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# Current and Future Communication Solutions for Smart Grids: A Review

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**ABSTRACT** A smart grid provides a bidirectional flow of electricity and information whilst ensuring well-balanced electricity supply and demand. The key enabler for the smart grid is its robust communication infrastructure. Choosing the best communication technology for the smart grid is crucial as it involves a mixture of critical and non-critical traffic. This study provides a comprehensive review on smart grid communication and its possible solutions for a reliable two-way communication toward supporting diversified power grid applications. Existing networking methods along with their advantages and weaknesses are highlighted for future research directions. The communication network architecture in the smart grid, with details on each networking technology, switching methods and medium for data communication, is critically reviewed to identify the existing research gaps. A discussion on issues and challenges encountered in smart grid communication for current implementation is highlighted together with the recommendations for further improvement. Overall, the highlighted issues and recommendations from this study are useful to researchers, technology providers and industries to develop new communication technologies for the smart grid that will provide reliable, robust, and suitable two-way communication in the future.

**INDEX TERMS** Communication technology, networking method, smart grid.

## NOMENCLATURE

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

| | |
|---|---|
| 6LoWPAN | IPv6 over low-power wireless personal area network |
| ABF | Air-blown fibre |
| ADSL | Asymmetric digital subscriber line |
| ADSS | All dielectric self-supporting |
| AMI | Advanced metering infrastructure |
| API | Application programming interfaces |
| CWDM | Coarse wavelength-division multiplexing |
| DoS | Denial of service |
| DSL | Digital subscriber line |
| DWDM | Dense wavelength-division multiplexing |
| FAN | Field area network |
| HAN | Home area network |
| HF | High frequency |
| ICS | Industrial control services |
| IP | Internet protocol |
| IP-MPLS | Internet protocol-multiprotocol label switching |
| IT | Informational technology |
| LAN | Local area network |
| LSP | Label switch path |
| LTE | Long Term Evolution |
| MAC | Media access control |
| MPLS-TP | Multiprotocol label switching–transport profile |
| NAN | Neighborhood area network |
| non-ICS | Non-industrial control services |
| OAM | Operations, administration and maintenance |
| OPGW | Optical ground wire |
| OT | Operational technology |
| OTN | Optical transport network |
| PHY | Physical layer |
| PLC | Power line communication |

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| | |
|---|---|
| QoS | Quality of Service |
| RF | Radio frequency |
| WAN | Wide area network |
| WDM | Wavelength-division multiplexing |

## I. INTRODUCTION

Current power grids are based on one-way interaction from generation to transmission, then distribution, and finally to consumers. It functions in an open-loop manner in which the control centre has minimal real-time information on the dynamic changes in the system's load and operating conditions. The insufficient communication infrastructure in the transmission domain, combined with aging infrastructures, has caused vulnerability of the grids toward regular disruptions [1]. Besides, connecting large-scale renewable energy resources to the distribution grid reverses the traditional direction of power flow [2]. Furthermore, electric vehicles can also serve as storage devices to feed power back to the grid, but this scheme requires a two-way energy flow [3]. These migrations have promoted the development of smart grids.

A smart grid is a decentralised and integrated energy supply network that provides bidirectional electricity and information whilst ensuring an almost real-time equilibrium in supply and demand. It is achieved with the implementation of advanced sensors known as Phasor Measurement Units (PMUs) that allow operators to evaluate grid stability; PMUs use advanced digital meters to provide customers with better information and automatically monitor failures, relay sensors which automatically detect and recover from substation failures, automated feeder switches that re-route power around problems, and batteries that store extra energy to be fed back to the grid [4]–[6]. The key enabler for smart grids is the robust communication infrastructure [5].

A survey of current state-of-the-art smart grid communication configurations was conducted by Faheem *et al.* [7], and they discussed on opportunities and challenges of smart grids from the perspective of Industry 4.0. Critical smart grid components were presented together with their standardisation and technologies related to Industry 4.0. A review and complete analysis of 5G network in a smart grid was presented in [8]. The authors discussed the current status of 5G and future roadmaps, with an emphasis on energy efficiency. An update on power line communications (PLC) was reviewed together with the current applications and challenges in [9]. The software defined network (SDN) was introduced into the smart grid to overcome its interoperability issue. Rehmani *et al.* [10] proposed a detailed survey of communication types on SDN-based smart grids. A review along with a compilation of challenges and issues on edge and fog computing for smart grid application was presented in [11]. A summary of recent related smart grid reviews is presented in Table 1.

Other notable smart grid papers published in the early 2010s that contributed to the current state of smart grid research include the following; i) Gungor *et al.* [12], addressed the critical issues on smart grid technologies primarily in terms of information and communication technology (ICT) issues and opportunities, and they provided a brief review of some of the available communication technologies at the time; ii) Gungor *et al.* [13] discussed application-specific communication requirements, provided a brief overview of potential smart grid communication technologies and discussed some of the challenges and opportunities for communication research in the areas of smart grid and smart metering; iii) Fan *et al.* [14], discussed some of the challenges and opportunities of using the smart grid, particularly in the aspect of smart metering communication research and then discussed the coordinated communication standards and protocol standardisation efforts in Europe; and iv) Yan *et al.* [15] discussed the background, motivation, and challenges of communication systems in the smart grid, with an emphasis on distributed energy resources (DER), smart metering and supervisory control and data acquisition (SCADA) applications.

Recent reviews either focused on a single communication technology used in a smart grid or customised them to a specific application. Reviews published in the previous decade may no longer be relevant, especially as newer or improved communication technologies have emerged in this new decade. Choosing the best communication technology for the smart grid is crucial as a smart grid involves a mixture of critical and non-critical traffics [16]. This mixture of traffic are handled by two different technologies, which will be reviewed in this study. The chosen technology needs to automatically support information exchange amongst a large number of smart meters, Intelligent Electronic Devices, sensors and actuators. With this motivation in mind, in this study we provide a detailed review of the networking method and possible communication solutions for smart grids.

The main contribution of this study can be summarised as follows.

- We provide a complete network architecture in the smart grid, with details on each networking technology, method and medium for data communication. We also review network technologies in current grids and the migration toward the convergence of the technologies.
- We review the networking methods in circuit-switching and packet-switching networks. The comparison of each method in terms of its advantages and disadvantages is summarised and tabulated.
- We review the complete data communication networking medium in smart grids for copper, fibre optics, and radio. The technologies of these media are compared in terms of their roles, advantages and disadvantages.
- We discuss the issues and challenges encountered in smart grid communication for current implementation in terms of cost, design, security, management, reliability, efficiency, distance, time, complexity, geographical, standard and compatibility. We also recommend improvements of current methods.

**TABLE 1. Summary of recent related smart grid reviews.**

| Author and Year | Reference | Description | Advantages | Main Focus |
|---|---|---|---|---|
| Faheem *et al.* (2018) | [7] | Provided a review on the opportunities and challenges of smart grid in the perspective of Industry 4.0 | Reviewed communication technologies in the smart grid | Specific for Industry 4.0 smart grid |
| Sofana Reka *et al.* (2019) | [8] | Provided a review and complete analysis on 5G network in the smart grid | Discussed the current status of 5G and future road maps | Emphasis is on energy efficiency |
| López *et al.* (2019) | [9] | Provided an update on PLC, their applications in the smart grid, and the main challenges PLC is facing | Discussed the possible solutions for PLC main challenges in the smart grid and the current research initiatives | Main focus is on PLC |
| Rehmani *et al.* (2019) | [10] | A survey of communication on SDN-based smart grids | Provided a survey and classification of SDN-based smart grid networks, discussed architectures, case studies, routing schemes, open issues, challenges, and future directions | Specific for SDN-based smart grid networks |
| Gilbert *et al.* (2019) | [11] | A review, challenges and issues on edge and fog computing for smart grid applications. | Provided a literature review to explore the research trend of the implementations, applications, and challenges of edge and fog computing for smart grid applications | Specific for edge and fog computing in the smart grid |

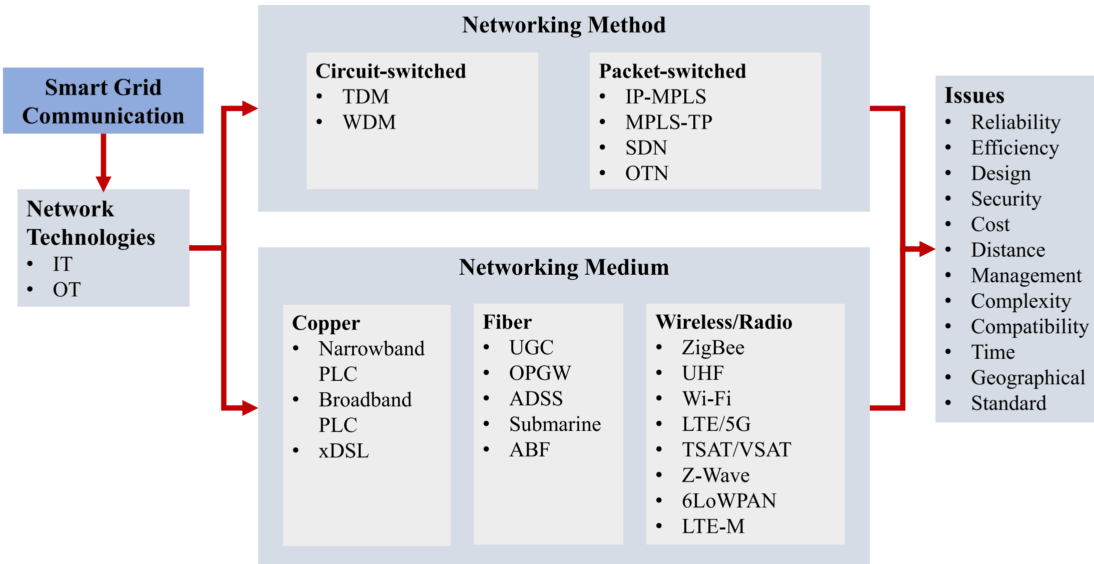


**FIGURE 1. Organisation of the paper at a glance.**

This study can be utilised by researchers, technology providers, and industries to new communication technologies for smart grids, thereby providing reliable and suitable two-way communication.

The rest of this paper is organised as follows. Section 2 provides an overview of the network technologies. Section 3 demonstrates the current studies about methods and techniques in a smart grid network. Section 4 describes the different types of media involved in the network architecture. The issues and recommendations for smart grid networks are presented in Section 5. Section 6 provides the conclusion. Fig. 1 provides an overview of the organisation of this paper.

## II. NETWORK TECHNOLOGIES

Traditionally, the current power grids are divided into two different technologies known as Informational Technology (IT) and Operational Technology (OT). In the age of big data when both IT and OT data need to be combined for strategic competitive advantage, the evolution manifests as the convergence of these two technologies [17]. Both the separation and convergence of systems have their own pros and cons, which will be elaborated and explained in detail in this section.

### A. IT AND OT SYSTEMS

IT is defined as the entire spectrum of technologies for information processing which includes software, hardware, communication technologies and other related services. In general, IT includes embedded technologies that generate data for enterprise use [18]. The application services belonging to this group are email, corporate network, CCTV and firewalls.

Meanwhile, OT is defined as hardware and software that detect or cause a change through direct monitoring and control of physical devices [19]. The devices are designed to work together as an integrated and homogeneous system. If one of the systems fails to operate, then the whole utility system can lead to a catastrophic domino effect. OT is divided into two different categories which are Industrial Control Services (ICS) and non-Industrial Control Services (non-ICS). ICS involves traffic control, such as teleprotection and Supervisory Control and Data Acquisition (SCADA) [20], whereas non-ICS, the traffic involved is online monitoring system.

ICS is an integration of hardware and software with network connectivity to support critical infrastructure. At present, almost all ICS networks are part of the global network owing to the revolution of Internet of Things (IoT). Thus, the monitoring and controlling operations of the actual plant can be conducted remotely from anywhere at any time [21]. Availability is the main priority as it ensure that the power system can stay up and run smoothly. The system must also be high in integrity by ensuring that data in the control room would match the real situation. However, this setup will raise some serious security concerns due to vulnerabilities and the difficulty of changing given the long life cycles of a certain equipment. As a result, this issue may lead to more difficult security testing and patching. Furthermore, the differences in technologies between IT and ICS environments may cause them to be out of sync with one another.

Meanwhile, Non-ICS acts as a complementary system to the ICS, and focuses more on the online monitoring system. An online monitoring system is highly needed, especially when a power equipment is operated in substations so that a continuous monitoring and controlling of the technical conditions can be carried out easily and remotely by operators [22]. Thus, an age replacement policy can be utilised through the online monitoring system, as well as condition monitoring maintenance, which means that the equipment in the power system can be replaced at failure or a specified replacement age. Age replacement is one of the most used maintenance policies based on preventive action in order to prevent the breakdown or failure of power system [23]. Moreover, various information about power system operating conditions can be obtained via the online monitoring system. However, engineering methods are lacking in terms of determining the state of current equipment according to the total measured values.

The comparison between IT and OT is summarised in Table 2.

**TABLE 2.** A summarised comparison between IT and OT [24].

| Category | Informational Technology (IT) | Operational Technology (OT) |
|---|---|---|
| **Function** | • Telecommunication equipment<br>• Focuses on the storage, recovery, transmission, manipulation, and protection of data | • More oriented to the control of processes or their change through the monitoring and control of devices |
| **Area** | • Business-oriented | • Industry-oriented |
| **Access** | • Connected with the outside world | • Very restricted access. Limited to people with certain privileges |
| **Assets vs. workers** | • The number of assets or tangible resources with economic value is usually equal (or close) to the number of professionals | • More autonomous. More assets than professionals |
| **Environment** | • Controlled, stable and constant | • OTs endure adverse weather conditions (extreme temperatures or humidity levels, amongst others) |
| **Interface and Network** | • Web browser, keyboard, and device | • Sensors, coded or touch screens |
| **Updates** | • Constant due to software updates. Service interruptions are tolerable and, in some cases, programmable outside of working hours | • Updates must be tested carefully in advance and usually involve restarting or stopping the machines. |
| **Life cycle** | • Shorter life cycles (3–5 years) | • Longer life cycles (15–20 years) |
| **Cessing requirements** | • Minutes–days | • Milliseconds—seconds |
| **Objective** | • Logical security (no lives at risk). The objective is to protect confidential information from any potential risk (human error, natural disasters, cyberattacks, etc.) | • The objective is to protect the environment, people and infrastructures |
| **Operating System** | • Standard operating systems | • Specific purpose equipment with proprietary operating systems (Custom-developed software) |

## B. CONVERGENCE OF IT/OT

In March 2019, a denial of service (DoS) attack successfully interrupted the electrical systems in Los Angeles County and Salt Lake County in the USA. Although typically, DoS attacks are easily preventable and most large organisations do not consider them as major threats, the US government has recently warned about the non-preparedness of utilities based the previous sophisticated attack [25].

Previously, on March 2016, 225,000 customers lost their power when an OT system in Ukraine Power Grid was under cyber-attack. Power supplied to 30 substations were cut down with the installation of a customer firmware. The OT system of Israel Electric Corporation was also attacked with DoS in 2003, although it failed to shut down the power grid. The possible results of these attacks are delay of information, connection interruption and value alteration from Remote Terminal Unit (RTU) to Master [26].

The attacks in OT systems are isolated from those attacks in IT systems as an OT system is not designed with a cyber-attack detection or defence objectives in mind. Thus, we need to understand the focus of each system. The IT system's main priority is the confidentiality of data, followed by integrity, and finally, availability. The order of priority changes for the OT system, in which the availability of data is the highest focus, followed by integrity and confidentiality. In summary, the main priority of the IT system is to protect data, whereas that of the OT system is to protect the asset base and its associated production. The convergence of these

**TABLE 3.** Advantages and disadvantages of circuit-switched and packet-switched technologies.

| Technology | Description | Advantages | Disadvantages | Techniques |
|---|---|---|---|---|
| Circuit-switched | Fixed path is used where a connection is set up before sending the information | • Consistent bandwidth, channels, and an ongoing data rate<br>• Data packets are delivered in correct sequence | • Dedicating one channel to a single service leaves it unavailable to other services<br>• Expensive to provision an entire channel to one service and one individual routing path<br>• Unable to provide support to the dynamic and flexible grid configuration<br>• Unable to cope with the agility needed for fast response in mission-critical services | • Time Division Multiplexing (TDM)<br>• Wavelength Division Multiplexing (WDM) |
| Packet-switched | Packets are transmitted individually, and they can follow different routes from the source to the destination | • Efficient; packets can find their own data paths to their destination address<br>• Eliminates packet loss; it ensures that packets reach their destination | • Unsuitable for applications that require minimal latency, such as distribution automation (DA) and wide-area situational awareness system<br>• Packets will be dropped in transit during excessive traffic | • Internet Protocol-Multiprotocol Label Switching (IP-MPLS)<br>• Multiprotocol Label Switching–Transport Profile (MPLS-TP)<br>• Software Defined Networking (SDN)<br>• Optical Transport Network (OTN) |

two systems is expected to leverage the best features of both systems, which can greatly benefit the power industry.

The other advantages of IT/OT convergence with respect to the smart grid domain include the digitalisation of information, asset mapping for easier maintenance planning, centralisation, minimisation of breakdown due to prediction, data accuracy and transparency, fast and accurate decision making and integration with the Geographic Information System (GIS) [27].

Despite the above advantages, a thorough study on the extent of OT should be integrated with IT needs. In particular, the following challenges need to be addressed [28]:

- By itself, the OT system is not designed for remote accessibility; hence, it encounters risk in terms of connectivity.
- The OT system is based on the non-standard protocol, making it challenging to interface with existing IT.
- As OT devices are accessible on a public network, they may lead to the wrong operation of the company's equipment and the misuse of information by devices if not controlled properly.
- Different bandwidth requirements may lead to a change in IT infrastructure.
- The data from multiple interfaces have different formats.

## III. MULTIPLEXING AND SWITCHING METHODS IN SMART GRIDS

Communication networks play a critical role in smart grids by allowing bidirectional data communication amongst the existing elements in power grids. Two different categories of switching technologies for data communication exist in the smart grid, namely, the circuit-switched and packet-switched technologies. With circuit-switched technology, a fixed path is used, and a connection is set up before sending the information, as shown in Fig. 2. The entire path used for the information exchange is defined prior to transmission similar to a classic telephone system. Once this path is established, it offers a fixed bandwidth and deterministic delay to the service. Multiplexing methods, such as using time and wavelength division, are needed for simultaneous transmission. These methods and their typical applications in the smart grid will be reviewed in this section.

Meanwhile, packet-switched technology breaks data into a smaller format called packets, as shown in Fig. 3. A packet is a basic unit of communication over a digital network acting as a container or a box that carries data over a protocol known as Transmission Control Protocol/Internet Protocol (TPC/IP) network and internetworks [29]. By using network switches and routers, each packet is transmitted individually where the packets can even follow different routes from the source to the destination [30], [31]. Once the packets arrive at the destination, they will be merged into the original message. Regarding the packet-switched technology, Internet Protocol-Multiprotocol Label Switching (IP-MPLS), Software Defined Networking (SDN), Software Defined–Wide Area Network, Metro–Ethernet and Multiprotocol Label Switching–Transport Profile (MPLS-TP) are some of the technologies that fall under this category.

The advantages and disadvantages of both circuit-switched and packet-switched technologies are tabulated in Table 3.

### A. CIRCUIT-SWITCHED TECHNOLOGY

Amongst the widely used circuit-switched technologies used at present in utilities, the Time Division Multiplexing (TDM) method is the most popular, especially for mission-critical applications [32]. TDM is a method of transmitting and receiving multiple independent signals over a single transmission channel [33]. It allows total available bandwidth to be shared based on time sharing. At the transmitter side, the multiplexer divides the channel into several numbers of

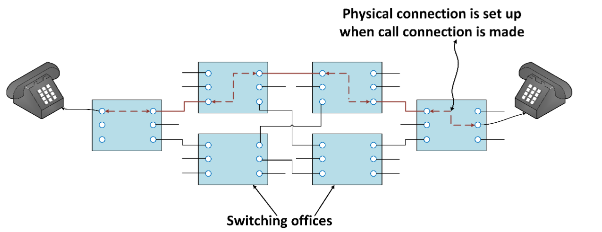


**FIGURE 2.** Electronic signals in modern circuit-switched networks pass through several switches before establishing a connection. Once the call connection is made, other network traffic is not permitted to use the switches.

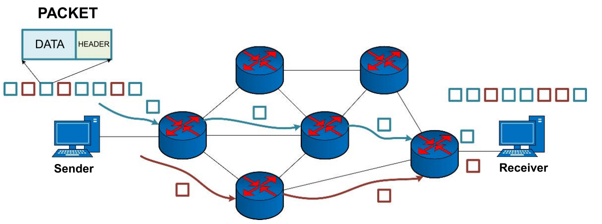


**FIGURE 3.** Data are broken into packets and sent to the receiver in packet-switched technology.

pre-allocated time slots for the message to be transferred. The reverse process is performed by the de-multiplexer at the receiver side. Both the transmitter and receiver sides are synchronised by a common clock to receive data in accordance with the transmission sequence. Nagananda *et al.* [34] proposed a simple TDM scheme for the transmission of phasor data from PMUs to a central server, with the objective of providing a robust communication infrastructure in the smart grid. The results of the research showed that TDM for scheduling the PMU transmissions leads to an improved performance of the fault detection scheme compared with PMUs transmitting at random.

TDM comprises two major categories, namely, synchronous TDM and asynchronous or statistical TDM [35]. With synchronous TDM, all clocks in the system must align with a reference clock, and vice versa, for statistical TDM. In synchronous TDM, each device is given fixed time slots to transmit data over the link irrespective of whether the device has any data to transmit. It has been used for long-distance communication links and for bearing heavy data traffic loads from the end users. Examples of synchronous TDM are Time Intervals, synchronous optical networking/synchronous digital hierarchy (SONET/SDH), and Integrated Services Digital Network. Meanwhile, in asynchronous or statistical TDM, each device has flexible time slots which are not fixed unlike synchronous TDM and it has been used for the high-speed transmission of data by passing through a medium. In network TDM, only one kind of existing technology known as Unidirectional Supply Driven Heuristic (USDH) is used [36].

Wavelength-division multiplexing (WDM) is a technique for modulating numerous data streams, and it enables the use of multiple light wavelengths to send data over a single optical fibre medium [37], [38]. Each laser is modulated by an independent set of signals. WDM has been increasingly used in power utility communication networks as it provides a separation between different types of services. Additionally, WDM supports certain capabilities, such as intrusion detection and low latency wavelength encryption, for operational and business communication traffic on the smart grid network [39]. WDM can be divided into wavelength categories, namely, Coarse WDM (CWDM) and Dense WDM (DWDM). CWDM is defined by the International Communication Union (ITU) ITU-T Rec. G.671 standard, and it has wider channel spacing compared with DWDM. It allows for the establishment of a reliable and cost-effective system, but at a lower capacity and shorter range than DWDM. By contrast, DWDM is a technology used for multi-channel long distance and/or very high-capacity links, mainly used by public telecom operators. It is defined by ITU-T G.694.1. The advantages and disadvantages of the TDM and WDM technologies are summarised in Table 4.

The majority of the current smart grid communication solutions are based on static scheduling for data transmission via synchronous networking schemes, such as TDM. However, this legacy technology cannot cope with the increasing demand of flexibility in grid configuration and the fast response of mission-critical smart grid services [32].

### B. PACKET-SWITCHED TECHNOLOGY

Packet-switched technology has emerged to overcome the disadvantages of circuit-switched technology. Amongst them is the Internet Protocol-Multiprotocol Label Switching (IP-MPLS) technology, a method for transporting multi-protocol data across an IP network by using a pre-engineered tunnel or a path known as the Label Switch Path (LSP), which has been setup by Resource Reservation Protocol–Traffic Engineering [41]. MPLS frames can be directed or traffic-engineered across the network by using labels because the tunnel has already been established through signalling protocols. Fig. 4 shows a typical MPLS network architecture.

As applications converge into one network infrastructure, they allow the network to transport a wide range of applications, from the most latency-sensitive to the best traffic, such as teleprotection to the Internet traffic [42], [43]. With the combinations of IP-MPLS and RSVP-TE, a complete route control is possible when provisioning a critical network path for a specific application. This scheme can be achieved by provisioning an LSP with a strict and explicit route to specify a series of hops to be taken by the LSP. IP-MPLS has an advanced routing architecture that enable manufacturers to provide low latency, increased reliability and deterministic services [44]. Furthermore, by utilising IP-MPLS technology, both customers and services can be kept separate and secured. Thus, each of them will not be able to see other networks or data. With reference to the Open Systems Intercommunication model, most packets are allowed to be forwarded at Layer 2 (switching) rather than at Layer 3 (routing). However, IP-MPLS cannot guarantee the same LSP in both upstream and downstream, which requires it to find different routes

**TABLE 4. Advantages and disadvantages of the methods under circuit-switched technology in the smart grid domain.**

| Technology | Description | Examples | Advantages | Disadvantages | Typical Applications |
|---|---|---|---|---|---|
| Time Division Multiplexing (TDM) | • Transmitting and receiving multiple independent signals over a single transmission channel<br>• It allows total available bandwidth to be shared based on time sharing | • Time Intervals<br>• Synchronous optical networking/synchronous digital hierarchy (SONET/SDH)<br>• Integrated Services Digital Network.<br>• Unidirectional Supply Driven Heuristic (USDH) | • TDM circuitry is simple<br>• Problem of cross talk is not severe<br>• Full available channel bandwidth can be utilised for each channel | • Synchronisation is required in TDM<br>• Complex to implement<br>• Due to slow narrowband fading, all the TDM channels may be wiped out | • Employed in the utilities' legacy system for teleprotection and remote recloser services<br>• Substation-to-substation and substation-to-control-centre communication |
| Wavelength Division Multiplexing (WDM) | • Modulating numerous data streams that enables the use of multiple light wavelengths to send data over a single optical fibre medium<br>• Each laser is modulated by an independent set of signals | • Coarse WDM (CWDM)<br>• Dense WDM (DWDM) | • Full duplex transmission is possible<br>• Easier to reconfigure.<br>• Optical components are similar and more reliable<br>• It provides higher bandwidth<br>• Simple to implement<br>• High security | • Signals must be relatively far away from each other<br>• Light wave carrying WDM are limited to two-point circuit<br>• Scalability is a concern<br>• Cost of system increases with addition of optical components | • Substation-to-substation and substation-to-control-centre communication<br>• Creation of transparent networks for the exchange of various mission-critical signals<br>• Improve applications with TDM technologies in which it provides greater bandwidth, security, and protocol transparency |

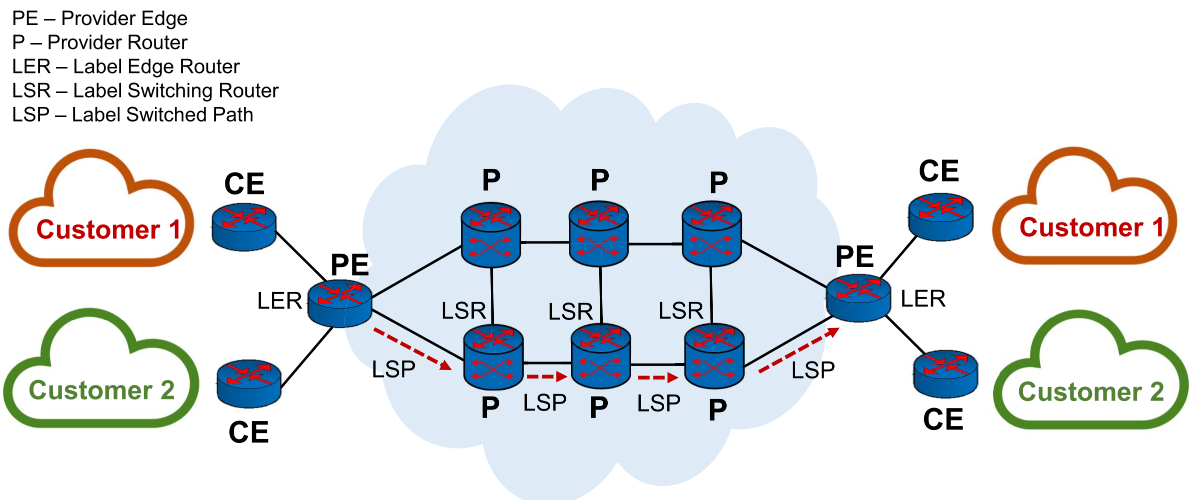


**FIGURE 4. Typical MPLS network architecture [40]. MPLS uses two kinds of routers: i) Label Switch Router (LSR) which operates at the core level and ii) Label Edge Router (LER) which operates at the network's edge where IP networks and MPLS networks intersect. The LER acts as a link between IP network domain and MPLS domain.**

for both processes. Moreover, the discovery, reservation and restoration of this technology is complex, which will overkill the static network. In forwarding the packet to the next node, a router needs to look up the IP address for each packet, which will consume more time and slow down the network traffic flow because a specific path has not been set up yet.

MPLS-TP is a packet transport technology that provides connection-oriented transport services to end users [45]. This technology also has been regarded as a successor to the TDM technologies in power utilities owing to its capability in maintaining the attributes of legacy technologies [32]. The transport service is represented by the end-to-end LSP or pseudowire emulation tunnel which is used to deliver the user traffic. The aim of this technology is to develop MPLS extensions when necessary to meet classical transport network requirements, such as scalability, multi-service, cost efficiency, high level of availability and extensive operations, administration and maintenance (OAM) [46], [47]. Some of the OAM functions in MPLS-TP technology are to measure packet loss and detect and isolate faults in the event of failure through rapid protection switching, which is sub 50 ms [48]. This technology supports all carrier-grade transport services via the LSP or pseudowire emulation tunnel at Layer 1 and Layer 2 [49]. MPLS-TP supports static network management system (NMS)-based provisioning, which does not require complex provisioning protocols, such as IP-MPLS technology, and it can be accomplished via a point-and-click user interface [50]. An automatic protection switching can be triggered by small control packets that follow the same path as the transported data; this scenario explains why MPLS-TP can guarantee a reconfiguration under all circumstances [51]. Furthermore, this technology has a comprehensive set of OAM fault management and performance monitoring features that allow the network to monitor services and engage proactive and easy fault location to limit downtime [52]. MPLS-TP involves the use of a standard bidirectional congruent LSP or switched paths that are co-routed upfront to avoid differential delay issues. Moreover, eliminating the connectionless features of MPLS, such as Penultimate Hop Popping, label merge, and EqualCost Multi Path, enhances the OAM and protection switching mechanisms, guarantees reliable quality of service (QoS) and provides statistical multiplexing. However, the carrier has to configure the overall network in case a user wants to take total control of one's own network. Moreover, this technology does not offer any inherent data protection, and improper implementation can open up the network to vulnerabilities because all devices and interfaces are not sufficiently secured.

SDN is a recently emerged architecture which separates the network control plane and data plane, and it is responsible in providing user applications with a centralised view of distributed network states [53]. As for the architecture, the three different layers are the application layer, control plane layer and data plane layer, as shown in Fig. 5. At the control plane layer, the SDN controller handles the network intelligence and states where it can be regulated globally via network policies in either centralised or distributed manner. Moreover, a set of application programming interfaces (APIs) called north-bound API are supported to communicate between the application layer and the control plane layer, eventually enabling network services. The data plane layer in SDN technology employs programmable OpenFlow [54] switches that can communicate with its SDN controller via the south-bound API [55]. The SDN paradigm offers a unified and global view of complicated networks, which then provide a powerful control environment for traffic flows in network management [56]. Furthermore, SDN has some unique features, such as visibility, programmability, openness and the ability to virtualise, that can pave a way for the development of new traffic engineering (TE) with inherently flexible, adaptive and customisable techniques. By combining SDN with a dynamic layer provisioning, dynamic router bypassing can be implemented as a service by the application layer, which can improve the efficiency without suffering from a link under-utilisation of the traditional bypass [57]. However, most of the studies conducted earlier by other researchers were devoted mainly to the development of SDN architectures, with less effort on the development of TE tools for SDN technology. When the TE system is not highly scalable and intelligent, the innovation and evolution of the SDN technology will be affected because it is highly dependent on the TE system. Hence, TE development for the SDN technology is important, and it has even become one of the issues to be addressed prior to achieving an efficient SDN system.

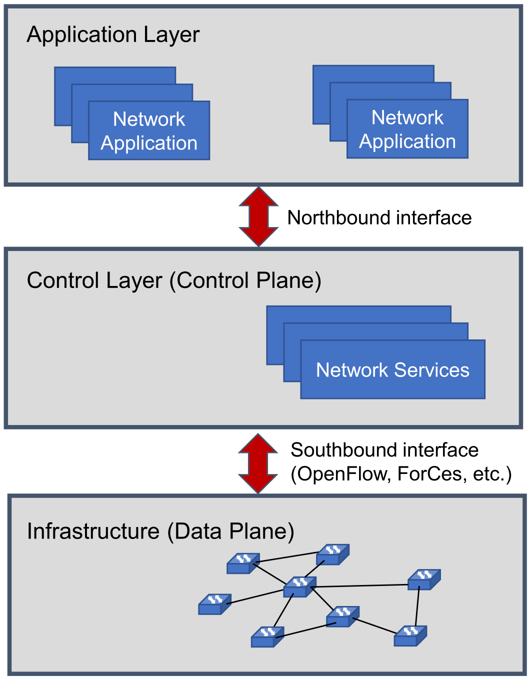


**FIGURE 5. Three layers in the SDN architecture [58].**

Meanwhile, Optical Transport Network (OTN) technology (defined by ITU G.709) is rregarded as a digital wrapper technology [59]. It is built on the SDH/SONET premise in which a system of laser pulses is used for the transmission process. These types of systems have emerged to handle large sets of data over the optical fibre systems by which more sophisticated protocols can better handle the synchronisation. Some of the advantages of the OTN technology are the ultra-capacity that comes with high accuracy over DWDM lines and the transparent transport of user signals which is attributable to the asynchronous mapping and demapping of the signals [60]. The mixing of synchronous signals with different clock sources, as well as the asynchronous signals, can be carried out on a common wavelength in this technology. Besides, the powerful forward error correction (FEC) function, simplified network design, low cost and ease of installation are the other features of this technology. The capabilities of networking and the enhancement of OAM can be accomplished for all services with dynamic electrical or optical layer grooming [61]. OTN also offers the benefit of extending performance management across a multi-carrier environment with six levels of tandem connection monitoring. As such, the OTN technology has been used by power utilities as a high-capacity data transport network, in which data are transported from one unit (e.g. substations) to another unit through Optical Ground Wire (OPGW) cables [32]. The advantages and disadvantages of the methods under the packet-switched technology are summarised in Table 5.

**TABLE 5. Advantages and disadvantages of the methods under packet-switched technology.**

| Technology | Description | Standard | Advantages | Disadvantages |
|---|---|---|---|---|
| Internet Protocol-Multiprotocol Label Switching (IP-MPLS) | • Transporting multi-protocol data across an IP network by using a pre-engineered tunnel or a path which is known as the Label Switch Path (LSP), setup by Resource Reservation Protocol–Traffic Engineering | • Internet Engineering Task Force (IETF) (open standardisation) | • Able to direct frames across the network by using labels<br>• Unified network infrastructure for applications<br>• Advanced routing architecture which provides low latency, increased reliability, and deterministic services<br>• Customers and services are kept separate and secure | • LSP for upstream and downstream are not guaranteed<br>• Complex discovery, reservation and restoration<br>• Time-consuming and slow traffic flow for forwarding packet across unknown paths |
| Multiprotocol Label Switching–Transport Profile (MPLS-TP) | • Packet transport technology that provides connection-oriented transport services to end users. | • IETF (open standardisation)<br>• ITU-T SG15 | • Supports all carrier-grade transport services<br>• Supports static NMS-based provisioning in which it does not require complex provisioning protocols, such as IP-MPLS technology, and it can be implemented via point-and-click user interface<br>• Can guarantee reconfiguration under all circumstances<br>• Comprehensive OAM fault management and performance monitoring features to limit downtime<br>• No differential delay issues<br>• Enhanced OAM and protection switching mechanisms | • Carrier has to configure the overall network for total user control<br>• No inherent data protection<br>• The network may be exposed to vulnerabilities because all devices and interfaces are not secured |
| Software Defined Networking (SDN) | • Architecture that separates network control plane and data plane, and responsible in providing user applications with a centralised view of distributed network states<br>• Three different layers, namely the application layer, control plane layer and data plane layer | • Monitored by SDX Central research repository | • Offers a unified view of complex networks<br>• Provides powerful control environment for traffic flows in network management<br>• Efficient link utilisation | • Highly dependent on the TE system |
| Optical Transport Network (OTN) | • Built on SDH/SONET premise in which a system of laser pulses has been used for the transmission process.<br>• Handle large sets of data over the optical fibre systems, where more sophisticated protocols could handle the synchronisation better | • ITU G.709 | • Ultra-capacity and high accuracy<br>• Transparent transport of the user signals.<br>• Allow mixing of signals on a common wavelength.<br>• Powerful FEC function.<br>• Simplified network design.<br>• Low cost.<br>• Easy installation.<br>• Networking and OAM enhancement for all services.<br>• Allow tandem connection monitoring for performance. management across a multi-carrier environment | • Requires new hardware and management system |

### C. MIGRATION FROM CIRCUIT-SWITCHED TO PACKET-SWITCHED TECHNOLOGY

Migrating from circuit-switched to packet-switched technology is necessary as the traffic increases at an unpredictable manner, in which the amount of traffic together with their source and destination are random and irregular. This situation is expected when the inverter-based distributed energy resources increase. In this case, the solar power, battery storage and electric vehicle may be connected anywhere in the grid. Hence, the utility company needs to cope up with the following issues:

- Increasing unpredictability of traffic patterns;
- Ensuring QoS for different types of traffic;
- Increasing network costs;
- Optimising network resources to minimise capital and operational expenditure;
- Maximising revenue opportunities.

Chevalier *et al.* [62] proposed three scenarios to cater the migration: 1) implement a packet-switched network based on the MPLS technology, in which all switching modes in the core network occur on a packet basis at each node; 2) implement a circuit-switched infrastructure based on an OTN, in

**TABLE 6.** Advantages and disadvantages of using networking media in the smart grid.

| Networking Medium | Features | Technology | Advantages | Disadvantages |
|---|---|---|---|---|
| Copper | • Consists of a series of individual copper wires that form circuits dedicated to specific signalling purposes | • Power Line Communication (PLC)<br>• Digital Subscriber line (xDSL) | • Low management cost<br>• Ease of installation | • High signal attenuation over a long distance<br>• Highly susceptible to electromagnetic interference |
| Fibre | • Data is transmitted as light-based by light emitting diode and is received by an optical detector | • Underground Cable (UGC)<br>• Optical Ground Wire (OPGW)<br>• All Dielectric Self-Supporting (ADSS)<br>• Submarine<br>• Air-blown Fibre (ABF) | • Fast data transmission<br>• Low attenuation over a long distance<br>• Impervious to electromagnetic interference<br>• Long lifespan<br>• Low asymmetrical delay | • More expensive installation cost than copper and wireless medium |
| Wireless | • Generated electromagnetic wave signals are transmitted via space by the transmitter and will be detected by a receiver's antenna<br>• The radio transceivers are typically designed to operate over a limited range of frequencies | • Zigbee<br>• UHF<br>• WiFi<br>• Radio Frequency (RF) mesh.<br>• Transformational Satellite Communication System/Very Small Aperture Terminal (TSAT/VSAT)<br>• Long Term Evolution/Fifth generation (LTE/5G).<br>• Z-wave<br>• IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN).<br>• Long Term Evolution for Machines (LTE-M) | • Provides easy access to information<br>• Offers workforce mobility with no restrictions on cables.<br>• Interoperability via different operators which allow redundancy and backup system.<br>• Reduced complexity and cost of network deployments.<br>• Various options on available technologies for different application needs | • Signal degrades with distance<br>• May not be viable in rural areas where wireless infrastructure is scarce |

which all switchings in the core network occur on a circuit basis and the switching ofthe packets only occurs at the edge of the network; and 3) implement an MPLS network similar to scenario 1 but with additional OTN multiplexers in each node to implement traffic bypass. The study favours MPLS as the solution to migrate from circuit-switched to packet-switched technology due to its ability to dissociate traffic bandwidth and capacity provision, its capability to differentiate numerous traffic types and accommodate traffic changes and its ability to offer the full range of carrier Ethernet services. From a business perspective, MPLS is expected to generate more revenues than OTN for the same capital expenditure investment, incur less operational expenditure compared with an OTN-based operator and enable the utility company to considerably reduce its power consumption.

## IV. NETWORKING MEDIUM FOR DATA COMMUNICATION IN SMART GRIDS

Various communication media are used by power utility companies for the operational communication networks. Generally, three different kinds of media can be implemented when transmitting information in smart grid systems, which consist of copper, fibre optics and wireless-based media. This section reviews each medium in detail together with its characteristics and usage in smart grids. The summary of the advantages and disadvantages of each medium is tabulated in Table 6.

### A. COPPER-BASED MEDIUM

Copper is the most commonly used medium for data communication owing to its low management cost and ease of installation. It is a type of cabling medium that uses copper wires to signal the data and control bits between network devices. It consists of a series of individual copper wires that forms circuits dedicated to specific signalling purposes [63], [64]. Data are transmitted on copper cables as electrical pulses. A detector in the network interface of a destination device must receive a signal that can be successfully decoded to match the sent signal. A copper cable is used to connect the nodes on a local area network to the intermediate devices, such as routers or switches. It is also used to connect wide area network (WAN) devices to data service providers. Each type of connection and the accompanying devices have cabling requirements stipulated by Physical Layer standards. In the copper medium, Power Line Communication (PLC) and the sum total of Digital Subscriber Line (xDSL) are the existing technologies. The Broadband PLC is a new technology under consideration for future implementation.

#### 1) POWER LINE COMMUNICATION (PLC)

Power Line Communication (PLC) is a technology that allows the existing electrical grid to be used as a medium for data communication. This communication technology is commonly classified into two categories, namely, the Narrowband PLC and Broadband PLC, based on the bandwidth criterion. Narrowband PLC is usually referred as low bandwidth communication by utilising the frequency band below than 500 kHz and providing data rates of up to 200 kbps [65], [66], as shown in Fig. 6. It provides reliable, low-power and cost-effective data communication capabilities, which makes

**FIGURE 6.** An example of powerline communication (PLC) systems in power transmission and distribution [68].

it an ideal solution to the grid communication needs [67]. Narrowband PLC is most suitable for transmitting small or low-speed data, such as teleprotection signalling consisting of alternating current and high-voltage (HV) direct current over long-distance HV power transmission lines. This setup can be attributed to the provision of a dedicated infrastructure integrated into the substation with a signal path that follows substation-to-substation connections over long distances (>500 km) without any repeaters.

Narrowband systems can be based on single-carrier modulation, such as Frequency Shift Keying, Binary Phase Shift Keying and Spread-Frequency Shift Keying, and multi-carrier modulation, such as Spread–Spectrum and Orthogonal Frequency Division Multiplexing (OFDM). The two main standards for narrowband, the G3 and PRIME, are responsible in ensuring that data can be received without errors in extremely noisy environments [69].

Meanwhile, Broadband PLC is a technology that allows data to be transmitted over utility power lines by utilising the frequency band over 2 MHz and providing data rates over 1 Mbps [70], [71]. Broadband systems are based on multi-carrier modulation, which is an OFDM, and this technology has been accepted as a last-mile solution for audio, gaming, HDTV, Internet distribution and home networking, allowing electric companies to provide high-speed access to the Internet across the last-mile applications [72].

Broadband PLC, with its much higher speed, can reduce the data collection period and ensure real-time remote control and tariff command. Furthermore, Broadband PLC is an effective technology for multimedia distribution within homes, and it offers high data rates and does not require additional wiring. Besides, it helps consumers to properly manage their energy consumption.

However, broadband PLC consumes more energy than the narrowband PLC, and its stability and reliability are still being determined based on the quality of power line. Technical difficulties are also encountered by the system, including interference to the transmitted signal; this situation explains why broadband PLC has not been accepted as a viable approach of delivering high-speed Internet access to subscribers [73].

Normally found in power distribution grids, PLC is used to build Advanced Metering Infrastructure (AMI) covering smart meters in customer premises, public lighting control and SCADA applications. It works at a more leisurely pace for its applications in the command, control and monitoring markets, such as smart building automation, renewable energy generation, street lighting and electric vehicles (EVs) [74].

However, PLC is unsuitable for transmitting current differential protection and coded sampled values (e.g. IEC 61850). Besides, given the potential synchronisation loss on line faults, it is also unsuitable for digital stream teleprotection signalling. Moreover, as PLC cables were originally designed to transmit power instead of data, they have the limitation of non-reliably coping to the harsh power line environment due to the variations of the basic single-carrier modulation, frequency fading, variations in the propagation medium from continuous switching of load and electromagnetic interference [9]. Another drawback of the PLC is the signal-to-noise ratio (SNR) reduction due to the signal attenuation and presence of a variety of noises and non-intentional emissions (NIE) generated by appliances connected to the grid, including boilers, Distributed Generation (DG) devices, EVs and power-line transformers, whose issues are all exacerbated over long-distance transmission [75]–[77].

### 2) DIGITAL SUBSCRIBER LINE (XDSL)

xDSL refers to different variations of digital subscriber lines (DSLs) such as Asymmetric Digital Subscriber Line (ADSL) and Symmetric Digital Subscriber Line (SDSL). The respective configurations are shown in Fig. 7 and Fig. 8. Generally, xDSL is a technology for bringing high-bandwidth information to the subscriber over ordinary copper telephone lines by using digital encoding to provide more bandwidth over the existing twisted pair copper lines [78]. The typical application of xDSL in the smart grid is for smart metering applications; it provides smart grid data backhaul from homes to utilities [79].

ADSL is a two-way or duplex bandwidth devoted to the downstream direction, whereas only a small portion of the bandwidth is available for the upstream direction [80], [81]. SDSL has the same incoming and outgoing bandwidths and the data rate is the same in both directions. The transmission methods of xDSL vary greatly depending on the carrier, equipment, geographical location and the customer.

As for ADSL, it can provide up to 2 Mbps bandwidth for distances that range from 3.7–5.5 km and 12–20 Mbps bandwidth in the 1.2–2.4 km range for newer versions of ADSL [82]. It utilises the frequency of 25–100 kHz in the upstream and 100 kHz–1 MHz in the downstream [83]. xDSL technology supports simultaneous voice and Internet transmission and video functions over the same copper-twisted pair wires, and it can transport data across the copper wire at faster rates by utilising carrier frequencies much higher than those used in voice communication. It requires no massive rewiring, making the cost of any initial deployment

**TABLE 7. Advantages and disadvantages of copper-based medium.**

| Networking Medium | Features | Advantages | Disadvantages | Applications |
|---|---|---|---|---|
| Narrowband PLC | • Frequency band below 500 kHz<br>• Data rates of up to 200 kbps<br>• Supports BPSK, FSK, and OFDM | • Reliable<br>• Low power consumption<br>• Cost-effective<br>• Allow long distance communication over power lines<br>• G3 and PRIME ensure data arrived without errors in noisy environment | • The deployed schemes unable to cope with harsh power line environment | • Transmit small or low speed data over long distances HV.<br>• Power transmission lines |
| Broadband PLC | • Frequency band over 2 MHz<br>• Data rates over 1 Mbps<br>• OFDM | • High speed.<br>• Reduce data collection period<br>• Ensure real-time remote control and command<br>• High data rates<br>• No additional wiring needed<br>• Consumer can manage energy consumption | • Consume more energy<br>• Stability and reliability depends on quality of power line<br>• Facing technical difficulties involving interference<br>• Cannot afford high-speed Internet access | • Real time remote control<br>• real time tariff command<br>• High data-rate multimedia distribution within homes<br>• Energy consumption management for consumer |
| xDSL | • Frequency 25–100 kHz for upstream and 100 kHz to 1 MHz for downstream<br>• Data rates up to 2 Mbps (distances 3.7–5.5 km)<br>• For newer ADSL, data rates of 12–20 Mbps (distances 1.2–2.4 km) | • Support simultaneous voice, Internet, and video over the same media<br>• Able to transport data faster<br>• No massive rewiring needed<br>• Ready to use | • Limited for short distance communication (last-mile technology)<br>• Need extra expenses to install frequency splitter.<br>• Currently considered an obsolete technology by many Internet providers | • Multiple substations and buildings on one site.<br>• Remote access to device on customer premises, such as AMI |

financially feasible. In addition, this technology is always available and ready to be used by the user.

xDSL is usually used for multiple substations and buildings on a single site and remote access to devices on customer premises, such as AMI. The disadvantage of xDSL is that it is a short-distance technique [84]. Besides, as voice and data traffic are transmitted simultaneously over the xDSL, a simple frequency splitter fitted at the termination point is needed to separate the traffic. Additionally, xDSL is considered to be an outdated and obsolete technology because many telecommunications providers, such as AT&T, are phasing out the service and support for this technology [85]. This phase-out consequently affects the usage of this technology for current and future smart grid applications. The advantages and disadvantages of each copper-based medium are tabulated in Table 7.

## B. FIBRE OPTICS

Fibre optics media are an advanced type of cable compared with copper and has been gaining more attention recently owing to its unlimited bandwidth, immunity to external factors, such as electromagnetic interference, and non-requirement for energy for passive components to operate, and it is extremely secure [86]. Data in the optical fibre are transmitted by light-emitting diodes or lasers as the light based rather than electricity, which then is received by an optical detector. However, the light signals do not travel at the speed of light due to the denser glass layers, and sometimes, repeaters are required at distant intervals to regenerate the optical signal throughout its journey. In fibre optics media, Underground Cable (UGC), Optical Ground Wire (OPGW), All Dielectric Self-Supporting (ADSS) and submarine are the existing technologies. Air-blown fibre (ABF) is a relatively new fibre installation technology that will be implemented in the network system.

### 1) UNDERGROUND CABLE (UGC)

UGC technology is used when it is impractical, difficult and dangerous to use overhead lines. It is normally utilised in densely populated urban areas and factories to supply power from the overhead posts to the consumer premises [87]. An underground cable consists of one or more conductors covered with suitable insulating materials surrounded by protecting cover and laid underground to transmit electrical power. UGC can be classified in two ways according to the voltage capacity or by the construction. On the basis of voltage capacity, UGC can be divided into five main groups, namely, low-tension cable, high-tension cable, super-tension cable, extra high-tension cable and extra super voltage cable, as shown in Fig. 9. On the basis of construction, UGC can be divided into three main groups, namely, belted cable, screened cable and pressure cable, as shown in Fig. 10. The three main methods of laying the UGC are direct laying, draw-in system and solid system [88].

The advantages of UGC are its smaller voltage drops and low chances of developing faults, which ensures non-interrupted continuity of supply. Besides, it entails low maintenance costs and has a long lifespan. UGC is able to eliminate hazards of electrocution caused by the breakage of overhead conductors, which makes it a much safer technology. Its appearance is good because wires are not visible, and there is no interference with the communication system.

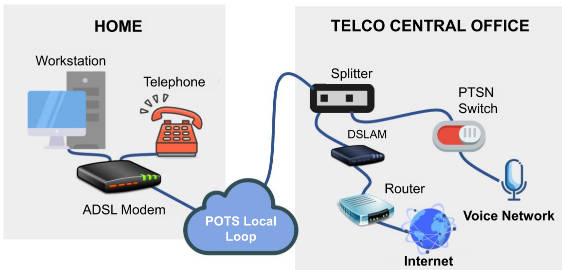


**FIGURE 7.** Typical ADSL configuration, which connects the home network and the telecommunication company (telco) central office networks via Plain Old Telephone Service (POTS). The ADSL modem in the home network splits the bandwidth of the phone line into a voice and data channel and feeds into the POTS line. The telecommunication company's splitter routes voice to the voice network, and data to a Digital Subscriber Line Access Multiplexer (DSLAM) unit. The DSLAM unit connects multiple ADSL lines to the Internet via a single fibre optic Asynchronous Transfer Mode (ATM) backbone connection.

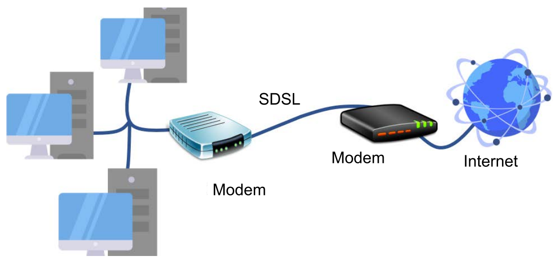


**FIGURE 8.** Typical SDSL configuration, which requires proprietary modems usually provided by the Internet service provider.

However, UGC is more expensive to manufacture, and its initial cost may vary depending on the construction and the voltage rating. Moreover, fault points cannot be easily located and repaired, and skilled labour and favourable weather conditions are required [89]. The current carrying capacity of the cable is also reduced due to the poor heat dissipation facilities [90]. UGC is not flexible, which means that new conductors need to be laid in new channels.

### 2) OPTICAL GROUND WIRE (OPGW)

OPGW technology is a protection ground wire for optical cables in overhead power transmission lines. It combines the functions of grounding and communication, in which one of the functions is to protect the high-voltage phase wire on the tower from lightning strike, while the other function is to transmit data from the substation to load dispatch centre. OPGW is an optical fibre composite ground wire containing a tubular structure that has one or more optical fibres and surrounded by layers of aluminium and steel wires. These layers serve to connect the tower to the ground. Meanwhile, the optical fibre is used for high-speed data telemetry. Fig. 11 shows the cross section of OPGW.

At higher voltages, OPGW is the preferred technology when the optical fibres are placed inside steel, aluminium or plastic tubes to protect the optical fibres according to different cable designs [93]. It is also normally used by electrical powerutilities owing to its near-invulnerable feature. OPGW has low installation costsin terms of new transmission line construction, and it plays an important

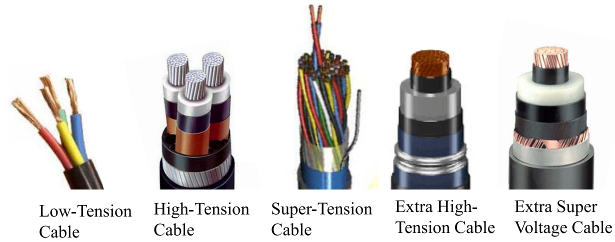


**FIGURE 9.** Examples of UGC classified under voltage capacity.

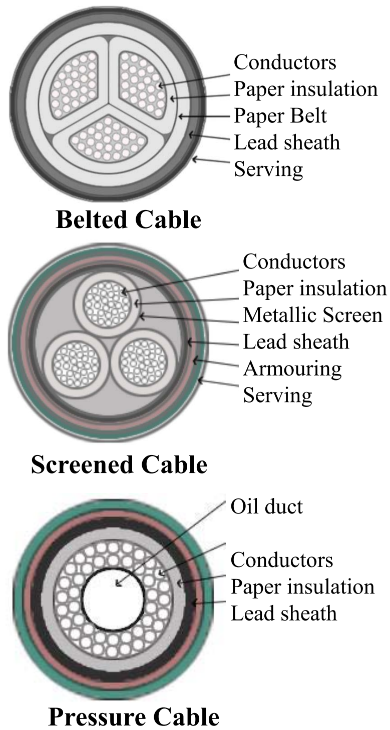


**FIGURE 10.** Cross section of a few UGC grouped under the construction category [91].

role in telecommunication networks. Besides, OPGW has a high reliability and requires less maintenance [94]. However, fibres in the exchange of right-of-way scheme presents many issues concerning the maintenance of OPGW, which is closely related to the maintenance of transmission lines [95].

### 3) ALL DIELECTRIC SELF-SUPPORTING (ADSS) CABLE

ADSS technology is also one of the optical cable types similar to the OPGW [94]. Its cross section is shown in Fig. 12. It is installed as an overhead line at the transmission tower [96]. The only aspect that differentiate ADSS from OPGW is that the ADSS cable is ideal for an installation in both distribution and transmission environments where the live wire has already been placed. It can be utilised for telecommunication purposes by power utility companies.

The cost of installation of the ADSS optical cable is minimal in contrast to OPGW, even during full live transmission wire replacement, as it can be easily switched in front of the transmission line [98]. No support or messenger wire is required owing to its self-supporting ability, which makes it the most preferred technology in power communication

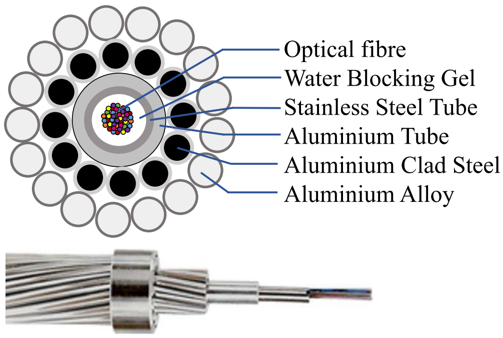


**FIGURE 11.** Cross section of OPGW [92].


**FIGURE 12.** Cross section of ADSS cable [97].

networks. The installation can be accomplished in a single pass, which makes it an economical and simple optical cable technology.

However, electromagnetic corrosion may affect the ADSS fibre optics cable, thereby weakening its sheath resistance [99]. Other problems are the weak designation of the line construction and the lack of a suitable method that fit with the equipped electrical apparatus, which is also related to exposure of ADSS sheath resistance. At the higher voltages, ADSS employment may be affected by the electrical field on its dielectric sheath [100].

#### 4) SUBMARINE CABLE

The submarine cable is one of the communication technologies laid on the ocean's floor [103]. It is deployed to provide a global connectivity, transporting 99% of the international voice and data traffic across the sea so that people can communicate even they are located in different countries [103]. Examples of typically used submarine cables, and their cross sections are shown in Fig. 13 and Fig. 14, respectively.

One of the advantages of the submarine communication cables is that their installation is faster and cheaper than those of satellites. Furthermore, more wavelengths can be added to the cable capacity, which can enhance the bit rate and transmit data over long distances.

However, the process of installing this technology is slow and tedious and involves expensive work. Submarine cables are exposed to attacks of sea creatures, especially shark bites, which can explain why the Internet is vulnerable underwater [104]. Major telecommunication outages can also happen because of shipping incidents or geological factors, and the

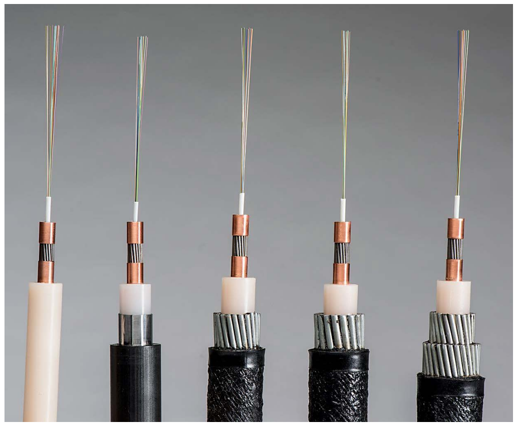

**FIGURE 13.** Typically used submarine cables from deep-water to shallow types. The cables are equipped with a core supporting pairs of optical fibres surrounded by a layer of wire to provide strength, a copper conductor to power the repeaters or amplifiers that process the light signal, and a case of polyethylene dielectric. Wire armour is added for protection [101], [102].

repairing works are not easy to complete because it is located on the sea bed [105].

#### 5) AIR-BLOWN FIBRE

Air-blown fibre (ABF) technology is the placement of a microfibre cable by using compressed air through a microduct (or microcable) [106], [107]. Air is used to reduce friction between the microfibre cable jacket and the inside wall of the microduct [108]. By using the ABF technology, a microcable (12 to 432 fibres) can be blown at a rate of up to 91 m per minute at distances of 2 km and beyond. Fig. 15 shows the cross section of an ABF cable. ABF has four components, namely the microduct or tube-cables, blowing apparatus, optical fibre bundles and connecting or terminating hardware.

Although the ABF cable is not a new technology (patented in 2002 by Park *et al.* [110]), it is relatively new compared with traditional cabling methods that date back to Alexander Graham Bell [111]. This technology can reduce both material and installation costs because it eliminates the need for splicing and interconnecting points [110], and it can improve the speed of deployment whilst providing high performance and reliability. Moreover, ABF can blow out previously installed optical fibre and blow in new fibres if necessary whilst reusing the original fibre bundle.

The ABF cable can easily be adapted for various environments (i.e. aerial, underground, and indoor environments) and smart grid applications (i.e. long-haul, WANs, local area networks (LANs), and home area networks (HANs) applications). Currently, the ABF technology is in mass deployment in fibre-to-the-home (FTTH) setup [111]. The ABF cable system provides the most cost-effective, adaptable and dependable option for scalability and flexibility to meet initial network needs, and it can adapt to future network requirements in contrast to traditional fibre systems [111].

However, no water blocking technology can be used inside the individual tubes, and insects may easily migrate from the tube distribution cabinets into the tubes and block future

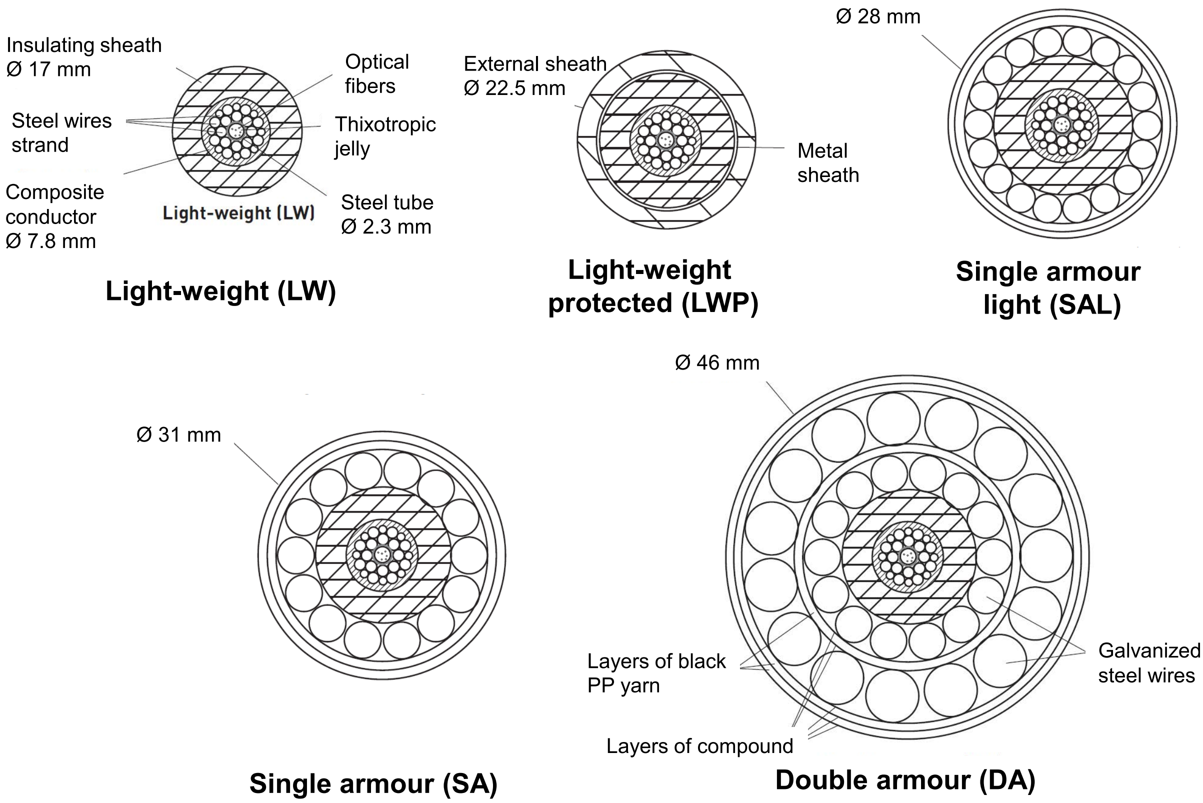


**FIGURE 14. Cross section of submarine cables, ranging from deep ocean-armoured varieties (top two) to the typically used shallow-water types [102]. Deep ocean types are roughly the size of a garden hose (17–20 mm diameter), whereas shallow water-armoured varieties can reach up to 50 mm diameter.**

ABF pathways. More importantly, no standards are currently in place to govern the cable performance and subsequently test the long-term reliability of these tube cables, tubes or installed fibres. The summary of the advantages and disadvantages of the different fibre cables is shown in Table 8.

### C. WIRELESS/RADIO

Wireless technology is a medium used to transmit the generated signals or waves by a transmitter into space, and then the signals will be detected by a receiver to pick up the energy from space by using the antenna. Typically, both transmitter and receiver are designed to operate over a limited range of frequencies. One of the best-known uses of radio media is communication application.

Radio wave is a type of electromagnetic radiation, and it has the longest wavelengths in the electromagnetic spectrum with the lowest frequencies. The nine different bands in the radio spectrum are the Extremely Low Frequency (ELF), Very Low Frequency (VLF), Low Frequency (LF), Medium Frequency (MF), High Frequency (HF), Very High Frequency (VHF), Ultra-High Frequency (UHF), Super High Frequency (SHF) and an Extremely High Frequency (EHF) [112], [113].

In radio media, Zigbee, UHF, WiFi, Radio Frequency (RF) mesh, Transformational Satellite Communication System/Very Small Aperture Terminal (TSAT/VSAT) and Long

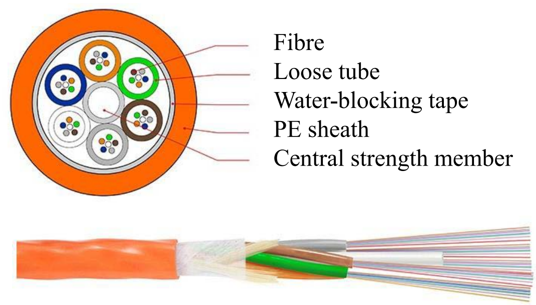


**FIGURE 15. Cross section of an ABF optic cable [109].**

Term Evolution/fifth generation (LTE/5G) are the existing technologies used. The new technologies under consideration for future implementation are Z-wave, IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) and Long Term Evolution for Machines (LTE-M).

#### 1) ZIGBEE

Zigbee technology is built for control and sensor networks based on the IEEE 802.15.4 standard for the purpose of wireless personal area network by defining both Physical (PHY) and Media Access Control (MAC) layers when handling devices at low data rates [114]. Essentially, it offers two-way communication between the sensors and control system in the short range because it supports the transfer of simple data

**TABLE 8. Advantages and disadvantages of different fibre optics cables.**

| Type of fibre optics cable | Reference and Approach | Advantages | Disadvantages | Usage |
|---|---|---|---|---|
| UGC | • [87] Hybrid optical protection schemes using passive fibre Bragg grating-based transducers for the distributed measurement of voltage and current.<br>• [88] Gravitational search algorithm at the design stage of UGC to find optimal solutions for dimensions of cable trench and bedding, interaxial spacing between power cables in flat formation, and cable ampacities<br>• [89] Proposed a method to detect and locate a multicycle incipient fault via analysis on the feature of the fault. The detection method was verified using simulation and laboratory tests.<br>• [90] Investigated the efficiency of four magnetic shielding techniques for UGC at 138 kV in terms of shielding factor (SF) and cable temperature. | • Smaller voltage drops<br>• Low chance in developing faults<br>• Non-interrupted supply<br>• Low maintenance cost<br>• Long lifetime<br>• Safer<br>• Appearance of wires is invisible<br>• No interference | • Expensive.<br>• Cost may vary depends on its construction<br>• Fault points hard to locate<br>• Requires skilled labour<br>• Favourable weather condition<br>• Poor heat dissipation facilities<br>• Inflexible | • Laid underground; Classified according to voltage capacity or construction |
| OPGW | • [93] Clarified existing study on failure analysis and proposed a method for developing new OPGW strand which calculates the melting and breaking characteristics of OPGW when hit by high-energy lightning strikes<br>• [94] Analysis on the operation and maintenance of OPGW communication system | • Preferred for high voltage<br>• Almost invulnerable<br>• Low installation cost<br>• High reliability<br>• No maintenance needed | • Issues concerning maintenance related to transmission line | • Overhead power transmission lines |
| ADSS | • [98] Contact angle-measurements on polyethylene sheath for analysis of damage on aging ADSS cables<br>• [99] Developed a model for calculation and analysis of electric field at ground surface and reliability of ADSS hanging points for 750 kV tower | • Minimal installation cost<br>• Easy to replace<br>• Economical<br>• Simple<br>• Able to self-support | • Possible electromagnetic corrosion | • Overhead power transmission lines; suitable for both transmission and distribution |
| Submarine | • [104] Integer Linear Program for disaster-aware submarine cable deployment in mesh network which minimises total cost with a slight increase in deployment cost<br>• [105] Submarine cable deployment optimisation using Integer Linear Program for minimising total loss cost Considerations include possibilities of breakage due to natural disasters, path uniqueness, deployment budget, shape of cable and linearisation constraints | • Faster<br>• Cheaper<br>• Flexible<br>• Able to transmit over long distance | • Slow installation process<br>• Tedious<br>• Expensive<br>• Exposed to sea creatures<br>• Can cause major telecommunication outage<br>• Hard to repair. | • Laid on the ocean's floor. Provide global connectivity by transporting international voice and data traffic across the sea |
| ABF | • [107] Single-mode and multimode fibres were installed using viscous flow of air in short-haul environment<br>• [108] Outer sheath material designed to use air flow's frictional features for propulsion. Patented FutureFlex system for ABF installation | • No need for splicing and interconnection points<br>• Less cost<br>• Can reuse the existing fibre bundle | • No water-blocking technology<br>• Insects may penetrate<br>• Block future pathways | • Blow out previously installed optical fibre and blow in new fibre if necessary whilst reusing the original fibre bundle |

from the sensors. In its architecture, there are three different types of devices, namely, the coordinator, router and end-devices [115]. Zigbee also supports different network configurations and can be operated in different modes. An example of the Zigbee Open System Interconnection (OSI) reference model is depicted in Fig. 16.

The Applications of Zigbee in the smart grid include the following: for fast and efficient network construction of AMI during LAN connection failure [117], as smart sensors for monitoring smart grid assets [118] and, as a communication medium for multi-functional electronic current transformers (ECTs), for overhead and underground line monitoring [119].

Zigbee is less expensive and requires a low-powered mesh network to make the battery life last longer [120]. Besides, it is simple to develop compared with other proprietary short-range wireless sensor networks, such as Bluetooth and WiFi [121]. The Zigbee network is extendable with the use of routers, allowing for many nodes to interconnect with each other to build wider area networks.

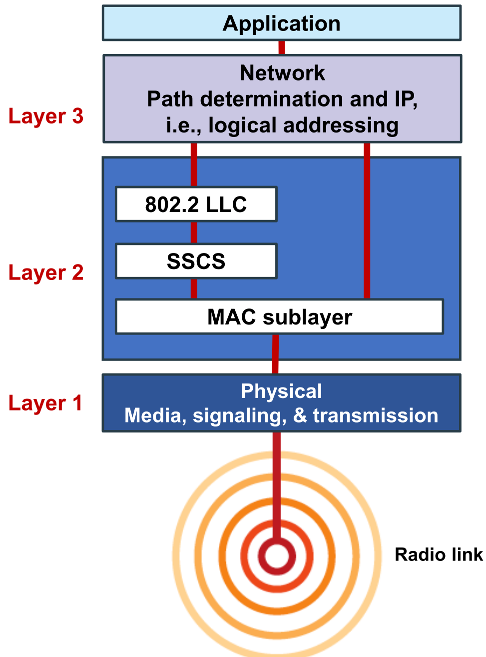


**FIGURE 16.** **Zigbee Open Systems Interconnection (OSI) communication model in compliance to the IEEE 802.15.4 standard [116].**

However, Zigbee is not as secure as the WiFi-based secured system, and it is highly risky to be used for official and private information. Furthermore, Zigbee has a low-transmission rate, and the coverage is limited, which can explain why most of its applications are located indoor, such as Home Automation and Control and Building Automation [122]. Additionally, the replacement cost is high when Zigbee-compliant appliances encounter a problem. Another issue is interference, as almost all Zigbee channels overlap with wireless local access networks (WLANs), which results in severe performance degradation [123].

### 2) ULTRA-HIGH FREQUENCY (UHF)

UHF refers to the International Telecommunication Union-designated frequency bands in the range of 300–3000 MHz [124]. In the smart grid, applications include the smart meter in the lower UHF band (412–475 MHz) [125] and 928–929 MHz for SCADA and meter reading systems [126]. One of the advantages of the lower UHF band are the larger coverage areas for smart metering or smart grid devices in contrast to the usage of GSM (900 MHz band) and Third Generation (3G) (1920–2190 MHz) versions [125]. This situation enabled the UHF technology to be highly attractive for rural areas, as it requires the lowest number of base stations per area covered in contrast to other technologies [125]. The other notable uses of the UHF technology are the partial discharge detection in field monitoring and smart substations owing to its sensitivity to typical insulation defects and noise rejection capacities [127] and the remote monitoring of smart meters via UHF Radio-Frequency Identification (RFID) systems [128], [129].

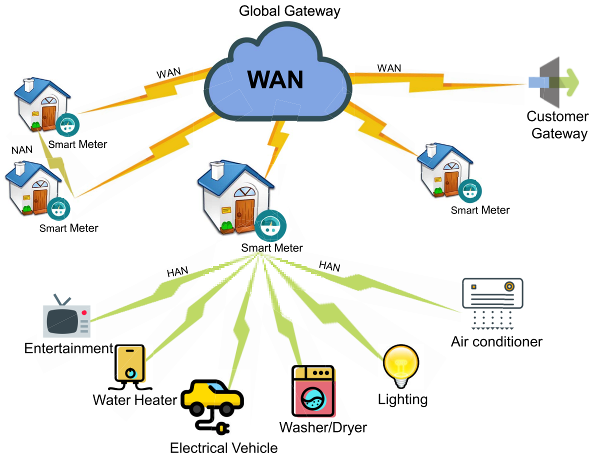


**FIGURE 17.** **A typical HAN architecture, which provides monitoring and control over energy usage in a home network. HAN typically connects to the utility's electric meter and provides a convenient way to turn on and off home appliances including water heater and air conditioner.**

The UHF technology utilises the 860–960 MHz band to operate the Radio-Frequency Identification (RFID) system [130]. The UHF band can be operated either in active or passive RFID systems [129], [131]. UHF allows for a faster data transfer rate, which enables quicker transaction capture times and faster data processing. It also has longer read ranges compared with LF and HF systems [132]. Passive UHF RFID tags also do not need batteries and have enhanced information storage abilities [133]. The active system offers long-range communication of up to 100 m, and it has the ability to continuously monitor and record the sensor inputs.

However, UHF technology is more sensitive toward radio wave interference, which is caused by the liquids and metals in the environment [133]. For a passive system, it entails short-range communication of less than 10 m, and its ability to read and transfer sensor values can be carried out only when the tag is powered by the reader.

### 3) WIFI

WiFi is a short-to-medium-range wireless networking technology used for HAN (Fig. 17) and Building Area Network (BAN) [134]. IEEE 802.11 n/ac is the standard for WiFi access network technology by defining the PHY and MAC layer specifications. This technology can provide high-speed network and Internet connections to clients.

WiFi is a simple and cost-effective way to wirelessly connect with other router or devices without the need of a physical wired connection. This technology allows expandability and can contribute to a sudden increase in the number of clients with the existing equipment, and it also allows users to access the WiFi network from nearly any convenient location within the access point coverage range [135]. The installation process is extremely quick and easy, and it does not require technical knowledge of the WiFi or WLAN system and its protocol.

The applications of WiFi technology in smart grids include the real-time DC/DC power converter control [136] and demand-side management for stabilising the power distribution network [137]. Additionally, in [138], WiFi was incorporated to acquire the total real and reactive power information in distributed generation (DG) units for the development of power sharing-based control strategies in microgrids. In [139], WiFi-5 GHz (IEEE 802.11a) was used to provide better High-Power Transients (HPT) interference immunity compared with both Zigbee (IEEE 802.15.4) and WiFi-2.4 GHz (IEEE 802.11g). This development makes WiFi-5 GHz a more suitable candidate for the real-time applications of smart grids. Another notable application for the smart grid is the hybrid wireless and fibre communication infrastructure for low-latency data acquisition under failures in the smart grid [140].

However, the data transfer rate decreases when the number of clients connected to the WiFi network increases. Proper security authentication protocols and configurations are needed to achieve a fully secured network system. Besides, the access range of WiFi is limited to a small area. To obtain additional range, repeaters or access points for a larger area are required, which add up to the cost. Besides, WiFi technology has a low reliability due to a wide variety of interferences [141].

#### 4) LONG-TERM EVOLUTION/FIFTH GENERATION (LTE/5G)

LTE/5G technology is also a wireless mobile telecommunication technology, but each of them differs in speed and features to improve the generation prior to it [141]. LTE is also known as the 4G technology of the cellular mobile network in the wireless communication field. The data rates for LTE (4G) is from 50–100 Mbps [135].

The data transmission speeds for the two aformentioned technologies are faster than those of the previous network generations. LTE technology can be implemented in private utility operation networks by providing very high communication capacities, and it can also fulfil the throughput, error rate and latency requirements for emergency situations [141]. The usage of LTE in smart grids include smart grid demand response applications over public LTE [142], transfer of synchrophasor data for smart grid monitoring, control and protection applications [143] and voltage control applications in medium-voltage (MV) and low-voltage (LV) networks [144].

As for 5G technology, it offers a low latency requirement with a high level of flexibility, especially with the sudden increase in the amount of data transmitted over the wireless system due to more available bandwidth and an advanced antenna technology [141], [145]. It also offers highly reliable communication, strong security mechanisms amidst malicious intrusion prevention, and high scalability [146]. 5G-based smart grid applications include the following: 1) Wide Area Measurement System (WAMS) in which metering devices have communication abilities to monitor, operate and control power systems in wide geographical areas [146]; 2) secure communication for outage monitoring in electrical grid systems [147]; and 3) demand response control through the efficient planning of 5G small cells [148].

5G has many broad uses in the smart grid. Depending on the performance characteristics, it may incorporate the following smart grid business necessities: 1) intelligent distribution automation; 2) LV power information collection, electric vehicle charging station/pile and distribution of terminal access requirements for information collection type uplink services; 3) power transmission and distribution monitoring status, high definition video and phone calls and power system inspection by remote monitoring and emergency communication; 4) millisecond accuracy load control; and 5) protection of industrial control downlink services which requires ultra-high reliability and ultra-low latency [149].

However, LTE technology is lacking in overall download speed and uplink spectral efficiency, which represents the efficiency of the rate for uploaded and transmitted data from devices. As for 5G technology, it costlier to implement the network services into a system, and there is a risk of overcrowding the frequency range with the addition of 5G to the wireless spectrum [150].

#### 5) RADIO FREQUENCY (RF) MESH

The RF mesh has been used heavily in utilities as a key communication technology in network systems, and it is the framework in deploying AMI to obtain daily meter readings for large population of service area [151].

The RF mesh network is a powerful and cost-effective way of building up a distributed network in large areas with longer distances. It also offers flexibility to adapt to the changing needs of the electric network. Moreover, this technology can be distributed regionally without needing to deploy the entire service territory. RF mesh has self-healing attribute in finding other network configuration in case of node failure [152]. Besides, the RF mesh technology is a self-forming network which enables the signal to find the optimal route back to the head-end system, especially in areas with many obstructions, such as mountains or high-rise buildings.

However, the RF mesh may require more infrastructures, especially in rural areas where distances are spread out across the service territory. Moreover, interference concerns may arise due to the unlicensed frequencies used by RF mesh technology [153].

#### 6) TELEMETRY VIA SATELLITE/VERY SMALL APERTURE TERMINAL (TSAT/VSAT)

The aim of the TSAT/VSAT technology is to communicate with remote sites by collecting and transmitting data signal to the control centre with the use of a satellite under a low data rate [154]. Fig. 18 shows an example of a satellite Internet-based data acquisition and control. This technology utilises the Ku band, which can operate at 14–14.5 GHz for the Transmit band (uplink) and 11.7–12.2 GHz for the Receive band (downlink) [155], [156].

The benefits of using this technology are that the installation time for this service is shorter than those of other services, and the VSAT dish can be carried or moved easily owing to its small size. It is also flexible as it allows reconfiguration and unlimited expansion. There are no last-mile issues because it offers wide features and protocols, which makes it an excellent service for broadcast transmission with its broad coverage [158].

The drawbacks of the TSAT/VSAT service include the high amount of delay for packet transmission due to the great distance between a satellite and earth. In addition, it is prone to intrusion by hackers. The service from this technology is also unstable and can be interrupted by poor weather conditions, which may happen between the dish and satellite.

#### 7) Z-WAVE

Z-Wave is a wireless transmission protocol synonymous with home automation used in HAN network. It allows the user to remotely control and monitor the installed devices. This technology adheres to the ITU-T G.9959 recommendation of ensuring interoperability between devices [159].

The Z-Wave protocol is simple and inexpensive and operates with a low-power consumption when communicating across multiple devices [160]. The connection is stronger and less likely to break over a long distance owing to its wider range.

However, the implementation and security analyses of this technology are lacking due to non-disclosure and confidentiality agreements, which further prevents the pursuit of open research conducted. The connection between Z-Wave devices and the Internet or existing devices cannot be directly performed as it is not an IP-compatible technology [161]. Additionally, as Z-wave is primarily intended for small data packets, it is not well suited for Neighbourhood Area Networks (NANs) and WAN, which have large aggregated data packets [162].

#### 8) IPV6 OVER LOW-POWER WIRELESS PERSONAL AREA NETWORK (6LOWPAN)

6LoWPAN is a technology for realising wireless network composed of low-power modules based on IEEE 802.15.4 PHY and MAC layers [163]. This technology enables IPv6 to be used efficiently over Low-Power and Lossy Networks (LLNs). It is normally used in NAN for automation and entertainment applications in home, office and factory environments. This technology is also used in smart grid applications, including AMI for the real-time monitoring of electric usage over the IPv6 protocol [164]. The power consumption of 6LoWPAN is low, and the approach employed by this technology is based on IP, which means that devices can be simply connected to other IP networks [165].

However, the fragmentation mechanisms in 6LoWPAN are vulnerable due to the lack of authentication at the layers [166]. Besides, both Transmission Control Protocol (TCP) and user Datagram Protocol (UDP) are not suitable for this technology, as IPv6 does not naturally fit with IEEE 802.15.4 networks. This situation can lead to higher energy consumption, packet loss and degraded throughput [167].

**FIGURE 18. Satellite Internet-based data acquisition and control [157]. The satellite Internet telemetry system includes a data transmitter and a rechargeable battery, as well as a ground-to-satellite antenna and mounting hardware.**

#### 9) LONG-TERM EVOLUTION FOR MACHINE (LTE-M)

LTE-M is an evolution from LTE technology, specifically for communication of machine-to-machine (M2M) devices [168]. It allows machine-type devices to communicate over long distances through an existing LTE cellular network covering large number of connected devices. It normally is implemented in IoT applications, such as smart cities, smart homes, smart meters and smart grid systems [169].

This technology supports secured communication and consumes relatively less energy for low-end devices. In addition, LTE-M is a cost-effective technology as it can operate on the existing LTE infrastructure without deterring mobile network performance [170].

Nevertheless, LTE-M is unable unlikely to cater the demands of future applications, which require delay and jitter to be less than 1 ms [171]. The summary of comparison for the different types of wireless approaches is shown in Table 9.

## V. ISSUES AND RECOMMENDATIONS

Several issues have been identified in smart grid networking methods and media which may affect the selection of these methods and as a specific medium for the smart grid's communication solution. These issues are tabulated in Table 10. The issues have been categorised into cost, design, security, management, reliability, efficiency, distance, time, complexity, geographical area, standard and compatibility.

### A. RELIABILITY

The main issue faced by most of the technologies is reliability. For the copper networking medium, the narrowband PLC cannot cope reliably with the harsh power line environment. The limitation is caused by the deployed schemes, which include variations of basic single-carrier modulation. As for

**TABLE 9. Comparison of different wireless approaches.**

| Wireless approach | Features | Advantages | Disadvantages | Usage | Smart Grid Network Domain |
|---|---|---|---|---|---|
| Zigbee | • Provides a two-way communication between sensors and control system in a short range.<br>• Supports transfer of simple data from the sensors. | • Less expensive.<br>• Low powered mesh network.<br>• Simpler.<br>• Extendable for wider area network. | • Less secure than WiFi.<br>• Low transmission rate.<br>• Limited coverage.<br>• High replacement cost. | • Control and sensor networks in WPAN. | • HAN |
| UHF | • Has a designated frequency band in the range of 300–3000 MHz. | • Faster data transfer rate.<br>• Long range of communication (up to 100 m in active system).<br>• Easy to manufacture (passive tags).<br>• Cheaper (passive tags).<br>• Continuous monitor (active system).<br>• Continuous record sensor input (active system). | • Sensitive to radio wave interference.<br>• Short range of communication (<10 m for passive system).<br>• Only able to read and transfer values when powered (passive system). | • Smart metering, and load balancing in smart grid. | • FAN<br>• NAN |
| WiFi | • Short to medium range wireless networking technology. | • Simple.<br>• Cost effective.<br>• No need for physical wired connection.<br>• Expandable.<br>• Convenient.<br>• Quick installation process. | • Data transfer rate decreasing (users increasing).<br>• Requires proper security authentication and configuration (for full security).<br>• Limited access range.<br>• Need extra expense for wider coverage.<br>• Less reliable. | • Power converter in smart grid. | • HAN<br>• FAN<br>• NAN |
| LTE/5G | • Both LTE/5G have different speeds and features that improve on the generation prior to it.<br>• Data rates for LTE (4G) are from 50 Mbps to 100 Mbps. | • Faster data transmission speed.<br>• High capacity (LTE).<br>• Meet required throughput (LTE).<br>• Minimal error-rate (LTE).<br>• Low latency.<br>• Flexible (5G). | • Less download speed (LTE).<br>• Less uplink spectral efficiency (LTE).<br>• Costly (5G).<br>• Overcrowd frequency range (5G). | • Smart grid demand response applications.<br>• Smart grid monitoring, control, and protection applications.<br>• Voltage control applications in MV and LV.<br>• 5G-based WAMS.<br>• Outage monitoring in electrical grid system. | • HAN<br>• NAN<br>• WAN |
| RF Mesh | • Suitable for building a distributed network over large areas with a longer distance. | • Cost effective.<br>• Wide coverage areas.<br>• Long distance. Flexible.<br>• Self-healing attribute.<br>• Self-forming in finding optimal route. | • Require more infrastructure (rural areas).<br>• Unlicensed frequencies.<br>• Raised interference. | • Key communication technology in network system.<br>• The framework in deploying the AMI in obtaining daily meter readings for large population of service area. | • HAN<br>• NAN |
| TSAT/VSAT | • Able to communicate with remote sites by collecting and transmitting data signal to the control centre through satellite under low data rate. | • Quick installation time.<br>• Transportable.<br>• Flexible.<br>• Unlimited expansion.<br>• No last mile issues.<br>• Offers wide of protocols and features.<br>• Wide coverage. | • Long distance.<br>• High latency.<br>• Prone to intrusion.<br>• Affected by bad weather condition. | • Communicate with remote sites by collecting and transmitting data signal to the control centre through satellite under low data rate. | • FAN<br>• NAN |
| Z-Wave | • A wireless transmission protocol suitable for HAN. | • Simple.<br>• Cheaper.<br>• Less power consumption.<br>• Bigger range.<br>• Strong connection. | • Lack of security analyses and implementation.<br>• Not IP-compatible. | • HAN for user to control and monitor the installed devices remotely. | • HAN |
| 6LoWPAN | • A wireless network composed of low power modules based on IEEE 802.15.4 PHY and MAC layers. | • Less power consumption.<br>• Approach based on IP. | • Lack of authentication.<br>• TCP and UDP not suitable with this technology. | • Automation and entertainment applications in home, office, and factory environments. Smart meters. | • HAN<br>• FAN<br>• NAN |
| LTE-M | • This technology is an evolution from LTE specifically for communication of M2M devices. | • Secured.<br>• Energy efficient.<br>• Cost effective. | • Unable to ensure delay and jitter is lower than 1 ms. | • Smart cities, smart home, smart meters, and smart grid systems. | • FAN<br>• WAN |

the broadband PLC, its stability and reliability are determined by the quality of the power line. Technical difficulties are also faced by the system involving interference to the transmitted signal. This problem can explain why broadband PLC is not a viable way to deliver high-speed data in the smart grid [73].

Fibre optics media of OPGW and ADSS also have reliability issues. The maintenance of OPGW is closely related to the maintenance of transmission lines as an exchange of right-of-way scheme to the fibre [95]. For ADSS, electromagnetic corrosion may weaken its sheath resistance [99]. At higher

**TABLE 10. Issues faced by each technology for the networking methods and media.**

| Technology | Cost | Design | Security | Management | Reliability | Efficiency | Distance | Time | Complexity | Geographical | Standard | Compatibility |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Method*** | | | | | | | | | | | | |
| **Circuit** | | | | | | | | | | | | |
| TDM-USDH | | X | | | | | | | | | | |
| WDM-DWDM | X | X | X | X | | | | | | | | |
| WDM-CWDM | | | | | | X | X | | | | | |
| **Packet** | | | | | | | | | | | | |
| IP-MPLS | | | | | | X | | X | X | | | |
| SDN | | X | | | | | | | | | | |
| OTN | | X | | | | | | | | | | |
| MPLS-TP | | | X | X | | | | | | | | |
| ***Medium*** | | | | | | | | | | | | |
| **Copper** | | | | | | | | | | | | |
| Narrowband PLC | | | | | X | | | | | | | |
| Broadband PLC | | | | | X | X | | | | | | |
| xDSL | | | | | | | X | | | | | |
| **Fibre Optics** | | | | | | | | | | | | |
| UGC | X | X | | | | | | | X | | | |
| OPGW | | | | | X | | | | | | | |
| ADSS | | X | | | X | | | | | | | |
| Submarine | | | | | | | | | | X | | |
| ABF | | X | | | | | | | | | X | |
| **Wireless** | | | | | | | | | | | | |
| Zigbee | X | | X | | | X | | | | | | |
| UHF | | | | | X | | X | | | | | |
| WiFi | | | X | | X | | X | | | | | |
| LTE/5G | X | | | | X | X | | | | | | |
| LTE-M | | | | | | | | | | | | X |
| RF Mesh | | X | | | X | | | | | | | |
| TSAT/VSAT | | | X | | X | X | | | | | | |
| Z-Wave | | | X | | | | | | | | | X |
| 6LoWPAN | | | X | | X | X | | | | | | |
| **Total** | 4 | 8 | 7 | 2 | 10 | 8 | 4 | 1 | 2 | 1 | 1 | 2 |

voltages, ADSS employment may be affected by the electrical field on its dielectric sheath [95].

Radio or wireless networking media possess the highest reliability issue. UHF technology is sensitive toward radio wave interference caused by the liquids and metals in the environment [133]. WiFi is also less reliable, similar to other radio frequency transmission, due to a wide variety of interferences [135]. 5G technology has a risk of overcrowding the frequency range with the addition of 5G to the wireless spectrum. RF mesh may also cause interference concerns due to the unlicensed frequencies used in RF mesh technology [153]. The service from TSAT/VSAT is unstable and can be interrupted by poor weather conditions, which may happen between the disk and satellite. 6LoWPAN is unsuitable for both TCP and UDP protocols, which may lead to congestion, as IPv6 does not naturally fit with IEEE 802.15.4 networks.

Various efforts are being conducted to increase the reliability of the aforementioned communication technologies. In the case of PLC, the impact of noise and interference on the quality of data transmission in PLC is largely determined by the coding and modulation techniques used to improve the robustness of PLC communication [9], [172]. Some of the techniques that can be used include OFDM, which provides a good performance against frequency selective fading and narrowband interference, and approaches based on multiple-input and multiple-output (MIMO) techniques, that utilise the various channels available given the multi-wire nature of power line feeders [173]. ADSS deterioration mitigation techniques include the use of fibreglass rod assemblies of similar diameters for the armour rods supporting the ADSS cable on the transmission structures, or the relocation of ADSS into areas with lower electric field activity [174]. In [175], a method was proposed to improve the reliability of wireless data communication in smart grid NAN via transmission redundancy whilst meeting the delay requirements of smart grid applications.

### B. EFFICIENCY

Inefficiency is also identified as one of the common issues faced by the networking method and medium technologies. For example, the CWDM circuit switching method has less tight tolerance toward the extent of wavelength imprecision or variability compared to DWDM technology. The precision of the laser beams in CWDM are also lower. In the packet-switched method, IP-MPLS cannot guarantee the same LSP for both the upstream and downstream. This aspect will require the identification of different routes for both processes.

For the copper networking medium, broadband PLC consumes more energy than the narrowband PLC. In Zigbee radio, it has a low transmission rate and a limited coverage. Hence, most of its applications are located indoor environments, such as Home Automation and Control and Building Automation [122]. WiFi connectivity is inefficient in terms of data transfer rate, as the connectivity decreases when the number of clients connected to the WiFi network increases. LTE is lacking in terms of overall download speed and uplink spectral efficiency, which is represents the efficiency of the rate for uploaded and transmitted data from devices. The TSAT/VSAT service has a high amount of delay for packet transmission due to the great distance between a satellite and earth. For 6LoWPAN, the congestion caused by TCP and UDP protocols may lead to higher energy consumption, packet loss and degraded throughput [167].

The setback in efficiency in the networking method and medium technologies may be tolerable depending on the targeted smart grid applications and the utilities' business models. For example, Zigbee radio's low transmission rate and limited coverage are not an issue for AMI and building automation applications, and TSAT/VSAT services have long been used by utilities when providing connectivityto rural or remote areas where other communication technologies' infrastructure is not feasible.

### C. DESIGN

Networking technologies beset by design issues revolve around their architecture, infrastructure and service planning. For the USDH circuit-switched method, the issue is on its design planning in which pricing at the service-level selection is not considered. Hence, the benefits of the tiered service cannot be quantified experimentally through the tiered-service network testbed. DWDM has imposed a strict network design, which affects its cost and adds to its complexity. The OTN method needs an extremely high minimum bandwidth requirement in its design, which is 40 Gbps. The development of SDN architectures has been the main attention for researchers, with less effort on the development of TE tools for the SDN technology. When a TE system is not highly scalable and intelligent, the innovation and evolution of the SDN technology will be affected because it is highly dependent on the TE system.

For the UGC fibre optics medium, the design issue is with its construction, as the cable's current carrying capacity is reduced by the poor heat dissipation ability [90]. UGC is also not flexible, which means that new conductors need to be laid in new channels. ADSS has a is constrained by the designation of the line construction and method that fits with the equipped electrical component, which is also related to the ADSS reliability issue of sheath resistance exposure. For the ABF, the internal design of its individual tubes has no water-blocking technology, and insects may easily migrate from the tube distribution cabinets into the tubes and block future ABF pathways. For the RF mesh, it needs more infrastructure, especially in rural areas where distances are spread out across the service territory.

### D. SECURITY

Security is amongst the important issues for resolution. DWDM circuit switching method lacks a protection capability for its network. Several typical DWDM solutions for securing the communication network include the installation of Optical Line Protection (OLP) devices and adopting the ring network topology to include redundancy. MPLS-TP also does not offer any inherent data protection, and improper implementation can open up the network to vulnerabilities because all devices and interfaces are not sufficiently secured. Organisations that rely on this technology can choose to encrypt their data before leaving their premises, hence resolving the issue pertaining to the MPLS-TP network's lack of encryption capabilities. The radio networking medium has many security issues. Zigbee is not as secured as the WiFi-based secured system, and it is risky to be used for official and private information. WiFi also needs proper security authentication protocols, and configurations are needed to achieve a fully secured network system. As for TSAT/VSAT, it is prone to intrusion by hackers due to the weak encryption and outdated IT equipment. Practical security solutions for satellite communication include network security infrastructure, which enables communications to be authenticated at each stage of data transmission, and encrypting communication at the networking level, which protects data transfer across the satellite ecosystem. The Z-Wave technology lacks implementation and security analyses due to non-disclosure and confidentiality agreements, which prevents future open research from being completed. For 6LoWPAN, its fragmentation mechanism is vulnerable due to the lack of authentication at the layers [166].

### E. COST

The pricing or cost issue limits the wide usage of certain technologies. For example, DWDM wavelengths are more expensive compared with CWDM wavelengths, and the difference is caused by the need for more sophisticated transceivers. The UGC fibre optics medium is also more expensive to manufacture, as its initial cost may vary depending on the construction and the voltage rating. For Zigbee, the cost issue manifests when replacement is needed for faulty Zigbee-compliant appliances. 4G technology is costlier than 3G, which hinders subscription to a service provider for obtaining 4G network connectivity. For 5G, the technology is new and it will cost more to implement the network services into a system.

### F. DISTANCE

The issue on distance or range of networking technologies may possess certain setbacks. The packet-switched method and all types of fibre optics media have no effect on their network distance or fibre length. The CWDM circuit switching technology has a smaller maximum realisable distance between nodes compared with DWDM technology. xDSL is a short-distance technique which can be used only between telephone switching stations and homes or offices and it cannot be used between switching stations [84]. It requires extra expense from the provider company to visit and install a simple frequency splitter fitted at the termination point to separate the voice call from the data or Internet connection, as both of them simultaneously use the same medium. UHF radio technology has a short-range communication for passive systems, which is less than 10 m. Its ability to read and transfer sensor values can be carried out only when tag is powered by the reader. However, this limitation can benefit certain applications that only need short-range communication, such as RFID tagging. For WiFi, its access range is limited to a small area and, when requiring additional range, repeaters or access points for larger area will quickly add up to the cost.

### G. STANDARDS

Standardised solutions are required for wide-scale and cost-effective deployment, interoperability and open interfaces for future extensions whilst addressing the general communication infrastructure requirements, including security, latency, reliability and criticality of data delivery. A number of organisations are currently working on the smart grid communication standards, such as the Institute of Electrical and Electronics Engineers (IEEE), the International Electrotechnical Commission (IEC) and the National Institute of Standards and Technology (NIST). A summary of the communication network standards in smart grid infrastructures is shown in Table 11. Notably, smart grid standards may conflict one another, as many differences in functionality have been developed in different countries or geographic areas. For example, although the main standards for AMI are IEC/TR 62051, IEC 61968, IEC 61969 and AEIC Guidelines v. 3.0, China and the USA are implementing GB/Z 20965, and ANSI/ASHRAE 135-2008/ISO 16484-5/BACnet, respectively [176]. As a result, a consistent set of cross-cutting requirements amongst the standards are difficult to define for facilitating the flow of classified information [177]. Other related issues include the lack of standards for some communication technologies. For example, the ABF cable still has no standard in place to govern the performance of the cables as a means of testing the long-term reliability of the tube-cable, tube, or installed fibre.

### *H. OTHER ISSUES*

Minor issues are management, complexity, compatibility, time, and geographical. The DWDM method lacks management capability, while the carrier in MPLS-TP has to play a role in the configuration of the overall network in case users want to take total control of their own network. IP-MPLS has the complexity issue of discovery, reservation and restoration processes, which can overkill the static network. It also has the time issue for forwarding a packet to the next node, in which a router needs to look up the IP address for each packet. This task will consume more time and slow down the traffic flow because the specific path has not been set up. The UGC fibre optics cable has complexity in terms of locating and repairing fault points due to its underground nature. It requires skilled labour and favourable weather conditions for the process [89]. The compatibility issue on Z-Wave technology occurs where the connection between its devices and the Internet or existing devices cannot directly be accomplished as it is not an IP-compatible technology [161]. As for LTE-M, it is unable to cater to the demands of future applications, which require the delay and jitter to be less than 1 ms [171]. The geographical area of the submarine fibre optics cable is its most prominent limitation. The installation process is slow and tedious, and it involves expensive work. Submarine cables are exposed tothe attacks of sea creatures, especially shark bites, which can explain why the Internet is vulnerable underwater [104]. Major telecommunication outages can happen because of shipping incidents or geological factors, and the repairing works are not easy to accomplish because it is located on the sea bed [105].

### *I. RECOMMENDATIONS*

Numerous technical issues in smart grid networking methods and related media have been identified and discussed in this section. All of these issues, especially reliability and efficiency, need to be addressed and resolved to realise a sustainable smart grid. The issues motivate the need for better management and performance measures in smart grid networking to ensure a reliable and smooth operation of the grid. This section will offer recommendations for smart grid improvements from several perspectives in relation to some of the previously discussed main issues.

#### 1) SMART GRID QOS

The smart grid facilitates advanced load management anad monitoring and control to efficiently generate, distribute and consume electricity. At the same time, the smart grid utilises a self-healing protection mechanism for the overall power system to become more reliable and achieve higher energy efficiency. Thus, a smart grid network should have a QoS management system, including requirements pertaining to functional behaviour, robustness, reliability and timeliness because data transmission is a critical issue, especially when it involves real-time monitoring and control.

The evolution of the smart grid is dependent on the secure and reliable features of communication networks. One key area in smart grid technology is QoS, which assures a certain level of performance for user data flow, to meet the requirements of various smart grid applications. In other words, QoS in the smart grid is related to network technical performance and the mechanisms that are used to differentiate traffic flows in a multi-service environment, entrusting each of them with priorities [95].

QoS parameters consist of delay, jitter and throughput. Each of these parameters has stringent requirements which must be fulfilled by time-critical operational applications to ensure the reliability and timeliness of critical data, especially in utility backbones. Lost or delayed data result in incorrect control actions and endangers the stability of the smart grid system. Thus, suitable protocols and techniques are mandatory for ensuring efficient service differentiation and performance assurance.

The smart grid benefits from the development of recent innovations, such as IoT and cloud computing, which have greatly increased the possibility of bidirectional communication in the grid. However, these advancements result in a tremendous number of connected devices which generate a massive amount of data, all of which must be analysed for value extraction. Traditional data computing, which relies on a centralised data centre, is no longer viable for moving the ever-increasing data due to bandwidth limitations, latency issues and unpredictable network disruptions. These data challenges need to be addressed for QoS improvement through the use of edge computing and big data analytics. Edge computing deploys computing and storage resources closer to the data source, essentially eliminating latency and congestion, whilst big data analytics assist energy organisations in effectively and quickly addressing challenges related to finances and grid operations.

Smart grid applications can be categorised into several classes with different service levels, which cover almost all aspects from the highest-priority to the lowest-priority traffic. Different kinds of traffic have their own pre-defined priority. The priority of data may change depending on the context or situation at a particular time. Hence, data prioritisation

**TABLE 11.** A summary of network standards supporting communication in smart grid infrastructures [176].

| Smart Grid Applications | Relevant Standards |
|---|---|
| Smart Transmission Systems | • IEC 60870-5-101<br>• IEC 60870-5-104<br>• Distributed Network Protocol 3 (DNP3)<br>• IEC 61850, Ed. 1.0–2.009-12 42/136 and later |
| Blackout Prevention Management | • IEC 61850<br>• IEEE C37.118 |
| Advanced Distribution Management | • IEC 61968<br>• IEC 61850-7-420 |
| Distribution Automation (DA) | • IEC 61850-7-4<br>• IEC 61970 |
| Distributed Energy Resources (DERs) | • IEC 61850<br>• IEC 61400<br>• IEC 61850-7-420 |
| Advanced Metering Infrastructure (AMI) | • IEC/TR 62051<br>• IEC 61968 to 9<br>• AEIC Guidelines v. 3.0<br>• GB/Z 20965 (China)<br>• ANSI/ASHRAE 135-2008/ISO 16484-5 BACnet (USA) |
| Demand Response/Load Management | • IEC 61968<br>• IEC 61850-7-420<br>• ISO 16484 series<br>• ISO/IEC 14543-3<br>• EN 13321 series<br>• EN 50090 series<br>• EN 50428<br>• EN 50491 series<br>• China: GB/Z 20965<br>• USA: ANSI/ASHRAE 135 |
| Smart Home and Building Automation | • ISO 16484 series<br>• ISO/IEC 14543-3<br>• EN 13321 series<br>• EN 13757 series<br>• EN 50090 series<br>• EN 50428<br>• IEEE P1701 to IEEE P1705<br>• EN 50491 series<br>• ISO/IEC 15045<br>• ISO/IEC 15067-3<br>• ISO/IEC 18012<br>• China: GB/Z 20965<br>• USA: ANSI/ASHRAE 135<br>• OpenHAN<br>• HomePlug AV and C&C<br>• Z-wave<br>• ITU G.996 |
| Smart Metering | • IEC 62056-x<br>• IEC 61334-x |
| Substation Automation (SA) | • IEC 61850 |
| Electric Storage | • IEC 61850-7-410<br>• IEEE P2030.2<br>• IEC 61850-7-410 (hydroelectric) |
| E-Mobility | • *Product and Safety Standards*: IEC 61982-1 to 5, IEC 62576, and IEC/NWIP 62619<br>• *Smart Grid Standards*: IEC 60364-5-53, IEC 60364-5-55, IEC 60364-7-712, IEC 60364-7-722, EC/NP 60364-7-760, and IEEE P2030.1<br>• *Physical Interconnection*: IEC 60309 Ed. 4.1, IEC 60309-1 Ed 4.1, IEC 60309-2 Ed 4.1 IEC 62196 Ed 1.0, and IEC 62196-1<br>• *Communication*: IEC 61850, IEC 61968, IEC 61851-31, IEC 61851-32, ISO/IEC 15118, and ISO/IEC 15118-1 to 3<br>• *Market Information*: IEC/TR 62325, and IEC/TR 62325-501<br>• *General Standards*: ISO/CD 12405, ISO 6469-1 to 3, SAE J1772, SAE J2836/1-3,SAE J2847/1-3 USA–SAE J1771, and USA–SAE J2836 |
| Condition Monitoring | • IEC 61970 (EMS)<br>• IEC 61968<br>• IEC 61850 |
| Renewable Energy Generation | • *Wind power*: IEC 61400 series<br>• *Solar voltaic*: IEC-60904 series, IEC 61194 IEC 61724, IEC 61730 series, IEC 61730-1 and 2, IEC/TS 61836, IEC 62446, IEC/TS 62257, IEC 61727<br>• *Fuel cells*: IEC 62282-x, IEC 62282-1, IEC 62282-2 IEC 62282-3-1 to 3, IEC 62282-5-1, IEC 62282-6-200, and IEC 62282-6-300<br>• *Pumped storage*: IEC 60193, IEC 60041<br>• *Distributed generation*: IEC62257-1 to 7, IEC 62257-7-3, IEC 62257-8-1, IEC 62257-9-1 to 6, IEEE 1547, IEEE 1547.3, MAIN Guide NO3B<br>• *Nuclear generation*: NERC/NUC-001-1<br>• *Conventional power*: IEC 60308, IEC 61850-7-410 |

needs to be redefined according to its context to ensure the reliability and stability of the smart grid system.

### 2) INTEROPERABILITY BETWEEN SYSTEMS IN THE SMART GRID

With the expected exponential increase in the number of interconnected devices with different communication systems/technologies to the grid as a result of the rapid advancements in the IoT sector and similar ones, ensuring the interoperability of these systems with the grid is even more vital to achieve the interoperability of business processes and reducing the risk of current system devaluation.

In this sense, the design and implementation of a safe and cost-effective energy supply network necessitates the incorporation of a reliable, efficient and interoperable communication system within the coexisting communication technologies and operations, which may be achieved through the development of standardised communication policies and an upgrade of the current available communication standards. For example, the IEC 61850 standard, which was initially introduced as a standard for substation communication, provides device interoperability between manufacturers. In recent years, this standard has been used for a variety of devices, such as smart meters, virtual power plants and vehicle-to-grid (V2G) [176].

### 3) SMART GRID STABILITY AND SECURITY

The shift from a conventional power grid to the smart grid paradigm can be largely attributed to several main factors, including the connection of large-scale renewable energy

**TABLE 12. A summary of the potential areas for further research in the smart grid based on the discussed main issues.**

| Issues | Potential Areas for Further Research |
|---|---|
| **Reliability and efficiency** | • Development of QoS management systems.<br>• Development of suitable protocols and techniques for efficient service differentiation and performance assurance.<br>• The implementation of edge computing and big data analytics in grid operations.<br>• Microgrids investigation for power grid stability. |
| **Security** | • Data and security encryption protocols.<br>• Microgrids investigation for power grid security. |
| **Distance** | • Repeaters and network configurations for optimum signal performance.<br>• Signal attenuation mitigation for improved coverage. |
| **Standards** | • Interoperability between systems and the coexistence of various communication technologies in the grid.<br>• Development of standards for some of the communication technologies. |

resources and storage devices, such as EVs, to the distribution grid. These connections of microgrids, which encourage two-way energy flow and offer advantages of enhanced local reliability and better local voltage support [178], pose a threat to the stability and security of the power grids, and they may even introduce a myriad of power quality problems.

To solve the issues pertaining to the smart grid stability and security, more in depth investigation must be carried out on the microgrids' network architecture and classification. The basic architecture of a microgrid generally consists of four distinct parts [179]: a) distribution system, b) distributed generation sources, c) energy storage and d) control and communication modules. Understanding these distinct parts and their integration to the main smart grid network, for example, either connected or isolated microgrids and AC or DC distribution networks, is necessary for improving grid stability and power quality in terms of reliability and efficiency.

The summary of potential areas for further research about the smart grid based on some of the discussed open issues are presented in Table 12.

## VI. CONCLUSION

Appropriate network technologies, techniques and protocols are essential in making the smart grid system run smoothly. Each application possesses its own strict requirements depending on its service categories, which further determine its priority. This article presents a detailed review of each networking technology in the smart grid. The study can be utilised by researchers, technology providers and industries to select new communication technologies for the smart grid that will provide reliable and suitable two-way communication. The contributions of this study are as follows:

- A complete network architecture for the smart grid is presented, along with its OT and IT services, and the networking methods and media available for communication in the smart grid solution are provided.
- The advantages and disadvantages of IT and OT services and their related network technologies are identified.
- Detailed networking methods for circuit-switched and packet switched technologies are reviewed. The comparison of each method is summarised in a table.
- Each data communication networking medium in the smart grid (i.e. copper, fibre optics and radio) is reviewed, analysed and compared in terms of roles, advantages and disadvantages.
- The issues and challenges encountered in smart grid communication for current implementation in terms of cost, design, security, management, reliability, efficiency, distance, time, complexity, geographical, standard and compatibility are discussed. Recommendations for improvement of the current methods are also presented.

Aiming to support the diversity of smart grid applications, a dynamic QoS management system is recommended across the entire grid so that the system can adapt to the unpredictable nature of incoming and outgoing traffic. We hope that the recommended algorithm can demonstrate improvements in terms of delay, jitter and throughput for a high-quality QoS in the smart grid network. Consequently, the QoS parameters of each traffic can be improved, and then time-critical applications can operate efficiently with a reliable and stable network system.

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