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Fiber Optics and Broadband over Power Lines in Smart Grid: A CommunicationS System Architecture for Overhead High-Voltage, Medium-Voltage and Low-Voltage Power Grids

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Abstract—This paper proposes a network system architecture that integrates the operation of two communications technologies of the smart grid, i.e., fiber optics and broadband over power lines, across the same overhead transmission and distribution power grid. This integration brings benefits for the power utilities, telecommunications providers and customers alike. The proposed system architecture is expandable by allowing more communications technologies of the smart grid, such as DSL, fiber, WPAN, WiFi, WiMAX, GSM (4G, 5G), and satellite, to connect. Issues concerning wireless sensor networks, towersharing, and terabit-class backbone networks are discussed.

NOMENCLATURE

4G	Fourth-generation wireless	LV	Low Voltage
5G	Fifth-generation wireless	MAN	Metropolitan Area Network
AAAC	All Aluminium Alloy Conductor	MTL	Multiconductor Transmission Line
ACSR	Aluminium Conductor Steel-Reinforced wire	MV	Medium Voltage
ADSS	All Dielectric Self Supporting	Omx	Optical Multi-mode x
BPL	Broadband over Power Lines	OPAC	OPtical Attached Cable
BPLeNM	Broadband over PowerLines-enhanced Network Model	OPGW	OPtical Ground Wire
DSL	Digital Subscriber Line	OPPC	OPtical Phase Conductor
EMI	ElectroMagnetic Interference	OSx	Optical Single-mode x
GbE	Gigabit Ethernet	PON	Passive Optical Networks
GSM	Global System for Mobile communication	WiFi	Wireless Fidelity
HV	High Voltage	WiMAX	Worldwide interoperability for Microwave ACCess
IoT	Internet of Things	WPAN	Wireless Personal Area Network
IP	Internet Protocol	WSN	Wireless Sensor Network
LAN	Local Area Network		

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1. INTRODUCTION

Transmission and distribution power grids represent an omnipresent widely branched hierarchical structure that provides almost uninterrupted power delivery from producers to consumers. Apart from the traditional power delivery characteristics, the recent transformation of the vintage power grids to a smart grid is the key for supporting a parallel advanced IP-based communications network that may further offer a myriad of broadband applications for power utilities, consumers, and third parties [1–6]. Among the available communications solutions for the smart grid, fiber optic backbone networks and BPL networks can play an important role since both technologies can exploit the already installed configurations and wired power grid infrastructure [7–15].

Despite its high cost in comparison with the other alternative solutions, the fiber optic technology may allow the installation of a terabit-class backbone communications network across the existing transmission and distribution power grids. Long range communications, high bandwidth, high data rates, and zero susceptibility to EMI are the killer characteristics of the fiber optic technology [7–9]. In this paper, a thorough investigation of the fiber optic network deployment across overhead transmission and distribution power grids is given. More specifically, by adopting a bottom-up presentation concept, the available fiber optic cables that can be deployed across the overhead transmission and distribution power grids are first discussed. Second, the amplification of the fiber optic signal and the extension of the optic cable distances are discussed. Third, the available architectures of the fiber optic backbone communications network across the overhead transmission and distribution power grids that can be adopted for use are presented.

Apart from the fiber optic backbone communications network, BPL networks are already deployed across the transmission and distribution power grids and can be further exploited through their integration with the upcoming fiber optic backbone network. However, the BPL networks are subjected to various inherent deficiencies such as high and frequency-selective channel attenuation, noise, and EMI [13, 14, 16–22]. As the channel modeling is concerned, the hybrid model is here employed to examine the behavior of transmission and distribution BPL networks [2, 13–17, 23–27], and for that reason MTL configurations and indicative BPL topologies for the overhead transmission and distribution power grids are reported in this paper [11, 15, 23, 28–30]. The already existing BPL networks can coexist with the fiber optic backbone communication network; the BPLeNM that has been presented in [3] and is suitable for efficiently delivering data generated by WSNs up to the power grid substations is here modified and extended so that the generated traffic from/to topologies of BPL networks can be delivered to/from the fiber optic backbone communications network, respectively. As the performance and coexistence potential of the fiber optic backbone communications network and BPL networks are assessed across the overhead transmission and distribution power grids, first, the theoretical maximum data rates of the fiber optic backbone communications networks are evaluated. Then, the combined field installation and operation of the fiber optic backbone communications network and BPL networks are presented across a real overhead MV power grid. Issues, such as the power grid equipment sharing, network scalability, and network expansion capabilities with other available communication technologies of the smart grid, such as WSNs, DSL, fiber optics, WPAN, WiFi, WiMAX, 5G, GSM, are also outlined.

The rest of this paper is organized as follows: In Section 2, the fundamentals for deploying a fiber optic network across the overhead transmission and distribution power grids, say, fiber optic cables, fiber optic cable distances, fiber optic network architectures, are detailed. Section 3 summarizes the basics of the overhead transmission and distribution BPL networks regarding the overhead MTL configurations, overhead BPL topologies, and modified BPLeNM. Section 4 assesses the combined performance of the fiber optic backbone communications network and BPL networks by offering interesting and useful conclusions for the further communication exploitation of the smart grid.

2. FIBER OPTIC NETWORK DEPLOYMENT ACROSS OVERHEAD TRANSMISSION AND DISTRIBUTION POWER GRID

By default, the optical fiber cables are exploited for the high-speed communications. When being deployed across the overhead transmission and distribution power grids as fiber optic backbone networks, a plethora of communication services can be delivered either to power utilities for their own purposes (e.g., system protection, load and distributed generation management, distribution automation, diagnostic monitoring) or to third parties by leasing or selling them [31, 32].

2.1. Fiber Optic Cables

As the installation of fiber optic cables across the overhead transmission and distribution power grids is concerned, there are four available wires, namely:

- *OPGW*: This wire is designed to combine the purposes of traditional grounding in overhead power lines and in communications. In Figure 1, a typical cross section of an OPGW is illustrated. Similar to ACSRs that are mainly deployed for the phase and ground wires in traditional power lines [15, 29, 33–36], OPGWs externally consist of layers of aluminium and steel conductors. But in OPGWs, the aforementioned layers surround a tubular structure, which may be a metallic or plastic tube, where one or more fiber optic cables are placed inside a filling gel. Depending on the application, several design options can exist such as loose or tight tube and helically stranded or single tube [37]. Apart from grounding adjacent overhead HV towers and protecting overhead HV power grid from lightning strikes, OPGWs are self-supporting and resistant to environmental factors such as the wind and ice [38]. Even though OPGWs are mainly applied in overhead HV power lines, overhead MV and overhead LV power lines may also carry OPGWs for grounding and communications.

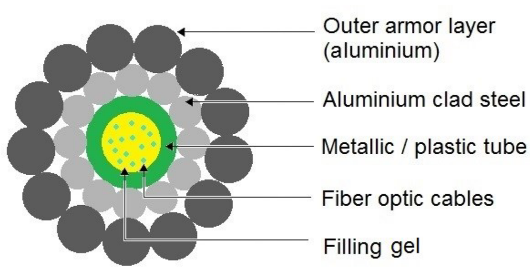

Figure 1. Typical cross section of an OPGW.

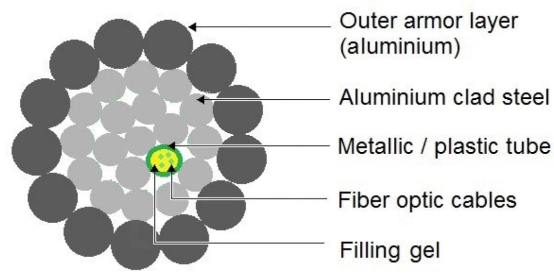

Figure 2. Typical cross section of an OPPC.

- *OPPC*: Similar to OPGWs, fiber optic cables are located inside the wire, usually contained within a stainless steel tube filled with gel [39]. In Figure 2, a typical cross section of an OPPC is demonstrated where layers of aluminium and steel conductors exist. Contrary to OPGWs, an OPPC replaces a phase conductor implying that any maintenance activities affect the operations of the power grid and the communications network. OPPCs are self-supporting due to their inner aluminium clad steel conductors while they are preferred for deployment across overhead MV and overhead LV power lines where no ground wiring exists [40].
- *ADSS*: ADSS wires are self-supporting and installed on the transmission and distribution towers and poles but separately from the power lines. Therefore, it must be verified that the transmission and distribution structures can withstand the load of ADSS wires and related equipment. In Figure 3, a typical cross section of an ADSS wire is illustrated. Contrary to the OPGWs and OPPCs, the ADSS wires externally consist of two layers of sheath, aramid yarn, and water blocking tape for the protection of the inner fiber optic cable configuration from the harsh environmental factors, such as the sunlight, temperature, ice, rain, and wind. Inside the water blocking tape, multiple metallic or plastic tubes contain multiple fiber optic cables inside the filling gel. The strength member preserves the integrity of the cable [37, 39]. ADSS wires are part of a completely independent communications network that may coexist with the traditional power grid on the same transmission and distribution structures but may be exploited by the power utilities or third parties.
- *OPAC*: OPACs are not self-supporting wires since they are installed by being attached to a ground phase wire or a phase one along the existing overhead transmission or distribution power line routes by clips or clamps. The OPAC installation requires special equipment (wrapped wire system) that travels along the overhead transmission or distribution power lines from tower to tower or pole to

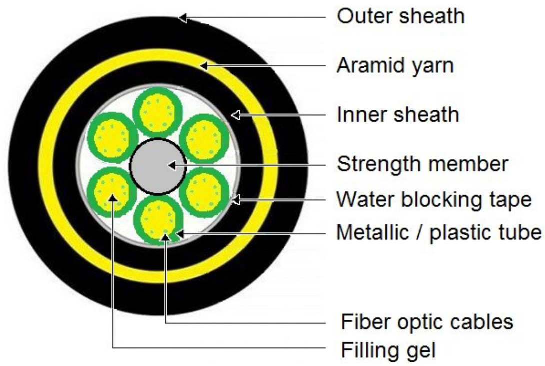

Figure 3. Typical cross section of an ADSS wire.

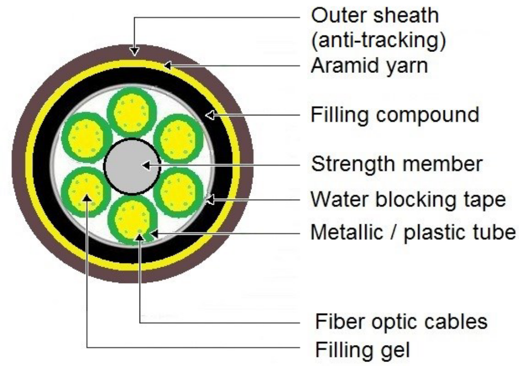

Figure 4. Typical cross section of an OPAC.

pole, respectively. Since 1980s, OPACs have been widely and globally deployed while the SkyWrap is the most successful OPAC wrapped wire system [31, 39]. OPACs are fiber optic cables that are small in size, flexible, and all-dielectric [37]. In Figure 4, a typical cross section of an OPAC is illustrated. Similar to ADSS wire, the inner fiber optic cable configuration needs to be protected from the harsh environmental factors, and for that reason the water blocking tape, aramid yarn, and outer sheath surround it. Since OPAC is supported by its host wire, the outer sheath should maintain additional anti-tracking properties and protection against the electric fields induced by the phase wires. Anyway, the presence of OPACs along the existing power lines has little impact on their mechanical and electrical performance as well as their appearance. OPACs are combined with the aforementioned fiber optic cables to support a denser communications network.

As the fiber optic cables are concerned, there are two primary types that may be used across the overhead transmission and distribution power grids whose main differences lie in the fiber core diameter, bandwidth, distance, and cost, namely:

- *Single-mode fiber optic cable*: This type of fiber optic cables is suitable for long-distance data transmission applications since it can carry huge amounts of information. Due to their narrow cores, the attenuation of single-mode optic cables remains low that permits higher fiber cable distances. Since single-mode optic cables allow only one light mode to travel across them, their bandwidth can be considered to be theoretically unlimited, but they allow their data transmission in only one direction. If data need to travel in both directions of downstream and upstream, a second fiber optic cable is required to be installed. The main application of single-mode fiber optic cables lies in carrier networks, MANs, and PONs [41]. In accordance with [39, 42, 43], communications networks that exploit single-mode fiber optic cables may transmit data up to 80 km without repeaters. By taking into account: (i) the fiber cable distances of the typical single-mode fiber optic cables (i.e., OS1 and OS2); (ii) the current optical transceiver, system, and installation cost; and (iii) the need for gigabit internet (> 10 GbE) [41], average single-mode fiber optic cable distances that range from 5 km to 10 km are assumed in the rest of this paper.
- *Multi-mode fiber optic cable*: This type of fiber optic cables is suitable for short-distance data transmission applications since it can carry high amounts of information. Due to their wider cores than the ones of single-mode fiber optic cables, and higher light gathering is enabled thus allowing higher amounts of the transmitted information. Because of the wider cores of multi-mode fiber optic cables, the higher attenuation due to the light reflections reduces the multi-mode fiber optic cable distances. Apart from the attenuation, more than one light modes that are supported by the multi-mode fiber optic cables produce the modal dispersion that further limits the used bandwidth and the multi-mode fiber optic cable distances. The main advantage of the more than one light modes across the multi-mode optic cables is the data transmission in both directions thus allowing the transmission and reception of signals from multiple locations. Due to their shorter reach, the main application of multi-mode fiber optic cables lies in industrial or commercial buildings, data centres, LANs, and universities [39, 42, 43]. In accordance with [39, 42, 43], the communications networks

that exploit multi-mode fiber optic cables may transmit data up to 5 km without repeaters. By taking into account: (i) the fiber cable distances of the typical multi-mode fiber optic cables (i.e., OM1-OM5); (ii) the current optical transceiver, system, and installation cost; and (iii) the need for the gigabit internet (> 1 GbE) [41], average multi-mode fiber optic cable distances of approximately 500 m are assumed in the rest of this paper.

Here, it should be noted that the mixing of the two different fiber optic cable types may result in high optical losses, link flapping, and system failure due to the different core sizes and supported light modes. Therefore, it is recommended that fiber optic cable types are carefully selected for the parts where they are applied across the different parts of the communications network of overhead transmission and distribution power grid.

2.2. Amplification of the Fiber Optic Signal and Extension of the Fiber Optic Cable Distances

Despite the limitations of the fiber optic cable distances (either single-mode or multi-mode fiber optic cables), the digital fiber optic signal can be repeated or regenerated virtually indefinitely, thus allowing the installation of a communications network across overhead transmission and distribution power grids and the delivery of long haul broadband applications. Towards the removal of the signal distortion and the increase of the signal level, two fiber optic communications system devices can be deployed, say:

- *Optical amplifier*: This fiber optic communication system device amplifies the fiber optic signal without regenerating it. The lack of the regeneration implies that the noise of the fiber optic signal is also amplified. Due to their design simplicity and consequent low cost, optical amplifiers can be deployed at frequent intervals.
- *Electro-optical repeater*: This fiber optic communications system device mainly consists of a receiver and a transmitter; say, the receiver detects the fiber optic signal and converts it into an electrical signal while the transmitter operates in a vice versa way. Between the receiver and transmitter, the signal processing unit first regenerates the signal by reducing its noise and readjusting its pulse timing and second amplifies it. Due to the intelligence and the described complexity of the electro-optical repeaters, their cost is higher than the optical amplifier one while a monitoring of their operation is required.

2.3. The Architecture of the Fiber Optic Backbone Communications Network across the Overhead Transmission and Distribution Power Grid

The imminent traffic growth due to the IoT and 5G (and beyond) is paving the way for new investments in backbone networks that allow the accelerating flow of the big data. It is inevitable for the fiber optic communications network across the overhead transmission and distribution power grid to be a prime backbone network due to its enormous bandwidth, high reliability, and long distance.

The fiber optic backbone communications network across the overhead transmission and distribution power grid acts as the set of pathways where the other communications network is connected for the purposes of the long distance communications. Various communications technologies, such as BPL, DSL, fiber optics, WPAN, WiFi, WiMAX, GSM, and satellite, can coexist through their respective gateways, which are the connection points between the aforementioned technologies and the backbone network. Except for the gateways, routers and switches are deployed across the fiber optic backbone communications network.

Several typical architectures of the fiber optic backbone communications network across the overhead transmission and distribution power grid are [44, 45]:

- *Serial backbone architecture*: Due to its simplicity, this type of backbone architecture could be deployed for enterprise WANs. In Figure 5, a typical serial backbone architecture is presented where a router and three switches are connected to each other by a single fiber optic cable in a linked serial mode. Switches can either extend the network or allow different communications technologies (e.g., BPL, GSM, Satellite, WPAN technology) to be connected through their gateways.

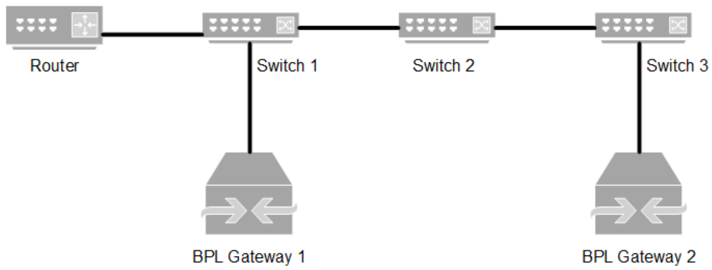

Figure 5. Typical architecture of a serial backbone network.

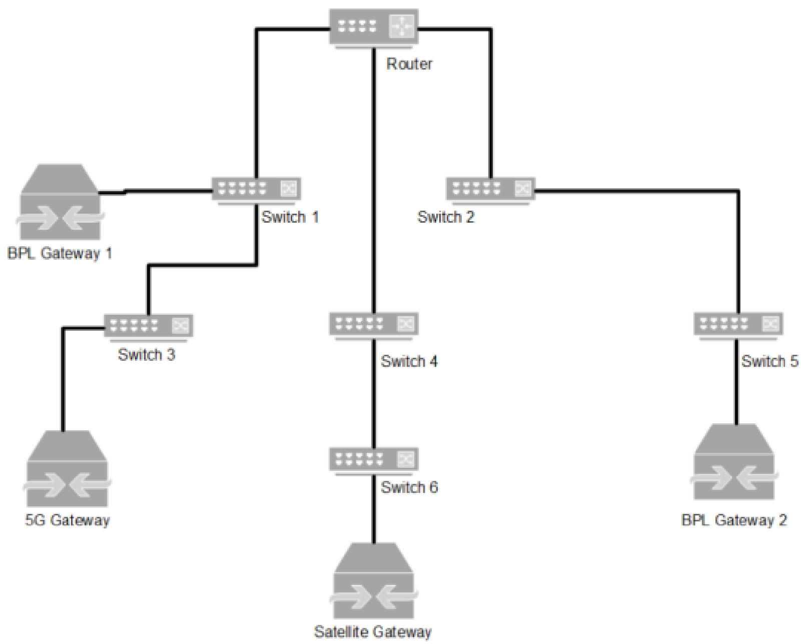

Figure 6. Typical architecture of a distributed backbone network.

- *Distributed backbone architecture*: This type of hierarchical backbone architecture that is demonstrated in Figure 6 could be deployed for any large-scale network. In fact, its main advantages are the easy installation, scalability, simple network management and network expansion. As the network expansion is concerned, this implies that more layers of gateways can be added to the existing layers [46, 47].
- *Collapsed backbone architecture*: On the basis of a single router that behaves as the central connection point for multiple subnetworks, multiple locations can be interconnected. In Figure 7, a typical collapsed backbone architecture is presented; say, a router and two switches define two separate subnetworks that may separately been managed in the context of switching and routing as well as been troubleshot. The collapsed backbone architectures resemble to star or tree LAN topologies.
- *Parallel backbone architecture*: To ensure continuous availability, higher speeds and high fault tolerance of its critical operations, parallel backbone architecture of Figure 8 can be seen as a modified collapsed backbone architecture. Enterprise WANs adopt parallel backbone architecture for its performance and trustworthiness as duplicate connections occur between the high level routers and subnetworks. The ensured network connectivity of all the areas of a WAN implies higher installation and maintenance costs due to the additional required cabling [47].

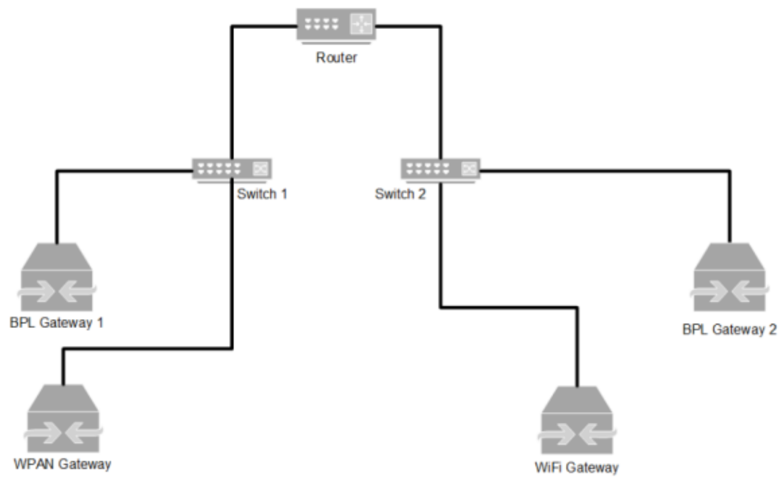

Figure 7. Typical architecture of a collapsed backbone network.

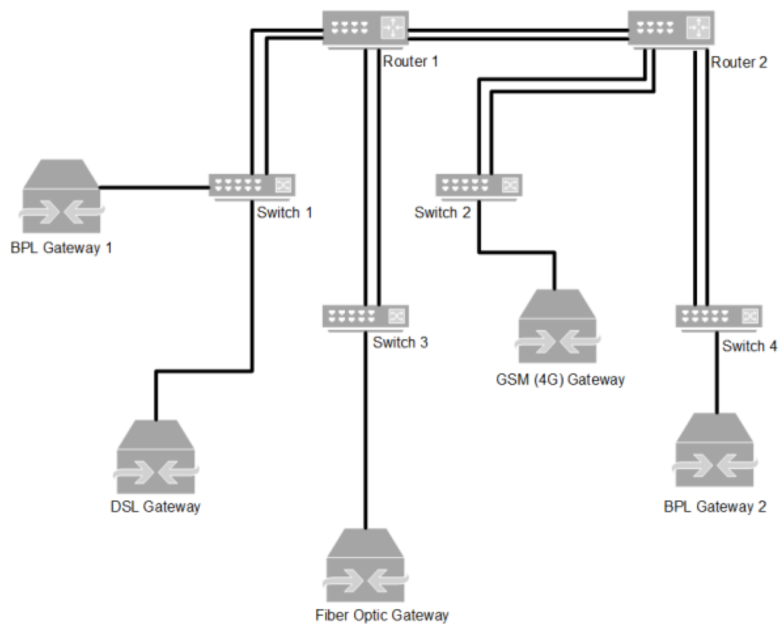

Figure 8. Typical architecture of a parallel backbone network.

3. OVERHEAD TRANSMISSION AND DISTRIBUTION MTL CONFIGURATIONS, RESPECTIVE BPL TOPOLOGIES AND NETWORK ARCHITECTURE

During the recent years, the transformation of the traditional power grid to the smart grid requires the operation of a parallel advanced IP-based communications network enhanced with a plethora of broadband applications and data analytics [48–53]. Among the available communications solutions, such as BPL, DSL, fiber optics, WPAN, WiFi, WiMAX, GSM and satellite, that support the IP-based communications network, BPL technology can play an important role through its networks since BPL networks exploit the already wired infrastructure across overhead transmission and distribution power grid [3, 5, 11, 12, 29, 54–56].

In this Section, a presentation of several typical overhead transmission and distribution MTL configurations is first given. Then, the topological characteristics of the typical overhead HV, overhead

MV and overhead LV BPL topologies are reported. Finally, a BPL network architecture is proposed for supporting: (i) power grid monitoring, metering and controlling applications; and (ii) the coexistence of fiber optic backbone communications network and BPL networks.

3.1. Overhead Transmission and Distribution MTL Configurations

As the overhead transmission MTL configurations are concerned, a typical overhead HV MTL configuration is illustrated in Figure 9. More specifically, the overhead 400 kV double-circuit configuration consists of six phase wires of radius $r_{\mathrm{p}}^{\mathrm{OVHV}}$ — i.e., wire 1, 2, 3, 4, 5, and 6 — and two neutral wires of radius $r_{\mathrm{n}}^{\mathrm{OVHV}}$ — i.e., wire 7 and 8 —. The six phase wires are divided into three bundles. The phase wires of each bundle are connected by non-conducting spacers. $\Delta_{\mathrm{n}}^{\mathrm{OVHV}}$, $\Delta_{\mathrm{p1}}^{\mathrm{OVHV}}$ and $\Delta_{\mathrm{p2}}^{\mathrm{OVHV}}$ are the separation spacings of the neutral wires, of the bundles and of the wires inside each bundle, respectively. Phase and neutral wires are hung at heights $h_{\mathrm{n}}^{\mathrm{OVHV}}$ and $h_{\mathrm{n}}^{\mathrm{OVHV}}$ above the ground, respectively. All the phase and neutral wires that are deployed across the overhead HV MTL configuration of Figure 9 are ACSR. The exact dimensions concerning the radii, spacings and heights are given in [15].

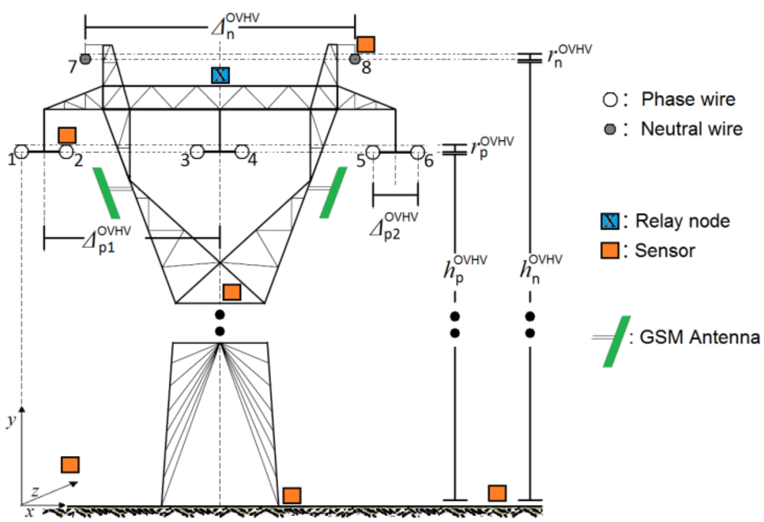

Figure 9. Typical overhead HV MTL configuration.

In accordance with [3] and Figure 9, overhead HV MTL configurations may support WSNs that consist of spatially distributed autonomous sensors, which are located at the overhead HV towers, across the overhead HV wires and the surrounding environment of the overhead HV MTL configurations, and relay nodes, which are located at the overhead HV towers [57–59]. Apart from the physical or environmental condition monitoring (e.g., temperature, sound, pressure, motion, earthquake, fire detection and control), these WSNs are useful for many industrial and civilian applications as well as the support of the power utilities towards the overhead transmission and distribution power grid line monitoring, metering and controlling. With reference to Figure 9, each overhead HV tower may be equipped with a relay node that can have both short- and long-range communications capabilities depending on the supported applications and its system design [60, 61]. The relay nodes receive data from their surrounding sensors. Due to their battery efficiency, sensors are usually preferred to have only short-range communication capabilities to communicate with their surrounding sensors and their corresponding relay node. By exploiting their long-range communications capabilities, the relay nodes of adjacent overhead HV towers can exchange the collected information between them [3, 62]. BPL networks, which are already installed across the overhead transmission power grid, or control centers at the ends of the overhead HV power lines may directly collect the information from the relay nodes and thus indirectly from the sensors.

In accordance with [63] and Figure 9, apart from WSNs, the recent developments concerning the GSM technology (i.e., 5G wireless communications networks) bring new challenges for the tower sharing of overhead HV MTL configurations [64, 65]. The need for denser wireless communications networks with the simultaneous absence of the ground resources promote the shared application of GSM antennas/base stations and overhead HV MTL configurations as a feasible and economical investment. The venture is further increasing its value by taking into account the installation of the fiber optic backbone communications network across the overhead HV power grid.

As the overhead distribution MTL configurations are regarded, a typical case of an overhead MV distribution line is depicted in Figure 10. This overhead MV distribution line consists of three parallel non-insulated ACSR phase wires of radius $r_{\mathrm{p}}^{\mathrm{OVMV}}$. The horizontal phase wire spacing is equal to Δ^{OVMV} while the phase wires are hung at heights h^{OVMV} above ground. Note that the overhead MV MTL configuration of Figure 10 does not comprise any neutral wires. The exact dimensions, material and structure of this overhead MV MTL configuration are given in [23].

In Figure 11, a typical overhead LV MTL configuration is illustrated. The examined overhead LV MTL configuration consists of four parallel non-insulated AAAC wires in a vertical arrangement being spaced from each other by a distance Δ^{OVLV}. The upper wire of radius r_n^{OVLV} is the neutral one while the other three wires of radius r_p^{OVLV} are the three phases. The lowest phase wire is hung at height h^{OVLV} above the ground. The exact dimensions, material and structure of this overhead LV MTL configuration are given in [23].

As the wooden poles of overhead distribution MTL configurations are concerned in Figures 10 and 11, the adoption of a dense fiber optic communications network across overhead distribution power grid may urge their replacement with concrete poles due to the durability of the latter ones. As already been mentioned in Section 2, the installation of ADSS wires, which are self-supporting and installed on the distribution poles separately from the power lines, can increase the load that should be withstood and for that reason concrete poles can be considered to be more suitable.

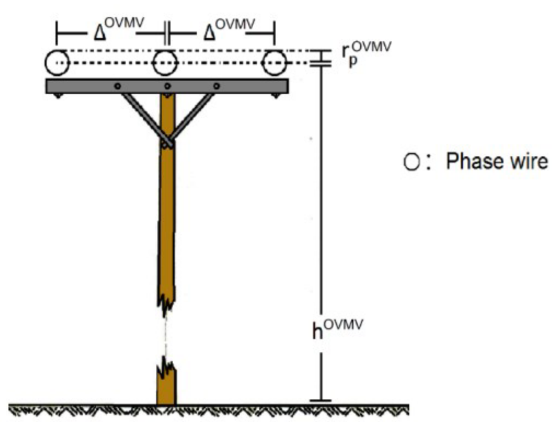

Figure 10. Typical overhead MV MTL configuration [23].

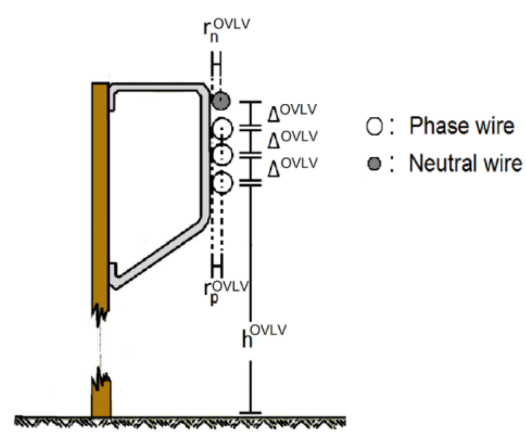

Figure 11. Typical overhead LV MTL configuration [23].

3.2. Indicative Overhead Transmission and Distribution BPL Topologies

The BPL networks may exploit the already existing wired infrastructure of overhead transmission and distribution power grids as well as their surrounding environment by deploying various BPL equipment units and other pieces of smart grid equipment that collect, receive and transmit information in the context of BPL signals.

To study overhead transmission and distribution BPL networks, each network is divided into cascaded simpler BPL topologies. A typical BPL topology is shown in Figure 12. Each overhead BPL topology is bounded by its transmitting and receiving ends where BPL equipment units are installed.

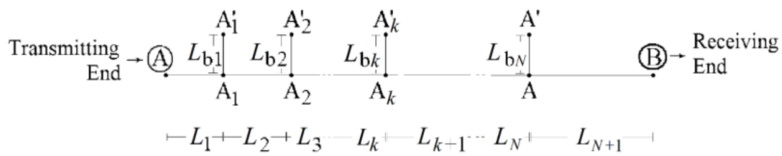

Figure 12. Typical overhead BPL topology with N branches [66].

Depending on the location of the BPL topology across the overall BPL network, these BPL devices can be the BPL signal injector, the BPL signal extractor and the BPL signal repeater. Also, to deliver the traffic from the BPL network into the fiber optic communications network, the BPL gateways, such those of Figures 5–8, can further be deployed with the aforementioned traditional BPL devices. Across the BPL signal transmission path, N branches with their respective terminations may be encountered. The arbitrary k branch has length equal to L_{bk}, $k = 1, \ldots, N$ while it is located at distance $\sum_{i=1}^{k} L_k$ from the transmitting end. The length of the BPL signal transmission path that is anyway the distance from the transmitting to receiving end, say, the end-to-end-distance, is equal to $\sum_{i=1}^{N+1} L_k$.

As the BPL signal transmission across the overhead HV BPL topologies is concerned, an average end-to-end distance of 25 km is assumed. In accordance with [15, 29, 30], the following five indicative overhead HV BPL topologies are presented, namely: (i) A typical overhead HV BPL urban topology; (ii) An aggravated overhead HV BPL urban topology; (iii) A typical suburban overhead HV BPL topology; (iv) A typical overhead HV BPL rural topology; and (v) The "LOS" transmission along the same average end-to-end distance of 25 km. This topology corresponds to the Line of Sight transmission of wireless channels. The topological characteristics of the aforementioned five indicative overhead transmission BPL topologies are reported in Table 1.

Similar to the overhead transmission BPL topologies of Table 1, five overhead distribution BPL topologies (i.e., typical urban, aggravated urban, suburban, rural and "LOS") can be defined so that a representative study of all the overhead distribution BPL topologies may be fulfilled [11, 23, 28]. In

Table 1. Indicative overhead transmission BPL topologies [15, 29, 30].

Overhead HV BPL Topology	**Number of Branches**	**Length of Transmission Lines**	**Length of Branches**
Typical overhead HV BPL urban topology	3	$L_1 = 1,150\,\text{m},\ L_2 = 12,125\,\text{m},$ $L_3 = 8,425\,\text{m},\ L_4 = 3,300\,\text{m}$	$L_{b1} = 27,600\,\text{m},$ $L_{b2} = 17,200\,\text{m},$ $L_{b3} = 33,100\,\text{m}$
Aggravated overhead HV BPL urban topology	4	$L_1 = 125\,\text{m},\ L_2 = 3,950\,\text{m},$ $L_3 = 3,275\,\text{m},\ L_4 = 13,875\,\text{m},$ $L_5 = 3,775\,\text{m}$	$L_{b1} = 19,000\,\text{m},$ $L_{b2} = 22,700\,\text{m},$ $L_{b3} = 17,100\,\text{m},$ $L_{b4} = 18,000\,\text{m}$
Overhead HV BPL suburban topology	2	$L_1 = 9,025\,\text{m},\ L_2 = 12,750\,\text{m},$ $\text{L}_3 = 3,225\,\text{m}$	$L_{b1} = 46,800\,\text{m},$ $L_{b2} = 13,400\,\text{m}$
Overhead HV BPL rural topology	1	$L_1 = 3,750\,\text{m},\ L_2 = 21,250\,\text{m}$	$L_{b1} = 21,100\,\text{m}$
Overhead HV BPL "LOS" topology	0	$L_1 = 25,000\,\text{m}$	-

Table 2. Indicative overhead distribution BPL topologies [11, 23, 28].

Overhead Distribution BPL Topology (Either overhead MV or overhead LV)	**Number of Branches**	**Length of Distribution Lines**	**Length of Branches**
Typical overhead distribution BPL urban topology	3	$L_1 = 500\,\text{m},\ L_2 = 200\,\text{m},$ $L_3 = 100\,\text{m},\ L_4 = 200\,\text{m}$	$L_{b1} = 8\,\text{m},\ L_{b2} = 13\,\text{m},$ $L_{b3} = 10\,\text{m}$
Aggravated overhead distribution BPL urban topology	5	$L_1 = 200\,\text{m},\ L_2 = 50\,\text{m},$ $L_3 = 100\,\text{m},\ L_4 = 200\,\text{m},$ $L_5 = 300\,\text{m},\ L_6 = 150\,\text{m}$	$L_{b1} = 12\,\text{m},\ L_{b2} = 5\,\text{m},$ $L_{b3} = 28\,\text{m},\ L_{b4} = 41\,\text{m},$ $L_{b5} = 17\,\text{m}$
Overhead distribution BPL Suburban topology	2	$L_1 = 500\,\text{m},\ L_2 = 400\,\text{m},$ $L_3 = 100\,\text{m}$	$L_{b1} = 50\,\text{m},\ L_{b2} = 10\,\text{m}$
Overhead distribution BPL Rural topology	1	$L_1 = 600\,\text{m},\ L_2 = 400\,\text{m}$	$L_{b1} = 300\,\text{m}$
Overhead distribution BPL LOS topology	0	$L_1 = 1000\,\text{m}$	-

Table 2, the aforementioned indicative overhead distribution BPL topologies are reported as well as their topological characteristics. Note that the indicative overhead distribution BPL topologies of Table 2 remain the same either overhead LV or overhead MV BPL networks are examined while their end-to-end distances are assumed to be equal to 1000 m.

3.3. Overhead Transmission and Distribution BPL Network Model for the Connection with the Fiber Optic Backbone Communications Network through BPL Gateways

In [3], the BPLeNM that is suitable for efficiently delivering data generated by WSNs to the power grid substations has been presented. In fact, BPLeNM exploits the already installed BPL units of BPL networks to deliver the generated data faster to power grid substations than transmitting them through the slower hop-by-hop communication links of adjacent relay nodes to power grid substations. Synoptically, the following steps are followed in BPLeNM: (i) Let assume that a sensor generates data and transmits them; (ii) Data are collected by the corresponding relay node; (iii) The relay node transmits the data to its representative relay node; (iv) Depending on its location and the emergency, the representative relay node transmits the data to its corresponding BPL unit or directly to one of the two power grid substations located at the ends of the BPL network; and (v) If the data are in the BPL unit, data are delivered to one of the two power grid substations located at the ends of the BPL network via the hop-by-hop communication links of adjacent BPL units.

Similar to BPLeNM of [3], the network model of overhead transmission and distribution BPL networks for their connection with the fiber optic backbone communications network through BPL gateways is appropriately modified and presented in Figure 13 while the following connection steps are followed during the BPL signal transmission, namely: (i) Let assume that a BPL unit has collected the data through its interfaces and needs to transmit them; (ii) Data are collected by the representative BPL unit. Note that the representative BPL units have either a BPL gateway or a direct connection to one of the two power grid substations located at the ends of the BPL network; (iii) Depending on its location and the emergency, the representative BPL unit transmits the data through its BPL gateway to the corresponding switch of the fiber optic backbone communications network or directly to one of the two power grid substations located at the ends of the BPL network; and (iv) If the data are in the switch of the fiber optic backbone communications network, data are delivered to one of the two power grid substations located at the ends of the BPL network via the hop-by-hop fiber optic transmission path as illustrated in Figures 5–8. The inverse procedure is followed during the BPL signal reception.

With reference to Figure 13, it is clear that the fiber optic backbone communications network across the overhead transmission and distribution power grid acts as the set of pathways where the other communications networks can be connected through their respective gateways. Similar network models can be assumed for the connection of the other communications technologies, such as DSL, fiber optics, WPAN, WiFi, WiMAX, GSM, and satellite, through the appropriate connection of their respective gateways and the switches of the fiber optic backbone communications network.

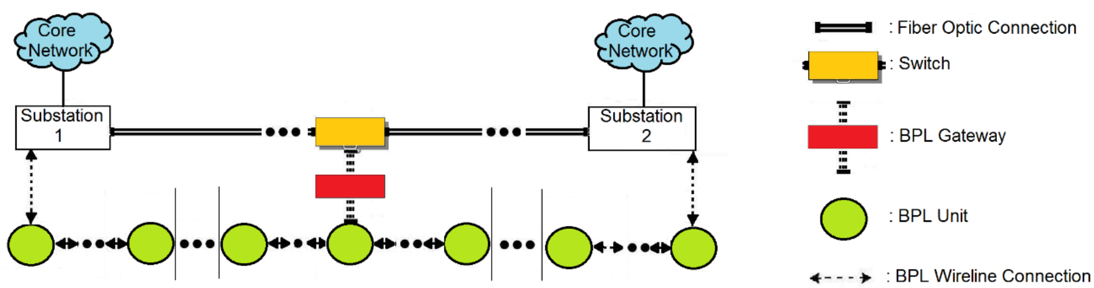

Figure 13. Overhead transmission and distribution BPL network model for the connection with the fiber optic backbone communications network through BPL gateways.

4. THEORETICAL MAXIMUM DATA RATES AND FIELD INSTALLATION

In this Section, theoretical approximations of the maximum data rates of the fiber optic backbone communications network across the overhead transmission and distribution power grid are first given by taking into account the overhead transmission and distribution MTL configurations of Section 3 and the alternative wiring solutions given in the Section 2. Then, a theoretical field installation of the fiber optic backbone communications network across a real overhead MV power grid is discussed. Also, the coexistence of the backbone communications network with an overhead MV BPL network is outlined.

4.1. Theoretical Total Data Rates of the Fiber Optic Backbone Communications Network across Overhead Transmission and Distribution Power Grids

In Table 3, the numbers of the wires per phase and neutral are first given for the overhead HV, overhead MV and overhead LV MTL configurations of Figures 9, 10 and 11, respectively. As the installation of the fiber optic cables across the overhead transmission and distribution power grids has been described in Section 2.1, there are four available wires with fiber optic cables; say, OPGW, OPPC, ADSS and OPAC. For each MTL configuration of Table 3, the maximum number of each of the available wires with fiber optic cables, which is allowed by the examined MTL configuration type, is given as well as an arbitrary number of the fiber cables per available wire from the online product catalogs. Finally, the total number of the fiber cables per MTL configuration is computed in the last column of Table 3.

From Table 3, several interesting observations can be pointed out, namely:

- Since the OPGWs require neutral wires to be installed, the overhead MV MTL configuration cannot support OPGWs due to its lack of neutral wires. Conversely, the number of OPGWs across overhead HV and LV MTL configurations can be equal to the number of neutral wires.
- As the OPPCs are concerned, all the phase wires of the overhead transmission and distribution MTL configurations can be theoretically upgraded to OPPCs. Hence, the number of OPPCs

Table 3. Wire types with fiber optic cables, average number of fiber cables per type of wire with fiber optic cables and total number of fiber cables per overhead transmission and distribution MTL configuration.

Type of MTL Configuration	**Number of Wires**		**Type of Wire with Fiber Optic Cables**				**Estimated Average Number of Fiber Cables per Type of Wire with Fiber Optic Cables**				**Total Number of Fiber Cables**
	Phase Wires	**Neutral Wires**	**OPGW (A1)**	**OPPC (A2)**	**ADSS (A3)**	**OPAC (A4)**	**OPGW [67] (B1)**	**OPPC [68] (B2)**	**ADSS [69] (B3)**	**OPAC [70] (B4)**	**(A1) × (B1) +(A2) × (B2) +(A3) × (B3) +(A4) × (B4)**
Overhead HV (Figure 9)	6	2	2	6	2	8	48	72	288	48	1,488
Overhead MV (Figure 10)	3	-	-	3	1	3	-	48	216	48	504
Overhead LV (Figure 11)	3	1	1	3	1	4	24	24	144	48	432

may be equal to the number of phase wires for each overhead transmission and distribution MTL configuration.

- As the ADSS wires are installed on the transmission and distribution towers and poles separately from the power lines, the only constraint for their installation remains the strength of the MTL configurations against the ADSS wire weight. By taking into account the overhead transmission and distribution MTL configuration of this paper, two ADSS wires are assumed to be installed on the overhead HV towers that can anyway withstand the load of the ADSS wires and related equipment while one ADSS wire is assumed to be installed in the overhead MV or overhead LV MTL configurations.
- According to [67], the OPACs can be easily installed across either the phase or neutral wires regardless of their types (i.e., wires that consist of fiber optic cables or not). Therefore, the number of OPACs can be equal to the number of wires in overhead transmission and distribution MTL configurations.
- The last column of Table 3 gives a rough and theoretical estimation of the total number of fiber cables that can be supported by the overhead transmission and distribution MTL configurations, which can be anyway assumed to be as a typical scenario of MTL configurations across the power grid.

With reference to the fiber distance Tables of [41, 71] and the average single/multi-mode fiber optic cable distances of Section 2.1, the typical fiber distance is given in Table 4 with respect to the fiber optic cable type. Note that the table cells of Table 4 that correspond to the average single/multi-mode fiber optic cable distances of interest are given in green background color.

From Table 4, it is easily observed that:

- The single-mode cable fiber distance is significantly higher than the one of the multimode fiber cables for given data rate except for the case of the Fast Ethernet 100BASE-FX. The significantly lower fiber distances of multi-mode fiber optic cables come from the modal dispersion of their multi-mode step-index fibers. Anyway, for the average single and multi-mode fiber optic cable distances of interest, which are equal to 5 km–10 km and 550 m, respectively, and are given in green background color, data rates of 1 Gbps can be securely supported.
- By comparing the average single and multi-mode fiber optic cable distances of interest with the average end-to-end distances of the overhead transmission and distribution BPL networks, the following observations can be made:

  - As the single-mode fiber optic cable distances of 5 km are assumed, these distances are greater than the 1 km average end-to-end distances of overhead distribution BPL topologies. BPLeNM of Section 3.3 is required so that the switches of the fiber optic backbone communications network of Figure 13, which permit the connection of the single-mode fiber optic cables across the overhead distribution power grid, can collect the BPL network traffic from the corresponding BPL gateways.
  - As the single-mode fiber optic cable distances of 5 km are assumed, these distances are lower than the 25 km average end-to-end distances of overhead transmission BPL topologies. In contrast with the overhead distribution BPL networks, BPLeNM of Section 3.3 is not applied in the overhead transmission BPL networks since there is no need for BPL gateways that collect the BPL traffic. Here, the BPL repeaters can act as the BPL gateways. Anyway, the end-to-end distances of the overhead transmission BPL topologies may be reduced so that higher data rates can be achieved and the fiber optic backbone communications network across the overhead transmission power grid can be further exploited.
  - As the multi-mode fiber optic cable distances of 550 m are assumed, these distances are lower than the average end-to-end distances of all overhead transmission and distribution BPL topologies. Similar to the deployment of single-mode fiber optic cables with overhead HV BPL networks, the BPL repeaters can act as the BPL gateways when multi-mode fiber optic cables are used in the fiber optic backbone communications network of the overhead transmission and distribution power grid.
  - Since the fiber optic backbone communications network across the overhead transmission and distribution power grid is proven to be a long-distance application, as expected, the single-mode fiber optic cables are preferred to be installed rather than the multi-mode fiber optic cables. Therefore, for the rest of the paper, only single-mode fiber optic cables are going to be adopted when field installations of the fiber optic backbone communications network across overhead transmission and distribution power grids are studied.
- According to [41, 71], single-mode cable fibers can support even longer distances from 5 km in 10 Gbps, 40 Gbps and 100 Gbps data rates. For example, 10 Gbps, 40 Gbps and 100 Gbps data rates can be supported by OS2 single-mode fiber optic cables in 10 km fiber distance but with respective higher total costs (i.e., higher optical transceiver, system and installation costs).

By combining the observations of Tables 3 and 4, it is evident that the *fiber optic backbone communications network across the overhead transmission and distribution power grid is going to primarily consist of single-mode fiber optic cables.* By taking into account the theoretically available total numbers of fiber cables per overhead power grid type, which are reported in Table 3, and the data rates of single-mode fiber optic cables for the average single-mode fiber optic cable distances, which are reported in Table 4, it can be easily computed that:

- As the fiber optic backbone communications network across overhead HV power grid is concerned, total data rates can theoretically reach up to $1,488 \times 1$ Gbps = 1.488 Tbps, 14.88 Tbps, 59.52 Tbps and *148.8 Tbps* when single-mode fiber optic cables of 1 Gbps, 10 Gbps, 40 Gbps and 100 Gbps are deployed.
- As the fiber optic backbone communications network across overhead MV power grid is concerned, total data rates can theoretically reach up to 504×1 Gbps = 0.504 Tbps, 5.04 Tbps, 20.16 Tbps and 50.4 Tbps when single-mode fiber optic cables of 1 Gbps, 10 Gbps, 40 Gbps and 100 Gbps are deployed.
- As the fiber optic backbone communications network across overhead LV power grid is concerned, total data rates can theoretically reach up to 432×1 Gbps = 0.432 Tbps, 4.32 Tbps, 17.28 Tbps and 43.2 Tbps when single-mode fiber optic cables of 1 Gbps, 10 Gbps, 40 Gbps and 100 Gbps are deployed.

From the previous computations, it is clear that the fiber optic backbone communications network across overhead transmission and distribution power grid can be considered to be a terabit-class fiber optic network. As the transmission and distribution power grids are omnipresent, high-capacity services may be provided between and inside large urban centers. Apart from an important asset for the power utilities to commercially exploit, the fiber optic backbone communications network across transmission and

Table 4. Typical fiber distance of various fiber optic cable types [41, 71].

<table>
<tr><th colspan="2" rowspan="2">Fiber Optic Cable Type</th><th colspan="6">Fiber Distance
(m)</th></tr>
<tr><th>Fast Ethernet 100BASE-FX [41]</th><th>1Gbps Ethernet 1000BASE-SX [41]</th><th>1Gbps Ethernet 1000BASE-LX [41]</th><th>10Gbps Base SE-SR [41]</th><th>40Gbps</th><th>100Gbps</th></tr>
<tr><td>Single-mode fiber optic cable</td><td>OS2</td><td>200</td><td>5,000</td><td>5,000</td><td>10,000</td><td>10,000 (Base LR4) [71]</td><td>10,000 (Base-LR4) [71]</td></tr>
<tr><td rowspan="5">Multi-mode fiber optic cable</td><td>OM1</td><td>200</td><td>275</td><td rowspan="5">550 (mode conditioning patch cable required)</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>OM2</td><td>200</td><td>550</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>OM3</td><td>200</td><td>550</td><td>300</td><td>100 (Base SR4) [41]</td><td>100 (Base SR10) [41]</td></tr>
<tr><td>OM4</td><td>200</td><td>550</td><td>400</td><td>150 (Base SR4) [41]</td><td>150 (Base SR10) [41]</td></tr>
<tr><td>OM5</td><td>200</td><td>550</td><td>300</td><td>400 (Base SR4) [41]</td><td>400 (Base SR10) [41]</td></tr>
</table>

distribution power grid could be the key to accelerating the digital transformation, driving innovation and contributing to higher growth of economies and societies.

4.2. Theoretical Field Installation of the Fiber Optic Backbone Communications Network across Overhead MV Power Grid

In this subsection, a field installation of a fiber optic backbone communications network across a real overhead MV power grid is theoretically demonstrated. In fact, by taking into account the findings of Section 4.1, a single-mode fiber optic cable backbone communications network is deployed across a real overhead MV power grid. At the same time, a BPL network also operates in the same parts of the power grid while it cooperates with the fiber optic backbone communications network via switches and BPL gateways by adopting BPLeNM.

With reference to [72, 73], the spatial distribution of a real world suburban power grid is shown in Figure 14. In accordance with Table 2 of [72], this suburban 10 kV Chinese MV power grid is characterized by its radial structure while it covers an approximate area of 66.2 km^2 with an approximate population of 31,908 residents. Initially, it is assumed that the power grid of Figure 14 is an overhead MV power grid and its main grid supply point can collect and deliver the information from/to fiber optic and BPL wireline connections (similarly to power grid substations of Figure 13). Two fiber optic subnetworks are assumed to be supported by the main grid supply point (i.e., fiber optic subnetworks A and B). Apart from the fiber optic subnetworks, that are part of the fiber optic backbone communications network of the real overhead MV power grid, an overhead MV BPL network may be also operating across the power grid. In Figure 14, the architectures of the fiber optic subnetworks and the BPL network are plotted as well as their cooperation.

From Figure 14, several interesting conclusions can be deduced concerning the combined operation of a fiber optic backbone communications network and a BPL network:

- With reference to Section 2.3, the distributed fiber optic backbone architecture of Figure 6 has been

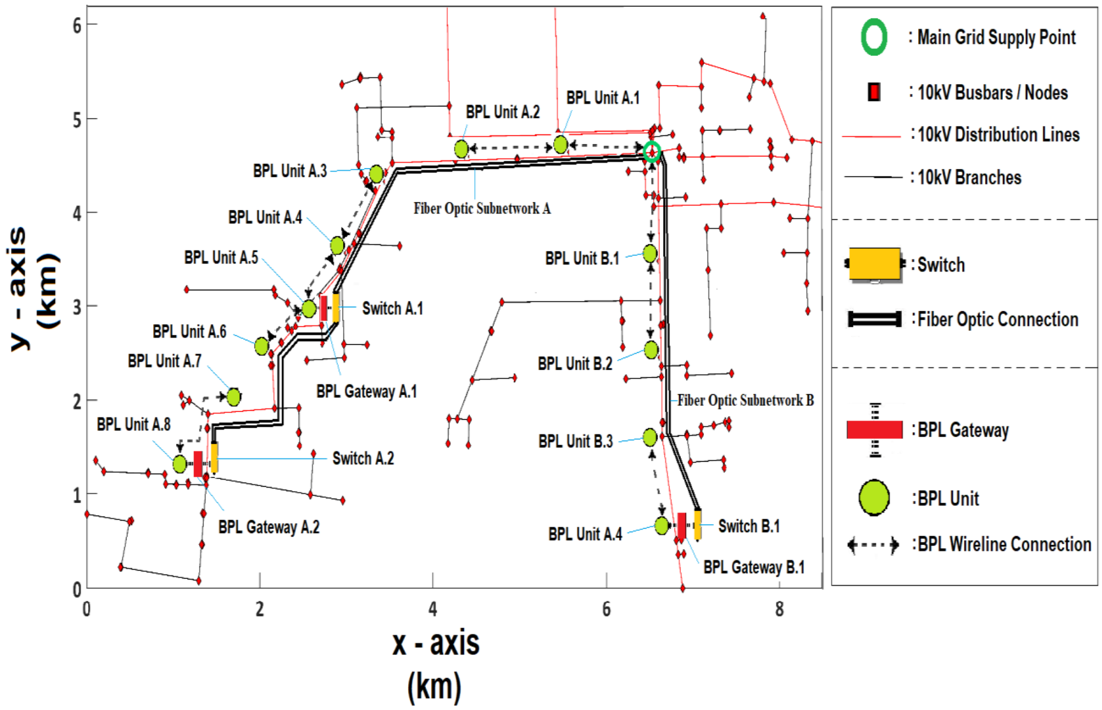

Figure 14. Theoretical field installation of a fiber optic backbone communications network and a BPL network across the real world overhead MV power grid of [72, 73].

implemented across the overhead MV power grid. Assuming that a router is installed in the main grid supply point of Figure 14, the distributed fiber optic backbone architecture has been chosen for its suitability for the large-scale overhead MV power grid of Figure 14. By using three switches and three BPL gateways, the proposed fiber optic backbone communications network can serve 12 BPL units. Apart from the overhead MV BPL networks, the main advantage of the applied distributed fiber optic backbone architecture is its scalability and its network expansion capabilities by adding more gateways for other available communications technologies, such as DSL, fiber optics, WPAN, WiFi, WiMAX, 5G, GSM and satellite.

- By adopting the BPLeNM, the existing overhead MV BPL subnetworks cooperate with the corresponding fiber optic backbone communications subnetworks in an easy and efficient way through the BPL gateways. However, the BPL networks can also separately act as the required redundancy for the fiber optic backbone communications subnetworks to ensure their reliability and maintenance of services in case of emergencies. Here, it should be noted that BPL networks may operate via their wireless interfaces when BPL wireline connections fail to be established.
- With reference to Table 3, depending on the traffic requirements, the future predicted region growth and the present region size, location and economic/social status, different total number of fiber cables can be deployed across the different fiber optic backbone communications subnetworks in order to satisfy the data rate requirements.
- It has been shown in Section 4.1 that each fiber optic backbone communications subnetwork across overhead MV power grid can reach total data rates that may range from 0.504 Tbps to 50.4 Tbps for the examined scenarios of total number of fiber cables; say, the terabit-class fiber optic network of the neighborhood. Indeed, the promised easy access to very high-speed communications services is a precondition to economic growth and development while these services can be delivered either to power utilities for their own interest or to third parties by leasing/selling or to consumers through the gateways of various communications technologies [31, 32].

5. CONCLUSIONS

In this paper, a system architecture that integrates the operation of the fiber optic backbone communications networks across the overhead transmission and distribution power grids and the BPL networks has been analytically presented. Initially, all the available fiber optic cables that can replace the vintage power cables of the existing overhead transmission and distribution power grids have been reported as well as the supported network architecture of the fiber optic backbone communications networks. Then, the characteristics of BPL networks that can be deployed across the overhead transmission and distribution power grids have been presented concerning the available MTL configurations, BPL topologies and BPL network architectures. Also, BPLeNM, which have been redesigned for the purpose of this paper, that allows the cooperation of the fiber optic backbone communications networks with the BPL networks has been presented. In addition, issues concerning the operation of the wireless sensor networks and tower sharing have been outlined. As the practical findings of this paper are regarded, it has been shown that the full exploitation of the fiber optic cable capabilities of the overhead transmission and distribution power grids may allow the transformation of the today's traditional power grid into the terabit-class fiber optic networks of the neighbourhood with total data rates that may range from 0.432 Tbps to 148.8 Tbps. Furthermore, exploiting the demonstrated system architectures of this paper, switches and gateways, the fiber optic backbone communications network across the overhead transmission and distribution power grids may allow the cooperation with other available communications technologies, such as DSL, fiber optics, WPAN, WiFi, WiMAX, 5G, GSM and satellite apart from BPL technology. The presented transformation may allow the delivery of a myriad of communications services not only to the power utilities for their own purposes (e.g., system protection, load and distributed generation management, distribution automation, diagnostic monitoring) and their consumers but to other communications providers and third parties by leasing or selling infrastructure or capacity.

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