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Review Article

An Overview of Recent Wireless Technologies for IoT-Enabled Smart Grids

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Smart Grid is a way of providing bidirectional energy flow with the integration of latest communication technologies and advanced control methods to overcome the issues associated with the current power grid such as unidirectional power flow, resource wastage, reliability, security, enhanced quality, and increasing demand of energy. Integrating Internet of Things (IoTs) makes Smart Grid hyperaware and agile to enhance the efficiency, reliability, and sustainability of electricity distribution. IoT-enabled Smart Grids use IoT devices and sensors to collect real-time data, allowing for automated monitoring, predictive maintenance, and better demand management. This study comprehensively reviews various wireless technologies for IoT-enabled Smart Grids that could be integrated into home area networks (HANs), neighborhood area networks (NANs), and wide-area networks (WANs). This work provides a comparison of wireless technologies for HANs, NANs, and WANs in terms of data rates, range, adaptability, internet protocol support, and various other parameters. IoT technologies, including ZigBee, Z-wave, Bluetooth, Wi-Fi, NFC, 6LoWPAN, wireless HART, and Thread, are suggested for operations in HANs according to the customer requirements with their operating characteristics. Similarly, for NANs and WANs, long-term evolution (LTE), WiMax, and LPWAN are explored in terms of requirements of utilities. The study further analyzes the applications of IoT-enabled Smart Grids and elaborates on the associated challenges and issues.

Keywords: HANs; IoT; NANs; Smart Grid; WANs; wireless technologies

1. Introduction

The current power grid system generally consists of one-way bulk power flow with centralized power generation, transmission, and distribution systems. This existing conventional power system lacks any consumer utility involvement and being quite an aged system, and it also endures the loss of energy and power quality management issues. In addition, the increase in fuel cost due to nonusage of renewable energy resources (RERs) and global warming–related environmental concerns enhance the severity of issues of the current grid. These concerns along with an increased demand for energy by consumers call for revolutionizing the traditional power grid [1]. The Smart Grid can overcome a consumer's concerns of reliable and cost-effective energy supply, the power quality, and global environmental effects with the system being secure and maintaining the consumers' privacy. The Smart Grid system is designed to help improve the efficiency of an electric supply system with the involvement of control, information, and communication technologies (ICT). The Smart Gird is supposed to not only overcome the abovementioned issues in the currently deployed system but also to provide an interactive medium among stakeholders such as consumers and electricity suppliers [2]. The basic components of a Smart Grid and its various applications have been shown in Figure 1. Smart Grid utilizes an advanced metering infrastructure (AMI) which has the concept to provide a two-way energy flow system, i.e., from utility to consumer and vice versa, enabling the consumer to have information regarding various related parameters and energy suppliers to monitor them in real time. The applications of Smart Grids mentioned in Figure 1 also elaborate the dependency of these applications on communication infrastructure which may include wide-area networks (WANs), neighborhood area networks (NANs) and home area networks (HANs). The objective of this study is to explore various wireless technologies emerging for the Internet of Things (IoT) to integrate with the Smart Grid applications. The IoT refers to billions of smart devices which are connected and communicate with each other by using advanced communication and automation technologies providing the fundamental features of functionality, scalability, availability, and maintainability. The IoT concept can be depicted with the trisectional relation of three aspects, i.e., human, internet, and things [3]. The basic architecture of IoT generally consists of four stages, viz., devices, gateway/data acquisition systems, edge IT (preprocessing), and data center/cloud analytics [4]. Based on these four stages, immense design choices are available to the architects. The architect of IoT must consider the choice of protocol that best suits the design, interference, resiliency, cost, procedures, and protocols in case of a change of cloud vendor, analysis of collected data, resources, and security. Figure 2 displays a basic five-layered architecture of IoT [5]. Based on this architecture, a cloud-centric (cloud between devices and application) or a fog computing architecture (in case of immediate response) is further designed. In fog architecture monitoring, preprocessing, storage, and security layers are added between the perception and transport layers for smart IoT gateway [6]. IoT finds its applications in the areas of manufacturing, energy, transportation, government, education, retail, healthcare, financial services, and smart cities. An electricity grid with IoT is called an intelligent grid which communicates, controls, detects faults, provides RER integration and security to the system by its self-healing quality and intelligent infrastructure. Furthermore, it enables power systems to implement real-time information and data flow, control, tracking, monitoring, and management of smart devices. However, interoperability, connectivity, sensing, identification, location, information handling, and bidirectional communication of smart devices in an IoT-enabled Smart Grid are done by means of protocol standards. A complete architecture of IoT-enabled Smart Grid is shown in Figure 2 along with the characteristics of IoT. The IoT technology-based smart power system covers HAN, NAN, and WAN. Different wired and wireless internet protocol standards by international standards governing bodies have been introduced to make power system's connectivity more reliable, secure, and effective depending on their pros and cons. However, it has been found that the advantages of using wireless technologies over wired are more pre-eminent due to their fast deployment, cost-effectiveness of the equipment, and enhanced flexibility [7].

1.1. Related Work. Lately, there has been enormous research in finding the best suited technologies for Smart Grids. A research based on suitable communication methods for Smart Grids and the challenges that are faced during the deployment are given in [8]. The ICT is also an integral part of integrating RERs with Smart Grids [9]. Smart Grids are a way of providing cleaner and sustainable energy to the economy while keeping the rate of greenhouse gases to the lowest. The authors in [10] provide a complete review of energy storage of Smart Grid by making it application-specific and making the system respond effectively to energy signals. The study also provides a comparison of legacy grids and Smart Grids along with advantages and disadvantages of various communication networks proposed for Smart Grids. A scheduling mechanism for resource allocation in Smart Grids improving the quality of service (QoS) has been presented in [11]. This research aims to provide an evaluation of various IoT-aided wireless techniques for Smart Grids. In [12], a wireless communication technique for HANs has been presented to model it using multiple access techniques including frequency division multiple access (FDMA) and time division multiple access (TDMA). The model is supported by an analysis of delay in packets through the experimental setup and proves how delay is reduced using TDMA between electronic devices and clients. In [13], applications of cloud computing, viz., flexible recovery, expenditure, mobility, control, and enhanced security, have been explained integrated with Smart Grids. The research focuses on the use of LTE to achieve a high packet delivery rate and less latency. Another application based on clustering has been provided in [14], in which a forecasting method for individual consumption of load by the end user has been proposed by experimenting on two smart meters and proved that the clustering-based smart meter provides a better forecasting of load and proves it to be scalable and accurate, reducing the error rate. In [15], a QoS-based LTE scheduling algorithm has been provided for Smart Grids. The authors consider LTE proposed by third-generation partnership project (3GPP) as a great solution of communication for Smart Grids and provide a scheduling algorithm to meet the QoS requirements of end users. A complete architecture of Smart Grids in comparison with the traditional grids is given in [16], which divides the architecture into two segments. The first segment comprises HANs using extremely high-frequency range (VHF), and the second comprises of direct connection between the generation and utility control distribution using super high frequency (SHF). The authors also give the conclusion that the use of wireless technologies can make the system achieve better signal-to-noise ratio and decrease the overall bit error rate and packet loss, increasing the overall system efficiency. In [17], a Unified Home Gateway (UHG) with an Extensible Messaging and Presence Protocol (XMPP)–based IoT system has been designed and implemented for large-scale data handling and energy management as a test bed for the smart home network. It is a combined user interface in a HAN which at one end connects smart devices using different protocol standards and, on the other side, is also connected to the main server. The UHG can control, communicate,

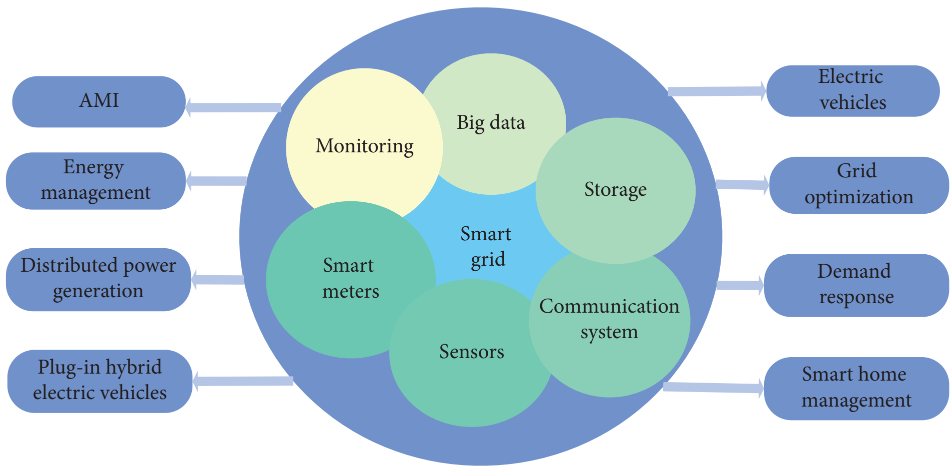

Figure 1: Components and applications of Smart Grids.

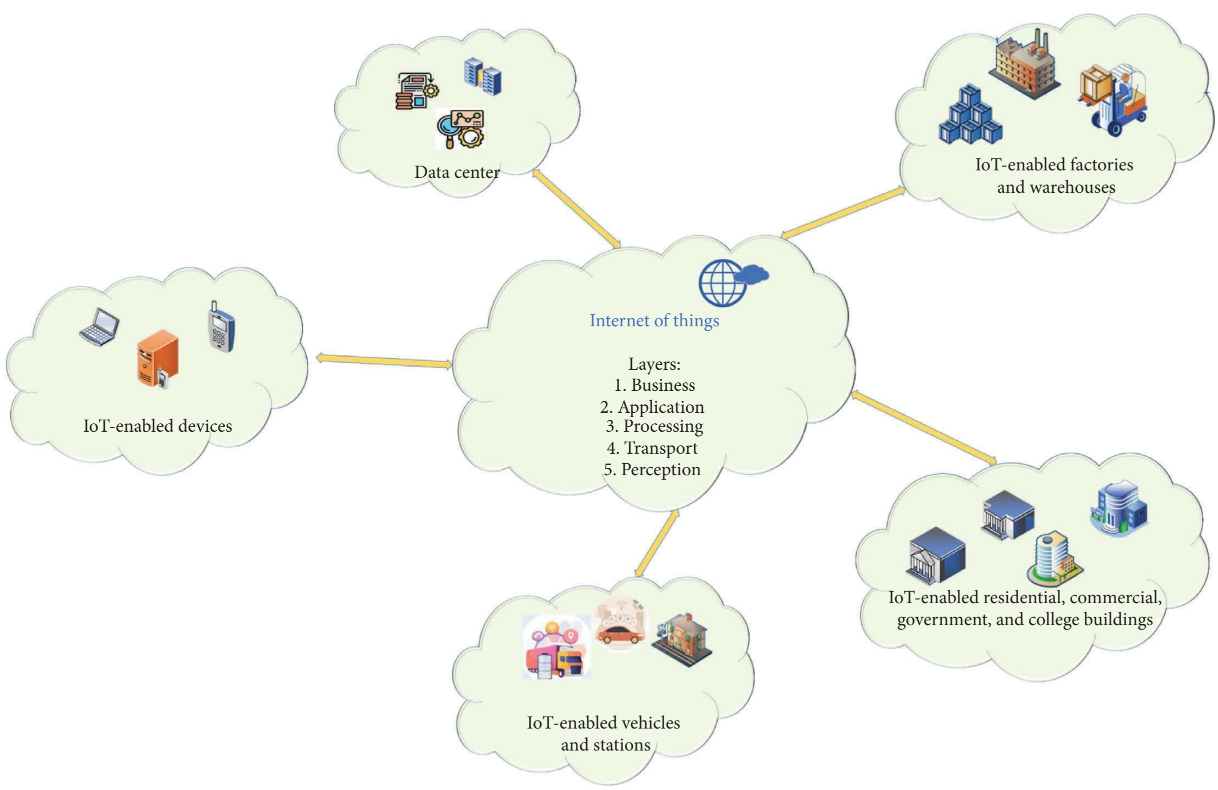

Figure 2: IoT-enabled Smart Grid infrastructure.

monitor, sense, detect faults, and provide secured data flow automatically and bidirectionally in a real-time manner.

A great amount of research has been done in finding the best suited IoT technology for Smart Grids. An application of ZigBee has been given in [18] in Smart Grids for the detection of faults. The ZigBee being able to support a data rate of 250 kbps has been theoretically proven to be suitable for the said application requirement for 48 kbps and 76 kbps depending on the sampling rate being used. The ZigBee has been proven to be better suited for low-reliability requirements in Smart Grid networks [19]. A comparison of ZigBee with Bluetooth and Wi-Fi for Smart Grid has been given in [20], and the issues of low data rates, heating up, latency, and interference with other wireless technologies for ZigBee have been highlighted. Wi-Fi has been identified as a satisfactory solution where high data rates are required, especially in applications of video monitoring. Research has also been done on the coexistence of ZigBee with other technologies. In [21], a detailed infrastructure has been explained which uses LTE in collaboration with ZigBee. The system uses the unlicensed frequency band of 2.4 GHz with file transfer protocol (FTP) for testing of the network. The research meets the requirements of an AMI using the said system and concludes that the capacity of ZigBee is affected more by the simultaneous operation of LTE. An under-research area for ZigBee is its limitation for interoperability with IP. When upgrading Smart Grids with IoT, possibilities and solutions for the coexistence of these two technologies are under research for Smart Grid researchers. Bluetooth technology has also been researched for electric vehicles (EVs) linking to the Smart Grids. Similar work has been presented in [22] where smartphone of the driver is connected through Bluetooth to the charging infrastructure of Smart Grid and vehicle. Smart Grids with only AMI are referred to as Smart Grids 1.0. The idea of integrating the Smart Grid with IoT upgrades the infrastructure to Smart Grids 2.0 also referred as web-based Smart Grid [23]. The IoT also characterizes devices to be interconnected, IPv6-enabled, and could be heterogeneous, and their number and state can be changed dynamically and provide safety for all devices and network infrastructure. Broadband WiMAX IEEE 802.16 standard can be deployed to be operational in Smart Grids in urban, suburban, and rural areas in various applications, viz., smart metering, device protection, monitoring, traffic control, and remote grid configuration [24]. The authors in [25] introduce a hybrid architecture named as 3G LoRa–SigFox for advanced monitoring systems for gas and electricity infrastructures and distribution projects that aim to validate different communication technologies for optimizing the distribution grid of Spain. The study's findings illustrate that the LoRa network has shorter transmission time and power consumption while SigFox network has better communication performance. The main purpose of this research is to review and compare various IoT technologies along with the challenges associated with them.

Smart Grids require technologies which are ubiquitous and reliable and provide real-time communication; hence, the wireless technologies, best suited, according to their area of application have been investigated thoroughly in this study. The HANs, for instance, require a low data rate, low power, and small range wireless application while for outdoor NANs, a long-range, high power, and high data rate and secure application is required. Hence, the study has been divided into two categories, i.e., wireless IoT technologies for HANs and NANs depending on their classifying parameters.

Nike et al. have presented a review of IoT and Smart Grid in [26]. The authors have adopted an approach of systematic literature review covering the reported items from 2016–21 and consisting a total of 35 citations. The survey deals with the basic question that what are the benefits of using IoT with Smart Grid infrastructure along with applications and challenges? The work is published as short conference proceedings and has covered limited items. A survey on Smart Grid communications has been conducted in [27]. The review work covers the reported literature till 2021 and deals with both wired and wireless communications for Smart Grid applications. The discussion on wireless communications consists of WiMax, ZigBee, Z-wave, and satellite communications. The applications discussed include AMI, grid monitoring, distributed energy resource (DER), distributed storage, vehicle-to-grid, demand response (DR), and HAN. A recent work is reported in 2023 by Khadija et al. in [28] in which they presented an overview and multi-criteria analysis of communication technologies for Smart Grid applications. The reported work covers a limited range of both wired and wireless technologies. A multicriteria analysis technique consisting of three weighing methods, namely, uniform weighing, CRITIC, and entropy method, has been introduced and implemented for the application of AMI as a case study. The authors have concluded that the WiMax is the most preferred technology for AMI, while the PLC is the least.

1.2. Contributions. The abovementioned review studies lack the comprehensiveness and detailed discussion on the specific aspect of the IoT-enabled Smart Grids. Therefore, in light of the above discussion, the contributions of this work are given as follows:

1. A comprehensive review for IoT-enabled Smart Grids with the specific aspect of the wireless technologies along with details of architectures, applications, and challenges is presented in this work.
2. This work covers the latest literature in a comprehensive manner and detailed discussion on IoT architectures, comparative analysis of wireless communications, applications, and challenges.

1.3. Paper's Layout. The rest of the study is organized as follows. Section 2 discusses various wireless IoT technologies for HANs along with their advantages and disadvantages. Section 3 comparatively discusses the wireless IoT technologies for NANs and WANs. Smart Grid applications and challenges are given in Sections 4 and 5, respectively. The study is concluded in Section 6.

2. Integration of IoT With HANs

The HANs are defined as networks used to provide communication among home appliances, smart digital devices, and external services such as utilities, usually employed over a range that covers residential environments or homes. Various modules are connected across HANs which include smart devices, smart meters, and energy management systems that share data and controls to operate efficiently. For HANs, usually, short-range communication technologies are required. This section elaborates and explores various short-range technologies that can be used for HANs. The ZigBee (802.15.4b), Bluetooth (802.15.1a), Wi-Fi (802.11), IPv6 over low-power wireless personal area network (6LoWPAN, IETF), Z-wave, Thread, wireless highway addressable remote transducer (HART) protocol, and near-field communication (NFC) for HANs have been considered in this study.

2.1. Bluetooth. Bluetooth [29] operates at 2.4 GHz of unlicensed industrial, scientific, and medical (ISM) bands. The technology of Bluetooth was evolved in 1994 with a typical range of 10 m, a speed of 1 Mbps, and a bandwidth range of

1 MHz. Later, various enhancements and improvements have been made in the technology. Currently, the operational version of Bluetooth is 5.0, launched in 2016, supports 2 Mbps of speed, which has been devised taking into the concern of IoT-supported devices.

Bluetooth follows two kinds of topologies, viz., piconet and scatter net [30]. Both topologies are based on master-slave mechanism of data transfer. In piconets, the master is connected to seven slave devices. Master can ask for and deliver data to the slaves, while slaves are only to receive and send data to the master. The slaves can also communicate with each other in the piconet. Similarly, in scatter net topology, two or more piconets are involved [31]. Bluetooth also comprises three classes depending on their power and ranges. Class 1 supports 100 mW of power with a range of 100 m, Class 2 supports 2.5 mW with 10-m range, and Class 3 supports a 1 mW with 10-cm range. Bluetooth has higher latency than Wi-Fi, so it is suitable for applications like audio streaming and peripheral connectivity.

Bluetooth technology offers a short range with a limited number of nodes. However, the latest version of Bluetooth offers a longer range and speed, but that can only be of any value if all the devices in the network are version 5.0 supported. Bluetooth is a low-power technology operating at 2.4-GHz range which makes it susceptible to interference and loss of signals. Bluetooth 5.0 also introduces low-energy technology (BLE) that can be explored to be operable with IPv4 or IPv6 [32, 33] and supports star topology with unlimited nodes.

2.2. ZigBee. The ZigBee is a product of ZigBee alliance [18] which uses IEEE standard 802.15.4 and is an economical, short-range, low-power, and reliable solution for WPAN [34]. The ZigBee, like Bluetooth, operates in a 2.4-GHz channel of ISM band and offers a speed of 250 kbps in the said unlicensed band. ZigBee also operates in 915 MHz and 858 MHz bands offering a speed of 40 kbps and 20 kbps, respectively, covering 10–100 m. ZigBee has been widely used for industrial applications due to reduced operational cost and reliability. More applications of ZigBee can be found in home automation, surveillance, smart metering, fault detection, Smart Grid monitoring, smart plugs, sensors, etc. Owing to the low cost, power and mesh topology support ZigBee has been extensively experimented and used in HANs, since it can provide meter-to-meter communication and home monitoring.

The ZigBee supports three types of topologies, viz., star, mesh, and tree topology [35]. In all these topologies, there is a coordinator that acts as a master and all other devices connected in the network are referred to as end devices. Star topology is mostly used in industries where a central controller is required with easy deployment. Mesh topology is very efficient due to the redundancy, decentralization, self-routing capabilities, scalability, and stability that it provides. Different nodes are connected using routers which use beacons at different time slots to communicate with devices initiating the session or they can actively communicate with the nodes utilizing more power.

The ZigBee is a product of ZigBee alliance with the latest version of ZigBee 3.0 that supports smart energy profile to make it interoperable with IoT technologies. It supports IP functionality which makes it interoperable with IPv6, Ethernet, and Wi-Fi for efficient working in smart energy meters, sensors, appliances, etc. In the network architecture of ZigBee, the IEEE 802.15.4 is defined by the physical and MAC layer that also uses beacons for communication while the network and application layers are defined by the ZigBee alliance. The ZigBee has been extensively used in intrusion detection and prevention in HANs [36] since it communicates using CSMA. ZigBee is also a solution for security due to the application of access control lists (ACLs) and encrypts data using AES-128. The typical range of latency for ZigBee is 30–100 milliseconds which is acceptable for noncritical IoT applications.

2.3. Wireless Local Area Network (WLAN). The WLAN (Wi-Fi, IEEE 802.11) uses frequency hopping or direct-sequence spread spectrum technology (FHSS or DSSS) which makes the users occupy the same frequency band without interference. It works in the 2.4-GHz band and operates at a speed of 1 to 2 Mbps [37]. However, various standards have been added further to the IEEE 802.11 family. The most commonly used standards of 802.11 are 802.11a, 802.11b, 802.11g, 802.11n, and 802.11ac. 802.11a, approved in 1999, operates at the 5-Ghz band and can provide a speed of 54 Mbps with orthogonal frequency division modulation (OFDM) with 12 nonoverlapping channels [38]. Channel association also varies around the globe. 802.11b operates in 2.4-GHz band with a maximum speed of 11 Mbps and uses only DSSS. 802.11g also uses a 2.4-GHz band with a maximum of 54 Mbps of speed employing DSSS or OFDM. Many upgrades were made with the introduction of the 802.11n standard. It operates in ISM band 2.4 GHz and 5 GHz, providing high data rates of up to 600 Mbps, and introduces MIMO technology while providing power-saving options. 802.11ac standard operates below 6 GHz band and provides a data rate of 1 Gbps and is known as Gigabit Wi-Fi. Certain other standards have been introduced as "h," "i," and "j" providing power saving, encryption, authentication, and interworking. Similarly, 802.11ah was specifically introduced for IoT operability providing long-range communication.

The Wi-Fi has been widely used all over the world in HANs. Almost all laptops, mobile, computers, etc., come with a built-in feature of Wi-Fi. At the network layer of Wi-Fi infrastructure, internet protocol is the most predominant standard. Appliances and domestic devices nowadays use IP to provide smart solutions to end users allowing connectivity to the internet. IP support, high data rates, nonoverlapping channels, scalability, fast deployment, and availability are major advantages of using Wi-Fi. Wi-Fi with Smart Grids offers various advantages owing to the attributes of worldwide deployment, received signal strength, robust performance, support for all IP versions, network management, low cost, data rates, and scalability [39]. Application of IEC 61850 has also been found in distribution systems. IEC 61850 is considered as a core enabling technology in Smart Grids using intelligent controllers and sensors. The security benefits, cost, and operational benefits have been given in detail in [40]. Reliability and redundancy can be achieved via Wi-Fi-enabled load tap changer sensors and protection based on intelligent sensing and control can also be provided with Wi-Fi. The Wi-Fi, when used in a mesh topology, can provide great scalability and coverage by deployment in smart meters with low transmission power and with the use of Wi-Fi-enabled repeaters and can also help in power monitoring systems [41]. These benefits are achievable in distribution systems as well. Wi-Fi, 802.11ac (Wi-Fi 5), offers lower latency compared to previous versions, while 802.11ax (Wi-Fi 6) further reduces latency and improves overall performance in high-density environments. The typical range of latency for Wi-Fi is 5–50 milliseconds. However, there are still some challenges associated with WLANs in general, which include electromagnetic interference due to the high voltage or interference between various wireless equipment and availability of wireless equipment at the industrial level. However, major contributions have been made to provide more reliable equipment that can avoid interference by the application of smart antennas and waveguides.

2.4. Z-Wave. The Z-wave was developed by Zensys, and later, it was acquired by Sigma Designs in 2008. The Z-wave technology also follows the master-slave concept. The master or controller controls all the end devices known as nodes and is responsible for maintaining the network topology. Nodes can communicate to each other directly or, if out of range, can communicate by making a connection to another node by acting as routers. Z-wave follows the unlicensed ISM band with FSK modulation and operates at 908.42 MHz band in the United States and Canada and follows 868 MHz in Europe covering a range of 30 m [42, 43]. A data rate of 9600 bps and 40 kbps is achievable in Z-wave which has been increased to up to 200 kbps with the introduction of Z-wave 400 series [44].

Z-wave is considered reliable and affordable and has an easy setup. It also has the advantage of supporting internet protocol, making it suitable for IoT sensors and monitoring with the least interference, unlike Wi-Fi and ZigBee, which operate in the same ISM band. However, research has been in progress regarding the security implications of Z-wave [45].

2.5. 6LoWPAN. The 6LoWPAN, an open IoT networking protocol, allows the IPv6 packets to flow on low-power wireless networks particularly IEEE 802.15.4 (2.4 GHz or 868/915 MHz) [46]. Low-power, large mesh networks, interconnection to heterogeneous objects, and being IP-driven make it more suitable for IoT applications [47]. The collaboration of IP with 6LoWPAN is explained by IETF RFC 9499.

The 6LoWPAN network comprises low-power wireless networks that are known as stub IPv6 networks. The nodes in 6LoWPAN may act as routers or hosts and an edge router sharing the same network prefix being able to share IPv6 packets. In [48], a 6LoWPAN network has been used for deployment in Smart Grids and a sharing mechanism is introduced to reduce the latency to a minimum. Another model of this technology has been proposed in [49] for smart homes to build a seamless handover and connectivity in wireless devices and sensors. Researchers are working on interoperability and combined the working of 6LoWPAN with other infrastructure technologies, e.g., ZigBee.

The 6LoWPAN offers many advantages over other wireless technologies including scalability owing to mesh networking, redundancy in case of broken links, and high interoperability due to IP support [50]. However, it still faces security challenges that are an active area of research, especially the IPSec integration along with IP in 6LoWPAN is under research.

2.6. Thread. Another low-power, open-standard IoT technology based on 6LoWPAN, IEEE 802.15.4 and IPv6 protocols, is Thread, introduced in 2014 [51]. Thread has been designed as an alternative to native Wi-Fi technology. It can support up to 250 nodes working in the same ISM 2.4 GHz band [52]. Thread has been designed particularly for smart homes like ZigBee and can find its application in smart metering and HANs with a data rate of 250 kbps. Given a drawback of only voice incapability, the authors in [53] give a higher score to Thread in comparison with Bluetooth, ZigBee, and Z-wave owing to the improved capabilities of the number of supported nodes, bit rate, cost, interference, and backward compatibility.

2.7. Wireless HART. Wireless HART offers almost the same features as Thread operating at 2.4-GHz band. It can connect to 250 nodes and can provide a range of 10–100 m for communication. Wireless HART offers a speed up to 250 kbps and mesh networking making it easier for the users to extend the network and provide redundancy [54]. Wireless HART provides the advantages of channel hopping in case of interference and multipath fading effects [55]. Wireless HART has been recommended for a wireless body area network in [56] for a network of sensors that covers a range of 2 m around the body. In Smart Grids, it is applicable in power generation for sensors and smart meters. However, wireless HART devices are expensive due to their requirements of possessing ultra-low-power electronics, high-frequency components, and explosion protection for industrial applications [57]. However, wireless HART still must overcome the security requirement due to the unavailability of any dedicated specification for security [58].

2.8. Comparative Analysis. A thorough comparison of Bluetooth, ZigBee, Wi-Fi, Z-wave, 6LoWPAN, Thread, Wireless HART, and NFC regarding data rate, range, cost, adoption rate, latency, advantages and disadvantages, and standard is presented in Table 1. A comparative analysis of the techniques mentioned reveals that Bluetooth has the advantage of secure communication with easy setup while being short-range. The ZigBee has been adopted widely owing to the low-cost, low-power functionality and

Table 1: Comparison of HAN IoT technologies.

	Bluetooth	ZigBee	Wi-Fi	Z-wave	6LoWPAN	Thread	Wireless HART	NFC
Data rate	1 Mbps (2 Mbps with 5.0)	250 kbps	11–300 Mbps enhanced rates with standards of 802.11n, 802.11ac, and 802.11ab	40 kbps (200 kbps with 400 series)	20–250 kbps	250 kbps	250 kbps	106–424 kbps
Range	1–100 m	10–100 m	100 m	30–100 m	200 m	100 m	10–10 m	¡20 cm
Cost	Low	Low	Low	High	Low	Low	High	Medium
Adoption rate	Very high	High	Very high	Medium	Medium	Low	Low	High
Latency	20 to 100 milliseconds (ms)	30 to 100 ms	5 to 50 ms	20 to 200 ms	50 to 500 ms	1 microsecond (mc) to 100 ms	4 to 30 ms	10–100 ms
Advantages	Low power, IPv6 support with version 5.0	Low-power, low complexity, IPv6 support with SEP2, higher number of nodes	IPv6-enabled, high speed, mature standard	No interference, reliable, low latency	Low power, high range, IP, and Bluetooth support, scalable	Low power, 250+ nodes supported, IPv6-enabled, backward compatibility	Low power, 250 nodes mesh topology, backward compatibility with wired HART	Secure, convenient, low power
Disadvantages	Low data rate, interference	Low data rate, low processing capabilities	Interference	Short range, only one proprietary for making chips	Low rate, extensive training required	Relatively new technology	Low adoption rate, expensive devices, and security	Limited no. of devices, low range
Standard	IEEE 802.15.1	IEEE 802.15.4	IEEE 802.11	Proprietary	IETF, RFC 9499	IEEE 802.15.4	IEEE 802.15.4	ECMA-340 ISO/IEC 18092

accommodates more nodes but provides low data rates, which is applicable in smart meters when operated in a mesh topology. The ZigBee has the advantage of strong encryption resulting in high security suitable for remote monitoring of smart metering. The Z-wave provides low latency, no interference, and high scalability and finds its application of reliability in the transmission of short messages from the controller to the nodes. Thread is a relatively new technology and has not been used that widely yet but offers almost all other benefits associated with the rest of the mentioned wireless IoT technologies except voice-enabled interface. Similarly, wireless HART offers advantages of range, data rate, and low power. However, it has been used in industries and in-vehicle networking but has not been experimented widely in HANs and faces security challenges. The 6LoWPAN uses IP along with being robust, low power, and scalable and is most suited for smart controllers and sensors; however, it needs extensive training. The Wi-Fi has benefits of long-range, high data rates, mature, and scalable with some issues of interference. Another technology that has not been mentioned earlier is NFC operating at 13.56 MHz on ISO/IEC 180003 with a data rate of 106–424 kbps. NFC provides peer-to-peer communication with the application based on radio frequency (RF) field and is extensively used in smart wallets, action tags, and access control.

Smart Grids are characterized by the two-way flow of power and information which requires a long range in a NAN. The next section covers various technologies that can be used and are suitable for NANs.

3. Wireless IoT Technologies for NANs and WANs

Communication among various utilities of a Smart Grid requires a large network with a well-defined architecture such as NANs/WANs. The NANs are used to connect multiple HANs in a specific area just like neighborhoods or communities. NANs are intermediaries which serve between HANs and WANs to facilitate communications and data management while the WANs are networks extended over a large geographical area used to connect multiple smaller networks. In this section, the wireless IoT technologies that can be used in NANs and WANs will be discussed.

3.1. Cellular/Mobile Network Communication. Existing cellular networks including 2 G/2.5G, 3G, and LTE providing a speed up to 9.6 kbps, 150 kbps, 2 Mbps, and 20 Mbps [59] and more, respectively, can be usable in operations in Smart Grids. Since these are the existing infrastructures, the deployment of the application in Smart Grids will be an economical solution.

The currently deployed system offers high mobility, high data rates, secure communication, low maintenance cost, IoT support, reliability, and sufficient bandwidth.

A cellular radio unit comprising a SIM or GPRS module integrated into smart meters can make the communication between smart meter and energy providers easier making their applications and services more efficient. Since GPRS/GSM-based networks provide the user with authenticity and privacy, their usage in Smart Grids has already been implemented in many areas around the globe for data communication. GSM and short message services have already been deployed in EVs using the application of Smart Grids [60].

The LTE (4G) uses OFDM and MC-FDMA and is the latest development among GSM, GPRS, EDGE, UMTS, CDMS, and IS-95. LTE, operating at 824–894 MHz/1900 MHz, provides a data rate of 300 Mbps at downlink and 75.4 Mbps at the uplink with various cell sizes ranging from 10 to 100 km [61]. The latest version of LTE is LTE advanced, which offers 3.3 Gbps since 2012. LTE-A in collaboration with IoT finds its applications in medical, e-governance, driver-less cars, mobile cloud computing, large data transfer, holographic, or 3D calls [62]. It also finds its applications in emergency scenarios where vehicular-based base stations also referred as eNodeB in LTE architecture can be used to provide quick network access reducing error rate [63]. The 4G LTE provides relatively low latency for mobile broadband, making it suitable for most applications including streaming and gaming. However, it is higher than newer technologies like 5G.

The LTE offering great coverage, reliability, and high data rate can extensively be used in Smart Grids in areas of automated smart metering [64] and in the distribution system. Automated control and distribution systems using LTE offer low latency [65]. Using the already deployed network operators for LTE the overall monthly cost of usage might increase for the utility, which calls for a separate cellular network for Smart Grids. However, these cellular networks can be used in Smart Grids for operations in AMI, automated DR and outage management, communication between the remote terminal unit and SCADA, noncritical message sharing using SMS, monitoring, and DER supervision [66]. Various new cellular standards of LTE have been introduced recently, viz., LTE-M, LTE Cat-0, LTE Cat-1, M1, NB1, and NB-LTE, which have been designed according to today's IoT requirement of end users providing low power and low throughput.

To support a large number of users' devices simultaneously in a massive machine-type communication, a new application narrowband Internet of Things (NB-IoT) is introduced in 3GPP. The NB-IoT is put forward to provide low power, low cost, and wide-area cellular connectivity for IoT architecture [67]. In mobile communication, the user equipment devices request uplink resources using a random-access procedure. Likewise, in NB-IoT, user equipment devices use the NPRACH channel that contains consecutive subcarriers for transmitting the preambles. At the receiving end, the NPRACH channel processes the signal by identifying active user equipment devices and estimating individual uplinks' channel parameters [68]. The LTE-Cat M1 is LTE cellular technology also developed by 3GPP. The LTE-Cat M1 can be used in low to medium data rate applications with both half and full duplex modes and requires a bandwidth of 1.4 MHz. The LTE-Cat M1 has a latency rate of 10–15 ms that is lower than NB-IoT. Unlike NB-IoT, the LTE-Cat M1 allows the porting from one cell state to other cell state which makes it suitable for mobile applications [69].

3.2. LPWAN

3.2.1. LoRaWAN. The LoRaWAN has been widely recommended these days in applications of Smart Grids. LoRaWAN follows low-power WAN (LPWAN) network infrastructure for connecting IoT devices in smart cities, M2M, and industrial networks [70, 71]. LoRaWAN provides a bi-directional information flow with enhanced end-to-end security. Data rates provided by LoRaWAN range from 0.3 kbps to 50 kbps with a coverage of less than 20-km area [72]. LoRaWAN covers the frequency bands of ISM-868 MHz, 915 MHz, and 433 MHz. In the architecture of LoRaWAN, the end devices in star-to-star topology communicate using LoRa and the data are communicated by using LPWAN architecture. Gateways of LoRa operate as a transparent bridge that converts the RF messages into IP packets and likewise [73]. Researchers have been working on providing a better communication network in Smart Grids based on LoRaWAN as it uses low power and low cost as compared to RF mesh technologies [74]. The latency between 100 and 500 milliseconds is associated with LoRaWAN which is optimized for long-range and low-power communications. It is ideal for applications like remote sensing and asset tracking. However, it has higher latency than other wireless technologies, making it unsuitable for real-time applications.

3.2.2. SigFox. Another LPWAN-based wireless technology gaining popularity is SigFox. SigFox is the first IoT LPWAN technology that was introduced back in 2009 [75]. The SigFox like LoRaWAN uses free ISM bands that do not require licensing to connect the devices without the need of setup of a separate IoT infrastructure by offering a software-based communication solution where computing is managed through cloud reducing the overall cost and power usage. The SigFox provides a data rate of 10 to 1000 bps using ultra-narrow band technology with a range of 30–50 km [76] depending upon the area environment. The SigFox has already been in use for M2M applications connecting thousands of objects with its low-power, efficient, and scalable network [77]. SigFox is finding its place in environmental sensors, smart meters, and security devices. Various private companies are dedicating themselves for using SigFox to connect millions of smart meters to IoT.

3.2.3. Neul. Like working with SigFox is Neul which was founded in 2010 and is not a very popular technology but is under research. Neul offers a data rate of a few bps to 100 kbps at a range of 10 km [78]. Neul uses a white space spectrum of TV and with its operating characteristics can compete with GPRS, 3G, and LTE-WAN.

In some areas, Neul has been tested on providing smart metering, M2M communication, managing urban infrastructure, etc. [79].

3.2.4. WiMax. The WiMax is a broadband wireless access technology belonging to the family of IEEE 802.16. It provides reliability and QoS in similar patterns to cellular networks with a range of 50 km [80]. The WiMax supports point-to-point, point-to-multipoint, and mesh topologies which are suitable for communication in a NAN. The home gateway can gather data from the smart meters and then forward the data to the utility through a dedicated channel of WiMax. The WiMax offers a bandwidth of 100 Mbps on a channel of 20 MHz. The properties of high security, scalability, reliability, high data rates, and uninterrupted communication [28, 81] make it suitable to use in DER, remote meter reading, distribution automation (DA), control, and detection of unauthorized energy usage. The interoperability and QoS scheduling features of WiMax are gathering the attention of researchers for operation in substations [82]. However, the initial installation and operational cost of WiMax are high.

3.3. Comparative Analysis. A thorough comparison of NAN IoT techniques such as LTE (Cellular), LoRaWAN, SigFox, Neul, and WiMAX, regarding data rate, range, cost, adoption rate, latency, advantages and disadvantages, and standard, is presented in Table 2. The already deployed cellular networks provide a big-time advantage of range, bandwidth, security, and privacy QoS for real-time communication, low latency, and overall low deployment cost and upgrading the system might require only software updates rather than changing the hardware say, antennas, etc., while for LPWAN, the whole infrastructure will need to be deployed resulting in an increased cost. Depending on already deployed cellular networks will also cause an increase in operational cost of monthly repetitive charges. A dedicated network in that case for the utility will result in lowering these expenses, depending on the policies and finances. LPWANs and cellular networks both provide high data rate resulting in a support of bulk end users. Sigfox and LoRaWAN are referred to as WiMAX of IoT. While LTE is releasing its new standards (CAT-M1 and NB-IoT), LoRa alliance and SigFox are already deploying their networks with LPWAN technology. LoRaWAN and SigFox can be used as a backup for emergency conditions in remote locations.

Communication between distribution/transmission substations and control units requires low latency, high throughput, security, high coverage, and data rates, which can be provided by WiMax and LTE for appropriate working [81]. For smart metering, LoRaWAN has been extensively recommended [83]. However, LoRaWAN still needs to be researched and tested for DA and ADA. In that case, the already deployed infrastructure of LTE can be used. A combined architecture of cellular networks with LPWAN for NANs and WANs of Smart Grids can result in a highly efficient Smart Grid communication system. The latency in wireless communications is defined as the delay between the transmission and reception of data. It is a critical performance metric which is influenced by various other factors such as network architecture, environmental situation, signal processing, and network setup times. To understand the variation of latency, a few examples are expressed as follows: Sigfox, an LPWAN technology, typically exhibits

Table 2: Comparison of NAN IoT technologies.

	LTE (Cellular)	LoRaWAN	SigFox	Neul	WiMAX
Data rate	300 Mbps (3.3) Gbps for LTE advanced	0.3 kbps to 50 kbps	10 to 1000 bps	100 kbps	100 Mbps
Range	10 km	15 km	30–50 km	10 km	100 km
Cost	High	Low	Low	Low	High
Adoption rate	Very high	High	Medium	Very low	Medium
Latency	30 to 50 ms	100 to 500 ms	2 to 6 seconds	0.5 to 5 seconds	20 to 50 ms
Advantages	High data rate, smooth handover, high QoS	Low power, simple architecture, adaptive data rate	No separate infrastructure required, low power, high range due to UNB technology, scalable network	Fully bidirectional, low power, low cost, highly scalable, weightless	High data rates, low latency, scalable reliable, high QoS, advanced security protocol, high throughput
Disadvantages	Network congestion, high deployment cost	Limited network size, not suitable, for low-latency applications	Limited downlink capabilities, signal interference	Relative less adopted and practiced technology	High operational and installation cost, power-consuming bandwidth decreases with clients
Standard	3GPP	Proprietary	Proprietary	Proprietary	IEEE 802.16

latencies ranging from 1 to 30 s, reflecting its design for low-power, infrequent transmissions. On the other hand, Neul, operating under the Weightless-N protocol, offers lower latencies of approximately 0.5–5 s, suitable for more time-sensitive IoT applications. The WiMAX offers latencies between 20 and 50 milliseconds, demonstrating its capability for higher-speed, lower latency applications such as real-time streaming and VoIP. The disparity in latencies among these technologies highlights the trade-offs between power consumption, range, and data rate inherent in different wireless communication protocols [84–87].

4. IoT-Based Smart Grid Applications

This section covers the applications of IoT-enabled Smart Grids. With the evolution of IoT, as stated by smart insiders, about 25 billion devices be connected to the internet by 2020 [88]. With IPv6, 3.4 × 1024 addresses can easily accommodate such an enormous number of devices. It can be observed that these devices connected to the internet and with Smart Grids will result in an efficient and reliable transfer of energy from the utility to the end users. A detailed overview of the applications of Smart Grids is given in the following section.

4.1. AMI. An AMI provides a bidirectional information flow between the consumers and utility using diverse technologies of HANs, smart meters, smart sensors, software-based user interfaces, and smart control systems [89]. A simple flow of information in AMI is given in Figure 3. It provides real-time restoration operation and information regarding power outages, voltage, load, and power quality without involving field trips by the supervisors [90]. This will also save the consumption of power by the end user receiving the information about the billing employing Home Energy Management System (HEMS) from the utilities at peak hours with the advantage of environmental factors like controlled carbon dioxide emission and grid reliability. AMI also provides demand management and conservation voltage reduction (CVR) solutions based on the information communicated bidirectionally. These functionalities require a suitable and secure network between the providers and end users. A NAN typically requires a data rate of 100–500 kbps with few square miles and a latency of 1–15 s. To avoid the issues of electricity theft, AMI can provide electricity theft detection and reduction in the distribution system; however, even AMI requires strong end-to-end encryption to provide high confidentiality and security to the data.

4.2. HEMS. Smart home management started in the early 1990 s. With the evolution of technology, the consumers at home demand management of their energy consumption. A HEMS provides the consumers and the providers' dynamic control over the consumption of energy to save cost, peak load management, and centralized remote control; automate the system; and improve reliability and efficiency by providing real-time feedback [91]. Figure 4 explains the working of a HEMS. Selective load shedding can be used in areas like Pakistan, where energy crisis handling is required based on efficient load selection criteria [92]. The implementation of HEMS in such conditions aids the mechanism of direct load control. HEMS comprises sensors (temperature, light, infrared, ultrasonic, etc.), smart devices, and a control server to control these devices and sensors. HEMS senses the data, with the help of sensors, coming from various devices and controls the level of energy consumption based on the processed data automatically [93].

A HEMS requires a HAN for the communication of all smart devices present in a particular area. In HEMS, a typical practice is to configure the smart meter with basic functionality and management for the users to avoid major and frequent software updates. However, based on the requirement in a specific field, a smart meter be configured to provide enhanced control and management of energy to the consumers. HEMS not only provides the consumer with effective monitoring of the energy consumption of various smart devices (TV, refrigerators, air conditioners, heaters, smart plugs, ovens, etc.) in real time to save the cost and consumption but also benefits the energy providers to monitor and control peak load times. DR, a desirable feature of Smart Grids, can be infused with HEMS [94] using the IoT technologies for HANs mentioned above. Efficient demand-side management implemented for HEMS can improve the overall Smart Grid efficiency [95].

4.3. Demand Automation and Renewable Energy Communities. Keeping the energy supply uninterrupted is not the only requirement of a home energy user nowadays. Consumers and utilities demand a reliable and efficient power distribution system. Providing real-time monitoring and remote control of the distribution system employed with smart sensors connected to the control system via a reliable communication channel will not only result in a reliable but intelligent distribution system that can control various electricity parameters either through a centralized or distributed system. An IoT-enabled Smart Grid with DERs will help increase the efficiency of the system by saving the cost of deployment of heavy cabling to the generation units and will be reliable owing to the advantage of backup. Figure 5 illustrates the communication and power flow in a DA system with DERs. However, Smart Grid provides a two-way data and power flow in a system, which when connected to the DERs, might cause problems for the distribution system operators since the traditional distribution systems were not designed to provide a two-way power flow [96]. This will require the integration of a distributed energy management system (DERMS) to monitor the direction of power flow, which will be changing constantly. This system will further require the deployment of various sensors at various places to provide uninterrupted and without any delay information flow from the sensors to the controllers using a communication network of minimal latency and higher bandwidth to provide updated information about the state of switches, breakers, faults, etc. A system as mentioned can be integrated into the already deployed infrastructure of power control systems like SCADA.

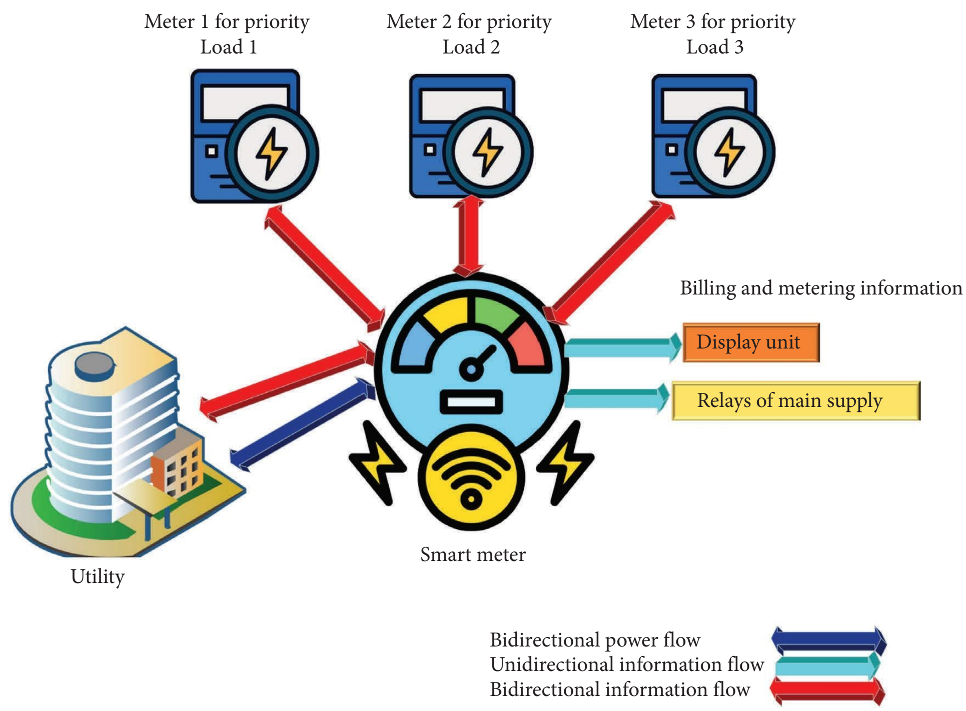

Figure 3: AMI data flow.

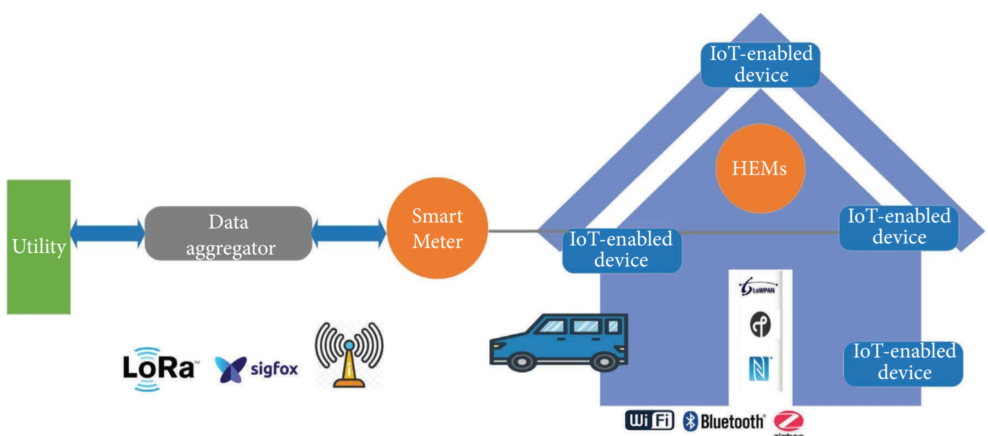

Figure 4: Home energy management system in Smart Grids.

Another emerging technology to empower the DERs implementation in Smart Grids is microgrids. Microgrids are independent, small entities with their own control system capable of operating in island mode providing resilience in case of failure [97]. These microgrids can operate in isolated mode or in collaboration with other microgrids to provide a better management system [98]. DERs also provide an advantage of load management based on classification. Load profile analysis can provide real-time price monitoring of microgrids [99].

Microgrids promote the usage of RERs integration with varying resources and storage systems in Smart Grids [100]. A prosumer produces and consumes power [101]. The prosumers can utilize the energy from the main grid when their own production is not sufficient and enough power is not generated from the local microgrid by paying for the used resources [102]. The monitoring of the power generation and consumption in renewable energy or prosumer communities is possible using IoT devices and wireless communication networks. The collection of data from prosumer communities leads to the development of a data-driven approach for optimal energy management and predictive maintenance [103]. The smooth integration of RERs to enhance the stability of the power system is possible using IoT technologies [104]. The IoT-enabled Smart Grids can play a significant role in demand–supply balance with the help of real-time data and analytics. Energy storage systems can be optimized to counter the fluctuations of RERs. Peer-to-peer energy trading for energy sharing at optimal cast is another application of the IoT-enabled platforms. The potential role and significance of

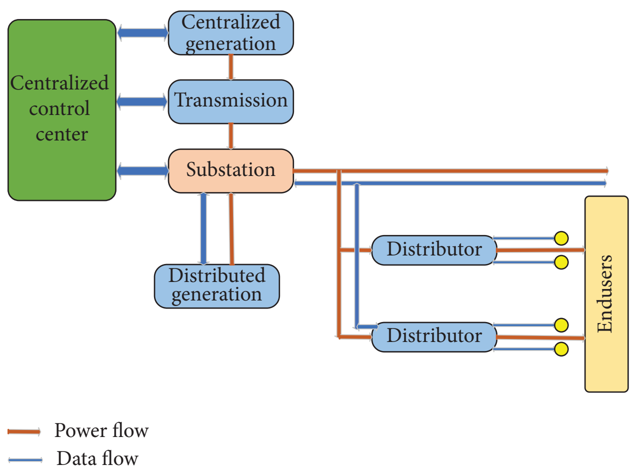

Figure 5: Distributed automation power and data flow.

blockchain-based IoT systems have been mentioned by the authors in [105] for smooth energy sharing and to address security concerns.

4.4. EVs. In recent years, EVs have become quite popular with advancements in fuel cell technologies. EVs, when incorporated with Smart Grids, on the one hand, provide the advantages of reducing greenhouse gas emissions, the energy flow to the utility, and energy independence with economic benefits, while on the other hand, must deal with the quality of electric voltage, current, and frequency. It might not be possible for all the utilities to maintain the peak capacity for charging the EVs at a large scale, and similarly, consumers might start discharging the batteries at a large scale increasing the instabilities in frequencies. All of this necessitates a management system for EVs that can provide real-time stats of the charging and discharging of vehicles, load distribution, data regarding electric flow, service management, and location-related information for the EVs. This is where IoT helps in all this communication with the help of VANETS for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) technologies. In [106], a monitoring system for EV batteries using the IoT application has been explored. A charging management system can be deployed with EVs aided with the IoT utilizing real-time monitoring via sensors and radio devices [107].

The already deployed cellular communication network (3 G/4 G/GPRS), wireless sensor networks, and other IoT technologies can aid in building a high-quality energy network for EVs since the bandwidth estimated, required for load balancing and invoice charging purposes, lies around 9.6 kbps–56 kbps. Wi-Fi can be used by EVs to communicate with the battery swap station smart terminals, flowing through the IoT gateways. For charging purposes at the home network, any of IoT technologies reviewed above including ZigBee or Z-wave can be used to connect the EV to HAN and to the utility, as shown in Figure 6. Different IoT technologies can be integrated at charging stations, battery swap stations, charging piles, between charging swap stations, and operation service centers [108].

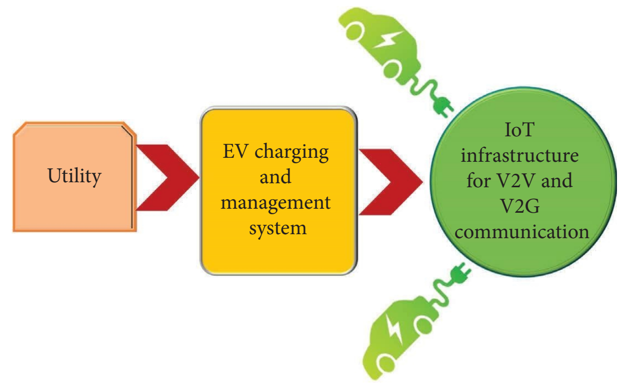

Figure 6: EV management system.

4.5. Distributed Energy Storage (DES). Smart Grids provide the advantage of maintaining a balance between the generation and consumption of electrical energy in real time. DES promotes the usage of RERs by incorporating solar PV and wind resources to improve the quality of power and balance of energy demand [109]. Research is being done on the DES system that efficiently integrates renewable energy in the main grid from commercial and residential buildings [110], since the building sector consumes nearly 30–40% of the total energy consumed globally [111]. Figure 7 gives an example of how various energy resources are integrated into the Smart Grid providing DES. DES implementation in residential and commercial buildings can offer the users and suppliers many advantages. The building sector is the major contributor to electricity consumption over the globe and can make the best use of available energy resources and employ the energy storage systems responding to alerts from Smart Grid and making use of the price difference [112]. Abrupt changes in load demand require high-power density ability. A hybrid energy storage system can provide high energy and power density storage battery bank with dynamic energy management [113].

4.6. Wide-Area Situational Awareness (WASA). WASA is considered as one of the key applications of Smart Grids as per the report of the Federal Energy Regulatory Commission (FERC), completed by the National Institute of Standards and Technology (NIST) [114]. WASA is defined by a wide-area monitoring of a power system. It monitors the state of power and information system components, behaviors and performance to predict, prevent, or respond to any disturbance before it occurs in real time with intelligent electronic devices (IEDs) and phasor measurement units (PMUs) that measure instantaneous voltage at buses, line current, and frequency for monitoring and controlling the transmission system [115]. The data generated through IEDs and PMUs are shared in the form of snapshots over a WAN link to central equipment [116]. WASA provides wide-area monitoring, protection, and control which require high security. The traffic requirement for communication from PMU is 20–200 ms. In [117], cognitive radio-based sensor networks are recommended to be used for communication between PMU and phasor data unit (PDU).

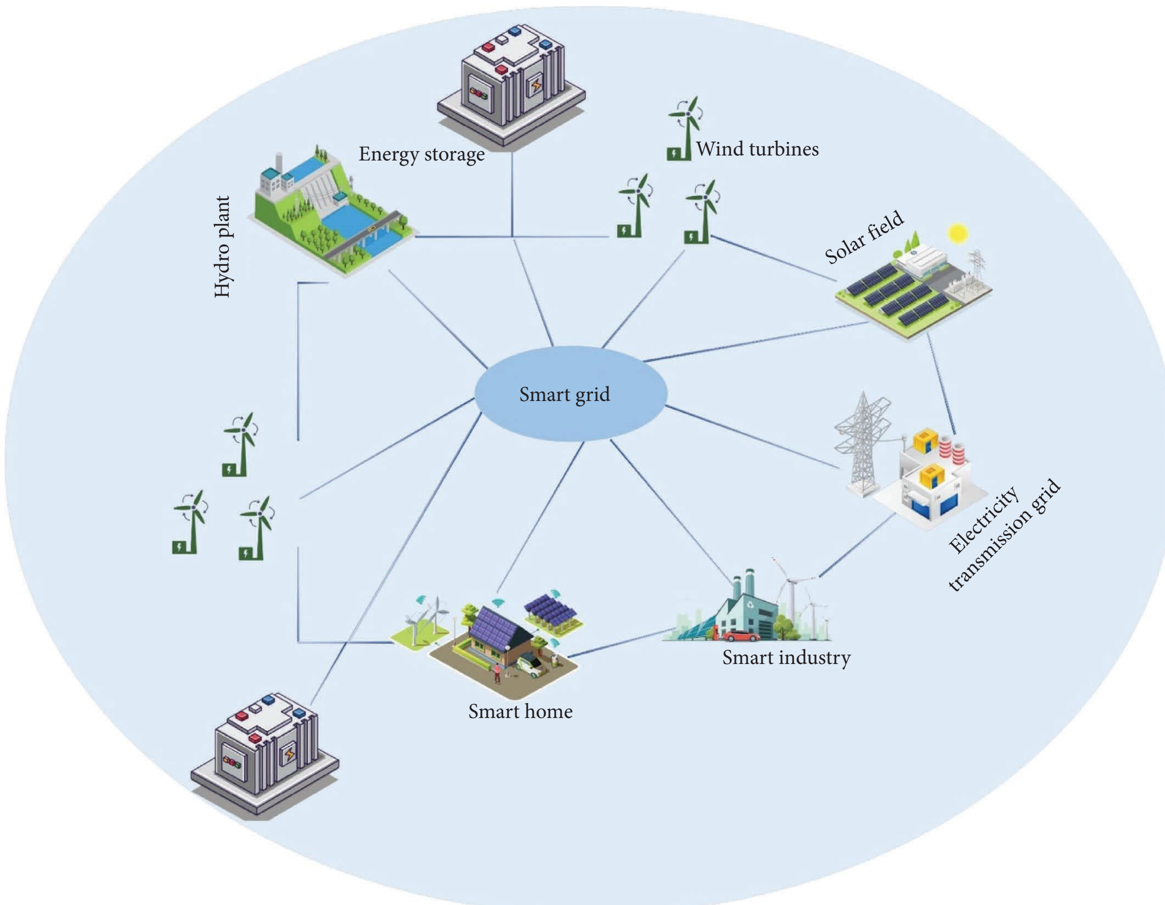

Figure 7: Distributed energy resources example of Smart Grids.

4.7. Outage Management System (OMS). With traditional power grid systems, detecting an outage and its location rapidly has been one of the key issues, especially in bad weather. With the increased number of power line systems in public and private sectors, frequent power outages reduce the efficiency of a power system. With the alliance of IoT and Smart Grids, the reliability of the system increases by continuous monitoring of the transmission lines. This enables the utility to locate, isolate, and resolve the faults in transmission lines efficiently. A hierarchical model [118] in this aspect helps if any control unit of an area is unable to restore the fault, the problem is shifted to the upper units for handling. Another hierarchical approach for outage management in Smart Grids is given in [119] which employs multi-microgrids. An OMS requires a high level of security and the required bandwidth for the transmission of data associated with it is 56 kbps with an affordable latency of up to 2 s. Hence, the IoT technology chosen for the communication of data to the grid must fulfill the purpose [120]. A flow of information in an OMS is given in Figure 8.

4.8. Smart Cities. IoT-enabled Smart Grids result in connected structures that are aimed to reduce the challenges of energy shortage, congestion, and environmental pollution by providing continuous monitoring, data aggregation, decision making, and security planning [121]. Smart cities enhance the quality and performance of urban services and sustainable development. Citizens interact with the system with smart devices, smart homes, smart industries, smart transportation, and smart healthcare devices. The author in [122] proposed a dynamic volatile ICT infrastructure for smart cities and communities to dynamically provide services requested by end users, companies, and public organizations. The data are collected with the help of various sensors from multiple components and are processed and analyzed. After that, decisions and actions are performed based on that processed data [123], e.g., a patient suffering from heart disease receives alerts and warnings when the blood pressure rises above a level and receives remote health monitoring [124] whenever required, or a person driving through a route receives alerts about congestion along the way providing traffic optimization and parking management [125]. However, for smart cities, real-time communication of devices, remote control, and cyber security are among the major issues for the choice of communication technology at multiple stages. The ranges and data rates of the technologies chosen will be different at each level.

The other applications associated with Smart Grids include customer information system (CIS)/billing, work management, consumer web portal, or in-home display (IHD) and using more renewable and sustainable sources of

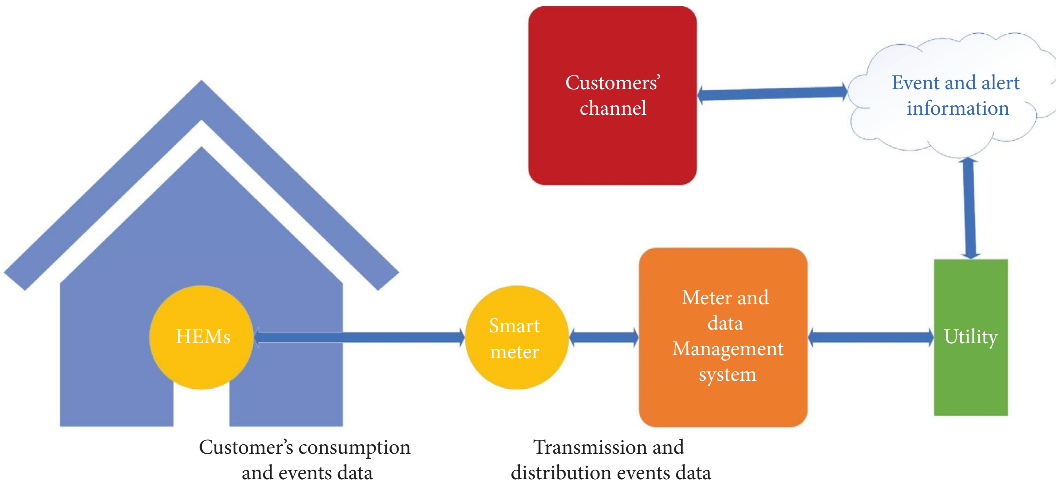

Figure 8: Information flow of events in OMS.

energy. Consumers with IHD installed to focus on the installation of more energy-efficient equipment and contribute to load reduction. Smart Grids provide many advantages to utility, and consumers yet face many challenges. Some of these challenges are summarized in the upcoming section.

5. Challenges and Issues

Upgrading the traditional power grids into Smart Grids faces major challenges [126], viz., technology development, quality management, renewable energy integration, cyber security, and customer support [127]. Among these challenges, the challenges associated with the integration of IoT in the Smart Grid infrastructure are discussed in this section.

5.1. Environmental Effects. IoT-enabled Smart Grids and devices operate under diverse environmental conditions. In adverse conditions, the IoT devices operating outdoors for monitoring must be able to withstand such conditions for reliability and availability of data. Devices must be able to provide a redundant path for communication of data in case of a route failure. The device and system must support a self-healing process to keep the system from falling toward failure. In some cases where stability toward the device is provided, other factors, e.g., memory and processing power, are compromised which can somehow be overcome using cloud-based data storage [128].

5.2. Network Infrastructure and Data Fusion. For an IoT-enabled Smart Grid, the co-action of devices and Smart Grids for the transmission of data and energy is one the major challenges. In IoT-enabled Smart Grids, the communication networks are of two types, i.e., wide-area and local area networks. As explained in Sections 2 and 3, various network communication technologies are operating at different levels of HANs, NANs, and WANs. Thus, a Smart Grid that is governed by IoT must have the capability to support various applications of IoT operating at varying protocols, which are being gained from different resources and various network providers and are integrated through the same gateway to the servers. Another issue associated with the network layer is the fusion of data that is being obtained from varying resources. Since the data must pass through the same gateway, which requires a lot of bandwidth and power at the same time, hence a smart aggregation [129] mechanism at this point will result in increasing the efficiency of the Smart Grid keeping and fusing the data that is important while filtering the unnecessary information.

5.3. Performance Parameters. Another important issue associated with IoT-enabled Smart Grid is maintaining the performance parameters of networks, especially packet loss and delay. These two parameters highly affect the efficiency of a network when the information from any of the nodes is important for decision making in the control domain. When many IoT devices, including cameras, sensors, and meters, are generating plenty of information at the same time, it might cause congestion of the network which can result in packet loss or delay in delivery of a packet that was needed on high priority. Hence, the entire infrastructure must be designed in such a way as to avoid bottlenecks and packet drops at gateways. High bandwidth and QoS [130] are to be considered in such cases to avoid delays, specifically in delay-sensitive applications. These data received through multiple sensors can be complex, and a complex event processing [131] mechanism is a necessity for handling such data. Besides the data associated with Smart Grids applications are huge, hence the storage, handling, and processing of such big data are also one of the issues being faced by the utility. A lot of work is being done in this area to provide solutions for handling big data from Smart Grids [132, 133]. A co-operative computation scheme is introduced for data flow in an IoT environment. According to this fruitful approach, a collector device divides the data processing task to helper devices as a subtask and calculates combined processing time. Computational control protocol (CCP) is used for cooperative computation to measure energy, power, and operational time of heterogeneous smart devices with low cost, short delay, and maximum reliability. The CCP significantly improves not only data processing time but also efficiency in terms of resource utilization, i.e., higher than 99% [134].

5.4. Standardization. Standardization is an important task in any infrastructure to provide reliability, interoperability, stability, and security. For Smart Grids, various standards have been approved by the standard governing bodies, including, IEEE, IEC, ISA, and NIST [135]. Similarly, the IoT operation standards have been built at different layers of the IoT infrastructure by IEEE, IEC ETSI, OMG, and IETF. However, there still is a need for building a standard for IoT-enabled Smart Grids. IoT-enabled Smart Grids also lack advanced test beds and simulation tools for the realization of applications of Smart Grids. A few protocols still have been gaining quite popularity in IoT-enabled Smart Grids, viz., LWM2M, TC57, WG13, and OneM2M based on simplicity and application requirement.

5.5. Security and Privacy. One of the major issues in the deployment of IoT infrastructure with Smart Grids is data security. Maintaining the most crucial factors of the CIA, i.e., confidentiality, integrity, and authentication, is a highly demanding and challenging job. In Smart Grids, various parts including the power plant, the control section, distribution, and transmission are interlaced, which demands a highly secure network. Any successful cyber-attack may result in exposing the entire infrastructure. Any entity that is connected to the internet today is vulnerable to cyber-attacks, in these scenarios, an attacker can easily manipulate the actual data and cause any action relating to generation or billing to be performed affecting the integrity factor along with the damage to the equipment [136]. Researchers have been in constant efforts to devise more secure protocols for IoT-enabled Smart Grids to keep the privacy and security of all nodes attached to the system. A policy-based security algorithm that evaluates the data as well as the source of the data and provides trustworthy sensing has been given in [137]. Another issue linked to the security provision is that the wireless sensors or smart objects operating within the network are usually not able to keep a high memory or run complex algorithms regarding encryption, which must be considered while designing the system. A security algorithm for certificate invocation has been proposed in [138] based on fog computing.

5.6. Compatibility. IoT at the physical layer has its devices that might be using the latest versions of technologies that might not be backward compatible or a device that might be supporting a technology that is not compatible with other IoT technologies. This needs the network for Smart Grids to be designed in such a way that the technologies employed must be compatible with each other in transmission, distribution, and generations and could communicate without causing the networks in Smart Grids to choke. Besides, building a trust relationship between different IoT-enabled devices operated by separate vendors is another challenging issue in IoT-enabled Smart Grids [139]. Another issue associated with the compatibility in Smart Grids is related to the compatibility of electromagnetic compatibility of Smart Grids with the underlying communication infrastructure. The Smart Grids elements with high voltage might interfere with any of the wireless technology for communication disturbing the system [125].

5.7. Energy Consumption of IoT Devices. Another issue associated with the IoT-enabled devices with the Smart Grids is the efficient energy supply to the devices. These devices include various sensors, surveillance cameras, and monitoring devices at transmission and generation nodes, which need energy storage sources. The use of renewable energy management policies for IoT devices can provide an economical solution to the problem [140]. The authors, in [141], perform a comparative analysis regarding the power consumption of state-of-the-art IoT wireless technologies for smart meters. The study findings indicate that the BLE is the most energy-efficient IoT wireless technology among BLE, LoRaWAN, Wi-Fi, NB-IoT, and SigFox. Furthermore, three energy harvesting techniques, photovoltaic (PV), RF, and magnetic induction (MIEH), are also studied for smart meters. Findings demonstrate that the MIEH is the most appropriate energy harvesting technique for smart meters because of its low cost and it also reduces the device complexity.

6. Conclusions

The efficient performance of Smart Grids relies strongly on the advancement and rapid growth of communication technologies and underlying network parameters. The study reviewed various IoT technologies for HANs and NANs according to the customer and utility requirements that can improve the functionality, energy, and cost-effectiveness of Smart Grids. The ZigBee and Z-wave (with 400 series) offer almost the same data rates, range, and low power. However, ZigBee gives an advantage of a higher number of supported nodes, but IPv6 compatibility is only with SEP2. Similarly, Bluetooth 5.0 is IPv6 supported; however, the older versions lack the compatibility to operate with version 5.0. The Bluetooth is secure in comparison with other technologies. The Wi-Fi in comparison with these technologies offers high data rates and long range but suffers from interference issues. The 6LoWPAN has now been widely adopted for HANs and smart metering services due to its interoperability with Bluetooth and IP, low power, and scalability. Thread is a relatively modern IoT technology with a major advantage like 6LoWPAN of no single point of failure due to its mesh topology but is relatively new and has not been very popular in smart home applications. Wireless HART finds its applications more in in-vehicle networks but has not extensively been used in HANs. NFC has been majorly suggested for smart wallets and access control due to its high security but is incredibly low range and supports only a limited number of nodes. The LTE employment in Smart Grids saves the capital investment of network deployment with high data rates, long-range, QoS but will require an operational cost for monthly repeated billing. In the case of delay-sensitive applications, network congestion sometimes can result in the degradation of overall performance for cellular networks. Similarly, the deployment of WiMax requires high installation and operational costs. In comparison with LTE and WiMax for NANs, LPWAN technologies have been reviewed. The LoRaWAN offers low power and adaptive data rates; however, it suffers from network congestion in case of delay-sensitive applications and offers short range. The SigFox, in comparison with all the abovementioned technologies, offers the longest range of up to 50 km and low power, but it has a low data rate and limited downlink capabilities. The Neul is a modern technology that has not been used extensively in Smart Grids yet but offers advantages of weightless technology, low power, and high scalability. It is being successfully used in some areas for smart metering based on white spaces, yet some features of Neul are being researched extensively. Apart from the technologies, applications and challenges of IoT-enabled Smart Grids are reviewed in the study. There have been varying issues that need to be addressed, viz., lack of standardization, development of applications, architecture, and lack of test beds and simulation tools [142].

Data Availability Statement

The datasets generated and/or analyzed during the study are available from the authors on request.

Disclosure

This work has been done as part of the employment at 1. Mirpur University of Science and Technology, Mirpur Azad Kashmir, and 2. Uppsala University, Sweden.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Conceptualization: Rashiqa Abdul Salam, Naeem Iqbal Ratyal, Anzar Mahmood; formal analysis: Rashiqa Abdul Salam, Ubaid Ahmed, Muhammad Sajid, Imran Aziz, Anzar Mahmood; methodology: Rashiqa Abdul Salam, Naeem Iqbal Ratyal, Ubaid Ahmed, Anzar Mahmood; resources: Muhammad Sajid, Imran Aziz, Naeem Iqbal Ratyal, Anzar Mahmood; supervision: Naeem Iqbal Ratyal, Anzar Mahmood; writing–original draft preparation: Rashiqa Abdul Salam, Naeem Iqbal Ratyal, Anzar Mahmood, Ubaid Ahmed; writing–review and editing: Ubaid Ahmed, Imran Aziz, Anzar Mahmood, Naeem Iqbal Ratyal, Muhammad Sajid. All authors agree to be accountable for the content and conclusions of the article.

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