigBee:* The ZigBee Alliance promoted the development and adoption of a set of network specifications and application profiles called ZigBee to meet the requirements of short range, low data rate, low duty-cycle applications. ZigBee has become a de facto network specification in WSN-based SG applications. It is dominant in the market due to not only ZigBee Alliance is a very active organization but also it brings advantages over other alternatives for SG applications. The ZigBee protocol stack consists of four layers: PHY, MAC, the network and the application layers [78]. While these layers are defined by the ZigBee specification, the PHY and the MAC layers are defined by the IEEE 802.15.4 standard. Due to the IEEE 802.15.4, it can provide data rates up to 250 kbps in the 868 MHz, 915 MHz and 2.4 GHz bands.
- *RPL:* It is an IPv6 routing protocol for low power and lossy networks (LLNs) [79]. It is well-suited for both one-to-many and many-to-one traffic patterns and can operate on highly constrained link layers with a maximum MTU of 127 bytes [80–82].
- *Wavenis:* It is highly suitable for ultra-low power (ULP) wireless solutions such as machine-to-machine (M2M) and WSN applications. Compared to the other existing technologies, it can provide longer range, up to 200 m for indoor applications [78,83]. It works over various mesh configurations and can provide data rates up to 100 kbps in the 433 MHz, 868 MHz and 915 MHz bands [83]. Wavenis-based devices can be deployed and used in different SG applications including AMI, automated meter reading (AMR) and meter monitoring.
- *Z-Wave:* ZenSys Inc. developed Z-Wave for monitoring and automation applications. It is composed of PHY, MAC, transfer, routing and APL layers and can provide data rates up to 200 kbps using the 868 MHz band in Europe and 908 MHz band in the US [5].
- *ISA-100:* It was designed for low data rate monitoring and automation applications low data rate. ISA-100 operates using 2.4 GHz radio and uses channel hopping to increase reliability and minimize interference [5].

Table 5
Different communication technologies for wireless sensor networks.

Protocol	Governing body	Topology	Radio	Security	Comments	Maximum data rate	Transmission range
6LoWPAN [5]	IETF	Star	IEEE 802.15.4	IPsec	IPv6 networking over WPAN	256 kbps [111]	10–75 m [111]
ISA100 [5,86]	ANSI/ISA	Star/Mesh	IEEE 802.15.4 (2.4 GHz only)	128-Bit AES, security manager	Similar, but incompatible with WirelessHART	256 kbps [111]	10–75 m [111]
WirelessHART[84]	HART Communication Foundation	Star/Mesh	IEEE 802.15.4 (2.4 GHz only)	128-Bit AES, security manager	Channel hopping TDMA	256 kbps [111]	10–75 m [111]
ZigBee [86]	ZigBee Alliance	Star/Mesh	IEEE 802.15.4	128-Bit AES, global key	Multi-vendor interoperability	256 kbps [111]	10–75 m [111]
ZigBee Pro [86]	ZigBee Alliance	Star/Mesh	IEEE 802.15.4	128-Bit AES, peer-to-peer key exchange	Adds routing options and security	256 kbps [111]	10–75 m [111]
ZigBee RF4CE [86]	ZigBee Alliance	Star	IEEE 802.15.4	128-Bit AES, peer-to-peer key exchange	Simplified ZigBee for RF remote controls	256 kbps [111]	10–75 m [111]
JenNet-IP [84–86]	Proprietary Jennic	Star/Tree	IEEE 802.15.4 (2.4 GHz only)	128-Bit AES	Support for large self-forming tree networks and IPv6 networking	256 kbps	10–75 m
MiWi [84–86]	Proprietary Microchip	Star/Mesh	IEEE 802.15.4 (2.4 GHz only)	128-Bit AES	Simpler MiWi P2P version has no routing	256 kbps	10–75 m
SNAP [84–86]	Proprietary Synapse Wireless	Mesh	IEEE 802.15.4 (2.4 GHz only)	128-Bit AES version available	Supports bridging to TCP/IP or ZigBee	256 kbps	10–75 m
SynkroRF [84–86]	Proprietary Freescale	Star	IEEE 802.15.4 (2.4 GHz only)	128-Bit AES, peer-to-peer key exchange	Basis for RF4CE	256 kbps	10–75 m

- *WirelessHART:* It is based on IEEE 802.15.4 and operates using the 2.4 GHz band [84]. It is compatible with most existing devices and systems.

While designing SG networks to meet their application requirements, all the layers should be taken into consideration. In the PHY layer, IEEE 802.15.4-based standards can operate in the 868 MHz, 915 MHz and 2.4 GHz bands and provide multi-channel support. Therefore, they can reliably operate in SG environments with heavy RF interference. In addition, using phase shift keying (PSK) modulation, they offer better signal-to-noise (SNR). Compared to the others, ZigBee is better at avoiding the multipath and narrowband interference by its proprietary spread spectrum techniques. On the other hand, ISA-100 networks increase reliability and minimize interference by using channel hopping technique.

In the link layer, all the above mentioned technologies provide acknowledgment and retransmission mechanisms for reliability in harsh environments and checksums for data integrity. When end-to-end delay is considered, the ZigBee protocol may provide lower latency than the others [78]. In the network layer, link-quality (LQ) is an important metric, especially in SG environments with multipath and heavy interference since LQ-aware techniques are generally preferred to ensure reliability. For this goal, ZigBee relies on the LQ indicator (LQI) provided by IEEE 802.15.4. Wavenis uses a received signal strength based LQ estimator. In the application layer, a set of commands and attributes can be advantageous for SG applications. For this objective, ZigBee, ISA-100, Wireless HART and Z-Wave provide proprietary sets of commands and well-defined attributes.

6. Conclusion

The potential applications of WSNs in power grid span a wide range, including real-time generation monitoring, power quality monitoring, distributed generation, equipment fault diagnostics, overhead transmission line monitoring, outage detection, underground cable-system monitoring, overhead and underground fault circuit indicators, demand response and dynamic pricing, load control and energy management, etc. However, the realization of all these WSN-based smart grid (SG) applications depends on effective networking capabilities of the electric power system elements.

Recent field tests point out that wireless links in smart grid (SG) environments show varying spectrum characteristics due to electromagnetic interference, equipment noise, and multi-path fading. This makes robust and reliable low-power wireless communication a challenging task for WSN-based SG applications. In this paper, first WSN-based SG applications have been explored along with their technical challenges. Then, design challenges and protocol objectives have been discussed for WSN-based SG applications. After exploring applications and design challenges, communication protocols have been explained in detail. Here, our goal is to elaborate on the role of WSNs for smart grid applications and to provide an overview of the most recent advances in MAC and routing protocols for WSNs in this timely and exciting field.

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References

[1] V.C. Gungor, L. Bin, G.P. Hancke, Opportunities and challenges of wireless sensor networks in smart grid, IEEE Trans. *Ind. Electron.* 57 (10) (October 2010) 3557–3564.
[2] E.F. Livgard, Electricity customers' attitudes towards smart metering, in: Proc. of IEEE ISIE, July 2010, pp. 2519–2523.
[3] V.C. Gungor, D. Sahin, T. Kocak, S. Ergüt, C. Buccella, C. Cecati, G.P. Hancke, Smart grid technologies: communication technologies and standards, IEEE Trans. Ind. Inform. 7 (4) (November 2011) 529–539.
[4] V.K. Sood, D. Fischer, J.M. Eklund, T. Brown, "Developing a communication infrastructure for the smart grid", in: Proc. of IEEE EPEC, October 2009, pp. 1–7.
[5] G. Tuna, V.C. Gungor, K. Gulez, Wireless sensor networks for smart grid applications: a case study on link reliability and node lifetime evaluations in power distribution systems, Int. J. Distrib. Sensor Netw. (2013) Article ID 796248 http://dx.doi.org/10.1155/2013/796248 .
[6] Y. Yang, F. Lambert, D. Divan, A survey on technologies for implementing sensor networks for power delivery systems, in: IEEE Power Engineering Society General Meeting, 24-28 June 2007, pp. 1–8.
[7] M. Yigit, V.C. Gungor, G. Tuna, M. Rangoussi, E. Fadel, Power line communication technologies for smart grid applications: a review of advances and challenges, Comput. Netw. 70 (2014) 366–383, doi:10.1016/j.comnet.2014.06.005.
[8] T. Sauter, M. Lobashov, End-to-end communication architecture for smart grids, IEEE Trans. Ind. Electron. 58 (April (4)) (2011) 1218–1228.
[9] K. Moslehi, R. Kumar, Smart grid—a reliability perspective, in: Innovative Smart Grid Technologies (ISGT), Jan. 19-21, 2010, pp. 1–8.
[10] S. Goldfisher, S. Tanabe, IEEE 1901 access system: an overview of its uniqueness and motivation, IEEE Commun. Mag. 48 (10) (2010) 150–157.

[11] Q. Yang, J.A. Barria, T.C. Green, Communication infrastructures for distributed control of power distribution networks, IEEE Trans. Ind. Inform. 7 (May (2)) (2011) 316–327.

[12] E. Felemban, C.-G. Lee, E. Ekici, R. Boder, S. Vural, MMSPEED: multipath multi SPEED protocol for QoS guarantee of reliability and timeliness in wireless sensor networks, IEEE Trans. Mobile Comput. 5 (6) (2006) 738–754.

[13] J. Shin, U. Ramachandran, M. Ammar, On improving the reliability of packet delivery in dense wireless sensor networks, in: Proc. of the International Conference on Computer Communications and Networks, August 2007, pp. 718–723.

[14] M. Erol-Kantarci, H.T. Mouftah, Wireless multimedia sensor and actor networks for the next-generation power grid, Ad Hoc Netw. 9 (4) (2011) 542–551.

[15] I.F. Khan, M.Y. Javed, F. Arif, Quality assurance of energy aware routing algorithm for wireless sensor networks, in: Proc. of the International Conference, Computer and Automation Engineering, vol. 1, February 2010, pp. 168–170.

[16] B. Kilbourne, K. Bender, Spectrum for smart grid: policy recommendations enabling current and future applications, in: Proc. of IEEE Int. Conf. Smart Grid Communications., October 2010, pp. 578–582.

[17] V.C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, G.P. Hancke, Smart grid and smart houses: key players and pilot projects, IEEE Ind. Electron. Mag. 6 (December (4)) (2012).

[18] S. Paudyal, C. Canizares, K. Bhattacharya, Optimal operation of distribution feeders in smart grids, IEEE Trans. Ind. Electron. 58 (October (10)) (2011) 4495–4503.

[19] T. Sauter, M. Lobashov, End-to-End communication architecture for smart grids, IEEE Trans. Ind. Electron. 58 (April (4)) (2011) 1218–1228.

[20] F. Benzi, N. Anglani, E. Bassi, L. Frosini, Electricity smart meters interfacing the households, IEEE Trans. Ind. Electron. 58 (October (10)) (2011) 4487–4494.

[21] *Communications Requirements of Smart Grid Technologies*. Washington, DC, Dept. of Energy, 2010.

[22] C. Cecati, C. Citro, A. Piccolo, P. Siano, Combined operation of renewable energy systems and responsive demand in a smart grid, IEEE Trans. Sustain. Energy 2 (2011) 468–476.

[23] *Annual Energy Outlook 2008 With Projections to 2030 (Revised PreliminaryReference Case)*. Washington, DC: EIA, U.S. Departmentof Energy, 2008.

[24] M. Amin, B.F. Wollenberg, Toward a smart grid, Power Energy Mag 3 (September/October (5)) (2005) 34–41.

[25] K. Moslehi, R. Kumar, Smart grid a reliability perspective, in: *Proc. of* ISGT, January 2010, pp. 1–8.

[26] K.S. Hung, W.K. Lee, V.O.K. Li, K.S. Lui, P.W.T. Pong, K.K.Y. Wong, G.H. Yang, J. Zhong, On wireless sensors communication for overhead transmission line monitoring in power delivery systems, in: Proc. of IEEE Smart Grid Communications, October 2010, pp. 309–314.

[27] C.M. Fuk, M.S. Demokan, On-line fault location system for overhead power transmission lines using passive quasi-distributed fibre-optic sensing, in: Proc. *of IEEE 2nd International Conference on Advances in Power System Control, Operation and Management*, Hong Kong, 1993, pp. 243–251.

[28] M.M. Nordman, T. Korhonen, Design of a concept and a wireless ASIC sensor for locating earth faults in unearthed electrical distribution networks, IEEE Trans. Power Deliv. 21 (July (3)) (2006) 1074–1082.

[29] E.C. Senger, G. Manassero, C. Goldemberg, E.L. Pellini, Automated fault location system for primary distribution networks, IEEE Trans. Power Deliv. 20 (April (2)) (2005) 1332–1340.

[30] O. Vhmki, S. Sauna-aho, S. Hnninen, M. Lehtonen, A new technique for short circuit fault location in distribution networks, in: Proc. of IRED, Turin, Italy, June 2005.

[31] T. Welfonder, V. Leitloff, R. Feuillet, S. Vitet, Location strategies and evaluation of detection algorithms for earth faults in compensated MV distribution systems, IEEE Trans. Power Deliv. 15 (4) (October 2000).

[32] B. Lu, V.C. Gungor, Online and remote energy monitoring and fault diagnostics for industrial motor systems using wireless sensor networks, IEEE Trans. Ind. Electron. 56 (November (11)) (2009).

[33] P.J. Moore, I. Portugues, I.A. Glover, A nonintrusive partial discharge measurement system based on RF technology, in: IEEE Power Engineering Society General Meeting, Toronto, Canada, 2003, pp. 629–633.

[34] B. Quak, E. Gulski, J.J. Smit, F.J. Wester, P.N. Seitz, PD site location in distribution power cables, in: Proc. of *IEEE 2003 International Symposium on Electrical Insulation*, Boston, MA, USA, 2002, pp. 83–86.

[35] P. Wagenaars, P.A.A.F. Wouters, P.C.J.M. van der Wielen, E.F. Steennis, Technical advancements in the integration of online partial discharge (PD) monitoring in distribution cable networks, in: Proc. of *IEEE Conference on Electrical Insulation and Dielectric Phenomena*, Eindhoven, Netherlands, 2009, pp. 323–326.

[36] T.P. Hong, P. Thinh, D.G. Trong, D.V. Hoang, Leakage current analysis for predicting flashover in distribution network, in: IEEE Electrical Insulation and Dielectric Phenomena Virginia Beach, VA, USA, 2009, pp. 462–465.

[37] G. Montoya, I. Ramirez, R. Hernandez, The leakage current as a diagnostic tool for outdoor insulation, in: Proc. of IEEE PES Transmission and Distribution Conference and Exposition: Latin America, 2008, pp. 1–4.

[38] S.C. Oliveira, E. Fontana, F.J.M.M. Cavalcanti, R.B. Lima, J.F. Martins-Filho, E. Meneses-Pacheco, Fiber-optic sensor system for leakage current detection on insulator strings of overhead transmission lines, in: Proc. of *IEEE MTTS International Conference on Microwave and Optoelectronics*, Brasilia, DF, Brazil, 2005, pp. 368–373.

[39] M. Suojanen, Effect of spruce forest on electric fields caused by 400 kV transmission lines, in: Proc. of International Conference on Power System Technology, Perth, Australia, 2000, pp. 1401–1405.

[40] Smart Sensor Networks: Technologies and Applications for Green Growth December 2009. Available: http://www.oecd.org/dataoecd/39/62/44379113.pdf.

[41] M.E. -Kantarci, H.T. Mouftah, Wireless sensor networks for domestic energy management in smart grids, in: Proc. of 25th Biennial Symposium on Communications, 12-14 May 2010, pp. 63–66.

[42] X. Guan, Z. Xu, Q.-S. Jia, Energy-efficient buildings facilitated by microgrid, IEEE Trans. Smart Grid 1 (December (3)) (2010) 243–252.

[43] Department of Energy, United States, Energy Technology Solutions Public Private Partnerships Transforming Industry, Washington, DC. Available: http://www1.eere.energy.gov/industry/pdfs/itpsuccesses.pdf.

[44] G. Zhou, T. He, S. Krishnamurthy, J.A. Stankovic, Impact of radio irregularity on wireless sensor networks, in: Proc. of ACM MobiSys, New York, 2004, pp. 125–138.

[45] M. Macit, V.C. Gungor, G. Tuna, Comparison of QoS-aware single-path vs. multi-path routing protocols for image transmission in wireless multimedia sensor networks, Ad Hoc Netw. 19 (2014) 132–141, doi:10.1016/j.adhoc.2014.02.008.

[46] S. Ullo, A. Vaccaro, G. Velotto, The role of pervasive and cooperative Sensor Networks in Smart Grids communication, in: Proc. of *IEEE Mediterranean Electrotechnical Conference*, 26-28 April 2010, pp. 443–447.

[47] Z. Fan, G. Kalogridis, The new frontier of communications research: smart grid and smart metering, in: Proc. of 1st International Conference on Energy-Efficient Computing and Networking, e-Energy, 2010, pp. 115–118.

[48] V.C. Gungor, F.C. Lambert, A survey on communication networks for electric system automation, Comput. Netw. 50 (May) (2006) 877–897.

[49] Ş. Temel, V.Ç. Gungor, T. Koçak, Routing protocol design guidelines for smart grid environments, Comput. Netw. 60 (February) (2014) 160–170.

[50] I.D. Chakeres, E.M. Belding-Royer, AODV routing protocol implementation design, in: Proc. 24th International Conference on Distributed Computing Systems Workshops, 2004, pp. 698–703.

[51] S.R.A. Aziz, N.A. Endut, S. Abdullah, M.N.M. Doud, Performance evaluation of AODV, DSR and DYMO routing protocol in MANET, in: Proc. of Conference on Scientific and Social Research, 2009.

[52] C.E. Perkins, E.M. Royer, S.R. Das, M.K. Marina, Performance comparison of two on-demand routing protocols for ad hoc networks, IEEE Pervasive Commun. 8 (1) (2001) 16–28.

[53] M. Quan-xing, X. Lei, DYMO routing protocol research and simulation based on NS2, in: Proc. of ICCASM, 14, 2010, pp. 14–44.

[54] F.J. Ros, “Implementing a new MANET Unicast Routing Protocol in NS2”, 2012. http://masimum.dif.um.es/nsrt-howto/html/nsrt-howto.html

[55] I. Zagli, M. Song, Topology unaware QOS routing protocol, in: Proc. of *WSEAS International Conference on Telecommunications and Informatics*, 2006, pp. 207–212.

[56] D. Sahin, V.C. Gungor, T. Kocak, G. Tuna, Quality-of-service differentiation in single-path and multi-path routing for wireless sensor network-based smart grid applications, Ad Hoc Netw. 22 (November) (2014) 43–60.

[57] D. Lai, A. Manjeshwar, F. Herrmann, E. Uysal-Biyikoglu, A. Keshavarzian, Measurement and characterization of link quality metrics in energy constrained wireless sensor networks, in: Proc. of IEEE Global Telecommunications Conference, 1, December 2003, pp. 446–452.

[58] M. Krogmann, T. Tian, G. Stromberg, M. Heidrich, M. Huemer, Impact of link quality estimation errors on routing metrics for wireless sensor networks, in: Proc. of *the 5th International Conference on Intelligent Sensors, Sensor Networks and Information Processing*, December 2009, pp. 397–402.

[59] J. Chen, R. Lin, Y. Li, Y. Sun, LQER: a link quality estimation based routing for wireless sensor networks, Sensors 8 (2) (2008) 1025–1038.

[60] K. Daabaj, M. Dixon, T. Koziniec, K. Lee, Trusted routing for resource-constrained wireless sensor networks, in: Proc. of the IEEE/IFIP International Conference on Embedded and Ubiquitous Computing, 2010.

[61] C. Lu, B.M. Blum, T.F. Abdelzaher, J.A. Stankovic, T. He, RAP: a real-time communication architecture for large-scale wireless sensor networks, in: Proc. of the Real-Time and Embedded Technology and Applications Symposium, September 2002, pp. 55–66.

[62] K. Akkaya, M. Younis, Energy and QoS aware routing in wireless sensor networks, Clust. Comput. 8 (2-3) (2005) 179–188 http://dx.doi.org/10.1007/s10586-005-6183-7.

[63] J. Sen, An adaptive and multi-service routing protocol for wireless sensor networks, in: Proc. of the 16th Asia-Pacific Conference on Communications (APCC), October 31-November 3, 2010, pp. 273–310.

[64] T. He, J. Stankovic, C. Lu, T. Abdelzaher, SPEED: a stateless protocol for real-time communication in sensor networks, in: Proc. of the IEEE International Conference on Distributed Computing Systems, 2003, pp. 46–55.

[65] B. Nefzi, Y.-Q. Song, QoS for wireless sensor networks: enabling service differentiation at the MAC sub-layer using CoSenS, Ad Hoc Netw. 10 (4) (2012) 680–695 http://dx.doi.org/10.1016/j.adhoc.2011.06.009.

[66] B.C. Villaverde, S. Rea, D. Pesch, InRout - a QoS aware route selection algorithm for industrial wireless sensor networks, Ad Hoc Netw. 10 (4) (2012) 458–478 http://dx.doi.org/10.1016/j.adhoc.2011.07.015.

[67] B. Deb, S. Bhatnagar, B. Nath, ReInForm: reliable information forwarding using multiple paths in sensor networks, in: Proc. of the IEEE International Conference on Local Computer Networks, 2003, pp. 406–415.

[68] K.Y. Shin, J. Song, J. Kim, REAR: reliable energy aware routing protocol for wireless sensor networks, in: Proc. of the 9th International Conference on Advanced Communication Technology, vol. 1, February 2007, pp. 525–530.

[69] S. Darabi, N. Yazdani, O. Fatemi, Multimedia-aware MMSPEED: a routing solution for video transmission in WMSN, in: Proc. of the 2nd International Symposium on Advanced Networks and Telecommunication Systems, December, 2008.

[70] S. Sanati, M.H. Yaghmaee, A. Beheshti, Energy aware multi-path and multi-SPEED routing protocol in wireless sensor networks, in: Proc. of 14th International CSI, Tahran, December 2009, pp. 640–645.
[71] S. Poojary, M.M.M. Pai, Multi-path data transfer in multimedia wireless sensor networks, in: Proc. of the Fifth International Conference on Broadband and Wireless Computing, Communication and Applications, Fukuoka, Japan, November 2010, pp. 379–383.
[72] M. Krogmann, M. Heidrich, D. Bichler, D. Barisic, and G. Stromberg, “Reliable, real-time routing in wireless sensor and actuator networks,” *ISRN Communications and Networking*, Article ID 943504, 2011. http://dx.doi.org/10.5402/2011/943504.
[73] B. Yahya, J. Ben-Othman, Energy efficient and QoS based routing protocol for wireless sensor networks, J. Parallel Distrib. Comput. 70 (8) (2010) 849–857.
[74] http://www.ieee802.org/15/pub/TG4g.html, 2011.
[75] “A standardized and flexible IPv6 architecture for field area networks,” Tech. Rep., 2011, http://www.cisco.com/web/strategy/docs/energy/iparchsgwp.pdf.
[76] http://www.ieee802.org/15/pub/TG4k.html, 2011.
[77] https://mentor.ieee.org/802.15/dcn/11/15-11-0607-00-004k-amac-proposal-for-lecim.pdf, 2011.
[78] C. Gomez, J. Paradells, Wireless home automation networks: a survey of architectures and technologies, IEEE Commun. Mag. 48 (6) (2010) 92–101.
[79] http://tools.ietf.org/id/draft-ietf-roll-rpl-19.html, 2011.
[80] J.W. Hui, D.E. Culler, IPv6 in low-power wireless networks, in: Proc. of the IEEE, vol. 98, 2010, pp. 1865–1878.
[81] T. Clausen, U. Herberg, M. Philipp, A critical evaluation of the IPv6 routing protocol for low power and lossy networks (RPL), in: Proc. of the 7th IEEE International Conference on Wireless and Mobile Computing, Networking and Communications, 2011, pp. 365–372.
[82] J. Tripathi, J.C. deOliveira, J.P. Vasseur, Applicability study of RPL with local repair in smart grid substation networks, in: Proc. of the 1st IEEE International Conference on Smart Grid Communications, 2010, pp. 262–267.
[83] http://www.wave2m.com/the-specification/the-platform-indepth?view=item, 2012.
[84] V.C. Gungor, G. Hancke, Industrial wireless sensor networks: challenges, design principles, and technical approaches, IEEE Trans. Ind. Electron. 56 (October (10)) (2009) 4258–4265.
[85] I.F. Akyildiz, M.C. Vuran, Wireless Sensor Networks, John Wiley & Sons, July 2010.
[86] V.C. Gungor, G.P. Hancke, Industrial Wireless Sensor Networks: Applications, Protocols, and Standards, CRC Press (Taylor & Francis Group), April 2013.
[87] O.D. Incel, A survey on multi-channel communication in wireless sensor networks, Comput. Netw. 55 (September (13)) (2011) 3081–3099.
[88] V. Poor, E. Hossain, Z. Han, Smart Grid Communications and Networking, Cambridge University Press, June 2012.
[89] B.K. Singh, K.E. Tepe, Feedback based real-time mac (RT-MAC) protocol for wireless sensor networks, in: Proc. of IEEE GLOBECOM, 2009.
[90] P. Hurni, T. Braun, MaxMAC: a maximally traffic-adaptive MAC protocol for wireless sensor networks, in: Proc. of EWSN, 2010.
[91] I. Al-Anbagi, M. Erol-Kantarci, H. Mouftah, Priority- and delay-aware medium access for wireless sensor networks in the smart grid, IEEE Syst. J. 8 (June (2)) (2014) 608–618.
[92] W. Sun, V. Yuan, J. Wang, D. Han, C. Zhang, Quality of service networking for smart grid distribution monitoring, in: Proc. of IEEE Smart Grid Communications, 2010.
[93] M. Kim, J. Kim, Y. Yoo, Design and implementation of mac protocol for smart grid HAN environment, in: Proc. of IEEE CIT, 2011.
[94] J. Yang, S. Ulukus, Delay minimization in multiple access channels, in: Proc. of IEEE Information Theory Symposium, 2009.
[95] S. Ullo, A. Vaccaro, G. Velotto, Performance analysis of IEEE 802.15.4 based sensor networks for smart grids communications, J. Electr. Eng. Theory Appl. 1 (3) (2010) 129–134.
[96] B. Yahya, J. Benothman, Energy efficient and QoS aware medium access control for wireless sensor networks, J. Concurrency Comput. Pract. Experience 10 (22) (2010) 1252–1266.
[97] I. Rhee, A. Warrier, M. Aia, J. Min, M. Sichitiu, Z-MAC: a hybrid mac for wireless sensor networks, IEEE/ACM Trans. Netw. 16 (3) (2008) 511–524.
[98] M. Yigit, E.A. Yoney, V.C. Gungor, Performance of MAC protocols for wireless sensor networks in harsh smart grid environments, in: Proc. of IEEE BlackSeaCom, Batumi, Georgia, July 2013.
[99] V.C. Gungor, M.K. Korkmaz, Wireless link-quality estimation in smart grid environments, in: Int. J. Distrib. Sensor Netw., February 2012.
[100] A. Cerpa, J.L. Wong, M. Potkonjak, D. Estrin, Temporal properties of low power wireless links: modeling and implications on multi-hop routing, in: Proc. of ACM MobiHoc, New York, NY, USA, 2005, pp. 414–425.
[101] A. Woo, T. Tong, D. Culler, Taming the underlying issues for reliable multihop routing in sensor networks, in: Proc. of ACM SenSys, New York, NY, USA, 2003.
[102] D.S.J.D. Couto, D. Aguayo, J. Bicket, R. Morris, A high-throughput path metric for multi-hop wireless routing, in: Proc. of ACM MobiCom, New York, NY, USA, 2003, pp. 114–146.
[103] R. Fonseca, O. Gnawali, K. Jamieson, P. Levis, Four bit wireless link estimation, in: Proc. of HotNets, 2007.
[104] M. Yigit, O.D. Incel, V.C. Gungor, On the interdependency between multi-channel scheduling and tree-based routing for WSNsin smart grid environments, Comput. Netw. 65 (2014) 1–20.
[105] B.E. Bilgin, V.C. Gungor, Adaptive error control in wireless sensor networks under harsh smart grid environments, Sensor Rev. 32 (July (3)) (2012).
[106] M.C. Vuran, I.F. Akyildiz, Error control in wireless sensor networks: a cross layer analysis, IEEE/ACM Trans. Netw. 17 (August (4)) (2009) 1186–1199.
[107] V.C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, G.P. Hancke, A survey on smart grid potential applications and communication requirements, IEEE Trans. Ind. Inform. 9 (February (1)) (2013) 28–42.
[108] Erol-Kantarci, et al., Energy-efficient information and communication infrastructures in the smart grid: a survey on interactions and open issues, IEEE Commun. Surv. Tut. 17 (1) (2015) 179–197.
[109] A. Mahmood et al.,“A review of wireless communications for smart grid, renewable and sustainable energy reviews,” vol. 41, January, pp. 248-260, 2015.
[110] Z. Fan, et al., Smart grid communications: overview of research challenges, solutions, and standardization activities, IEEE Commun. Surv. Tut. 15 (1) (2013) 5–20.
[111] E. Ancillotti, et al., The role of communication systems in smart grids: architectures, technical solutions and research challenges, Comput. Commun. 36 (17-18) (2013) 1665–1697.