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Communication Solutions for LVDC Island Networks

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Abstract

Production and generation of electrical power is evolving to more environmental friendly technologies and schemes. Pushed by the increasing cost of fossil fuels, the operational costs of producing electrical power with fossil fuels and the effect in the environment, like pollution and global warming, renewable energy sources gain constant impulse into the global energy economy.

In consequence, the introduction of distributed energy sources has brought a new complexity to the electrical networks. In the new concept of smart grids and decentralized power generation; control, protection and measurement are also distributed and requiring, among other things, a new scheme of communication to operate with each other in balance and improve performance.

In this research, an analysis of different communication technologies (power line communication, Ethernet over unshielded twisted pair (UTP), optic fiber, Wi-Fi, Wi-MAX, and Long Term Evolution) and their respective characteristics will be carried out. With the objective of pointing out strengths and weaknesses from different points of view (technical, economical, deployment, etc.) to establish a richer context on which a decision for communication approach can be done depending on the specific application scenario of a new smart grid deployment.

As a result, a description of possible optimal deployment solutions for communication will be shown considering different options for technologies, and a mention of different important considerations to be taken into account will be made for some of the possible network implementation scenarios.

Acknowledgements

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Because of your advice, love and support, I have gotten further than I could have ever got alone. Thank you all from the bottom of my heart. Gracias.

I. Abbreviations

3GPP	3rd Generation Partnership Project
AC	Alternate Current
AMI	Advance Metering Interface
AMR	Automatic Meter Reading
BESS	Battery Energy Storage System
BPL	Broadband over Power Lines
BS	Base Station
DC	Direct Current
DEI	Drop Eligible Indicator
DES	Data Encryption Standard
DSL	Digital Subscriber Line
DSSS	Direct-Sequence Spread Spectrum
eNB	Evolved Node Base-Station
EMI	Electro Magnetic Interference
EMS	Energy Management System
EPS	Evolved Packet System
FBWA	Fixed Broadband Wireless Access
GSM	Global System Mobile Communication
HAN	Home Area Network
HV	High Voltage
ICT	Information and Communication Technology

IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISO	International Organization for Standardization
LN	Line to Neutral
LTE	Long Term Evolution
LV	Low Voltage
LVAC	Low Voltage Alternate Current
LVDC	Low Voltage Direct Current
MAC	Media Access Control
MIMO	Multiple Input-Multiple Output
MPPT	Maximum Power Point Tracking
MV	Medium Voltage
NN	Neutral to Neutral
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OSI	Open Systems Interconnection
PCP	Priority Code Point
PLC	Power Line Communication
PMP	Point to Multi-Point
RS	Repeater Station

RJ45	Registered Jack 45 connector
SC-FDMA	Single Carrier Frequency Division Multiple Access
SS	Subscriber Station
STP	Shielded Twisted Pair
TCI	Tag Control Information
TE	Terminal Equipment
TPID	Tag Protocol Identifier
UTP	Unshielded Twisted Pair
VID	VLAN Identifier
VLAN	Virtual Local Area Network

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1. INTRODUCTION

The focus of the research is to analyze different communication schemes for islanded power grid distribution systems and its characteristics, advantages, drawbacks, limitations and other aspects to define the optimal communication for different situations giving special importance to reliability.

A communication or telecommunication network is a set of end nodes, intermediate nodes and the links that enable data transmission between nodes. Within the context of this work, the end nodes are defined as any device that requires communication within the power distribution grid, like meters, relays, monitors, some protections, etc. The intermediate nodes are the network switches, modems, transceivers, repeaters, routers, and any other device that handles data from the network without been the end destination of the information. Finally, the links refer to the communication channel utilized for the data transmission, like optic fiber, Ethernet UTP cable, power line, or air depending on the communication technology used.

Also, regarding communication involved in this thesis is defined as the data transmission between the devices that control, monitor and protect the grid, including power generation facilities, energy storage facilities, loads, customers, etc. Each one of these parts of the distribution grid has their own characteristics and requirements communication wise. This is due the fact that devices for different application generate different data, in the means of size, frequency and transmission behavior, meaning that some devices transmit constant data, while some others do it intermittently or in specific situations, for example when emergency occurs in case of a fault, or when a data poll presents, such as controlling unit requesting values to update the status of the power grid.

It is important to note that a well designed and implemented electricity distribution smart grid should be able to react and operate, or at least to protect itself and the customers at all time, even when the communication is lost, while optimal operation strongly depends on the communication, since real time consumption and production data is base for the performance optimization of the grid.

1.1. Smart Grids and Communication

In the old or traditional concept of power distribution grid, the electricity generation has been centralized. Large generation power plants, usually hydropower, nuclear, coal fired etc. generated great amounts of energy to be distributed in different levels of voltage to varied distances to the end users and consumers. Protection and control of the grid was, in any case, a challenge and the energy flows were ideally unidirectional (see figure 1).

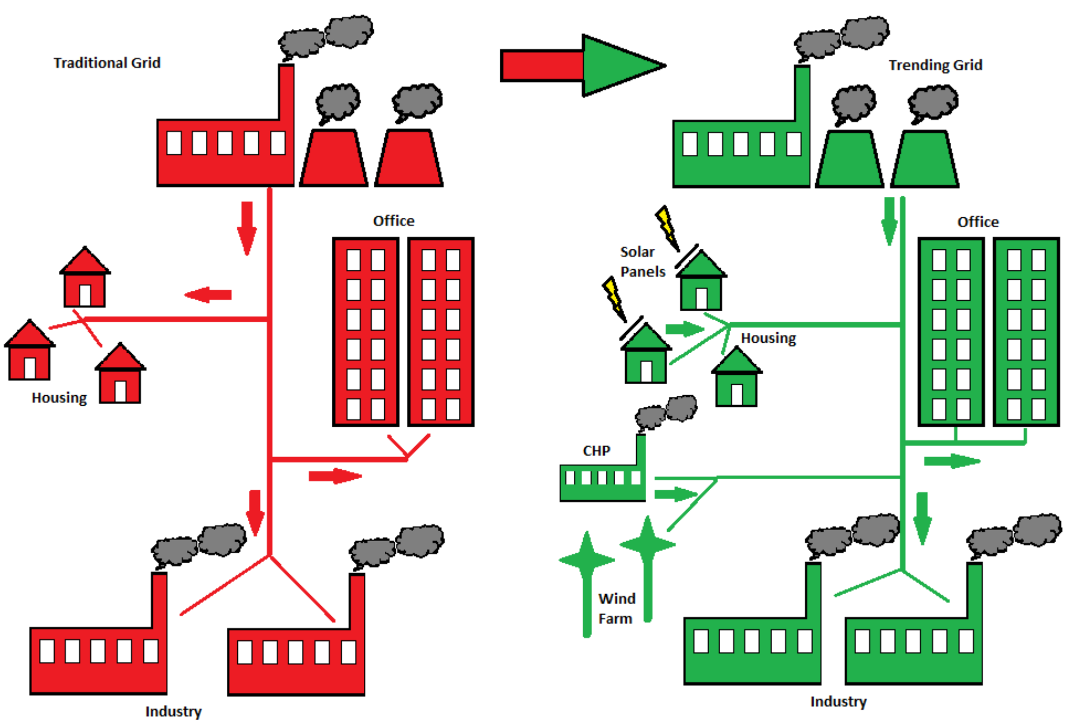

Figure 1: Modernization of the grid [1]

With the introduction of distributed energy sources and renewable energy the management principle has changed. Now the energy generation and distribution is, in principle, not centralized (or at least not entirely). Multiple and intermittent generation sources have to be taken into account when designing distribution networks, and so control, protection and management gain complexity.

Because of this, devices in grids (been updated or under installation) are experiencing strong technological evolution. Control, monitor, sensor, protection etc. smart end devices in the new distribution grids require communication for the power grid to flexibly adapt to the real time energy situation in order to optimize the performance, and making the power grid “Smart”.

This new capability of processing and communication requires a reliable and effective mean of transmission of information from and to the grid. The whole concept of smart grid works with the principle of communication, and for this reason extensive research has taken place and is ongoing in the data transmission field. New technologies arise and existing technologies either evolve or lose ground, and therefore communication schemes are constantly changing.

Also every grid context is different in many aspects, and since geographical location, grid size, capacity, distance etc. have an effect not only in distribution but also in communication network architecture, so multiple options are required to enable proper and optimized data transmission, because a certain characteristic of technology that would excel in situation “A”, may not be compatible in the context for situation “B”, for example, wireless in a flat landscape is much more suitable than in a mountain or jungle landscape.

1.2. LVDC Power Distribution Networks

There are two possible types of voltage regarding distribution grids; alternate current (AC) and direct current (DC) voltages. Promoted by Thomas Alba Edison, the first electricity distribution systems were actually DC, but the voltage and current levels achieved in the beginning of the electricity era were not high enough to reach long distances efficiently. Therefore, with the possibility of use of transformers, technology later adopted AC as the standard type of voltage for power distribution, situation that continues up to the day. But now, the introduction of alternative energy sources have raised the question; “Is it really AC the most efficient way of electricity distribution?” situation that has opened research on the DC side in power distribution.

Depending on the magnitude, each type of voltage used for distribution can be categorized in five levels; ultra-high voltage, extra-high voltage, high voltage (HV), medium voltage (MV) and low voltage (LV). While the ranges depend on the location of the power grid, meaning that the limits may vary between Europe, America, Asia, etc. The focus in this research will be to the low voltage distribution defined by the European commission. LVDC stands for ‘low voltage direct current’. This type of power distribution brings a novel ground for research, and a big part of it been conducted at Lappeenranta University of Technology. This research concept explores an alternative mean for electricity distribution aiming to find the optimal and most efficient way of power transmission in the actual and future scenarios of electricity generation, distribution and consumption.

According to the European Commission Directive 2006/95/EC low voltage directive, equipment, devices and power lines are limited by the voltage level from 50 to 1000 volts for AC and 75 to 1500 volts DC to be considered low voltage. Based on these limits, on existing power transmission grids that provide AC power, it is possible to transmit potentially more power if switched to DC power and without exceeding standardized the low voltage boundaries, while using the same power transmission cables and even some of the protection devices [2][3].

Some of the distributed energy sources recently introduced, like solar panels, already work with and produce DC power, and with the continuous development of power electronics, it has become very efficient the conversion between DC voltages, and therefore making DC distribution more and more feasible. On the other hand, different types of energy sources like wind mills or turbines that produce AC power also experience a simplified transition from generation to distribution, because rectifying is simple and relatively cheap [4], while the synchronization being necessary to the AC distribution grid is not required anymore, representing an additional advantage to the already higher voltage range for LVDC distribution.

Nevertheless there are also disadvantages in DC distribution such as immaturity and still low penetration of the technology. As a concept that has gained popularity only in the recent years, is a distribution system that is not at all wide spread. Therefore most of the control, protection and monitoring technologies developed for the power distribution sector are focused on AC distribution, and if well some of them are transparent between AC and DC, some others require some adaptations or modifications, and a few others can be not compatible at all [2]. Also customer side inverters are required, because most of the house appliances are designed to work exclusively on AC power and in different levels depending on the region (127V for America, 220V for Europe, etc.).

Quoting previous research conducted at LUT; *"In the LVDC distribution network protection scheme can be used devices designed for LVAC system, but the usage requires special functionalities to be integrated to system. This complicates the protection system design and implementation. For example, customer-end short circuit protection using circuit breakers requires current limiting circuit integrated to inverter*" [2].

"*With the use of the experimental setup, faults were measured and advantages and disadvantages in the protection scheme were discovered. The proposed protection system scheme was found to protect against the most common fault situations. Only few fault cases was discovered to need more consideration. One of the cases is one switch fault protection*." [2]

Eventually if the DC power distribution gains ground, home appliances that internally work with DC (like digital home appliances such as televisions, radios, computers, etc.) may have access to DC power supply, increasing the efficiency by avoiding rectifiers. Also with the advance in power electronics, the conversion from DC to AC can be made more and more efficient, for the appliances that work in principle on AC (laundry machines, water pumps, refrigerators, etc.).In the meantime, integration between devices, such as advanced (also called smart) meters and converter can provide a feasible solution for a customer interface that provides service both to the customer and to the grid in the way of information for house and grid power management as well as status reports and protection depending of the current grid situation.

1.3. Proposed System Description

With the objective of providing a scope to the research, some characteristics of the proposed system have been defined. Otherwise a completely open research about all possibilities of smart grid communications would become too extensive for a masters research work, some limitations and characteristics for the studied system have been set, in order to provide a guideline towards what the end application of the communication system might be.

The proposed communication and power distribution system is an island network. Island network as a system is basically the division of a population into small groups that interact with each other as a unit, but can operate independently as a cell when and if the situation requires it. When the concept is applied to a power distribution grid, it becomes an island power distribution network, which implies that every element within the cell (like consumers or loads, power generation and/or storage, control, management and protection) communicates with each other to maintain the cell and the system in an optimal operation point. This way every cell can interact with each other by trading power and exchanging information, but can be kept operational if separated from the unit by a fault (like a short circuit), an emergency (such as low production due to bad weather) or just management reasons.

Smart grids, island networks and LVDC power distribution systems are mentioned because these are the three main characteristics of the system that the research is about. In addition to this, there are other characteristics of the system that have an effect in the communication scheme and have been predefined. The description of the system is presented here separated by type of distribution (chapter 1.3.1), type of generation (chapter 1.3.2) and type of energy storage (chapter 1.3.3), because these factors influence the way protection and control are implemented, which have a direct effect on the communication solution.

An LVDC system can be implemented as unipolar or bipolar. The LVDC distribution voltage can be divided into different number of levels, which will determine the type of distribution. Unipolar refers to the fact that only one pole, or conductor of the cable, will conduct the total of power while having at least one return path, meaning no division of the voltage (0V to 1500V for example). Bipolar is when the voltage level is divided into 2, and conducted in different conductors of the same cable, for example +/-750V and 0V (or neutral), again achieving the total of 1500V range.

1.3.1. DC Network

This section presents some characteristics of the system from the electricity distribution point of view, predefined by the project. Illustrated in figure 2, the underground four conductor cable AXMK, commonly used in Finland, is shown used as a bipolar LVDC distribution, connecting two of the conductors for the neutral level, and using the two remaining conductors for +/-750V. Other types of cables can be used for LVDC distribution, which for bipolar requires at least 3, but could be more (for example, some use 5 conductor cable to add physical ground to the cable).

- The size of the LVDC network: The Island Network covers the area of which diameter is approximately 6 kilometers. The populated areas can be considered as small villages that have spread randomly around the area of the network. Estimated number of customers connected to the network is around 200 and groups of 10-15 customers are considered per section in order to build the island network (see figure 2). The size of the covered area and number of customers in the area and per sector are predefined by the project.

- Typical average peak power of the single customer connection is approximately 200 W in the beginning. However, it is assumed to grow to be around 800 W within a next few years. Therefore, the power handling capability of the total network can be estimated to be at least 160 kW in a 200 customer network.

- Network topology: Radial in normal operation. Ring topology in case of communication fault. The network operates normally in radial mode and the ability to feed a single point in the network from two directions is only used if the primary feeder is faulted.

- Information and communication technologies (ICT) and automatic meter reading (AMR). Technology already available in the market is used. The international standardization organization (ISO) open systems interconnection (OSI) physical layer to be used in this case will be defined by the geographical context and distributions, taking into account the points and considerations to be made further in this thesis work about different communication technologies.

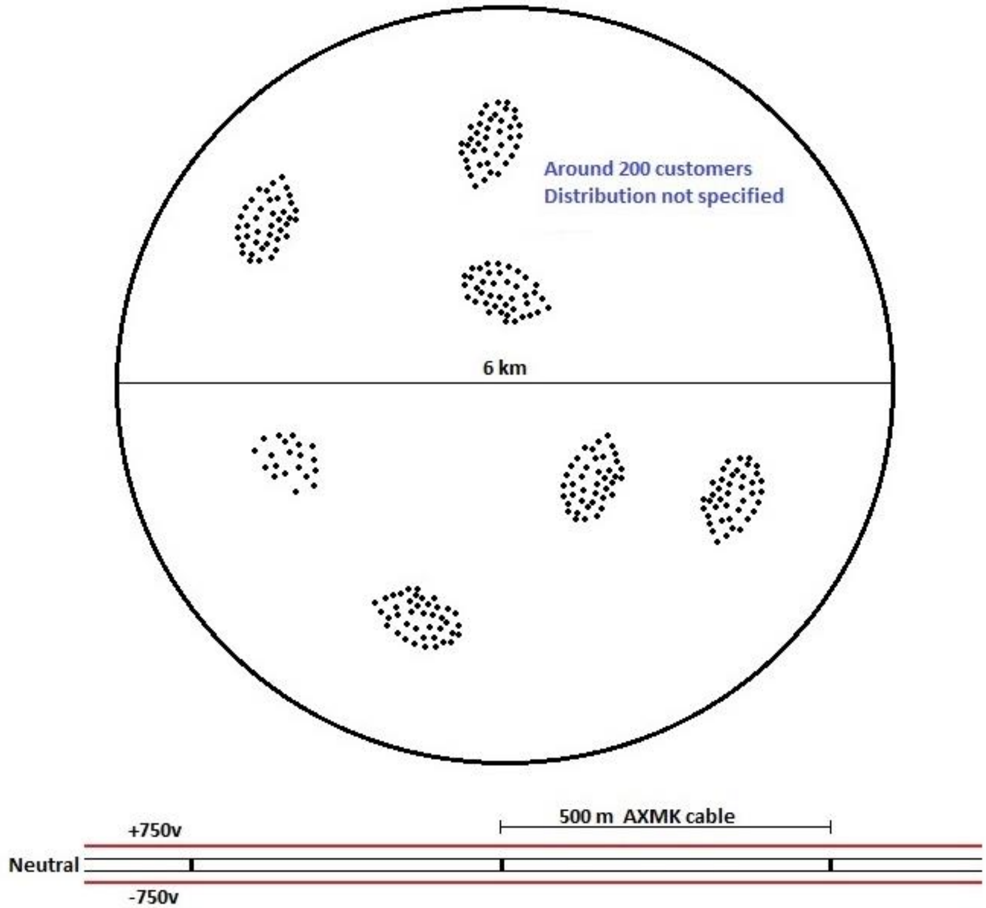

Figure 2: General example illustration of the system area and type of power conductor.

1.3.2. Electricity Production and Conversion

This part describes the type of power generation and conversion that will be utilized in the system as indicated by the project.

- The power is to be produced from photovoltaic solar panels.

- Centralized or decentralized: Both can be used, meaning that the optimal solution to be use will be the one found in the research, or a hybrid solution between these 2.

- With or without DC/DC-converter: DC/DC-converter will be used to enable maximum power point tracking (MPPT). When the customer connection is galvanically isolated, the solar connection is also made galvanically isolated. The option of bypass the DC/DC converter in the battery bank connection is considered to possibly increase efficiency.

- ICT: Forecast of the power production for the day is available. Calculation of the close future power production is required.

- The need for inner communication of the solar plant e.g. indication and locating of the panel faults. The system controller is located at the battery energy storage system (BESS).

1.3.3. Battery Energy Storage System

- Centralized or decentralized: Decentralized to the different parts of the network. The network parts can thereby operate as independent units for a certain period of time. Centralization or optimal segmentation should be considered as possibilities; the decision is taken based on the Energy Management System (EMS) and the system location characteristics.

- ICT: The system is aware of the charge level and consumption in different points of the network. Balance in load and energy should be achieved between sectors when interconnected.

As exposed by the previous details, several network defining factors are still not specified. Because the actual distribution grid structure is not known, and the networking context that a specific location implies is not totally clear, several decisive data is still missing. Therefore, one optimal solution to implement communication network is not clear, and options must be kept open in order to adapt to the end location. Later on the thesis possible scenarios will be presented with some of the possible different communication approaches.

1.4. System Communication Requirements

The concept of island networks by definition involves communications. For a unit of cells to properly interact with each other, exchange of information is necessary. Even within the cells, data collection and information about consumption, production and status (ok, fault, battery state of charge, etc.) has to be registered before the cell can interact with other cells in any type of power exchange or status report.

The communication system requirements can be divided into two main groups. Control and management is the group of communication required devices that are necessary to maintain optimal performance of the grid in any production or consumption circumstances. The control and management group involves for example grid converters, grid relays, customer inverters, advanced metering devices, battery state of charge monitors, etc. and, thus communication signals generated and transmitted by the control and management group is very important, a large part of it is not time critical [5]. Yet it is usually generating the highest amount of data traffic in periodic intervals.

On the other hand, some protection and safety monitoring devices can generate data traffic only in case of emergency or fault event (instead or along with constant data traffic), so the possibility exist that one particular device which takes care of some protection in the grid never sends an information package if there is no faults registered. However, emergency and safety related information is time critical in every case, so it really is important to have always the lowest possible latency for when these situations occurs.

Also, it is important to take into account the utilization ratio. By definition, utilization ratio is a simple relation of utilized data rate over available data rate. Just like how is considered for transmission of power, water, etc. is not wise to plan a utilization ratio of 1 (which is to use all transmission capacity). According to [5] it is a good practice to consider a utilization ratio of 0.3 over the peak of maximum communication rate generated in a worst case scenario of data traffic in order to ensure reliable communication over any circumstances, while also providing some flexibility for expansion if required.

The data packages generated by the advanced metering infrastructure (AMI) are considered as 100 bytes (or 800 bits) per meter per measurement based in commercial appliances in previous research, presented in [6]. Additionally, a device that is VLAN ready will add 30 bytes (240 bits) for data processing and addressing following the standard 802.1Q (as it will be explained in 1.5 IEC61850).

From this number, and just to make an example, if the time required for the information to get from the point where is been generated to the receiving end is 10 milliseconds (considering no hops required and no transmission delays on the media). As a speed calculation, is just “distance” (or number of bits) over time, so 1040 (800 + 240) bits over 0.01 seconds, meaning the channel requires a bandwidth of 104kbps per device attached to the same line or media (or 347kbps considering the 0.3 utilization ratio recommended in [5]).

In other words, if the data rates are similar to the example taken (and without considering technology specific inserted delays), 20 advance meters in a sector will require around 7Mbps considering again the utilization factor 0.3. Then, depending on the distance and if the time limitation maintains, higher data rates can be required once hops and transmission delays (especially for slower media) are taken into account. However, smart metering data is often not very time critical.

Because at this stage of the research and the fact that the project it is still yet not possible to know how much the processing time will be from the control unit, (even the amount of data generated by the actual devices) or how will certain amount of delay affect the performance on the control and management side. Previous research has been conducted in the field of effect of delay in communication for information networks; however, every communication system is application dependent, distance dependent, distribution dependent, and the algorithm to be implemented also has an effect in the acceptable delay and sampling frequency. Because of the application to be analyzed is different from the previous, the final location is not defined and the algorithm is still under development, only later with simulations will come the understanding on the effect of the delay in different working environments and situations.

Different sources of delay will be taken into account with the purpose of having a clearer option set when the end location is defined and analyzed. These delays can be considered for protection system and control & management system and will be mentioned in the respective chapter of every technology.

1.4.1. Control and Management System

Control and management are the functionalities of the smart grid in charge of administrating the production and consumption of power in the grid. In the beginning of the electricity production era, the principle of administration was quite simple; estimate a peak load, install capacity to continuously deliver the maximum required power, and then let it flow through the power lines. When additional load is aggregated, more capacity is installed. The problem with this scheme is that either a large amount of the generated power was wasted (or sold to external consumers) during the low consumption hours, or the production needs to be controlled. Nowadays, the smart grid management principle is based on the real time information about energy available, power being generated and power consumption, so energy is stored when the consumption is low, that will later on meet the consumption requirements when the load is at its peak, with the objective to avoid over-generating or under-supplying.

Therefore, a flow of the required information needs to be considered so the control and management unit is aware of the status of the grid at any point, in order to provide a reliable service. The communication logic from control and management point of view of the grid is presented in figure 3.

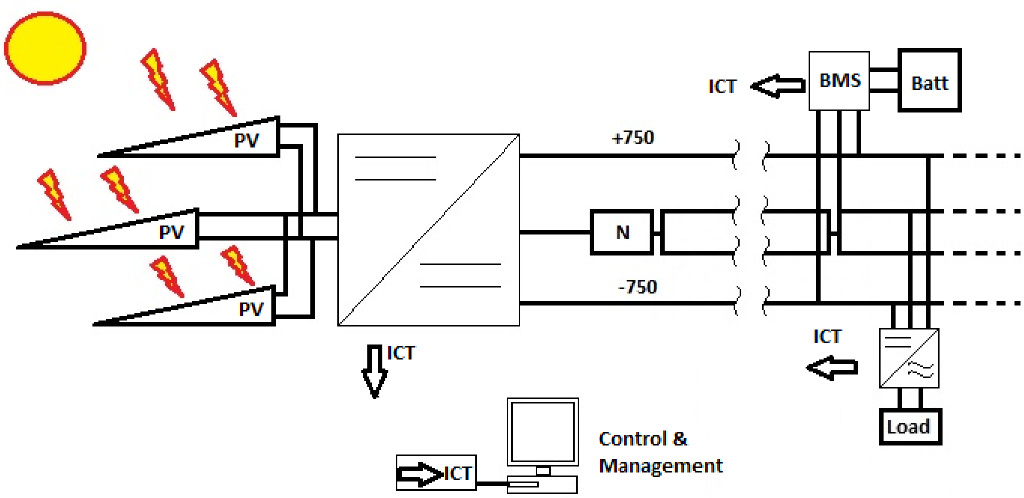

Figure 3: Communication logic of the system from control and management point of view.

The main requirements to take into account in the communication scheme are; data rate or bandwidth, latency (or delay) and time interval (frequency) of communication signals of certain applications. Different devices and signals have varied characteristics and requirements, and the communication system should be able to handle and deliver all data properly. To evaluate data rate needs, it has to be considered as volume of data over time. But for a communication system, not only the generated data by the device is considered, part of the traffic information belongs to addressing and processing of the data, depending on the information transfer protocol utilized. Therefore the information transmitted will always be more than the information generated (been the generated data the larger part of the transmitted information), and thus there will always be overhead in the data.

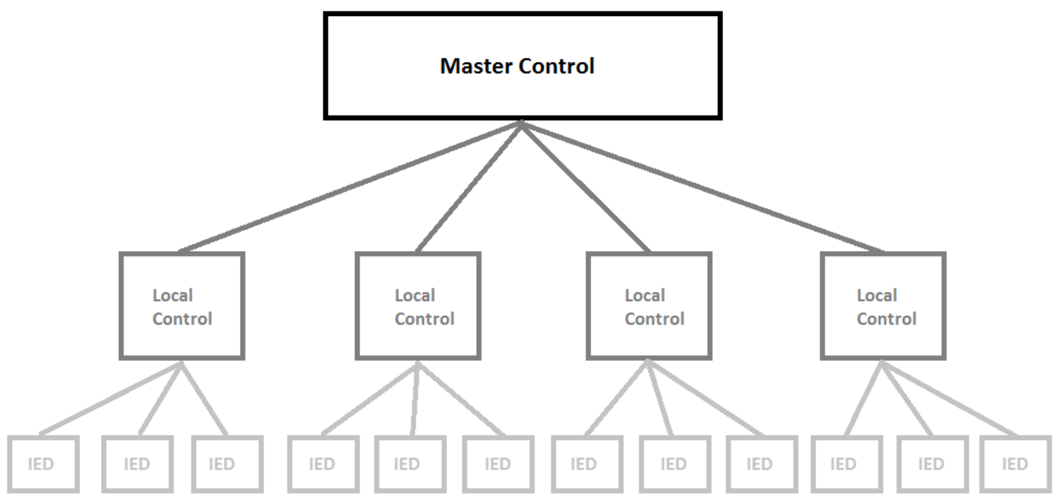

Figure 4: Multi-level communication and control hierarchy.

The control scheme considered is a multi-level communication and control hierarchy shown in figure 4. A multi-level communication hierarchy means that the data traffic of every intelligent electric device (IED), which can be a measurement device, protection device, or any device generating information required by the network is not broadcasted to every point of the network, but rather processed locally by a data concentrator or local control. This scheme brings the advantage of lower data transmission rate requirements compared with a system that has all IED's communicating straight to the master control, since information traffic remains isolated within local sectors with a number of devices much lower than the one of the total network. To be able to implement this scheme, control needs to be designed so a certain amount of functions can be performed independently by the sector control, (preferably most of them), and only some functions require involvement of the master control. Besides the lower bandwidth requirements, other advantages like lower response time and independent operation in case of fault are achieved. Also, data measurements can be done at higher sampling rate and with higher sample definition compared with a single level system.

The frequency of the data sampling is limited by the following factors; the maximum processing time from the controller will set a maximum to the frequency that the data can be requested. For example, if the processing of the data takes one second, requesting data in shorter intervals will only lead to saturation of buffers and information loss. The factor that determines the minimum frequency is defined by the needs of the controller, or often by other external factors like pricing, that determine the rate of which the status of the power in the grid needs to be updated.

The latency requirement is defined in the system by the maximum delay the system can accept for a response to a request (open a load, poll information, etc.) without the delay having a negative effect on the performance on the system, for example, if the delay is too high and the reaction time too short, it can lead to instabilities of the electricity distribution system (having the system correcting a status that is not anymore the current status), or generating a response too slow for risky situations such as faults. Bandwidth, extent and latency are the main factors that define or limit the technology and physical layer to be used for communication from the delay point of view, will be defined later along the analysis of the end location.

1.4.2. Protection System

From the protection point of view, communication is different than from management and control perspective. Protection as a functionality of a distribution grid has to be designed in a way that will operate with or without communication, in other words, the grid should be able to protect itself and the customers at all time, independently of the status of the communication system. Because of the time criticality of situations when devices or even humans can be endangered, protection devices are designed in a way that those will not send a request for operation, but rather automatically act and then, in the case of some devices, send measurements or a status/fault report.

In the particular case of an island network, the communication for protection plays one extra role. Because a fault may occur at any point of the network it might be perceived by more than one network cell (being a cell a sector of the network capable of independent operation), so in order not to generate a chain reaction of cells disconnection, communication is important so the cells can identify where the faults are within other cells boundaries, so isolation of the fault is done without isolating non faulted sections of the network.

Some protection schemes have a high dependence on communication, such as differential protection systems, which are strongly communication based. Microprocessor integrated protection devices, like circuit breakers and relays, are capable of monitoring and taking measurements. Compilation of such information in real time by a monitoring station, can detect even very small faults or building up faults. Specific sample times and delay requirements for implementation of such depend strongly in distances within the network, and therefore cannot be defined yet before the final deployment location is decided, so then a specific requirement for communication can be set, and have a strong effect in the decision of what communication technique and technology will be used.

1.5. IEC 61850

The communication standard IEC 61850 deserves a special mention in this research. Developed by the International Electrotechnical Commission (IEC) with the participation of around 60 members working together since 1995, the IEC 61850 is a standard for the design of electrical substation automation, to which specifications of distributed and renewable energy sources and smart grids have been added. Due to the limited open access to the IEC 61850, this part of the work is based on applications and previous research on the standard from [7]-[9].

The IEC 61850 standard defines in details the communication protocols and nomenclature for every type of communicating device. Also communication priorities are considered. The IEC 61850 proposes for communication an IP based network, utilizing the advantages of virtual local area network (VLAN) for data traffic isolation improving the performance.

The VLAN tagging protocol is defined by the standard IEEE 802.1Q. Along with the addressing and data processing information involved by the IP protocol, the IEEE 802.1Q includes the VLAN tagging field that defines both VLAN to where the package is destined, but also a field that defines priority (3 bits or 8 levels of priority, see figure 5).

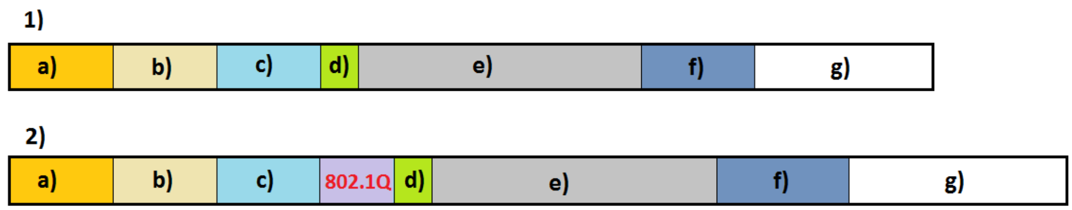

Figure 5: Ethernet frame structure with 2) and without 1) VLAN tagging.

In figure 5, 1) is a regular Ethernet frame. An standard Ethernet frame consist of a) 8 bytes of preamble, b) 6 bytes of destination MAC address and c) another 6 bytes of source MAC address, d) 2 bytes of Ethernet type/size, followed by 46 to 1500 bytes of data and 12 bytes of inter frame gap g). On the other hand frame 2) includes a field for VLAN 802.1Q tagging, otherwise the structure is practically the same. The only difference remains in the addition of a 4 byte field between c) and d), which also changes the data field now from 42 to 1500 bytes of information. The composition of the 802.1Q field is shown in figure 6.

<table>
<tr><td>16 bits</td><td>3b</td><td>1b</td><td>12 bits</td></tr>
<tr><td rowspan="2">TPID</td><td colspan="3">TCI</td></tr>
<tr><td>a)</td><td>b)</td><td>VID</td></tr>
</table>

Figure 6: 802.1Q VLAN tagging field in detail. a) field is PCP and b) field is DEI.

From figure 6, TPID field is the tag protocol identifier (given the fixed value of 0x8100). The function of this fixed value is to distinguish VLAN tagged messages from non VLAN messages, since in a normal Ethernet frame the field d) from figure 5 is present in that same position. TCI stands for tag control information and is the actual field that contains the information about the VLAN tagging. VID stands for VLAN identifier, this 12 bit field defines the VLAN to where the packet belong, which mathematically allows up to 4094 VLAN’s, but in real life is usually limited to much less depending on the capacity of the deployed devices for data management.

Drop eligible indicator (DEI) is a 1 bit flag that, if enabled for the package, will allow the data management device to drop the message in case of congestion. It can be used in conjunction with the PCP field to extend the prioritization of communication of data. Finally PCP stands for priority code point, and is a three bit field used to define a 0 to 7 level of priority on the package. In this field, 0 is best effort priority and 7 is highest priority. Because IP protocol is without this fields a non-deterministic data transmission protocol, the IEEE 802.1Q ensures high priority data reach its destination in the lowest time possible.

The priority field in combination with the capacity of dividing the communication into several different virtual networks greatly enchants the performance of the data transmission. Within the focus system application for example, control, protection and management data traffic can be isolated into different VLAN's to divide the data traffic into different separate virtual media, greatly improving the performance and allowing different levels of priority within different applications.

2. COMMUNICATION TECHNOLOGIES CHARACTERISTICS

With the evolution of technologies, communication has been improved continuously through the development of civilization. Centuries ago data transmission relied mostly in post, pigeons, and occasionally beacons, flags or even smoke signals. In the latest era, the introduction of electrical data transmission began a new age of communication that continuously reached new horizons until it became part of the contemporary way of life.

The increasing requirement for communication has grown fast with the technologic advance. Just couple of decades ago, commercial hard drives had just a few megabytes of capacity, CD-ROM was a luxury, and a 56kbps dial-up modems common, for a person or application to aspire for communication, situation that has rapidly changed. Experienced not only from people but also devices and systems, extensive research is continuously taking place, improving some of the existing technologies, expanding to new fields and creating new communication options. From analog to digital and from copper to wireless and optical, contemporary options for communication are very diverse, and the different characteristics of each option present strengths and weaknesses that allow optimal operation in different communication contexts.

Despite the constant evolution so far achieved, the challenge for communication is still present. Perfect communication is still well away from reach and both existing and coming applications show different scenarios and have diverse requirements. Besides, data transmission is not only about establishing communication, but also involves maintaining the communication in a reliable way, while keeping affordable cost and following the required standards. Also in the past years other requirements have been set regarding matters not strictly related to communication, such as environmental considerations, acoustic noise, electric and electromagnetic compatibilities, etc. which increases complexity of, and bring challenges to the communication devices.

Eventually as the power distribution grids started requiring communication, the communication network for smart grids got involved in the evolution of communication technologies, both in the development and application side. Providing new challenges and requirements for communication, smart grids have been important factors in the development and evolution of protocols, standards and technologies to extend the use of communication to the new environments of application and adapt to different situations. An example of this is the island smart grids, a communication system that provides different communication scenarios within the system itself, requiring both short and long distance links for communication.

Therefore, in this chapter, different technologies considered and utilized in grids and smart grid applications for control, protection and management will be presented along with their respective principles, characteristics, capabilities and also disadvantages, in order to provide a context about the decisions and considerations to be made in the following part of this thesis work. The focus will be on the different technologies, rather than in the commercial devices, which will be mentioned to some extent later on in the research just as an example of the contemporary market of devices.

2.1. Power Line Communication

Power line communication (PLC), as the name indicates, is based on the principle that power lines used for power delivery can simultaneously work as a data carrier line. In other words, power and data can be transmitted through the same wires. This is possible because the power transmission frequencies are relatively low (or zero in the case of LVDC) compared with the data transmission frequencies, which allows data to be modulated, demodulated and coupled to and from the power signal and therefore provide communication possibilities.

However, PLC is not a very recent concept; data communication over power lines has experienced a strong developing impulse recently. The introduction of smart appliances in homes (Televisions, smartphones, game consoles, laptops and even refrigerators with internet connection option or requirement) has powered the birth of Home Area Networks (HAN's). But especially in old houses where there is no previously deployed internet cable installation, Internet is not very easy to distribute by other means. Here is where power line communication excels, because cable installation is not considerable and wireless links are obstructed by walls and other barriers.

Power transmission lines are neither common nor standard communication environment. Unlike other transmission media like unshielded/shielded twisted pair (UTP/STP) or optic fiber, that have standard and known construction and behavior as a communication channel, power transmission lines have variations in their behavior as a channel media depending on the location, operation environment, type of installation, etc. Also power transmission lines are constantly exposed not only to the noise introduced to the line by the loads, but also since power transmission lines are not shielded they can act like antennas and be both vulnerable to, and emitter of electromagnetic radiations. In addition power lines include branches which cause deep notches to the channel response in frequency domain, and power lines are time-variant channels with respect to frequencies applied in PLC.

Because of this, for each application of PLC there is a very specific channel context (for example, data transmission characteristics of a power line are different in a house plug to an underground distribution four conductor cable, to a three conductor overhead line, etc. because they have different isolation types, load types, conductor cross-section, etc. that influence the cable as a data transmission media), and before knowing the actual architecture of the system is difficult to predict the behavior of the power line as a communication media.

PLC can be categorized into two types; narrow band power line communication (NB-PLC), and broad band over power lines (BPL). Narrow band PLC utilizes typically the frequencies between 9 and 500 KHz [10] for control by power distribution substations for decades because it provides several advantages [10]. Due to the inductance, distribution transformers behave like a low-pass filter, attenuating high frequency signals, but allowing low frequency signals like narrow band PLC (under 500kHz)[10] to travel through the transformers and to longer distances. But, also because of the low frequencies, the data transmission rates are low, so this technique of communication is more commonly [11][12] (but not only) used as a point to point bidirectional control signal, which is just one of the functionalities of the communication required by a smart grid.

Therefore, in the need of more communication capacity by the smart grids, research for using BPL in power distribution grids has grown in the last decade. BPL is considered as transmission frequencies the band between 1 MHz to 50 MHz [11] on the power conductor cable, and with BPL it is possible to achieve higher data transmission rates compared with narrow band PLC. But also due to the high frequencies, this communication signals cannot go through distribution transformers, and also the resistance and dielectric losses in the isolation material of the power line limit the transmission distance range of the media to a few hundreds of meters [13].

Taking into account the proposed system descriptions, the focus of the research will be on the LVDC bipolar power distribution cable for communication. Because LVDC power distribution has experienced research popularity mostly in the past few years, the research of the LVDC power transmission line as a power line communication media has been conducted recently, and mainly done at Lappeenranta University of Technology. Different types of cables can be used for a bipolar LVDC system. Studies in AXMK cable have been conducted in [11] and [13], and also AMCMK cable in [14] as possible environments for power line communication. From these studies is clear that not only the architecture of the grid, but also the type of power conductor utilized has a strong impact on the data transmission capabilities of the media. Between the previous presented options (AXMK and AMCMK), the AXMK cable it is possible to create current loops by short-circuiting the neutral conductors (N) at the beginning and at the end of each cable roll (500 meters) as shown in figure 3. This arrangement presents better data transmission environment for PLC because of the lower differential noise level between the N conductors and cable section isolation because of the short circuiting at the end and start of every 500 meters of cable.

The three factors that define the data transmission capacity of a given channel are channel gain, signal transmission and noise power spectral densities [11], [13]. In order to define these parameters for the specific environment of the LVDC power distribution network, both simulation and experiment has been previously conducted in [11], [13]. The laboratory set up for the AXMK four conductor cable with inverter, rectifiers and loads as a grid section test bench is shown in Figure 7.

For the experiment a standard Homeplug1.0 compliant PLC modem is used in [11], for the PLC connection capacitive coupling can be used as well as inductive coupling as done in [11]-[15]. More details about the laboratory set up are specified in [15]. This set up, as shown in figure 7, already includes loads to study the behavior of not only the cable conductor as a channel but a more complete working context as a data transmission media. Figure 7 only shows one of the options for PLC connection that is the neutral to neutral (NN) transmission loop formed by the neutral lines of the cable connected at both ends of every cable segment of 500m. Another considered scenario is the usage as a data transmission media the line to neutral loop. The characteristics of both are very different and therefore to consider and analyze both cases is desirable. This can be particularly useful in the case that the utilized cable is changed for another one that cannot provide a NN loop for data connection.

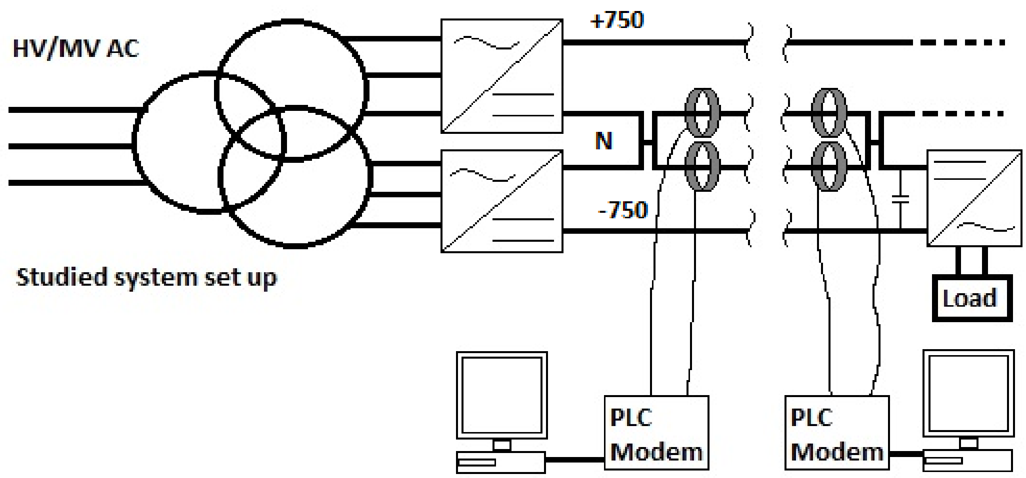

Figure 7: Laboratory set up for PLC modeling in an AXMK cable. [11]

As a result of the experiments conducted [13]-[15] it was determined that the channel has optimal capacity for data transmission to a maximum of 500 meters. Because of the characteristics of the cable as a data transmission channel, and just as any other data transmission media (though in optic fiber media does not have as much effect), the HF-band PLC data transmission range is limited due to the signal attenuation in the channel, which increases as a function of frequency.

Besides the channel characteristic measurements in the laboratory system and the theoretical calculation, a practical data transmission test is conducted in [11] and [14] using the laboratory set up presented in figure 7. The test is conducted not only in a real cable length of 198 meters but also in different load situations, adding the type of loads to the cable that are usually present in the grid, such as rectifiers and inverters. Measurements are done in LVDC installation presented in [14].

From the measured results from [11], it can be noticed that the performance of the line as a data transmission media is strongly affected by the type of coupling and the direction of the communication. In the test, when the communication coupling utilized was the NN, the data transmission rates maintained in relatively stable levels around 5 Mbps for all tested cases (for a cable length of 198m [11]). In contrast, when the LN coupling was tested, a noticeable decrement is shown.

The data transmission rate is strongly affected by the introduction and operation of fast switching power electronics in devices on the grid. Because these noise sources are mostly on the customer side, data transmission has a better performance from inverter to rectifier than from rectifier to inverter, meaning that data flow from the customer side can be faster and more reliable than the data flow to the customer side. This is an interesting situation because in one hand, more data from the customer is expected than in direction to the customer, but on the other side, the data to the customer, though is less, consist mostly in control or protection signals, which may require very low latencies for optimal functionality, so the challenge communication wise is in the direction to the customer.

But the electrical or power environment of the line is not the only factor affecting data transmission. Also the data traffic generated by other power line communication devices can generate problems according to [11]. Algorithms integrated to HomePlug 1.0 devices like data encryption standard (DES) can improve the performance against problems like mutual interference between several PLC modems communicating simultaneously, but still latency remains higher than the minimum requirement for protection and emergency signals [11]. However this can be improved using lighter data transmission protocols.

The research presented in [11] shows that according to past and ongoing research PLC is a possible data transmission media. BPL is a relatively recent technology and still presents several drawbacks, mainly the strong signal attenuation, but also for example commercial devices (other than smart meters) are not as tested as other more standard communication technologies, specifications about reliability and functionality are not always detailed enough or even available for all products, and the focus of the devices on the market has been mostly home area networks, which implies that for utilization on power grids, some adaptations are still required. Also, for using inductive couplers in the NN coupling available in the AXMK cable for PLC that provides the best possible transmission environment, specific coupling techniques are necessary, which increases the complexity and (slightly) the cost of the connections and installation on the data management device's side (Ethernet switch, gateway, etc.). Also, not in every case there is even available a double neutral conductor, situation that eliminates the option of the NN coupling and therefore diminish the capacity of PLC as a data transmission media.

Either way, the media has proven capable, technology in devices such as AMR meters already present options for communication over power line and is an option to be considered in order to be as flexible as possible to be able to achieve optimal data connection to all points required.

2.2. Ethernet over Optical Fiber Media

Transmission of information over light is by far not a new concept. Light travels very long distances and in instantaneous manner as perceived by the human eye. Because of this, for thousands of years, beacons, light houses, etc. were used by civilizations, mostly as warning systems, for orientation purposes, etc. in the way of light signals.

However, data transmission via light is a lot more recent. Some people consider the Photophone the first device to transmit data over light [16] and the predecessor of optical fiber as a data link. The device created by Alexander Graham Bell in collaboration with Charles Sumner Tainter was capable to transmit voice and sound over a light beam. Though the common light sources of the time were not as high density as there are available today, so the transmission link was only about a couple of hundred meters and the application was no competition to copper electric data transmission. Either way the concept was revolutionary.Later on, with the development of optic fiber and compact lasers, actual long distance communication was achieved. Even though optic fiber is still under development and research, it is actually not a very new concept either. The first research papers published about channel modeling and data communication through fiber can be found of times as back as the late 1960's and early 1970's, even then showing potential for communication capacity beyond the data transmission capacity requirements of the time and with increasingly longer distances as the development went on.

Since fiber optics has been for a longer time in the communication field, and smart grids are a more recent term and trend, it has always been an option for communication in the application. Either if is been used for real time control and monitoring of distributed energy sources like in [6] or used for distribution automation systems and smart metering infrastructures as in [17], optical fiber as a data transmission media includes important advantages within its characteristics.

There are two main types of optic fiber for data transmission, multimode and single mode (see figure 8). Single mode fiber uses a protected thin optical core to transmit a straight high data rate signal over the fiber. This type of fiber for communication allows better flexibility for the cable bending and has very low attenuation, typically around 0.2dB/km, which allows ranges for commercial devices of 20km, 40km, or even more. Multimode optic fiber, on the other hand, consist on a protected thick core that allows multiple high data rate signals, like parallel channels over the same fiber. This characteristic of multimode fiber enables much higher data rates, even compared with single mode optical fiber, but has a reduced range of transmission of normally about few hundreds of meters up to one or two kilometers for commercial devices. Because in smart grids so far the data generated, and therefore transmission rate required are not large enough to require multimode optical fiber, single mode fiber will be addressed as optical fiber in the rest of the work, since range is the main advantage to take into account for the application.

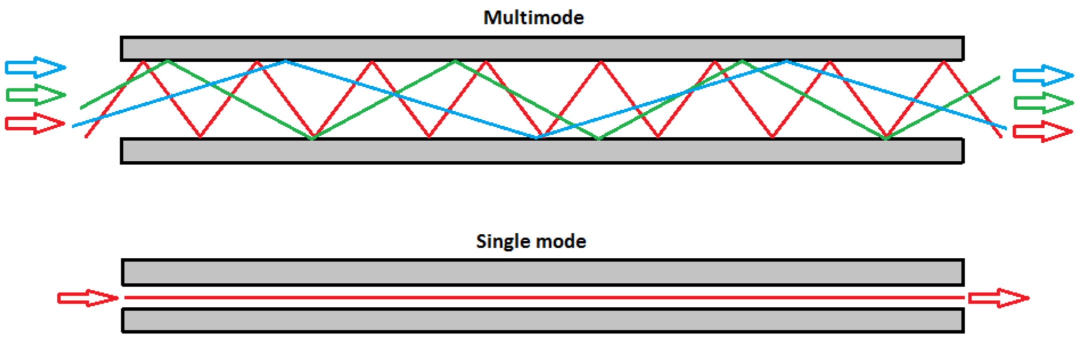

Figure 8: Multimode and Single mode optic fiber principles.

Due to the low attenuation of the media, data transmission over optic fiber can be more energy efficient compared with other data transmission techniques. Especially if the links are utilized for very long ranges, high power wireless transmitters for other technologies like LTE are more efficient for covering area than reaching farther locations. Repeaters required to extend the range of every technology, besides other disadvantages (like cost or delay), also involve power consumption. The more repeaters and Ethernet switches are used just extend the range, the more energy the communications network will consume, which to the grid can be regarded as losses, although almost insignificant in comparison to the customer loads.

Long range communication links can be common within a smart grid. Due to regulations, some types power generation facilities (like wind generators) cannot be placed very close to the consumers and other generation facilities, or also sectors within the same network can be separated by long distances. Since data transmission over optical fiber has the longest range between the technologies used for power grid and smart grid communications, as the distance increase, using optic fiber as a long range media becomes more feasible, though nowadays is mostly used in distribution grids between substations.

Also, not only as part of the requirements of the system, but is recommended for reliability of the network by several researches [6]-[7], [17]-[18] to have a ring topology for data transmission so communication has redundant path. By utilizing different cores of a multicore optical cable (see figure 9), the ring topology can be achieved on a linear distribution of clients (to be explained in detail in the distribution scenarios chapter). The main advantage of optical fiber on case of failure of the default path is that alternate path (logically longer than the default path) will not add noticeable delay because of the speed and range of transmission of the media.

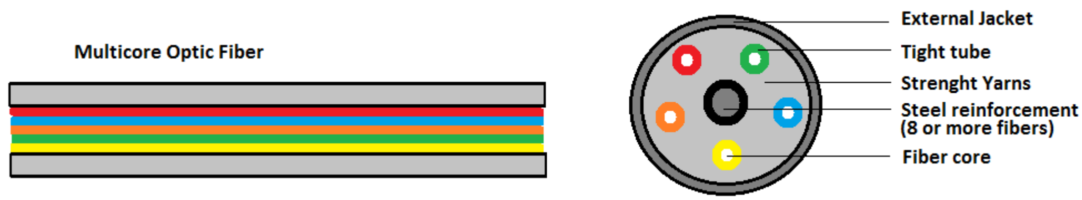

Figure 9: Structure of a multicore optical fiber cable.

Another benefit of the optic fiber over all other data transmission medium is being immune to electromagnetic interference (EMI). Typically, the data transmission media of a network can be exposed to constant (like fast switching power converters, transformers, electrical motors or generators, etc.) and occasional (like cellphone calls, electromagnetic pulses due to transformer breakdowns, etc.) electromagnetic radiations that can negatively affect the communication. But, since communication over optical fiber is carried out by light pulses instead of the electromagnetic pulses utilized by wired (PLC & UTP) and wireless data transmission, the optical fiber media is immune to such phenomena, providing it with an extra grade of resilience and reliability.

Despite the fact that the use of optical fiber as a data transmission media is not recent, the advance of manufacturing technology has made the media more affordable in the last decade. Because of the constant introduction of commercial devices complying with already well-established standards and manufactured by a wide range of producers has constantly lowered the price of the technology from a point where only big companies could afford fiber connection to a point where it has much deeper reach into low level markets, consequently increasing the use of the media. In response, the availability of devices and the research on them provides with well detailed characteristics and information about the devices that can be analyzed to evaluate factors like reliability and durability, data not available for all devices in all technologies.

But, despite all these advantages, not all characteristics of the optic fiber are positive. Optical fiber, as a dedicated media, implies material and installation cost, and even if the cost of the fiber cable is not high (when acquired in big quantities) compared with the power conductor cable, the installation, connections and maintenance are. Even after a constant cost decrease, the optic fiber connections and devices optic fiber ready are still more expensive than many of the other possible options for communication (based on a device and cable market research in different continent zones like Asia, Europe and America), and because of this, it is used only when one or more of the main advantages of the fiber (range, bandwidth, etc.) are strictly required by the communication network, or are planned to be used in the future.

Since the optic fiber is a very sensitive media, patching and repairing is not a simple task and, require a specific set of tools, materials and training, that may not be available in every possible location, and depending on the location, can cause a big repair time of the link (for example, if the system is deployed in a small village far from any place with supplies and capable workforce for the task, repairing can involve days just for traveling of qualified people and shipping of the required materials or tools).

Installation of the fiber itself can also be a challenge. In an ideal situation, the installation of the optic fiber cable can be made in parallel with the power cable, but this might not be always the case. Power cables are very mechanical stress resistant, depending on the flexibility and strength of the conductor and isolator of the cable, installations overhead, buried, underwater, or to moving locations is possible. But optical fiber is much more delicate. As shown in figure 9, the cable is reinforced with yarns (often Kevlar) and a steel core just as a safeguard against the mechanical stress of installation. All this protection is because the optical fiber cores are not mechanical stress resistant at all, and even after all this reinforcement, the mechanical characteristics of an optical fiber cable are not as flexible as the power conductors, being especially fragile against bending and constant movement. Because of this, installation that just for the power cable could be easier, now for both power and optical fiber cable can be very complicated and more costly, like for example across rivers, or connecting floating platforms. Moreover, considerations about data security will be discussed to some extend later in the research work, in the chapter 3.2.6 Data safety and risk management.

2.3. Ethernet Twisted Pair

Copper wires for communications have a long history. It was in the very early 1800's when forms of electric telegraph started to appear in central Europe and with it the first type of data transmission over copper lines. At first it was only two simple copper lines, one for transmission and other for return were set parallel to each other from the sending point to the receiving end.

The increasing demand of communication on this new long distance technology for data transmission happened in parallel with the continuous development of electrical distribution grids and devices. Therefore when more copper lines (both for communication and power distribution) were deployed next to each other, often using the same overhead poles, and a the new phenomena of crosstalk and interference was experienced.

It was then when the engineers of the time recommended transposition of the wires every determined distance, so both lines are exposed to the same amount of interference and the differential noise gets cancelled to some extent. As the technique was proven effective, twisting of the pairs started to become a common practice, and later on a requirement for the deployment of new telegraph lines, thus giving birth to the predecessor of the unshielded twisted pair (UTP).

Unshielded twisted pair cable is one of the most utilized media for Ethernet and other network communication. At the beginning of networking, the used media was coaxial shared cable, which later on has been substituted by UTP cable. As with the telegraph, unshielded twisted pair, instead of relying on external shielding (like the coaxial cable) trusts the twisting of the cable pairs to cancel the external noise. UTP cable is manufactured under different categories, where Cat 5 and Cat 6 are the ones used nowadays for high speed network communication. These cables contain different pairs of color coded conductors that built in a way that every pair has different twisting rate in order to avoid crosstalk interference [19]-[20](see figure 10).

The utilization of the UTP cable for Ethernet networking was introduced by the IEEE 802.3i standard in the early 1990’s. Networking until then was carried out on coaxial cable, which allows slightly longer distances but is more difficult and expensive to manufacture, and is less flexible making it not as comfortable for in-house installation. The affordability, availability, high data rate and flexibility provided by the UTP turned it then into the preferred solution for end point connection, and the default connectivity option for most of the devices nowadays that can access or require access to an Ethernet network.

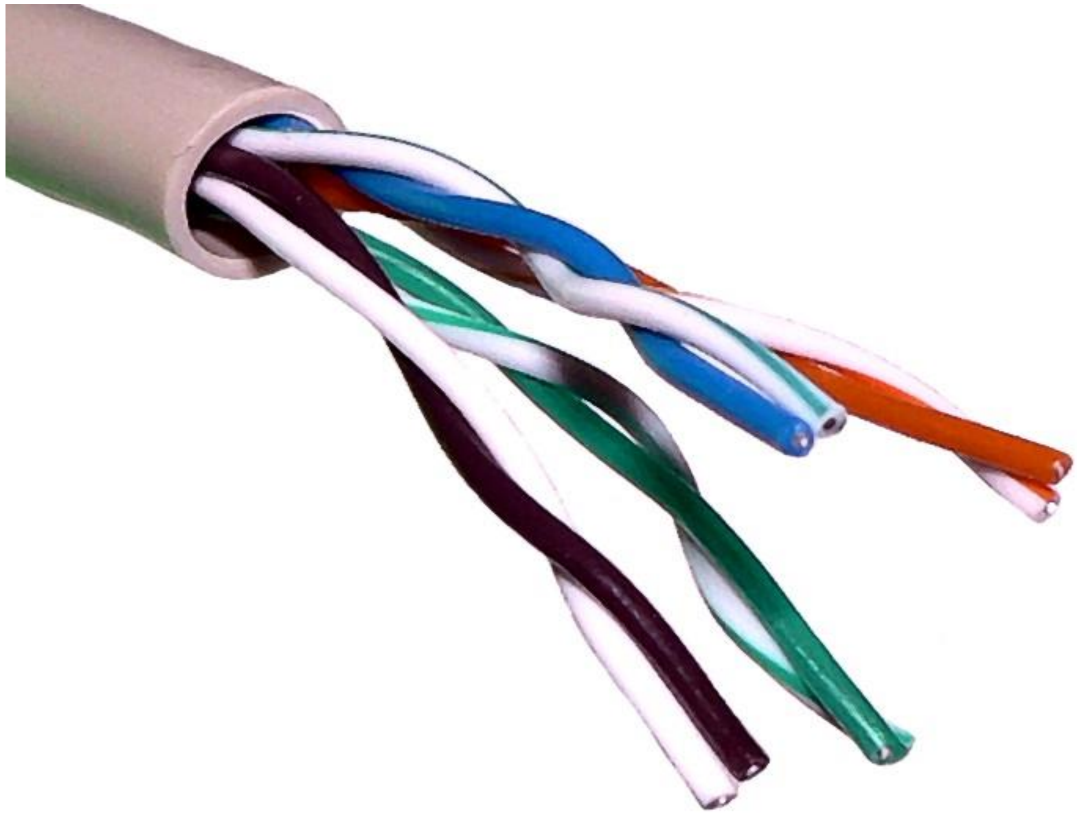

Figure 10: Color coded UTP cable with different twist rates for crosstalk protection. [21]

The evolution of Ethernet networking has improved the data transmission capacity of the media [22]. Although the standard 802.3 cover different types of dedicated media (such as single mode and multimode fiber, coaxial cable, printed circuits, etc.) data transmission rates have expanded from the original 10Mbps for the 802.3i version, to rates as high as 10 Gbps over (distances as short as 10 meters) UTP cable (802.3an) on different cable categories, and still growing.

Different versions of the standard not only define different data rates, but also modify the range. Unfortunately, the data rates are evolving to speeds that the UTP cable as a communication media cannot maintain with long reach. The communication rates up to 40 Gbps and 100 Gbps are being developed, but the distance on copper wires is restricted to a maximum of ten meters, which is useless for the application of smart grid, not only because of the short range but also because such speeds are by no means required yet. Data rates from 100 Mbps (with CAT 5 UTP cable) and up to 10 Gbps are still possible within the hundred meters range (with UTP cables CAT 6 and CAT 7).

UTP cable as a data transmission media provides several advantages. It is the most commonly used media for wired data transmissions in end point (for the last mile), which means that not only the availability and quality of devices focused on UTP media has a very wide range, but also when a device is provided with more than one connectivity options, is very likely to have UTP port as one of them. The universality of use for this type of data transmission provides a wide range of devices ready to operate with the technology, in comparison with other technologies that might have less flexibility. Also, the data rates within the range of communication of the UTP can be superior to wireless technologies (like WiMAX and LTE) and match optic fiber speeds. Another advantage is that, as a very established and used transmission media, devices that manage and communicate over UTP can have lower cost due to the long time market development, and the registered jack connector utilized for UTP cables is the cheapest way of connection between the analyzed communication technologies

As the previously mentioned transmission medias, UTP cable also have disadvantages. As a dedicated wired media, it requires purchase and installation of dedicated UTP cables per communicating device to the communication management device (Ethernet switch, router, hub, etc.). Also as a physical copper media, is to some extent vulnerable to electromagnetic radiations and noise, which can be produced by different devices within the power transmission network. But the main disadvantage of the media is the short range. Data transmission distances in a smart grid can easily exceed the 100 meters supported by the media, which is the lowest range from the analyzed technologies.

2.4. Wireless

In this chapter, some of the available wireless technologies will be analyzed as a possible data transmission media for a LVDC smart grid. In this case, wireless media will consider radio frequency transmission such as Wi-Fi, WiMAX and LTE, and no other types of wireless communication like infrared link.

Using the air-space as a communication media, as mentioned before for optic fiber, is not a new concept and was used for centuries in the way of beacons, horns, bells, smoke signals, etc. all used the air and line of sight or sound to transmit simple messages, more regularly warnings or calls for meetings (such as religious ceremonies). But after the before mentioned photophone in the early 1880's, one of the first wireless devices invented for wireless data communication (using light in this case), and in parallel with the development of electric data transmission for the telegraph, the history of optical data transmission separates from the electromagnetic waves (see figure 11) that gave birth to what is today wireless communication.

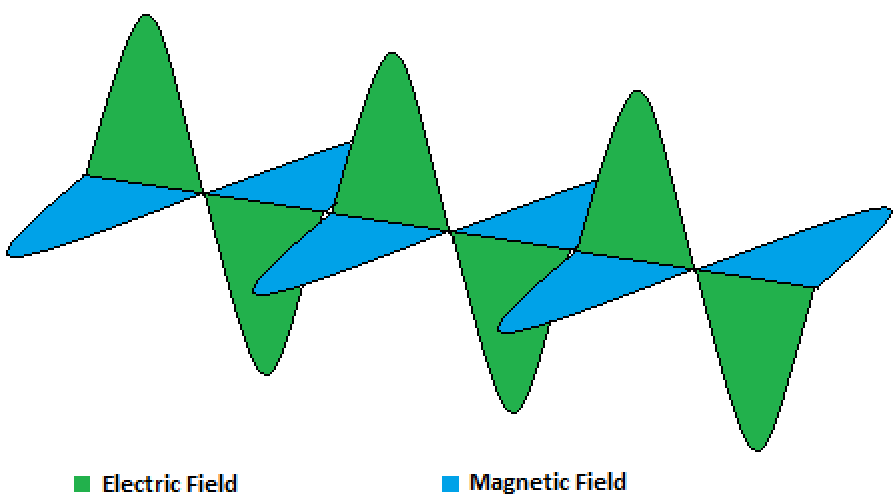

Figure 11: Propagating electromagnetic wave.

With the work of Heinrich Hertz, J.C. Maxwell and Michael Faraday in the late 1880's, was later given a practical use by the hands of Nicola Tesla, the first electromagnetic waves radio communication began the course of what now has come radio and wireless data transmission. First starting as radio telegraphy in a way of point to point communication, big antennas were set in transmission/reception points, and information that previously required a wire to be transmitted suddenly was available without the long distance dedicated wire. With evolution accelerated by necessity of military communication during the First World War, radio communication gained a lot of popularity for the convenience of geographical flexibility for transmission and reception required to keep informed moving armies and fleets, pointing from the beginning at the main advantage wireless communication offers to the users; a fast an flexible transmission link.

Later on different techniques of modulation, separation of frequency bands (considering between 9 kHz and 300 GHz), encryption, coding, etc. were developed, not only with the purpose of a better wireless communication, but also separating different applications of it. Nowadays this application frequency band distribution is controlled by the government and some international agreements that set specific frequencies for universal messages or specific application (for example, emergency frequencies for marine and aircraft alerts and SOS). The technologies to be presented in this chapter have different characteristics and follow separate standards, thus requiring separation for proper analysis.

2.4.1. Wi-Fi

Wi-Fi is one of today's most popular wireless networking technologies. Regulated by IEEE with the standard 802.11, though the technology was previously used for private company purposes, the standard was officially introduced in 1997. Originally allowing data rates of only 2 Mbps, and as all other communication technologies has experienced constant evolution which continues to the day.

In a similar way as it happens with some other technologies, there is an organization in charge of improving and developing the standard. The Wi-Fi alliance is the union of manufacturers, developers and promoters of Wi-Fi technology. Though not all products and manufacturers are affiliated to the organization because of the cost of affiliation and logo rights, Wi-Fi compliance is not limited by this. Due to the fact that Wi-Fi is a very well established technology, it has a very developed market and set of manufacturers. Every time a device is engineered with more than one connectivity option, there is a high chance of Wi-Fi been one of them. Laptop computers, smartphones, bank terminals, ATM's, etc. are examples of devices that have in most cases Wi-Fi as a connectivity option for networking access.

New and more efficient modulation protocols, going from direct-sequence spread spectrum (DSSS) to orthogonal frequency-division multiplexing (OFDM), and combined with the development of antennas and materials, the range and data transmission capacity of the Wi-Fi devices has been strongly increased. The latest upgrade of the IEEE 802.11 standard, the version 802.11n released in October 2009 reaches a range up to 250 meters outdoors and 70 meters indoors and data rates of up to 150Mbps[23]. The frequency band used for Wi-Fi has been also changed during the evolution of the IEEE 802.11 standard. Initially utilizing the frequency band up to 5 GHz and applying different frequency multiplexing techniques (OFDM for the latest releases) is divided into channels of 20MHZ or 40MHz, but preferably 40MHz for higher speed of connection [24].

Wi-Fi technology for data transmission presents several advantages. Wi-Fi despite not requiring installation of additional physical channel provides a relatively high speed of data transmission, matching the speeds (within close range) of wired dedicated media technologies. In addition, in highly dense populated areas, it can provide redundant connection when installed overlapping coverage area between access points, ensuring at all times path of connection at least for the most important devices if desired.

The link between devices is made mainly software wise once the transceivers are installed. For Wi-Fi (and in common to other wireless technologies) addition of devices into the network does not represent the mechanical challenge the previous technologies imply with connections and couplings, but is done by the network management control. Also, as a well-established technology, standards are well developed and the availability of devices and manufacturers in the market is wide. Exhaustive studies on different products provide well detailed characteristics (in some cases) for the devices, and information about performance over different situations and environments, and also reliability and durability characteristics are already available, which provides a better reasoned background for decision making over actual device selection for the specific end location application.

Wi-Fi as well, like some other non-dedicated media technologies, has the advantage of flexibility of connections. Even though a Wi-Fi access point can provide service to a limited amount of devices, (depending on the specific access point model) the limitations are not as strict as dedicated media technologies, which have a limited number of ports and take one device per port. In contrast, Wi-Fi provides area of coverage, and all devices within the area (when not exceeding the limit) can get access granted, facilitating connection for changing environments where connection required devices may be added or reduced within the coverage and without extra work required.

Disadvantages are also present for Wi-Fi technology. As a relatively short range technology, it can only be used as an end point link. The 250m maximum range turns unviable the use of this technology for long distances, not only great investments would be required to create long distance links, but also the delay of retransmission between hops can grow way beyond the delay accepted by the control and management system to keep an optimal working point.

Despite being a well spread connection technology, not every device (and especially within the electricity distribution sector) is Wi-Fi ready, so transceivers are required in many cases, increasing the cost and complexity of implementation. Also, installation of access points is more costly and complex than other dedicated media data management devices. Also, all wireless technologies are very location and landscape dependent, but Wi-Fi is slightly more vulnerable to such obstacles. In contrast to long range wireless technologies, the setup of access points is made closer to ground level, and in direct obstacle range of medium size trees, and living structures, along with other bigger obstacles like hills or big boulders. Nevertheless, Wi-Fi is intended for short range connections, so the number of obstacles outdoors is likely to be very limited.

Based in these considerations, once the analysis of the end location is carried out and the specific environment final characteristics of the environment are known, using Wi-Fi is a viable option to be considered for the application, if not for the whole deployment of the communication, then can also be used in specific areas or situations where the characteristics of the environment present a convenient scenario for Wi-Fi utilization.

2.4.2. WiMAX

WiMAX stands for Wireless Interoperability for Microwave Access. WiMAX is a middle range (Or last mile) communication technology, which for the focus system application of this research can also be considered as long range, due to its capability of covering the entirety of the area of the system with one or few transmission/reception facilities.

WiMAX is regulated by the IEEE 802.16 standard. Developed and regulated by the IEEE 802.16 working group on broadband wireless access standards [25] under the name of WirelessMAN, was baptized and is promoted by the name of WiMAX given by the WiMAX Forum (equivalent of the Wi-Fi alliance, but for the IEEE 802.16

standard). The WiMAX Forum alliance is a group of manufacturers and promoters that certifies devices for WiMAX compatibility. According to the standard IEEE 802.16 release 2 [25], the utilized frequency band WiMAX is divided into two main bands depending on the application. The band from 10GHz to 66GHz for point to multipoint communication (PMP), and the band from 2GHz to 11GHz for mesh application.

Taken from the architecture definition on the standard about PMP systems: "*PMP systems comprise Base Stations (BS), Subscriber Stations (SS) and, in some cases, Repeater Stations (RS). BSs use relatively wide beam antennas, divided into one or several sectors providing up to 360° coverage with one or more antennas. To achieve complete coverage of an area, more than one BS may be required. The connection between BSs is not part of the fixed broadband wireless access (FBWA) network itself, being achieved by use of radio links, fiber optic cable, or equivalent means*." [26]

"*Links between BSs may sometimes use part of the same frequency allocation as the FBWA itself. Routing to the appropriate BS is a function of the core network. SSs use directional antennas, facing a BS and sharing use of the radio channel. This may be achieved by various access methods, including (orthogonal) frequency division, time division, or code division*." [26]

Regarding the Mesh architecture, the standard mentions: "*Mesh systems have the same functionality as PMP systems. BSs provide connections to core networks on one side and radio connection to other stations on the other. A SS may be a radio terminal or (more typically) a RS with local traffic access. Traffic may pass via one or more RSs to reach a SS*." [26].

In the architecture (presented in figure 12), different types of nodes have specific roles. The node defined as terminal equipment in the standard is equivalent to the referred end point in other parts of the research, and represents the origin or final destination of the information (measurements, control commands, etc.). The subscriber station is what provides the communication link between the wireless signal and the terminal equipment, usually is a transceiver or modem. Base station is the device that provides the main area of coverage for the wireless link. The area and zone of coverage can be manipulated by the setup and focus of antennas and of course also depends in the characteristics of the selected base station.

Repeater stations can be part of both PMP and mesh structure, but with different functions. In PMP architecture, the main function of the repeater stations is to extend the range of communication for in the edges of coverage of the base station, meaning that if the base station possesses enough range to cover the full area, repeater stations are not required. Whereas in mesh architecture, repeater stations are installed within the range of communication between each other and the communication is sent from one point to another hopping between repeater stations which have access to the wireless media and can also be connected to a core network (e.g. optic fiber). Under mesh scheme, the actual base station is or may not be required for the communication.

This implementation flexibility allows WiMAX to adapt to varied presented scenarios. It is because of this characteristic that WiMAX has participation in many different markets and applications. From mobile communications, internet providers to grid solutions, WiMAX has proved a viable option for communication.

The transmission range of a base station depends on the model of the device, antenna type height and size. From bas station to base station, the maximum distance link is in the order of 60 km, while from subscriber station to base station is a maximum of 12 kilometers [26].

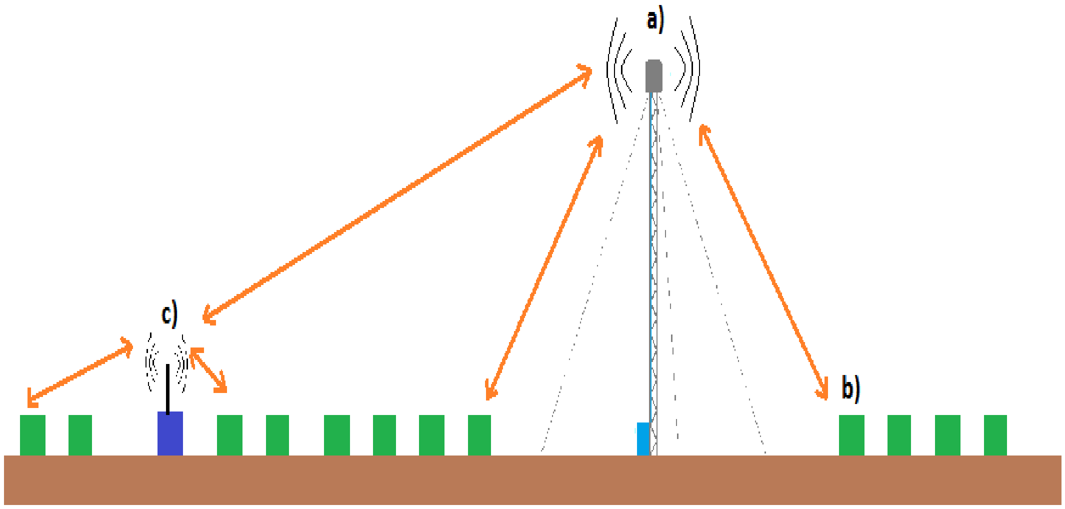

Figure 12: WiMAX system architecture. a) Base station (BS). b) Subscriber Station (SS) + terminal equipment (TE). c) Repeater station (RS).

Along with the long range, WiMAX wireless transmission also provides very high data rates. WiMAX is capable (in theory) of delivering up to 100Mbps to mobile stations and up to 1Gbps [27]. As other wireless technologies, the further the distance of connection, the less bandwidth is available. Despite this fact, the data transmission rates are high enough at any point within the covered area to surpass options like PLC even through the long range. Because of the range and data rates, in the case of use of WiMAX technology it is possible to eliminate intermediate links and, if subscriber stations are compatible for all communicating devices, establish direct long range links to all devices, which can highly improve the latency by eliminating hopping (with PMP architecture).

Despite these advantages (and like in the previous technologies case) WiMAX presents also some drawbacks. In the same way as other wireless technologies, physical obstacles have a great impact in the range of connection of the technology. Long range wireless technologies are slightly more adaptive to local environments through the option of installation of taller towers. However this implies a bigger challenge (explained in more detail in the installation chapter) and cost. This vulnerability to the geographical situation of the location reduces the reliability of the technology, which already finds availability difficulties in remote locations.

Also, despite been a relatively well established technology, the devices market and development for different applications is still somehow limited, and detailed information of performance for application specific devices is either not available or not easy to find. In addition to this (but for the same reason) the devices for this technology are more costly that their Wi-Fi counterpart. Furthermore, WiMAX is administrated by the network operator, which causes cost and problems with permission to use the technology. Plus, in different parts of the world the regulation of the usable frequencies may conflict with the technology, if it is even available for the location.

All this characteristics, advantages and disadvantages, define WiMAX as an option for communication. The details of the end location will define the applicability of WiMax, or other from the possible options.

2.4.3. LTE

LTE stands for Long Term Evolution, and is another long range wireless technology for data transmission. Unlike the previous described technologies, LTE standard is not regulated by the IEEE, but instead by the 3rd Generation Partnership Project (3GPP).

As defined by the 3GPP group: "*The LTE access network is simply a network of base stations, evolved Node Base-station (eNB), generating a flat architecture. There is no centralized intelligent controller, and the eNBs are normally interconnected by the X2-interface and towards the core network by the S1-interface. The reason for distributing the intelligence amongst the base-stations in LTE is to* *speed up the connection set-up and reduce the time required for a handover. For an end-user the connection set-up time for a real time data session is in many cases crucial, especially in on-line gaming. The time for a handover is essential for real-time services where end-users tend to end calls if the handover takes too long."*[28] The system described is shown in figure 13.

From figure 13, the packed switched EPC refers to the evolved packed system (EPS) which for the release 8 and onwards of the standard is purely IP based [28]. The 3GPP was formed in the early 1990's but is only recently that the standard for LTE as released. The 3GPP group is in charge of other communication standards utilized mostly for mobile and cellular communications (being GSM the most known and utilized of their communication standards). But it was until 2008 that the first standard defining LTE was released (release 8), followed by the first applications in 2009 as a 3G mobile communication provider. Later on, in 2011, release 10 updated the capability of LTE to 4G service provider under the name of LTE-Advanced.

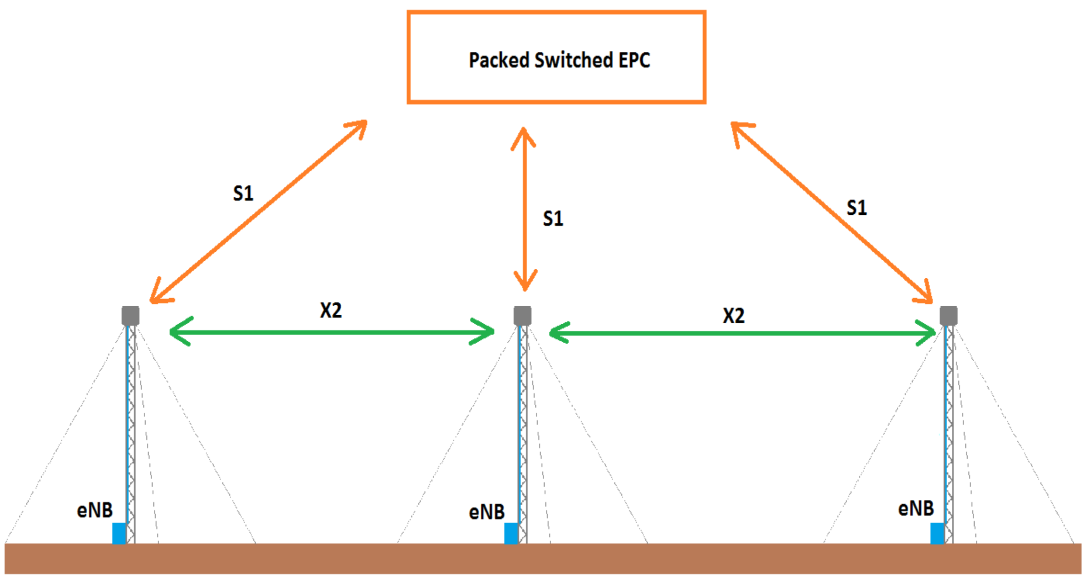

Figure 13: LTE architecture.

The main advantage brought to the mobile communication service providers is that LTE uses the same interface and access method that GSM, strongly facilitating the migration of technologies [28]. Just as WiMAX, can operate on multiple input-multiple output (MIMO) transmission, utilizing the frequency bands (depending in the location) from 800MHz to 3.5GHz divided into 20MHz bands by orthogonal frequency division multiple access (OFDMA) for downlink and single carrier-frequency division multiple access (SC-FDMA) for uplink, achieving data rates of up to 300Mbps for downlink and 170Mbps for uplink.

For LTE the optimal cells range for not highly dense populated areas (like the focus system) is in the order of 5 km, but can be extended much more on the cost of performance, or reduced to achieve better rates. Because LTE is a relatively new technology and is still under development and evolution, applications on smart grids have not yet been made, or at least published. However, feasibility studies have been already conduced to some detail in [29] and [30].

As a flexible range technology of communication (with the capability of establishing long range connections but also option to work in mesh mode with short links) shares most of the advantages and disadvantages with WiMAX. The main difference (and advantage), especially for developed urban areas, is that with present GSM mobile communication systems is easy to evolve to LTE (some modifications and additions required of course). Because of this, and backwards compatibility with GSM, most of the mobile communication service providers are migrating to LTE.

However, in the smart grid field of application, LTE is by no means well established and not necessarily the obvious evolution path for communication, but just another possible option. Without deep reach into markets outside mobile communication, devices for LTE connection are not widespread and often also lack of detailed characteristics. The device market and price will define (in case of long range wireless selected for the application) the optimal solution between LTE and WiMAX.

2.5. Summary of technologies

Some of the physical transmission characteristics of the different technologies and types of transmission media have been presented within the chapter are summarized in table 1 in the following page. In order to provide a fast comparison to the reader, table 1 concentrates some of the most important characteristics of the type of connection in order to facilitate the choice of what technology to use in different distribution and environment situations.

Table 1: Technology transmission characteristics

Technology / Transmission characteristics	Maximum Range	Data Transmission	Type of Media
LTE* (Wireless)	5km ideal rates, much more at lower rates.	Up to 300Mbps down-link, 170 Mbps up-link, distance de-pendent latency.	Long range Non-dedicated
WiMAX* (Wireless)	12 km Base Station (BS) to Subscriber Station (SS). 60km BS to BS.	Up to 100Mbps, distance dependent latency.	Long range Non-dedicated
Wi-Fi (Wireless)	250m (line of sight, with no obstacles)	Up to 150Mbps, medium latency.	Short range Non-dedicated
Ethernet over Optic Fiber	Single mode 10 to 100 km. Multimode 2km.	From 100Mbps to 10Gbps, very low latency.	Long range Dedicated
Ethernet over UTP	100 meters	From 100Mbps to 10Gbps, low latency.	Short range Dedicated
BPL	400 meters	5Mbps (NN), 20 to 200ms [11].	Short range Non-dedicated

*** May require service provider, other network infrastructure and sometimes ground cabling.**

3. POSSIBLE SCENARIOS AND IMPLEMENTATION RESTRICTIONS

This chapter will present considerations of different situations that can be faced by the system and how those situations can affect communication and can be dealt with. The aim of the considerations is to prepare the system to as many scenarios as possible and achieve enough flexibility of implementation. The scenarios to be presented here are not all possible scenarios, but the ones thought about during the research. Other situations can arise that need to be dealt with, so further research could come from the analysis of such cases.

As mentioned in the introduction, within the system description a fixed location and distribution are not defined, and both factors that could have an effect in the decision of what technology is used, and in some cases, what technology cannot be used. Because of this, the possible scenarios to face can have an important impact in the price, type and structure of communication system network.

3.1. Client distribution scenarios

This chapter will focus in the effect of the geographical distribution of the clients' data transmitters and receivers over the area covered by the network. Distribution of data sources and sinks is one of the factors that affect the most to the possible structure of the network. Segmentation of the covered area, technology for the connection, cost and even the power that will be used for the data transmission is strongly affected by the client population distribution, and due to the fact that distribution of the clients is not defined for the proposed system, it is important to analyze different scenarios. Information of how the distribution of clients affects communication and extreme cases of distribution (along with the possible approach for communication solution) are presented in this chapter.

To understand the effect of client distribution, knowing the effective ranges of communication is necessary, exemplified in figure 14. Ranges mentioned in the description of every technology are usually referred as the direct line, and in the case of wireless technologies, direct line of sight. Therefore, the effective range of different technologies tends to be shorter in real environments, due to the fact that, with wired dedicated media is not always possible to install a straight line of wire between the communication required devices, since for practicality and also protection are set following or next to the installation of electrical power, water or gas pipes, etc.

Figure 14: Effective ranges of different technologies.

On the other hand, the wireless media encounters obstacles in hills, big boulders, dense foliage and vegetation, buildings, which is a double challenge since not only existing landscape obstacles affect, but new buildings, trees, dunes, etc. can constantly modify the communication range or path. This can also cause uneven range in all directions, and have to be taken into consideration when electing the proper location for a transmission tower or hot-spot.

As shown in figure 14, effective ranges vary a lot between proposed technologies. For open environments, the minimum range of UTP is considered when the hundred meters of maximum range are divided into two sections of fifty meters right angled, that in contrast with the straight line range is about 30% less reach. With the wired technologies, dedicated or non-dedicated media, this is a useful way to approximate the reach in a real situation of implementation. For wireless technologies is much more difficult, since it is very location dependent, and expected to change. Because of that, is not possible to approximate to the minimum reach of the technology, and therefore only maximum range is shown.

Other communication techniques exist which have not been evaluated or included in this research. ZigBee is a short range, low bandwidth, low power consumption wireless communication technique. While already tested for smart metering with success, however metering data is not as time restricting as control and protection signals, and the high latency delay over long distance transmissions turns unviable ZigBee for other purpose than metering in the grid. Physically, a parallel network for control and protection would be required, while with higher capacity and lower latency communication techniques the separation is either not necessary or can be done logically, running over the same communication media.

Coaxial baseband modulated cable and digital subscriber line (DSL) data transmission provides decent ranges of transmission, up to 3.6km, and up to 10Mbps data transmission rate in a point to point connection [31] while still having a cheaper connection than optical fiber Ethernet. However, the devices for smart grid application found during this research did not have the option of coaxial connection, which implies the need of a transceiver or modem for end point connection, limiting the convenience of been used for end point connection. If considered only for long range connection between data management devices, competes directly with optical fiber media, with the only advantage of cheaper connection cost, while optical fiber offers higher data transmission rates, lower delay, longer ranges, more stable performance over distance, between others. Coaxial baseband modulated cable data transmission was not mentioned nor considered in the research papers taken into account so far in this research, and the advantages of optical fiber as data transmission media present good reason for this.

3.1.1. Best Case Scenario

The best case scenario for a network, from both data and power perspectives, is when all clients are in short distance from between each other, the full population, or even groupings from the population (as shown in figure 15). Short distances between clients provide advantages in the way that; if dedicated media is utilized, less cable is required, less (or not at all) repeaters of data are required to complete communication links.

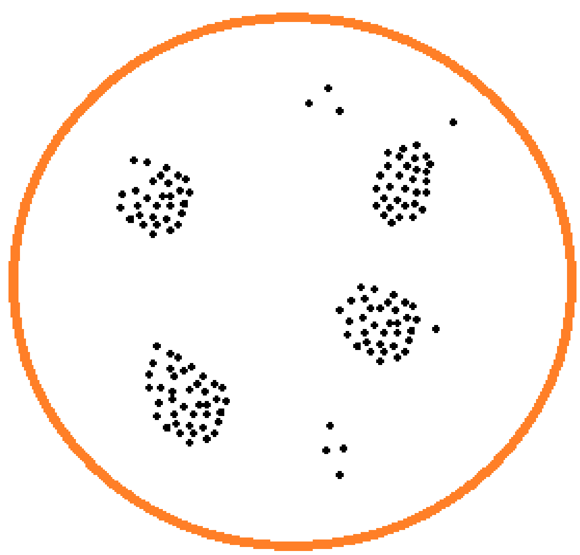

Figure 15: Best case scenario of the distribution grid; tight groupings of communicating devices.

In this case, technologies which are short range, high throughput and lower in cost (Ethernet over UTP, BPL) provide a better option for the end point communication, while an optical fiber backhaul can connect the groups and control & management.

High capacity data management devices can be installed in strategic positions to give service to the most possible devices in the high density populated areas (working as data collectors) and sending through optical fiber the collected data to control and management.

Also, the closer the communicating devices are to each other and to the data concentrator or local control, the less delay is experienced between the data generation or transmitter and the reception (of course the impact of distance is less where the links are optic fiber). When the intermediate link between information destination and data transmission point is made in more than one step due to the distance (hopping in wireless repeaters, been retransmitted in Ethernet switches and changing media, e.g. going from PLC to optic fiber) every step adds a delay on the information.

Population distribution is different in every location by tendency. Due to different cultures and social behaviors, in some places the population will (consciously or unconsciously) tend to keep tight groups of distribution, often seen in Asian tribes. In some other places, people are more comfortable when the distance between neighboring houses is as big as possible, with the good example of Finland. Fortunately, since the application is oriented for developing countries' environments, in most cultures around the world the tendency is to settle within close distance, therefore increasing the chances of a more friendly distribution, both from the power distribution and communication perspective.

3.1.2. Worst Case Scenario

The worst case scenario, by logic, is the opposite situation to what is described in best case scenario. When a population of communication devices and clients is evenly distributed along the whole area of the network, and the density is low enough to keep long distances between devices, power distribution and communication become more challenging (In figure 16 an example of even distribution over area is shown). Not only a lot more material is required in forming of cable if the communication is conducted over dedicated media, but also the number of end point links that a data management device can attend is reduced by the limited range of copper data transmission (in the case of UTP and BPL) and short range wireless technologies.

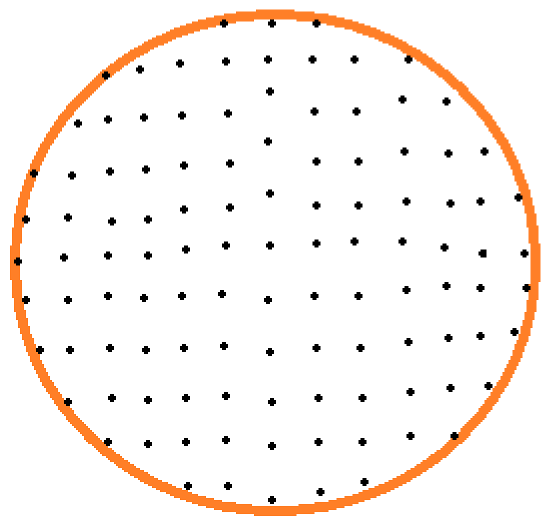

Figure 16: Worst case scenario of distribution grid structure; even population distribution over the network area.

Is in this type of distribution scenario where long range wireless techniques thrive. Despite the high cost and complexity of a WiMAX or LTE network, the possibility of saving extra investment in materials and installation of dedicated media, and the higher bandwidth in comparison to PLC give these techniques the advantage in such situation. In a flat landscape, powerful enough base stations can provide service to the whole required area, while requiring some repeater stations in case of geographical (landscape) obstacles. Repeater stations can also work as the transceiver between communication techniques, providing options to the end point devices, useful situation since not necessarily all grid communicating devices are WiMAX or LTE ready.

3.2. Implementation Characteristics and Economic Analysis

In this chapter, details of implementation and deployment will be addressed. Further research is made in order to understand to some extend the characteristics of the commercially available devices. Every aspect of the devices has a different effect on the possible end solution, and has to be taken into account to achieve the most reliable, robust, and cost effective way to transmit data between devices and between the control and management units.

3.2.1. Devices

Technologies and devices are related to each other, but at the same time are different concepts. Technology is referred in this research as the principle of which devices work on, while devices are developed so the customers (commercial market, military, scientific field, etc.) can make use of the technology. The evolution of technology has always effect on the devices, but devices often evolve in directions not related to the technology itself. For example, devices are constantly improved so that they become easier, cheaper cleaner and better to manufacture, or to comply with other markets standards and tighter new regulations, like electro-magnetic compatibility, and this research and development is carried mostly by the manufacturers themselves.

The fact that the development for better manufacturability is done by the producers brings both advantages and disadvantages for the devices development. In one hand, the technology becomes more accessible, constantly reducing price and increasing quality to improve the competitiveness in the device’s market. On the other hand, this tendency sometimes causes incompatibilities of products between manufacturers and parallel standards, especially at the early incursions of technologies in the commercial markets.

Due to the wide commercial application, devices focused on Ethernet UTP, optic fiber and Wi-Fi are very easy to find, and usually are provided with very detailed sets of information and have a wide range of well-established manufacturers. In contrast, for technologies which have no deep penetration in the market (mostly because they are new, but may be other reasons like price or specific application) finding detailed and trustworthy information is not necessarily easy, especially in the reliability and durability field.

Another interesting tendency encountered is the direct competition between WiMAX and LTE for long distance wireless technologies. Big manufacturers and service providers made a bet on either one of these technologies, mainly focusing on the market of smartphones, broadband mobile, and other data intensive applications. In both cases, base stations are required to be installed in the center of the area which requires coverage; both allow relatively long distance connections (Over four kilometers) and have similar markets of technology ready devices. Also, when the device to be connected is not technology ready, both technologies have good compatibility through USB adapters, but still both are operator based services, causing an extra operational cost and player.

WiMAX as an older technology in comparison with LTE gained strong popularity at the beginning, but the tendency in the device's market is for the WiMAX technology to be slowly replaced by LTE in some applications (like in the mobile applications that are the main focus of the technology because of the constant expansion and high profit potential) to the point of manufacturers discontinuing some of the WiMAX products previously offered. Despite this fact, WiMAX still provides a very viable option for backhaul of a smart grid communication network, and its presence in such applications still continues.

In the specific field of power distribution networks and smart grids, the device's market has very unique tendencies. End point devices (like smart meters or controllable relays) from different manufacturers have several options for connection; within the usually available there are PLC, UTP Ethernet cable, ZigBee, Wi-Fi and in rare cases direct fiber optic connection (due to the high connection cost). Only recently WiMAX and LTE have started to have presence in the smart metering application, in contrast, for control and protection devices are either still not available or were not found during the device market search.

3.2.2. Economic Analysis

This chapter will focus on the economic implications of deploying a communication network for a smart grid application. A decision of network deployment is often strongly influenced by the required investment for different options rather than other characteristics of the available possibilities, due to the fact that in the industrial business, the final decisions are made by the part providing the capital, whose main goal is always to generate as much profit, as quickly as possible and with the less possible investment required.

Even after having some details of the distribution system to be implemented, is not possible to determine a precise number for investment without having known all characteristics of the end location. This is due to the fact that the costs (as many other aspects of a network planning) are, to some extent, location dependent especially workforce, and factors like distribution have a huge impact in the cost of the communication network deployment. Therefore, mathematical models for different types of network deployments will be analyzed.

With the purpose of achieving a more practical approach, and gain enough flexibility to adapt the calculation to multiple options of communication, the cost calculation will be divided into two main groups; end point communication links and long range links. End point communication links are the last short range (last mile) connection (Wi-Fi, UTP and PLC) between the emitter and transceiver end for the end point devices. On the other hand, long range links refer to the connections with higher distances, but often not used to the end point due the higher cost. In all cases installation cost will include not only the materials for installation but also the cost of workforce, which is the network installation party.

End point communication links

There are three main end points communication technologies; UTP, PLC and Wi-Fi. For UTP end point connection, the cable only covers the last distance connection while having access through a data management device to a long range link as seen in figure 21 from the installation chapter. The cost of communication per sector exemplified by the figure 21 is given in (1).

$$SUTPcc = Inst1 + ESwC + \sum_{1}^{n}[CaCo * Dn] + LRTCc \qquad \textbf{(1)}$$

Where the factors are the following, SUTPcc is the sector UTP communication cost, Inst1 stands for Installation type 1 (for ground level data management device), ESwC means Ethernet switch cost, n = number of communicating devices per sector, CaCo is UTP cable cost per meter (plus tubing if required), Dn is nth element connection distance (100 meters maximum for UTP), and LRTCc is long range technology connection cost (different for O.F., LTE and WiMAX).

This equation considers the deployment cost in the factor Inst1. This factor can vary greatly depending on the type of deployment required for the cable, labor required, and if is going to be deployed in parallel with the power cable. If the power cable is not installed in some tubing to protect from moisture that could be used to protect also the communication cable, additional tubing for the UTP cable will be required and included in the term CaCo. As a dedicated media type of technology, the communication cost is influenced by the distance between the devices (included in the term Dn). The RJ45 connector used by the UTP cable is not included in the equation because compared with the cost of all other parts of the equation is low enough to be neglected.

For power line communication end point connection the situation is different. As a non-dedicated media for data transmission, cost is not related by the distance (as long as is within communication range) but is more strongly influenced by the necessity of PLC modems and couplings, defined by the number of devices in the sector and expressed in (2);

$$SPLCcc = Inst1 + ESwC + MCoCo * [n + 1] + LRTC \tag{2}$$

In equation (2), SPLCcc stands for sector PLC communication cost and MCoCo is modem (PLC) + coupling connection cost. From (1), the terms “n”, “ESwC”, “LRTC” and “Inst1” represent the same. This is due the fact that a local data management device deployed at ground level, with a long range connection to the rest of the network (O.F., LTE or WiMAX) is still required as shown in figure 17. Figure 17 includes optic fiber connection, but other long range links can be used. Also, is worth to note that the connection distance, even though is not in the equation because it does not affect the price, cannot be bigger than 400 meters. Figure 17 shows only LVDC connection to clients, which PLC utilizes as the communication channel, so no other communication media is included in the figure to the client.

The last type of end point connection technology analyzed is Wi-Fi. Unlike the previous types and as it will be detailed later on in the installation chapter, the set up for a Wi-Fi access point is different, and therefore the installation is a different term. The example sector is shown in figure 18.

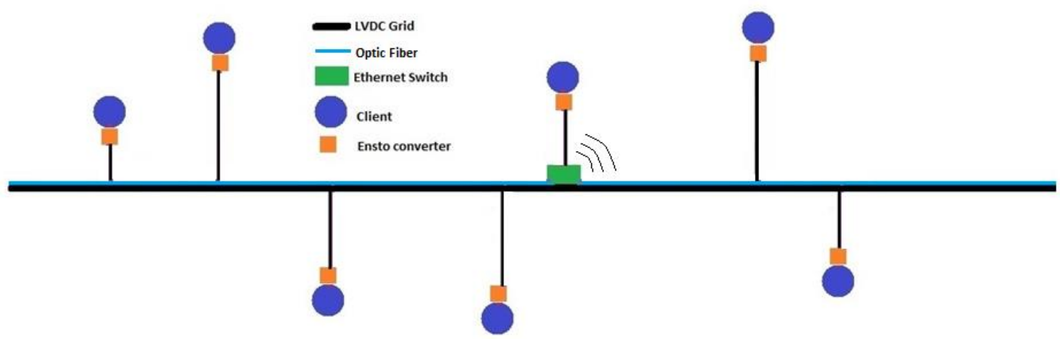

Figure 17: Sector communication when PLC based.

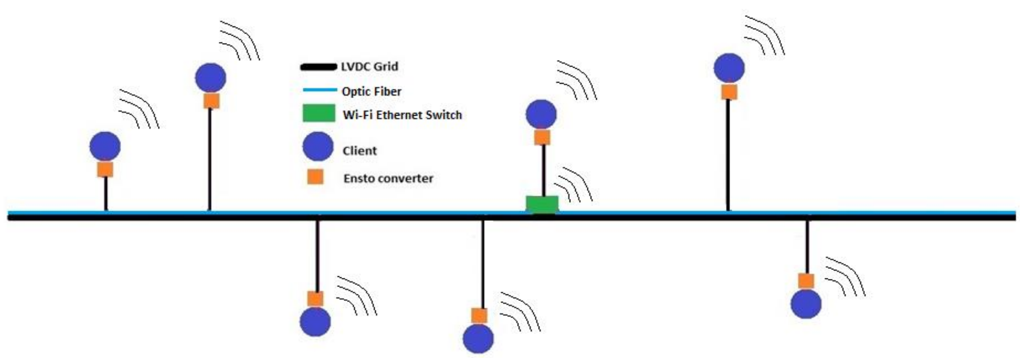

Figure 18: example sector with Wi-Fi end point connection.

And (3) follows as;

$$SWFcc = Inst2 + WESwC + WFCo * n + LRTC \quad \textbf{(3)}$$

In (3), SWFcc is sector Wi-Fi communication cost, Inst2 stands for tower installation for Wi-Fi access point, WESwC is Wi-Fi Ethernet switch cost (outdoor) and WFCo is Wi-Fi connection transceiver. Again, the terms “n” and “LRTC” remain unchanged in meaning. It is worth to note that Inst2 is in principle higher in cost than Inst1. Also, outdoor Wi-Fi Ethernet switch with connection option to a long range link is more costly that the previously mentioned ESwC. If the communicating device is Wi-Fi ready, the factor WFCo*n from the equation can be ignored. Similarly to PLC, the connection cost over Wi-Fi is not distance dependent, but limited to a maximum distance of 250m between the access point and the communicating device.

Long Range Links

Long range links work in combination with the end point communications, which can be done to all different options. Once again, long range wireless links share characteristics from the cost point of view and can be treated under the same scheme (just as is done later on the installation chapter). Taking into account only the set up for the long range links, the formulas for cost calculation become very simple, but (especially when speaking about long range wireless) depending on the end location distribution can turn this into the most significant factor of the calculation.

$$WLRLc = X * Inst3 + X * BaSt \quad \textbf{(4)}$$

Where the term WLLRLc means wireless long range link cost, Inst3 is installation type 3 cost (for long range wireless technologies), BaSt is base station cost and X = required number of towers to cover the network area.The details of the long range wireless technology installation are again explained in the corresponding chapter later. The number of installed base station towers will depend in the area requiring coverage and the power and range of the base station itself. For the area delimited by our focus system, one tower should be enough, but additional ones can be considered for redundancy and reliability of communication.

For optical fiber cost calculation the situation is the following:

$$OFLRLc = DL * PoF + Inst4 \quad \textbf{(5)}$$

In (5) the term OFLRLc stands for optic fiber long range link cost, DL is deployment length (meters), PoF is price of fiber cable (per meter) and Inst4 is installation type 4 (for optical fiber, underground or overhead). Again as a dedicated media communication technology, for optical fiber the distance is a factor affecting the cost, represented by the term "DL". Installation type 4 is the treatment required to deploy the fiber, either buried or overhead. When the fiber cable is deployed along with the power cable, the installation cost 4 can be strongly reduce, or almost neglected.

From these equations, derivations of overall communication network cost can be obtained by combining long range links with end point links, taking into account the networking sectors and their density distribution of communicating devices. If all the communicating devices can be selected as long range wireless ready, the short range connection step can be skipped for this particular option, meaning that when all the devices in the network have (e.g.) LTE interface, the only other cost for setting a communication link is the deployment of towers for area coverage.

The way to integrate the short and long distance cost equations to the particular scenario presented by a system is the following:

$$TCC = XLRLc + \sum_{1}^{NS} nEPSc \quad \textbf{(6)}$$

Finally, for (6) TCC is total communication cost, XLRLc means "X" or any long range link cost, NS is number of sectors and nEPSc is nth end point sector cost (from the available options). The number of sectors is defined by the distribution of communicating devices in the end location, the control and management system, and number of communicating devices. It is important to take into account that for specific locations, different communication technologies or qualities of devices can be preferred (or even if they use the same, the cost may not be the same due to the distances when dedicated media is utilized), and that is the reason to count as the sum every sector with different cost.

Because of the changing markets and unspecified details about the network, using actual numbers for this part of the calculation may turn irrelevant. Despite this fact, it is clear (based on a local market study) that the cost of the communication network may vary up to around 5 times the cost of a relatively good and possible case to the worst case scenario.

3.2.3. Connections

In this research, connection will be considered as the link that unites a device to the network, and is different for every type of technology used, and is one of the most important factors to consider for a network deployment. The price, complexity, availability of interfaces, compatibility, materials and tools, etc. have influence connection capabilities of different technologies.

If the connection is analyzed from the economical point of view, clear tendencies can be noticed. Due to the specific characteristics of every technology, the reach and cost for different connections of physical layers define optimal economic situation for technologies to be used under different circumstances. In figure 19 is shown how the number of connections per data management device (switch, gateway, etc.) affects the price of connection.

As can be seen in figure 19, when the number of connections increases per management device, some technologies experience a cost increase per connection. Non-dedicated media technologies are in the case in the constant increase, since the data management device represents an initial high cost, and then (within the range of connection) every new device attached to the network implies a transceiver cost (assuming devices that are not technology ready, but can be linked to the network in one step of compatibility, e.g. a device that has a USB port can be easily adapted to Wi-Fi, LTE or WiMAX). On the other hand, dedicated media technologies, since use a type of wired connection, have strictly limited the number of available ports per management device, and the number of connections allowed is then one connection per port. However, the price of management devices does not experience an equivalent dependence on the number of available ports per device. As a general tendency, a data management device from the same family of a manufacturer, that doubles the amount of available ports, will not exceed the price of the initial device by more than 20%, and therefore, for a situation where the population density is high enough to consider higher connection capacity, the price per connection becomes lower (clearly seen in the case of the UTP cable, whereas in the case of optic fiber still the high price of connection module keeps the price rising).

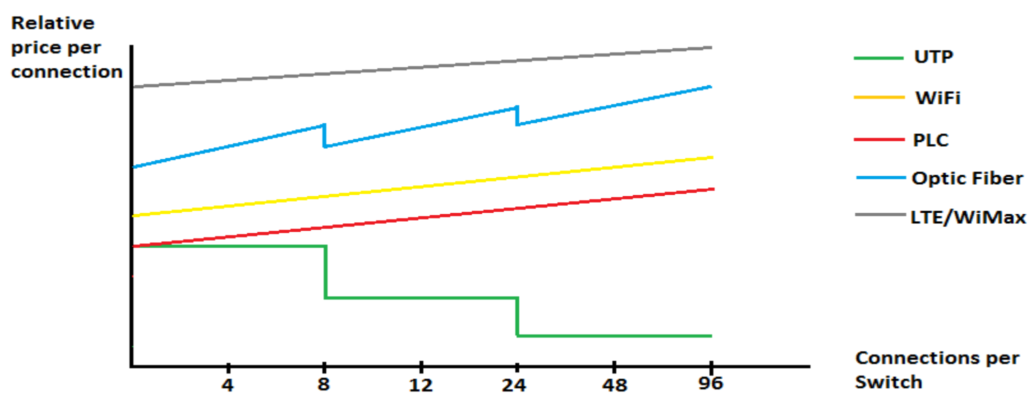

Figure 19: Relative price per connection.

When only the connections are analyzed, by far the most complex and expensive is the optic fiber connection. Almost doubling the price of connection from the cost following technology, and as high as 100 times the price of the less costly connection (UTP connection is practically free without taking into account the cable price).Other transceivers like PLC modems are often integrated to grid devices, and even if they are not, the cost of adapting to PLC is much lower than optical fiber. LTE and WiMAX are more difficult and expensive to adapt to grid devices because these technologies have very low penetration in grid applications, since the main market for both LTE and WiMAX are commercial mobile devices that have the capacity to make use of high speed internet connectivity.

Another factor to be considered is the complexity of connection. Smart grid ready devices are provided with integrated communication options, commonly PLC, Ethernet RJ45 or a short range wireless connectivity. For connecting to other types of communication technologies, the process may gain complexity, especially to the technologies not deeply introduced to the smart grid environment like LTE.

In the matter of availability of capable personal for maintenance, repair of connection, the biggest challenge is faced by optical fiber. Transceivers for wireless access are commonly ‘plug and play’ simplifying the replacement of damaged links or transceivers (again when not integrated to the IED), and a break in the power line (that would cause a break in communication in case of PLC) can be easily patched even by not highly trained personal. However with optical fiber, the set of tools, materials and competences required by the maintenance party to fix a line break are not only be very difficult to patch, but also very slow if the remote location do not have available all necessary for the patching and reconnection.

3.2.4. Installations

This chapter will explain details about the physical deployment of the communication network and data management devices. As with all previous topics, physical deployment of every technology has its own demands and challenges that have to be taken into account when a decision of what type of technology to use is to be made. From the physical deployment of the cable for wired dedicated media, to the setting of transmitter/receiver base station towers for wireless technologies, understanding the implications of installation provides a more complete context to achieve better decision making towards the technology to be used.

Optic Fiber

Optic fiber, as a dedicated media technology, requires the deployment of additional cable for communication along the power transmission cable. There are two ways to deploy optical fiber for long distance communication, just as there are two ways for the power distribution cable; underground or overhead deployment. Because overhead fiber is more expensive due to the fact that requires to be reinforced to stand higher tensions, and overhead lines are also more vulnerable (a falling tree or a car crashing to the holding pole can cause the breaking of the cable) the best way of deployment when possible (in a very rocky soil, digging a trench may not be very suitable) is underground.

When the deployment of optic fiber the cable is being done in parallel with the deployment of the power distribution cable, in order to achieve a certain level of protection and avoid the breaking of both cables simultaneously during an accidental digging, a protection distance in the depth of burial can be a suitable solution for deployment (see figure 20).

As seen in figure 20, half a meter depth (at least) difference between the power cable and the optical fiber is a good deployment practice to protect both lines from simultaneous accidental breaking. It is also worth to note that the optical fiber should always be deployed deeper than the power cable. This is due to the fact that a power cable break can be fixed with relative ease, while an optic fiber cable is more difficult to patch, so in this manner the power distribution cable is also set as a protection barrier to the optic fiber.

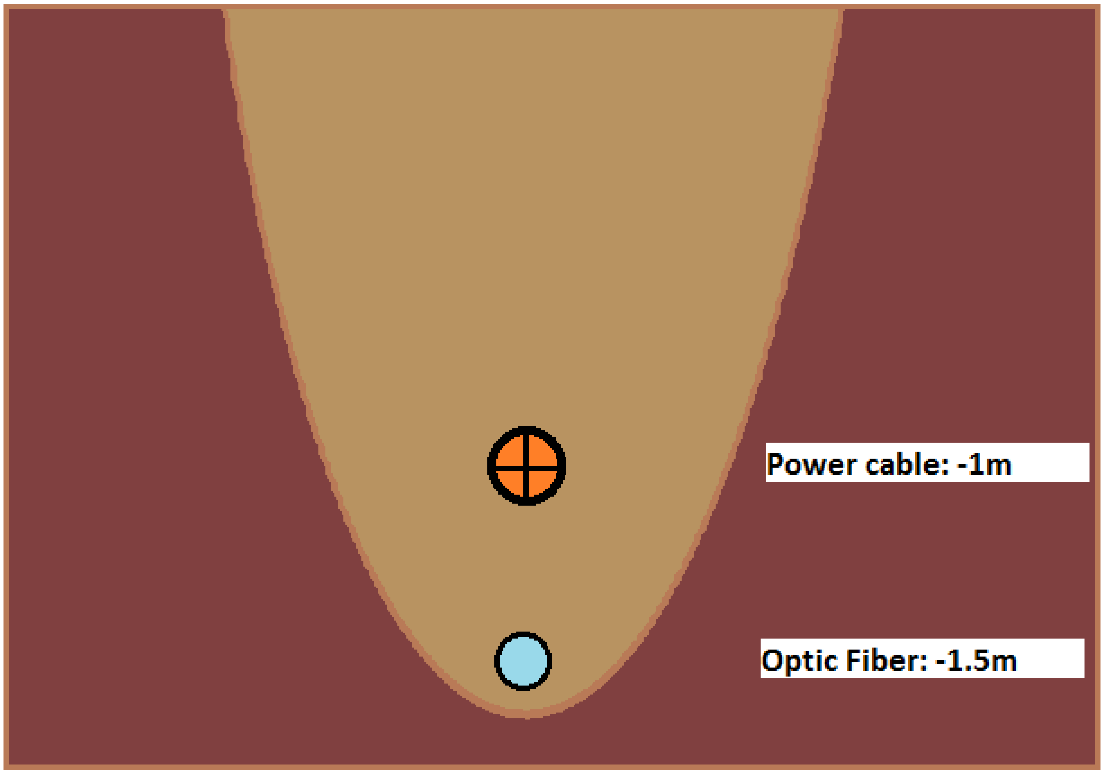

Figure 20: Optic fiber underground ideal deployment.

Besides the cable, optic fiber technology uses also Ethernet-based switches in branch connection points (in other words, connecting switch to switch). These data management devices require a deployment set up for proper functionality and protection from environmental conditions. Because the connection to optical fiber devices is more expensive, the optimal use is as an intermediate or long distance link, while the end of line connection is done with another more practical media, for example UTP cable (using the right cable type and/or tubing for protection from moisture sunrays, rodents, etc.) as shown in figure 21, but other options like Wi-Fi, PLC, etc. can be utilized.

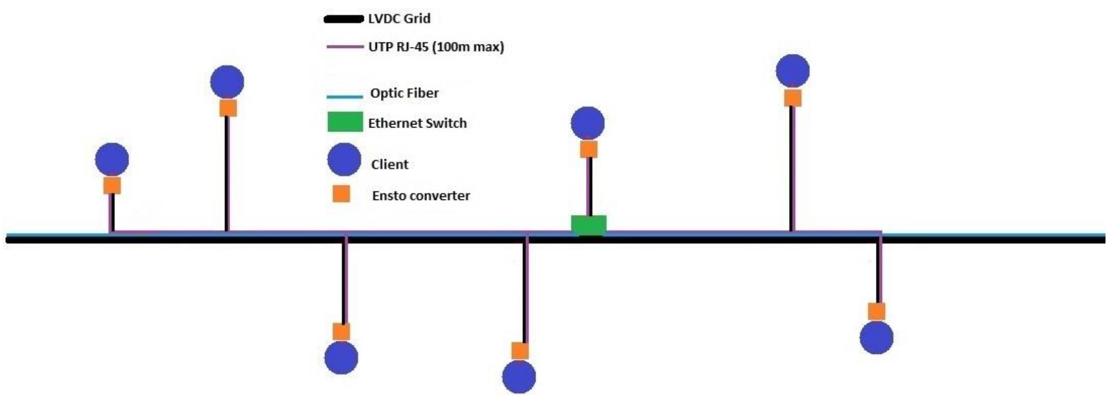

Figure 21: End of line optic fiber based deployment combined with UTP cable.

The Ethernet switch (marked as a green square in figure 21) is used as a long distance link within the communication network and as an intermediary to the end point connection. This data management device cannot be only connected and lay down on the ground, but it requires power supply, a reinforced compartment to protect it from the dust, water etc. but with some ventilation, especially if the location is in a very hot environment.

LTE and Wi-Max

Even though LTE and WiMAX are different in the means of standards for data transmission and frequency bands, from the deployment point of view the technologies are the same, and follow the same principles of installation. Both also share the need of licensing or permission (in most places) for the installation of towers and usage of frequency band.

Since both are wireless technologies, deployment of dedicated media is not necessary, and in the particular case of both of these technologies, they can cover both long distance links and (if the end point devices are technology ready or can be adapted in one step) the connection all the way to the end point can be set as seen in figure 22.

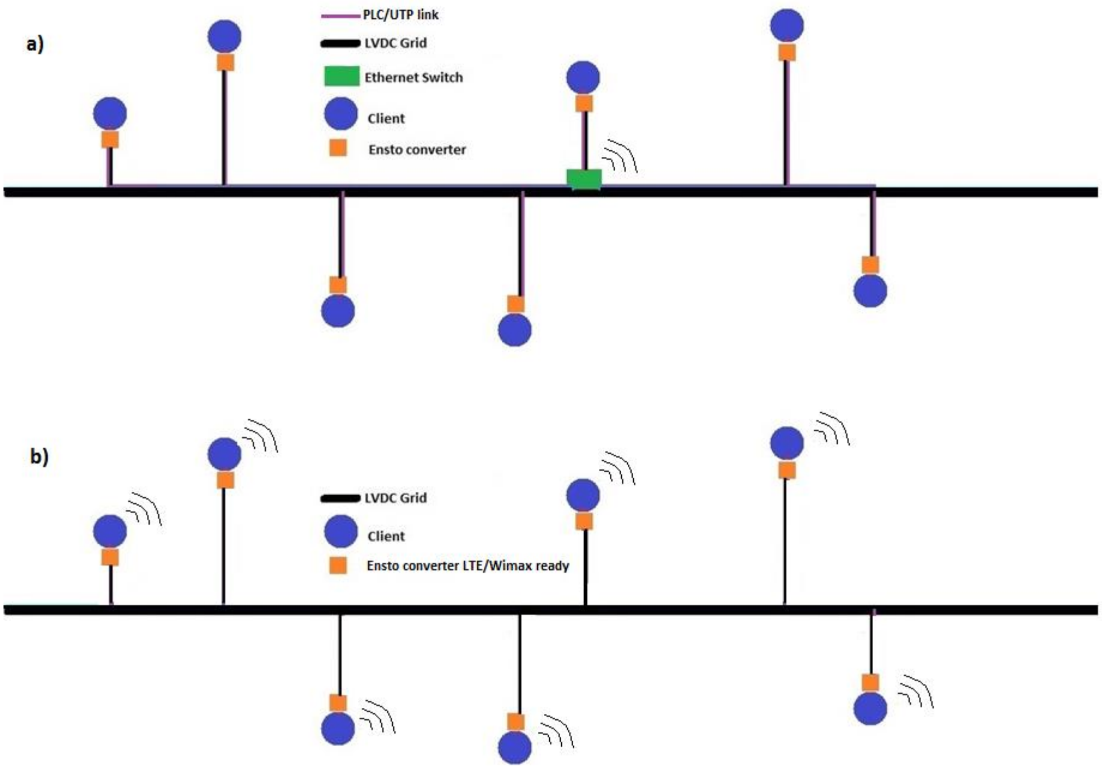

Figure 22: Two main options for LTE/WiMAX deployment; a) As a long range intermediary between zones and b) As a direct end point connection.

The main challenge of installation, while considering this scheme of technologies, is the main transmission tower. Also known as base station, the main transmission tower is the structure that holds the technology transmitter and receiver antenna, and usually holds in the base data management devices, power supplies required for the transmission, etc. in a cabinet that protect all vulnerable equipment from environmental conditions (See figure 23).

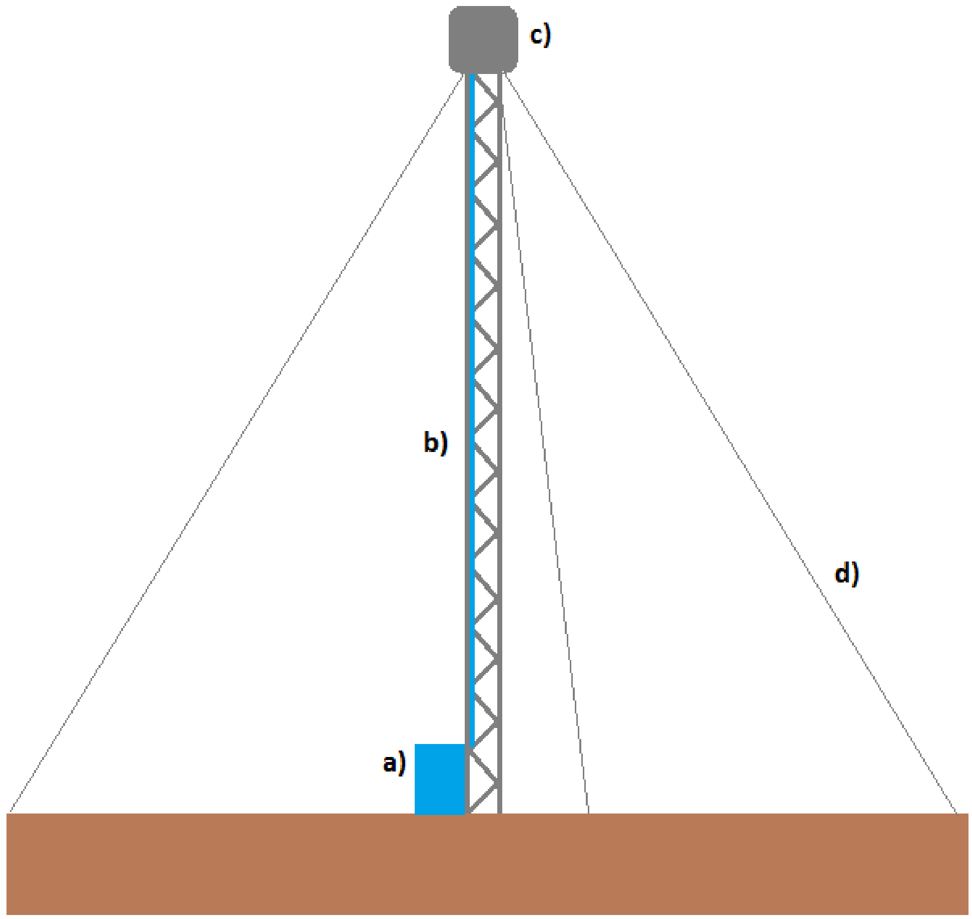

Figure 23: Base station tower set up; a) protecting cabinet for power supply, management and control devices, b) tower structure, c) Antenna(s), d) tensor steel cables.

Figure 23 is just a schematic example of the set up for a base station tower for LTE/WiMAX. The type of structure required for this type of data transmission is not fixed to a standard, but will also depend in the destination geographical local conditions and landscape. The height of the tower will depend strongly on the landscape, range desired and type of base station, heights can vary from 30 to 85 meters for example [32]. For a very flat landscape and shorter distances the antenna can be shorter than in the case of very uneven landscape. The height and common or maximum wind speeds experienced by the area will determine the type of foundations and amount of reinforcements in the way of steel cables. The temperatures and corrosiveness of the environment will determine the materials both for the supporting structure of the tower and the antennas and cabinet. Also, as a high metal structure, lightning protection is definitely required, the average amount of electrical storms striking the location will define also the capacity required from this protection. Finally, a perimeter set up might be necessary to protect the structure from big animals (cows, elephants, buffalos, etc.), vehicles and people intrusions.

Wi-Fi

Wi-Fi within the wireless technologies has a special case. Is a short range wireless technology, meaning that in case of use will be for end point connections as an alternative to UTP or PLC installation. A tower structure still needs to be erected for the wireless access point to be installed, however different and much more simple and smaller than the ones used for LTE and WiMAX, and with the advantage that the use of frequency spectrum and placement of the tower (in self owned land) do not require further licensing or permits.

A tower set up for a Wi-Fi access point is very similar in shape to the one of LTE and WiMAX, but in smaller scale and without the cabinet, since the transceiver module has usually integrated antennas, data management devices, and sometimes even power supply. The tensor cables can even be avoided if the environment of the focus site is not too windy. In reference to Figure 21, the wireless media would replace the UTP/PLC link, while the access point would be set in the place where the equivalent Ethernet router is placed.

An example of the setup of a Wi-Fi outdoor access point is shown in figure 24. Because the short range (Maximum line of sight 250 meters) of Wi-Fi allows the technology to be only end point link or short distance high bandwidth connection between 2 points where optical fiber may not be compatible (e.g. across a river) in figure 24 is shown a connection to optical fiber and electrical power for power supply of the device as an example. The height of the tower will depend of the geographic characteristics of the surroundings, aiming to maintain a direct line of sight between the Wi-Fi devices' antennas and the access point. Other connection options from the long range side are of course LTE and WiMAX. Such devices already exist in the market and are an option for this scenario.

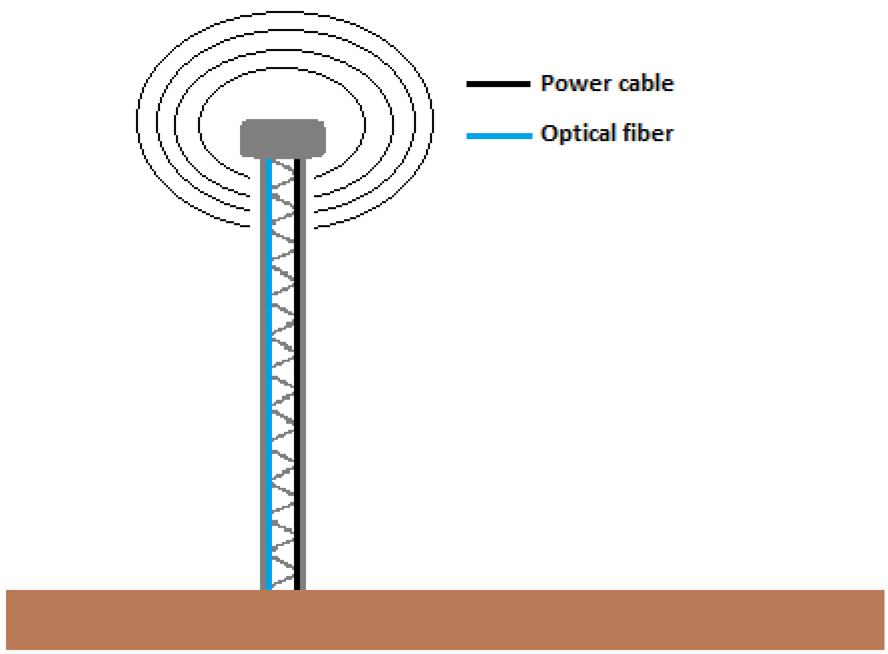

Figure 24: Tower Set up for Wi-Fi access point.

UTP installation.

UTP cable as an end point link from the network can be deployed in parallel with the power distribution cable between the Ethernet switch and the communication required device. Besides the selection of the adequate cable for the application (in tube installation, underground installation, outdoor, armored, etc.) the deployment of UTP cable is not very challenging. Deployed in parallel with the power distribution cable opens the vulnerability of been simultaneously broken, loosing communication and power, but as an end point connection, in the case of cable damage only one device is isolated from the network and therefore the effect on the network is not to negative. Also repairing the link is neither difficult nor expensive. However the advantage of parallel deployment with power transmission cable to the end point is no extra cost of deployment besides the cable itself making this option the most suitable for UTP installation.

Power Line Communication

The main deployment challenge of PLC is the coupling to the power transmission line. As a non-dedicated media technology of transmission, deployment of extra cables is not required. Because of the relative short range (referring to BPL since speed and bandwidth required for the application are high) PLC is ideally deployed as an end point link. Then, it is connected in combination with a backbone long range link (optic fiber, LTE or WiMAX) which still requires the installation of a data management device nearby. Due to the fact that data management devices (Ethernet switches, gateways, access points, etc.) are still not PLC ready, coupling to the power transmission line from both sides (IED and data management device) is required, unless the IED has PLC communication integrated. The two possibilities for PLC coupling are inductive and capacitive (capacitive coupling is often the one used by the PLC ready devices). From the deployment point of view, both types of coupling require direct access to the power distribution cable (and even to the conductors in case of capacitive coupling) in the connection points, in consequence making both couplings similar to deploy even when techniques are different, having inductive coupling the advantage.

A short summary of installation requirements is presented in table 2. The field "permission requirement" addresses especial permission or licensing required from the local authorities. For setting cable or other equipment that does not require especial licensing, still may require permission from land owners (when installation takes place in a land not owned by the distribution company). The 'cable*' mark for Wi-Fi is to mark that the long distance network link to the access point can be done by optical fiber for example, but also the access point can work as a repeater station from a long range wireless technology like WiMAX. Data collectors** can be used for advance metering data concentration and there are devices available in the market. However, for a small system like the one proposed may not be necessary.

Table 2: Summary of installation requirements

Technology/ Installation Requirement	PLC	Ethernet over Optic Fiber	Ethernet over UTP	Wi-Fi	WiMAX/ LTE
Structure / Equipment Requirement	Modem / transceiver, data collectors**, data management, couplers if not integrated.	Data management (Ethernet switches, gateways, etc.), cable.	Data management (Ethernet switches, gateways, etc.),, cable.	Small Tower, cable*, access point	Base station, big tower, perimeter protection.
Permission Requirement	No	No	No	No	Yes, for frequency band and tower.

3.2.5. Possibilities of Expansion

As the customer consumption of energy in the network is expected to grow in time, it is very useful to consider also the possibility of the network itself to grow in time. Growth has to be thought or considered both in the power side, as in the communications side, which brings extra factors to consider when deciding what type of network topology, and communication media to implement.

In the matter of expansion, all technologies have their advantages and limitations, and the type of expansion has also to be considered. There are three ways of network expansion to be considered in this research; one is population growth (which means increase of population density over the same area), coverage growth (covered area experience a growth), and functionality growth (adding functionalities or services to the existent network) and each one presents different challenges.

Population growth, as the simplest of the cases, emphasizes the challenge in the transmission and connection capacity, which will be tackled separately. From the transmission capacity point of view, depending on the type of media used and the extra capacity the network was designed for, an unexpected and aggressive growth in a sector can lead to saturation of the media, communication breakdowns, big delays or information loss due to the limited transmission capacity of the media, decreasing the performance of the communication network. Prioritization of data can solve or minimize these problems to some extent.

Therefore, in the matters of transmission capacity, dedicated media usually has the advantage. Dedicated media not only has higher initial transmission capacity, which allows a higher number of devices to communicate through the same communication line, but also, provides the possibility to add parallel channels (as in setting an extra UTP cable or using another fiber core, since setting a parallel power line just for communication would not make much sense) for extra capacity that will not cause mutual interference. But it also has disadvantages, for example, networking set up is necessary to add the new devices to the network, especially when extra ports or channels available in the network that were blocked for safety reasons and are now required.

Non-dedicated media, on the other hand, provides the advantage of connection capacity. Dedicated media requires data managers (switches, routers) with ports available per each communication required device, and the number of ports for the data manager devices is limited always. If the projection of growth is clear, switches with higher capacity than the required can be installed from the beginning of the project, without having a great impact in the cost. When the data transmission capacity available in the media is enough to provide communication to the new devices, the access to the media is the only necessary step to add the new device to the network, which in case of shared media like PLC or wireless, is simple and cheap.

Coverage growth involves the extension of the range of reach that on the installed network. Likely to happen simultaneously with population growth (since the only good reason to increase the range is to reach new customers) the increase of range affects in different ways each type of communication.

For dedicated media, expansion of the media itself implies material, installation and connection costs. When an expansion takes place in a way that was not previously planned or expected, chances are that dedicated media (Optic fiber or UTP cables) will not be there, and needs to be installed. When the communication expansion takes place in parallel with power expansion, installation cost can be reduced, but the price of the media and the necessary connections will remain. On the other hand, the range capability of expansion for optic fiber is practically unlimited, and the speed of transmission of the media is so fast that the distance as a factor would have no effect on the communication.

For PLC and short range wireless media the situation is different. The farther the communicating node is attached, the longer the delay of communication will be experienced. This happens not only because the media is slightly slower for transmission of data, but also due to the repeaters in the way to add range of communication also add a delay. Combination of technologies can be used to reach distant points is a possible solution for this.

LTE and WiMAX, being both long range wireless technologies, experience one of two situations. If the size of the network is increased in a way that all new devices are within the range of coverage of the WiMAX/LTE transmission tower, then is the best scenario for expansion because the new devices just need access to the media to join the network. The other scenario, is when the network is expanded out of the boundaries of coverage of the transmission tower, in which case, the expansion becomes the most complicated and expensive of the options because either the transmission station needs to be replaced or upgraded for more range capacity (which is not always possible) or additional towers are required which implies a big investment to the expansion.

The other considered type of expansion is the functionality growth. This implies that not necessarily more customers are added or more area of coverage is required, but instead means that more services are provided by the same network. The consideration of this type of expansion can be not as clear as the previous ones, because different services imply different requirements from the network. Services such as VoIP, grid video surveillance (for power generation and storage facilities for example) or even internet access are functions that could be later considered to be added to the system. The main characteristic of this scenario is that not necessarily customers are added, but still the data transmission capacity requirement is strongly increased.

Depending on the new requirements, dedicated media is likely to have the best performance under these circumstances, especially because, as stated before, has a "default" higher transmission capacity. Also, services such as VoIP (which could be considered as a useful service in an isolated community) are very delay sensitive, which may not allow long distance links within the network to work properly if only PLC or short range wireless connections are used (where hopping of the signal would be required). Usually this type of expansion is very simple if the communication network already has the capacity to transmit the data, but can become rather complicated and expensive if the new needs require extra capacity to be installed.

These considerations should be taken into account while making decisions about the network design. The decision of what technology to implement as a communication channel must be ready to face growth, especially if one or more of the mentioned types of growth are expected. These are just the types of growth thought about during the research, other types of growth in the requirements besides the considered could exist, arise, and, in that case, proper analysis to the new situations should be carried out.

In table 2, a summary of the capacities of expansion of different technologies is presented. In the table, “ + ” plus represents easy expansion, the “ - “ minus represents difficult expansion and finally “ * ” means very difficult expansion.

Table 3: Summary of capacity of expansion

Technology/ expansion	PLC	Optic Fiber	UTP	Wi-Fi	WiMAX/ LTE
Range expansion	+	+	-	-	-
Capacity expansion	*	+	+	+	+
Functionality expansion	*	+	+	+	+

3.2.6. Data security and risk management

Data security and risk management is a very important part of any information-based system. Therefore, a smart grid should take into consideration the possible effect of data obstruction, corruption, leaking or undesired insertion. Due to the limited time of this research, the chapter's depth on the subject can be further extended with later work; instead, only physical access security will be taken into account.

Every technology and data distribution media have different vulnerabilities, strengths and also protection schemes, mostly in the way of data encryption. Because of the varied ways different technologies access the media, accessibility of the data is the first vulnerability to be addressed. Physical access to the communication network is the first vulnerability to take into account. Because of the media for data transmission, wireless technologies represent the highest risk of data corruption, obstruction, leaking or infiltration. The wireless media is in constant contact with everything exposed within the area of coverage of the wireless communication provider device. To gain access to the media, any antenna or transceiver for the specific frequency band is required, which even without any intelligent device operating it can already cause interference by adding noise in the transmission frequency causing obstruction. Access to information however can be protected by various encryption and data protection protocols already available and integrated to the data management devices, however, there is the possibility of presence of other Wi-Fi networks the media and bandwidth is shared, and less reliable.

The next more vulnerable media is the UTP transmission cable. As a very standard and longtime used communication link, not only the media and connectors are easily available to the public, but also spying devices and softwares. Because of this wired communication protocols and devices have increased the security options for networking. Encryption, verification tables of registered users, blocking of unused ports and device integrated firewalls, different manufacturers of data management devices provide with a range of options for security in their devices.

Less physically vulnerable, but under an increasing risk is the optic fiber. Tools and knowledge required to access the media are not easily available to all the general public, especially in developing countries. However as the use of optic fiber becomes more popular, access to the means of intrusion for an optic fiber based network become easier to reach. Again, manufacturers tackle this problem in different ways providing with a varied set of security options equivalent to the security of UTP wired network (Ethernet switch port controls, encryptions, etc.).

Power line communication faces a special case in our focus system. In AC low voltage distribution networks every open plug represents access to a whole area or sector of information. However for the focus system of our research, every client is supplied of electrical power through a DC-to-AC converter, and since the best communication channel for PLC is within the double neutral conductor line, the plugs of in the clients facilities have no access to the actual data transmission media. Also, tools for accessing communication over power line are still not widespread making it less accessible for the undesired parties. And even if access is achieved, PLC also counts with a range of encryption protocols for data transmission to prevent easy undesired access.

Access security (in this context) refers to the analysis of risk of unwanted physical access to the data transmission and management facilities. Accidents, vandalism, or even wild life intervention (for example falling trees, rodents biting wires, elephants crushing transmission tower supports, etc.) on the devices and their facilities represent a risk to the communication network. Under consideration of mechanical safety, the safest options are long range wireless direct connections. It is less costly to protect the perimeter and facilities of a single transmission tower in the network than it is to protect distributed network management devices. Details of installation provided in the installation chapter explain the challenge of providing the required facilities for data management devices necessary in the case of short range wireless, optical fiber, UTP and PLC. Depending on the location, reinforced facilities, perimeter protection and even surveillance may be required. Further research on data encryption and other software oriented security protocols should be conducted later on.

4. CONCLUSION

The evolution of electrical grids is leading to a more efficient and environmental friendly ways of power generation and distribution, but also to more demanding management, control, protection and communication schemes. The bilateral flow of energy and information, on which smart grids are based on by definition, require a constantly increasing communication capacity in range, bandwidth, latency, safety, etc.

Communication wise, a universal optimal solution is still unavailable. The different characteristics of different communication technologies and possibilities of application environments prevent a singular solution to excel in every situation. It is also impossible so far with the technologies available to reach a solution which is the absolute optimal from the economical, security and performance point of view.

Besides, not only every location is different, but also the priorities of every implementation location and the parties involved might be different. Along with the different communication challenges a specific location presents, priorities of the network implementing party are also different in every place. For example, developed countries will always give special importance to safety, when in other places the main priority is often something else, usually profit.

Also, adaptability of the different technologies and the availability of devices managing several technologies bring new communication options. The flexibility of combination of different communication technologies provides higher adaptability to different environments, where a single solution would not properly cover the communication needs of the whole network, and the option of exploit the advantages of more than one technology simultaneously is a tendency been developed in the communication device's market.

Emerging technologies like PLC, WiMAX and LTE constantly gain ground in the smart grid application field. Means of data transmission that a few years ago were experimental applications are today being integrated as standard communication options to the new grid IED's. In consequence, the flexibility for the coming implementations facilitates the design of a communication network to an optimal point in cost, performance, safety, and other decisive factors.

On the other hand, well established technologies still count with some advantageous characteristics plus the experience and the reliability in previous applications. Communication wise, emerging technologies are not in every case intended to replace existing technologies, but rather to provide options and balance to the different disadvantages each technology presents.

Equilibrium can be reached where all the decisive factors receive the appropriate attention and an efficient solution. With all the options available, and the continuous development of communication technologies, for every communication requiring system and depending on the environment, selected devices, etc. there will be a suitable communication solution.

5. APPENDICES

5.1. Appendix 1; Equations

Equation 1: Sector UTP communication cost

$$SUTPcc = Inst1 + ESwC + \sum_{1}^{n}[CaCo * Dn] + LRTCc$$

Equation 2: Sector PLC communication Cost

$$SPLCcc = Inst1 + ESwC + MCoCo * [n + 1] + LRTC$$

Equation 3: Sector Wi-Fi communication cost

$$SWFcc = Inst2 + WESwC + WFCo * n + LRTC$$

Equation 4: Wireless long range link cost

$$WLRLc = X * Inst3 + X * BaSt$$

Equation 5: Optical fiber long range link cost

$$OFLRLc = DL * PoF + Inst4$$

Equation 6: Total communication cost

$$TCC = XLRLc + \sum_{1}^{NS} nEPSc$$

5.2. Appendix 2; Symbols

- SUTPcc = Sector UTP communication cost
- Inst1 = Installation type 1
- ESwC = Ethernet Switch Cost
- n = number of communicating devices per sector
- CaCo = UTP Cable Cost per meter

- Dn = nth element connection distance
- LRTCc = Long Range Technology Connection cost
- SPLCcp = Sector PLC communication cost
- MCoCo = Modem (PLC) + coupling connection cost
- SWFcc = Sector Wi-Fi communication cost
- Inst2 = Tower installation for Wi-Fi access point
- WESwC = Wi-Fi Ethernet Switch Cost
- WFCo = Wi-Fi Connection transceiver.
- WLLRLc = Wireless Long Range Link cost
- Inst3 = Installation type 3 cost
- BaSt = Base Station cost
- X = Required number of towers to cover the network area
- OFLRLc = Optic Fiber Long Range Link cost
- DL = Deployment Length
- PoF = Price of Fiber
- Inst4 = Installation type 4
- TCC = Total Communication Cost
- XLRLc = “X” or any Long Range Link cost
- NS = Number of Sectors
- nEPSc = nth End Point Sector cost

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