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EVALUATION OF DEPLOYMENT AND TECHNOLOGY SCENARIOS FOR METROPOLITAN WIRELESS NETWORKS IN SMART DISTRIBUTION GRID

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Abstract

Smart grid deployment consists of one of the major priorities in different countries, in order to guarantee a safe, reliable, price affordable and environment-friendly energy. However, the realization of a smart grid is only possible if there is a two-way communications platform, which should allow data exchange between all components, systems and players of smart grid landscape. In this paper, we study the techno-economical aspects of deploying a private wireless communication network for power utilities based on WiMAX technology. The study covers cost modelling as well as propositions to optimize the deployment cost. Such optimisation is possible using WiMAX infrastructure together with other low-priced solutions, such as Power Line Communication and clustering of smart meters by Bluetooth communications. In this work, we calculate the Cost of Expenditure (CAPEX) as part of Total-Cos-of-Ownership (TCO) for different scenarios and technologies hybridisation to generate numerical results for different deployment environments (city centre, suburban, rural and low-density rural areas).

Keywords: CAPEX/OPEX, Communications networks, Cost modelling, Cost optimisation, Network deployment, PLC, Simulations scenarios, Smart grids, Smart metering, WiMAX.

1. Introduction

The energy sector plays a vital role in today's society and the national economy. In fact, energy grid is the most critical national infrastructure, on which, different vital national organizations and sectors are depending, such as telecom networks, hospitals, industrial companies, security bodies, etc. Therefore, different national governments took the objective to make the energy grid smarter, in order to react very quickly to any incident that could affect negatively the operation of the grid, and indirectly the national security. A smart grid should help to guarantee safe, reliable, expectable, economic affordable and environmentally friendly energy. The value-chain of energy involves different entities and players (i.e., energy generation, transmission, distribution, (pro)-consumers, solar/wind parks, etc.) that are organizationally and geographically distributed. A smart grid involves all these entities and organizations by exchanging energy and information inside and between different domains, as illustrated in Fig. 1. The building of the future smart grid brings several challenges for the utilities. One of these challenges is the deployment of a reliable and secure two-way communications infrastructure, or the purchase of communication services. To make the right decision, utilities have to find an optimal trade-off between different aspects, such as an acceptable quality of service, optimal communications cost and the level of control on the communication network. Therefore, utilities started different pilot projects, in order to evaluate the technical performance in the field and to validate their business model(s) for different communications technologies.

Different works have discussed the communications requirements of the different smart grid applications in general and presented the alternative technologies for Home Area Network (HAN), Neighbourhood Area Networks (NAN) and Field Area Networks (FAN) or Metropolitan (called also Distribution) Network Area (MAN), such [2-4] among others. The applications of smart distribution gird belong to Machine-to-Machine (M2M) communications, which changed the traffic pattern for mobile networks, because they generate more traffic in uplink than in downlink, in contrast to traditional Internet/data usage that requires more (or very large) bandwidth in the downlink. Furthermore, most M2M applications generate a small data packet in parodic time, as it is explained later in the paper, e.g., for smart meters, which send packets of 2kBytes per 15 minutes.

However, very few works have focused on the techno-economical aspects of the deployment of SG communications networks, which is a major challenge facing the power utilities. As an example of these works, Charni and Maier [5] discussed the cost of deployment of fibre in form of Next Generation Optical Network (NGOA) and Ethernet Passive Optical Network (EPON) for the smart grid. The works presented by Chaini and Maier [5], Haidine et al. [6] and Robichon [7] in which, they discussed the deployment of CDMA450 network for power Distribution System Operators (DSO) and utilisation examples from Europe. Therefore, this paper focuses on two points. On one hand, we evaluate different strategies for the deployment of networks for smart grid communication in energy distribution part. On the other hand, we analyse the techno-economical aspects of different technologies in different deployment environments, which are city centre, suburban, rural and low-density rural areas. In addition, different mixes of technologies are considered, in order to optimize the total deployment costs.

The rest of the paper is organised as follows: in the second section, we give a short overview of the communications layer for smart distribution grid, together with the technical requirements of its different applications. In the third section, we give the technical aspects and specification for the communications technologies considered in this paper, i.e., WiMAX, power line communications and Bluetooth. In the fourth part, we analyse the techno-economical aspect of the deployment of private networks based on WiMAX technology. Generally, the network cost can be based on Net Present Value (NPV), or Total-Cost-of-Ownership (TCO), cost depreciation, etc. In this paper, we focus only on the Capital Expenditure (CAPEX) for the hardware/software system implemented in the radio access part (no backhauling and or Operation and management costs are included).

This is done because we discuss options to optimise this part of costs, based on building the "smart meters clustering" by means of Power Line Communications (PLC) and/or Bluetooth, which is available in its classical form or a more advanced variant called long-range low-power Bluetooth. In addition, the effects of using Data Concentrators (DC) in the transformer station, as usual in PLC networks, is taken into consideration for further cost optimisation. Costs calculation for network deployment in four deployment environments (city centre, suburban, rural and low-density rural areas) are given in the last section with the discussion of numerical results.

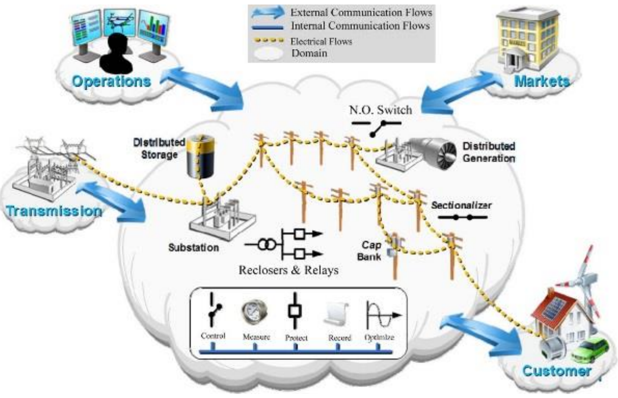

Fig. 1. Smart distribution grid as core part of the smart grid landscape [6].

2. Smart Grid Reference Model and ICT Role

2.1. Smart grid layered model

In the grid of the future, Information and Communications Technologies (ICT) build the foundation to support different smart grid-related applications, each with different quality of service requirements. This allows interconnecting and enabling the two-way flow of real-time information within the power utility, as well as between the electricity company and its suppliers, partners and consumers. The ICT cover three categories of technologies: sensing and control devices, applications, and communication networks that bridge them all together.

Therefore, a layered model can represent the smart grid, where the communication layer plays a central role as represented in Fig. 2. The decision about the type of communication technology to be deployed depends on different factors, such as deployment location/environment, traffic amount/type, realizable QoS, investment volumes, etc. Therefore, several technologies are nowadays under test or in deployment in the smart distribution grid depending on these factors.

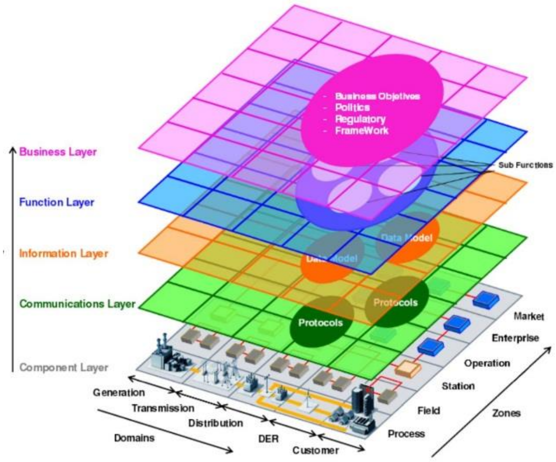

Fig. 2. Layered model for smart grid architecture [8].

2.2. Different technologies to build communication layer

The main challenge in building the two-communication network is to deploy an infrastructure with acceptable investments, and which is performing well (capacity and low latency), easy to install/operate/maintain, reliable, etc. In the last years, utilities have tested and evaluated different communication solutions to make the right decision about technology selection. In the practice, different solutions are used (either in small scale for pilot projects or in large scale for full roll-out), whose a summary and possible mix are represented in Fig. 3. Depending on the coverage area, the network can be categorized either as Local Area Network (also called HAN: Home Area Network), Neighbourhood Area Network (NAN), access network, metropolitan and backbone area network. Digital Subscriber Line (DSL) is not shown because this access solution brings other challenges, on one hand, the DSL router is owned generally by the telephony network operator, and some legal issues can face the utilities to use it for their services. On the other hand, the DSL can fail at any time, the utility has no control on it, in order to start a procedure to repair it, and this brings more uncertainties and risks for smart grid services.

Wireless technologies are an attractive solution for the utilities to build their communications infrastructure in parallel to the grid, because of the ease of deployment, time-saving, easy to repair in case of disasters, avoiding massive civil engineering work, etc. However, the widely deployed wireless networks are public networks, on which millions of users have access at the same time. This affects the quality of service and the level of security and reliability, which are strongly required by a critical infrastructure like the power grid. The easiest solution would be the GSM/GPRS service, which is offered by the Mobile Network Operator (MNO); however, this service is characterised by low reliability (in some sub-urban regions can be under 70%) and no Service Level Agreement (SLA) is guaranteed by the mobile service provider. Furthermore, some network operator started switching off their GSM/GPRS infrastructure, which Operational Expenditures (OPEX) costs are very high and their spectrum efficiency is very poor, to replace it by 4G/LTE. Therefore, several operators have already switched their GSM/GPRS infrastructure, since the GSM/GPRS are disappearing from the mobile market [9].

For the selection of adequate technology solution(s) for smart grid applications, different factors must be taken into consideration. The main factors can be classified into three categories: i) Technology performance: this include different evaluation criteria like the peak and/or average throughput, delay, security aspects, etc., ii) Deployment environment: this constitutes a challenge for the technology, in order to check if the solution performance can deal with the different challenges in the deployment environment. Applications and their distribution/density are the major challenges. Also, national regulatory can be a facilitator or blocking factor, because it regulates the use of infrastructure, standards and spectrum; and finally iii) Business aspect: It includes the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) and any actions to optimize them.

One of the most relevant wireless solutions for the metropolitan smart grid communication is the WiMAX. WiMAX (i.e., IEEE802.16) was involved a strong competition with 3GPP Long Term Evolution (LTE) to build the Next Generation Mobile Network (NGMN), which should offer very high bit rates and low latency for usual applications, IP telephony (Voice over Internet Protocol -VoIP), video/TV/Audio streaming, etc. Both systems were based on new approaches, such as Orthogonal Frequency Division Multiplexing (OFDM), Adaptive Coding and Modulation, Multi-Input Multi-Output (MIMO), etc. The race was finally gained by 3GPP LTE, which started a speedy and successful rollout worldwide. After this setback, stakeholders were looking for new application fields for the already developed WiMAX technology and systems, where smart grid/power utilities, as well as oil and gas services, were the main targets [10-12]. Therefore, Paolini [10], Crozier and Tedrow [11], WiMAX Forum [12], Huh et al. [13], Aquirre and Magnago [14], Aalamifar and Lampe [15], Al-Omar et al [16] and Hyder et al. [17] presented the works in different scientific research works, which focused on the performance evaluation of the WiMAX networks as platform for smart grid applications.

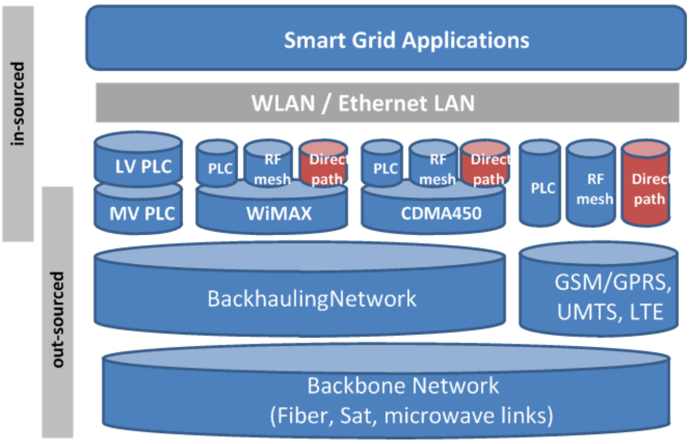

Fig. 3. Widely used technologies and mix of solutions for Smart Grid.

2.3. Technical Requirements of SG Applications

However, before designing the communications network, it is important to analyse the applications that will use this infrastructure. The applications should give a quantification of the required quality level of service (QoS) in terms of required capacity, type of traffic to be generated, maximal delay, etc. For example, in the case of MV/LV distribution automation, there are twelve key applications going from fault detection to smart metering, among others.

The estimated required QoS, represented by data rate, traffic type, maximum latency, Bit Error Rate (BER) and Mean-Time-To-Repair (MTTR) is described in details by [18, 19]. Table 1 shows the main requirements and traffic characteristics from applications in the smart distribution grid. It is worth to indicate that these requirements have been considered in developing PLC systems. The data throughput of 5.3 Kbps was calculated for the average of 300 meters connected to PLC data concentrator. The meters are read in 15 minutes time interval, where each read generate 2kByte of data.

Table 1. Main requirements of applications in smart distribution grid [19].

Applications	Bandwidth (Kbps)	Traffic type	Max. latency (s)	BER
AMR	5.3*	Periodic	0.5	NA
SCADA	1.8-9.6	Random	0.5	10^{-6}-10^{-14}
Operational telephony	8	Random	1	0.001
Video surveillance	15-128	Random	1	0.0001
Load management and DSM	NA	Periodic	1	NA
SW download/ upgrade firmware	32	Random	NA	NA
Street lighting, traffic control, and maintenance	0.025	Random	300	NA

3. Smart Grid Reference Model and ICT Role

3.1. Smart grid layered model

For the techno-economical investigations, we focus on WiMAX. Its last version allowed data rates up to 100 Mbit/s for mobiles and 1 Gbps for fixed use, known as Mobile WiMAX Release 2 or WirelessMAN-Advanced and aiming to fulfil the ITU-R IMT-Advanced requirements on 4G systems. However, the 3GPP standards are known as Long Term Evolution (LTE) and its development to LTE-Advanced (LTE-A) won the race of 4G and major roll-out started around the globe; while WiMAX roll-outs have been interrupted. After that, WiMAX Forum started activities to find new domains for WiMAX applicability in the industry, automation and other professional sectors. Furthermore, different activities have been started to encourage the use of new frequency bands that various Utilities hold, namely 1.4 GHz, 1.8 GHz, 2.3 GHz, 3.65 GHz and 5.8 GHz. According to Motorola [20], a different component of WiMAX architecture is illustrated in Fig. 4.

For the deployment of a communication network, we must be sure that the system capacity of selected technology architecture can cover the generated traffic from all different applications and services offered. The calculation of the WiMAX capacity is complex because it depends on several factors, where some of them are stochastic. As examples for these parameters, we can cite: the channel model, path-loss model, size of the allocated signal bandwidth (5 MHz, 10 MHz or 20 MHz), the used frequency to carry the WiMAX signal in the spectrum (laying in the range from 2.3 GHz to 3.8 GHz), used QoS classes, the used combinations of Adaptive Code and Modulation (ACM) schemes, the number of subcarriers in the OFDM system, size of cyclic prefix, type of Robust Overhead Compression (ROHC), etc.

Tareco [21] found a detailed analysis of the WiMAX system capacity, in which, So-In et al. [22], Omprakash and Sabitha [23], Ozdemir and Retnasothie [24], Belghith and Nuaymi [25], Ahmadzadeh [26] and Aguiar [27] make a synthesis and improvement of works done. Furthermore, this work made also a comparison between the calculated theoretical capacity and the measured values from the live network in the city Lisbon (Portugal). In this paper, we will only take one of the scenarios of this analysis and use directly in our estimations. Therefore, with the scenario extracted by Tareco [21], we consider it as a system with the main technical parameters and characteristics as shown in Table 2.

Table 2. Main technical parameters for WiMAX system; scenario from [21].

Parameters	Scenario value
Signal bandwidth	10 MHz
Spectrum range [GHz]	[2.496, 2.690] (Band class 3:USA/Europe, IMT2000)
Number of subcarriers	1024
Subcarrier spacing [kHz]	10.93
Adaptive code and modulation scheme	Modulation QAM-16 and coding rate ½
Resulting throughput (theoretical)	12.67 Mbps Downlink/9.4 Mbps uplink

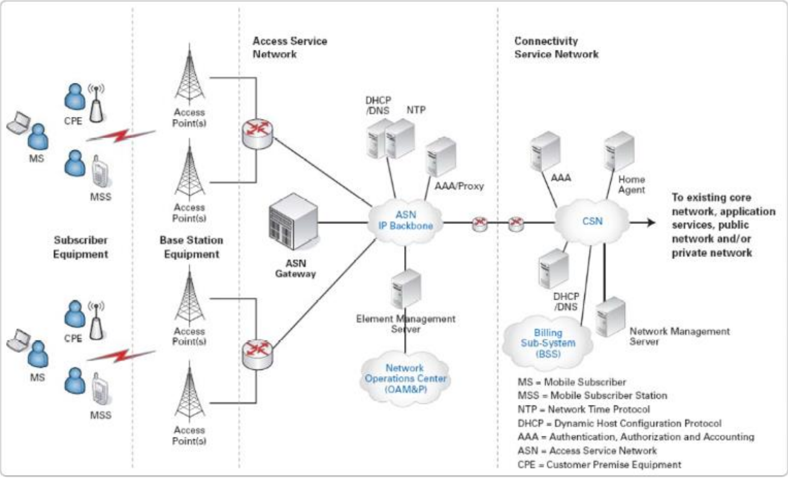

Fig. 4. Reference model for WiMAX architecture [20].

3.2. Power line communication for smart grid

Power Line Communications (PLC) is a communications technology that was used already with the first electricity distribution installations. Existing infrastructure (electricity cables) and simple installation make it very attractive as for home so for industry users. In the last two decades, *t* was intensively researched and improved for smart grid usage. Mudriievskyi [28] found a detailed description and classification of all PLC variants. This work divides PLC technologies and systems in narrowband with the usage of frequency bands from 9 to 500 kHz and broadband with frequencies from 2 up to 80 MHz Standardization in both narrow and broadband PLC was behind the development causing a high number of different systems. In the narrowband, there are two public solutions called Power Line Intelligent Meter Evolution (PRIME) and PLC-G3 that were afterwards included and supported in the ITU G.Hnem and IEEE P1901.2 standards. The main technical aspects of these two technologies are given in Table 3 [29].

Table 3. Technical characteristic of PLC system for smart metering [29].

	PLC G3	PRIME
Frequency range	35-91 kHz	42-89 kHz
No. of carriers used	36	97
Subcarrier spacing Δf	1.5625 kHz	488 Hz
Max. data rate	33.4 Kbps	128.6 Kbps
Interleaving	per data packet	per OFDM symbol
Modulation	BPSK, QPSK	BPSK, QPSK, 8PSK

3.3. Bluetooth for meters clustering

In this paper, we propose also to use the “Smart Meters clustering” or “Cluster communication” to optimise the deployment cost for smart grid communications layer. In fact, when we observe the electricity meters distribution, especially for high buildings, we see that they are distributed as clusters. Figure 5 shows the electricity meters of a building with four stocks contain twenty flats. Therefore, instead of connecting each meter through a WiMAX modem or PLC modem, we propose to select one SM to play the role of Cluster Head. This meter collects the data from its neighbouring meters over a short range, low-cost and low-energy connection, such as Bluetooth or ZigBee. Afterwards, the collected data can be transmitted to the utility over either WiMAX modem or a PLC connection towards the PLC-DC.

In the meters cluster, one metre will be selected as the central node (i.e., Head Smart Meter-H-SM). This central node with collect the data from all the meters in the cluster. The collected data will be then over another communication links, which must be long-range and must reach the WiMAX base station. For reliability issues, two cluster heads can be selected, one as primary head and the other as a backup head. For the cluster communication three solutions can be taken into consideration; namely Bluetooth, Wi-Fi and ZigBee [30]. The main technical characteristics of these short-range communications solution are summarised in Table 4. Furthermore, Bluetooth has issued a recent version that is optimised for communications for the M2M and IoT applications.

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characteristics of these short-range communications solution are summarized in Table 4. Furthermore, Bluetooth has issued a recent version that is optimized for communications for the M2M and IoT applications.

The SM cluster head can have WiMAX modem to communicate directly with the BS, or can forwards the data over power lines to the PLC-DC at the transformer station, which in its turn forward the data to the WiMAX BS.

We propose the use of Bluetooth as it presents a good compromise between achieved bit rates, coverage and power consumption. A slightly high bit rate is necessary for smart metering for remote Software/Firmware updates/upgrades. However, because the cluster communication is a local communication, the power utilities can change this decision at any time during the deployment and start with using ZigBee without affecting the correct functioning of the already installed Bluetooth SM clusters.

Table 4. Characteristics of solutions for cluster communication [30].

	Bluetooth	**WiFi**	**ZigBee**
Specification	802.15.1	802.11 g/n	802.15.4
Frequency	2.4 GHz	2.4/5 GHz	868 MHz (EU) 915 (US) 2.4 GHz
Range Indoor (m)	30	25/50	45
Data speed max	3 Mbps	54/540 Mbps	100 Kbps
Data speed type	2 Mbps	25/200Mbps	40 Kbps
Network Topology	Star	Star	Star, tree, mesh

Fig. 5. Typical cluster of electricity meters in a 4-levels (21 meters).

4. Cost Structure and Optimization by Technology Hybridisation

4.1. Cost components

The important factor to consider as part of the technology/strategy business model is the Total Cost of Ownership (TCO), which typically involves Capital Expenditures (CAPEX) and Operating Expenditures (OPEX) of the operator. CAPEX usually constitutes a larger percentage but OPEX will outweigh CAPEX over time because it is accumulated over the entire network life cycle. Table 5 gives a brief breakdown of categories within the cost of ownership, these categories comprise of CAPEX and OPEX costs. A reference architecture of cost modelling for wireless communications in smart metring infrastructure.

Some deployment costs have been estimated for “native” telecom Mobile Network Operators (MNO) [31]. However, in case of the network for utilities, there are some facts to be taken into considerations:

- The CPE modem inside the end-devices (smart meters, CCTV, etc.) are in ownership of network owners also (utilities) and it is responsible for any repairs and substitution in case of HW/SW failures. HW failures could require HW substitution, while SW failure could require SW upgrades. By considering the smart metering, these modems is in millions, for example in France there more about 38 millions of metering points in households, shops, offices, high buildings that must be managed by the major French electricity distribution utility ERDF (Électricité Réseau Distribution France).
- All these millions of deployed modems in smart meters must be included in the Operation and Management Centre (OMC) systems.
- In addition, the network owner must pay the energy consumed by the communications module at the end-device.
- Communications modules at the end-device must be operated managed and controlled by the network owner and must be integrated into the existing OMC.
- Cost estimation available in the literature has been established some years ago - by end of the last decade when WiMAX was considered as a candidate technology for the 4th generation of mobile communication network (4G) for the MNOs. However, the 3GPP Long Term Evolution (LTE) was selected for 4G deployment, and indeed this technology has met a full success around the world in industrial as well as in developing countries. Therefore, the numbers must be actualized and updated for the new business models for utilities.
- For native MNO the deployment would be based on reuse of an existing strong and well-developed ecosystem, built through decades over the infrastructure of GSM/GPRS (or 2G), UMST/HSPA (3G/3G+) or even on LTE/LTE-A (4G). This would result in a significant cost reduction by reusing the existing sites, pylons, data centres, Untreatable Power Supply (UPS), databases, (mobile) workforce, fibre-based recently upgraded backhauls, etc.

Table 5. Cost categories for the deployment of WiMAX in case of SG.

Infrastructure	Site/PoP	Core	Backhaul	IT	Ops
WiMAX BS HW/SW	Acquisition	Edge and core IP network elements	Wireless backhaul equipment	OSS/BSS develop	Maintenance
WiMAX service edge network	Rental utilities	Content management and delivery	Wireline backhaul installing and leasing	Integrating in OMC	Support and warranty
Modem for CPE (smart metres, CCTV)	Development (civil engineering, cabs installation, etc.)	Media gateways		Data centre	Subscriber acquisition and marketing
Spectra licence	Power supply, cooling, PHY protections				BI and big data analysis

4.2. Cost optimization

The important task of the network planning and optimization is the design and deployment of HW/SW in an optimal way so that the total cost and investment are as low as possible, however, there is some threshold of quality of service that must be guaranteed for the SG applications.

Some significant factors for the cost optimisation are:

- Infrastructure sharing (data centres, antenna pylons, base stations sites, etc.)
- More efficient frequency spectrum usage
- Lower OPEX, such as using Green IT and communications technologies, which should optimize the energy consumption and efficiency
- Reuse of previous investments for licenses and technical equipment, or any other legacy system or existing eco-system
- Optimized network architecture by using technology hybridisation through the addition of cost-optimal technologies. One of the well-known hybridisation is the use of Power Line Communications (PLC) to collect smart meter data from smart meters at a PLC Data Concentrator (PLC-DC) in the low-voltage transformer station. The data collected by the PLC-DC are then transferred to the utility throughs GSM/GPRS connection/service, as it is adopted by the leading smart metering project using PLC; namely by electricity utilities ERDF in France as well as ENEL in Italy. This configuration guaranteed low design costs; however, MNOs around the work are currently switching their GSM/GPRS infrastructure off, because of the poor spectral efficiency (in bits/Hz/sec), high cost per transmitted Kbits, high-energy consumption of the old mobile technologies, etc. This tendency is also underlined in the latest Ericsson Mobility Report [9].

4.3. Cost modelling

In this work, we analyse the effect of the hybridizing different technologies in the access part by including PLC and/or Bluetooth clustering. Because of that, we focus only on the cost of the access part from WiMAX bases station to the end-device is investigated and modelled, while the backhaul part is postponed to future work. The different part of WiMAX architecture and costs are illustrated in Fig. 6. The backhaul part ensures the connection of BSs to the Internet and other parts required for the operation of WiMAX, such as Access Service Network-Gateway (ASN-GW), Connectivity Service Network either Home or Visited (CSN-H/-V), etc. This CSN englobes different components like Authentication Authorization and Accounting (AAA) Server, Policy Control Server, Mobile IP Home Agent (HA), Dynamic Host Configuration Protocol (DHCP) Server, and other servers and interworking gateways.

In general, different economic aspects can be taken into consideration for the modelling of the communication networks, like the cash flow, net present values, return on investment, the total cost of ownership, etc. However, most of these models have been developed over the last decades for the case of “native” mobile network operators. For the case of utilities, they build the network for their own use; therefore, we model in this work only the Total cost of ownership, especially the CAPEX, while the OPEX is considered in this stage as future work.

We define in Table 6 different variables and symbols used to develop the mathematical model of the total cost of investment for the deployment of the last mile (or access network) solution of the smart grid communication.

We define five possible scenarios, which the related total CAPEX cost models can be formulated as follows:

- **All-WiMAX**: In this architecture, we use only the WiMAX technology from end-device to the BS. So that each end-device should have a WiMAX modem. This will be taken as a reference scenario for the cost optimisation through technology hybridization. In this case, the total CAPEX investments can be represented as in Eq. (1).

$$\mathrm{T}_1 = n_{BTS}^{Wi} \cdot C_{BTS}^{Wi} + n_{BTS}^{Wi} \cdot C_{BH}^{Wi} + N_T^{sm} \cdot C_{\mathrm{mod}}^{Wi} \qquad (1)$$

- **WiMAX hybridized with PLC using PLC data concentrator** (PLC-DC) in the Medium-Voltage/Low-Voltage Transformer Station (MV/LV TS). Data are collected from the end-devices by the PLC-DC over the LV powerlines. The collected data are then sent to the utilities over the WiMAX connection. Thus, the PLC-DC should have also a WiMAX modem. The CAPEX of this configuration is given by Eq. (2).

$$\mathrm{T}_2 = n_{BTS}^{Wi} \cdot C_{BTS}^{Wi} + N_T^{sm} \cdot C_{\mathrm{mod}}^{plc} + n_{DC}^{plc} \cdot C_{DC}^{plc} + n_{DC}^{plc} \cdot C_{\mathrm{mod}}^{Wi} \qquad (2)$$

- **WiMAX hybridized with Bluetooth clusters**: In the real case presented in Fig. 6, we propose here not to put one WiMAX modem in each smart meters, rather we use a Bluetooth communication between these 21 meters. One meter will be selected as Head Smart Meter (H-SM), which collect the measurement values from all other SMs over a Bluetooth link. The collected data will be transferred over WiMAX connection to the utilities. Thus, we will need 21 communications links or module of Bluetooth and only one WiMAX modem. The CAPEX generated by this scenario is modelled by Eq. (3).

$$\mathrm{T}_3 = n_{BTS}^{Wi} \cdot C_{BTS}^{Wi} + N_{Singl}^{sm} \cdot C_{\mathrm{mod}}^{Wi} + \Omega_{Cltsr} \cdot C_{\mathrm{mod}}^{Wi} + N_{in-Clustr}^{sm} \cdot C_{Blth} \qquad (3)$$

- **WiMAX hybridized with PLC clusters without data concentrators**: This is similar to the previous scenario (the third case), we use PLC connections between the smart meters of the same cluster and not a Bluetooth link. The idea here is to use PLC, but at the same time to try to save the costs of PLC data concentrators. The required investments are represented by Eq. (4).

$$\mathrm{T}_4 = n_{BTS}^{Wi} \cdot C_{BTS}^{Wi} + N_{Singl}^{sm} \cdot C_{\mathrm{mod}}^{Wi} + \Omega_{Cltsr} \cdot C_{\mathrm{mod}}^{Wi} + N_{in-Clustr}^{sm} \cdot C_{\mathrm{mod}}^{PLC} \qquad (4)$$

- **WiMAX hybridized with Bluetooth clusters connected by PLC and PLC-DC** at MV/LV transformer stations. In this scenario, we have a full hybridization where we include all possible technologies (WiMAX, Bluetooth cluster communication and PLC using data concentrators). The cost of involving all these technologies are included in Eq. (5).

$$\begin{aligned}\mathrm{T}_5 = {} & n_{BTS}^{Wi} \cdot C_{BTS}^{Wi} + N_{Singl}^{sm} \cdot C_{\mathrm{mod}}^{plc} + \Omega_{Cltsr} \cdot C_{\mathrm{mod}}^{plc} + \\ & N_{in-Clustr}^{sm} \cdot C_{Blth} + n_{DC}^{plc} \cdot C_{DC}^{plc} + n_{DC}^{plc} \cdot C_{\mathrm{mod}}^{Wi}\end{aligned} \qquad (5)$$

Table 6. Variables for cost modelling.

Variables	Definition
n_{BTS}^{Wi}	Number of WiMAX btss
n_{mod}^{Wi}	Number of WiMAX modems
n_{mod}^{PLC}	Number of PLC modems
n_{DC}^{PLC}	Number of PLC data concentrators
n_{blth}	Number of Bluetooth modems
Ω_{Clstr}	Set of clusters in the environment
N_{T}^{sm}	Total number of smart meters
N_{SH}^{sm}	Smart metres of single homes (no clustering is possible)
N_{Biz}^{sm}	Smart metres of shops and single offices (no clustering is possible)
$N_{Singl}^{sm} = N_{SH}^{sm} + N_{Biz}^{sm}$	SM not involved in any cluster
$N_{in-Clustr}^{sm} = N_{T}^{sm} - N_{Singl}^{sm}$	SMs involved in a cluster
C_{BTS}^{Wi}	Cost of WiMAX BTS
C_{mod}^{Wi}	Cost of WiMAX modem in CPE
C_{BH}^{Wi}	Cost of Backhauling of WiMAX BTS
C_{mod}^{plc}	Cost of PLC Modem in CPE
C_{DC}^{plc}	Cost of PLC data concentrator
C_{blth}	Cost of Bluetooth modem in CPE

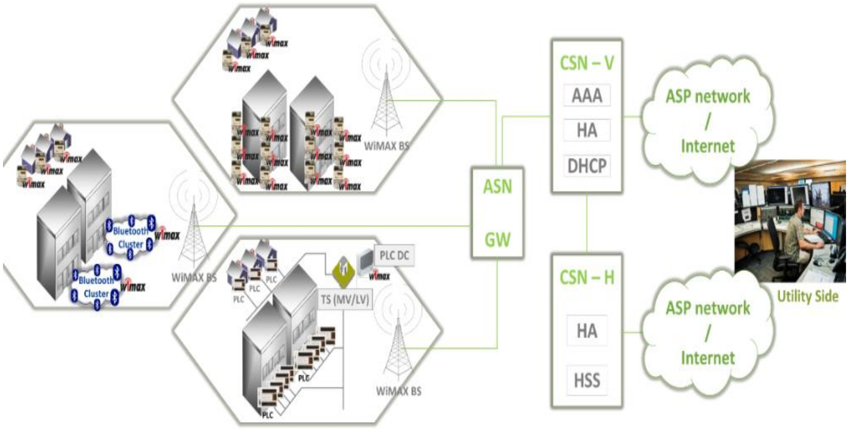

Fig. 6. Network and cost architecture for different deployment scenarios based on three technologies.

5. Simulation and Results

Simulation scenarios

For the simulation, we calculate the total CAPEX needed to deploy each of the above-discussed five technology scenarios for the last mile connection of smart grid communications. We consider the deployment of communication solutions for smart meters in a medium city with 100.000 habitats. The city is divided into four deployment areas: city centre, suburban, rural and low-density rural areas. The characteristics of each of these deployment areas are summarised in Table 7.

Smart meters of the shops have been considered separately to the residential HH because they have no possibility to be involved in a cluster. In rural areas, the shops are considered as normal households, just as a simplification.

In this work, we analyse also the role of cluster communication in the CAPEX structure, where the size of the Sm cluster plays an important role. Therefore, we define two types of high buildings: a) Buildings type-B that are 12-storey buildings with 4 apartments per level, which results in a cluster of 48 electricity meters; and b) Buildings type-C that are 6-storey building having a cluster of 24 meters in each building. In future work, we will consider very large cities with very high building and having large Sm cluster sizes, which will be referred to as Building type-A. A summary of building types in each deployment areas is given in Table 8.

Concerning the performance evaluation of the deployed WiMAX systems, we consider that the WiMAX is serving only smart metering end-points, in this first phase of our research work. Therefore, we have a kind of machine-to-machine (M2M) communications, where the uplink part of communications is more loaded than the downlink direction (in contrast to usual Internet/Data utilisation where the downlink is more loaded than the uplink).

Let us consider one BTS with the tri-sectorial site and having the maximal throughput of 9.4 Mbps as indicated in Table 2 willing to serve all the smart meters of the densest scenarios (city centre with 10500 smart meters. These meters must be read each 15 minutes (90 seconds), where each metres generates 2 kBytes (16.103 bytes). The total generated traffic in 15 minutes can be easily supported by the capacity of 9.4 Mbits per seconds offered by the BTS. However, one critical aspect has to be analysed in future work, which is the delay caused by waiting for the right to transmit. This depends on the scheduling mechanism/algorithms of medium access control (MAC) layer.

Table 7. Characteristics of different deployment areas used in simulation.

	City centre	Sub-urban	Rural	LD rural
Habitants	50000	40000	8000	2000
Pers/HH	5	5	4	4
Number of HH	10000	8000	2000	500
Shops/offices (%)	0.05	0.02	0	0
Biz. SM	500	160	0	0
Total SM	10500	8160	2000	500
HH/LV TS	200	100	20	10
Total LV TS	50	80	100	50
PLC DC	50	80	100	50

Table 8. Type of buildings per area to build cluster communication.

	City Centre	Sub-Urban	Rural	LD rural
Nbre cluster-B	125	42	0	0
Nbre cluster-C	167	84	0	0
Total clusters	292	126	0	0
Single home	0	4000	2000	500
Single shops	500	160	0	0
Single SM	500	4160	2000	500
SM in clusters	10000	4000	0	0

6. Results and Discussions

The total CAPEX investment needed for each of the five technology scenarios at each deployment area is represented in Fig. 7. To simplify the cost discussions, we calculate the costs in Cost Unit (cu). As stated previously, we take the cost of all-WiMAX scenario as a reference and to check if the hybridization with technologies will any cost lowering. The all-WiMAX is the most expensive configuration. The hybridization through another technology will results in the cost optimization; either by using PLC-DC and/or only Bluetooth. Two main reasons are responsible for this clear optimization: on one side, the high buildings dominate the city centre, where we have mainly cluster of smart meters. The use of Bluetooth communication/modems instead of WiMAX modems decreases considerably the CAPEX cost. Furthermore, the use of Bluetooth, which is short range and low-cost communication, achieves the lowest investment. On the other hand, the use of PLC with Data concentrators also guarantees lower costs than all-WiMAX scenario. This is because in city centres we have a very dense energy consumer distribution, which is characterised by an average of 300 households per MV/LV transformer station in Europe. In the rural and low-dense rural region, we have a very light consumer concentration per transformer.

When we go from city centres to sub-urban, we will have a lower number and size of clusters, but always existing, as well as lower consumers/households per transformer station. This will affect slightly the resulting CAPEX, as it can be seen in Fig. 8. The highest cost is always generated by the all-WiMAX scenario; however, the difference in the cost of the different technology scenarios are not as large as it is the case in city centres. The utilization of Bluetooth in cluster communication is not more the optimal solution, this is caused by the lower number and reduced size of the metre clusters encountered in the suburban regions. So, the optimal solution (lowest costs) is then guaranteed here through the utilization of PLC with data concentrator together with the Bluetooth clusters.

In the rural deployment areas, only two technology scenarios are possible, either all-WiMAX or PLC with data connectors to reach the user end-device. In the opposite of the urban area, there no high buildings in these areas and therefore no cluster communications is possible. The generated costs of rural areas and low-density rural are represented in Figs. 9 and 10 respectively. We keep in the diagrams also Cluster-Bluetooth, just to simplify the comparison with the previous diagrams. However, the scenario all-WiMAX is the same as WiMAX with Bluetooth or PLC (without PLC-DC) clusters, since no cluster are encountered in these areas. For the same reason, the scenario of PLC-DC is the as scenarios with PLC-DC plus Bluetooth clusters.

In rural areas, we can see the advantage of using WiMAX (or wireless only) communication, because of the low-density and large distribution of end-devices (i.e., electricity meters). The low number of households per MV/LV transformer station causes the non-optimality of PLC with data concentrator. The optimality of all-WiMAX (or WiMAX only) scenarios becomes clear and important when we go to low-density rural regions.

The different simulation results show that the optimal technology for smart grid communications depends on the deployment areas. As such, wireless communications (cellular and long-range) is optimal for the low density and rural areas, where a large coverage is needed. In the areas with high density, like city centres, which are characterised by the existence of electricity meter clusters in different number and different sizes, the use of cluster communications through short-range and low-cost wireless is better. However, the optimal is reached when we add the PLC with data concentrators.

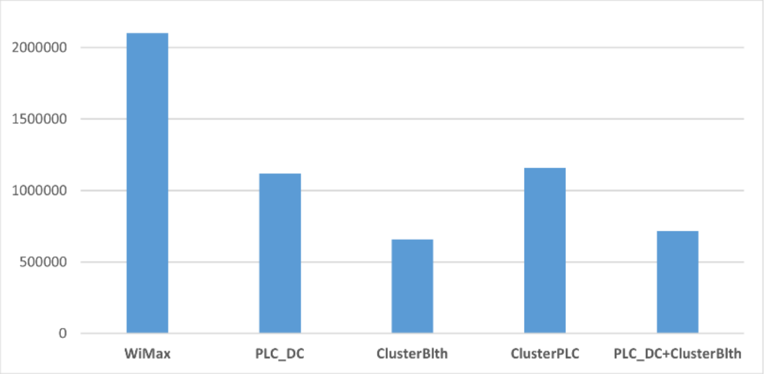

Fig. 7. CAPEX for five technology scenarios in city centre environment.

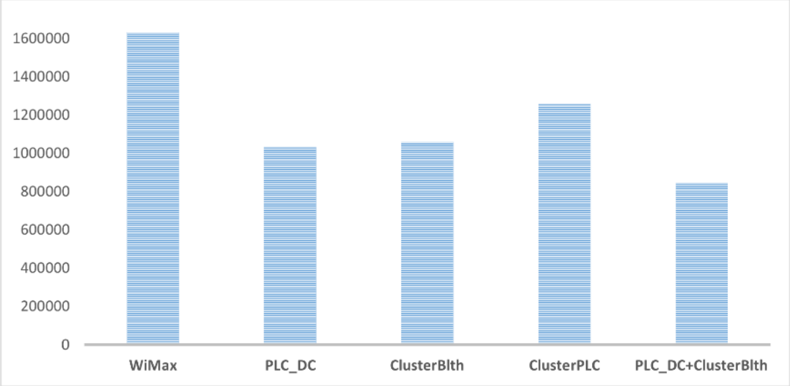

Fig. 8. Network costs for sub-urban area.

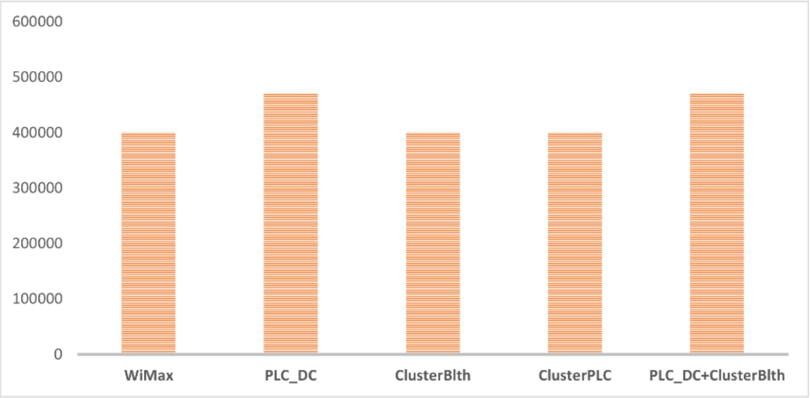

Fig. 9. CAPEX for five technology scenarios in rural area.

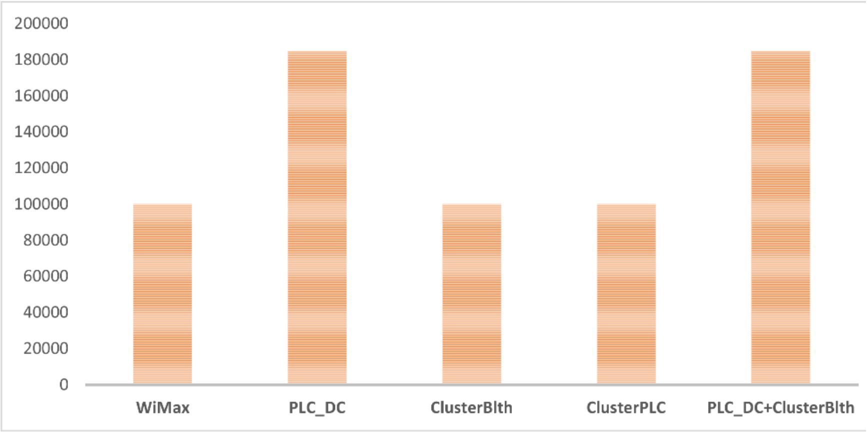

Fig. 10. Network costs for low-density rural areas.

7.0. Conclusions

In this paper, we discuss the techno-economical aspects of the deployment of WiMAX networks to support applications of smart distribution grid, which are dominated by smart metering with a large number of metering end-points. These types of applications, referred to as machine-to-machine, do not require any large bandwidth in the downlink as it is the case for normal Internet/data usage. In facts, they generate more traffic in uplink than in downlink, but they are known by generating very small packets in much spaced time intervals (e.g., 15 minutes in case of European electricity utilities. In this paper, we focus on the CAPEX part of the TCO for the Radio Access Network (RAN) part.

Besides the CAPEX modelling for WiMAX RAN, different aspects for the optimization of the investment costs through technologies hybridisation/mixing are discussed. These have been analysed by simulating the deployment in different areas, city centre, suburban, rural and low-density urban areas. In the low-dense areas, the WiMAX alone can build (relative) optimal solutions. However, in the dense areas like city centres, the hybridization through cluster communication using short-range and low-cost Bluetooth modems. The optimality of Bluetooth cluster together with WiMAX disappears in the suburban regions so that adding the PLC with data concentrator to the Bluetooth clusters decreases significantly the total CAPEX investments.

Nomenclatures

C_{BTS}^{Wi}	Cost of WiMAX BTS
C_{mod}^{Wi}	Cost of WiMAX modem in CPE
C_{BH}^{Wi}	Cost of backhauling of WiMAX BTS
C_{mod}^{plc}	Cost of PLC modem in CPE
C_{DC}^{plc}	Cost of PLC data concentrator
C_{blth}	Cost of Bluetooth modem in CPE
n_{BTS}^{Wi}	Number of WiMAX Btss
n_{mod}^{Wi}	Number of WiMAX modems
n_{mod}^{PLC}	Number of PLC modems
n_{DC}^{PLC}	Number of PLC data concentrators
n_{blth}	Number of Bluetooth modems
N_{T}^{sm}	Total number of smart meters
N_{SH}^{sm}	Smart metres of single homes (no clustering is possible)
N_{Biz}^{sm}	Smart metres of shops and single offices (no clustering is possible)
N_{T}^{sm}	Total number of smart meters

Greek Symbols

Ω_{Clstr}	Set of clusters in the environment

Abbreviations

3GPP	3rd Generation Partnership Project Standardisation
4G	Fourth Generation Broadband Mobile Networks
AMR/AMI	Automated Meter Reading/Infrastructure
BS	Base Station
CAPEX	Capital Expenditure
CDMA450	Code Division Multiplexing Access at 450 MHz
DSL	Digital Subscriber Line
FAN	Field Area Network
GSM	Global System for Mobile Communications
GPRS	General Packet Radio Service
HAN	Home Area Network

HH	Households
HSPA+	High Speed Packet Access-evolved
ICT	Information and Communications Technologies
IoT	Internet of Things
Kbps	Kilobits per second
LTE-A	Long Term Evolution-Advanced (4th Generation)
LTE-M	Long Term Evolution for M2M
LV/MV	Low-voltage/Medium-voltage
M2M	Machine-to-Machine Communications
Mbps	Megabits per seconds
MNO	Mobile Network Operator
MTTR	Mean-Time-To-Repair
NAN	Neighbourhood Area Network
OFDM	Orthogonal Frequency Division Multiplex
OPEX	Operational Expenditure
PLC	Power Line Communication
PLC-DC	PLC Data Concentrator
PLMN	Public Land Mobile Network
QoS	Quality of Service
RoI	Return in Investment
SM	Smart Meter(s)
SG	Smart Grid
TCO	Total Cost of Ownership
TS	Transformer Station
UE	User Equipment
WiMAX	Worldwide Interoperability for Microwave Access

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