A Survey of Communication Technologies for the Low Voltage Distribution Segment in a Smart Grid

António Grilo, Paulo Rogério Pereira, Mário Serafim Nunes, Augusto Casaca
Inesc-ID/Inesc INOV, Instituto Superior Técnico, Universidade de Lisboa, Rua Alves Redol, nº 9, 1000-029 Lisboa, Portugal.
e-mails: {antonio.grilo, prbp, mario.nunes, augusto.casaca}@inesc.pt

***Abstract*—This paper presents a survey of technologies for data transmission in an electricity distribution network between the controllers at the electrical secondary substations and the home equipment. The selected technologies can be used for implementation of advanced monitoring and control functionalities in the Low Voltage (LV) network of the electricity distribution system within the smart grid paradigm.**

***Keywords*—Smart Grid, PLC, RF Mesh, Wireless.**

I. INTRODUCTION

In the recent past, the concept of Smart Grid has gained relevance as a paradigm for the future energy grids. This concept spans all levels of the energy business model, comprising the generation, transport, distribution and consumption of energy. However, this paper only deals with the Low Voltage (LV) distribution segment.

The communication network that overlays the LV distribution segment of the Smart Grid is the LV Distribution Network (LVDN). The main components and interfaces related with the LVDN functionality are depicted in Fig. 1. The top level comprises the Energy Management System (EMS), which supervise, manage and control the energy infrastructure based on the gathered metering and energy infrastructure status data. The mid-level corresponds to the Local Controller near the MV/LV power transformer in the secondary substation, which provides concentration of data from LVDN. It is capable of automation, fault detection, event reporting and also quality of supply monitoring. The data that is collected by the Local Controller is typically sent to the EMS through a Wide Area Network (WAN). The lower level comprises the LVDN properly said, which interconnects sensors and actuators attached to LV infrastructure devices, as well as the Energy Meters (EMs) located at the customers' houses, to the Local Controller. Adding sensors to the LV infrastructure allows new metering, automation and management of the energy network functionalities, as well as location of faults and increased energy efficiency, among other applications. The EM provides metering and contractual functions, and enables micro-generation integration and control. Through a wireless Home Area Network (HAN), the EM can monitor and control energy devices inside a house. The producer/consumer (prosumer) can interact with the EM through a local interface.

Several communication technologies have been presented in the literature as candidates to provide the underlying support for the Smart Grid functionalities. However, given the dimension, complexity and scenario diversity of the Smart Grid, it is doubtful that the market will converge to a single winner, since all technologies have advantages and disadvantages with respect to this or that evaluation metric or scenario peculiarity. In fact, some published papers consider the possibility of integrating several technologies, from low-rate short-range wireless communications to fiber optic segments capable of aggregating data rates in the order of Mbit/s or Gbit/s spanning distances in the order of many kilometers [1][2][3].

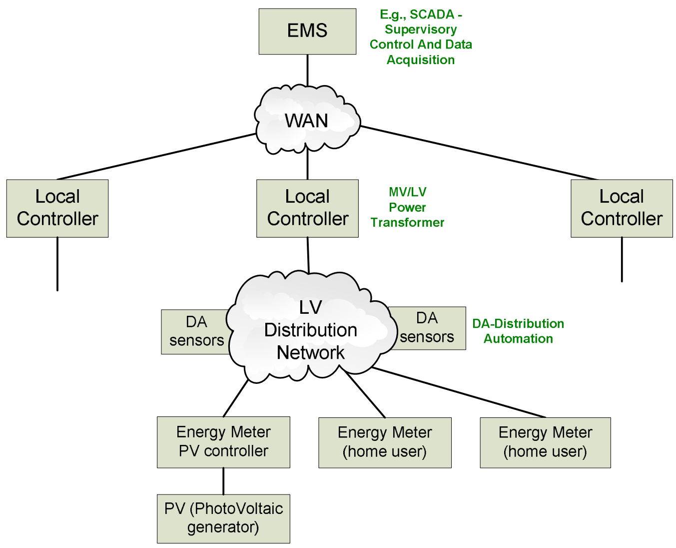

Fig. 1. Smart Grid Communication Infrastructure.

This paper presents a state-of-the-art of the communication technologies that are relevant for monitoring and intelligent control of the LVDN under the MONITOR-BT project, partially supported by the QREN program.

MONITOR-BT aims to sense and monitor utility's field devices, as well as to control micro-generation equipment at the customer premises, with both of them being located in the LV section of the electricity distribution grid. In terms of the architecture, this corresponds mainly to the LVDN section of the communications infrastructure. Although some of the sensor data is to be remotely monitored by the EMS – which also involves the Wide Area Network (WAN) – the project shall here rely on existing communications infrastructure. This state-of-the-art will thus restrict its scope to the technologies that are considered suitable for LVDN deployment:

- Power Line Communications (PLC);
- Infrastructure-based Wireless Networks;
- Radiofrequency Mesh (RF-Mesh) networks.

The reasons why these groups of technologies are more relevant in this case, have mainly to do with the following factors:

- Since LVDN is already located at the edge of the Smart Grid, the amount of traffic is much lower in comparison with the WAN, since the latter must aggregate traffic from several LV islands.
- For cost-effectiveness reasons, the footprint of the communications network in terms of additional equipment and/or requirement for changes in existing grid equipment must be minimized. Wireless technologies avoid the deployment of cabled infrastructure (RF-Mesh) or employ existing infrastructure from a telecom operator (Public Land Mobile Network – PLMN). On the other hand, PLC also avoids the deployment of cabled infrastructure, since the latter already exists in the electricity grid.

This paper presents an analysis of these three groups of candidate technologies, presenting their advantages, disadvantages and constraints.

II. Analysis of Technologies

A. *Power Line Communications (PLC)*

Power Line Communications (PLC) technology is used since the 1950s by the electricity distribution companies in order to remotely perform some control functions on electric network equipment [4]. Recently, this technology has earned more relevance because the technology evolution has led to an increase of the achieved data rates, both in medium and low voltage. The advantage of PLC comes from the fact that it uses the same infrastructure for both energy distribution and communications, which greatly reduces the deployment costs.

The PLC systems are usually classified according to three different bandwidth classes: Ultra Narrowband (UNB), Narrowband (NB) and Broadband (BB) [5][6]. Although the attained data rates and ranges are highly dependent on the specific characteristics and transient conditions of the network (e.g., the impedance is highly dependent on the number and characteristics of attached electrical devices), some approximate figures shall be provided as a reference to allow a better comparison between the different classes.

The UNB-PLC systems operate in the Very Low Frequency (VLF) band, which corresponds to 0.3-3.0 kHz. The attained bit rates are usually in the order of 100 bit/s, with ranges of up to 150 km. The relevant UNB-PLC applications comprise Automatic Meter Reading (AMR), and fault detection in the distribution grid, as well as voltage monitoring.

The NB systems operate in the Low Frequency (LF) band, which corresponds to 3-500 kHz. In Europe, the European Committee for Electrotechnical Standardization (CENELEC) has defined four frequency bands for PLC use: CENELEC-A (3-95 kHz), CENELEC-B (95-125 kHz), CENELEC-C (125-140 kHz) and CENELEC-D (140-148.5 kHz). CENELEC-A is reserved for exclusive use by energy providers, while CENELEC-B, CENELEC-C and CENELEC-D are open for end user applications. In NB-PLC, the attained data rates span from a few kbit/s to around 800 kbit/s – depending on the technology, bandwidth and channel conditions –, while the range is in the order of some kilometers. Some standards for Building Automation Applications (BAA), such as BacNet (ISO 16484-5) and LonTalk (ISO/IEC 14908-3), employ NB-PLC with a single carrier. The IEC 61334 standard for low-speed reliable power line communications by electricity meters, water meters and SCADA, uses the 60-76 kHz frequency band, being able to achieve 1.2-2.4 kbit/s with Spread Frequency Shift Keying (S-FSK) modulation. Yitran Communications Ltd. and Renesas Technology provide solutions based on Differential Chaos Shift Keying (DCSK) – a form of Direct-Sequence Spread Spectrum (DSSS) –, which are able to achieve bitrates as high as 60 kbit/s in the CENELEC-A band. On the other hand, PoweRline Intelligent Metering Evolution (PRIME)[1] and G3[2] are multi-carrier systems based on Orthogonal Frequency Division Multiplexing (OFDM), which allows them to support higher data rates. PRIME operates within the CENELEC-A frequency band, more specifically in the 42–89 kHz range, and is able to achieve 21-128 kbit/s. G3 may operate in the CENELEC-A and CENELEC-B bands, being able to achieve 2.4-46 kbit/s. The G3-PLC MAC layer is based on the IEEE 802.15.4 MAC. In order to unify the OFDM-based NB-PLC systems, ITU has approved recommendations G.9955 (G.hnem physical layer) [7] and G.9956 (G.hnem data link layer) [8], while IEEE has approved recommendation P1901.2 [9].

BB-PLC systems operate in the High Frequency (HF) and Very High Frequency (VHF) bands, which corresponds to 1.8-250 MHz. The achievable data rates may be as high as 500 Mbit/s, but the range is significantly shorter than for NB-PLC. Consequently, BB-PLC is normally used for local connectivity in the HAN or as a broadband access technology. The most recent BB-PLC standards are IEEE P1901 (also designated Broadband Over Power Line – BPL)[3] and ITU G.996x (G.hn), which are based on OFDM. The ITU G.9963 recommendation [10] also incorporates some MIMO concepts through the use of multiple cables.

Despite the advantages of PLC for Smart Grid applications, namely the reduced costs and easier management of a single infrastructure (i.e. energy distribution plus communications in a single network), PLC faces some obstacles and challenges, which are often similar to the ones faced by RF-Mesh (see below):

---

[1] PoweRline Intelligent Metering Evolution: http://www.prime-alliance.org

[2] http://www.maxim-ic.com/products/powerline/g3-plc

[3] IEEE P1901 is based on the HomePlug AV system developed by the HomePlug Powerline Alliance.

- The shared medium is subject to significant attenuation and noise, which limit the data rates and ranges that can be effectively achieved.
- A failure in the energy distribution infrastructure usually means that the communications cannot take place while the malfunction rests unresolved, which may negatively affect some applications. Another consequence of the latter is that a communications failure may be wrongly interpreted as a malfunction in the energy distribution infrastructure.

B. Infrastructure-based Wireless Networks

The technologies that fall within the Infrastructure-based Wireless Networks category rely on a fixed infrastructure of base stations, together with switching equipment and management systems, in order to provide wide coverage communication service to the end user. Fixed wireless access and mobile cellular networks, both fit into this category.

The WiMAX technology is defined in the IEEE 802.16 standard for fixed and mobile broadband wireless access [11], being able to achieve a coverage range in the order of 50 km and data rates in the order of tens or even hundreds of Mbit/s. Despite its advantages, the widespread adoption of Long Term Evolution (LTE) by mobile operators has brought down the initial popularity that WiMax was, for some time, able to enjoy. Moreover, the lack of WiMax networks and operators in Portugal constitute significant obstacles to the adoption of this technology to support Smart Grid functionalities in this country, since the energy provider would have to deploy its own WiMax infrastructure. IEEE 802.16 shall be addressed again in this paper, but in the context of RF-Mesh technologies.

The mobile cellular communications technologies divide the covered territory into smaller areas designated cells, each served by a base station. If the base station is equipped with directional antennas, the cell may be further sectorized, which increases the frequency reuse and hence its capacity to support more users. Before a call is established, the mobile user terminal is tracked as it moves between different sectors or cells, allowing the mobile terminal to be paged at any time. Moreover, handover signaling procedures allow the user to move even while a call is taking place. Mobile cellular technologies have already spanned two digital generations starting on the 2nd Generation (2G) and are already in their fourth generation.

Examples of 2G technologies available in Europe (and Portugal in particular) are Global System for Mobile Communications / General Packet Radio Service (GSM/GPRS) and Terrestrial Trunked Radio (TETRA). GPRS is the packet switched complement of GSM and supports effective data rates up to 177.6 kbit/s in the downlink and 118.4 kbit/s in the uplink. The effective data rate depends on the required error protection, class of terminal and sharing with other users using the same frequency channel. The TETRA technology is primarily used by security and civilian protection entities, as well as transportation services, due to the support of specific functionalities like direct mode operation and group calls. The supported data rates span from 2.4 kbit/s to 28 kbit/s, depending on the required error protection and channel allocation.

The 3rd Generation (3G) arrived in the beginning of this century with the Universal Mobile Telecommunications System (UMTS), which offered 2 Mbit/s (shared) in urban areas. UMTS suffered a number of upgrades to increase the supported data rates, namely the High-Speed Downlink Packet Access+ (HSDPA) and HSDPA+ for the downlink, and High-Speed Uplink Packet Access (HSUPA) for the uplink. HSDPA can support data rates up to 42 Mbit/s, though later releases specify data rates up to 337 Mbit/s with HSDPA+. In the opposite direction, HSUPA may support data rates up to 23 Mbit/s, though existing mobile operators might offer a lower value.

CDMA450 is also a 3G technology, based on the adaptation of the American standard CDMA2000 to operate in the 450-470 MHz frequency band. The supported total bitrates depend on the specific mode of operation. For Multicarrier EV-DO, overall bitrates may be as high as 9.3 Mbit/s for downlink and 5.4 Mbit/s for uplink, with average rates per user in the order of 1.8-4.2 Mbit/s for downlink and 1.5-2.4 Mbit/s for uplink. This technology was offered in Portugal by the Zapp operator until 2011, being abandoned afterwards. This means that in order to use CDMA450 as a Smart Grid infrastructure, the utility will have to deploy its own network infrastructure, like for WiMax.

Currently, most European mobile operators already offer LTE, including the Portuguese mobile operators. Although marketed as 4G, LTE does not satisfy yet all the 4G requirements defined by 3GPP. LTE employs Orthogonal Frequency Division Multiple Access (OFDMA) in the downlink and Single-Carrier Frequency Division Multiple Access (SC-FDMA) in the uplink. Supported peak data rates are 299.6 Mbit/s for the downlink and 75.4 Mbit/s for the uplink.

Given their proven reliability, technology maturity and extensive coverage, mobile cellular networks constitute important candidates to support the Smart Grid communications infrastructure, being used already in applications such as Automatic Meter Reading (AMR). However, these technologies face the following challenges:

- The difficulties related with radiofrequency (RF) penetration inside buildings constitute sometimes an obstacle for its use in some Smart Grid applications, namely AMR.
- The fact that the mobile cellular network is most of the time managed by an external operator, means that the utility will have to pay the latter for the provisioning of communications services. Alternatively, the utility might deploy its own communications infrastructure (e.g., WiMax or CDMA450), though that would certainly constitute a substantial investment on communication systems.

C. Radiofrequency Mesh (RF-Mesh)

An RF-Mesh is a network formed by RF capable nodes, which are self-organized in a mesh topology [12][13][14].

This self-organization capability brings several advantages in the context of Smart Grid communications, namely deployment flexibility and automatic connection re-establishment and topology reconfiguration in the presence of link or node failure. This explains why this family of technologies is so popular in the USA, where it is used to support Smart Metering applications. Within the RF-Mesh family, we can distinguish between broadband and narrowband technologies.

The most representative broadband technologies are currently WiFi [15] and IEEE 802.16j [16]. Even if the IEEE 802.11s mesh extension is not used, IEEE 802.11 can be configured to operate as a mesh by performing ad-hoc routing at the network layer (e.g., IP layer). These technologies support communication ranges in the order of hundreds (IEEE 802.11) or thousands (IEEE 802.16) of meters, as well as high data rates in the order of Mbit/s, which makes them multimedia capable. Besides physical and Medium Access Control (MAC) aspects, IEEE 802.11s specifies the routing protocol, which is the Hybrid Wireless Mesh Protocol (HWMP). The latter is a hybrid between a tree routing protocol and the Ad-hoc On-Demand Distance Vector (AODV) protocol [17]. In case IEEE 802.11 is used without the mesh extension, a myriad of routing protocols such as AODV, Optimized Link State Routing Protocol (OLSR) [18], or Routing Protocol for Low-Power and Lossy Networks (RPL) [19] can be used at the network layer. As to IEEE 802.16j, it does not specify how the path evaluation and selection is done, there being freedom for manufacturer specific implementations. However, it constrains the topology to be tree based. Although the high bitrates supported by broadband RF-Mesh allow the support of virtually any Smart Grid applications, both real-time and non-real-time, these technologies also have some disadvantages that can hinder their global applicability:

- Broadband communications means operating at higher frequencies, which are more vulnerable to path loss and other causes of signal attenuation.
- Broadband RF-Mesh transceivers often present higher energy consumption in comparison with narrowband RF-Mesh. This is made even worse by the need to increase the transmit power in order to compensate for path loss and attenuation. The deployment of a huge number of nodes means that the energy overhead introduced by the Smart Grid communications may start to be non-negligible.
- High bitrates demand a corresponding processing and storage capacity to be available on the network nodes, which will likely be translated into an increase of the unit cost.
- The deployment of these technologies by the utility requires the choice of the operating frequency. IEEE 802.11 operates mainly on the unlicensed bands of 2.4 GHz or 5 GHz. The 2.4 GHz band is cluttered, since it is subject to the interference of both private and public WLANs. On the other hand, the 5 GHz band has a reduced range for the same transmit power. IEEE 802.16 supports frequency bands between 2 GHz and 66 GHz, both licensed and unlicensed. Besides the problems related with spectrum occupancy, the use of unlicensed bands also raises the problem of communications security. On the other hand, the use of licensed bands usually represents additional costs for the utility.

The narrowband RF Mesh technologies correspond to those that belong to the Wireless Sensor Network (WSN) and Internet of Things (IoT) domains. These are usually characterized by simpler hardware and operating systems, leading to a lower unit cost [13]. The lower power consumption that characterizes these technologies allows greater autonomy and effectiveness of energy harvesting techniques, which can feed the network nodes in case they cannot be directly fed by the LV network.

In the context of WSNs, the IEEE 802.15.4 standard is nowadays prominent, constituting the basis (PHY and MAC layers) of several protocol stacks such as ZigBee, WirelessHART, ISA100.11a and IoT, which are recommended for industrial and Smart Utility Networks (SUN) applications [14]. The IEEE 802.15.4 MAC protocol is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), but also includes an optional Time Division Multiple Access (TDMA) operational mode. The latter is reserved for traffic that requires stringent access delay guarantees. While the original IEEE 802.15.4 standard restricted operation to the unlicensed frequency bands of 868-870 MHz (Europe), 902-928 MHz (USA) and 2.4 GHz, the IEEE 802.15.4g standard for SUN extends the set of supported Ultra-High Frequency (UHF) bands, adds new transmission modes (e.g., OFDM) and extends the MAC layer functionalities to allow the efficient and fair coexistence of networks using different transmission modes within the same frequency range. IEEE 802.15.14g can achieve a maximum bitrate of 1094 kbit/s and maximum ranges in the order of tens of kilometers.

ZigBee is a standard protocol stack brought forth by the ZigBee Alliance consortium, which includes IEEE 802.15.4 at the lower layers, but defining its own network and application support layers. ZigBee, together with its ZigBee Smart Energy application profile, were defined by the National Institute of Standards and Technology (NIST) in USA as standards for communications within the Home Area Network (HAN) domain of the Smart Grid [20]. ZigBee was also selected by many energy companies as the communication technology for smart meters, since it provides a standard platform for data exchange between the latter and HAN devices [21]. The functionalities supported by the Smart Energy profile include load management, AMR, real-time billing and text messaging [22]. The ZigBee Alliance also developed an IP networking specification called ZigBee IP which is based on existing IETF protocols defined for IoT (see below). The ZigBee Smart Energy version 2.0 specifications already make use of ZigBee IP. It is an enhancement of the ZigBee Smart Energy version 1 specifications, adding services for plug-in electric vehicle (PEV) charging, installation, configuration and firmware download, prepaid services, user information and messaging, load control, demand response and common information and application profile interfaces for wired and wireless networks. The application function sets implemented in this release were mapped to the IEC Common Information Model [23].

WirelessHART [24] is another protocol stack, based on a TDMA MAC protocol implemented over IEEE 802.15.4. It was developed as an adaptation of the HART protocol defined for wired industrial networks. While it was initially developed by a private consortium, the stack was standardized by the International Electrotechnical Commission (IEC) as IEC 62591. ISA100.11a is a standard protocol stack developed by the International Society for Automation (ISA), which is functionally very similar to WirelessHART [14].

In the meantime, IETF has defined a protocol stack adapted to the characteristics of the IoT, which is suitable to support Smart Grid applications in a way that is more compatible with the standard Internet protocol stack [25]. The core of the IoT protocol stack is IPv6 over Low power WPAN (6LoWPAN), which specifies how to support the IPv6 protocol over low bitrate wireless technologies, such as IEEE 802.15.4. 6LoWPAN specifies the protocols and procedures needed for address assignment and deconfliction, Ipv6 and higher layer header compression and fragmentation. Energy efficiency lies at the core of 6LoWPAN. Header compression exploits the redundancy between the MAC and IPv6 header fields – namely the addresses –, and/or simplifies the range of IPv6 header field value options in order to achieve higher compression rates. Regarding the routing function, the Routing Over Low power and Lossy networks (ROLL) group in IETF has specified the already mentioned RPL protocol [19]. RPL is based on the formation of routing trees designated Destination Oriented Directed Acyclic Graphs (DODAGs), supporting the overlapping between two or more of these, possibly with different root nodes. RPL is designed to minimize the routing overhead in stable networks, which is done by increasing the routing message period exponentially when there are no topology changes. On the other hand, the protocol keeps its responsiveness to topology changes by restoring the initial routing update period once a topology change is detected. As already seen, ZigBee Smart Energy version 2.0 takes advantage of these IP-oriented functionalities.

Besides the standard RF Mesh solutions described above, there are a number of proprietary RF Mesh solutions that were developed in the USA and have been enjoying significant popularity among energy operators. These products usually operate within the ISM frequency band of 902-928 MHz and employ Frequency Hop Spread Spectrum (FHSS) to increase the robustness and security of the links, namely to prevent jamming attacks and interference from other equipment operating in the same ISM band. Offered bitrates range between 9.6 kbit/s and 300 kbit/s, with ranges in the order of 2 km with 1 W of transmit power. An example is the Landis+Gyr's Gridstream, which employs a proprietary geographical based routing protocol in order to minimize the routing overhead [12]. Another example is the Silver Spring Networks solution [26].

The advantages of narrowband RF Mesh solutions are mostly related with deployment flexibility, increased range and use of less cluttered ISM frequency bands such as the 900 MHz in the USA and 868 MHz in Europe. The main disadvantage is, of course, the reduced bitrates as compared with broadband RF Mesh solutions.

Some additional disadvantages can be identified for RF Mesh solutions in general, which are the following:

- Performance is highly dependent on the propagation and interference environment.
- Depending on the scenario and inter-node distances, the deployment of additional relay nodes may be needed, which adds to the deployment costs.
- Wireless communications propagate through a shared medium, which poses some threats in terms of security. The protocol stack must implement security mechanisms that are able to meet the requirements of the Smart Grid applications. These requirements are often different from application to application.

It should be noted that the European Utilities Telecom Council (EUTC) is seeking to reserve 6 MHz in the 450-470 MHz frequency band for use by grid utility operators, together with a frequency band above 1 GHz (e.g., 1.5 GHz band spanning 10 MHz) [27]. In this way, both low rate and high rate applications would be supported.

III. Comparative Analysis and Conclusion

The previous section presented the state-of-the-art of communication technologies for the LVDN. Three types of communication technologies were analyzed: PLC, Infrastructure-based Wireless Networks and RF-Mesh. The main characteristics of these technologies are listed in Table I in order to facilitate the comparison.

From the table, it can be concluded that narrowband RF-Mesh and NB-PLC offer the best compromise between bit rate, range and cost, especially if the supported Smart Grid services require only a low bit rate. Mobile cellular solutions are easy to deploy, since mobile cellular coverage is very extensive. However, this communication service must be paid to the operator, which may result into significant operational costs.

One possible adequate solution for deployment in the LVDN might be an RF Mesh based on a Narrowband (IEEE 802.15.4g) radio, such as the XbeePro operating on the 869.4-869.65 MHz band [28] as it allows 500 mW transmission power, medium range and standard radio. RF Mesh Narrowband does not require hiring the services of an operator (unlike a mobile cellular solution) and it can be designed to be fault tolerant (at least temporarily) to failures in the energy grid (unlike PLC) if nodes are capable of energy storage (through a small battery or supercapacitors).

However, RF Mesh may be affected by radio communication problems. Consequently, the integration of different technologies can bring many advantages, increasing the robustness and reliability of the Smart Grid.

TABLE I COMPARISON OF COMMUNICATION TECHNOLOGIES FOR THE LVDN IN A SMART GRID

Type	Subtype	CAPEX	OPEX	Maximum Bit rate	Range[4]
PLC	UNB	Low	Negligible	100 bit/s	150 km
	NB	Low	Negligible	128 kbit/s (CENELEC-A)	Several km
Infra-structure-based Wireless Networks[5]	2.5G (GPRS)	Low	High	177.6 kbit/s downlink 118.4 kbit/s uplink	Coverage dependent
	3G (HSDPA, HSUPA)	Low	High	42 Mbit/s downlink 5.76 Mbit/s uplink	Coverage dependent
	4G (WiMAX, LTE)	Low	High	299.6 Mbit/s downlink 75.4 Mbit/s uplink	Coverage dependent
RF Mesh	Broadband (IEEE 802.11n/s)	High	Negligible	600 Mbit/s	Hundreds of meters
	Narrowband (Silver Spring Networks)	High	High (if license is required from ANACOM)	100 kbit/s	Several km
	Narrowband (IEEE 802.15.4g)	Medium	Negligible	1094 kbit/s	Several km (e.g., XbeePro 868 @ 24 kbit/s)

ACKNOWLEDGEMENT

This work was partially supported by national funding from QREN through the “Monitorização e controlo inteligente da rede de Baixa Tensão” (MONITOR BT) project and by FCT – Fundação para a Ciência e a Tecnologia, under project PEst-OE/EEI/LA0021/2013.

REFERENCES

[1] N. Saputro, K. Akkaya, S. Uludag, “A Survey of Routing Protocols for Smart Grid Communications,” Computer Networks, Elsevier, 56 (2012), pp. 2742–2771, 2012.

[2] X. Fang, S. Misra, G. Xue, D. Yang, “Smart Grid – The New and Improved Power Grid: A Survey,” IEEE Communications Surveys & Tutorials (COMST), 14(4): 944-980, IEEE, 4th Quarter 2012.

[3] Z. Fan, P. Kulkarni, S. Gormus, C. Efthymiou, G. Kalogridis, M. Sooriyabandara, Z. Zhu, S. Lambotharan, W. Chin, “Smart Grid Communications: Overview of Research Challenges, Solutions, and Standardization Activities,” IEEE Communications Surveys & Tutorials (COMST), 15(1):21-38, IEEE, 1st Quarter 2013.

[4] I. H. Cavdar, “A solution to remote detection of illegal electricity usage via power line communications,” IEEE Transactions on Power Delivery, October 2004.

[5] M. Nassar, Y. Mortazavi, I. Kim, “Local Utility Powerline Communications in the 3-500 kHz Band: Channel Impairments, Noise, and Standards,” IEEE Signal Processing Magazine, IEEE, July 2012 (to appear.)

[6] H. Ferreira, L. Lampe, J. Newbury, and T. Swart. Power line communications: Theory and applications for narrowband and broadband communications over power lines. John Wiley and Sons, 2010.

[7] ITU-T G.9955, “Narrowband orthogonal frequency division multiplexing power line communication transceivers – Physical layer specification”, ITU-T, December 2011.

[8] ITU-T G.9956, “Narrowband orthogonal frequency division multiplexing power line communication transceivers – Data link layer specification”, ITU-T, November 2011.

[9] IEEE P1901.2, “IEEE Draft Standard for Low Frequency (less than 500 kHz) Narrow Band Power Line Communications for Smart Grid Applications”, IEEE, approved Project Authorization Request, March 2010.

[10] ITU-T G.9963, “Unified high-speed wireline-based home networking transceivers – Multiple input/multiple output specification”, ITU-T, December 2011.

[11] IEEE 802.16-2009, “IEEE Standard for Local and metropolitan area networks Part 16: Air Interface for Broadband Wireless Access Systems”, IEEE, May 2009.

[12] B. Lichtensteiger et al, “RF Mesh Systems for Smart Metering: System Architecture and Performance,” IEEE SmartGridComm 2010.

[13] V. Gungor, B. Lu, G. Hancke, “Opportunities and Challenges of Wireless Sensor Networks in Smart Grid,” IEEE Transactions on Industrial Electronics, IEEE, vol. 57, no. 10, October 2010.

[14] B. Akyol, H. Kirkham, S. Clements, and M. Hadley. “A survey of wireless communications for the electric power system,” Prepared for the U.S. Department of Energy, 2010.

[15] IEEE 802.11-2012, “IEEE Standard for Information technology– Telecommunications and information exchange between systems Local and metropolitan area networks–Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications”, IEEE, March 2012.

[16] IEEE 802.16j, “IEEE Standard for Local and metropolitan area networks Part 16: Air Interface for Broadband Wireless Access Systems Amendment 1: Multihop Relay Specification”, IEEE, June 2009.

[17] C. Perkins et al., “Ad hoc On-Demand Distance Vector (AODV) Routing”, RFC 3561, IETF, July 2003.

[18] T. Clausen, P. Jacquet, “Optimized Link State Routing Protocol (OLSR)”, RFC 3626, IETF, October 2003.

[19] T. Winter et al., “RPL: Ipv6 Routing Protocol for Low-Power and Lossy Networks”, RFC 6550, IETF, March 2012.

[20] National Institute of Standards and Technology. NIST Framework and roadmap for smart grid interoperability standards, release 1.0, http://www.nist.gov/public_affairs/releases/upload/smartgrid_interoperability_final.pdf, January 2010.

[21] H. Farhangi, “The path of the smart grid”, IEEE Power & Energy Magazine, 8(1):18–28, 2010.

[22] P. Yi, A. Iwayemi, and C. Zhou, “Developing ZigBee deployment guideline under WiFi interference for smart grid applications”, IEEE Transactions on Smart Grid, 2(1):110–120, 2011.

[23] IEC 61970-301, “Energy management system application program interface (EMS-API) – Part 301: Common Information Model (CIM) Base”, IEC, Edition 1.0, November 2003.

[24] IEC 62591, “Industrial communication networks – Wireless communication network and communication profiles – WirelessHART™”, IEC, Edition 1.0, April 2010.

[25] P. Kulkarni, S. Gormus, Z. Fan, B. Motz, “A Mesh-Radio-Based Solution for Smart Metering Networks,” IEEE Communications Magazine, IEEE, July 2012.

[26] Silver Spring Networks, “Smart Grid Standards”, whitepaper, 09/04/2012.

[27] EUTC, “Spectrum needs for Utilities”, EUTC position paper, http://eutc.org/system/files/UTC_private_file/EUTC%20Spectrum%20Position%20Paper-9April2013.pdf, last access 5/09/2013.

[28] XBeePro 868, http://www.digi.com/products/wireless-wired-embedded-solutions/zigbee-rf-modules/point-multipoint-rfmodules/xbee-pro-868, last access 6/09/2013

[4] Maximum ranges are usually achieved with the lowest bitrates only.

[5] It is assumed that the Infrastructure-based Wireless Network Service is hired from an operator.