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A Review of Cognitive Smart Grid Communication Infrastructure System

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Abstract The reliance on obsolete communication infrastructure and outdated technologies, in order to meet increasing electricity demand, consists of major challenges confronting traditional power grids. Therefore, the concept of smart grids (SGs) has been adopted as an ideal solution. This concept entails the integration of advanced information and communication technologies (ICTs) into power grids, as well as allowing a two-way flow of communication. However, recent development in cognitive technologies – internet of things (IoT) smart devices particularly in home area network (HAN) – as well rapid growth in wireless applications have enabled the traffic of huge data volumes across SGs. Data gathered in SGs are distinguished by quality of service (QoS) requirements such as; latency, security, bandwidth, etc. In order to support the level of QoS requirements in SGs, stable and secure communication infrastructure is of great importance. Therefore an in-depth review of the state-of-the-art of existing and emerging communication architectures of SGs is conducted. Therefore, this work proposes communication architecture based on fifth-generation (5G) and cognitive radio networks (CRN).

Keywords Cognitive Radio (CR) · Information and Communication Technologies (ICTs) · Fifth Generation (5G) · Smart Grids (SGs) · Fog Computing · Cloud Computing

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1 Introduction

Traditional power grids have been designed to fulfill the 20^{th} century needs of consumers. These power grids consist of four major domains: generation, transmission, distribution and consumption. A typical traditional power grid is depicted in Fig.1. In this configuration, ICTs and intelligence (cognitive) features, if any, are usually found within high-voltage domain [1]. Bai et al. [2] argued that existing grids could be considered as a mere power transportation from a few central power plants to numerous consumers. These grids are prone to power disturbances and unplanned outages, electricity theft as well as inaccurate electricity metering and billing. These shortcomings stem from obsolete communication infrastructure and outdated technologies continuing to be relied upon in order to carry out the primary function of power grids. Furthermore, existing or traditional power grids are known by their characteristic feature of a one-way flow of information and electricity [3]-[5]. This implies that centralized generating plants (e.g, combined heat and power (CHP), hydro plants, etc.) can only distribute power to consumers and not vice versa. As shown in the literature, traditional power grids have revolutionized daily lives of consumers since their inception. Recently, the concept of SGs has been identified as a new paradigm that aims to incorporate advanced ICTs to address issues faced by traditional power grids [5],[6]. The distinguishing aspect of SGs is known as a two-way flow of communication as shown in Fig.2. Furthermore, SGs have been gaining significant popularity in industry recently. To address existing grids issues, SGs aspire to take advantage of the following concepts; dynamic pricing, smart meters (SMs) [7],[8], micro-

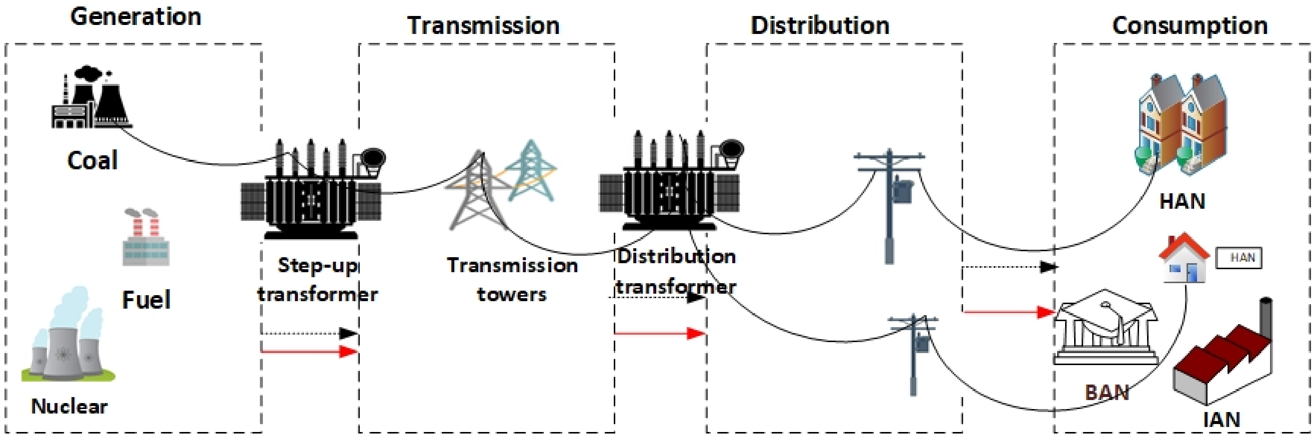

Fig. 1 Conceptual model of traditional power grids

grid [9], and distributed generation (DG) [10] which are discussed in Section 3. However, these concepts comprise distinct and stringent quality of service (QoS) requirements (e.g., latency, security, reliability and efficiency) to be fulfilled [11]. To support the level of these requirements, ICTs, open architecture for plug and play smart appliances as well as software and hardware interfaces should be developed and implemented [12]. Therefore, this paper aims at proposing a single-hop architecture based on 5G [13] and cognitive radio network (CRN) [14] to enhance reliability as well as spectrum and energy-efficiency of the network. This is achieved by initially investigating how the combination of CRN and 5G can exploit the optimization of unused spectrum bands. The main components of SGs include large-scale deployment of smart devices, sensors and utility control center (UCC) with SMs serving as a gateway between them. In order, to allow remote and advanced control services within grids, these components should be connected to the servers via an internet backhaul network, known as cloud servers [15]. Traditional SGs adopt cloud services for data storage, processing, analysis, and decision-making. Since cloud servers do not possess features such as scalability, edge analytic as well as real-time interactions and service delivery, they fail to manage huge data volume. For instance, cloud servers are geographically distributed. Thus, consumers and power providers fail to access some particular services from the cloud. In essence, cloud servers are not latency-sensitive for real-time applications. This results in bulk of data on the network and packet losses. Security and privacy are major challenges in cloud servers since they operate on shared backgrounds (public servers). Also, internet of things (IoT) devices generate raw data transmitted to UCC periodically via cloud servers. This data contains personal information of consumers, which if compromised may place the safety of consumers at risk. However, with the evolution of advanced technologies, fog computing has been identified as an effective technique to resolve the issues in traditional cloud servers. Fog computing can be defined as an extension of cloud servers by incorporating essential features that cloud servers do not have. This includes its ability to support latency-sensitive real-time communications, location awareness for IoT devices in HAN, analyzing data without the need to be transmitted to cloud and its ability to manage a huge volume of data. This paper aims at employing the combination of fog and cloud computing models in order to address latency and security issues faced by existing communication infrastructure. Furthermore, IoT smart devices are designed to communicate over long-range wireless communication technology with the ability to support their level of communication requirements such as cellular mobile technologies. Considering the large number of smart devices and wireless applications, the deployment of ICT infrastructure is a critical design issue in SGs. In addition, this paper also presents a review of the state-of-the-art architectures such as currently proposed in this field, and of the issues posed by designing and implementing ICT infrastructure in the context of SGs. The key outlines of this paper are as follows;

- To provide an extensive review on the state-of-the-art architectures proposed, to fulfill the distinct and stringent QoS requirements in SGs wireless network.
- The incorporation of fog and cloud computing with the aim to support the level of SGs and QoS requirements such as latency and security.
- The Identification of possible communication technologies which can mitigate QoS issues such as spectrum and energy-efficiency, security as well as latency.
- To propose an architecture based on the combination of 5G and CRN in order to improve the reliability and efficiency of the network. In order to promote the benefits of 5G network, a combination of FC and CC is incorporated to enhance latency and scalability issues in SGs.

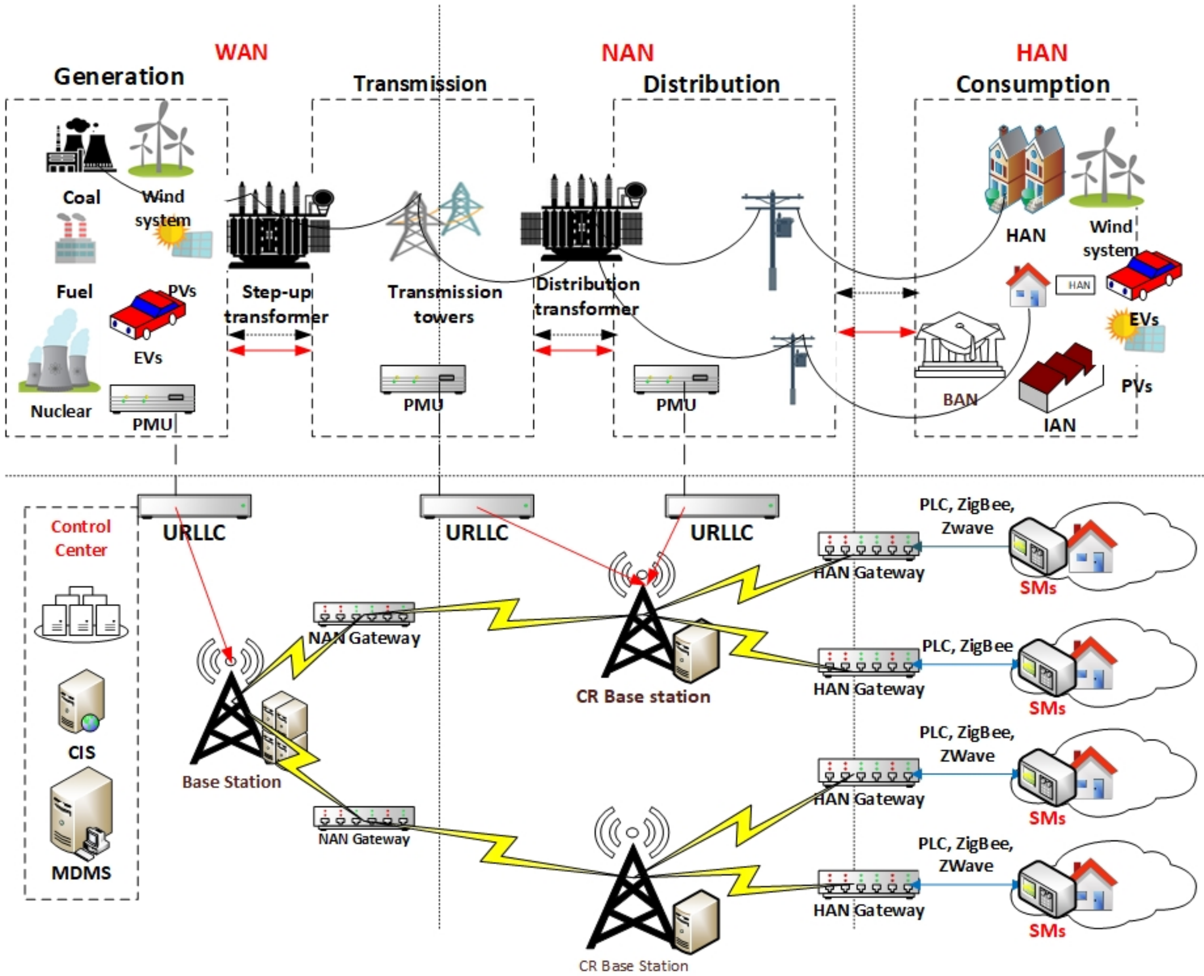

Fig. 2 Conceptual model of smart grids

The rest of this paper is organized as follows; In Section 2, the literature review based on the state-of-the-art architectures such as discussed in previous and current works is presented. Furthermore, issues in the context of SGs information processing are outlined. In Section 3, next-generation power grids are explored by investigating stringent QoS requirements as well as short and long-range communication technologies. The hierarchical communication layers of SGs are explored in Section 4. The fog and cloud computing-based architecture is presented in Section 5. The paper is concluded in Section 6.

2 Related Works

The significant increase in SGs wireless applications yields rapid growth in the vulnerability of network stability and data privacy. In addition, SGs encounter the challenge to intelligently optimize network configuration and issue control demands autonomously without intervention of third party. Erol-Kantarci and Mouftah [16] reported the significant innovation which ICTs bring into major domains of grids. To resolve QoS issues in SGs, several works proposed several types of ICT architectures. Each of which has different research directions and objectives. The work in [16] is among the initial works which surveyed energy-efficient SGs communication infrastructure enhancing the grid. Fang et al.[4] outlined vital aspects in the deployment of SGs including standard interoperability, SGs applications, communication technologies both wired and wireless. Gungor et al. [12] reviewed issues related to SGs communications architecture. In [4],[17] energy-efficiency, instability nature of DG, interoperability, and security are identified as challenging issues in the design and implementation of SGs. With the significant increase in wireless applications, conventional architecture finds it difficult to manage and control data traffic in the network. To control, monitor, analyze and optimize the complex and dynamic SGs environment, reliable and secure infrastructure is of great importance. However, several aspects of SGs need to be investigated and established, to design communication infrastructure [18]-[19]. Prior research has conducted surveys on existing technologies using wired and wireless medium to address a variety of issues in diverse SG environment [17]. Furthermore, SGs are expected to employ more than one technology due to its dynamic nature. In essence, design and implementation of SGs infrastructure is a challenging task. To enable communication between home area network (HAN) and wide area network (WAN), advanced metering infrastructure (AMI) architecture has been proposed [20]. In this architecture, the IEEE 802.11/IEEE 802.15.4 standard is considered to be ideal for short and medium-range communication (i.e from SMs to SMs and SMs to gateways). AMI has been identified as an initial step in the realization of SGs [21]. An indoor architecture design has been developed in [2], based on preliminary analysis. In the development of their proposed architecture three aspects have been investigated; advanced meter reading (AMR), advanced meter management as well as AMI. In this model, the focus was solely placed on improving the energy-efficiency, reliability which were reported to be achieved. However, the communication technology employed within this proposed architecture was not mentioned. Due to the diverse SG, massive data volume is generated by SMs. These data require a reliable architecture for transmission in a secure and scalable manner. In [22], the authors proposed a CR based communication architecture to address the traffic issue within HAN/WAN frameworks. To improve the resilience of the network and allocate the spectrum bands, an optimization problem was formulated to control data traffic between licensed and unlicensed users. This is achieved by identifying the available spectrum in the framework as well as defining the state of the licensed users. Prior works proposed architectures based on 5G and CRN separately. This paper proposes an architecture based on the combination of 5G and CRN in order to improve the reliability and efficiency of networks.

3 The Next-Generation Power Grid

The conceptual model represents the essential components of next-generation power grids. The system is divided into two layers from the top. The top layer represents the smart energy, which comprises bulk generation, transportation, distribution and consumption of electricity. The bottom layer represents the communication architecture of the network. This includes; advanced ICTs, software and hardware interfaces as well as UCC.

3.1 Smart Energy

3.1.1 Smart Generation

Renewable energy sources (RESs), such as wind and solar systems, has emerged as one of the most popular and efficient technologies of the modern era. As RESs gain significant popularity in next-generation power grids, fossil fuels are slowly depleting. Due to their instability and unpredictable nature, RESs are perceived to be unreliable sources of energy. In order, to resolve this issue a concept of distributed generation (DG) has been realized in SGs. DG can be defined as an integration of various power sources and storage technologies in the vicinity of consumer's premises and power generation domain. This comprises the integration of RESs with advanced communication technologies as well as storage technologies(i.e plug-in electric vehicle (PEV)) [23]. The enhancement of energy-efficiency and reliability using these techniques will be achieved by supplying energy into the macro grid when renewable energy production is low or simultaneously stores energy when renewable power production is high. This technique is known as vehicle-to-grid (V2G)/ grid-to-vehicle(G2V), respectively. Previous research focussed on the issue of managing the DGs as a result of instability issue and geographical deployment. To address the above-mentioned issues, virtual power plant (VPPs) have been identified as a solution. VPP can be defined as an aggregation of DGs as a single entity, and thus improving the stability and reliability of power grids.

3.1.2 Smart Transmission

In today's electrical grids, the transmission domain plays an essential role in the delivery of power to consumers in an efficient, reliable and secure manner. The advanced technologies such as flexible AC transmission systems (FACTS), optimized transmission dispatch, high capacity conductors, advanced storage systems and others offer a great solution to enhance network capacity. Power transmission is responsible for transmitting power at high voltages over long distances using transmission lines. The corona effect or arcing which occurs during the clearing of high voltage transmission fault by circuit breakers takes an estimation of one-half cycle to completely clear. However, in next-generation power grids, a technique needs to be established to shorten this time duration. Smart transmission system will enable constant reconfiguration of power generation sources depending on power demand and availability [24].

3.1.3 Smart Distribution

The design of distribution systems in conventional grids is dependent on radial design architecture, with the centralized generation, limited sensors as well as manual monitoring and restoration abilities [25]. However, SGs introduce the deployment of sensors throughout the network, which increase the level of intelligence features within the distribution domain. In smart distribution, data aggregation points

(DAPs) also known as gateways can serve as the communication link between HAN and WAN, which are usually employed on distribution electric poles. These gateways aggregate the information generated from SMs and transmit it periodically to the UCC. Among other benefits of DAPs in distribution systems: reduction of power consumption of SMs, enabling communication between HAN and WAN, control and management of data traffic in HAN.

3.2 Communication Parameters

3.2.1 Latency

The information processed within SGs applications and services is distinguished by its latency-sensitivity. For instance, communication delay in non-real time communication can be tolerable. Whereas in real-time communications such as fault detection, power or service restoration, quality monitoring, etc., the level of latency-sensitivity is extremely high. In [19], latency is defined as the time between when the state occurred and when it was acted upon by the application (delay). However, in a diverse SGs environment, the latency requirement for each application will vary.

3.2.2 Bandwidth

The variety of wireless applications and services employed in SGs consists of distinct level of bandwidth requirements which range from low, medium, to high radio frequency range. In small-scale SGs applications, such as AMI and demand response (DR), the low to medium radio frequency should be sufficient for data delivery in the network. Whereas in large-scale applications, such as VPPs and meter data management system (MDMS), medium to high radio frequency is required. In essence, bandwidth can be defined as a range of frequencies required for each application.

3.2.3 Security

Security is the ability of the communication infrastructure to combat physical and cyber-security attacks to protect the critical data gathered from various smart grid components. SGs applications and services consist of crucial information, which if accessed and/or leaked by unauthorized person, can be utilized to break the stability of the grid and/or to access daily routines of consumers. Information leakage can occur during data transmission or storage [26]. Traditional power grids utilize electromechanical meters installed in customer's premises to measure, gather, and store power consumption data. However, this system poses several concerns or issues to both utilities and customers such as the possibility of meter reading errors/under billing or over-billing of customers since manpower is hired to acquire data from the consumer's premises manually. To mitigate security issues in SGs, HAN and SMs are deployed within the customer's premises.

3.2.4 Reliability

Reliability can be evaluated as the probability of successfully transmitting a specified number of bytes within a certain user-plane latency, given a certain channel quality, e.g a few SMs, or coverage-edge [27]. To ensure accurate continuity of communication between the devices, reliable communication architecture is required. Reliability is considered as the basic requirement of communication networks in SGs which determines the availability of data transmission links [28]. This shows the significant impact that power outages have on the economy. In traditional power grids, detection of power outages on time is still a challenge due to lack of automated analysis and few sensors deployed in the network which yields poor visibility. The concept of "load shedding" has been another technique to improve the system reliability to an acceptable level by reducing the load when all the available generation units are exhausted[29]. In SGs, features such as smart load control (direct or indirect) are allowed to improve reliability and QoS of the network.

4 Communication Parameters

4.1 Communication Technologies

4.1.1 Power Line Communication (PLC)

In this technology, information is transmitted through existing transmission lines which result in low installation cost at a ratio of 2-3 Mb/s. It is also known for its characteristic feature of utilizing existing power lines for data transmission. PLC is suitable for HAN applications due to its characteristic features of low data rate, low bandwidth, etc. Furthermore, it is usually applied in remote metering and home automation applications. However, Fang et al. [5] reported that the debate regarding the application of PLC in SGs is still an open issue. However, signal attenuation is a major drawback in PLC due to the nature of transformers [4]. Among other issues of PLC as indicated in [24], include the inability to transmit data over long distances and the noise level generated by power lines. Considering the amount of data that needs to be transmitted over the same medium for other applications, a massive data traffic volume will be another issue that needs to be addressed.

4.1.2 Optical Fibre

Optical fibre is considered as the appropriate wired communication technology to be implemented for various WAN applications, due to its ability to withstand the noise levels and also transmit the information over long distances. Optical fibre can be an ideal communication technology for SGs applications such as distribution automation, DR, AMI, etc [30]. Optical fibre comprises several benefits such as high bandwidth, immune to radio interference, its ability to virtually eliminate unauthorized access of information such as eavesdropping which yields to secure network structure. Despite its benefits, it poses some disadvantages such as high installation costs due to mapping them along with the existing distribution and transmission network lines, its limitation in terms of the geographical areas can be implemented on and also the time it takes to be practically implemented.

4.1.3 ZigBee

ZigBee is a wireless technology that is designed for radio frequency applications that require low data rate, long battery life, secure networking [5] and is also based on IEEE 802.15.4 standard [31]. This technology is ideal for short-range communication such as HAN applications. SGs comprise a variety of wireless applications and IoT smart devices with distinct QoS requirements. Considering, huge data volume generated from these components, ZigBee may not be appropriate for latency-sensitive applications such as remote monitoring and distribution automation because of its inability to share the same communication medium with other applications as well as low processing capabilities.

4.1.4 Cellular Technologies

In recent years, Long-Term Evolution (LTE) also known as the fourth generation (4G) have been making waves in the industry as the promising technology for crucial applications such as smart homes, health care, etc. As compared to other existing technologies, 4G is the most preferred technology in most cases due to low installation and maintenance costs as well as its ability to transmit large volumes of data over long distances. 4G is defined as the cutting-edge technology which includes some features that were not used before in wireless and mobile technologies [32]. In addition to 4G benefits, includes its flexible nature, high-data ratio and efficient capacity for SGs applications and services. However, security is among the major challenge in 4G since it operates on shared backgrounds. Considering the information generated by smart IoT devices and sensors, reliable technology with the ability to ensure the privacy of such information is required. With the evolution of advanced ICTs, 5G has recently been gaining popularity or preference over other technologies in the industry. 5G can be considered as an extension of 4G by incorporating features which were not possessed by previous generation technologies. In [13],[33], the authors defined 5G as the revolutionizing mobile communications providing a pervasive and ultra-broadband fiber-like experience for everyone and everything to consume emerging mobile services, such as three-dimensional or ultra-high-definition video sharing, machine type communication (MTC), intelligent transportation systems (ITS), and smart homes. Since SGs are among the main applications of 5G, this technology can be an appropriate technology for real-time latency-sensitive applications and services.

4.2 Communication Layers

4.2.1 WAN

Conventionally, WAN comprises a backhaul network with cloud servers geographically distributed over the network. To enable communication within the diverse SGs network, WAN serves as a communication link between UCC and HAN. Also, WAN links these servers to UCC to enable communication among them. 5G can be considered as an ideal technology for WAN applications and services. The CRN can also be adapted to improve the spectral efficiency of the network by dynamically accessing the unused spectrum bands.

4.2.2 NAN

NANs interconnect HANs and also serve as the communication link between HANs and WANs. NANs serve as an intermediary node, by transmitting SMs information to UCC. The selection of communication technologies in this layer varies due to the SGs applications. Hence, both wireless and wired communication technologies are an ideal solution for NANs applications with diverse QoS requirements. Optical fibre and 5G are considered ideal technologies for NAN applications due to the ability to support real-time latency-sensitive applications. Furthermore, implementing a suitable information architecture between smart meters, sensors, and utility data centers is still a challenge. As a result, NAN gateway needs to be deployed to transmit information from heterogeneous IoT smart devices to WAN [34]. In [35] the authors reported the adoption of wireless communication technologies as the appropriate technologies for NAN applications due to their ability to enable rapid deployment in a cost and energy-efficient manner.

4.2.3 HAN

The customer's premises area network can be categorized into three depending on the environment: HAN, business area network (BAN) and industrial area network (IAN) [30]. These areas can be distinguished by climate, economic conditions among other factors. The load demand in HAN is determined by the daily routine of the consumers integrated into the network as well as the change in climate conditions. The load demand from consumers during peak hours and winter season is expected to be higher than during sunny seasons and off-peak hours. Whereas, in BAN the load demand is determined by the economic condition and is less impacted by the change in climate condition. Hence, HAN serves as a communication link between smart devices and SMs. Considering data generated from DGs integrated into the vicinity of HAN as well as a large-number of heterogeneous devices, the architecture to manage and control these data is of great importance. AMI has been realized as the paradigm to support the level of QoS requirements in HAN [8]. Furthermore, AMI enables two-way communication between smart devices and SMs. The DR and demand side management (DSM) are among the concepts which emerge with the innovation of AMI to enhance reliability and stability of grids. DR concept can be achieved by employing advanced communication technologies that will enable electric utilities to wirelessly turn on/off smart power plugs within consumer's households based on the on/off-peak hours. However, finding suitable communication technology is still a challenge. Several works have proposed power line communication (PLC) as the candidate technology, but there is still a debate on the role of PLC in SGs. HAN applications require a coverage area ranging up to 100 m, tolerable latency and also support low bandwidth within the smart meters and electrical appliances. ZigBee, Wi-Fi, HomePlug, Z-Wave, and M-Bus are identified by the Association of Home Appliance Manufacturers (AHAM) as the best candidate technologies for HAN applications [12].

4.2.4 Cloud Computing

In traditional SGs, cloud servers are employed for storage, processing and analyzing of data. These data are transmitted from NAN gateways to UCC through cloud servers. However, this paradigm comprises geographical distribution of servers throughout the network. Furthermore, this paradigm requires multi-hop communication architecture which yields communication delay. For data packets to reach the cloud, it needs to travel through all the hops employed in the network. This yields communication delay for latency-sensitive communication. The significant increase of IoT functionalities in SGs, results in huge data volume. Therefore, transmitting this data to cloud servers for further processing yields to data congestion or bottleneck on the network, which further increase communication delay.

4.2.5 Fog Computing

In 2012, Computer Information System Company (Cisco) identified fog computing concept as a solution to address the issues in cloud computing. Fog computing is not a replacement of cloud computing, but an extension of cloud computing by offering additional features to traditional SGs. Additionally, this concept is considered as an essential requirement of 5G. In order to realize 5G innovation, fog computing requires to be integrated in SGs. Fog nodes serve as the intermediary between SGs and cloud servers.

5 Smart IoT edge-based architecture

The conceptual model considers the adaption of the IEEE 802.11 standard for short-range communication in HAN. Whereas for long-range communication from SMs to UCC, 5G is ideal. In the extension of our architecture, integration of CRN within the communication layers is deployed to enhance the spectrum and energy-efficiency by dynamically utilizing unused spectrum bands. In the presence of CRN, HAN gateway enables a bi-directional flow of communication between the smart devices deployed within the customer's premises. Furthermore, the gateway provides an application of cognition capability to enable SGs to adapt to changes brought by emerging and future radio technologies in the field [36]. For management purposes, the collected data is further transmitted to UCC to initiate necessary commands such as dynamic incentive programs. Concurrently, IoT smart devices within HAN allow consumers to manage their power consumption. As a result, CR NAN gateway reduces data traffic on the network by detecting the unused frequencies on the network. Also, NAN gateways allocate IP addresses and channels to all smart devices deployed in HAN, and thus reduce data traffic on the network. Traditional SGs design comprises cloud servers for data storage, processing and analysis. In order to address issues related to traditional cloud servers, an integration of fog computing is proposed. To manage and analyze data volume generated, a fog computing architecture illustrated in [15] is proposed in this paper. The proposed architecture comprises group of fog gateways that transmit raw data to the servers for further preprocessing and analytic purposes. However, since fog servers are located close to HAN, data can be analyzed in fog servers without the intervention of third party. Furthermore, fog computing aspires to merge the smart devices into clusters/classes based on a certain criterion to reduce the data traffic. These clusters are distinguished by two criterion data ratio and packet size. In order to reduce traffic on the network, fog gateways receive merged data from their associated clusters. As a result, the data merged in small sizes is further transmitted to cloud servers depending on their priority classes.

6 Conclusion

This review paper presents an overview of state-of-the-art communication architectures in SGs context. Furthermore, existing and advanced communication technologies have been presented which pose the strong potential to fulfill the QoS requirements of SGs. Considering the distinct and stringent QoS requirements, an architecture based on the combination of fog and cloud computing is proposed. The proposed architecture is also an ideal solution to experience the benefits which emerge with 5G.

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