IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 24 November 2022, accepted 12 December 2022, date of publication 15 December 2022, date of current version 30 December 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3229328

SURVEY

Active Electric Distribution Network: Applications, Challenges, and Opportunities

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This work was supported by the 202210025YCU grant and UNITEN iRMC BOLD publication fund J510050002.

ABSTRACT Traditional electrical power grids are transitioning from centralised operation with unidirectional energy and information flows (from the generation domain to customers) to smart grids with decentralised mode of operation and bidirectional flows. This reversal of traditional power flow direction is due to the connections of active loads such as distributed energy resources (DERs) and renewable energy sources close to the distribution network. Through advanced and sophisticated information and communication technologies (ICTs), efficient DER management and various applications for reliable and secure power delivery are enabled. However, before the adoption of any ICT solution in the grid, several challenges remain, which include interoperability, security and privacy concerns, and the ever-increasing demands to support various services and applications. Although the information within the grid is becoming more visible because of bidirectional communication flow, this only applies to transmission networks and not active distribution networks, which house numerous smart grid applications. There is also little research that supports the automatic operation of active distribution networks. Hence, this article explores and reviews active distribution network communication technologies, as well as the applications and communication standards. This review paper also highlights issues and challenges with active distribution networks and opportunities and research trends in the distribution domain from an ICT perspective.

INDEX TERMS Active distribution network, communication requirement, distributed energy, information and communication technology, smart grid.

ACRONYM

The list of acronyms used throughout this paper is as follows.

AMI	Advanced metering infrastructure.
BPL	Broadband power line.
CIS	Customer information system.
DA	Distribution automation.
DCU	Data concentrator unit.
DER	Distributed energy resource.
DG	Distributed generation.
DMS	Distribution management systems.
DR	Demand response
EI	Energy Internet
EPON	Ethernet passive optical network
ES	Energy storage.
FAN	Field area network.
FiWi	Fibre-wireless.
GIS	Geographic information system.
GPRS	General Packet Radio Services.
GSM	Global System for Mobile Communication.
HAN	Home area network.
HV	High voltage.
ICT	Information and communication technology.
IEC	International Electrotechnical Commission.
IED	Intelligent electronic device.

The associate editor coordinating the review of this manuscript and approving it for publication was Salvatore Favuzza.

IoT	Internet of Things.
IP	Internet Protocol.
ITU	International Telecommunication Union.
LoRaWAN	Long-range wide-area network.
LPWAN	Low power wide-area network.
LTE	Long-term evolution.
LV	Low voltage.
MCDM	Multicriteria decision making.
MDMS	Metering data management system.
MV	Medium voltage.
NAN	Neighbourhood area network.
NB-IoT	Narrowband Internet of Things.
NBPLC	Narrowband powerline communication.
OMS	Outage management system.
P2P	Peer-to-peer.
PLC	Power line communication.
PMU	Phasor measurement unit.
PV	Photovoltaic.
RES	Renewable energy source.
RF	Radio frequency.
RTU	Remote terminal unit.
SA	Substation automation.
SCADA	Supervisory control and data acquisition.
TCP	Transmission Control Protocol.
UNB-PLC	Ultra-narrowband PLC.
V2G	Vehicle-to-grid.
WAN	Wide-area network.
WANET	Wireless ad-hoc network.
WASA	Wide-area situational awareness.
WSN	Wireless sensor network.

A. INTRODUCTION

Since the first introduction of the electricity grid in the form of isolated power generation systems in the 1880s [1], the current power grid is undergoing several drastic changes, including the mode of operation, communication flow, and the interdependence relationship with the rapidly evolving information and communication technologies (ICTs). More specifically, the current power grids are transitioning from a centralised mode of operation with one-way energy and communication flow, to smart grids with a decentralised operation and two-way energy and information exchange. These changes are partly driven by the emergence of numerous "active loads" such as the distributed energy resources (DERs) and green renewable energy sources (RESs) close to the distribution grid (which inadvertently reverses the traditional power flow direction [2]), and the various issues in the traditional power grid including reliability, scalability, and the delayed response problem from its centralised mode of operation [3]. As such, the smart grid paradigm is made possible with the integration of advanced and sophisticated ICT and control technologies. These technologies provide efficient DER management and integration while supporting various applications such as smart metering and providing reliable and secure power delivery.

Although the integration of ICT into the grid alleviates the two-way information requirements, there are still several challenges that must be considered before the adoption of any ICT solution in the grid. These issues include a large number of complex interconnected components with interoperability, security, and privacy concerns, and the increasing demands to support various services and applications. Ultimately, utilities' overall goal is to use a small number of low-cost, simple, reliable, and future-proof technologies for holistic long-term solutions [4], which complicates the adoption of any ICT solution.

Another major concern is that, although information within the grid is becoming more visible due to the availability of bidirectional communication flow, this mostly applies to transmission networks, and not distribution networks, which house a large number of smart grid applications [5]. More specifically, the vast amount of information from advanced sensors deployed in the distribution grid is usually stored in stand-alone servers and is not fully integrated into the supervisory control and data acquisition (SCADA) system and control centres [6]. Although numerous wired and wireless communication technologies are available for smart grid communications infrastructures, relatively little research is dedicated to providing an updated and comprehensive review to support the automatic operations of active power distribution communication networks [7]. Particularly, the study regarding active distribution communication network is crucial to realise the complete operation and control capabilities of decentralised and distributed energy within the distribution grid, described as follows [8]: 1) Concurrent monitoring capability of the distribution network and consumer's side, while providing trend prediction and development of coordinated optimisation control strategy; and 2) effective control of distributed generation (DG), DERs, and load through the dynamic perception and customisation of the optimal control strategy.

During the last decade, most research on communication technologies in active distribution networks has focused on application-based frameworks and viability [9], [10], [11], [12], security in advanced metering infrastructure (AMI) and smart meters [13], [14], [15], reliability and quality of service (QoS) [16], [17], [19], and network deployment and optimisation [20], [21], [22], [23], [24]. Table 1 provides a summary of these research areas. Additionally, recent reviews usually focused on a specific smart grid communication technology or application spanning over the general smart grid paradigm, except for a few studies (e.g., [7] and [25]), which focused on the active distribution network. Table 2 summarises the reviews, along with their area of focus in the smart grid.

Thus, based on the motivation to provide better visibility to the active distribution networks through the ICT perspective, the main contribution of this study can be summarised as follows.

- We discuss the communication requirements and applications of active distribution networks.

TABLE 1. Summary of research areas in active distribution network.

Research category	Ref.	Focus
Application-based	[9]	Review of coordination efforts of home energy management systems (HEMS)
	[10]	Development of energy trading framework for distribution management systems (DMS)
	[11]	Development of an incentive-based energy trading framework
	[12]	Development of a decentralised energy trading framework for electricity load management
Security	[13]	Research on the development of a secure and lightweight authentication scheme for the AMI application
	[14]	Research on the development of a secure and lightweight protocol based on physically unclonable function for communication between the neighbourhood gateways and smart meters as a protection against cyber and physical attacks
	[15]	Proposed a security system as a protection against quantum computer attacks by integrating lattice-based public-key encryption and key exchange techniques to provide mutual authentication between smart meters and the neighbourhood gateway.
Reliability and QoS	[16]	A survey on reliability issues, focusing on network architecture, reliability requirements, and challenges of both communication networks and systems.
	[17]	Proposed a scheme to improve the smart grid routing capability of wireless local area network (LAN) mesh networks (IEEE 802.11s)
	[18]	Research on providing QoS in wireless neighbourhood area network (NAN) based on IEEE 802.15.4g standard
	[19]	Research on traffic control and differentiation
Network deployment and optimisation	[20]	Proposed a systematic approach to generating scale-free topology of wireless-mesh NANs in smart grid
	[21]	Research in optimising the broadcasting schemes with low-latency constraints
	[22]	Channel allocation through clustering-based approach in cognitive radios
	[23]	Proposed a cost-effective, flexible, and sustainable wireless NAN design for deployment
	[24]	Proposed a hierarchical uplink transmission power control scheme to solve energy efficiency issue

- We review the wired and wireless communication technologies applicable in the active distribution network in terms of their roles, advantages, and disadvantages, as well as examples of their use cases.
- We discuss the issues and challenges encountered in active distribution networks for the current communication solutions in terms of the evolving communication requirements and demands, stringent reliability and security issues, interoperability problems, and more, and we provide some suggestions as countermeasures.
- We also discuss the research opportunities and trends in the active distribution network from the ICT standpoint.

This paper is organised as follows. Section 2 provides an overview of the active distribution network, the ICT roles in the active distribution network, and communication requirements and some of the applications in the network. Section 3 discusses the applicability of several communication technologies in the active distribution network, including wired and wireless communication technologies. This section also provides a brief overview of the standards and protocols directly applicable to an active distribution network. Section 4 provides a discussion of the issues, challenges, and opportunities in active distribution networks through the ICT perspective. Finally, Section 5 concludes this review paper. Fig. 1 shows the general overview of the structure of this paper.

I. ACTIVE DISTRIBUTION NETWORK

A. GENERAL OVERVIEW

A traditional power grid generally consists of a large number of synchronous alternating current (AC) grids that are loosely interconnected via a static (or passive) and centralised network [29]. It has three core functions, which are the generation, transmission, and distribution of electrical energy [33], with electricity flowing in one direction from electricity generation substations to consumers. Table 3 provides a brief comparison between the traditional grid, smart grid, and future decentralised smart grid. Since the traditional grid has been operating in a centralised mode, electricity is generated and output by geographically appropriate power plants and transmitted to load centres via high voltage (HV) cables before being distributed to end users through the distribution network, and central control strategies are used to monitor the grid at all levels. In this regard, the medium- and low-voltage distribution networks are considered as the power system's ''passive'' loads, with the following complications from the centralised mode of operation [8]:

1. The power grid's operational status is approaching the critical safety margin.
2. The lack of adaptability to changes such as the construction of new transmission lines and large-scale power plants.
3. The continued rise in global electricity usage and demand in all countries.
4. Government-backed policies that promote the development of low-power, and ecologically beneficial forms of energy generation.

The complications imposed on the existing power grid led to the increasing adoption of DER worldwide. DERs include distribution-connected generation systems, energy storage (ES) systems, and controllable loads, as well as EMSs and microgrids [34]. DERs are often positioned within the distribution network near the end user or load centre, which has an impact on power flow distribution and the power grid control and protection system [8]. As the existing distribution networks are primarily designed based on maximum or

TABLE 2. A Summary of smart grid review papers related to the ICT field.

Author and year	Description	Smart grid domain	Communication technology categorisation	Area of focus
Suhaimy *et al.* (2022) [3]	Provided a review of smart grid communications and possible solutions for reliable two-way communication. Also reviewed existing networking methods in terms of their advantages and disadvantages, and the communication network architecture in the smart grid, with a highlight on the details of each networking technology, switching methods, and data communication medium	General smart grid	Segregated the communication technologies into: 1. Networking method - Circuit-switched: time division multiplexing (TDM), wavelength-division multiplexing (WDM) - Packet-switched: Internet protocol multiprotocol label switching (IP-MPLS), multiprotocol label switching – transport profile (MPLS-TP), software-defined networking (SDN), and optical transport network (OTN) 2. Networking medium: - Wired technologies: • Copper: narrowband power line communication (NBPLC), broadband power line (BPL), and digital subscriber line (DSL) • Fibre optics: underground cables (UGC), optical ground wire (OPGW), all-dielectric self-supporting (ADSS) cable, and air-blown fibre (ABF) - Wireless technologies: • Zigbee, ultrahigh frequencies (UHF), WiFi, long-term evolution (LTE), the fifth generation (5G), terrestrial satellite (TSAT)/ very small aperture terminal (VSAT), Z-Wave, IPv6 over low-power wireless personal area networks (6LoWPAN), and LTE for machines (LTE-M)	Networking methods and communication technologies in the smart grid
Abrahamsen *et al.* (2021) [26]	Provided a survey of smart grid communication focusing on communication requirements for selected smart grid applications, physical layer technologies, network architectures, and research challenges	General smart grid	Communication technologies are categorised into: 1. Wired technologies: Power line communication (PLC), fibre optics, and ethernet 2. Wireless technologies: cellular, worldwide interoperability for microwave access (WiMAX), ZigBee, Z-Wave, satellite, and free-space optical communication	Communication requirements for selected smart grid applications, physical layer technologies, network architectures, and research challenges
De Almeida *et al.* (2020) [27]	Discussed the main communication technologies employed in the smart grid and mission-critical scenarios, with a focus on the application of the communication technologies for energy transmission and distribution	Transmission and distribution domains	Communication technologies for control networks covered are as follows: ethernet, PLC (narrowband and broadband), DSL, fibre optics, plesiochronous digital hierarchy (PDH), SDH, OTN, ethernet passive optical network (EPON), radio over fibre (RoF), gigabit passive optical network (GPON)), fibre-wireless (FiWi), MPLS, cellular (LTE and 5G), SDN, VSAT, and future internet architectures (FIAs)	Mission-critical and operation technologies in the transmission and distribution domains
Alotaibi *et al.* (2020) [28]	Discussed the recent advances in reliability and resiliency indices in smart grids, with a focus on the energy data management, cybersecurity, and pricing mechanisms in smart grids	General smart grid	N/A	Smart grid applications in terms of reliability and resiliency indices
Saleem *et al.* (2019) [29]	Provided a discussion on the applications, architectures, and current prototypes of IoT-aided SG systems. Discussed big data analytics and cloud in the IoT-aided SG systems. Also provided an overview of IoT and non-IoT communication technologies for SG systems, along with a discussion on the open issues, challenges, and future research directions of IoT-aided SG systems	General smart grid	Segregated the communication technologies into IoT-enable and non-IoT communications: 1. IoT: 5G, Z-Wave, 6LoWPAN, LoRaWAN, ZigBee, WirelessHART, Bluetooth, Bluetooth low energy (BLE), and NB-IoT 2. Non-IoT (wireless): Cellular communication, wireless mesh, WiMAX, mobile broadband wireless access, and digital microwave technology 3. Non-IoT (wired): PLC, DSL, and fibre optics	The focus is on IoT-enabled communication in the smart grid
Ghiani *et al.* (2018) [25]	Provided a discussion on the design of smart distribution networks involving the cyberphysical interactions of the system. The issues considered are monitoring, management control, communication, and security, to achieve better organisation and optimisation of smart distribution networks	Distribution domain	Communication technologies discussed (mainly covers characteristics such as data rate, frequency, range, and application network): NBPLC, BPL, fibre optics, wireless sensor networks (WSNs), WiMAX, and cellular communications (second generation (2G) to 5G)	
Kalalas *et al.* (2016) [7]	Provided a review of cellular communications in smart grid NANs. Also identified the limitations of LTE and provided a review of the most relevant proposed architectural and protocol enhancements for the communication infrastructure associated with smart grid NANs	Distribution domain	Provided a brief discussion on wired and wireless technologies: 1. Wired technologies: copper, fibre optics, ethernet, DSL, and PLC 2. Wireless technologies: Zigbee, LoWPAN, WiFi, WiMAX, satellite, and cellular communication	Focused on cellular communication technology with a brief review of other popular communication technologies in the distribution domain
Baimel *et al.* (2016) [30]	Covered several communication technologies, their implementation in smart grids, and their advantages and disadvantages. Showed a comparison of communication infrastructure between the legacy grid and the smart grid and smart grid communication standards Also presented research challenges and future trends in communication systems for smart grid applications	General smart grid	The communication technologies discussed are: Zigbee, wireless LAN, cellular communications (2G-4G), WiMAX, and PLC	
A. Bari *et al.* (2014) [31]	Discussed some features of the smart grid such as communications, demand response (DR), and security. Also discussed microgrids and issues with the integration of DER were also discussed	General smart grid	Categorised communication technologies into the following: 1. Wired technologies: copper cable, fibre optics, and PLC 2. Wireless technologies: cellular, satellite, microwave, and WiMAX 3. Short range wireless communication technologies: WiFi and Zigbee	Several smart grid applications and security issues
R. Ma *et al.* (2013) [32]	Identified three major challenges to implementing smart grid communication, which are standards interoperability, cognitive access to unlicensed radio spectra, and cybersecurity. Also identified the key communication technologies and reviewed their state-of-the-art research activities. Discussed the issues on security and WSN for their applications in the smart grid, and future trends of smart grid research	Transmission and distribution domains	Covers wireless communication only but divided the communication systems into transmission and distribution domains: 1. Transmission domain: wide-area frequency monitoring system and cognitive radio-based wireless regional area network 2. Distribution domain: wireless smart utility networks (Wi-SUN), machine-to-machine (M2M) communication, Bluetooth, WiFi, ultrawide band (UWB), Zigbee, and 6LoWPAN	WSN implementation in the smart grid

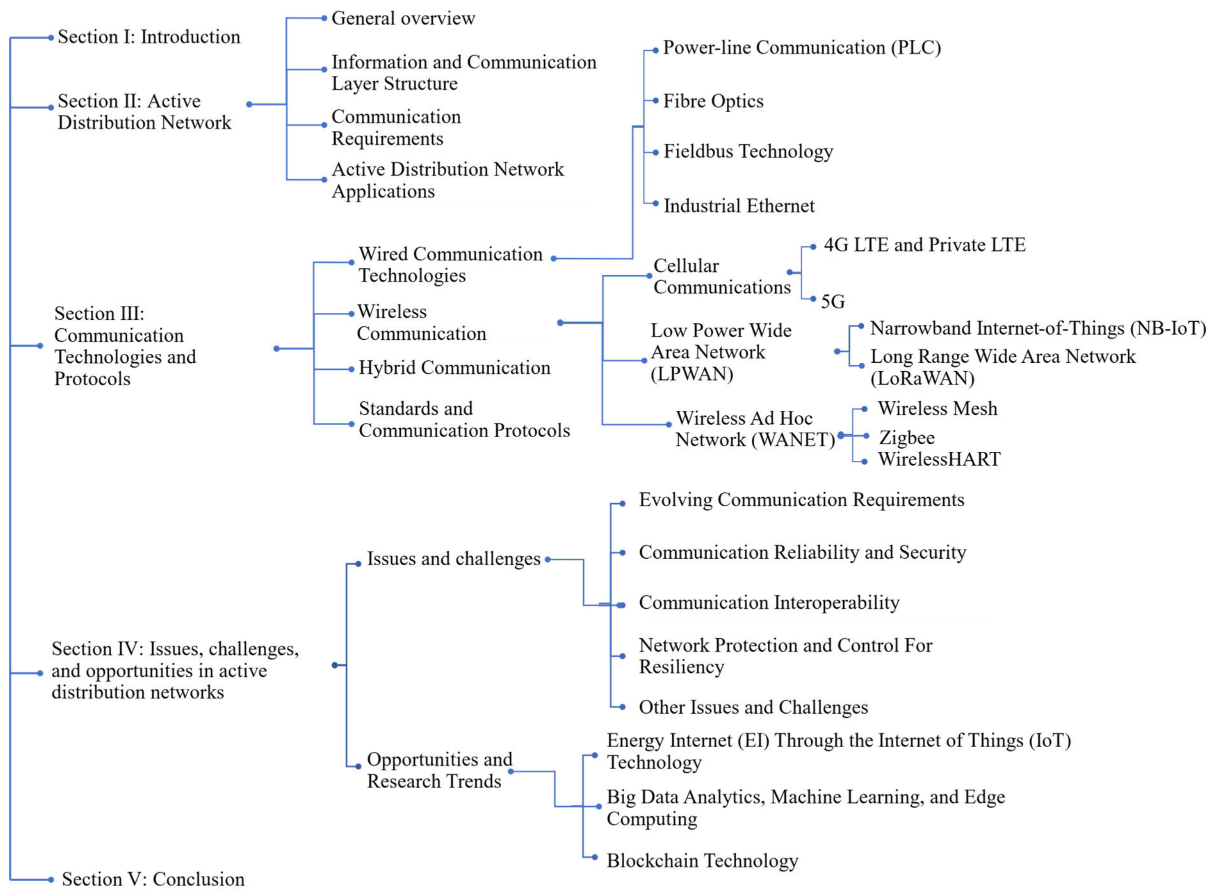

FIGURE 1. Organisation of this article.

TABLE 3. Brief comparison between traditional grid, smart grid, and future decentralised smart grid [4].

Category	Traditional grid	Smart grid	Future decentralised smart grid
RES and DER	Difficulty in integrating RES and DER	Utilised more RES and DER and integrated with a centralised grid	Moving towards building a decentralised system through the integration of various energy resources
Focus	Power delivery to consumers	The integration of advanced sensing and control technologies into traditional grid	Real-time monitoring, auto-adjust controlling and optimisation
Market	Dominated by utility providers	Relied on intermediaries and centralised markets	Support peer-to-peer (P2P) trading
Communication technology roles	Basic communication technologies	Utilised advanced communication technologies	Dominated by the EI to realise Internet-like seamless energy and information sharing
Communication Flow	One-way communication from the transmission to the customer	Characterised by the bidirectional communication capability	Support advanced plug-and-play functionalities
Computation and communication cost	Minimal computation and communication between entities	High computational and communication costs	Distributed costs among entities
Scalability	Little to no option for network expansion	Small option for network expansion	Have the option to expand fast and support a large number of connectivity
Resiliency	No resiliency against single point of failures	Minimal resiliency against single point of failures	Have resiliency against a single point of failures
Integration with other energy sources	Allow integration with electric energy networks only	Allow integration with electric energy networks only	Allow integration with other energy networks

average load conditions, the addition of these intermittent and dispersed distributed resources with large-scale accessibility to the distribution network jeopardises the networks' reliability, stability, and flexibility. Consequently, the networks are forced to be operated as active distribution systems, with real-time control and optimisation of multiple DERs [35].

An active distribution network is defined as a distribution network comprising distributed or decentralised energy sources with real-time operation and control capabilities [36]. An electrical distribution network typically comprises a large number of substations, primary feeders, transformers, distributors, and service mains, along with other devices and equipment, such as circuit breakers and load switches, for effective control and distribution of electricity to the end users. In parallel with the smart grid paradigm, the distribution networks are becoming more intelligent and complex, especially with the integration of DERs (and microgrids), and new equipment and services with communication capabilities, such as intelligent electronic devices (IEDs), smart meters, and advanced sensors. Besides the monitoring capabilities, an active distribution network could leverage a variety of advanced sensing technologies to forecast its growth trajectory and propose a coordinated optimisation control strategy to improve system reliability and operational efficiency.

An active distribution network is closely linked with the overall goal of smart grid and its architecture and can only be realised with the support of various subsystems in the smart grid [37]. Generally, the smart grid paradigm can be represented by a hierarchical multilayered, interactive platform involving [38] 1) a power system layer, which refers to the core functions of power generation, transmission and distribution, and customer systems; 2) a power control layer, which enables monitoring, control, and management capabilities; 3) a communication and information layer, which allows two-way communication and information transfers in the smart grid; 4) a security layer that ensures data confidentiality, integrity, authentication and availability; and 5) an application layer, which provides various smart grid applications to customers and utilities using the existing communication and information infrastructure. Fig. 2 shows the multilayered smart grid architecture with a few examples of applications such as wide area situational awareness (WASA), DMS, and electric vehicles (EVs). Additionally, the communication and information layer is categorised into wide-area networks (WANs) for the generation and transmission domains, NANs and field area networks (FANs) for the distribution domain, and home area networks (HANs), building area networks (BANs), and industrial area networks (IANs) for the customer domain.

Regardless of the evolution of the conventional power grid to the smart grid paradigm, the primary function of the grid remains to provide users with stable and reliable normative electrical power. This objective is realised by maintaining a delicate balance of power generation, consumption, and loss throughout the grid. However, this balance is under threat partly due to the widespread introduction of DERs and the subsequent presence of bidirectional energy flows. As the usage of DERs grows, there will be multiple energy sources feeding the distribution grid at multiple locations, complicating efforts to restore service [39]. As such, the distribution network must take an active role in ensuring uninterrupted electricity supply by monitoring the power grid in real-time and taking necessary corrective action in a timely manner. This goal can be accomplished by enhancing automation, protection, control, and bidirectional information transfer capabilities of the distribution network through the implementation of reliable and secure communication technology infrastructures.

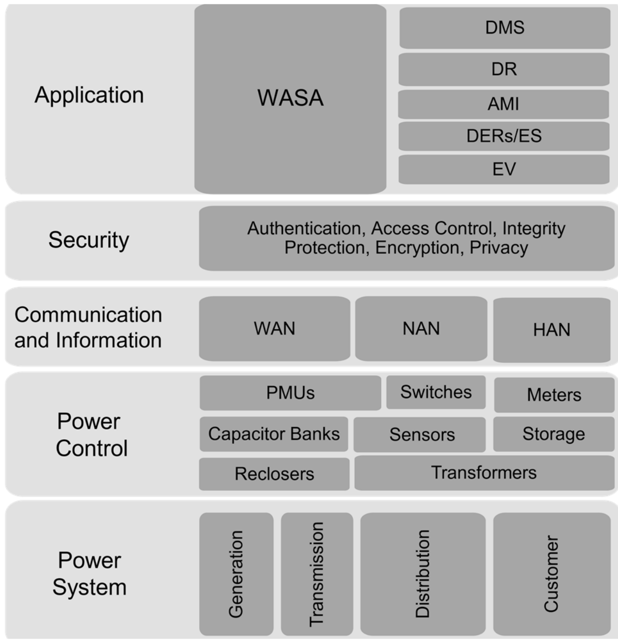

FIGURE 2. **Multilayer smart grid infrastructure.**

B. INFORMATION AND COMMUNICATION LAYER STRUCTURE

The information and communication layer of the power grid shown in Fig. 2 can be further categorised based on the data rate and coverage area, encompassing the power system layer of the transmission, generation, distribution, and customer domains. Particularly, the communication network for an active distribution grid can be represented by NANs. NANs are characterised by the communication infrastructure for medium voltage (MV) electric distribution, between the HV power transmission system and the final low voltage (LV) end-user applications [7]. It has a data rate specification of 100 kbps to 10 Mbps and a large coverage distance of up to 10 km [38]. These specifications are necessary for supporting NAN applications such as smart metering, DR programs, and distribution automation (DA), which require quite a large amount of bidirectional data transmission from multiple HANs to a data concentrator unit (DCU) often located within substations.

HANs represent the communication network installed within the consumers' domain, such as residential, commercial, and industrial buildings. HAN applications include home and building automation, the collection of sensor data from smart devices in the home network, and the delivery of utility control commands to the devices. These applications generally do not have stringent communication demands. Therefore, communication technologies that provide data rates of up to 100 kbps with short coverage distances of up to 100 m are generally sufficient [38].

At a higher level, metering data from multiple NANs are aggregated and routed to data centres owned by utility providers through WANs. WANs are commonly used as the communication backbone for smart grid communication systems, providing broadband connectivity across an extensive geographical area that includes the generation and transmission domains [7]. WAN applications include wide-area control, monitoring, and protection, which require a large transmission of data with stringent requirements from a huge number of communication terminals. Thus, communication technologies capable of significantly higher data transfer rates (10 Mbps to 1 Gbps) and long coverage distances (up to 100 km) are required [38]. Fig. 3 shows the summarised hierarchical information and communication layer connections in parallel to the power system layer with respect to the classification based on data rates and coverage. The power system layer shows the generalised electric power system structure in the United Kingdom, adapted from [40], whereas the communication and information layer shows a few examples of active distribution network applications, which are DR, AMI, and DA.

C. COMMUNICATION REQUIREMENTS OF AN ACTIVE DISTRIBUTION NETWORK

Although the active distribution network can be characterised by NANs, which have specific data rates and coverage ranges, the communication requirements in the distribution network are further determined by various factors. These factors include the network's size and complexity, as well as the level of intelligence and sophistication expected for each of the network applications [41]. Generally, there are five fundamental concepts for designing an integrated and technically sound communication system for the smart grid including the active distribution domain [42], [43], [44]:

1. **Interoperability** is defined as the ability of two or more grid architectures and their components to communicate and operate effectively and securely in a timely and actionable manner, without requiring significant user intervention. It is a critical smart grid capability because it guards against technological obsolescence, increases the value of equipment investments by increasing secondary use, and promotes combinatorial innovation among diverse stakeholders and devices.
2. **Interconnectivity** refers to the ability of the system to communicate with all other participants in the energy ecosystem. Generally, it refers to all equipment and functions that are utilised to connect a DER unit to a specific domain in the power grid, such as the distribution system.
3. **Classified access to information** refers to the ability of a communication system to provide quick, easy, and secure access to critical information at all phases of energy production.
4. **System monitoring capability** provides critical services such as data collection and analysis, real-time monitoring, and command distribution to connected devices.
5. **Decentralised decision making**, refers to the fact that the communication system must be capable of making autonomous optimal decisions. Normally, a higher level of the hierarchy will intervene only if there are conflicting objectives.

Additionally, there are multiple quantitative requirements or application-dependent performance metrics that must be observed for efficient and reliable operation of the active distribution network. These requirements may include the following:

1. **Latency:** The requirements for latency are dependent on applications. Some mission-critical applications, such as DA, requires deployment in substations within 2 ms [39], whereas applications such as DR management are more delay-tolerant and able to tolerate 500 ms to several minutes latency.
2. **Data rate:** Data rate is defined as the amount of data transmitted in a network during a specified period. The requirement for data rate is different for each application. For example, the communication data rate for AMI is typically small at approximately 300 kbps for each meter reading while WASA systems require high data rate values for effective transmission of video/audio data.
3. **Coverage area:** Referred to a geographical area in which the communication technology can monitor and control all relevant locations in real time.
4. **Security:** The power grid is a critical infrastructure that must be resistant and robust to failures and attacks. This is particularly of the utmost importance for mission critical applications such as grid control and billing where security must be provided to the communication network for the protection of critical assets and sensitive data from any vulnerabilities [45]. Effective security mechanisms should be developed as well as standardisation of distribution power grid security to avoid cyberattacks.
5. **Reliability:** System reliability has become one of the most prioritised requirements for power utilities in which the communication network is supposed to be always reliable for the continuity of communications. Link/node failures, routing inconsistencies, radio frequency (RF) interference, harsh/hostile environment, aging infrastructure, and overloading are some of the possible causes for network failures impacting the reliability of communication devices [45], [46], [47]. Some of the critical distribution network applications such as DA necessitate a high level of data communication reliability, whereas others can tolerate brief interruptions in data transfer. The communication reliability issue can be further discussed in terms of the availability of

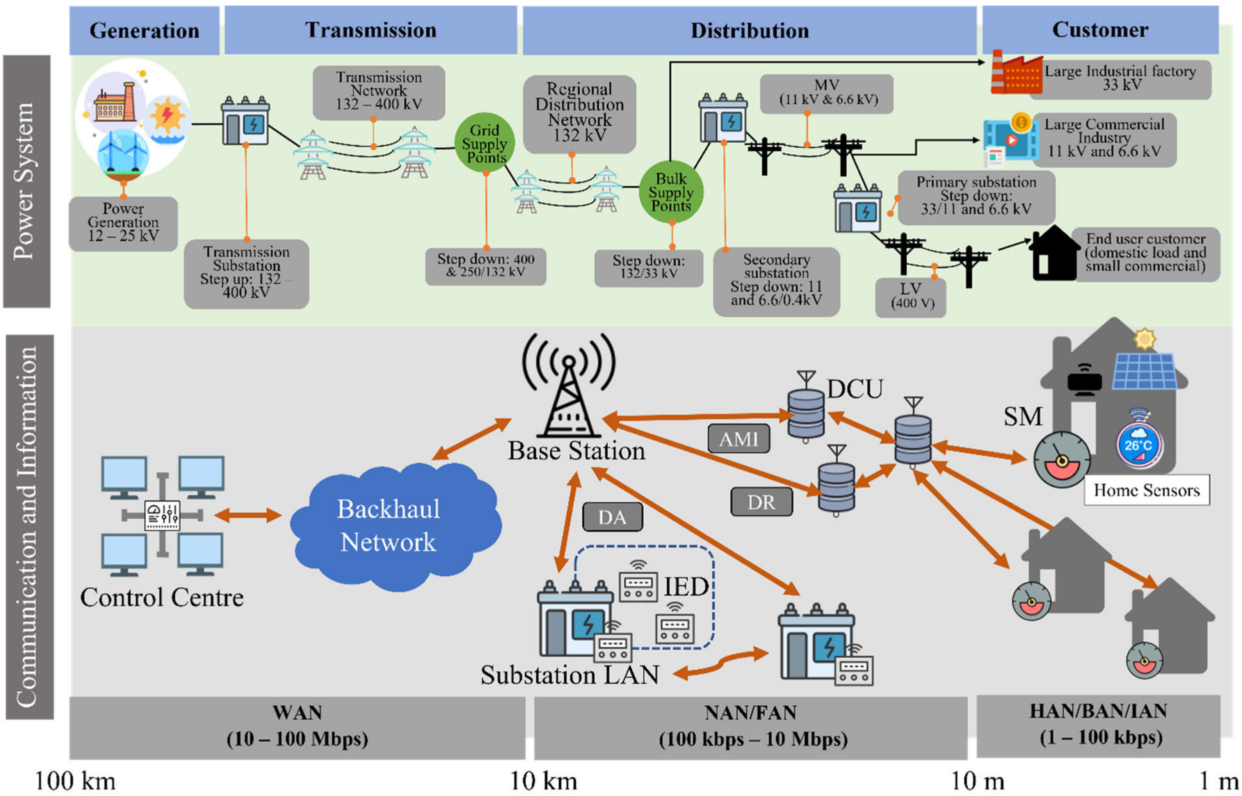

FIGURE 3. Hierarchical smart grid architecture with two interdependent smart grid domains: the power system layer and the communication and information layer with respect to the classification based on distance and data rates.

backup power, priority of service, network design and management, and availability of spectrum [39].

6. **Scalability:** An active distribution communication network can involve a huge number of IEDs including smart meters and sensor nodes. To deal with the growing number of devices and data traffic, the network should address topology changes and scalability by integrating advanced web services and reliable protocols with advanced functionalities such as self-configuration and security [45].
7. **Flexibility:** Flexibility refers to the ability of communication technologies to support multiple concurrent heterogeneous applications with varying data rates and reliability requirements [46].

Other requirements that may be considered important include the following: a) mobility is defined as the ability for the technology to be moved freely, and is important for applications such as EV charging and vehicle-to-grid (V2G); b) resiliency in terms of minimising packet loss, jitter, and latency for enhanced QoS; c) technology maturity, which might affect the availability of support for troubleshooting operational and management issues; d) regional and geographic factors that will affect the implementation of standards and may cause interoperability issues; and e) operational convenience, which considers the installation and maintenance costs and complexity of a communication system. The upper and lower bounds of these requirements are usually determined based on the targeted applications in the network, which will be discussed further in the next section.

D. ACTIVE DISTRIBUTION NETWORK APPLICATIONS

The United States Department of Energy categorised smart grid applications into six wide, and functional categories [39], all of which are directly related to active distribution networks. These applications are as follows:

1) AMI

AMI allows utilities to collect, measure, and analyse energy consumption data for grid management, outage notification, and billing purposes through two-way communication, while also providing effective customer (or "prosumer") participation in the power system as it provides historical energy consumption data, comparisons of energy use in similar households, dynamic pricing information, and suggested approaches to peak load reduction via in-home displays.

AMI deployment typically consists of three key components [48]:

1. **Smart meters**: smart devices installed at the customer's premises that collect data on electricity consumption in 5, 15, 30, or 60 min intervals.
2. **Communication networks**: either new or upgraded communication networks for the transmission of the

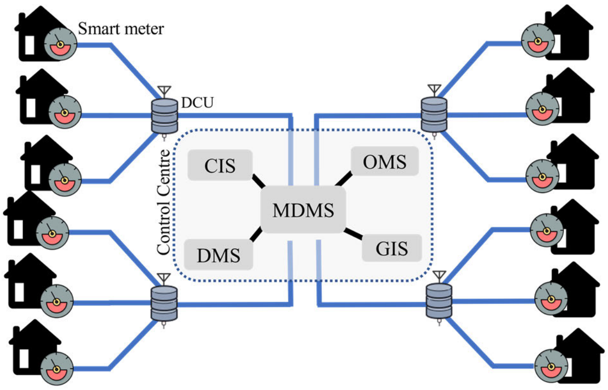

FIGURE 4. AMI communication infrastructure.

large volume of interval load data from the smart meters to the utility data centres.

3. **Metering data management system (MDMS)**: to store and process interval load data, as well as to integrate meter data with one or more key information and control systems, such as head end system, billing systems, customer information system (CIS), geographic information system (GIS), outage management system (OMS), and DMS.

One of the objectives of smart meter deployments for utilities is to integrate smart meter data with one or more information data management systems, such as [48] 1) MDMS, which processes and stores interval load data for billing systems, web portals, and other information systems; 2) billing systems, which provide automated bill generation from processing interval load data; 3) CIS, in which data from MDMS are processed and are connected to the billing systems for storing customers' information (e.g., location, contact information, and billing histories); 4) OMS, which process meter on/off status data to isolate outage locations and frequently connect with GIS for managing service restoration; and 5) DMS, which process outage and voltage level data for the implementation of Volt-VAR optimisation procedures. Fig. 4 shows the AMI communication infrastructure. The integration of AMI with multiple information and management systems enables the development of a variety of emerging applications that improve grid operation efficiency. For example, ongoing research using AMI data to include machine learning load research and forecasting based on historical energy data [49], [50], prediction study of customer's eligibility in DR program [51], the development of hourly tracking capability of renewable electricity [52], and full energy management analysis capability [53].

AMI requires near-real time data transmission with a tolerable latency of 2 – 5 s and data rates of 10 – 100 kbps per node or approximately 500 kbps for backhaul [39]. As with other existing systems, AMI must adhere to the security primitives of customer data confidentiality, integrity against illegal data alteration, availability of data on demand, and accountability (nonrepudiation) or timely response to the command and control [45], [54]. AMI implementation generally uses a 900 MHz wireless mesh network or fixed P2M RF networks, which allow easy network expansion [39]. Other common communication technologies for AMI include PLC and next generation cellular technologies.

Although AMI is often regarded as the inevitable part of the smart grid plan, this application requires significant investments in both cost and deployment time. The authors in [55] studied the feasibility of using an automatic meter reading-based power management system, which is an AMI predecessor technology. However, the results from the testbed in Korea showed marginal performance degradation than AMI but with the added advantage of low implementation cost and deployment delay.

2) DR

DR refers to the supply and demand balance of energy in the grid through the understanding of the data collected from smart meters and sensors. DR involves the participation of both electricity providers and customers; providers have the option to reconfigure the distribution network or increase electricity price during peak demand and customers can reduce electric energy consumption in response to the increased price or heavy burdens on the system. DR has the advantage of lowering peak loads on the system and is based on the concept of shared conservation of energy to ensure that there is enough energy for all users [56]. Several DR programs are currently available, such as the following: 1) direct load control (DLC), in which customers agree that their electricity consumption will be automatically reduced during peak load periods by powering down appliances in HANs; 2) automated DR, which enables on-premises equipment to respond dynamically to grid conditions for near real-time load consumption adjustments; and 3) dynamic pricing, which allows customers the option to curtail electricity use manually.

The communication requirements for the DR programs are dependent on the sophistication and control required; the usage of higher data rate systems will allow for two-way communications and the implementation of more time-sensitive applications [39]. For example, DLC typically requires low data rates for sending shut-off commands to HAN appliances such as air conditioners, whereas mission critical applications (e.g., blackout prevention through reducing energy use) may need lower latencies and higher data rates. Generally, the typical range for latency is 500 ms to several minutes, whereas the data rate requirement is approximately 14 to100 kbps per node or meter.

Fig. 5 shows a general DR system model for an urban area [18]. Each premise has a smart meter, which acts as a communication gateway between a HAN and NAN. There are also sensor nodes deployed at the substations and feeders throughout the distribution grid for monitoring and control purposes. These smart devices must send data packets containing various information, such as energy consumption and temperature, to their respective DCUs, either through wired

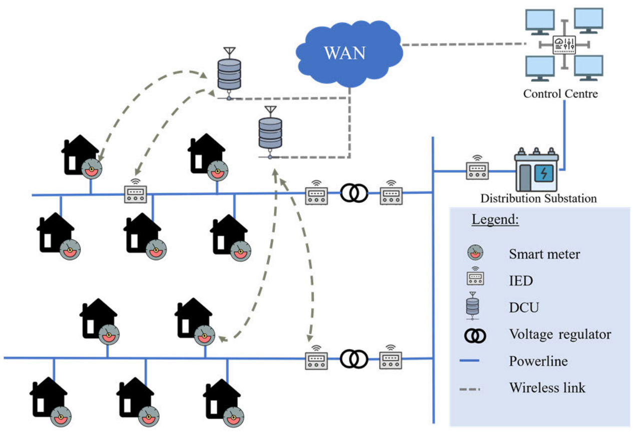

FIGURE 5. Typical DR system model in a dense urban area using wireless communication NAN to communicate with the control centre.

or wireless NAN. Although the typical wired NAN technologies, such as PLC and fibre optics, offer superior data bandwidth and network security, wireless NAN technologies (e.g., wireless mesh) allow for rapid and cost-effective deployments. Current DR research from the ICT perspective includes solving reliability issues as demonstrated by managing DR communication delays [57], [58], feasible DR system architecture, framework and strategy studies [59], [60], and cloud-based DR research [61], [62].

3) WASA

WASA refers to the deployment of a set of technologies designed to improve power system monitoring across large geographic areas. It provides grid operators with a comprehensive and dynamic picture of grid operation while providing strategic countermeasures to power system instability and blackouts [63]. WASA systems use PMUs to measure synchrophasor data (such as voltage and current phasor measurements synchronised to Coordinated Universal Time (UTC)) and prior information (such as network topology and parameters) to provide a state estimation or quantitative snapshot of the state of an entire network. Although PMUs were initially designed to improve responsiveness and diagnostic coverage in power transmission systems, they have recently gained popularity at the distribution level because of their ability to measure phase values with a few milliradian accuracies [64].

Fig. 6 shows the typical WASA system configuration, where synchrophasors data from PMUs and micro PMUs (μPMUs) in the distribution gride are sent to DCU to be distributed to end users for various power monitoring applications. In a conventional grid, measurement data are collected via the SCADA system, which generally operates in quasi-steady-state conditions and is incapable of monitoring fast transient phenomena such as load variations and topology changes [65]. As such, the SCADA measurement data during these transient phenomena may lead to inaccurate state estimates of the grid. PMUs solved this problem by providing precise measurements of amplitude, phase, and frequency of voltage or current waveforms synchronised to UTC. The use of PMUs in the distribution grid has several advantages, including the elimination of the need for new transmission lines, the facilitation of the integration of intermittent and renewable resources, and improved system modelling, planning, and contingency analysis by simulating the effect of removing equipment and post-event analysis of power disturbances [39].

WASA applications require a latency of less than 20 ms for real-time monitoring and data transfer rates between 600 and 1500 kbps for synchrophasors. Additionally, WASA systems require ultrahigh reliability, with the most critical communication paths needing a one-way availability of 99.99995%, which is equivalent to being out of service for 16 seconds a year [39]. There are numerous communication network technologies for networking synchrophasors. These include fibre optics and BPL [66].

4) DERS AND ES

DERs refer to small-scale units of local generation connected to the grid at the distribution level and may include RES and nonrenewable generation, EV batteries, inverters, and other controlled loads (such as hot water systems). Common examples of DERs include rooftop solar photovoltaic (PV) units, natural gas turbines, microturbines, wind turbines, biomass generators, fuel cells, battery storage, EV and EV chargers, and DR applications [67], [68]. These distinct elements combine to form DG, which necessitates reliable communication infrastructure for effective monitoring and resource management, and smooth integration to the grid.

Furthermore, larger DG sites, such as commercial-scale wind turbine farms (frequently located in remote locations away from utility infrastructure), will necessitate updated communications to connect to the existing utility's communication systems.

A DER generates AC or direct current (DC) and interacts with RES and the AC grid [68]. With the high penetration of DERs to the grid, bidirectional energy flow is introduced, resulting in increased variability in energy supply and a variety of system issues. Utilities need effective and reliable communication technologies for real-time data transfer, energy management, and smooth integration and power exchange. Reliable communication is especially needed for applications such as [39]: 1) real-net metering, which requires precise measurement of electricity drawn from the grid minus the energy provided by the energy sources on the premises; 2) energy management for the allocation of excess energy from instantaneous energy generation; and 3) microgrid, for DER islanding and balancing with local energy loads through P2P communications with a patch into the utility's central communication systems. Similar to AMI applications, the data rate requirements for DERs range from 9.6 to 56 kbps per unit, with as little as 20 ms of latency during faults when protection devices are switching [45]. Notably, existing AMI systems may be capable of supporting the integration of DER to the grid; however, greater capabilities, such as those

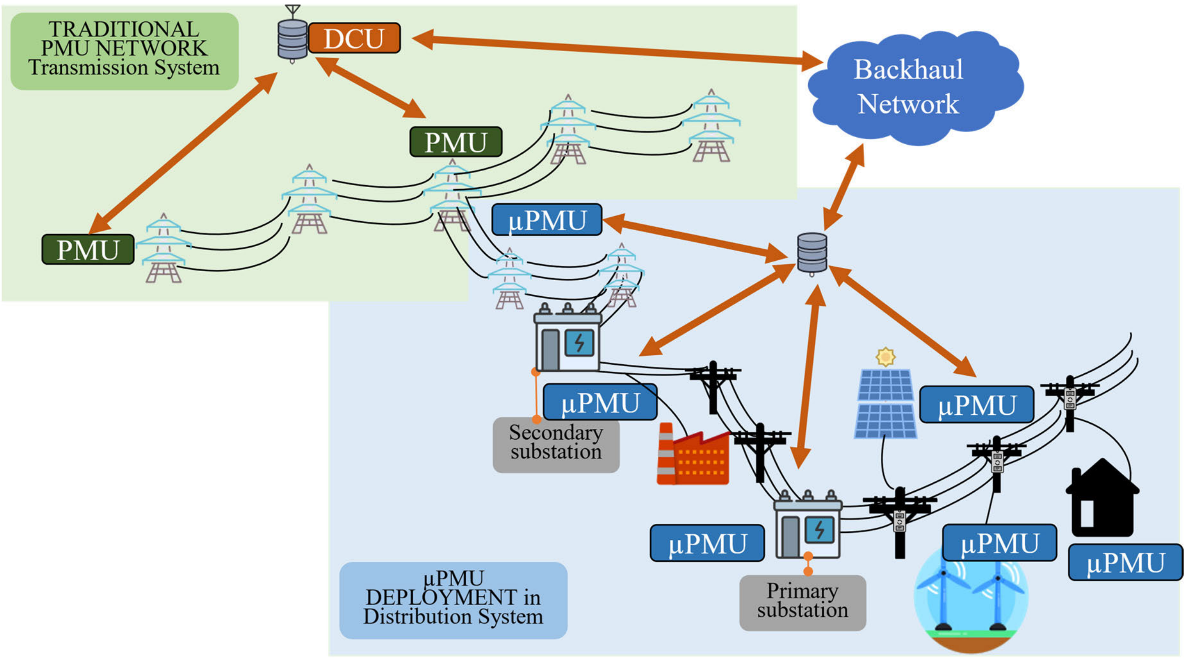

FIGURE 6. Typical WASA system configuration. Traditionally, PMUs are installed at each measurement point in the transmission grid. μPMUs are now available for active distribution network implementation. Data from PMUs are sent to the control centre via DCUs to be distributed to various power monitoring applications.

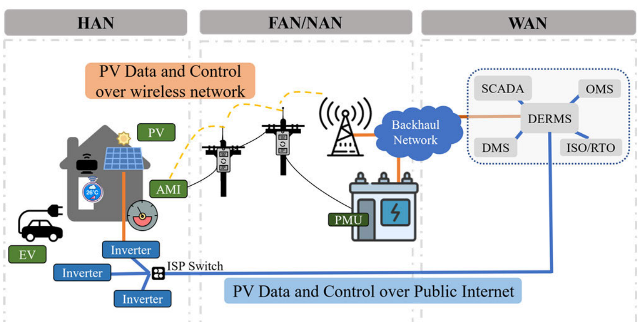

FIGURE 7. Example of DER control network architectures [69].

provided by P2P microwave or satellite communications, are required for large-scale operations [39]. The selection of an appropriate communication network in DERs is a significant challenge due to the many variables and different component requirements that depend on applications and utility expectations [68].

An example of DER control network architecture is shown in Fig. 7 in which the communication for solar PV cells takes place either via wired or wireless network to connect to applications such as DER management system (DERMS) and to independent service operators (ISO)/regional transmission organisations.

5) EV

The U.S. EIA defined an EV as a vehicle propelled by an electric motor that draws power from rechargeable storage batteries, fuel cells, PV arrays, or other electric current sources [70]. EVs offer the advantage of carbon emission reduction, energy independence, and an alternative to ES. However, several challenges must be tackled related to energy and load management, V2G operations, and billing issues. Fast and reliable communications between charging systems and EVs are vital for the efficient management of power supply and demand.

A high current EV charger is typically equivalent to one or two additional homes drawing electrical power on a transformer. During peak hours, when a large number of EVs are charging, improper load distribution for multicar charging facilities could cause system overloading [39]. Similarly, in-home or public EV charging stations face challenges in matching supply and demand with speed and precision, particularly in avoiding long delays in the EV charging cycle's initiation. In terms of V2G operations, which enable EVs to store and discharge electricity generated by RESs, the challenges are similar to those faced by DERs in ensuring the smooth integration of EVs as a power source and a viable outlet for excess energy in the grid. Conversely, billing issues concern billing roaming electric usage to a customer's monthly bills.

The communication requirements for EV applications would not be much different from other HAN applications, with data rates of 9.6–56 kbps for load balancing and billing, and up to 100 kbps for DR [45]. Latency ranges from 2 s to 5 min, depending on whether billing and DR are considered. Other additional requirements include mobility for onboard communication technology, compatibility and interoperability and security for charging at public locations. A review on the communication technologies for EV can be found in [71], while [72] provided a comparative analysis of the architecture models and frameworks for connected EVs, smart charging stations, and information systems.

6) DMS

DMS provides real-time visibility into utility operations, including circuit loading and system performance. Through DMS, utilities can dispatch service crews to fix outages even before customers call to report a power outage. Utilities are also using GIS to share critical information spatially, such as locating potentially damaged or malfunctioning assets, which allows sectionalising faulted circuits to impact fewer customers. More capabilities, such as DA, substation automation (SA), and fleet management, emerge as more ''intelligence'' is added to the distribution side of the electric grid.

DA enables the utility to remotely monitor and control assets in its distribution network through automated decision-making, providing more effective fault detection and isolation, and automated power restoration. DA typically includes SCADA or DMS-based control and monitoring systems, as well as DA field equipment such as remote terminal units (RTUs), IEDs, circuit breakers, switches, and transformers that can be remotely monitored, controlled, and operated. As such, the communication requirements include a 9.6–100 kbps data rate, stringent latency requirements of less than 1 s latency for alarms and alert communication, less than 100 ms for P2P messaging within RF mesh configuration, and a maximum tolerable latency of 2 s [39]. The commonly used technologies for DA backhaul communication include cellular technologies and the unlicensed 900 MHz spread spectrum band.

SCADA is applied for SA, in which this programme is installed at each switching station and distribution substation to perform time-sensitive operational data measurements at critical grid nodes every 2–4 s. These data include instantaneous values of power system analogue and status points like volts, amps, megawatts, mega volt-ampere reactive, circuit breaker status, and switch position [39]. The SCADA data are used to monitor and control the power system, for example opening circuit breakers and indicating equipment failure. SCADA requires less than 100 ms latency to improve polling performance and prevent communication front ends from timing out. Additionally, because SCADA is used at all substations, the coverage requirements are congruent with the utility footprint. Wireless communications are generally preferred because of the inherently hazardous electrical environments with a possibility of GPR in substations. GPR generated problematic currents in the ground, which may cause damage to nearby conductive materials; thus, wired technologies often require costly and complex protection at substations. Notably, the SCADA equipment industry is migrating toward IP-enabled networks and open systems, which enable users to access data from various platforms remotely and allow room for future grid updates [73].

Another application under DMS is the automatic vehicle locator (AVL), which provides fleet management ability to track and direct vehicles to field locations needing repair, and asset tracing capability. AVL requires efficient routing of vehicles over broad coverage areas for service restoration, which can be translated to low latency, high reliability, and high-security communication requirements [39]. Additionally, AVL applications are not data rate intensive with each AVL message size typically around 50 bytes. For larger areas, installing vehicular routers with voice and data routing capability to currently available technologies such as cellular communication and satellite may be a viable option.

Utilities typically view video surveillance capability as a fundamental communications requirement for substations and storage facilities. This is because these facilities are frequently unattended and widely dispersed which necessitates real-time video surveillance. By implementing this application, utilities can reduce manpower management costs for manpower and achieve complete network automation, all while ensuring normal operations for power equipment and protecting them from unauthorised tampering and intrusion. For instance, intruders, physical obstructions, or smoke indicating a fire can be viewed via video so engineers no longer need to visit the site in person each time to diagnose an anomaly, saving time and costs. With the integration of video surveillance capability and available SCADA systems in substations, system administrators will also have a better understanding and control over the network [74]. However, this application has a high data bandwidth requirement for the simultaneous transfer of video, voice, and data.

TABLE 4 shows a summary of the requirements of smart grid applications applicable to active distribution networks, in terms of latency, data rate, security, and reliability.

II. COMMUNICATION TECHNOLOGIES AND PROTOCOLS

Communication technologies available for the active distribution network can be broadly classified into wired and wireless technologies. Wired technologies are often considered to be superior to wireless technologies in terms of reliability, security, and bandwidth. Wired solutions also do not have any interference issues and are not dependent on batteries unlike wireless communication solutions [45]. However, wireless communication solutions offer low installation costs and flexible deployments with minimal cabling, allowing connectivity to be provided over large areas or in areas where there is no pre-existing communication infrastructure. As such, each of these communication technologies has advantages and disadvantages which must be considered depending on the targeted applications and functionalities.

A. WIRED COMMUNICATION TECHNOLOGIES

1) PLC

PLC is a data transmission technology that utilises existing cables such as AC and DC power lines and coaxial cables, thereby reducing the number of cable types in a network.

TABLE 4. Communication requirements for applications in the active distribution network domain [39], [41], [75].

Application	Latency	Data rate (kbps)	Security	Reliability (%)
AMI	2–15 s	10–100 kbps per smart meter/node, 500 kbps for backhaul	High	99–99.99
MDMS	56 kbps	9.6–100 kbps	High	99.00–99.99
WASA	20–200 ms	600–1500 kbps	High	99.999–99.9999
DR	500 ms to several minutes	14–100 kbps per node/device	High	99-99.99
DER/ES	20 ms to 15 s	9.6–56 kbps	High	99–99.99
OMS	2000 ms	56 kbps	High	99.00
DMS	100 ms to 2 s	9.6–100 kbps	High	99.00–99.99
DA	20–200 ms	9.6–56 kbps	High	99.00–99.99
SA	15–200 ms	9.6–56 kbps	High	99.00–99.99
V2G	2 s to 5 min	9.6–56 kbps	High	99–99.99
EVs charging	2 s to 5 min	9.6–56 kbps (load balancing and billing) 100 kbps (DR)	Relatively high	99–99.99

This technology takes advantage of the frequency difference between electrical voltage and data signals: electricity travels at relatively low wavelengths, whereas digital data travels at a higher frequency. This enables various cables to transmit data and electricity at the same time [76]. The PLC technology can be classified into three categories based on the transmission bandwidth [77], which are ultra narrowband PLC (UNB-PLC), NBPLC, and BPL. Table 5 shows the summary of the three PLC categories.

Other than the quick and low-cost network construction due to the existing power line infrastructure, additional advantages include reliability and maturity as it has already been used for decades for commercial broadband, as well as relatively easy maintenance when compared with other wired technologies. However, PLC has numerous drawbacks such as the difficulty in modelling the communication channel due to the presence of harsh electrical noise in power lines [66]. Moreover, PLC technologies such as the UNB-PLC and NBPLC typically have low data rates, which made these technologies unsuitable for high bandwidth applications due to fading and interference. PLC has a low signal-to-noise ratio, which requires hopping of the PLC signal around transformers by using a bridge, such as a wireless connection, that bypasses this grid element that would normally scramble the PLC signal [39]. This technology is usually combined with other communication technologies, such as cellular communication, to provide a hybrid solution for power grid communications [66].

Some of the in-depth reviews on the role of PLC in the smart grid can be found in [77], [78], [79], [80], [81], and [82], in which Galli et al. [77] focused on PLC applications within the smart grid from the sensor networking and network control perspective, whereas Yigit et al. [78] focused on the standards of PLC and its implementation worldwide. Sharma et al. [79] provided a review of PLC implementation in distributed power systems and DERS in terms of monitoring, controlling, and management purpose. A more recent review is presented by López et al. [82] in 2019, which provides an update on PLC technologies and their applications in smart grids, their main challenges and possible solutions, and the current research initiatives. Conversely, Güzelgöz et al. [80] and Bai et al. [81] focused on reviewing the PLC propagation channel characteristics, noise modelling, and mitigation. Additionally, Haidine et al. [83] discussed the NBPLC technology, with an overview of distribution line carrier: verification, integration and test of PLC technologies and Internet protocol (IP) communication for utilities (DLC+VIT4IP), an EU-funded project for the development of efficient transport of IPv6 protocol, automatic measurement, configuration and management, and security in the frequency range of up to 500 kHz.

The application of PLC in DR is presented by Cortés et al. [84], in which the authors implemented NBPLC using the G3-PLC standard as a communication network for demand-side management systems in Manizales City, Columbia. Conversely, Sausen et al. [85] presented an NBPLC solution for smart metering systems in Brazil based on the PRIME standard. Sendin et al. [86] proposed BPL and NBPLC for smart grid communications architecture, in which BPL is proposed as the telecommunication backbone for secondary substation (the interface between the MV and LV distribution power system), whereas NBPLC using PRIME specification is proposed for smart meter access communication. These proposals are based on the extensive PLC deployment on the electricity distribution grid of Iberdola, a multinational electric utility company based in Bilbao, Spain. Current research on PLC also focused on PLC channel reliability. For example, Aderibole et al. [87] focused on tailoring the PLC for applications such as DR and load control through improved measurement and modulation techniques in the PLC modem. The proposed method was demonstrated in a 24-floor high-rise building with challenging channel conditions. Conversely, Wang et al. [88] proposed an adaptive sparse code multiple access modulation technique, which can adapt to the features of power line channel strong signal attenuation, background noise and impulsive noise and increase spectral efficiency and user capacity in PLC.

2) FIBRE OPTICS

Fibre optic technology is a method of delivering high-speed data connectivity by using infrared light instead of electrical

TABLE 5. Summary of PLC technologies.

Categories	UNB-PLC	NBPLC		BPL
Brief description	Referring to systems using very narrow bandwidth for low data rate transmission (~100 bps)	Referring to systems that work with medium data rates in the frequency range of 3–500 kHz. Can be further classified into LDR NBPLC and HDR NBPLC		Encompasses a large variety of systems that aim at high data rates (up to 200 Mbps), operating in a 1–250 MHz range
		Low data rate (LDR)	High data rate (HDR)	
		Based on single carrier modulations for data rates of a few kbps	Based on multicarrier modulations and transmit data rates of hundreds of kbps (~500 kbps)	
Example technologies or standards	• X10 • Aclara Two-Way Automatic Communication System (TWACS)	• ISO/IEC 14908-3 • ISO/IEC 14543-3-5 (KNX) • CEA-600.31 (CEBus) • IEC 61334-3-1 • IEC 61334-5-1 • Insteon, • C&C • SITRED • Ariane controls	• IEEE 1901.2 • ITU-T G.hnem • PRIME • G3-PLC	• IEEE 1901 (notably the Access System specification) • ITU-T G.9960 (also known as ITU-T G.hn) • HomePlug* • HD-PLC *HomePlug has been discontinued/ceased service since 2016. The website is unavailable as of May 2022
Frequency bandwidth	30–300 Hz or 0.3–3 kHz	3–500 kHz: European CENELEC bands (3–148.5 kHz), US FCC (10–490 kHz), Japan ARIB band (10–450 kHz), China EPRI (3–500 kHz)		1–250 MHz
Distribution network scope	LV and MV sections as the signal can go beyond the transformer	Mostly in LV but there are some research on the applicability in MV [89]	Applicable in both LV and MV sections	Can be used in LV and MV sections
Main applications	• Home automation, • Remote meter reading • Direct load control application • DR	Preferred for the last mile of smart metering applications. • AMI (mainly used in the EU, mostly for the communication between smart meters) • EV charging system • Telecontrol applications • Smart cities • DG • Grid topology connectivity • Cable health monitoring • Fault location		• Home network multimedia communications (LV) • Distribution automation/ telecontrol (MV) • AMI • EV charging system • Telecontrol applications • Smart cities • DG • Grid topology connectivity • Cable health monitoring • Fault location
Advantages	• Less affected by transmission losses due to their low frequency bandwidth • Reach long distances and go beyond transformers without the use of repeaters • Mature (at least 2 decades)	• Provides real-time data to devices connected to the grid, facilitating an intuitive understanding of the network and an effective management of events and failures [82]. • NBPLC signals have the inherent capability to communicate over longer distances, since these low-frequency signals can pass through LV and MV transformers, thereby requiring fewer repeaters and reducing the implementation cost [90].		• BPL provides real-time data to grid-connected devices, allowing for a more intuitive understanding of the network and more effective event and failure management [82]. • BPL is more flexible and provides a better trade-off between data rate, latency, robustness, and energy efficiency than NBPLC.
Disadvantages	Very low data rate, adopt proprietary technologies [91].	Limitation in data rates in comparison with BPL		• Some countries prohibit the use of BPL outdoors (e.g., Japan) • Europe: stricter regulations that limit the allowable transmit power, requiring smaller repeater spacing and thus increasing deployment costs
Repeaters	Able to go beyond transformers without repeaters (can cover approximately 150 km distance)	The typical radial branched MV feeder has a distance limit of 10-15 km before repeaters are required		Due to high path loss, BPL over LV networks may necessitate small repeater spacing, whereas larger repeater spacing can be tolerated over HV/MV networks

impulses for data transmission. This technology is generally preferred over electrical cabling as it offers high bandwidth, high data-rate, low latencies, long-distance data transmission, and immunity to electromagnetic interference (EMI), albeit having high installation and maintenance costs and being difficult to upgrade [27], [29]. Because of its EMI immunity, fibre optics has become a more popular choice in the power industry for connecting different equipment installed in substations, eliminating numerous errors commonly seen with electrical connections. This mode of communication is commonly used in long-distance applications such as backbone communication and for the connection of substations to the utility's control centres, where its full transmission capacity can be utilised while offsetting the increased cost.

The fibre optic cables can be categorised into multimode and single-mode optical fibres. A multimode optical fibre has a larger core of more than 50 μm, which allows the connection of less precise, less expensive transmitters, receivers, and connectors. Multimode fibres support multiple propagation modes; consequently, they are susceptible to multimode distortion, which frequently limits the bandwidth and length of a connection. Therefore, multimode fibres are typically implemented in short-range communication (less than 50 m) such as those used in work and home premises, and within data centres for rack-to-rack communication [92]. By contrast, the core of a single-mode fibre is smaller (less than 10 μm), necessitating more expensive components and interconnection methods, but enabling much longer, higher-performance connections. Additionally, single mode fibres are highly suited for long distance communication such as NAN and WAN applications because they have low dispersion and no signal degradation.

With decreasing material and installation expenses, fibre networks are more cost-effective to be deployed in recent years. These advancements have enabled the delivery of smart grid services directly to users, as evidenced by well-known programs such as fibre to the premises (FTTP), which provides a fibre network to both homes and small businesses directly from an operator's central office. For example, LUS, a publicly owned utility business in Louisiana, USA, built a municipally owned fibre to the home (FFTH) broadband network, which also served as a communication backhaul in smart grid projects [93]. Additionally, the EPON technology, which permits the use of a conventional Ethernet communication protocol over an optical network, is attracting great attraction from grid operators because of its interoperability with the current IP-based network [29].

Various standards related to fibre optic communication have been developed to enable the development of fibre optic-compatible components from various manufacturers. The International Telecommunication Union (ITU), in particular, publishes several standards related to the characteristics and performance of fibres, including 1) ITU-T G.651 [94], which detailed the characteristics of a 50/125 μm multimode graded index optical fibre cable and 2) ITU-T G.652 [95], which detailed the characteristics of a single-mode optical fibre cable. Other standards provide performance requirements for fibre, transmitters, and receivers used in complying systems. Some of these standards are synchronous digital hierarchy (SDH), synchronous optical networking (SON), and OTN.

3) FIELDBUS TECHNOLOGY

The term "Fieldbus" refers to a class of industrial networking solutions designed for real-time distributed control, which allow the connection of instruments and tools in FAN and NAN. This technology is used in various industries such as manufacturing, process and building automation, and the energy and smart grid industry. HMS Industrial Networks reported that Fieldbus remained the second dominant industrial networking solution behind industrial ethernet in the year 2020 despite having a major drop in market share from 71% in 2014 to 30% in 2020 [96]. Bitbus, developed by Intel Corporation in the early 1980s, was the first commercially available Fieldbus solution. However, it is no longer widely used today, with Siemens' PROFIBUS being the most popular solution on the market [97]. Other Fieldbus technologies currently in use include Modbus and LonWorks [8].

Fieldbus solutions can be categorised based on the implemented physical layer (e.g., RS485 and Ethernet) or data protocol level such as PROFIBUS and Modbus. PROFIBUS was first promoted in 1989 for fieldbus communication in automation technology. This solution is openly published as part of the IEC 61158 standards, with two variations currently available [98]:

- PROFIBUS Decentralised Peripherals (DP) for the operation of sensors and actuators via a centralised controller in production automation applications.
- PROFIBUS Process Automation (PA) for process automation applications to monitor measuring equipment via a process control system. This variant is intended for use in explosive/hazardous environments. The physical layer (i.e., the cable) is compliant with IEC 61158-2, which allows power to be delivered over the bus to field devices while limiting current flows to prevent explosive conditions from forming even if a malfunction occurs. This feature limits the number of devices that can be connected to a PA segment. The data rate of PA is 31.25 kbps. Available data transmission technologies for PROFIBUS are RS485 serial communication, Manchester-coded Bus Powered, fibre optics, and several wireless transmission technologies such as WirelessHART and wireless sensor and actuator network [98].

Modbus was first introduced in 1979 as a data communications protocol for programmable logic controllers and has since evolved into a de facto standard communication protocol widely used for connecting industrial electronic devices [99]. Generally, there are three variants of Modbus, namely, Modbus RTU, Modbus ASCII, and Modbus TCP [100]. As the physical transmission layer, Modbus RTU and ASCII typically use a serial interface (RS485 or RS232), whereas Modbus TCP is the Modbus RTU with Ethernet Transmission Control Protocol/Internet Protocol (TCP/IP) interface and wireless communications such as General Packet Radio Services (GPRS) [8]. In the distribution network, Modbus RTU is frequently used in SCADA systems to connect RTUs to the control panel. Although the Modbus protocol is supported by a wide range of modems and gateways, this protocol has the limitation of only facilitating data types that were supported by programmable logic controllers in the late 1970s.

Topologically, Fieldbus operates on a network structure that supports daisy-chain, star, ring, branch, and tree network topologies. Fieldbus has several advantages that have helped it become a popular networking solution, including: 1) high durability, because Fieldbus cables and components are specifically designed to be extremely durable, robust, and capable of withstanding extreme physical conditions in industrial applications; 2) high reliability, as Fieldbus networks have short signal paths and better interference protection, which increases network stability and reliability; 3) maturity, as most Fieldbus solutions have been in existence for some time and are standardised, making it easy to integrate equipment from various manufacturers into a single system.

However, this technology has several disadvantages including high equipment cost and maintenance complexity, as the networks rely heavily on complex proprietary manufacturer equipment that requires specialised professionals for maintenance. Despite each technology sharing the generic name of Fieldbus, the various Fieldbus solutions are not readily interchangeable. They cannot be easily connected to each other because of their profound dissimilarities. Furthermore, Fieldbus typically has low data transmission rates as most of the solutions operate at data transmission rates of hundreds of kilobytes per second, with only a few standards that can reach speeds of over 10 Mbps.

4) INDUSTRIAL ETHERNET

Industrial Ethernet has gained popularity in recent years, as it has become more pervasive and offers faster speeds, longer connection distances, and the ability to connect more nodes in comparison with conventional Ethernet. This technology employs ruggedised hardware and copper cables for data transmission via electrical impulses, with various industrial Ethernet protocols supported by various industrial equipment

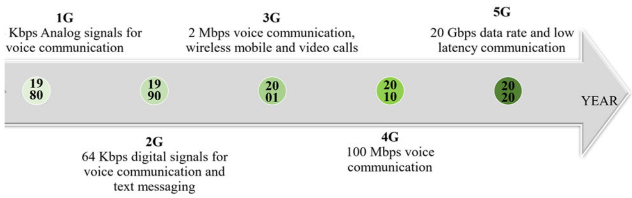

FIGURE 8. **Evolution of cellular communication technology throughout the years.**

manufacturers, including EtherCAT, PROFINET, and EtherNet/IP [101]. Ethernet communications with TCP/IP are typically nondeterministic, with response times of around 100 ms. By contrast, industrial Ethernet protocols generally apply a modified MAC layer for deterministic and low-latency responses, whereas the cables and connectors can adapt to the harsh industrial environment.

The industrial environment is often harsh because of the presence of many environmental conditions that are not present in commercial environments such as extreme temperature, humidity, vibrations, and the presence of RF interference (RFI) or EMI. Since commercial Ethernet relies on unshielded copper cables to transmit electrical signals, it is more susceptible to RFI/EMI. Additionally, data transmitted in this manner is also vulnerable to hardware-level hacking, which could pose a security and privacy risk [102]. Therefore, industrial Ethernet is an optimal solution to industrial network connectivity as this technology provides reliable performance and real-time data transmission in harsh environment applications such as SA, and SCADA [103]. This mode of communication is not only suitable for communication between substations and control centres in NAN and WAN, but also commonly used in HAN for communication between smart meters and home central units [26]. Additionally, various industrial Ethernet protocols and attendant hardware such as switches, routers, and connectors form the power grid communication backbone [103], with a notable proof of concept (PoC) of digital electrical substation communications over Ethernet demonstrated in Sanchez-Garrido et al. [104].

Another capability supported by the Ethernet is power over Ethernet (PoE), which provides the ability to transfer both data and power within an individual Ethernet cable, similar to the PLC concept. The IEEE has established several standards, particularly the IEEE 802.3af, IEEE 802.at and IEEE 802.3bt, which govern how networking equipment should operate to promote interoperability between devices. Many commercial applications of PoE capability have been established such as voice over Internet protocol (VoIP), and surveillance cameras [105], with many emerging high-powered applications, such as facility monitoring controls, and LED lighting and sensors. Table 6 summarises some of the widely used industrial Ethernet communication protocols along with their features and limitations.

B. WIRELESS COMMUNICATION TECHNOLOGIES

1) CELLULAR COMMUNICATIONS: 4G LTE AND PRIVATE LTE

Since the launch of the first generation (1G) of commercial cellular networks in the early 1980s, cellular communication technologies have been making their way into various sectors' communication solutions including the power industry. Fig. 8 shows the evolution of cellular communications from 1G to the current 5G. As more capabilities such as faster data rates and ultralow latencies are realised throughout the years, more applications implementing the cellular communications emerge, for example, monitoring and management of DERs and SCADA [29], and smart meter deployments [106].

Because of its ubiquitous usage, this technology offers various advantages including existing infrastructure and a wide area of deployment [30] and supports a huge number of devices [107]. Additionally cellular communication technologies are equipped with security elements such as uniquely addressed devices, cryptographic capability, and redundancy features [108], [109], [110]. Its operation within the licensed spectrum reduces interference issues [107], whereas ensuring control over the number of users and protocols used [110]. However, its service availability is not guaranteed especially in harsh environmental conditions, natural disasters, and peak user density [29], [111]. Other deterring disadvantages include latency issues and high costs [112].

Although there are several cellular communication protocols available, such as the code division multiple access and Global System for Mobile Communication (GSM)/GPRS used in 2G and 3G networks, and 4G LTE, cellular power grid applications are usually centred on networks supporting the transmission of both voice and data at the same time, for example, the usage of T-Mobile's GSM in Echelon's smart meters to enable smart meter communication to the backhaul servers [45] and the application of GSM in AMI for the identification of AMI security requirements [113].

Contrary to the 3G technologies, 4G LTE provides more flexibility, faster communication speed, and more refined features, which are suitable for active distribution grid communication [114]. As such, more applications are using 4G LTE such as monitoring and management of DERs, SCADA [29], and smart meter connectivity in rural areas [106]. There is also the option to use a private 4G LTE network, in which utilities may outsource to service providers or own, operate and have some kind of priority access to the network infrastructure or spectrum as opposed to public 4G LTE networks [115]. This communication network provides access to authorised users and is interoperable with public cellular networks while also providing coverage, capacity, and improved security [116], [117]. Additionally, private LTE networks are cost-effective, because they reduce the number of disparate networks to manage, with competitive pricing from other vendors [118]. However, this solution is only viable as a whole-system communication solution when all FAN and NAN applications feed into the private LTE network via the fibre backbone [118].

TABLE 6. Summary of some of the widely used industrial Ethernet communication protocols [101], [105].

Industrial Ethernet protocol	Management body	Description	Features	Limitations
EtherNet/IP	ODVA	EtherNet/IP is an application layer protocol that is transferred inside a TCP/IP Packet for industrial automation and process control environments. Implements Common Industrial Protocol (CIP) onto the foundation of Ethernet	• EtherNet/IP uses the standard Ethernet and switches; thus, it can have an unlimited number of nodes in a system • Flexible with star, tree, or line topology, but prefers managed switches for industrial applications (allow network to be configured to perform near real-time behaviour) • Data rate up to 100 Mbps • Physical layer is defined by Ch 8 of the "EtherNet/IP Adaptation of CIP"—includes cables and connectors specification • Compatible with many standard Internet and Ethernet protocols	• The majority of processor bandwidth goes to the processing of the TCP/IP layers • No real information modelling: objects cannot be linked into any sort of hierarchy • The EtherNet/IP motion extension, CIP Motion, is not nearly as widely accepted as EtherCAT and SERCOS • Better suited for discrete control, not in process control • Requires custom diagnostics for devices as there are no built-in generic diagnostics for EtherNet/IP devices • No EtherNet/IP standard for device replacement. Replacing a device can be as difficult as the initial configuration of the device. • Has limited real-time and deterministic capabilities
Modbus TCP	Modbus-IDA User Organisation	Is the Modbus RTU protocol with a TCP interface running on Ethernet. TCP provides a transmission channel for Modbus TCP messaging. Frequently used in programmable logic devices, SCADA systems, and sensors and actuators	• Typically used in industrial environments due to ease of deployment and maintenance, and because it was developed for industrial applications • Open-source protocol • Can be used with star, tree, or line network topologies and can be implemented with Ethernet technology that has been adapted for industrial environment use	• Relatively low data rate • Has no form of object and space only reserved for addresses • Uses only two types of data (Boolean and 16-bit unsigned integer) • Issue with security
PROFINET	PROFIBUS and PROFINET International	Features a modular structure allowing users to select cascading functions including standard TCP/IP for non-real-time applications, real-time applications for the transfer of critical information, and isochronous real-time for applications requiring functionality like motion control	• Can be used with line, ring, star, and tree network topologies • Uses adapted Ethernet technology for industrial environments • Widely used by major industrial equipment manufacturers such as Siemens and GE • Communication is available up to 100 Mbps	• Issue with security
EtherCAT	EtherCAT Technology Group	Uses a clear master/slave communication model. Enables on-the-fly packet processing and can deliver real-time Ethernet to automation applications. EtherCAT is the MAC layer protocol and is transparent to any higher-level Ethernet protocols such as TCP/IP, UDP, and Web server	• The master/slave communication model maximises the use of bandwidth, and consequently increases speed • Can provide scalable connectivity for entire automation systems, from large programmable logic circuits to the I/O and sensor level • Does not require external switches or routers as they use an embedded switch • Can be used with line, tree, and star network topologies • Communication is available up to 100 Mbps	• Slave devices need to embed a specific hardware ASIC to implement this protocol • Data model is very different and can be difficult to understand

2) CELLULAR COMMUNICATIONS: 5G

The 5G network is a vastly enhanced cellular communication technology in comparison with its predecessor, 4G LTE, in terms of the number of connected devices, mobile data volumes, latencies, reliability and security [109], [110]. This technology supports a wide range of different use cases, especially in industrial applications such as the smart grid sector on top of the traditional user segments [26]. Additionally, 5G supports network slicing using the same physical infrastructure [109], providing three major service classes, namely, enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultrareliable and low latency communications (URLLC); 5G also supports interoperability among devices and networks, which is enabled by the in-band and guard-band operations [110], and is also reliable and offers high flexibility and scalability [109]. However, 5G disadvantages include costly infrastructure setup and expensive migration to 5G-enabled devices. This is because 5G operates at significantly higher frequencies and bandwidths, which cannot fully operate on existing 4G radio masts [29].

Despite its promising features, this technology has yet to mature [113] for successful and widespread implementation in the high-stake power industry. Conversely, this new technology with vastly improved capabilities is facilitating numerous research opportunities in the electrical energy domain, such as Zerihun et al. [109], who investigated and proposed a methodological approach for evaluating the reliability and dependability of 5G-based power grid monitoring systems; Zhou et al. [119], who investigated intelligent resource scheduling of 5G edge computing-empowered distribution networks through digital twin (DT) technology with promising results in terms of cumulative iteration delay, DT loss function, energy consumption, and access priority deficit; Zou et al. [120], who investigated the impact of 5G communication base stations on the distribution network and proposed a statistical model to accurately represent the 5G base stations load profile for the analysis of load characteristics in the distribution network; and Yong et al. [121], who proposed a methodology to utilise the dispatchable capacity of 5G base stations backup batteries in the power distribution network to reduce 5G base stations' electricity consumption while satisfying the reliability requirements. There are also several review papers on the discussion of 5G technology applicability and future prospects in the power domain, such as that of Tao et al. [122], who analysed the role of 5G networks in IoT and power systems, and Esenogho et al. [112], who discussed the implementation of artificial intelligence in 5G IoT for future smart grids.

3) LPWAN: NB-IOT

NB-IoT is a licensed LPWAN technology that provides cellular-level QoS and is based on existing LTE functionalities [46]. NB-IoT relies on existing cellular infrastructure, which offers reduced investment costs on the utility-dedicated communication infrastructure and deployment time [46]. This technology is standardised by the 3rd Generation Partnership Project (3GPP) in LTE Release 13 [123] and has attracted strong support from major telecommunication companies such as Qualcomm, Ericsson, and Huawei [29]. Some of its main features include a low-cost device, maximum uplink latency of 10 s, the ability to support 40 connected devices, and a device battery life of 10 years (200 bytes of data transmission limit per day) [124]. Additionally, this technology operates on 900–1800 MHz frequency bands with coverage of up to 35 km [46]. It has data rates of up to 250 kbps for uplink and 230 kbps for downlink communications [124]. NB-IoT is mainly suitable for low data rate applications at HAN and NAN, such as home automation and AMI [46]. However, it is incompatible with delay-tolerant applications such as DA and DERS [46].

Current research on NB-IoT in the power distribution field includes 1) network reliability and feasibility, as in [125], which investigated the AMI NB-IoT network reliability and redundancy through studying the hardware design and operation of dual-SIM NB-IoT modem, and [126], which investigated channel characteristics for NB-IoT for smart meter reading system in a rural scenario using ray tracing method; 2) security [127], in which an end-to-end security authentication protocol for NB-IoT in the smart grid was proposed by providing secure data transmission and bidirectional identity authentication between IoT devices and terminals; and 3) grid applications, such as NB-IoT in outage restoration and management (ORM) [128], last mile communication [129], tunnel monitoring system for preventive maintenance of underground cable [130], and real-time DR [131].

4) LPWAN: LORAWAN (LORA)

LoRaWAN [132] is an LPWAN communication technology that wirelessly connects LoRa (long-range) battery-powered devices to the internet and targets key IoT requirements, such as bidirectional communication, end-to-end security, and mobility [132], [133]. Although it is mainly designed for WAN coverage in IoT, it is also applicable in NAN [29], with applications such as monitoring sensors, asset management, and controlled automation. Some of its features include mobility, secure bidirectional communication and localisation services, and interoperability. This technology also offers a data rate range of 0.3–50 kbps and 2–5 km coverage in urban environments and 15 km coverage in suburban environments. There is no interference with different data rates during the communication because this technology employed the use of wide spectrum bands. Although most of the existing wireless communication technologies have been designed to optimise their peak data rates, LoRa devices' main design attributes are low power consumption and a long communication range with a compromise on their peak data rates [134]. Additionally, this communication has no defined standards, is protected under proprietary technology, and is relatively new in the field, which may deter the implementation of this technology in the active distribution network.

Current LoRa research mainly focuses on the performance evaluation of LoRa in the power grid domain, as presented by Persia et al. [135], who investigated and analysed the coverage connectivity of NB-IoT and LoRa for novel IoT smart grid application requirements; Haidine et al. [136], who evaluated the LoRa system in smart metering with a conclusion that LoRa solution is better suited for applications with very short packet sizes and long interval period; and Tang et al. [137], who demonstrated a combination of LoRa and NB-IoT in a wireless network for fault indicator application.

5) WANET: ZIGBEE

Zigbee is an open wireless network protocol built based on the physical layer and media access control defined in the IEEE 802.15.4 standard for WPANs. This technology supports WANET in the form of tree, star, and mesh topologies, offering scalability advantages. In both tree and mesh topologies, Zigbee routers can be used to extend communication at the network level. Zigbee offers short-range communication, with a line-of-sight coverage of 10–100 m and has a low data rate of 20–250 kbps [26]. Zigbee devices have low power consumption due to their low-duty cycle operation, which allows the devices to sleep and wake in active mode for brief periods. These devices also have a battery life of at least 2 years to pass certification. Other advantages include mobility, low cost, fast and simple network configuration, and the ability to connect a large number of nodes in the network. ZigBee operates on the industrial, scientific and medical (ISM) radio bands: 2.4 GHz in most jurisdictions worldwide at 250 kbps per channel, 868 MHz in Europe at 20 kbps per channel, and 915 MHz in the United States and Australia at 40 kbps per channel [26], [138]. Zigbee networks are secured by AES-128 access control, providing secure communications besides protecting establishment and transporting cryptographic keys and encrypting data.

However, given that this technology has low transmission power, it is more susceptible to multipath distortion, noise and interference, which may affect communication reliability [138]. Zigbee, which operates on the 2.4 GHz band is also affected by interference from technologies that operate on the same unlicensed frequency spectrum such as WiFi, USB, Bluetooth, and microwave ovens [26]. This technology is also highly vulnerable to intended and unintended jamming because of the lack of frequency diversity since the entire network shares the same static channel [139]. Moreover, there is no path diversity in the Zigbee network in which in the event of link failure, a new path from the source to the destination

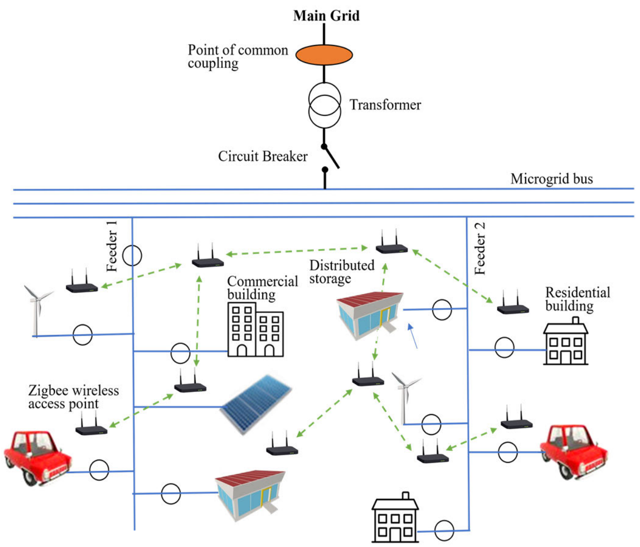

FIGURE 9. A conceptualisation of ZigBee WSN for distributed control in a microgrid, in which microgrid components such as wind turbines and EVs are connected to the nearest Zigbee wireless access points.

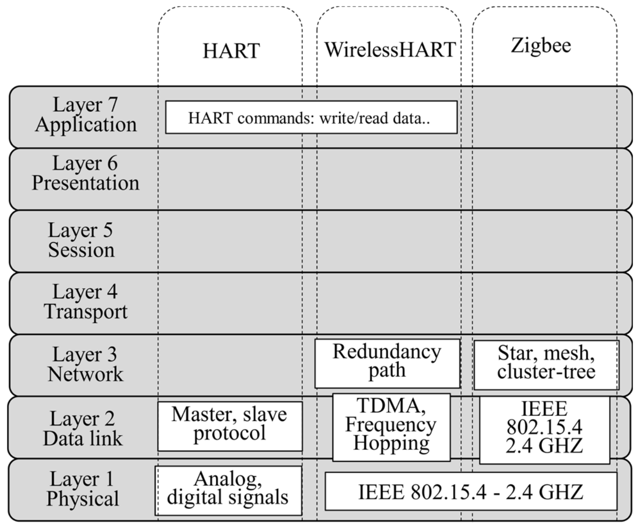

FIGURE 10. OSI model comparison for HART, WirelessHART, and Zigbee protocol stack.

must be established. Thus, increasing both time and overhead costs for route discovery efforts that may eventually use all available bandwidth [139].

Zigbee is typically used for short range and low data rate applications that require long battery life and secure networking, such as device control and energy management applications. Examples include home device communication and automation within HAN and NAN energy management and smart meter communications of homes and apartments [26], [140]. Ke et al. [141] focused on the establishment of Zigbee network in AMI, in which they proposed fast join process and enhanced fast join process to shorten the time of Zigbee network construction for an AMI data concentrator network. Zigbee is also used in microgrids, as discussed by Wu and Shahidehpour [142], who focused on the area coverage problem of Zigbee WSN-distributed control with nonpenetrable obstacles in microgrids. The microgrid at the Illinois Institute of Technology (IL Tech) was used as a practical example. A conceptualisation of Zigbee WSN in a microgrid is shown in Fig. 9. Chang et al. [143] focused on the implementation of decentralised decision-making in DR using Zigbee communication. The PoC has been demonstrated using IEEE 33 bus systems.

Another application of Zigbee in the power distribution grid can be found in the study of Chen et al. [144], who proposed a Zigbee-based communication for multifunctional electronic current transformers (ECTs) for overhead and underground power line monitoring. Their proposed method includes a transmission strategy to tackle Zigbee's low transmission data rate and satisfy both measurable and protective purposes of multifunctional ECTs. Because Zigbee is notorious for its interference challenges from other technologies operating within the same frequency spectrum, Chi et al. [145] presented an interference-mitigated ZigBee-based AMI system for high-traffic smart meters system. The system has a multiradio, multichannel network architecture and a multiobjective optimisation-based interference mitigation design. While Sallabi et al. [146] investigated the reliability of Zigbee-based WSN in harsh power system environments, which is simulated in a laboratory through the generation of switching transient events under different conditions.

6) WANET: WIRELESSHART

WirelessHART is a centralised and real-time wireless sensor networking protocol extension of the Highway Addressable Remote Transducer (HART) protocol, a protocol designed for industrial automation [147]. This low-power communication protocol is based on the IEEE 802.15.4 standard and is intended for industrial process monitoring and control [147]. It operates on the 2.4 GHz ISM band and utilises a time-synchronised time division multiple access-based network, self-organising, and self-healing mesh architecture. It has a 200-meter coverage range, a data throughput of 115 kbps, and employs 128-bit AES encryption for security, similar to the Zigbee standard [147]. One of the advantages offered by WirelessHART is backward compatibility, in which systems operating on the wired protocol can be connected to WirelessHART networks by utilising simple adapters that provide the least-resistant path in the wireless medium [148].

Although this protocol shares the same operating frequency band as Zigbee, this protocol has a clear advantage over Zigbee in terms of robustness, reliability, and message delivery. Comparison studies between WirelessHART and Zigbee are presented in [139] and [149], in which Levennall et al. [139] focused on the suitability of WirelessHART in industrial applications, while Habib et al. [149] provided a simulation case study for control applications. Fig. 10 shows the comparison between HART, WirelessHART and Zigbee protocol stack in the OSI model. Although WirelessHART addresses some of Zigbee's shortcomings, it has no dedicated specifications of security requirements. Consequently, the developer's ability to design and develop applications is limited because they must first learn all the core specifications before any application development [29]. Applications of WirelessHART in the active distribution network include control and automation of industrial appliances, DLC, and mesh sensor networks [150].

7) WANET: WIRELESS MESH/RF-MESH

Wireless/RF-mesh is a wireless technology that uses free unlicensed ISM bandwidth to create a mesh topology for applications such as smart meters and data collector connections in an AMI. This technology has a long track record and has been proven to be highly reliable in remote telemetry and distributed control applications [151], [152]. It is widely used in the industry, as evident from [153], in which three of the most prominent smart meter manufacturers (Aclara, Itron, and Landys&Gyr, with a combined market share of 76.5% in North America) use RF-Mesh radios in their smart meters. Some examples of its usage in the AMI include automatic meter readings, facilitating DR programs via fast and reliable communication between smart meters and head end systems, and providing connection between a large number of smart meters to the utility's MDMS. This communication technology offers up to 100 Mbps data rates with advantages such as the ability to dynamically form ad-hoc communication with its neighbours, to increase communication range via performing multihop, to self-heal, and to overcome variable propagation conditions by finding alternative paths, supporting remote firmware upgrade over the air interface in a secure and controlled manner as well as low equipment cost, and having high scalability feature [29], [152]. However, this technology is susceptible to interference because of its operation in the densely populated wireless environment, which inevitably affects overall network performance. Additionally, RF-Mesh performance analysis is even more challenging than other wireless technologies because it is less standardised and its implementation specifics such as routing, and frequency channels are often covered by strict confidentiality agreements [151]. Consequently, publicly available data are scarce, and the literature on its performance is not as extensive as other alternative technologies.

Some of the examples of RF-Mesh research can be found in [151] and [152]: Malandra et al. [151] attempted to solve the problem of performance analysis by proposing a performance analysis framework of an RF-Mesh-based AMI, based on the packet collision probability and the delay. Conversely, Lichtensteiger et al. [152] provided a simulation of the system using a frequency hopping spread spectrum for efficient and reliable deployment of the smart metering system.

Table 7 shows a summary of the wired and wireless communication networks in the active distribution network.

C. HYBRID COMMUNICATIONS

As discussed in previous subsections, both wireless and wired communication technologies are significant components of the active distribution network, with each having its own advantages and disadvantages. In many circumstances, a hybrid communication technology combining wired and wireless solutions can be employed to improve system stability, resiliency, and reliability [26]. One of the popular hybrid communication solutions is FiWi, which combines optical fibre and wireless technologies (e.g., WiFi and WirelessHART) for providing two-way communication in various industries including the power grid. Ridwan et al. [154] provided a survey of FiWi implementation in the smart grid and proposed a testbed for the testing of FiWi protocols and algorithms in the smart grid environment. More related to the distribution domain, Maier [6] proposed an Über-FiWi network, which combines wireless mesh networking and fibre optic communication, and demonstrated its suitability as a holistic end-to-end smart grid communications infrastructure for next-generation power distribution networks. Experimental and simulation studies on emulated power blackouts during a security breach and coordinated plug-in EV (PEV) charging demonstrated positive results without any deviation in voltage profile and deterioration of power quality. Conversely, Lévesque et al. [155] explored a converged FiWi infrastructure based on EPON, WiMAX, wireless mesh network and sensor technologies to support coordinated charging of PEVs. Another interesting study in FiWi for distribution management system is proposed by Liu et al. [156], who provided an architecture of FiWi-enhanced smart grid and study the problem of resilient and low-latency information acquisition under failures.

Another hybrid communication network study in the electricity grid is presented by Salvadori et al. [157], who proposed network architecture for condition monitoring, diagnosis, and supervisory control, which comprised wired infrastructure including PLC, a wireless sensor network, and a controller area network. This hybrid communication network is implemented in an underground electric power distribution substation. Rafiei et al. [158] proposed a smart-metering approach using a combination of PLC and WiFi protocols for both automatic meter reading and AMI applications. Rerkratn et al. [159] presented a technique for integrating WirelessHART and PLC for plant monitoring. Another interesting approach is demonstrated by Agrawal et al. [160] who performed an outage analysis based on a hybrid PLC and wireless communication network.

D. STANDARDS AND COMMUNICATION PROTOCOLS IN ACTIVE DISTRIBUTION NETWORKS

Power utility companies are gradually deploying a vast variety of distributed communication systems and numerous application systems, each with its own hardware platform, database technology, and communication protocols. During the operation of services, users frequently switch

TABLE 7. Summary of technical features, advantages, disadvantages, and several use cases of wired and wireless communication technologies in active distribution network and the smart grid.

Type	Technology	Data rates	Coverage	Advantages	Disadvantages	Application and use case
Wired Communication	**PLC**	100 bps to 200 Mbps	Several metres to 150 km	• Provides connectivity, topology estimation abilities, and automatic fault detection • Existing infrastructure • Low cost of deployment • Extensive coverage • Dedicated network • Utility's own ownership and control	• High signal attenuation • High noise • Interference with electric appliances and electromagnetic sources • Signal quality affected by the type and number of devices, wiring distance between nodes, and network topology • Limited frequency of communication • Noninteroperable • High bit rates difficulties • Complex routing • Sensitive to disturbances • High cost of ownership • Complexity of management	• Monitoring and management of DERs, automation and protection of SA [29] Examples: • **India:** Analysis of industry reports reveal that India will install 130 million smart meters having both PLC and wireless technologies by 2021 [54] • **Japan:** PLC for smart meter connectivity of high-rise buildings [106] • **Germany:** Testbed supervised by Vattenhall covers only the LV part of the distribution grid (underground with two secondary substations 10/0.4 kV, 24 direct load control nodes on customer premises). Moreover, an urban grid with high user concentration [83] • **Israel:** Testbed supervised by IEC, MV (up to 25 secondary substations 22/0.4kV, underground). Represented all typical MV underground topologies in the Israeli distribution grid, and covers approximately 1.5km^2, including 32 secondary substations (22/0.4 kV) and approximately 10 km of MV lines [83]
	Fibre optics	Up to 100 Tbps	10–60 km	• High capacity • Stable characteristics • Very long distance • Ultrahigh bandwidth • Robustness against interference • Provides the best value for latency, jitter, and current differential • Provide teleprotection	• High deployment cost • High cost of terminal equipment • Difficult to upgrade • Not suitable for metering applications	• NAN, WAN, and physical network infrastructure in smart grids [29] Examples: • **USA**: 100% fibre optic network for smart grid applications in Chattanooga, Tennessee by Electric Power Board (EPB) [161] • **USA**: Fibre optic network across Northern Georgia for its smart grid initiatives [93] • **USA**: LUS, a publicly owned utility company in Louisiana built a municipal-owned FTTH broadband network. This is later extended to smart grid projects using the network for communications backhaul [93]. • **Thailand:** Partnership between the Provincial Electricity Authority (PEA) and Huawei for smart grid solutions. PEA serves 17 million customers in 99.98% area of Thailand (approximately 101713 km and 24000 km of optical fibres) [162]. • **Singapore**: Dedicated fibre optic link at Experimental Power Grid facility to mainland Singapore [163]
	Fieldbus	9.6 kbps–10 Mbps	200 m–1.9 km	• High durability • High reliability • Mature • Standardised	• High equipment cost • Complex maintenance • Rely heavily on complex proprietary manufacturer equipment • Various Fieldbus solutions are not readily interchangeable • Low data transmission rates	• FAN/NAN communication: field devices communication, • Modbus RTU is frequently used in SCADA systems to connect RTUs to the control panel
	Industrial Ethernet	Up to 100 Mbps	100 m	• Reliable performance • Ruggedised hardware for harsh environment • Supported by various industrial equipment manufacturers	• High cost • Low scalability • Distance limitation • Deployment limitations • Need regular maintenance • Susceptible to noise	• FAN/NAN, HAN, communication between substations and substations to control centres, communication between smart meters and home central units
Cellular Communication	**4G LTE**	Up to 100 Mbps	10–20 km	• Existing infrastructure • Wide area of deployment • High data rates • Security features • High communication speed • Operation within the licensed spectrum ensures control over a number of users and protocols used • Supports millions of devices • High flexibility, suitable for different use cases • Licensed spectrum • Open industry standards	• Availability is not guaranteed in harsh environmental conditions • Network congestion for high user density area • Critical for emergency applications	• Monitoring and management of DERs, SCADA [29] Examples: • **Japan:** For smart meter connectivity in rural areas [106]
	Private LTE	Up to 100 Mbps	10 – 20 km	• Reliable and secure • Licensed spectrum • May be managed either by a utility or an outsourced provider • Can be managed to the desired reliability and security levels and coverage • Provides more control over the product life cycle • Cost-effective • Great spectrum addressing for both coverage and throughput • Competitive pricing	• Only viable if FAN and NAN applications feed into private LTE via fibre backbone	• Field area network (FAN) applications, IoT asset management, DA, DER, SCADA, and AMI backhaul Example: • **Japan**: Nokia private wireless LTE solution for industrial applications is complemented by Nokia's mission-critical IP-MPLS, optical, wireless backhaul, and passive optical LAN solutions [164]. • **Brazil:** Metering support for utility providers [165] • **China:** Smart meter deployment in Yingtan, Wuxi, Zhuhai, Chengdu, Chongqing, and Beijing [166] • **Mexico:** Private LTE as a backbone for AMI [167]

TABLE 7. *(Continued.)* **Summary of technical features, advantages, disadvantages, and several use cases of wired and wireless communication technologies in active distribution network and the smart grid.**

	5G	Up to 20 Gbps	10 m to several hundred meters (depending on cell size)	• Enhanced from 4G LTE • Supports a wide scope of different use cases • High flexibility and scalability • Network slicing ability • interoperability among devices and networks • Reliable, often equipped with redundancy features • licensed spectrum	• Technology is yet to mature • Security and privacy issues are yet to be solved • Costly migration to new devices • Low penetration, low coverage • Expensive infrastructure setup	• NAN, WAN, and distributed monitoring and control [29] Examples: • **China**: 5G power splicing by China Telecom Jiangsu, SGCC Nanjing Power Supply Company and Huawei in April 2019 under the 5G SA specs (3GPP) [168] • **Finland:** WIVE project focuses on uRLLC and mMTC features of 5G for low latency remote control of machines [169]–[171] • **Finland**: VPP project to test 5G and IoTs for DR. Batteries will supply power for short periods of time when peak load occurs [169],[172] • **UK**: 5G is considered for ubiquitous connectivity in power systems via neural grid connection [169],[173],[174] • **EU**: VirtuWind for control and communication in inter and intradomain scenarios [169],[175] • **EU:** Smart5Grids from Jan 2021 – 2024 for 5G network platform customised for modern smart grids [176] • **China:** State Grid electric IoT (SG-eIoT) system will be equipped with comprehensive state awareness functions, efficient info processing functions, and flexible response functions to accelerate the building of smart homes and cities [169]
LPWAN	**NB-IoT**	127 kbps to 10 Mbps	Up to 10 km	• Low cost • Low energy consumption • Low complexity • High scalability • Uses existing cellular infrastructure • Strong coverage • Secure and reliable because NB-IoT is a licensed cellular standard	• Reduced bit rates and higher transfer delays • High latency • Low data volumes	AMI and smart meters Examples: • **India**: Tata Power Delhi Distribution deployed 230,000 smart meters with NB-IoT communications [177] • **Sweden**: ○ Olofström Kraft energy utility upgraded from PLC to NB-IoT communication for smart metering, in partnership with Landis+Gyr for software and maintenance in 2019 [178] ○ Telia Company and E.ON energy utility partnership for connecting smart meters in one million homes in Sweden [179]
	LoRaWAN (LoRa)	0.3–27 kbps	15 km	• Low power • Long range • No interference with different data rates • Enhances gateways capacity by creating virtual channels • Low-cost secure bidirectional communication	• Low data rate • Cybersecurity: no defined standards, hence ongoing upgrades (not a mature technology) • Use cases for utilities are scarce • Low coverage for rural/remote areas	• NAN, WAN, management of operation and equipment, online monitoring of power transmission lines and tower [29] Examples: • **Germany**: Netze BW, the largest electricity, gas, and water distribution network company in Germany's third-largest state, has launched the country's largest LoRaWAN deployment [180]. • **Rwanda**: Pilot project in Kigali where the Inmarsat Consortium deployed a network of LoRa-based IoT devices that uses satellite communication exclusively as the backhaul [181]
WANET	**Wireless mesh/RF-Mesh**	10–100 kbps per terminal	3–5 km (urban, no repeaters)	• Able to dynamically form ad-hoc communication • Highly reliable in remote telemetry and distributed control applications • Able to increase communication range via performing multihop • Able to overcome variable propagation conditions • Supports remote firmware upgrade over the air interface in a secure and controlled manner • Low cost • Self-healing • High scalability • High data rate	• Prone to interference and fading • Low network coverage in rural areas due to a low density of smart meters • Prone to loop problem due to the inclusion of multiple relay nodes • Complex network management	• HAN, NAN: monitoring and management of DERs, automation and protection of SA. Examples: • **Australia:** The government mandated the roll-out of the smart metering program in 2009 which ended in 2013 with 2.8 million installations of smart meters having radio frequency mesh technology and WiMAX [54]
	Zigbee	250 kbps	10–100 m (line of sight)	• Low cost • Small size • Uses a relatively small bandwidth • Unlicensed frequency • Allow real-time energy monitoring for customers • Good energy consumption • Provide real-time dynamic pricing • Zigbee is at least two times more cost-effective and efficient than WiFi	• Small battery (limited lifetime) • Small memory • Limited data rate • Low processing rate • Possible interference with other signals • Low bandwidth	• HAN, NAN, energy monitoring, smart lighting, home automation, and automatic meter reading [29] • Leading smart-meter manufacturers, such as Landis+Gyr and Itron, use Zigbee technology or IEEE 802.15.4 standard for wireless communication of their smart meters [182] Examples: • **USA:** smart thermostat and HEMS for energy control via Zigbee gateway and customer's home broadband in Georgia [93]. • **Finland:** Gridstream smart metering solution from Landis+Gyr for Helen Electricity Network uses Zigbee technology[183] • **France**: A first lot of 300,000 smart meters installed by Enedis Operator (Paris, France) communicate to in-home displays using Zigbee or KNX interface [184]
	WirelessHART	250 kbps	10–100 m	• Backward compatibility, robust, reliable • Long battery life (10 years) • Works with most existing field devices to support field calibration and diagnostic • Uses multihop mesh network topology to increase range • Self-configuring • self-healing	• Low data rate • Short range • No dedicated security specification	• HAN and NAN: Smart meters, substation monitoring, energy management, and industrial automation Examples: • Smart home testbed: WirelessHART network for the dynamic control of power converters in smart home applications [185] • DER: WirelessHART sensor node for solar energy harvesting mechanism via PV cell array [186]

TABLE 8. **Commonly used IEC protocols in power systems and distribution network [8],[194].**

Family standard	Description	Standard no.	Title
IEC 60870	- Proposed by IEC Technical Committee 57 Working Group 3 (IEC TC57 WG3) - Interface of information between station-side RTU and the dispatching system - Constantly evolving with the development of software and hardware technology - Remote protocol is the interface between RTU and the dispatching system for information exchange - Standardised protocols enable equipment from different suppliers to interoperate - IEC 60870-5 define systems used for telecontrol and SCADA in electrical power system automation applications - IEC 60870-5-101: improved real-time communication capability; adopts 3 layers (physical layer, data link layer, application layer); application layer is directly mapped to the data link layer to enhance the real-time information; provides a set of communication files for sending basic messages between the primary station and RTU; suitable for P2P, machine to person (M2P), star, and ring network topologies; Require fixed dedicated telecontrol channel - IEC 60870-5-104: focuses on telecontrol protocol; employs a reference model derived from the ISO-OSI Reference Model but uses only the physical, data link, network, transport, and application layers; is a combination of IEC60870-5-101 and network transmission functions provided by TCP/IP, making IEC60870-5-101 compatible with a variety of network types supported by TCP/IP; provides the transport layer using the TCP protocol; uses application protocol control information (APCI)	IEC 60870-5-1	Transmission Frame Formats
		IEC 60870-5-101	Transmission Protocols—Companion Standards Especially for Basic Telecontrol Tasks
		IEC 60870-5-102	Transmission Protocols—Companion Standard for the Transmission of Integrated Totals in Electric Power Systems (Not Widely Used)
		IEC 60870-5-103	Transmission Protocols—Companion Standard for The Informative Interface Of Protection Equipment
		IEC 60870-5-104	Transmission Protocols—Network Access for IEC 60870-5-101 Using Standard Transport Profiles
		IEC 60870-5-2	Data Link Transmission Services
		IEC 60870-5-3	General Structure of Application Data
		IEC 60870-5-4	Definition and Coding of Information Elements
		IEC 60870-5-5	Basic Application Functions
		IEC 60870-5-6	Guidelines for Conformance Testing for the IEC 60870-5 Companion Standards
IEC 61850	- For communications within an electrical substation with the aim to facilitate interoperability between different electrical equipment manufacturers - Current mappings of abstract data models are to Manufacturing Message Specification (MMS), Generic Object Oriented System Event (GOOSE), Sampled Values (SV), or Sampled Measure Values (SMV) - The IEC6150 features include the following: a) Data modelling—Primary process objects and substation protection and control functionalities are modelled into different standard logical nodes and grouped under different logical devices b) Reporting schemes—various reporting schemes or reporting data from the server via a server-client relationship that can be triggered based on pre-defined trigger conditions. c) Fast transfer of events—Generic Substation Events (GSE) are defined for the fast transfer of event data for a P2P communication mode d) Setting groups—handle the setting groups so that user can switch to any active group according to the requirement e) Sampled data transfer—Schemes are defined to handle transfer of SV using SVC blocks (SVCB) f) Commands—supports various command types g) Data storage—Substation Configuration Language (SCL) is defined for complete storage of configured data of the substation in a specific format Supports all TCP/IP-based wired and wireless communication technologies, as specified in IEC 61850-7-420	IEC 61850-1	Introduction and Overview
		IEC 61850-2	Glossary
		IEC 61850-3	General Requirements
		IEC 61850-4	System And Project Management
		IEC 61850-5	Communication Requirements for Functions and Device Models
		IEC 61850-6	Configuration Description Language for Communication in Electrical Substations Related to IEDs
		IEC 61850-7	Basic Communication Structure for Substation and Feeder Equipment
		IEC 61850-7-1	Principles and Models
		IEC 61850-7-2	Abstract Communication Service Interface (Acsi)
		IEC 61850-7-3	Common Data Classes (CDC)
		IEC 61850-7-4	Compatible Logical Node Classes and Data Classes
		IEC 61850-7-410	Hydroelectric Power Plants—Communication For Monitoring And Control
		IEC 61850-7-420	DER Logical Nodes
		IEC 61850-8	Specific Communication Service Mapping (Scsm)
		IEC 61850-8-1	Mappings to Manufacturing Message Specification MMS (ISO 9506-1 And ISO 9506-2) and to ISO/IEC 8802-3
		IEC 61850-9	SCSM—Sampled Values Over ISO/IEC 8802-3
		IEC 61850-9-1	Sampled Values Over Serial Unidirectional Multidrop P2P Link
		IEC 61850-9-2	Sampled Values Over ISO/IEC 8802-3
		IEC 61850-10	Conformance Testing
IEC 61968	- Developed by IEC TC57 WG14 - For standardising the integration of the DMS application function	IEC 61968-1	Interface Architecture and General Requirements
		IEC 61968-2	Glossary
		IEC 61968-3	Interface For Network Operations

TABLE 8. ***(Continued.)*** **Commonly used IEC protocols in power systems and distribution network [8],[194].**

	- The standard divides the DMS into several abstract application components and defines the interface specifications for each component from the overall business function point of view - Addresses: DMS architecture; data modelling; functional design; and subsystem interface design - Facilitates system integration of multiple distributed software applications that support grid management	IEC 61968-4	Interfaces For Records and Asset Managements
		IEC 61968-5	Interfaces for DERs Optimisation
		IEC 61968-6	Interfaces for Maintenance and Construction
		IEC 61968-7	Interfaces for Network Extension Planning
		IEC 61968-8	Interfaces for Customer Support
		IEC 61968-9	Interface Standard for Meter Reading and Control
		IEC 61968-10	Interfaces for Business Functions External to Distribution Management (Includes Energy Management & Trading, Retail, Supply Chain and Logistics, Customer Account Management, Financial, Premises, and Human Resources)
		IEC 61968-11	Common Information Model (CIM) Extensions for Distribution
		IEC 61968-12	CIM Use Cases For 61968
		IEC 61968-13	CIM RDF Model Exchange Format for Distribution
		IEC 61968-100	Application Integration at Electric Utilities - System Interfaces for Distribution Management
IEC 61970	- A series of international standards of EMS-API, for facilitating the integration of various applications within EMSs from different manufacturers	IEC 61970-1	Guideline
		IEC 61970-2	Terminology
		IEC 61970-3xx	CIM
		IEC 61970-4xx	Component Interface Specification
		IEC 61970-5xx	Component Interface Specification Technology Mapping

between several systems, which regularly causes issues such as interoperability across network protocols and management information. Thus, standardised solutions are required for wide-scale and cost-effective deployment, interoperability, and open interfaces for future extensions, all while satisfying general communication infrastructure requirements such as security, latency, reliability, and data delivery criticality. Although standardisation is critical for the construction of the active distribution network and the smart grid, the standards generally include standardisation of interface and products, which details common requirements (but not specific applications and business cases) with rooms for innovation and development in the power grid industry. Several organisations such as the IEEE, the International Electrotechnical Commission (IEC), and the National Institute of Standards and Technology (NIST) are actively working on smart grid and active distribution network communication standards [3]. Table 8 summarises the family of IEC standards directly applicable to the active distribution network, while Table 9 summarises the network standards which support the communication of active distribution network applications.

III. ISSUES, CHALLENGES, AND OPPORTUNITIES IN ACTIVE DISTRIBUTION NETWORKS

This section highlights some of the issues and challenges in active distribution networks as well as several opportunities and research trends in the distribution domain through the ICT perspective.

A. ISSUES AND CHALLENGES

1) EVOLVING COMMUNICATION REQUIREMENTS

As ICT advances, the way electric energy is produced, stored, and saved on the grid changes, paving the way for a growing smart energy infrastructure. In contrast to traditional grids' one-way information flow, modern power grids are complex interconnected systems with bidirectional energy and information transfer from utility to customers, introducing new energy ecosystems and diverse applications and services close to the active distribution network. For example, consumers are now able to become energy producers (prosumers) and engage in energy trading at the edge of the power grid, whereas utilities are able to gain real-time insights into the supply and demand trend of electricity and detect outages and issues instantaneously through sensors in the distribution network. These applications come with stringent communication requirements that must be anticipated while building the communication infrastructure of the grid. Current and future grid communication infrastructure must be able to support the exponential increase of connected devices, the emergence of bandwidth-hungry applications such as on-site video surveillance of remote substations, and the increasing connections of DERs and microgrids, all while maintaining high reliability and QoS.

2) COMMUNICATION RELIABILITY AND SECURITY

Reliability is one of the most important requirements for a communication network in the energy transmission and distribution domains. Some of the possible causes of network failures affecting the reliability of communication devices are link/node failures, routing inconsistencies, RFI, harsh/hostile environment, aging infrastructure, and overloading [45], [46], [47], as well as other technical challenges such as limited data rates, availability of backup power for wireless devices, and low transmission power level. Some important distribution network applications, such as DA, require a high level of data connection reliability, whereas others may tolerate minor data transfer disruptions. As previously discussed in Section 3, both wireless and wired communication technologies are significant components of the active distribution network, with each having its own set of advantages and disadvantages. In many circumstances, hybrid communication technology combining wired and wireless solutions (refer to Section 3.3) can be employed to improve system reliability, stability, and resiliency [26]. Additionally, redundancy topology may be employed to improve reliability. For example, employing a dual ring topology in a communication network provides redundancy in case of failure and acts as an additional data path.

Maintaining a secure network against hostile attacks is becoming increasingly crucial as distribution grids become more interconnected with various smart devices. These interconnections inevitably come with more vulnerable points that must be safeguarded against malicious attacks. Security measures must cover issues involving communication and automation that affects the operation and management of the distribution grid. It must address deliberate attacks, such as malware, as well as unintentional accidents, such as user error and equipment failure [26]. For example, if the communication between a smart meter and the network is compromised, any malicious party could manipulate the billing for the utilities. As with any other communication system, active distribution communication security can be improved at multiple layers of the protocol by employing approaches ranging from traditional upper layer encryption and authentication [187], [188], [189] to physical layer security [190], [191], [192]. For short-range P2P wireless communication, the use of a directional antenna to limit the availability of signals outside of the targeted area may be one of the possible physical layer security measures [193].

3) COMMUNICATION INTEROPERABILITY

The active distribution networks are interconnected with various communication and networking systems delivering various applications to the consumers while interacting with other smart grid domains such as transmission and generation. These interconnections and interactions necessitate smooth communication interoperability in-between multiple systems, applications, and domains. This problem can be solved by developing standards like those issued by IEC, NIST, and IEEE, with some stakeholders suggesting standardisation on the implementation of the IP for Smart Grid communications [39]. However, some standards may not be interoperable and may contradict with one another due to functional variances produced in different countries or geographic areas. For example, China and the USA are implementing GB/Z 20965, and ANSI/ASHRAE 135-2008/ISO 16484-5/BACnet for AMI instead of the primary AMI standards of IEC/TR 62051, IEC 61968, IEC 61969, and AEIC Guidelines v. 3.0 [3], [42].

TABLE 9. Summary of the network standards which support communication of active distribution network applications.

Applications	Relevant standards
DMS	IEC 61968 IEC 61850-7-420
DA	IEC 61850-7-4 IEC 61970
DERs	IEC 61850 IEC 61850-7-420 IEC 61400 (wind turbine)
DR/load management	IEC 61968 IEC 61850-7-420 AEIC Guidelines v. 3.0 GB/Z 20965 (China) ANSI/ASRAE 135-2008/ISO 16484-5 BACnet (USA)
Smart metering	IEC 62056-x IEC 61334-x
SA	IEC 61850
ES	IEC 61850-7-410 (hydroelectric) IEEE P2030.2
RES	Wind power (IEC 61400) Solar (IEC 60904, IEC 61194, IEC 61724, IEC 61730, IEC TS 61836, IEC 62446, IEC 62257, IEC 61727) Fuel cells (IEC 62282) Pumped storage (IEC 60193, IEC 60041) DG (IEC62257, IEEE 1547.3) Nuclear generation (NERC/NUC-001-1) Conventional power (IEC 60308 -hydraulic turbine, IEC 61850-7-410 - hydroelectric)

4) NETWORK PROTECTION AND CONTROL FOR RESILIENCY

The large interconnections of DERs to the distribution grids create several critical problems that impair the reliability and resiliency of the power grid. Although the integration of these energy sources into the power grid is one of the reasons for the digitalisation of the grid, it also increases cybersecurity risks due to the massive amount of critical data and introduces random bilateral power flow and variable power load in the distribution network. These issues present a significant difficulty in the implementation of a resilient and reliable network, which drives great changes in the operation and planning of electric grids [195]. Active research on network protection and control addressing these issues is needed, including cyberphysical vulnerability analysis of the ever-changing distribution network topology, investigation on state-of-the art resilient network practices, and active management, planning, and operation of the mass distribution network information.

5) OTHER ISSUES AND CHALLENGES

Other issues and challenges in the active distribution network include the following:

a: MIXED CRITICALITY SYSTEM

One of the challenges in the distribution grid communication network is the mixed criticality systems, in which data traffic with different levels of criticality (or importance), and varying delay and reliability requirements need to be delivered. A mixed-criticality system typically comprises of safety-, mission-, and low-critical data types, which reflects the consequences to the systems if the data failed to be delivered within its corresponding deadline bound. Failures of adhering to the criticality requirements affect the reliability of the network and consequently may lead to network failures. Farag et al. [196] focused on the fundamental problem of integrating different traffic classes in a disciplined way to meet their respective requirements, e.g., delay and reliability, in resource-constrained networks. Particularly, they proposed a wireless Fieldbus protocol to enable real-time communication and service differentiation for cluster-based mixed-criticality networks, which may be applicable in distribution SA. Conversely, Mohamed Radzi et al. [197] presented a context aware traffic scheduling algorithm for scheduling data traffic that can react to changing power network conditions. The traffic on the power distribution network is classified based on diverse traffic demands and then classified into weighted quality groups.

b: REAL-WORLD TESTBED

Current distribution networks have evolved from a physical electrical system with one-way communication flow to complex cyberphysical systems involving a variety of hardware and software elements working together for innovative grid automation, control, and management. As the ICT and power sectors expand more innovative applications and services emerge. For example, the adoption of blockchain technology from the Bitcoin financial system for P2P energy trading, as presented by Wu et al. [198], and the implementation of IoT for distribution network monitoring [86]. Although various innovative studies and inventions to improve power grids emerge, these research efforts tend to stay as theoretical frameworks or limited computer simulations with no real-world testing and feasibility assessments. This problem is largely due to the prohibitively expensive cost of developing and deploying real-world testbeds, as well as the risks of jeopardising the grid's reliability and resiliency during the testing of new smart grid technology [8]. Hence, this issue has become one of the main challenges in determining the benefits of these innovations and research efforts.

c: COMPLEX CONSIDERATIONS

Other than the real-world testbed issue, the implementation of new ICTs in the active distribution network is highly dependent on the goal of the utilities in using simple and reliable solutions, which are low costs and future-proofed for holistic long-term solutions. Many complex considerations must be made involving technical criteria (e.g., whether the technology can support future network expansion in terms of bandwidth, latency etc.), economics (cost–benefit analysis and life-cycle cost analysis of the technology/project), standards and regulations which must be adhered to, and types of service (either privately owned by the utility or using public infrastructure/hiring commercial communication industry), geographical constraints (e.g., dense urban environment and vast coastal area). Utilities may use decision making tools such as the multicriteria decision making (MCDM) using The Technique for Order of Preference by Similarity to Ideal Solution [199] or MCDM analytical hierarchy process (AHP) [200], which provide rational, systematic, and reliable frameworks for decision making involving both qualitative and quantitative criteria. MCDM techniques have been implemented in various fields and applications, such as Lee et al. [201] who used several MCDM approaches to rank the priority of a list of RES for implementation in Taiwan and Balioti et al. [202] who used fuzzy MCDM to present an optimal spillway selection in water management.

B. OPPORTUNITIES AND RESEARCH TRENDS

This subsection briefly discusses some of the emerging technologies and research opportunities in the active distribution network including the energy Internet (EI) (or Internet of energy/Enernet), big data analytics, machine learning, edge computing, and blockchain technology

1) EI THROUGH THE IOT TECHNOLOGY

The EI is one of the most recent advancements in the power industry, and is dubbed as the smart grid 2.0, which is an Internet-style solution for energy-related issues that integrates IoT, advanced ICT, power system components, and other energy network components [4]. Through IoT, any object including power system equipment, may be connected to the Internet by utilising a protocol for exchanging information and communication among smart devices to achieve monitoring, tracking, management, and location identification goals [203]. These objects perceive, analyse, control, and decide independently or in collaboration with other objects via distributed, autonomous, and ubiquitous high-speed and two-way digital communications. Hence, IoT technology can assist active distribution networks realise the EI vision by embedding IoT devices such as sensors, smart meters, and actuators, and providing connectivity, automation, and tracking capability of those devices [29]. Although IoT has been applied in various industries, the smart grid is considered to be one of the largest applications of the IoT [33], with numerous research currently underway for the implementation of IoT in the power grid domains.

Examples of IoT applications and studies pertaining to the active distribution network can be found in [204], [205], [207], [208], [209], and [210], with an in-depth review of IoT-aided smart grid in [29]. Particularly, Li et al. [204] presented the connection of a group of smart homes in a neighbourhood through a NAN to form a smart community, and Zhang et al. [205] demonstrated the IoT smart distribution network, which ensures monitoring and secure operation of the distribution grid in Hebi, China, using various sensors such as temperature and noise sensors over Zigbee, GPRS, 3G,and power over fibre. Conversely, Zhuang et al. [206] presented an insulation condition monitoring of the distribution power grid application using IoT-based partial discharge sensing networks through LoRa/NB-IoT-based network structures. Chen et al. [207] focused on the problem of QoS guarantee by proposing a priority-queue-controlled multiservice access mechanism for IoT-based DG management system, whereas Chen et al. [208] proposed a robust and expansion-available framework design for IoT monitoring devices in power distribution network, using NB-IoT communication. Tom et al. [209] proposed an IoT-based SCADA integrated with fog computing for DA system, which takes care of consumer utilisation, outage management, power quality control, and pole transformer health. These capabilities are supported by fog computing, which does real-time streaming analytics to reduce the internet bandwidth and latency for immediate control action. Lastly, Yunshuo et al. [210] proposed an IoT-based distribution power quality monitoring system, which adopted the top-level technical architecture of ''cloud, channel, edge, and terminal'' and takes the intelligent transformer terminal unit as a core. Although there have been considerable IoT studies conducted in the power distribution network, much more remains to be done for the better and complete realisation of EI through the implementation of IoT in the power distribution and the grid.

2) BIG DATA ANALYTICS, MACHINE LEARNING, AND EDGE COMPUTING

The distribution grid is becoming more connected with a multitude of interconnected smart devices performing various monitoring and control functions, which inevitably give rise to an avalanche of data that needs to be processed and analysed for value extraction. Through the advancement in big data analytics, machine learning and edge computing fields, power utilities are more equipped to evaluate and analyse the massive incoming data from smart meters, network monitoring and management systems, and field devices, among others [27]. Big data analytics describes the process of identifying trends, patterns, and correlations in vast amounts of raw data to make data-informed decisions. These procedures employ well-known statistical analysis approaches, such as clustering and regression, and apply them to larger datasets with the assistance of newer tools and technologies such as machine learning. Conversely, edge computing brings processing and storage resources closer to the data source, reducing latency and congestion [3].

Through these data processing tools, utility providers can learn from the data, adapting the characteristics of the users and quickly programming themselves for potential damaging events that may occur in the energy networks. An overview of the promising applications of big data analytics in the distribution network can be seen in [211], in which Yu et al. highlighted energy theft detection, modelling of customer consumption behaviour, forecasting spatial load and renewable energy, distribution system visualisation, state estimation, and distribution system planning. Conversely, Miao et al. [212] discussed the opportunities and challenges of big data analytics in distribution grids. Some of the big data analytics researches in the distribution grid include distribution network state detection [213], analysis of operation and maintenance status of a power communication network [214], the study of data identification in power system optimisation [215], and flexible distribution network load analysis [216].

Machine learning research in the active distribution network includes load forecasting process for maintenance planning [217], fault detection, and intelligent monitoring of power distribution network [218], [219], [220], [221], power flow management [222], [223], optimal planning of distribution network [224], and decision making problem in communication technology selection of power distribution substation [225]. Some of the research on edge computing applied in the distribution network can be found in [119], [226], [227], and [228]. The utilisation of big data analytics, machine learning, and edge computing is becoming increasingly crucial as more data-driven applications arise in the active distribution network, which are needed for generating meaningful insights on the large volume of data in the network. Hence, future studies should be directed to these areas.

3) BLOCKCHAIN TECHNOLOGY

Another emerging technology that is garnering considerable attention in the power industry is blockchain. Blockchain technology is one of the pillars of Bitcoin, an innovative financial system introduced by Satoshi Nakamoto in 2008 [229]. Blockchain operates as a distributed and decentralised database, with nodes connecting to one another via a communication network. One of its primary qualities is the guarantee of information accessibility, transparency, immutability, and integrity [4], [27]. Other features include decentralisation, scalability, resiliency, and secure script deployment through smart contracts, which enable the automation of agreement execution when predetermined conditions are met [4]. Additionally, this technology can improve the following challenges in communication systems [230]:

1. **Security and privacy issues:** Blockchain solves these issues through data decentralisation and encryption, which allow only authorised users to access any collection of data. Furthermore, because each record on a blockchain's distributed ledger is linked to the preceding and subsequent entries, cybercriminals would have to change the entire chain to change a single record.
2. **Interoperability issues**: For example, TOP Network, a decentralised blockchain ecosystem, creates a standard communication protocol to make all the decentralised apps in its ecosystem interoperable [231]. IoT and EI, which demand the smooth integration of multiple applications and devices, can benefit from blockchain interoperability.

3. **Cost and communication speed issues:** This technology substitutes the centralised access point used in conventional VoIP solutions by routing the signal to a receiving number and replacing it with a distributed network shared by all network users. This removes any routing costs because the distributed ledger has already defined all routes while ensuring security and maximising data transmission speed.
4. **Reliability issues**: Blockchain allows for the optimisation of unused bandwidth from servers all over the world. It connects them into a complicated nest of servers that can transport data around the world in real time. Because blockchain decentralises bandwidth points, any single server crash or service outage can be nearly instantaneously repaired by rerouting through the network's many thousands of other points, consequently improving reliability of the communication network.

Despite being a relatively new field of study, blockchain has already garnered considerable attention in the energy industry, as evident from the review of blockchain technology for future smart grids in [4] and the various studies in [232], [233], [234], [235], and [236]. Particularly, this technology can be used to commercialise DG energy [232], register and trace power supply chain and renewable energy generated by third parties and provide real-time energy markets [233], provide access to EV charging and discharging systems [234], and provide security tools against cyberattacks on microgrids and power grids [235], and secure node switching in power distribution IoT [236]. Another possibility is adopting blockchain in SCADA technology as briefly discussed in [27]. Blockchain's distributed ledger technology enables the sharing of data from other control and management systems to provide QoS without any privacy concerns.

IV. CONCLUSION

Power grids are transitioning from a centralised mode of operation with one-way energy and communication flows to smart grids with decentralised operation and bidirectional energy and information exchange. These changes are driven by the connection of numerous ''active loads'' such as DERs close to distribution grids, which reverses the traditional power flow direction. Through the implementation of advanced and sophisticated ICTs, efficient DERs management as well as various applications for reliable and secure power delivery can be realised. Nonetheless, several challenges remain before adopting any ICT solution in the grid, such as interoperability, security and privacy concerns, and increasing demands to support various services. Although the information within the grid is becoming more visible as a result of bidirectional communication flow, this only applies to transmission networks and not active distribution networks, which house numerous smart grid applications. Additionally, there is relatively little research providing an updated and comprehensive review to support the automatic operations of active power distribution communication networks. Therefore, this review article explores and reviews the communication technologies applicable in active distribution networks, as well as several applications and communication standards in smart grids and active distribution networks. This review paper also highlights some of the issues and challenges associated with active distribution networks and several opportunities and research trends in the distribution domain from an ICT perspective.

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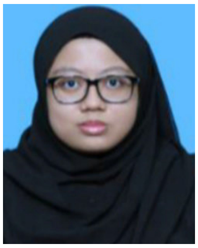

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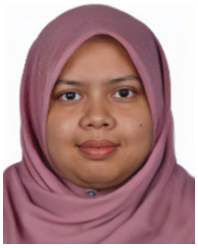

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