Performance Evaluation of Future AMI Applications in Smart Grid Neighborhood Area Networks

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***Abstract*—Smart Grid constitutes the next generation of electricity delivery systems that intend to enhance reliability, efficiency, and security of the power grid. A fundamental component of this intelligent network is the Advanced Metering Infrastructure (AMI), which provides a two-way communication network between Utilities and a collection of smart meters located at the customers side. The interconnected meters form Neighborhood Area Networks that provide a platform for the deployment of customized AMI applications. In this paper, we study the operation of AMI in Colombia. While several Utilities are implementing first approximations to AMI that mostly focus on automated consumption readings, there is no certainty that traffic of different natures, corresponding to future AMI applications, can be supported by these initial deployments. As there is a lack of study of these issues, we carry out an extensive performance evaluation through simulations of current technologies delivering traffic from future AMI applications. Our simulations are based on an extensive review of the communication technologies that are currently employed for AMI in Colombia, and on a characterization of the future AMI applications. With our study we pursuit a better understanding of the primary challenges that will have to be faced for the development and enhancement of AMI networks in the country.**

I. Introduction

Smart Grid constitutes the next generation of electric grid systems, which incorporates different renewable energy resources, automatic and intelligent management of energy, and a more effective and interactive communication with the client [1]. A fundamental component of the Smart Grid is the Advanced Metering Infrastructure (AMI), which results from the integration of advanced sensors, smart meters, monitoring systems, and energy management systems. The AMI enables the bidirectional communications between the Utility and the final users [2]. Overall, Smart grid's communication infrastructure comprise three types of networks: *i)* Home Area Networks (HAN), which serve as the communication infrastructure for sensors and devices inside homes; *ii)* Neighborhood Area Networks (NAN), which connect smart meters and data collectors, and correspond to the platform for AMI implementations; and *iii)* a Wide Area Network (WAN), which communicates data collectors in the AMI with a Utility Control Center [3].

In this paper, we study the operation of AMI in Colombia. While information of how the AMI is currently working in the country is scattered, it is known that several Utilities are implementing prototypes or early commercial segments with AMI. Such deployments are mostly focusing in the collection of energy consumption readings from customers premises, as well as the transmission of basic commands from the Utility back to the customers. However, to the best of our knowledge, there is a lack of a study about how current deployments will support the expected data flows in a full-fledge AMI, which is the main motivation of our work. In a full-fledge AMI, the nature of traffic will be highly diverse, due to a variety of applications that range from low-frequency meter readings to real-time monitoring and pricing. Some of the future applications that may become prevalent include: Demand Response Management (DRM), detection of power outages, Wide Area Measurements (WAM), and electric vehicle charging [4]. Hence, we provide a structured characterization of future AMI applications and present a performance evaluation of communication technologies for such applications in the NAN scenario, based on results yielded from extensive simulations of an AMI network.

The remainder of this paper is organized as follows. In Section II, we first perform a review of the communication technologies proposed for the NAN domain, as this is the network infrastructure that enables the deployment of AMI applications. Next, we present a survey of the current state for AMI implementations around the world and in Colombia. In Section III, we present future AMI applications and characterize them for simulations, followed by Section IV, where we characterize the communications technologies selected for the performance evaluation. In Section V, we present our simulation scenarios and a detailed evaluation of performance in the context of a full-fledge AMI, with several applications running simultaneously. Finally, Section VI concludes this paper.

II. State of the Art of AMI deployments

In this section we present the most relevant communication technologies utilized or proposed for the NAN domain of Smart Grid. We also review the current global deployments and survey the state of the art of AMI in Colombia.

A. Communication technologies in the NAN domain

1) Power Line Communication (PLC): PLC is a technology that uses the existing electric grid to transmit data. Thus, it becomes a well suited alternative as it is a no-cost medium for the Utility and is spread across the electric distribution system. By reusing the electric grid as communication media, the implementation investment can be low. Two main types of communication technologies based on PLC have been defined: NarrowBand PLC (NBPLC) and Broadband PLC (BPLC).

NBPLC generally operates in transmission frequencies of up to 500 kHz, as opposed to BPLC, which targets much higher bandwidth at shorter distances and operates over a much higher frequency band. Frequencies of 148.5 kHz and less have been recognized by CENELEC standards for use in NBPLC systems on a public Utility's power wires. Regarding the BPLC, the operation bands go from 1.8 MHz up to 250 MHz. Some examples of NBPLC technologies are described in IEEE 1901 and ITU-T G-hn (G.9960/G.9961) recommendations. BPLC generally refers to PLC systems supporting data rates over 1 Mbps [5].

As un upgrade to NBPCL, now exists a PLC technology called Power Line Intelligent Metering Evolution (PRIME). This technology is based on ITU G.9903/G.9904 standards, and is one of the most mature OFDM-based technologies to address issues related to the inherent harsh environment on power lines [6]. As power lines are a shared media, there is always significant interference that hinders reliable data transfer. PRIME was developed within the PRIME Alliance, which comprises a set of Utilities that are in the pursuit of the development of an open, public, and non-proprietary communications solution to support current and future smart grid applications [7]. PRIME delivers up to 1Mbps when operating the full FCC/ARIB band (3kHz / 490kHz) [6]. Some of the factors impairing physical performance include: typical line noise (as different kinds of electric devices are connected to the power lines), impedance, and frequency/selective channels [7]. Periodic Impulse Noise (PIN), which is synchronous to 50Hz or 60Hz, and Narrowband Interference (NI) synchronous at 10ms, are the two prevalent noises in such environments. Forward Error Correction (FEC) methods are employed to handle such issues.

2) IEEE. 802.15.4g: This technology is an amendment to the IEEE 802.15.4 standard with the objective of facilitating very large scale process control applications such as the ones found in Smart Utility Networks. This wireless mesh technology is capable of supporting large and geographically diverse networks with minimal infrastructure and millions of fixed endpoints. The amendment features transmissions in the frequency bands from 700 MHz to 2.4 GHz, frames sizes up to 1500 bytes (the previous standard only supports up to 127 bytes), and a data rate up to 1 Mbps (the original standard is limited to 250 Kbps) [8] . As for the advantages of the adoption of this standard, one could mention that it provides backward compatibility built into the standard, reliability in outdoor environments, interference resiliency, and support of high density operation by Frequency Hopping Spread Spectrum techniques.

3) IEEE. 802.11s: The IEEE 802.11s standard envisions a small-to-medium scale WLAN mesh network configured with a maximum of 32 mesh nodes, also named Mesh Points. An amendment to the standard has been made with the aim of developing a more flexible and extensible standard for wireless mesh networks based on the IEEE 802.11 technology. One of the most important functionalities of the new IEEE 802.11s is the multi-hop routing feature, which sets up the paths for wireless forwarding. Mesh capabilities are provided to the mesh points, so they are able to participate in the forwarding process [9].

4) Digital Subscriber Lines (DSL): It is a high speed digital data transmission technology, which employs the wires of the voice telephone network for data transmission. As with PLC, this technology may be a suitable candidate for the implementation of network segments within the AMI, as it reuses the existing infrastructure, thus reducing installation costs compared to completely new deployments. As for the technical specifications, the network performance and perceived throughput will depend on how far away the subscriber is from the serving telephone [2]. Commonly, the frequencies on which this technology works are greater than 1MHz through an Asynchronous DSL-enabled telephone line.

B. AMI around the world

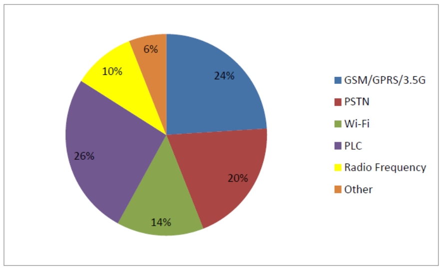
The Advanced Metering and Demand Response Survey performed by FERC [10] indicates that, in the U.S., AMI rollouts have increased significantly since the last survey in 2008. Full scale AMI deployments are currently around 40% in the U.S. Moreover, the European Union (EU) has set a target of 72% smart meter deployment by 2020. Regarding the penetration of advanced metering approaches in Europe, Italy, Finland, and Sweden are pioneers and have already around 80% penetration with full-scale AMI [11]. In Spain, there is an AMI rollout of 2 million endpoints managed by Iberdrola, one of the main utilities that services the country, and 10 million of smart meters are expected to be deployed by 2018 [12].

In Canada, the largest AMI project in the region, called Hydro-Quebec, considers the deployment of four million smart meters. This is expected to be completed by 2017. As for Asia, China is on the way to expand their energy metering infrastructure by promoting projects aimed at providing a two-way communication architecture between Utilities and final consumers. Similarly, in Latin America, Brazil leads the AMI initiative, with over 1 million installed smart meters [13].

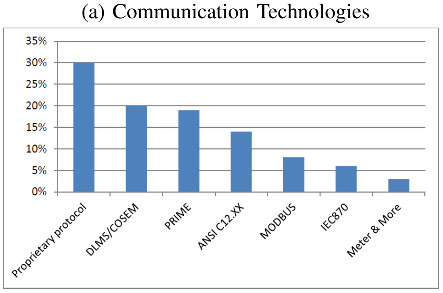
C. AMI in Colombia

As part of this study, eleven Utilities of the Colombian electricity sector were surveyed, in order to establish the current state of the information systems and communication networks for Smart Grid deployments in the country. Interviews were conducted by the authors and the poll employed for data collection included questions for matters related to Smart Grid such as: economic activity, ownership of management information systems, existence of technical support from suppliers, periodicity of information gathering regarding clients consumption, ownership of Automatic Meter Reading (AMR) and Advanced Metering Infrastructure (AMI) Systems, communication technologies for deployment of AMI/AMR systems, and communication protocols used for data forwarding within the network. In the following, we outline only aspects regarding the communication technologies and the main applications that have already been implemented, since they have the relevant information for our performance evaluation.

Regarding the communication technologies in the AMI system, a majority of 26% of the surveyed Utilities indicated to be using PLC as the predominant technology in



(a) Communication Technologies



(b) Protocols

Fig. 1. Communication technologies and Protocols used for AMI in the Colombian Electricity Sector

the communication backbone. Other technologies employed are GSM/GPRS/3.5G cellular networks, the Public Switched Telephone Network (PSTN), Wi-Fi (802.11), radio frequency, among others. A more detailed view of the distribution of communication technologies employed in the AMI is depicted in Fig. 1a. In addition, the protocols deployed in such networks are illustrated in Fig. 1b, where proprietary protocols are the most widely deployed.

When surveyed about the main applications that were currently running in the AMI network, all of the Utilities highlighted mainly three: Meter Reading, Automatic Power outage and Automatic Power restoration. Some of them also pointed out the implementation of a web-based application to track the status of the grid, so that any event related to energy losses (technical and non-technical) can be identified in due time. Regarding the applications and features in which Utilities might be interested in the future, five of them stand out: Current Limitation, Energy Supply Limitation, Awareness of Grid status, Prepaid Energy, and Demand Response Management (DRM).

III. Characterization of Future AMI applications

While many different AMI applications are expected to emerge in the Smart Grid [4], we have focused only on three of them, in order to keep the scope of the simulations limited. The applications that have been characterized for simulation purposes, and according to the interests detected from our survey are: Automatic Meter Reading (AMR), Wide Area Measurement (WAM), and Real Time Pricing (RTP). Table I provides a summary of the three selected applications, together with the main communication and traffic requirements.

A. AMR

Automatic Meter Reading (AMR) refers to the collection of consumption readings, events, and alarms sent by meters. Considering this application in the simulation of AMI networks is a must, as it enables the gathering of essential information for Utilities (clients consumption, non-technical losses, etc.). The average size of an AMR packet is around 200 bytes, and this may be sent every 5 minutes, 10 minutes, 15 minutes, 30 minutes or one hour. A data rate from 10Kbps to 128Kbps is generally required for transmission of meter reading reports [4].

TABLE I
Characteristics of the selected AMI applications

Application	Packet Size (bytes)	Time Interval (s)	Data rate (kbps)	Requirements	Critical Aspects and Traffic Characteristics
AMR	200	300, 600, 900, 1800, 3600	10-128	-HTTP and TCP -Latency Accepted : 100ms	-Delay tolerant - High reliability
RTP	210	900, 3600	10-100	-HTTP and TCP -Latency Accepted : 100-200ms	- Delay sensitive - Continuous transmission - Dedicated bandwidth - Periodic Limited retransmission
WAM	48	0,04, 0.1	6-24	-IP and UDP -Latency Accepted : 10ms	- Real time communication - Delay tolerant - High reliability - Semi-periodic / broadcast and multicast communication

B. WAM

Wide Area Measurement (WAM) refers to a sensing and measurement system that continuously monitors the power grid state. Due to the precise synchronization of the measurements, the Utility control center can gather phase information. This enables the Utility to prevent black-out events or respond more properly in such cases. While WAM systems were usually located on the generation and transmission domain, in Smart Grid they are expected to be deployed at the distribution domain as well, in order to enable real-time monitoring of the overall power grid. The average size of a WAM packet is around 46 bytes. Packet sending occurs every 0.4s or every 0.1s. Data rate required for this application ranges between 6Kbps to 24Kbps [14].

C. RTP

Real Time Pricing (RTP) belongs to the category of Demand Response applications. Prices are exchanged with the aim of improving energy efficiency by encouraging customers to limit their energy consumption or shift it to other periods [4]. In addition, since customers can also be active agents of the energy market, by selling energy back to the Grid, they can get profits from the unused energy [14]. In the RTP application, packets carry price information of the real market cost of delivering electricity. Size of packets varies between 100 bytes to 210 bytes. The packets are sent every 15 minutes or every hour. It usually requires a data rate between 10Kbps to 100Kbps [14].

IV. Characterization of Smart Grid NAN Technologies

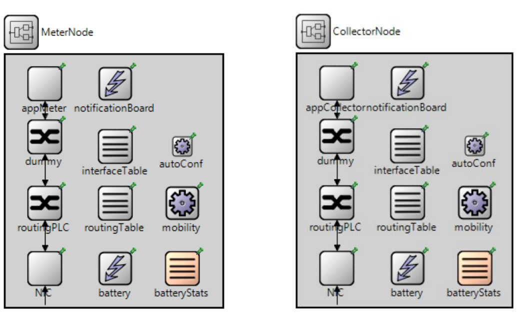
Considering the popularity that PLC has among Utilities, we have selected two PLC technologies for simulations: The

NBPLC technology that has been widely adopted for AMI deployments in Colombia, and the PRIME upgrade that offers up to 1 Mbps of data rate. To simulate the network, we employ OMNeT++ and its libraries INET and MiXiM. In the following sections we present the characterization of the technologies for our simulation setup.

A. PLC Protocol Stack

We have considered the IEEE P1901.2 standard, on which NBPLC is based, for characterizing the technology [15]. The IEEE P1901.2 leverages the standard IEEE 802.15.4 for PHY and MAC layers. PLC follows a bus topology and two well distinguished types of nodes are identified: Meter Node and Collector Node. The meters are the ones located in the customer premises, utilized for measurement purposes and for sending traffic toward the Utility. The collectors are meant to forward traffic from Utility to customers throughout the distribution lines, as well as to receive and route consumption readings data and traffic from other AMI applications.

The composite modules of meter and collector nodes are depicted in Fig. 2. The protocol stack is formed by four layers: appMeter, dummy, routingPLC and NIC. The appMeter layer generates traffic of different natures that will be transmitted throughout the network. The type of traffic in the meter node will be different from the collector node, according to the applications that each is running. The dummy layer serves as a bridge between the app layer and the routing layer, connecting control gates through which control information is passed. This dummy layer could be adapted in the future to support the IP protocol for IP-enabled AMI networks. The routingPLC layer performs all routing and packets forwarding process. The MAC/PHY layers are provided by the MiXiM library. MAC layer is defined by the IEEE 802.15.4 with a CSMA/CA channel access method. The channel is modelled following the Packet Error Rate (PER) model, which describes the losses of a typical PLC network according to measurements obtained from previous field experiments in real PLC networks [16].



(a) Meter Node (b) Collector Node

Fig. 2. PCL Compound Node Modules in OMNeT++

As indicated previously, the app layer submodules of Meter and Collector are different. In the appCollector only RTP packets carrying information from Utility to customers are generated at the collectors. The RTP application entails the sending of information regarding energy price, which is done in the Utility-to-customer direction. On the contrary, AMR and WAM packets, which are sent from the customer premises to the Utility collectors, are generated only in the appMeter module.

B. Channel Modelling

We have used the methodology presented in [16] for the channel modeling of each PLC bus. According to the results obtained from the trial campaign in [16], the PER is modeled as a uniformly distributed random variable. We have assumed that $PER \sim U(0, 0.056)$ in all representative cases that have been part of this performance assessment. Accordingly, we have developed our own PLC channel model class in OMNeT++. The method that filters signals has been overwritten from other channel models, according to the expected behavior of PER in PLC.

C. Network Setup

According to interviews conducted by the authors, in Colombia one collector serves around 20-50 meters in urban scenarios. The collectors are strategically positioned according to the area to be covered and the corresponding meters density. In [17], a 250 meter AMI network was tested in a 10.000 m^2 area, so we adopt the same density in our network setup (i.e., 25000 meters per km^2). Fig. 3 shows the geographical distrubution of 20 nodes in our network setup for simulations.

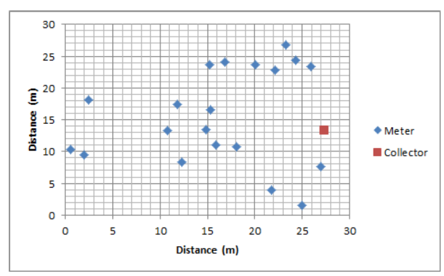


Fig. 3. Node's spatial distribution for network setup

V. Performance Evaluation

In this section, we discuss the results obtained for several scenarios tested with both Current PLC and Enhanced PLC technologies. The comparison of the two technological approaches will be performed on the basis of latency and reliability. The latency metric provides information regarding the delay of the data transmitted between the smart grid components, which is relevant since, as shown in Table I, applications in the smart grid have different latency requirements. The latency is measured through the End-to-end delay (EED). End-to-end delay for application X ($EEDAppX$) is calculated in (1) as the sum of individual time spent to deliver S packets to the destination over the number of received packets at the destination.

$$EEDAppX = \frac{\sum_{j=1}^{S} EEDP_j}{N}, \tag{1}$$

where $EEDP_j$ is the end-to-end delay of packet j, and N is the number of received packets in all nodes.

The reliability metric gives information about how effective packet delivery is throughout the network. While high frequency applications such as WAM may expect highly reliable data transmission, others such as AMR may tolerate some outages in data transfer. For reliability measurement purposes, Packet Delivery Ratio (PDR) was calculated for every application. PDR for application X ($PDRAppX$) is calculated as follows:

$$PDRAppX = \frac{R}{S}, \tag{2}$$

where R is the number of packets received at the destination, and S is the number of packets sent by all sources of application X.

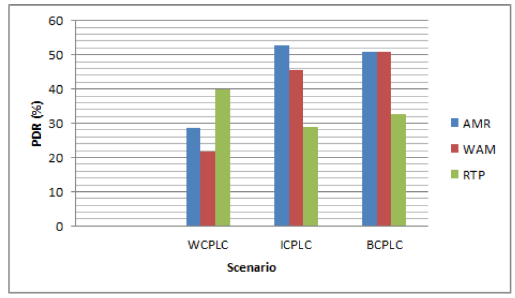
A. Simulation Parameters for Current PLC Deployments

Given that meter reading reports in current PLC deployments in Colombia are sent at around 128kbps, PLC scenarios are simulated employing this data rate. A bus topology has been setup, and we assume there are no collisions among different PLC buses. Therefore, results have been gathered per bus, with a 100-node PLC network comprised by 5 different buses each covering a 64m×64m area. Within each bus of every scenario simulated, 20 meters generate AMR and WAM traffic towards the collector, which in turn transmits RTP traffic to the meters. We have considered three different cases for PLC performance assessment: *i)* Worst case (WCPLC), which corresponds to the highest sending frequencies for every application; *ii)* an intermediate case (ICPLC), in which an intermediate packet inter-arrival time is simulated; and *iii)* the Best case (BCPLC), which refers to the lowest packet sending frequencies for each application. Table II provides a general overview of the PLC scenarios simulated and their correspondent parameter values.

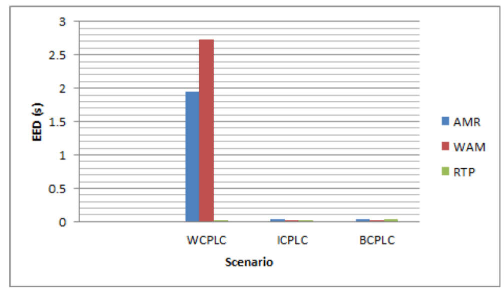
TABLE II
PARAMETERS FOR CHANNEL MODEL IN THE PLC SCENARIOS

Scenario ID	AMR Time Interval (s)	WAM Time Interval (s)	RTP Time Interval (s)	Number of Buses	Bus density (meters per collector)	Total Network Density	Data Rate (kbps)
WCPLC	300	0.04	900	5	20	100	128
ICPLC	600	0.1	900	5	20	100	128
BCPLC	1800	0.1	900	5	20	100	128

Fig.4 shows the summarized results for the whole PLC network in the worst, intermediate, and best cases. As shown in Fig.4a, better values of PDR for all applications are obtained in the intermediate and best cases. However, the poor packet reception shows a lack of resources when current PLC deployments are subjected to transmit traffic of different natures, as is expected in the full-fledge AMI. Regarding EED, results in Fig.4b show that higher values of latency are obtained in the worst case. In particular, the transmission of WAM packets experiment high delays in such a case, which is a straightforward result from generating traffic at very high frequencies in a bandwidth-limited network such as the current PLC.



(a) PDR



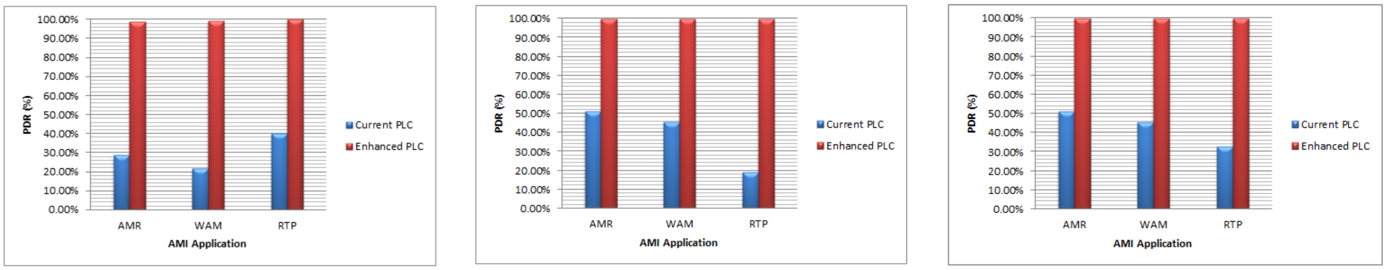
(b) EED

Fig. 4. Simulation results of current PLC network in the Worst, Intermediate and Best Cases

B. Performance Comparison of PRIME (Enhanced) PLC and Current PLC Deployments

We have evaluated the impact of an improved data rate, as provided by PRIME, in the performance of the future AMI applications. The same 100-node PLC network has been tested, this time with a data rate of 1Mbps to represent PRIME deployments. The MAC layer is still based on the IEEE 802.15.4 standard. Fig.5a illustrates the comparison results. When comparing to the same scenario in a typical PLC deployment at 128kbps, one can observe a significant improvement in the reliability of the whole network, for all the involved application. Results yielded by the simulation show that a reduced number of packets are lost during data communication, and an average PDR of 98.75% is obtained for AMR in the worst case. Similarly, WAM and RTP data packets transmissions become more reliable with the PLC upgrade. Averages PDR for these applications are 99.19% and 100%, respectively. When testing the intermediate case scenario, there is also a significant improvement with respect to the current PLC deployment.

Regarding the EED, PRIME PLC shows better performance than that of current PLC technology in terms of delay. In the worst case, a WAM packet lasts an average of 2.73s to reach the collector in the current PLC deployment. In PRIME PLC, the transmission of such a packet takes around 9ms. This leads to a decrease in delay of around 99.67% when transmitting WAM packets in the upgraded PLC network. In the worst case scenario for AMR packets, latency is significantly increased in the Current PLC deployment, as 1.93s are required to transmit



(a) Worst Case PDR (b) Intermediate Case PDR (c) Best Case PDR

Fig. 5. PDR Comparison of Current PLC and Enhanced PLC

the packets throughout the network. Conversely, the Enhanced PCL achieves 11.5ms for latency, which means a decrease around the 99.94% with PRIME.

VI. Conclusion

In this paper we have presented a performance evaluation of two different technologies for the implementation of AMI in Colombia. We have conducted surveys directly with the Utilities, as to identify the relevant communication technologies and the future AMI application of more interest to the electricity sector. PLC has been chosen for the evaluation purposes, as it has become the most widely adopted technology for AMI rollouts in NAN scenarios. Overall, simulation results show that current NBPLC AMI deployments in Colombia fall short in terms of performance for future AMI applications. Results gathered from simulations of several AMI scenarios with different traffic being run simultaneously, as it is expected to occur in the future AMI, show that current AMI infrastructure would not support all traffic load expected to emerge in such a network. A data rate increase becomes one of the possible solutions, which will require a change in the technology being used so far. Better levels of packet delivery efficiency and latency were obtained with the Enhanced PLC proposed by PRIME, an upgrade of the technology that has been defined by the ALLIANCE consortium.

As part of our future work, we will consider open research issues regarding the evaluation of other communication technologies proposed for the NAN domain. The analysis of suitability of technologies such as wireless mesh networks and LTE when deploying future AMI applications is yet to be shown. Further study should also be devoted to the interoperability issues that implies the adoption of proprietary protocols. The integration of legacy AMR systems to IP-based networks in a standardized architecture becomes a critical issue to be addressed.

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