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Cognitive Radio Based Sensor Network in Smart Grid: Architectures, Applications and Communication Technologies

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ABSTRACT The cognitive radio-based sensor network (CRSN) is envisioned as a strong driver in the development of modern power system smart grids (SGs). This can address the spectrum limitation in the sensor nodes due to interference cause by other wireless devices operating on the same unlicensed frequency in the Industrial, Scientific and Medical band. These sensor nodes are used for monitoring and control purposes in various components of a SG, ranging from generation, transmission, and distribution, and down to the consumer, including monitoring of utility network assets. A reliable SG communication network architecture is required for transferring information which needed by the SG applications, alongside the monitoring and control by CRSN. Hence, this paper investigates and explores the CRSN conceptual framework, and SG communication architecture with its applications; vis-à-vis the communication access technologies, including implementation design with quality of service support. Consequently, this paper highlights various research gaps, such as implementation design model, utilization of LPWAN for CRSN based SG deployment, and so on. This includes discussion on the future direction for various aspects of the CRSN in SG. To address these research gaps, we introduced a smart unified communication solution to improve the efficiency of the SG and mitigate various associated challenges.

INDEX TERMS AMI, CRSN, distributed automation, LPWAN, protocols, QoS, reliability, smart grid, WAMR.

I. INTRODUCTION

Smart Grids can be fully realized by integrating communication network technologies infrastructures. Integration of CRSNs (a combination of cognitive radios and wireless sensor networks (WSNs)) in Smart Grids enables power generation, transmission, distribution, utilities and customers to transfer, monitor, predict, control and manage energy usage effectively and in cost efficient manner. A Smart Grid CRSN can communicate with its end and remote devices in a real-time manner which can lead to efficient monitoring of the following Smart Grids applications: load management and control, wireless automatic meter reading (WAMR), fault diagnostic and detection, remote power line monitoring, and automated distribution. However, there are constraints in WSNs such as limitations of the battery supply life, processing capability, operating frequency and memory. Because of these, researchers are seeking ways to increase the lifetime of this resource-constrained wireless sensor node. The issue of resource constraint has been highlighted in [1]–[4]. In addition, SG applications require a guaranteed quality of service (QoS) as part of its network parameters. Hence, it is challenging to meet QoS requirements in a SG due to the varying characteristics of the network parameters [5]. Also, sending a huge amount of data in a timely manner by WSNs requires that it should be sent concurrently with minimal interference. This cannot be easily achieved due to the limited power and spectra efficiency in WSNs. Hence these requirements need the use of an integrated CRSN within the SG [6].

In addition, distributed renewable energy generators (DGs) in a SG can have an adverse impact on a power system causing imbalance in the power system if appropriate stability and control are not considered [7]. This imbalance between the DGs and the area load demand usually leads to mismatches in frequency and scheduled power interchanges. Based on this, frequency regulation of source-grid-load systems is an essential consideration in a CRSN SG. Hence, Palensky and Dietrich [8] proposed a compound control strategy for frequency regulation of source-grid-load systems whereby the power sources, grids and loads are all participating in the process. Similarly, Fu *et al.* [9] proposed an approximate model for the frequency dynamic process to address the problem of distributed frequency regulation in a SG. In general, there is a need to design an effective monitoring and control system with control strategy for frequency regulation to efficiently delivers SG sensed data in a reliable and timely manner.

Numerous works have been reported in the literature and this paper presents a survey that focuses jointly on the CRSN and SG. Only a very few studies jointly cover CRSNs and DGs and the application of a CRSN into a SG. Reference [10] presented a review on possible design opportunities with cognitive radio ad-hoc networks (CRAHNs) and cross-layer considerations for implementing viable CRSN routing solutions. A survey article was presented in [11], and in this work a comprehensive survey of the physical architecture of a CRSN, including cognitive capability and the spectrum sensing method. In [12], a survey was carried out on the recent advances in radio resource allocation in CRSNs. This survey states that radio resource allocation schemes in CRSNs can be classified into three main categories: centralized, cluster-based, and distributed. Reference [13] presented a survey paper on CRSNs; in this work, current scenario protocols are examined together with the prerequisites for a CRSN. These can mutually eliminate the difficulties that are encountered in the CRSN scenario. In [14], a survey entitled "CRSN: Applications, Challenges and Research Trends" was presented. This describes the advantages of cognitive radio wireless sensor networks including the differences between ad hoc cognitive radio networks, wireless sensor networks, and CRSN networks and the potential application areas of CRSN. Challenges and research trends in CRSN are also presented. Reference [15] presented an overview article on the design principles, potential advantages, application areas, and network architectures of CRSNs. Existing communication protocols and algorithms devised for CRSNs were discussed. Another survey article on CRSNs was presented in [16]. It put forward a high-level review on how cognitive radio primarily forms dynamic spectrum access support for emerging applications such as SGs, public safety and broadband cellular, and medical applications. Despite the benefits that cognitive radio would bring, some challenges are yet to be resolved. Survey articles on SGs that do not involve CRSNs include the work presented by Kuzlu *et al.* [17]; they present information about the different communication network requirements for a range of SG applications, cutting across those used in a home area network (HAN), neighborhood area network (NAN) and wide-area network (WAN). Emmanuel and Rayudu [18] conducted a review on the integral components of the emerging grid and communication infrastructures enabling the six SG applications. In addition, they summarized the communication and networking requirements such as payload (size and frequency), physical (PHY) and media access control (MAC) layer latency based on the IEEE Guide for Smart Grid Interoperability and National Institute of Standards and Technology frameworks. Reference [19] presented an overview and discussion of some of the major communication technologies which included: IEEE specified ZigBee, WiMAX and Wireless LAN (Wi-Fi) technologies, GSM 3G/4G Cellular, DASH7, and PLC (Power Line Communications), with special focus on their applications in SGs. Also, [20] conducted a review of communication and networking technologies in SGs. This included communication and networking architecture, different communication technologies that would be employed in this architecture, consideration of the quality of service (QoS), optimization of assets utilization, control, and management. An additional survey of the SG is given in [21] where a survey of the enabling technologies for the SG is put forward. This survey also explored three major systems, comprising the smart infrastructure system, the smart management system, and the smart protection system.

Survey works that jointly involve CRSN and SG are few; one of such article is [22]. In this work, a systematic investigation is detailed which addresses the novel idea of applying the next generation wireless technology and cognitive radio network to the SG. This considers the system architecture and algorithms, including the study of a hardware test bed. Reference [23] reports on how Cognitive Radio, as a means of communication, can be utilized in an end-to-end SG, ranging from a home area network to power generation. They also considered how Cognitive Radio can be mapped to integrate the different possible communication networks within large scale SG deployment. In addition, information security issues were discussed as pertaining to the use of Cognitive Radio in a SG environment at different levels and layers, and possible mitigation techniques. The work in [24] provided a comprehensive survey on the CRN communication standard in SGs, including discussion on system architecture, communication network compositions, applications, and Cognitive Radio based communication technologies. It highlighted potential applications of Cognitive Radio based SG systems including a survey of Cognitive Radio based spectrum sensing approaches with their major classifications. Reference [25] presents a survey on the spectrum utilization in Malaysia, explicitly in the UHF/VHF bands, cellular (GSM) 900, GSM 1800 and 3G), and WiMAX, ISM and LTE band. The goal was to determine the potential spectrum that can be exploited by Cognitive Radio users in the SG network. In [6], a case study for the implementation of SG network using CRSN specifically in the remote areas of Pakistan was presented.

For clarity, a tabulated survey work with respect to SG communication network architectures and SG implementation design is shown in Table 1.

TABLE 1. A comparison of survey work in SG communication network architecture and implementation design.

Survey References for SG Architecture	Conventional SG	SG Implementation design	CRSN/CRN Approach in SG
Gao *et al.*[20]	Yes	No	No
Qiu *et al.*[22]	No	No	Yes
Shuaib et al.[23]	No	No	Yes
Wang *et al.*[16]	Yes	No	No
Gungor *et al.*[26]	Yes	No	No
Rayudu et al.[18]	Yes	No	No
Rehmani *et al.*[24]	No	No	Yes
Khan *et al.*[6]	No	No	Yes

From the above discussion, it can be seen that some of the surveys mainly focus on the CRSN while some focus on the integration of the CRSN into the SG. However, this paper complements and extends the surveys that involve the integration of CRSN in SG. While a few of these surveys have presented overviews of SG communication architecture, communication technologies, and SG applications (including their motivations and challenges in SG), none has considered the full implementation design with QoS support in the entire CRSN based SG. Also, none has considered the suitability and utilization of Low Power Wide Area Networks (LPWANs) as the communication access technology in a CRSN based SG for delivering SG applications. So far, the existing survey is on cognitive radio network (CRN) context whereas the author's focus of this survey work is on cognitive radio sensor network (CRSN).

The focus here is to explore in the context of the CRSN based SG, SG communication architecture, SG applications, and their communication access technologies. This includes SG implementation designs with QoS support; thus, leading to the following contributions in this survey article:

- An extensive survey of communication network architecture for the CRSN based SG is provided.
- Also included is a survey of SG applications and their communication access technologies in CRSN based SG.
- The potential for an implementable design with QoS support in a CRSN based SG is identified.
- The potential for suitability and utilization of LPWAN in a CRSN based SG is discussed.
- Challenges, recommendations and future research in CRSN based SGs are highlighted.

The remainder of this paper is structured as follows: Section II describes the conceptual framework of the CRSN in a SG. Section III discusses the challenges of the CRSN based SG. Sections IV and V present SG communication network architecture and CRSN based SG applications with respect to communication access technologies. Recommendations and future research work are discussed in section VI. The survey article ends with a conclusion in section VII.

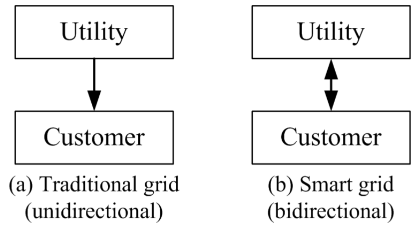

FIGURE 1. Evolving grid communications.

II. CONCEPT AND OVERVIEW OF CRSN IN SMART GRID

A. SMART GRID

The SG is replacing traditional power grids and is intended to be the next generation of electric power system operation. SGs will integrate diversified renewable energy resources in addition to primarily supporting power systems. Control centers equipped with smart communication network infrastructure will utilize modern communication technologies to monitor and control remote smart electric devices in real time. Currently, traditional power grids use a top-down layer approach where the communication flow is only in one direction from the utility to the consumers as depicted in Fig. 1(a). A SG has a bidirectional communication flow between utility and consumer as shown in Fig. 1(b). By definition, according to Cisco, the SG is a data communications network integrated with the power grid that collects and analyzes data, captured in near real-time, about power transmission, distribution, and consumption. Based on this data, SG technology then provides predictive information and recommendations to utilities, their suppliers, and their customers on how best to manage power delivery and consumption. The SG has functional areas comprising: (I) power system layer - this is made up of power generation, transmission, and distribution by utilities, with power supplied to the customers (consumers); (II) power control layer, which enables SG monitoring, control, and management functions; (III) communication network layer - which allows two-way communications in a SG environment; (IV) security layer- which provides data confidentiality, integrity, authentication and availability; and (V) application layer - which delivers various SG applications to customers and utilities based on an existing information infrastructure [24]. The communication layer domain is one of the most critical domains that enables SG applications. In the SG scenario, the consumer can benefit from real-time energy management and pricing through demand response management, thereby enabling energy conservation and cost-effectiveness [26]–[31].

B. COGNITIVE RADIO BASED SENSOR NETWORK (CRSN)

Traditionally, wireless networks are regulated by a spectrum assignment and management policy which makes fixed assignments of the spectrum to license holders for a long time within large geographical regions. This fixed assignment under-utilizes spectrum with utilization levels that ranges from 15 % to 85 % [11]. Cognitive Radio which has the capability of Dynamic Spectrum Access (DSA) is a promising option to solve these spectrum inefficiencies [32]. A Cognitive Radio Sensor Network (CRSN) is a network comprising of Cognitive Radio and Sensor nodes that are equipped with cognitive capability and reconfigurability, and can change their transceiver parameters based on interactions with the environmental circumstance in which they operate [33]. In a CRSN, there are two types of users: primary and secondary. Primary users (PUs) are the licensed or authorized users, which have the license to operate in an assigned spectrum band accessing the primary base station. Secondary users (SUs) also called the Cognitive Radio users (CRs) are unlicensed users without a spectrum license. CRs use the existing spectrum through opportunistic access without causing interference to the primary or licensed users. CRs look for the available portion of the spectrum known as spectrum hole or TV white space. The optimal available channel is then used by the secondary or CR users if there are no licensed users operating in the licensed bands [33]. These CR users need additional functionalities to share the licensed spectrum band. Such functionalities include:

1) Spectrum Sensing- this is the means of detecting unused spectrum called spectrum holes or white spaces and the presence of the PUs [34].
2) Spectrum Management- this involves the selection of the best available channels with respect to the received signal strength, transmission power, number of users, interference, energy efficiency and QoS requirements. This process also includes spectrum sharing process for best channel and power allocation, and some of the functionalities are related to the main functionalities of medium access control (MAC) layer protocols. Hence, it can be incorporated into the MAC layer. However, there are challenges associated with efficient spectrum sharing which include time synchronization and distributed power allocation
3) Spectrum mobility- implies the maintenance of seamless communication and ability to vacate the channel whenever the PU arrives CRs [32], [35].

A typical block diagram structure of a node of a CRSN is shown in Fig. 2. A sensor or sensing unit is used for sensing data. The processor processes and commands the activities of various units. The transceiver with CR capability is used for transmitting sensed data. The battery or power unit supplies the necessary power to the rest of the units.

A group of CRSN nodes can be deployed in a cluster based architecture as illustrated in Fig. 3. This deployment can be accomplished in a SG environment for monitoring and control activities, thus resulting in CRSN based SG. A designated node, usually known as the Cluster Head (CH), controls a group of sensor nodes for opportunistic spectrum access to a licensed or primary network in SG environment.

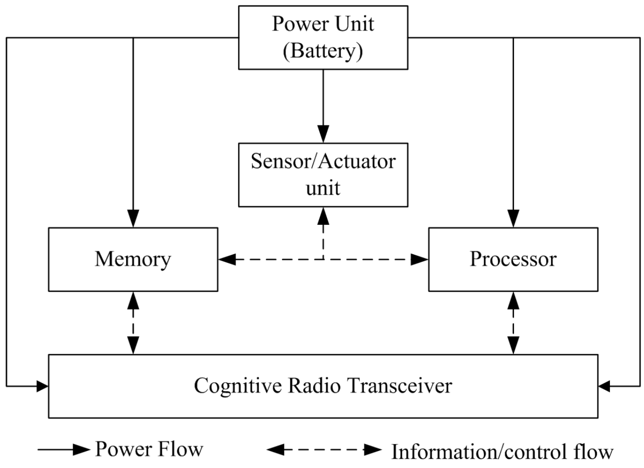

FIGURE 2. CRSN node structure.

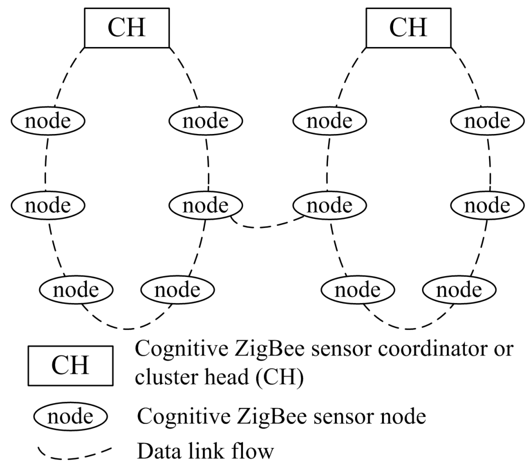

FIGURE 3. Cluster based CRSN architecture.

III. CHALLENGES OF CRSN BASED SMART GRID

The communication required for SG applications are associated with some challenges including problem of severe wireless signal propagation conditions which is common in communication in the SG environment, e.g., through high power disturbances [36]. In addition, many SG applications require guaranteed communications QoS, e.g., demand response applications [35], [37] require reliable and timely communication. Hence, the key design challenge is to reliably and timely deliver the sensed data using the wireless sensor devices that are installed at various locations for efficient decision making [38]. These challenges of SG communications have necessitated the development of CR communications mechanisms that are designed for the SG. The SG encompasses a wide range of settings from inside individual homes to outdoor neighborhood areas, and from electrical power distribution stations and up to generation and transmission substations. These settings are associated with challenging wireless communication conditions. A major challenge in wireless communication is the area of electrical power equipment that usually contains coils. Electrical wiring loops in coils can behave like antennas that radiate electromagnetic waves which can cause interference with wireless communication [39]. Also, impulse noise and high power transients from switching power electronic components can adversely affect wireless communications [10], [39]–[45]. Furthermore, wireless communications from indoor appliances to outdoor smart meters do suffer from high path losses [43]–[48]. SG application requires reliable and low-delay communication. Many key SG applications require high communications QoS [49]–[51]. For example, the demand response application [35] controls and adjusts the operation of electrical appliances in homes and businesses to lessen demands on the power grid. Reliable bi-directional communication between homes and the utility control center is required for efficient functioning of the load management [52], [53]. Again, monitoring and control of the power grid depend on low-delay delivery of real-time data [53], [54]. Also, there exists a problem of interoperability due to multiple interconnection communication technologies in different parts of the SG; thus, ensuring interoperability within heterogeneity in the SG. The communication network structure is envisioned to address this challenge [31]. Therefore, when building a workable SG communication infrastructure, it is required to address the interoperability issue. To address these challenges, a reliable CRSN SG communication network architecture design can be implemented for realizing satisfactory data delivery for a SG application.

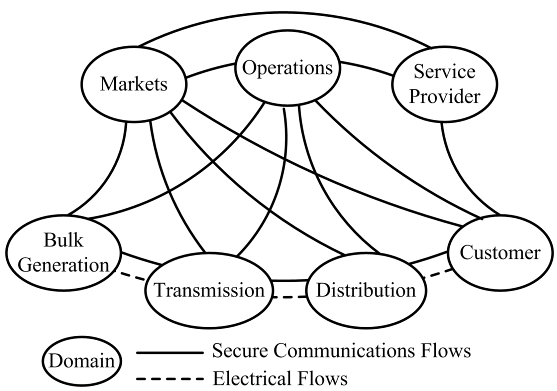

FIGURE 4. The NIST smart grid conceptual architectural reference model [50].

In parallel to the issue of interoperability, the American National Institute of Standards and Technology (NIST) [55] proposed a Framework and NIST Smart Grid Architectural Interoperability Standards Roadmap. The conceptual SG architecture standard is composed of seven domains as illustrated in Fig. 4. These describe the functional areas and scope of the SG infrastructure. Table 2 gives the descriptions of the NIST Framework architectural model.

IV. CRSN BASED SMART GRID COMMUNICATION NETWORK ARCHITECTURE

In this section, work on SG communication architecture is described. Several requirements such as latency, delay, QoS, reliability, etc., must be met in the communication network infrastructure [56]. To successfully achieve these communication requirements, some open research issues need to be addressed. Much works [29], [38], [57], [59] have been conducted in this area. Many SG architectures have been proposed. For example, NIST proposed the SG architectural reference model in the NIST Framework and Roadmap for Smart Grid Interoperability Standards [55]. Cisco proposed an architecture that is totally different because it argues that the whole system would use an independent "network of networks" [60]. Cisco also maintained that the best standard suite of protocols for the SG is the Internet Protocol (IP) [61]. Since IP has already achieved great success in the current internet in terms of flexibility, security, and interoperability. Cisco therefore asserted that the interoperability standards of the SG should use IP architecture as a [61].

TABLE 2. Domains and actors in the NIST smart grid conceptual reference model [50].

Domain	Actors in Domain
Customers	The end users of electricity. May also generate, store, and manage the use of energy.
Markets	The operators and participants in electricity markets.
Service Providers	The organizations providing services to electrical customers and utilities.
Operations	The managers of the movement of electricity.
Bulk Generation	The generators of electricity in bulk quantities. May also store energy for later distribution.
Transmission	The carriers of bulk electricity over long distances. May also store and generate electricity.
Distribution	The distributors of electricity to and from customers. May also store and generate electricity.

Many other researchers have proposed SG architectures with certain features that they want to add into the system or modification. A wireless SG architecture that has the capability to remotely sense power delivery was proposed in [60]. Dvian and Johal [63] presented a hierarchical architecture for the SG, which is a multilevel decentralized platform that handles the potential impacts of harsh power environments. Other presented SG architectures [63]–[65] that are focused on one part of the whole system in some way and are intended to deal with specific requirements that are worthwhile addressing. SG architectures must address the following critical issues [66]:

- transmitting data over multiple heterogeneous media,
- collecting and analyzing massive amounts of data rapidly,
- changing and growing with the industry,
- connecting large numbers of devices,
- maintaining reliability,
- connecting multiple types of systems,
- ensuring security, and
- bring returns on investments.

After consideration of these proposed architectures, it can be deduced that NIST's model is the most fully described SG architecture proposed. It contains nearly every scope brought up by various organizations, from bulk generation to end users. Also, it provides a means to evaluate cases, to identify communication network interfaces for which interoperability standards are needed, and to aid the development of a cyber-security strategy [55]. Therefore, a communication network architecture based on the improvement of this model as the basic framework is envisioned. Consequently, various communication network architectures which can connect to the SG for distribution automation, that reflects the NIST framework, have been proposed.

Communication Networks can be represented by a hierarchical layer architecture in a CRSN based SG environment, which can be classified by data rate and coverage range. Hence, SG communication layer architecture comprises:

1) Home Area Network (HAN); Building Area Network (BAN); Industrial Area Network (IAN); Commercial Area Network (CAN).
2) Neighborhood Area Networks (NAN); Field Area Network (FAN).
3) Wide Area Network (WAN).

Communication network parameters such as latency, delay, QoS and reliability must be met for any successful SG communication architecture. In addition, it will be better for the architecture to cut across the seven domains of the NIST Framework. A lot of work did not simultaneously fulfill the requirements. However, it will be advantageous for the NIST Framework architecture on the SG roadmap for interoperability and CISCO SG architectural Reference model to be complementary. Consequently, research is needed for SG communication network architecture that includes an implementation design model for guaranteed QoS of SG applications. Such envisioned SG architecture should cut across the seven domains of the NIST Framework while simultaneously addressing the network parameter issues in the SG for efficient monitoring and control. A typical smart grid communication network will be addressed in section VI.

The SG communication architecture presented by the work in [20] utilizes the NIST Framework, though not in the context of the CRSN approach for the SG. They did not consider the implementation design model for guaranteed QoS in their SG architecture. Refence [17] presented a SG communication architecture covering some aspects of the NIST SG Framework; although not in the context of the CRSN approach in the SG. However, their work details typical communication implementation scenarios in various sections of the SG, although not with specific implementation designs. Another study [67] describes an implementation design without consideration of the NIST Framework in the SG communication architecture.

In their SG implementation illustration, they investigate the employment of multi-homed wireless transceivers; multihoming over heterogeneous wireless networks is expected to increase the available data rate, and reduces the data transfer latency common with delay sensitive applications such as multimedia video monitoring for wide area situational awareness. However, their work is still not in couched in terms of a CRSN in a SG. Reference [68] highlighted the NIST framework without any specific proposed SG communication architecture. However, they show a typical network topology architecture in various segments of a CRSN based SG. They also show implementation design specifically for information security in CRSN based SG using Role-Based Access Control (RBAC). Their implementation design is not an overall SG implementation design, rather it is specifically an information security implementation design. A communication network architecture and design procedure for the SG was presented in [69]. They proposed a communication network architecture that reflects some aspect of the NIST Framework. They highlighted network topologies and a logical connection model for the SG and integrating legacy applications in the SG. To the best of the authors of this paper, no work has been done in relation to a CRSN in a SG that has a communication network architecture that cut across the entire 7 domains of NIST Framework for SG interoperability standard. This includes the CRSN based SG implementation design. Table 3 shows a comparison that reflects either or both the NIST Framework for SG architecture and the implementation design model.

TABLE 3. A comparisons of proposed or existing work in SG communication network architecture and implementation design model including NIST framework.

References for Proposed or existing SG Architecture	Cut Across NIST seven SG Domains	Implementation design with Guaranteed QoS in the entire SG	CRSN/CRN Approach in SG
Gao *et al.* [20]	Yes	No	No
Shaban *et al.* [67]	No	No	No
Barka *et al.* [68]	No	No	Yes
Wang *et al.* [59]	No	No	No
Kuzlu *et al.* [17]	No	No	No
Budka *et al.* [66]	No	No	No
Rehmani *et al.* [21]	No	No	Yes
Shuaib *et al.* [23]	Yes	No	Yes

V. CRSN BASED SMART GRID APPLICATIONS VIS-A-VIS COMMUNICATION ACCESS TECHNOLOGY

A. ADVANCED METERING INFRASTRUCTURE (AMI)

The AMI is a collection of inter-related systems that allow utilities and service providers to collect, measure and analyze energy usage data from advanced devices such as electricity meters through a heterogeneous communication network on demand for billing and power grid management. It extends over the communication network layer (Wide Area Network (WAN), Neighborhood Area Network (NAN), Field Area Network (FAN) and Home Area Network (HAN)) of the SG.

AMI in the WAN provides the backbone or core communication for all distributed area networks that exist at different area of the grid. AMI in the NAN is implemented within the distribution system for pricing provision messages, monitoring and controlling power delivery to the various end users or customers, and determines the grid efficiency [69]. In general, it collects all the energy usage data from various HANs and sends to the Utility core/backbone through its gateways. AMI in the HAN consists of the smart meter that interconnect various home appliances, sensors, in-home display, gas meter, water meter [68], photovoltaic panel and home energy management system (HEMS) [69], [71], [72]. Table 4 summarizes the layer architecture with their respective coverage area, data rates and possible communication access technologies.

TABLE 4. Three tiers of smart grid architecture [69].

Network Type	Coverage	Data rate	Standard
Home Area Network (HAN)	1 – 10 m	1 – 100 kbps	IEEE 802.15.4/802.11 & proprietary protocols—Z-wave, PLC
Neighborhood Area Network (NAN)	10 m – 10 km	100 - 1000 kbps	Wireless—IEEE802.11s, RF Mesh, WiMAX, cellular stds (3G, 4G, LTE) Wired—Ethernet, PLC, DOCIS
Wide Area Network (WAN)	10 – 100 km	10 – 100 Mbps	Wireless—RF, Mesh, WiMAX, cellular stds (3G, 4G, LTE) Wired—DSL, PON

Generally, the AMI comprises of communication networks, smart meters, local data aggregators, backhaul networks, utility provider data centers, Meter Data Management Systems (MDMSs) and software application platforms [57], [73]. The heterogeneous characteristics that exist within the various components of the AMI make interoperability a major challenge, without open standards put in place [74]. Hence, to have a reliable, scalable and successful integration of an AMI architecture, there is a need for power system and communication technologies interoperability to be taken into full consideration during the design stage. The communications access technologies for the AMI must employ open bi-directional communication standards [57] to provide seamless connection between the utility, customer and the controllable electrical load. Various communication access technologies are deployed in the AMI architecture, depending on bandwidth requirements, reliability, cost effectiveness, future expansion and ease of installation [56]. Examples are:

- Power Line Communication (PLC)
- Copper or Fiber Optic
- Broadband over Power Lines (BPL)
- WIFI & Low Power WIFI
- Cellular/LTE/GSM
- WiMax
- Bluetooth & BLE (Bluetooth low energy)
- General Packet Radio Service (GPRS)
- Internet
- Satellite
- Zigbee.
- 6LoPWPAN- IP Version 6 Low Power Wireless Personal Area Network
- Z-Wave
- Wireless Hart

Also, though not mentioned in the above literature, is the Low Power Wide Area Network (LPWAN), such as: LoRa, Sigfox, RPMA, NB-IoT, LTE Cat-1, and LTE-M1. The LPWAN [75] is a promising access technology for a wide area network for delivering SG application data and control.

The information flow in an AMI system architecture is bi-directional; data is collected from a group of smart meters in the customer premises network local concentrator (CPN), and then transmitted via a backhaul link to the utility core backbone servers, where all the data collected are analyzed by various applications for management and billing [56]. Reliable communication access technologies or network media are required for successful information flows in the AMI system. Gobena *et al.* [76] presented an AMI architecture service and their communication requirements as a middleware solution, it supports the capability of handling the huge amount of smart meter data in terms of scalability, flexibility and performance adherence. Also, the communication access technologies for AMI applications must have sufficient bandwidth (2–5 Mbits/s), be security proven [77], [78], and be able to support current and future technologies [79], [80]. Due to the interference issue caused by other devices using the spectrum free band, CRSN technology is the only suitable solution as the communication access between the consumers and the utility control centers (as the AMI communication backhaul system) and provides dynamic and opportunistic spectrum access for improved data communication performance [51].

B. HOME ENERGY MANAGEMENT SYSTEMS (HEMS)

This application is specifically for the HANs. It provides home automation and control for household appliances that communicate with smart meters and in-home displays. HEMS can minimize energy costs through adaptive control such as load balancing [81]. HEMS can be used by commercial and industrial customers for building automation, heating, ventilation, and air conditioning (HVAC) control [72], including industrial energy management applications. HEMS require real-time information transmission for reliable and efficient operation. Consequently, the communication access technologies for this application should be QoS guaranteed with an appreciable bandwidth for better throughput. A CRSN is beneficial for the real-time information sharing among HEMS [17], [48].

C. DEMAND RESPONSE MANAGEMENT (DRM)

This is also called Demand-side management (DSM), it operates within the Customer premises and interacts with the utility providers, markets and operational regions. Demand response (DR) applications are designed to alter the energy consumption pattern of the customers in response to price and other forms of incentives to better utilize the utility capacity so that the capacity does not have to be expanded [74], [81]. Reliable bidirectional communication between consumers and utility is needed for effective DRM [53]. Smart meters installed at the customer premises provides a two-way communication between the utility provider and customer, this enables the utility to shape customer load profile in an automated and comfortable manner [82]. DRM helps users to turn selected devices on or off by sending communication signal commands to a load controller installed at customer premises [17], [48].

A successful DRM scheme requires reliable and efficient communication access technologies for real-time DR applications. Communication access technologies for DR applications are IEEE 802.15.4, IEEE 802.11 or power-line communication (PLC) which connects user appliances to smart meters installed within the home, building and industrial area networks [80]. [84] analyzed the use of long-term evolution (LTE) as the communication link between the aggregator and customer premises. This provides low latency and packet drop for DR.

DRM helps the utility enhance operations and efficiently maximize and optimize the use of Distributed Energy Resources (DER), including renewable energy. It helps the customer to make more informed choices about how and when to use power. Above all, DRM is a vital component in a SG. However, there exists an open issue to be addressed in a DRM, especially for many utility SG networks, where each entity is concerned about taking full advantage for its own benefit. Hence, Maharjan et al. [30] proposed a Stackelberg game between utility companies and end-users to maximize the revenue of each utility company as well as giving each customer a payoff. They developed a distributed algorithm which brings together the local information available for both utility companies and customers. In addition, they also proposed a scheme based on the concept of shared reserve power to enhance grid reliability and ensure its dependability which mitigates attempts of an attacker trying to manipulate information of the price from the utility.

D. DISTRIBUTED ENERGY RESOURCE (DER)

DERs have renewable and non-renewable energy resources with the following functions: electric power generation, conversion, storage, and interconnection to the area electric power system (EPS). They are made up of photovoltaic arrays, micro turbines, wind turbines, fuel cells, traditional diesel and natural gas reciprocating engines, and energy storage such as batteries technologies and other energy storage techniques [58]. The power flow between the energy sources into the grid is bidirectional since there is storage, unlike the traditional unidirectional power flow paradigm. DERs form a microgrid by integrating controllable loads and power storage devices [31]. These are usually deployed as alternate sources of power to meet local needs of consumers. These needs are typically lightings, elevators and security surveillance in case of utility blackouts [85]. Also, SG functionalities are geared towards the decentralization of power generation to enable bidirectional flow of electricity from DERs and power storage devices [86]. Therefore, reliable and efficient communication technologies linking DERs and distribution system operators (DSO) remain a critical issue [87]. DERs are connected to the grid using communication access technologies and intelligent electronic devices (IEDs) for control, monitoring and islanding [88]. Consequently, DER applications require reliable communication links for efficient control and monitoring. In addition, DER integration into the grid requires low latency. Hence reliable and scalable communication access technologies with stringent latency requirements between 12 and 0 ms are required for correct integration, [79], [88]. Reference [89] proposed using GPRS and existing power line communication (PLC) for connecting photovoltaic (PV) cells to a low voltage (LV) data concentrator. A case study with a SG demonstration project (known as the Future Renewable Electric Energy Delivery and Management (FREEDM) system) which had PV and storage as part of the power resource system, was presented in [59]. Kanabar *et al.* [90] presented studies using different communication technologies. An IEC 61850 based 69 kV/11 kV distribution substation IED, and DER IED GOOSE messages, were studied within the context of transfer trip and islanding operations using wire line and wireless (IEEE 802.11) communication access technologies. Wire line gave a higher throughput and less latency which makes it suitable for a densely populated urban region; while for spatially distributed DERs, wireless would be a better communication access technology option for economic and technical reasons. However, wireless networking faces several challenges, such as network congestion, noise, obstructions, and interference due to overcrowding in the ISM free band. One possible approach to address these issues is to improve the spectrum utilization and wireless communication performance through the opportunistic spectrum access of CR communications [35]. Wi-Fi and ZigBee communication access technologies can be deployed for real-time pricing data, while in continuous carrier and smart meter reading systems, and for islanding prevention, PLC is mostly used in [91].

E. WIDE-AREA SITUATIONAL AWARENESS (WASA)

WASA involves real-time data monitoring, protection and control of the power system across large geographic areas using intelligent electronic devices (IEDs) and Phasor Measuring Units (PMUs). WASA application provides automatic self-healing with local control and faster response than manual control by a control center. It can fully and automatically protect power systems against extensive blackouts or unexpected events [17], [48]. Sanchez *et al.* [87] presented the use of PMUs for distribution, dynamic monitoring, protection, harmonic estimation, load modeling, parameter estimation, and fault location and detection. WASA also retrieves information about components, e.g., transformers, capacitor banks, and network protection devices. Many communication access technologies can be used for these purposes. However, the choice of appropriate communications access technologies for handling huge amount of data provided by the WASA system remains a critical issue for a high voltage network [86]. Reference [74] presented a performance analysis of the communication system between the PMUs and phasor data collector (PDC) over a WiMAX network. PMU traffic has a stringent traffic requirement ranging from 20 to 200 ms. Amidst the various communication access technologies for networking synchrophasors, fiber optic is a preferred choice due to its robustness and insusceptibility to electromagnetic disturbances or capacity constraints [92]. But due to the high cost of implementation of fiber optic for WASA over a wide geographic area, wireless may be appropriate option for wide area monitoring, control, and protection. However, wireless suffers from interference due to competition in the ISM free band. Reference [14] describes how CRSN is suitable for real-time surveillance applications which have a minimum communication delay requirement. These are applications such as traffic monitoring, biodiversity mapping, habitat monitoring, environmental monitoring, environmental conditions monitoring that affect crops and livestock, irrigation, underwater WSNs, vehicle tracking, inventory tracking, and disaster relief operations. They also show the suitability of CRSN for indoor and outdoor monitoring. Hence CRSNs, with their opportunistic spectrum access, are a promising alternative for wide area monitoring, control, and protection [35].

F. DISTRIBUTION AUTOMATION (DA)

Distribution Automation (DA) monitors, controls and manages the distribution grid. DA provides real-time operational information concerning distribution-level devices, such as capacitor bank controllers, fault detectors, switches, and voltage regulators. This information is distributed to other intelligent field devices such as IEDs and integrates them with transmission systems and customer operations [86]. The communication access technology requirement for DA varies between utility providers. The CRSN appears to be a promising technology in terms of successfully fulfilling the DA requirements of a given utility [17].

From the described SG applications and their communication access technologies, it can be seen that access technologies such as WIFI, Z-wave, PLC, 3G, 4G, LTE, DSL, etc., are recommended media for delivering SG application data, control and information [27], [86]. Table 4 tabulates the communication access technologies in various SG segments. However, it is worth noting that LPWAN could be considered as the most promising access technology for a wide area network in terms of delivering SG application data, control and information due to its features, which are:

- Long range
- Low/Medium data rate
- Low power consumption, and
- High receiver sensitivity

The only work that briefly highlights LPWAN for SG smart metering applications is in [93], though not in the perspective of CRSN. They provide a study of European SG projects including the technological solutions with a focus on smart metering low voltage (LV) applications. Apart from the work in [93], no any other work, to the best of the authors' knowledge, has highlighted the suitability of the LPWAN in a SG. The authors are unaware of work that has demonstrated the suitability of the LPWAN for use in a CRSN based SG.

TABLE 5. Comparisons table for access technologies with respect to LPWAN consideration in SG.

References of Comm. Access Technologies	Approach in Conventional SG	LPWAN Considerations	CRSN Approach in SG
Lu *et al.* [51]	Yes	No	No
Gobena *et al.* [27]	Yes	No	No
Gungor *et al.* [35]	No	No	Yes
Vuran *et al.* [32]	No	No	Yes
Khan *et al.* [6]	Yes	No	Yes
Ergul *et al.* [33]	Yes	No	Yes
Laverty *et al.* [89]	Yes	No	No
Andreadou *et al.* [93]	Yes	Yes	No
Whitaker *et al.* [91]	Yes	No	No
Kanabar *et al.* [90]	Yes	No	No
Sood *et al.* [79]	Yes	No	No
Roy *et al.* [84]	Yes	No	No
Akyildiz *et al.* [11]	No	No	No

Table 5 helps summarize the work discussed in this review regarding communication access technologies with respect to the discussion on the suitability of LPWAN for CRSN based SG applications delivery. Furthermore, different SG applications require different communication access technologies to meet the QoS requirements. The communication access technologies at the various levels of a network layered architecture (WAN, FAN, NAN and HAN) are considered. From the discussions put forward here, it is believed that LPWAN is a good enabler for various components in the CRSN SG communication access system.

VI. FEATURED CRSN INTEGRATION IN SMART GRID

A typical cognitive radio based sensor network integrated into a SG should have the potential for possessing a smart unified communication solution that can holistically efficiently monitor and control power and renewable energy generation systems, power transmission and distribution automation, utilities, distributed energy resources at the customer side, security and privacy systems, smart meters, customer load, and demand response management. To accomplish the task of monitoring and control of the entire SG system, the following are required:

1) Implementation design consideration of CRSN in SG.
2) Utilization of cognitive radio wireless multimedia sensor and actuator network (WMSAN) [6], [94], [95].
3) Utilization of LPWAN as communication access technology for CRSN in SG.
4) Consideration of security strategy [22], [23], [95], [96].
5) Consideration of an energy-efficient cross layer framework of the CRSN nodes in SG [97], [98].
6) Consideration of energy efficient control strategy/ optimization in radio resource allocation and spectrum sensing [96], [99], [100].
7) Consideration of energy efficient optimization of communication protocols/algorithms [22], [35], [96], [101].
8) Perpetual energy harvesting for the CRSN nodes in SG.

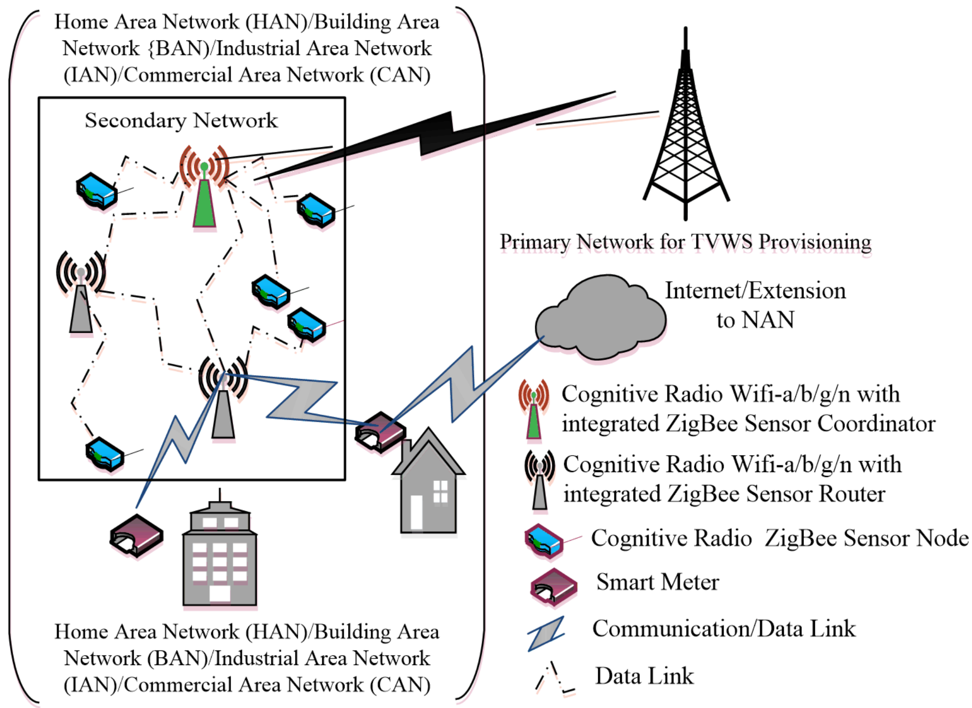

FIGURE 5. A typical SG communication in customer premise (HAN/BAN/IAN/CAN).

Considerations of the requirements for CRSN integration into a SG, when implementing a SG, will indeed lead to the full benefits of a SG. It will certainly help in addressing the challenges of a SG as highlighted in section III such as interference, impulse noise, and path lose, delay, interoperability within heterogeneity in SG, etc.

A typical example of a CRSN based SG is that of a case study in Pakistan in which Khan *et al*. [6]. In their work, they discussed the benefits of deploying CRSN in a SG such as helping in sustainable production of renewal energy and minimization of power theft. They also pointed out the network communications aspect in a SG can be accomplished by cognitive radio technology using software defined radio (SDR). However, their study is specifically for a Pakistan environment by considering the broadband and cellular availability in Pakistan as the communication access technologies for the CRSN in SG. Hence, it was not a general unified smart CRSN communications solution in SG that has been highlighted here.

A typical illustration of a communication network in SG is shown in Figs. 5 and 6. The CRSN architecture shown in Fig. 3 can be deployed in strategic locations for various SG components (generation, transmission, distribution, control canter/utility, and customer premises). Taking the earlier stated requirement into consideration will help in the formation of smart unified communication solutions using CRSN. This is together with communication access technologies such as LPWAN. This unified communication solution can then be integrated into SG to yield holistic efficient monitoring and control in the entire SG ecosystems.

With regards to the works on utilization of the cognitive radio (CR) paradigm and the sensor network (SN), most of the works surveyed the CR paradigm in SG [22]. Their focus is mainly on the cognitive radio network (CRN) in SG and not on the cognitive radio based sensor network (CRSN), i.e. the intersection of CR and SN in SG. Obviously, no survey work has been done in the context of the intersection of CR and SN in SG, except the work presented by Khan and Faheem [6] which is somewhat related to a survey. It is basically a case study for CRSN in SG at Pakistan as discussed earlier. For clarity, Table 6 helps to show various survey works on the CR paradigm, giving the focus area and whether it is in the context of CRSN in SG or CRN in SG. It notes whether the survey work considers a unified smart communication solution for holistic efficient monitoring and control in SG.

VII. RECOMMENDATIONS AND FUTURE WORK

A SG involves key scientific and technological areas such as (i) power quality; (ii) reliability; (iii) resilience; (iv) widespread integration of distributed renewables energy along with associated large-scale storage; (v) widespread deployment of grid sensors; and (vi) secure cyber based communication within the grid. To account for these areas, it will be good for the SG communication architecture to cut across the entire 7 domains of the NIST Framework for Smart Grid Interoperability standards. Based on this, from Table 3, it can be deduced that research attention needs to address

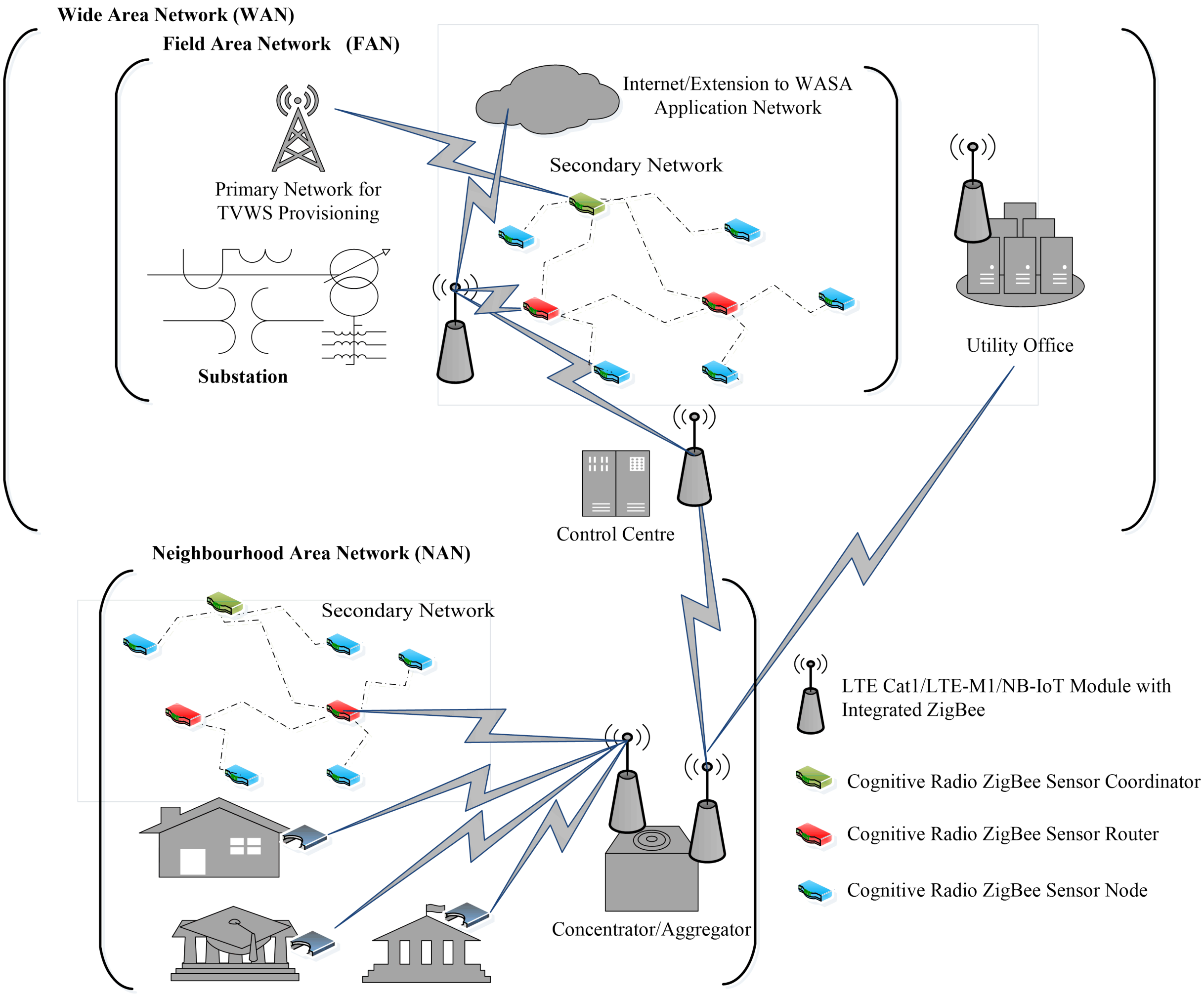

FIGURE 6. **A typical smart grid communication in WAN/NAN/FAN.**

this issue. Hence, the authors believe that a communication network architecture, which reflects the entire 7 domains of NIST Framework, alongside the implementation of a design model, could yield successful SG integration and deployment.

Table 5 highlights that research attention needs to address the consideration of a LPWAN in a CRSN based SG. Looking at the highlighted SG applications and their communication access technologies, as well as LPWAN consideration, it is believed by the authors that the integration of hybrid and multihomed communication access infrastructure to operate at different segment of the SG will lead to efficient and seamless communication in the SG network. For example, a CRSN SG design requirement consideration could consider the Network topology that comprises of cognitive radio dual band (5 GHz and 2.4 GHz) WIFI (802.11a/g/n) with integrated ZigBee to operate in the HAN, BAN, IAN and CAN. Also, the topology for WAN, FAN and NAN could comprise of LTE cat1/LTE-M1/NB-IoT (private/dedicated) with integrated ZigBee. In addition, as a further example, the authors also believe that Table 7 could help in developing the design requirement for correct CRSN based SG integration and deployment for efficient holistic monitoring and control.

The problems of severe wireless signal propagation conditions [33], including impulse noise [102], and high power transients and switching power electronics components [103], [104] that adversely affect wireless communication link in SG environment, can be addressed by:

- An energy efficient modulation scheme that has an excellent signal to noise ratio (SNR) capability with low complexity detection mechanism and an appreciable bit error rate (BER). This can be integrated in the physical and media access (MAC) layer protocols for enhanced link quality.
- Consideration of Link budget analysis in CRSN deployment in a SG for enhanced signal strength and link quality.

Similarly, the issue of interference caused by electrical wiring coil loops that radiate electromagnetic waves can be addressed by a cross layer protocol that will operate jointly

TABLE 6. Summary of focus area and consideration of unified communication by various survey works in SG.

References	CRN SG	CRSN SG	Architecture utilizing NIST Framework in the entire SG 7 domains	SG implementation design model	LPWAN consideration	Unified Comm. Solution for holistic monitoring and control in CRSN SG
Khan *et al.* [6]	√	×	×	×	×	×
Our survey	×	√	√	√	√	√
Gungor *et al.* [35]	√	×	×	×	×	×
Rehmani et al.[24]	×	√	×	×	×	×
Zhang *et al.* [68]	√	×	×	×	×	×
Qiu *et a*l. [22]	√	×	×	×	×	×
Ranganathan *et al.* [99]	√	×	×	×	×	×
Gao *et al.* [20]	×	×	√	×	×	×
Le *et al.* [96]	√	×	×	×	×	×
Gungor et al. [26]	×	×	×	×	×	×

×: Not considered, √: Considered

TABLE 7. Smart grid deployment design requirement guide.

Communication Standard	Data rate	Consumption Power	Deployment cost	SG Segment	Distance covered & Latency	SG Applications
Power Line Communication (PLC)/BPLC	High	Medium	Medium/Low (existing line)	HAN/NAN	Long range, Low latency	Distribution Automation, AMI
Optic Fibre	Very high	Medium	High	NAN/WAN	Long range, Low	Core/Backhaul Infrastructure
ADSL/DSL	High	Medium	High	HAN/NAN/WAN	Long range, Low	AMI, SCADA, DA
WIFI	Very high/ High	Medium	Low	HAN/NAN	Medium range, Low	DA, AMI, DER, DRM
Cellular/GSM/GPRS	Low	Medium	Low	HAN/NAN/WAN	Long range, High	Distribution Substation
LTE-A	Very high	High	Low	HAN/NAN/WAN	Long range, Low	SG wireless Surveillance, SCADA , WASA
ZigBee	Low	Low	Low	HAN	Short range, Low	Home Automation, AMI, DRM, DER, DA
Bluetooth	Low	low	Low	HAN	Short range, Medium	Home Automation
WIMAX	Very high	High	Medium	HAN/NAN/WAN	Long range, Medium	Distribution Automation (DA) AMI, DER
Satellite	Very high/high	High	High	HAN/NAN/WAN	Long range, High	AMI, DA, SCADA
LoRa	Low	Low	Low	HAN/NAN/WAN	Long range, Low	Home Automation, AMI
Sigfox	Low	Low	Low	HAN/NAN/WAN	Long range, Low	Home Automation, DA
RPMA	Medium/low	Low	Low	HAN/NAN/WAN	Long range. Low	AMI, DRM, DA
NB-IoT	Low	Low	Low	HAN/NAN/WAN	Long range, Low	AMI, DRM, DA
LTE Cat-1	Medium/Low	low	Low	HAN/NAN/WAN	Long range, Low	SG Wireless Surveillance,SCADA, DER, DRM, DA
LTE –M1	Low	Low	Low	HAN/NAN/WAN	Long range, Low	SCADA, DER, DRM, WASA, DA

Data Rate Range: Very low (1 kbps to < 250 kbps), Low (250 kbps to 1000 kbps (1Mbps)), Medium (>1Mbps to 10 Mbps).High (> 10 Mbps to 100 Mbps, Very high (> 100 M)

at the physical, MAC, and network layer for interference mitigation; thus, yielding to excellent link quality.

The interoperability issue in the SG due to the heterogeneous method of communication in the SG environment can be addressed by development of a workable communication standard for SG infrastructure.

The problems of security in a CRSN based SG can be addressed by 'end-to-end' security of high bit-rate SG applications. This will involve consideration of security of the air interface and the delivery of the application interface software to the SG infrastructure. Hence, the need for a workable acceptable use policy for improving end-to-end security in a CRSN based SG is recommended.

Future work is required in the utilization of hybrid systems together with a LPWAN infrastructure for the design of an CRSN SG. Also, future work is needed in the area of design and optimization of the communication cross layer protocol that will operate on a heterogeneous communication platform in a SG. This is due to the different SG applications. Other future work includes radio resource allocation for dynamic spectrum access (DSA) in the wireless devices and the sensor nodes. Due to the limited battery life of some sensor nodes, reliable energy harvesting remains an open research issue. In addition, research into a unified solution for holistic mitigation of all sort of interferences in the SG environment is urgently needed. Likewise, research on end-to-end security for mitigating security breaches in a CRSN based SG will be a welcome development.

VIII. CONCLUSION

In this paper, CRSN based SG architecture and applications vis-à-vis communications access technologies are explored, and a conceptual framework for a CRSN in a SG, including challenges of a CRSN based SG, is highlighted. Overall, the CRSN based SG communication network architecture alongside implementation of a design model, and associated communication access technologies, are presented. The NIST Framework for SG Interoperability standard is discussed. Recommendations are made with regards to a CRSN based SG communication network architecture and implementation design model. This includes a discussion on the suitability and utilization of a LPWAN infrastructure for correct SG integration and deployment. Finally, future work is discussed and this includes: utilization of hybrid communication access systems and a LPWAN infrastructure in a CRSN SG, communication network protocols, radio resource allocation, and energy harvesting in a SG. These are presented as an open research issues.

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