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**Evaluation of communication technologies and routing mechanisms for future AMI applications in the Colombian Electricity sector**

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****ABSTRACT****

Smart Grid is defined as the modern infrastructure of the electric grid, whose objective is to improve efficiency, reliability, and security. This is achieved through the control automation of the transmission and distribution lines, the enhancement of consumption metering technologies, the implementation of new renewable energy sources and new energy management techniques. The growing demand of energy, changes in global weather, problems in the storing and distribution, and the need to implement more efficient consumption metering systems, are some of the factors that have led to transit towards a more complex and robust electric grid. Through an advanced metering infrastructure (AMI), which results from the integration of advanced sensors, smart meters, monitoring systems, and energy management systems, the bidirectional communications between the Utility and the final users are enabled.

In this study, we first outline the main features of the AMI, including communication technologies, topologies for deployment, and routing requirements. The importance of the abovementioned subjects lies in the benefits that accrue for both Utilities and consumers, when enhancing the distribution system’s efficiency. On the one hand, Utilities will benefit from an automated information gathering system, reducing thus operational costs, as the system will collect and process data from the smart meters to its collectors located in strategic points within the service territory. Not only will the Utility benefit from an automated system for information gathering. A better understanding of how AMI works will allow utility to have a reduction in costs arising from lines losses (thefts and other kinds). On the other hand, users will have a better service experience as the two-way communication scheme enables a more interactive communication with the service provider.

Furthermore, in this thesis we focus on the operation of AMI in Colombia. While several Utilities are implementing first approximations to an AMI, there is no certainty that future traffic of different natures can be supported throughout these initial deployments. As there is no a study regarding these issues, we will carry out an extensive review of the communication technologies and communication protocols that are employed for the implementation of AMI in Colombia, as well as a performance evaluation and comparison of such technologies when future AMI applications are deployed, in pursuit of a better understanding of the primary challenges that will have to be faced for the development and enhancement of AMI networks in Colombia.

1. **BACKGROUND AND MOTIVATION**

The emerging energy crisis, caused by the depletion of fossil fuels and the corresponding reserves, has called global attention to find alternative renewable energy sources, so that the industry can be sustained in the long term [2]. It is in this context that the concept of Smart Grid arises as a strategic solution to the energy optimization problem, since it is proposed that this new type of electric grid responds, in a dynamic and periodic way, to changes in the energy load that is being consumed. The new business model that involves the client now (who can be a consumer as well as a producer), would allow energy provision depending on climate changes, number of appliances switched on, and peak hours [3]. By these means, Smart Grid constitutes itself in the next generation of electric grid systems, which will incorporate different renewable energy resources, automatic and intelligent management of the energy, and a more effective and interactive communication with the client.

Other motivation for the transition towards a more automated, modern, and efficient electric grid is the information exchange, in real time, between the Utility and the customer premises. At the same time, the improvement in the response time to network faults, natural disasters, interference problems, and energetic resources loss, constitutes a strong reason to structure an electric grid with better energy transport, generation, and distribution technologies. All these issues must be addressed taking into account the very nature of the scenarios in which the AMI is intended to be deployed, so a choice according with the particular needs of each scenario and data flows can be made. The choice of technology will be subject to diverse factors, such as the deployment’s time and process, the nature of the environment (rural/urban), and the operational costs derived from the implementation.

In [4], a study of the communication media used for smart metering in Belgium addresses the advance metering considering different levels of intelligence associated to the meter. Three types of meters are distinguished there: Advanced Metering Reading (AMR), Advanced Metering Management (AMM) and Smart Metering. According to the operation to be performed, a smaller or broader band communication medium will be needed. In Flanders, city in which the study took place, a total of 3 million advanced meters are required for measurement purposes. With an average 0.51MiB required per meter, 1.28TB traffic is being generated in the city. It is clear, however, that not only transferring of data is being performed within the European country’s AMI scope. If other real time constraints are taken into account (in case of demand side management is required, in which case the amount of data per meter can increase with 2 or 3 orders of magnitude), then the complexity of the communication architecture grows, as the requirements for an effective end-to-end packets delivery become more specific and extensive.

While information of how the AMI is currently working in Colombia is scattered, it is known that several utilities are implementing prototypes or early commercial segments with AMI. However, to the best of our knowledge, there is no a study regarding how current deployments will support the expected data flows in a full- fledge AMI. Through an extensive review of the communication technologies proposed for different AMI deployments, an information-collection process of how the integration of the information technologies and the AMI concept is being performed in other places, and an evaluation of the main communication requirements for the networks in rural and urban scenarios, this work will contribute to a better knowledge and understanding of how the AMI approach should work in Colombia, also allowing the identification of the paramount challenges for its future development and enhancement. A comparison among the different technologies for AMI deployment will also be performed.

1. **PROBLEM DEFINITION**

Although several utilities in Colombia have deployed prototypes and implemented early commercial segments of an Advance Metering Infrastructure (AMI), there is no a clear long term vision towards supporting future AMI applications that may be part of the system. Currently, the main concern and motivation of the Utilities for the implementation of AMI in Colombia is focused on Automated Meter Reading (AMR) and energy losses. Therefore, an analysis of how the current deployments would support future AMI applications traffic has been left out. Under this perspective, and considering that there is no such a study in the context of the Colombian electricity sector, the opportunity for research arises.

Not having a clear long term vision towards supporting applications that could potentially be part of the AMI system may lead to cost overruns, reprocesses, and systems integration issues. As Smart grid technologies evolve far more rapidly than traditional utility assets, and considering the increasing communication requirements of the emerging AMI applications, technology adoption is a critical step to be considered in the planning and designing process for AMI deployments in Colombia.

1. ****PROJECT RESTRICTIONS****

In the following, we define the restrictions that may affect the study of the performance of future AMI applications considering the communication technologies selected in this research:

* Reluctance from Utilities to provide information about their AMI deployments. In this case, information can be gathered by peer consultation instead. By these means, relevant data about the deployment of AMI applications in Colombia can be obtained.
* Restricted information about real AMI deployments. This may affect the characterization of the bidirectional communication network in the simulator, as technical parameters and deployment conditions might not be well defined. Under this circumstance, data from previous studies can be adapted to characterize the network and build the simulations.

1. ****OBJECTIVES****

**4.1 General Objective**

To evaluate the performance of the main communication technologies and routing mechanisms in AMI networks, considering the deployment of future AMI applications and the different requirements and operation needs identified in the Colombian electricity sector.

**4.2 Specific Objectives**

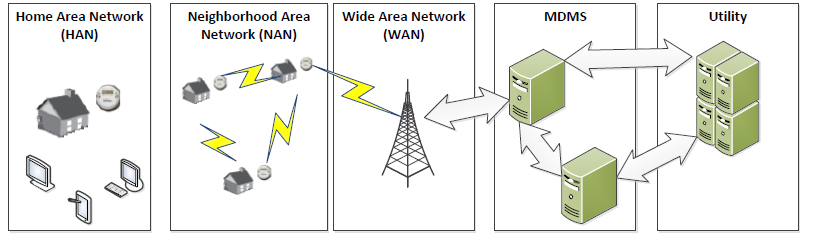
* To survey the different communication technologies and compare the routing protocols employed overall in the AMI architecture and in particular in the neighborhood area networks formed by interconnected meters.
* To implement extensive simulations of AMI networks, over two different technologies, considering technical parameters aligned to the real deployment conditions in the Colombian electricity sector and the response of these current deployments to future AMI applications.
* To make a comparative analysis of the different AMI technologies and communication mechanisms.
* To identify suitable technologies for deployment of future AMI applications in the Colombian electricity sector.

1. **THEORETICAL FRAMEWORK**

Smart Grid has become the new electric grid. With an enhanced and more reliable, efficient, and secure grid, the objective of developing more modern cities is near to be fulfilled. A fundamental component of this new grid is an Advanced Metering Infrastructure (AMI), which provides a two-way communication flow between Utilities and meters and the customer side. In this section, we outline the main features of this infrastructure, including communication technologies, topologies for deployment, and routing requirements. For this purpose, we present the communication requirements for the AMI network (such as scalability, interoperability, and latency, among others), and routing protocols used in the communication backhaul.

**5.1 Advanced Metering Infrastructure (AMI)**

Smart grid communications comprise three types of networks: Home Area Networks (HAN), which serve as the communication infrastructure for sensors and devices inside homes; Neighborhood Area Networks (NAN), which connect smart meters and data collectors; and a Wide Area Network (WAN), which communicates data collectors with a utility control center [4]. The Advanced Metering Infrastructure (AMI) refers to the architecture that provides a two-way communication between the Utility and the Home Area Networks (HANs). It includes smart meters, a Meter Data Management System (MDMS), a communication network, access points, and a head-end [5] [6]. An example of a typical AMI deployment is depicted in Fig. 3.1.



**Fig. 5.1. Basic AMI Architecture**

The main purpose of the AMI is to measure, gather, and analyze energy consumption as well as patterns of energy use. The AMI must support traffic generated at a variety of sources (meters, data collectors, and Utility). Therefore, the AMI network must fulfill the needs of different natures of traffic while it may face constraints such as limited bandwidth and interaction with low-capacity devices (in terms of memory, processing capacity, and others). While many utility companies started deploying AMI networks based on proprietary protocols, it is expected for the AMI communications architecture to be IP-based to guarantee interoperability with standard applications. As discussed in [7], an IP-based network will provide an effective solution for the communication needs of the smart grid, as it becomes a non-technology dependent deployment. Thus, the cost of implementation and maintenance can be reduced significantly using an IP-based approach. The main requirements for the IP-based communications network deployed in the AMI are as follows [5] [8]:

* Interoperability: The IP suite and protocols should be standards-based with the purpose of enabling the communication between segments using different technologies and networking protocols, as well as providing end-to-end services.
* Scalability: Supporting large and dense deployments is a must in the AMI network.
* Security: Smart meters transmit sensitive information on a regular basis; hence, the network must provide security for data transfer. Security services must cover different types of traffic and be provided at both network and application layers [6]. Real time information, for instance neighbors’ energy consumption habits, becomes data that must be protected since third-party visibility of this information would constitute an invasion of privacy.

* Reliability: It refers to the ability of the system to avoid, detect and repair eventual network faults. This involves avoiding data corruption, isolating faults in case of uncorrectable errors and eventually reporting them to recovery mechanisms.

* Quality of Service: It refers to the ability of a system to provide different priority levels to different applications and types of traffic, so a certain level of performance of a data flow can be guaranteed.

An important aspect of the AMI’s network operation is the routing of packets. The implementation of efficient routing strategies becomes paramount to guarantee that the information reaches its final destination. Therefore, routing protocols should be designed according to the aforementioned requirements. Furthermore, routing should be more or less robust, depending on the type of communication technology over which the AMI is deployed.

In this study, we will compare and discuss the routing strategies and protocols that have been adopted in the communications backbone of the AMI context.

**5.2 Communication Technologies in AMI**

In this section, we address the communication technologies suitable for AMI deployments. Although we introduce technologies related to the other domains in the smart grid (HAN and WAN), we devote a more detailed analysis for technologies in the NAN domain.

* + 1. **HAN domain**

**5.2.1.1 802.15.4-based technologies**

The IEEE 802.15.4 standard specifies the physical and medium access control layers for Low Rate-Wireless Personal Area Networks LR-WPAN). Some technical characteristics of the 802.15.4 standard are listed below:

* Frequency bands: 868 MHz/915 MHz and 2.4GHz
* Raw data rates: 868 MHz: 20kbps; 915 MHz: 40 kbps; 2.4GHz: 250 kbps
* Channels: 11 in the 868/915 MHz ; 16 in the 2.4 GHz
* Range: 10-20 m
* Latency: Down to 15ms
* Addressing: Short 8 bit or 64bit IEEE
* Channel access: CSMA-CA and slotted CSMA-CA
* Modulation technique: DSSS (Direct Sequence Spread Spectrum)

One of the most well-known 802.15.4-based technologies is ZigBee [12]. It is a wireless communications technology considered ideal for real time monitoring of multiple targets, due to its low power consumption, low deployment cost, self-organization and self-configuration characteristics

There is also the possibility of employing standard Internet protocols directly over the 802.15.4 technology. 6LowPAN, a standard defined by the IETF, builds an adaptation layer between MAC layer and network layer to enable the transmission of IPv6 packets over IEEE 802.15.4 [15]. It describes the way packets of large sizes (i.e., IPv6 packets) can be transported through a wireless link that only accepts packets of a maximum 127 bytes size. For this purpose, header compression and fragmentation of IPv6 packets is performed, and mesh forwarding is also allowed for the delivery of packets from source to destination over multihop scenarios. Among the advantages of technologies based on the 802.15.4 standard we can mention simplicity, robustness, low bandwidth requirements, low deployment cost, easy implementation, and the fact that they operate over a non-licensed spectrum band. They also allow for mobility of devices.

Regarding the drawbacks, one could mention the interference caused by other devices using the same transmission media, and the fact that technologies based on the 802.15.4 standard suffer from the scope expansion of sensor networks, the reason why these kinds of technologies are only appropriate for small-scale networks deployments [16].

* + - 1. **802.11 and WiFi**

IEEE 802.11 standard [17] specifies PHY and MAC layers for WiFi. It operates in the ISM 2.4 GHz. The IEEE 802.11b version of the standard is the one that has been widely adopted for WiFi. Main technical specifications of this standard are as follows:

* Frequency bands: 2.4GHz
* Maximum data rate: 11 Mbps
* Channels: 13 overlapping 22 MHz wide frequency channels
* Range: 30.48m at 11 Mbps; 91.44m at 1 Mbps
* Channel access: CSMA-CA
* Modulation technique: DSSS)

As WiFi is a very mature technology (it’s estimated that more than 100 million households worldwide have a WiFi installation for home networking) [18], it becomes a suitable communication technology inside the HAN through which devices at home send information to the smart meter. WiFi becomes a very scalable technology, providing extensive radio performance and network management mechanisms to provide records of radio quality, history reports and channel selection optimization. Regarding technical specifications, WiFi offers data rates from 1 Mbps (at 802.11b) to 1Gbps (at 802.11ac), and support multichannel in the 2.4GHz and 5 GHz ISM bands.

WiFi operates in unlicensed spectrum, so it’s resilient to many types of interference but can coexist with other technologies that share this bands (it provides mechanisms to deliver robust performance in shared-spectrum and noisy RF environments [18]). Other advantages of this technology include the fact that it enables IP-based applications, as it transports all IPv4 and IPv6-based protocols, the fact that many vendors implement the technology in a wide range of devices and enhancements in power management. As for the drawbacks, one could mention higher power consumption (when compared with other HAN technologies such as ZigBee).

* + 1. **NAN domain**

**5.2.2.1 IEEE. 802.15.4g**

This is an amendment to the 802.15.4 standard whose objective is to facilitate very large scale process control applications such as the ones found in Smart Utility Networks. It is capable of supporting large and geographically diverse networks with minimal infrastructure and millions of fixed endpoints. The standard features an alternate PHY and the MAC modifications needed to support its implementation. The amendment features the following [19]:

* Frequency bands: 700 MHz to 1GHz and the 2.4 GHz band.
* Frame Sizes: up to a minimum of 1500 bytes
* It addresses geographic requirements of Smart Grid by defining appropriate power levels
* It increases data rates formally to hundreds of kbps, and even Mbps, thus broadening the applicability of mesh systems beyond AMR and AMI to support the full sweep of smart grid applications.
* The standard defines technologies supporting up to 1 Mbps
* It establishes a global standard by explicitly including unlicensed and region-specific frequency ranges, or spectrum bands
* It supports for Frequency Hopping Spread Spectrum (FHSS) transmission techniques.

As for the advantages of the adoption of this standard, it provides backward compatibility built into the standard; thus, utilities’ hardware can be integrated with no changes, so their investment in the technology is protected.

* + - 1. **Power Line Communication (PLC)**

PLC is a technology that uses the existing electric grid to transmit data. PLC becomes a well suited alternative as it is a no-cost medium for the Utility and is spread along the distribution system. Thus, PLC is a natural solution for the communication between the Utility and the Smart Meters. By reusing the electric grid as communication media, the implementation investment is low. In a typical PLC network, the smart meters are connected to the data center through power lines. Two main types of communication architectures based on PLC have been defined: NarrowBand PLC (NBPLC) and Broadband PLC (BPLC). The first type allows data transmission at lower rates than those provided by BPLC. The main technical specifications of this technology are stated below.

* Frequency bands: from 3KHz to 148.5kHz in NBPLC and from 1.8MHz to 250MHz in BPLC.
* Maximum data rate: 1Mbps
* Range: 9.75m – 100.28m
* Channel access: CSMA-CD

The main advantage of PLC is associated to the low implementation costs. Additionally, the coverage provided by PLC is exactly the one intended by the Utility. As it uses the power feeder, PLC behaves as an enabler for sensing, control, and automation in large systems comprising tens or even hundreds of components spread over relatively wide areas, which contributes to provide scalability.

Nonetheless, the very nature of PLC’s physical transmission media generates some challenges. It is highly susceptible to signal degradation due to the harsh power lines. Besides the fact that feeder cables are not designed for data transmission, they are also prone to be interfered by the inverters outcome.

* + - 1. **Digital Subscriber Lines (DSL)**

DSL 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 cost of an implementation from scratch. As for the technical specifications, the network performance and perceived throughput will depend on how far away the subscriber is from the serving telephone [1].

* + 1. **WAN domain**

**5.2.3.1 Cellular Networks**

Cellular Networks became a popular technology for the communication between meters and the Utility, as a solution for Automatic Meter Reading systems. By employing short messaging services (SMS) or data plans through a cellular operator, the AMR system is supported over existing infrastructure, thus avoiding incurring in additional installation and deployment costs from the Utility’s viewpoint. Furthermore, this technology is also suitable for communicating collectors to the central data center at the Utility’s premises.

Among the advantages of employing this technology we can mention that by outsourcing the communications network to a mobile operator, utilities can significantly reduce operative costs, as they do not have to bear the cost of deploying and maintaining the infrastructure. On the contrary, among the drawbacks identified are those associated to information security. As the physical medium used for transmission is susceptible to interceptions, sensitive information (such as contractual data or bills) must be protected, to guarantee that it reaches its intended recipient with no understanding by other individuals or devices attempting to intercept it. In addition, given that the communication channel is shared with mobile telephony users, the network performance may be impaired at certain times or places.

* + - 1. **WiMAX**

Wimax (Worldwide Interoperability for Microwave Access) is a wireless broadband technology based on the standard IEEE 802.16 [20]. One of the main characteristics of Wimax is that its adaptive modulation and coding scheme allows the whole network to adjust signal modulation or coding depending on how noisy the link is. This is why the technology provides high data rates, as the modulation increases when signal to noise ratio is also increasing. Some technical specifications of the technology are [21]:

* Data rates: up to 70 Mbps
* Not protocol-dependent
* Low latency: 100 ms round trip
* It supports QoS, policy and traffic management
* It provides secure communication and provides 128 -bit Advanced Encryption Standard (AES)

Regarding the advantages of Wimax as technology enabling communications in the NAN domain, one could focus mainly on the fact that it provides a balance between deployment cost, complexity, flexibility, and control. Being based on a flat architecture, the technology is flexible and scalable. On the other hand, it can use a wide range of frequencies and this gives Utilities the possibility to deploy a wide range of applications with different bandwidth requirements and priority levels [22]. As for the drawbacks, while Wimax provides a solution with a large communication range and high data rates, it tends to be costlier due to the greater licensing and subscription fees.

**5.3 ROUTING IN THE NAN DOMAIN**

The Advanced Metering Infrastructure (AMI) is expected to be deployed on networks with a dense number of nodes (meters) that connect to numerous data collectors. Furthermore, the AMI network should provide efficient and suitable routing functionalities, which guarantee a reliable and effective delivery of information.

Considering the importance behind the implementation of efficient routing strategies and protocols lies in the need of an effective data packet delivery mechanism, we focus on routing for the NAN domain of AMI. As it is required that information from data collectors can be successfully received by the Utility, through the bidirectional communication channel outlined under the AMI concept, and conversely information from Utility must reach data collector and meters at the customer side, we analyze several routing protocols that have been proposed for the NAN domain. In [13] several routing protocols have been classified and evaluated according to a certain set of metrics that will further be explained.

**5.3.1 RPL**

IETF has proposed the Routing Protocol for Low Power and Lossy Networks [24]. This protocol is of the distance-vector type, and is based on IPv6. It was designed considering the requirements specified in RFC 5826 [25], RFC 5673 [26], RFC 5548 [27] and RFC 5867 [28].

One of the main advantages of this protocol is that it does not define a unique routing metric, but gathers a set of metrics. This is a must in the AMI network, given its heterogeneous and diverse traffic natures. Multiple devices involved in the AMI, as well as the different types of applications uploaded to the network, entails a need to define several types of metrics to ensure the protocol efficiency.

A detailed implementation of RPL for AMI networks is presented in [30]. The authors considered a static multi-hop wireless AMI network that consists of n meter nodes and one gateway node. In the proposed protocol, a DAG structure is maintained at the gateway node. Data forwarding rules are introduced once it is defined the information to be stored and maintained by each node. The authors also provide a detailed characterization for the DAG construction and maintenance, and propose a reverse path recording mechanism in order to enable routing support for outward unicast traffic, which flows from the gateway to each meter. The practical implementation of RPL presented in [30] aims at providing reliable and low-latency routing support for large-scale AMI networks, through the integration with CSMA-based MAC layer protocols.

**5.3.2 Geographic routing**

Geographic routing considers packet forwarding by means of position information instead of network addresses and routing tables. The destination location is employed to route packets. Through the knowledge of neighbors’ locations, each node selects the next hop that is closer to the destination. Regarding the determination of every node’s position, GPS devices are the main tool for making position information available. In order to enable the node’s awareness of its neighbors’ positions, it is required the broadcasting of the position information to other nodes. To determine the position of the destination, a location service that maps network addresses to geographic locations is needed [31].

One of the main advantages of this routing protocol is that routing tables maintenance and route discovery are unnecessary tasks, as the packet forwarding function is only based on geographic information.

A performance analysis of geographical routing in AMI networks through a simulation set up is presented in [8]. The routing protocol has been widely used in smart utility networks and AMI deployments, currently running in over 2 million metering end-points. For analysis purposes, a 100-node network obtained from a rural real AMI deployment was set up. Several data was collected, such as the ratio of total transmitted packets to received packets per node, the packet success probability, and the latency.

**5.3.3 AODV**

Ad Hoc On-Demand Vector routing protocol builds on the Destination-Sequenced Distance-Vector (DSDV) protocol and is based on the RFC 3561 [32]. AODV creates routes on demand, which minimizes the number of required broadcasts. This protocol uses hop count as routing metric.

In [33], a test-bed implementation of AODV in an AMI small-scale scenario is presented. In the simulation, the nodes were placed at distances such that the transmitted signal was only received by the neighboring nodes. As the number of hops increased, the throughput decreased, which is evident due to the routing overhead increment. Regarding the scalability of AODV, it was tested in a large scale string scenario, showing an inverse relationship between the throughput and the number of nodes.

**5.3.4 DSR**

Dynamic Source Routing protocol is an on-demand routing protocol and is based on the concept of source routing. It is based on the RFC 4728 [34].

In [35] an evaluation of DSR together with AODV in a grid based cluster network is performed. For this purpose, Qualnet 5.0.2 simulator was used to execute the performance analysis. A total of 33 nodes are deployed in an area of 1500m x 1500m. The evaluation considered the following performance metrics: i) energy consumed in transmission mode; ii) energy consumed in received mode; iii) energy consumed in idle mode; and iv)residual battery capacity (remaining battery after simulation). Regarding the first three metrics, AODV shows a better consumption of energy that DSR (0.1 mWh vs. 0.3 mWh in the transmission mode, 0.1 mWh vs. 0.3 mWh in the received mode, and 1 mWh vs. 2.5 mWh in the idle mode). The residual battery capacity shows similar values for both protocols (around 99.7 mAhr).

**5.3.5 DADR**

Distributed Autonomous Depth-First Routing (DADR) [36] is a proactive distance vector protocol that uses a control mechanism to provide at most k (if available) paths for each destination. It also utilizes Depth First Search algorithm for path recovery in cases of link failures [37].

A simulation scenario of more than two thousand smart meters is presented in [38]. The authors present an analysis of the routing protocol while it is tested in a 1500-node network topology. As for adaptability, the protocol shows the capability of learning new routes in both indoor and outdoor environments. In addition, the protocol demonstrated it does not need too much control overhead when updating routes, which is an advantage in a large-scale network. The study also shows that packet latency in a flat mesh network is affected by the several hops that data packets need to traverse in order to reach the destination.

**5.3.6 HYDRO**

Hybrid Routing Protocol [39] is a link state routing protocol for Low Power and Lossy Networks.

In [39], a performance evaluation of HYDRO with different metrics is presented. It involves the implementation of a set of testbeds and a real network deployment. In the latter, a 57-node network was run for six months, with HYDRO as the routing protocol. The offered load consisted of each node transmitting a packet to an external server every minute. The statistics collected showed that the PDR is an average 98.9%. As for the scalability, every node’s state is bound by the number of destinations it communicates with.

**5.3.7 HWMP**

The Hybrid Wireless Mesh Protocol (HWMP) is the multihop default routing protocol for IEEE 802.11s WLAN mesh networking. With the purpose of allowing interoperability between devices from different vendors, HWMP serves as a common path selection protocol for every IEEE 802.11s-compliant device. The term hybrid is due to the use of both reactive and proactive approaches in the routing scheme. HWMP results from an adaptation of AODV called Radio-Metric AODV (RM-AODV).

In [42] the authors considered the use of HWMP in a smart grid deployment, utilizing the air cost (failure rate of each node calculated by MAC retransmission count of each packet) as a performance metric. The new method gives more priority to retransmission of small packets, as they are likely to have fewer bit errors. As a consequence, the protocol becomes more adapted for the NAN domain and the applications that are part of that architecture.

1. **COMPARISON OF ROUTING PROTOCOLS**

The communication infrastructure in AMI involves an important exchange of information, which is the foundation for the location-distributed electric power devices to work in a coordinated manner. Unsatisfactory communication performance not only limits the AMI from achieving its full energy efficiency and service quality, but also poses potential damages to the grid system. To protect the AMI and ensure optimal operation, the communication infrastructure must meet a number of requirements. In this chapter we make a comparative analysis, based on a set of selected metrics, of the routing protocols for NAN environments in AMI networks introduced in the previous chapter.

* 1. **Metrics used for Comparison**

**6.1.1 Routing strategy**

Depending on the layer in which the routing decision takes place, the data forwarding mechanisms can be classified as route-over or mesh-under.

1. **Route-over**

In a route-over scheme, all routing decisions are taken in the network layer where each node acts as an IP router. In route-over, each link layer hop is an IP hop. The IP routing supports the forwarding of packets between these links. In the forwarding process, IP routing tables and hop-by-hop options are used. For routing and forwarding processes, the network layer makes decisions using the information encapsulated in the IP header.

1. **Mesh-under**

In this mechanism, the network layer does not perform any IP routing. The forwarding decision is made below the IP layer and the packet is forwarded to the destination over multiple radio hops. Since multiple hops based on link layers are used to complete a single IP hop, it is called the mesh-under mechanism.

* + 1. **Latency**

The concept of latency refers to the maximum time in which a particular message should reach its destination through a communication network. It is important to state that the messages between various entities within the AMI may have different network latency requirements. Thus, while commands exchanged between devices in the distribution network may require lower latency values, information exchanged between sensors and control centers may accept higher values. In [45], two limit value for latency are specified on the basis of the components that generate the traffic. As for the Phase Measurement Units (PMU) and Control Centres, 10ms is considered as the limit for an accepted value of latency. Regarding the AMI, and considering a reporting rate less than 1 Hz, accepted latency is under 1s.

* + 1. **Availability**

This metric indicates if the network services are available and will survive possible attacks or failures that could occur. In the HAN scenario, for example, resource depletion is typically not a concern when it comes to a resource such as energy, where both the smart meter and appliances are assumed to have access to the grid power. However, computation capabilities and memory constraints could be exploited by keeping these resources fully loaded, affecting the ability of the network to function as desired.

Equipment failures may also be more common, especially with the low cost devices of wireless HAN (such as the ones provided by ZigBee).

* + 1. **Data delivery priority**

This refers to the priority of arrival of packets throughout the network, and it depends on the needs of the application. The priority may be decided at the time of connection establishment between two applications. Different levels of data delivery priority can be considered, as following: i) high, which is used when the confirmation of end-to-end data delivery is a must and a retry is mandatory in case of absence of confirmation; ii) medium, which is used when end-to-end confirmation is not required but the receiver is able to detect data loss; and iii) non-critical, which is used when data loss is acceptable to the receiver. In the latter case, reliability can be improved by means of repetitive messages. The non-critical level can be used for periodic data employed for monitoring purposes.

* + 1. **Reliability**

The grid stability will depend, to a great extent, on the reliability of the distribution network. Hence, it becomes extremely important for the communication backbone to be reliable, in order to enable successful and timely messages exchange. Different events may affect the communication backbone reliability. Some of these failures include time-out failures, network failures, and resource failures. A time-out failure occurs if the time spent in detecting, assembling, delivering and taking action in response to a control message exceeds the timing requirements [46]. A network failure occurs when there is a failure in one of the layers of the protocol suite employed for communication (i.e., the failure may be originated in a logical level, and it prevents packets from reaching their destination although the physical link is operative). Other factors can affect the communication, such as noise and interference. A resource failure means that one end node (i.e., sender or receiver) has failed. One of the mechanisms utilized for reliability measurements purposes is through the Packet Delivery Ratio (PDR), defined as the quotient between the number of packets received and the number of packets sent.

* + 1. **Interoperability**

Interoperability of a smart grid is the ability of diverse systems to work together, use the compatible parts, exchange information or equipment from each other, and work cooperatively to perform tasks. It enables integration, effective cooperation, and the two-way communications proposed in the AMI concept, among the many interconnected elements of the smart grid. The NIST, which works as the first International Coordinator for smart grid interoperability, developed a framework that includes protocols and standards for information management to achieve interoperability of smart grid devices and system.

* + 1. **Scalability**

This metric can be considered as the ability of a system to handle increasing amounts of work in an efficient manner [47]. Most of the time, the concern lies on the load scalability, which is the easiness for a system to increase its resources to accommodate the increasing load. For this purpose, it is necessary to define the specific requirements for scalability in this dimension. In the AMI case, scalability is related to the ability of the routing table on a router (meter) to scale with the number of nodes in the AMI network. Another form of scalability is related to the costs associated to the deployment of the network when the number of nodes becomes large. It is expected for the communication architecture to work equally well for a small network as well as for a large network.

* + 1. **Easiness of deployment**

This refers to the level of feasibility and easiness with which the network can be deployed.

* + 1. **Adaptability**

This refers to the ability of a routing protocol to adapt to different network topologies

**6.2 Performance Analysis of Routing protocols in the NAN domain**

We employ the description of operation, as well as the performance results reported in the literature to make the comparison. In [6], a performance analysis of RPL and Geographic Routing in a Smart Grid context was presented, utilizing OMNeT++ as the simulation tool to implement the routing algorithms. Simulations were run for 500 nodes AMI scenarios, which were configured for gathering statistics of hop count and end-to-end delay. In the scenario, each of the 500 nodes sends multipoint-to-point traffic directed towards the collector. The application packet rate was set at 1 packet/second. All other nodes in the network simply participated in the routing and were not allowed to transmit when one of the nodes was transmitting. Each node transmitted 100 packets with the collector as the destination. An average of 160ms and 173ms of end-to-end delay were obtained for RPL and Geographical routing, respectively. Regarding reliability, it was measured by computing the PDR, defined as the total number of received packets at the collector over the total number of packets transmitted by each node. On this matter, RPL showed a constant packet delivery ratio between 98% and 100% for each packet and an average of 99.98% while Geographical routing showed similar performance with an average of 99.30% [6].

Other protocols such as DADR and HYDRO have been also analyzed, considering their behavior in testbeds and real AMI deployments. In [41], a study was conducted to determine the behavior of DADR in a 1500 node network topology. The study showed an average PDR of 97.8%. HYDRO, as a combination of both centralized and distributed forwarding mechanisms, showed to have a high reliability according to [42], as multiples routes are provided to a given destination. By constantly evaluating the qualities of the links, HYDRO becomes robust in terms of adaptability, as any change in the topology is quickly detected and the protocol reacts to it. An average PDR of 98,9% was obtained when examining the performance of the HYDRO in a 57-node real deployment. The comparative analysis that summarizes the works in [33], [34], [35], [36], [37], and [42], is presented in Table 6.1.

Table 6.1 Comparison of Routing Protocols in the NAN domain of AMI networks



****7. OVERVIEW OF AMI DEPLOYMENTS AROUND THE WORLD AND THE COLOMBIAN CASE****

In this chapter we describe the general status of AMI around the world, as well as in Colombia. We outline aspects regarding the business model, communication technologies employed in the AMI domain, communication protocols utilized within the network and main applications that have already been implemented. Interviews conducted by the authors and previous surveys have been used as sources for the gathering of information described herein. We also point out the applications that will become prevalent in the near future.

****7.1 Overview of AMI Global deployment status****

The Advanced Metering and Demand Response Survey performed by FERC [10] indicates that, in the U.S., the AMI penetration together with potential peak load reductions from electric power demand response have increased significantly since the last survey in 2008. The growth is around four percentage points (from 4.7% in 2008 to 8.7% in 2010). The study also shows that the Upper Midwest, West, and Texas have advanced metering penetration exceeding 13%. But not only has the U.S showed a significant increase in AMI deployments. The European Union (EU) has set a target of 80% smart meter deployment by 2020. However, there are still many questions to answer regarding demand response, off-peak usage, and planning for the deployment and support of electric vehicles. The main motivation in Europe for installing AMI appears to be limited to the operational efficiency of the Automatic Meter Reading (AMR) systems. However, due to the diversity of EU members and country-specific goals, the definition of a common AMI deployment methodology is a challenging task. Regarding the penetration of advanced metering approaches in Europe, countries such as Italy and Sweden have a near 100% AMI implementation, but a large percentage of these deployments only have unidirectional communication capabilities (for AMR purposes). Functionalities such as demand response and load-shifting applications are restricted to larger customers [10].

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 by considering projects that contribute to the implementation of a more automated metering approach, in the pursuit of investment recovery [5].

****7.2 Overview of AMI status in Colombia****

****7.2.1 Business Model****

In [43] 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. The poll employed for data collection included questions for matters 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.

The structure of the Colombian Wholesale Energy Market (MEM, from its Spanish initials) classifies the utilities according to their specialty. Thus, there are four well distinguished types of domains or subsystems to which a Utility may belong: Generation, Transmission, Distribution, and Commercialization [44]. Among the utilities interviewed, 48% were in the marketing and commercialization sector, 33% were in the distribution domain, 15% of them were devoted to the generation subsystem, and 4% were devoted to the transmission subsystem. Fig. 7.1 shows the distribution of utilities according to their specialty domain.

Fig 7.1. Classification of utilities according to their specialty domain

The study in [43] also shows that, up to now, industrial clients have been more involved in the AMI business model. While residential customers are also a valuable target for utilities, the deployment of AMI in Colombia has been more focused on industrial clients. Nevertheless, some early prototypes of an AMI network capable of executing consumption readings, power outage, and remote power restoration in small residential towns have already been implemented. One of the most outstanding projects of AMI implementation is located in Buenaventura (a town in the South West of Colombia). About 9000 smart meters have been deployed by one of the main Utilities that service this region of the country, together with 250 MV/LV power transformers. As for the communication network, GPRS/3G technology has been used in the Collector-Utility backbone. This Utility expects 36% increase in the coverage in the region.

According to data collected by the authors through interviews with managers of the electricity sector in Colombia, in Cali, the main city in the South West of Colombia, an AMI pilot has also been carried out. With 12000 smart meters distributed in popular sectors of the city and PLC as the communication technology between meters and collector, the utility that leads this project expects a 40% growth in the next five years, concentrating efforts in intelligence of non-technical losses.

Thus, the business model of AMI in Colombia has considered the implementation of a two-way communication network that supports sending of data from client to the utility (basically consumption readings) and data from the utility to the client (mostly commands for power outage and power restoration purposes). Utilities save operation costs by having a system that controls and performs periodical queries of network faults and resource losses. Therefore, the business model is justified by the implementation of systems that manage non-technical losses and income from energy sales.

****7.2.2 Communication Technologies and Protocols****

Regarding the communication technologies in the AMI system, a majority of 24% of the surveyed utilities indicated to be using GSM/GPRS/3.5G as predominant technology in the communication backbone. Also, 20% of the respondents indicated they used the Public Switched Telephone Network (PSTN) for communication purposes, while satellite Wi-Fi was stated as communication technology used in the AMI, with a 14% of acceptance among utilities. Finally, 26% of the utilities interviewed said they used PLC as main communication technology within the AMI network, 10% indicated the use of radio frequency and a total 4% stated to be using other technologies different from the mentioned above [43]. A more detailed view of the communication technologies employed in the AMI is depicted in Fig. 7.2.

Fig 7.2. Communication technologies used for AMI in the Colombian Electricity Sector.

As for the standards and protocols used by the meters, a vast majority of 30% of the surveyed utilities indicated they were using a proprietary protocol. This matter may become an issue, as one of the communication requirements in the Smart Grid Concept is interoperability [45]. DLMS/COSEM is the second most commonly used protocol, while PRIME and ANSI C12.XX are the third and fourth most widely used standards in the communication backbone, respectively [43]. While IP is a standard protocol, none of the utilities employs it, affecting the interoperability requirement that becomes extremely important for the integration, cooperation and two-way communications among all the elements involved in the grid. In Fig. 7.3 we show the distribution of the communication protocols used in the AMI.

Fig 7.3. Communication protocols used for AMI in Colombia

Managers and technical staff interviewed about the future of AMI in Colombia claim that the great challenge will be the integration of distributed generation technologies in the current distribution systems within a new standardized architecture, so a two-way communication system between customers and utilities may be enabled in both industrial and residential markets.

****7.2.3 Applications****

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 any event related to energy losses (technical and non-technical) can be identified in due time [46].

Furthermore, when asked whether they owned systems for real-time operations management (such as power outages and power restoration), 69% of the utilities surveyed stated a positive answer. Also, 90% of these utilities, which own regulatory management systems such as Supervisory Control and Data Acquisition (SCADA) or Geographic Information System (GIS), indicated to count with support from the software supplier (Fig. 7.4). The survey also asked for the holding of Consumer Relationship Management Systems (CRMs), to which a total of 92% claimed to own this type of software for sales, customer service and billing purposes [43].

Fig 7.4. Support of management systems from the software supplier

On the question of whether the utility counted on a system for automated meter readings, load profiles management, and the treatment of other energy variables, all of the utilities surveyed gave a positive answer. A total of 69% of them stated that the applicability of these systems was for industrial customers, while a 31% indicated that these systems covered residential customers. Regarding the acquisition of a Meter Data Management system (MDM), a majority of 69% of the utilities interviewed stated not to own this type of system. Out of those who claimed not to have a MDM, 63% expressed interest in getting one in two years or less [43].

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 the Grid status, Prepaid Energy and Demand Response Management (DRM) [46].

****8. performance analysis of future AMI applications with NAN technologies****

In this thesis, we compare the performance of two PLC architectures for AMI deployment: A PLC technology that has been adopted for AMI deployments in Colombia, and an upgrade of this technology that offers up to 1Mbps of data rate. We also evaluate the performance of Wireless Mesh networks based on IEEE 802.15.4g for NAN environments. To this aim, OMNeT++ [1] has been used as the simulation tool to model both approaches. All simulations of this work have been implemented in a C++ builder using OMNeT++ and its libraries INET [2] and MiXiM [3]. OMNeT++ is an open source, object-oriented component-based discrete event simulation framework in which basic components, also called simple modules, are programmed in C++ and then combined into larger components (compound modules), using a network description language (NED). By connecting all compound modules together, the whole network can be assembled. Simulations in OMNeT++ run under several user interfaces, being the graphical ones especially useful for debugging purposes, while the command-line user interfaces are better for batch execution. In the following sections we present the simulation setup and discuss the results obtained from all of the statistics collected.

****8.1 Characterization of Applications****

While many different applications are expected to emerge in the Smart Grid, we have focused only on three of them, in order to keep the scope of this work limited. The applications that have been characterized for simulation purposes are: Automatic Meter Reading (AMR), Real Time Pricing (RTP), and Wide Area Measurement (WAM). In the rest of this section we shall discuss the characteristics and main requirements and features of these applications in the communication backhaul.

****8.1.1 AMR****

Automatic Meter Reading (AMR) refers to the collection of consumption readings, events and alarms data from the 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 a 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 10 to 128kbps is generally required for transmission of meter reading reports [10] [11].

****8.1.2 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 [10]. The average size of a WAM packet is around 46 bytes. Packet sending occur every 0.4s or every 0.1s. Data rate required for this application ranges between 6-24 kbps [10] [12].

****8.1.3 RTP****

Real Time Pricing (RTP) is one of the different Demand Response (DR) programs, which main expectations are encouraging energy efficiency and encouraging customers to limit their energy usage or shift it to other periods [10]. Thus, DR programs entail the control of the energy demand and loads during critical peak hours. In this way, customers can be an active agent of the energy market, as they are no longer subject to fixed prices, but instead they can get profits from the unused energy [12]. Benefits for the utilities are also envisaged, as they can manage more efficiently the power generation and supply, according to the specified demand. In RTP application, the price information is conveyed to the smart meter at the customers’ premises, so that they can take the necessary actions to regulate their consumption patterns. Basically, an RTP packet carries the price of the real market cost of delivering electricity, and its size varies between 100-210 bytes. The packets are sent every 15 minutes or every hour. It usually requires a data rate between 10-100kbps [12] [13].

In Table 8.1 we provide a summary of the three applications described above, together with main communication and traffic requirements.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Application** | **Packet Size (bytes)** | **Frequency (s)** | **Data rate (kbps)** | **Requirements** |
| Automatic Meter Reading (AMR) | 200 | 300, 600, 900, 1800, 3600 | 10-128 | HTTP and TCP |
| Real Time Pricing (RTP) | 210 | 900, 3600 | 10-100 | HTTP and TCP, Delay-tolerant, reliability, sensitive to packet loss |
| Wide Area Measurements (WAM) | 48 | 0,04 - 0,1 | 6 - 24 | IP and UDP, delay-sensitive (max 20ms) |

Table 8.1 Applications simulated

****8.2 Characterization of PLC Network****

As stated in Chapter 5, PLC becomes a well suited alternative as a communication technology for the implementation of an AMI network, as the electric grid is reused for data transmission between meters and utility. Also, the coverage is the one achieved by the distribution lines. In [4] the authors use the IEEE 802.15.4 MAC layer, which is based on CSMA/CA, to structure a PLC node. PLC follows a bus topology and two well distinguished types of nodes are identified in the characterization of the PLC-based AMI network: Meter Node and Collector Node. The meters are the ones located in the customer premises, utilized for measurement purposes and sending of traffic in the Client-Utility direction. Moreover collectors are meant to forward traffic from utility to customers throughout the distribution lines, as well as to receive and route data regarding consumption readings and other electric grid variables. In this work, we have adopted the IEEE 802.15.4 NIC to specify PHY and MAC layers of two different protocol stacks for meters and collectors involved in several PLC network scenarios. The channel is modeled following the Packet Error Rate (PER) model defined for PLC in field measurements [4]. We shall further describe the channel modeling approach for PLC that we have adopted in this work.

The composite module of the meter node is depicted in Fig. 8.1. The protocol stack is formed by four layers: *appMeter*, *dummy*, *routingPLC* and *NIC*. The *appMeter* layer generates traffic of different nature that will be transmitted throughout the network.

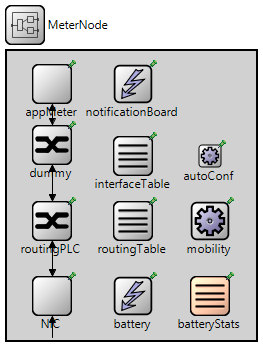


Fig 8.1. PLC Meter Node Protocol Stack

The *routingPLC* layer performs all routing and packets forwarding process in both meters-utility and utility-meters directions. Finally, Fig. 8.2 shows the compound module for the IEEE 802.15.4 NIC used in simulations. The MAC/PHY layers of this NIC are provided by the MiXiM library. MAC layer is defined by the CSMA/CA channel access method, while PHY layer models the losses of a typical PLC network according to measurements taken on-field deployments. On the other hand, *dummy* layer serves as a bridge between the app layer and the routing layer, connecting control gates through which overhead information is passed.

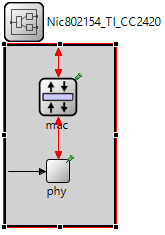


Fig. 8.2 Compound module for IEEE 802.15.4 NIC

Similarly, the collector node is formed by a four layer protocol stack, which also includes an application layer for traffic generation (which, in the case of this type of node will be of a different nature than the one generated from the meters), a routing layer for packets forwarding decisions, and the NIC. The *autoConf* submodule is used in both Meter and Collector Nodes to fill in the interface table with the correspondent IP and MAC addresses. A more detailed view of the protocol stack for the collector node is depicted in Fig. 8.3.

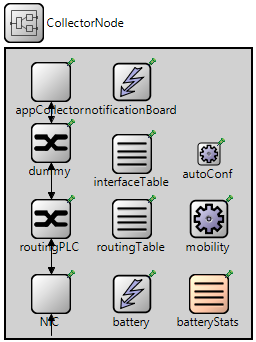


Fig. 8.3 PLC Collector Node Protocol Stack

As indicated previously, the App layer submodules of the Meter Node and the Collector Node are different. The appCollector submodule is defined by a different logic. In this layer, only those packets carrying information from Utility to customers are generated and forwarded through collectors. As mentioned before, RTP entails the sending of information regarding energy price, and this is done in the Utility-Customer way. Thus, RTP packets are generated in the appCollector submodule, while AMR and WAM packets are sent from the customer premises to the Utility collectors, in the appMeter module.

****8.2.1 Channel Modeling****

We have used the methodology presented in [4] for the channel modeling of each PLC bus. According to the results obtained from a trial campaign in [14], PER is modeled as a uniformly distributed random variable. Following the analysis performed in [4], we have assumed that *𝑃𝐸𝑅* *∼ 𝒰* (0*,* 0*.*056) in all representative cases that have been part of this performance assessment.

For simulation purposes, we have developed our own PLC model channeling class in OMNeT++ (PERModelPLC). The method to filter signals has been overwritten from other channel models, according to the expected behavior of the PER in PLC. In this case, every time a packet is received at PHY layer, random variable PER is uniformly distributed between the specified boundaries, and thus we take the decision of accepting or dropping the packet. Parameters for the channel modeling of this network are presented in Table 2.

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Packet error rate (PER) | 0.05 |
| PER lower bound | 0 |
| PER upper bound | 0.056 |

Table 8.2 Parameters for Channel Model in the PLC scenarios

****8.2.2 network set up****

According to interviews conducted by the author, in Colombia collectors serve around 20-50 meters in urban scenarios. These collectors are strategically positioned according to the area to be covered and the corresponding meters density. In [5], a 250 meter AMI network was tested, in a 10.000 m² area with LTE and Wi-Fi as technologies for evaluation. Since the purpose of this work is to compare PLC and a mesh topology for the implementation of an AMI network in Colombia with several applications running simultaneously, we will adopt the same density defined in the previous research work (i.e. 0,025 meters per m² or its equivalent 25000 meters per km²). Finally, the *connectionManager* module establishes connections between nodes that are within the maximal interference distance of each other [6]. Fig. 11.4 shows the NED design for the PLC network.

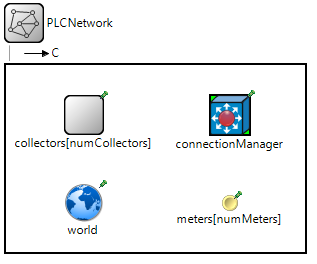


Fig. 8.4. PLC Network Set up

Meter are deployed as shown in Figure 8.5.

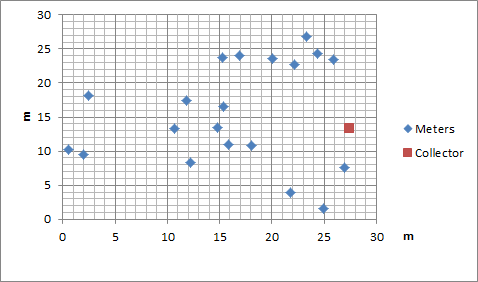


Figure 8.5 PLC bus topology

****8.3** **Characterization of the mesh network****

One of the reasons because mesh networks have become an appealing research topic in the field of networking is the possibility to conform networks in an adaptive, infrastructureless and self-organizing way. Through multihop connections, coverage area of the network can be expanded. This has an impact on both the transmission power and power consumption of the mesh nodes. Since mesh networks are usually intended for static radio nodes (as the ones that form the AMI network in a mesh approach), we will compare the performance of such a mesh network with that obtained with PLC.

The choice of IEEE 802.15.4 standard for the characterization of such networks is quite suitable, as it is the predecessor of the 802.15.4g standard for NANs [9]. Thus, the NIC submodules in the Meter Node and Collector Node are also based on IEEE 802.15.4. However, unlike PLC, the routing process is performed differently, as the collector is not one hop away and multiple meters must be passed by in order to reach the final collector. Protocol stacks for both the Mesh Meter Node and Mesh Collector Node are depicted in Fig. 8.5 and Fig. 8.6, respectively.

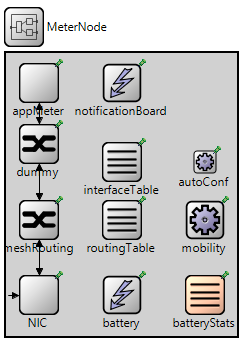


Fig. 8.5. Mesh Collector Node Protocol Stack

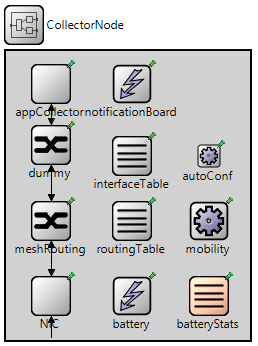


Fig. 8.6. Mesh Collector Node Protocol Stack

****8.3.1 Channel modeling****

In this wireless mesh network, we modeled the channel following a Log Normal shadowing path- loss model. This model is overall used in large and small scale systems, and previous research works have shown that it provides an accurate multipath channel modeling [1]. Mean attenuation and standard deviation for Log Normal Shadowing model were set at 2.42 and 3.12, respectively, according to field-measurements taken in an outdoor 500kv electric power system environment [2]. Parameters for the set-up of this propagation model are listed in Table 8.3.

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Mean attenuation (dB) | 2.42 |
| Standard deviation (dBm) | 3.12 |
| Time interval to define attenuations (s) | 0.001 |

Table 8.3 Parameters for Channel Model in the IEEE 802.15.4g scenarios

****8.3.2 network set up****

A 60 node network was simulated in a 60mx60m area, with a single collector strategically located. Packets are generated from every meter and forwarded towards the collector through a multihop routing mechanism. As in the case of PLC, the density we have adopted for simulation purposes is 25000 meters per km².

**8.4 Simulation Parameters**

In this section main parameters used for building the simulations are listed. Basically parameters at PHY, MAC, Routing and App Layers are presented. While Mesh network has a multi-hop topology, different from the bus topology on which PLC operates, main difference between them rests on the packets forwarding process. In PLC traffic from a meter is directly forwarded to its associated collector (which is previously specified in the simulation configuration file). On the other hand, in the mesh approach a packet is forwarded through several hops before it gets to the corresponding collector. As discussed earlier, the routing algorithm used to this aim uses a distance parameter to determine whether two nodes are neighbors or not. As this distance decreases, increases the number of hops the packet must pass by to reach the collector. In the mesh approach, the maximum distance between two nodes is set at 10m. In PLC, this distance is around 200m [8]. Parameters for the PHY, MAC, and connection manager submodules are listed in Table 8.2, Table 8.3, Table 8.4, and Table 8.5, respectively. Similarly, parameters for the same modules in the Mesh architecture are described in Table 8.6, Table 8.7, and Table 8.8.

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Propagation model | PERModelPLC |
| Receiver Sensitivity | -94dBm |
| Transmission Power | 1.1mW |

Table 8.2 Parameters for PHY submodule in the PLC scenarios

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Transmission power | 1.1mW |
| Data rate | 128 kbps |

Table 8.3 Parameters for MAC submodule in the PLC Scenarios

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Maximum transmission power | 1.1mW |
| Minimum signal attenuation | -94dBm |
| Minimum path loss coefficient (alpha) | 2.1 |
| Minimum carrier frequency of the channel | 2.4 GHz |

Table 8.4 Parameters for connection manager in the PLC scenarios

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Propagation model | LogNormal |
| Receiver Sensitivity | -94dBm |
| Transmission Power | 1.1mW |

Table 8.6 Parameters for PHY submodule in the Mesh scenarios

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Transmission power | 1.1mW |
| Data rate | 128 kbps |

Table 8.7 Parameters for MAC submodule in the Mesh scenarios

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Maximum transmission power | 1.1mW |
| Minimum signal attenuation | -94dBm |
| Minimum path loss coefficient (alpha) | 2.1 |
| Minimum carrier frequency of the channel | 2.4 GHz |

Table 8.8Parameters for connection manager in the Mesh scenarios

**9. Results and recommendations**

**9.1 SIMULATION RESULTS**

**9.1.1 PERFORMANCE ANALYSIS OF PRIME PLC AGAINST CURRENT PLC DEPLOYMENT**

According to interviews conducted by the author, utilities in Colombia are in the testing phase of 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 Orthogonal Frequency Division Multiplexing-based technologies to address issues related to the inherent harsh environment on power lines [1]. 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 is 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 [2].

Iberdrola, leader of the PRIME Alliance consortium, was one of the first utilities to deploy PRIME in large scale AMI networks, and proved performance in the Spanish grid and in other countries. PRIME delivers up to 1Mbps when operating the full FCC/ARIB band (3kHz / 490kHz) [1]. 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 [2]. 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 needed to handle such issues [1]. More detailed information about PRIME can be found at [3]

In order to evaluate how data rates affect the performance of AMI with simultaneous application running throughout the network, we have tested a 60 node PLC network, at a data rate of 1Mbps. Basically MAC layer is based on IEEE 802.15.4, with CSMA/CA as channel access method. Data rate in both PHY and MAC layers is set at 1Mbps.

When comparing to the same scenario in the typical PLC deployment, one can observe a significant improvement in the reliability of the whole network, for every single application. Table 9.1 shows the PDR obtained for AMR, WAM and RTP in both Current PLC deployment and enhanced PLC with higher data rate. 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. Figure 9.1 displays the discussed results.

|  |  |  |
| --- | --- | --- |
| Application | Current PLC | Enhanced PLC |
| AMR | 28.75% | 98.75% |
| WAM | 21.73% | 99.19% |
| RTP | 40% | 100% |

Table 9.1 PDR values for Current PLC and Enhanced PLC in the Worst case

When testing the intermediate case scenario, there is also a significant improvement with respect to the actual PLC deployment.

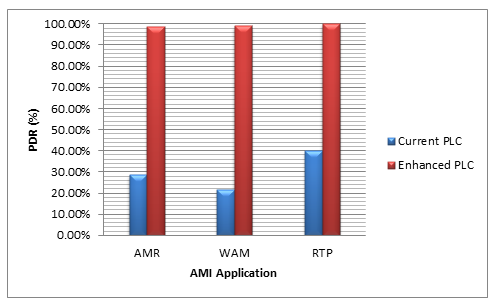


Figure 9.1 Comparison of Current PLC and Enhanced PLC on the basis of PDR for the Worst Case

Intermediate and best cases show consistent higher values of PDR for all applications, as displayed in Tables 9.2 and 9.3.

|  |  |  |
| --- | --- | --- |
| Application | Current PLC | Enhanced PLC |
| AMR | 51.33% | 100.00% |
| WAM | 45.46% | 99.98% |
| RTP | 19% | 100% |

Table 9.2 PDR values for Current PLC and Enhanced PLC in the Intermediate Case

|  |  |  |
| --- | --- | --- |
| Application | Current PLC | Enhanced PLC |
| AMR | 51.00% | 100.00% |
| WAM | 45.46% | 100.00% |
| RTP | 32.67% | 100.00% |

Table 9.3 PDR values for Current PLC and Enhanced PLC in the Best Case

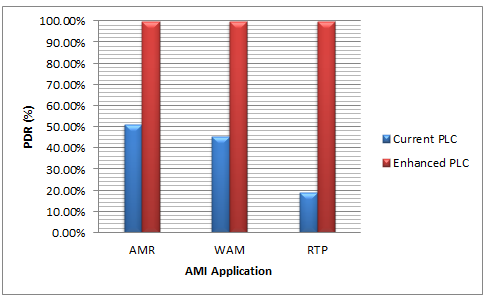


Figure 9.2 Comparison of Current PLC and Enhanced PLC on the basis of PDR for the Intermediate Case

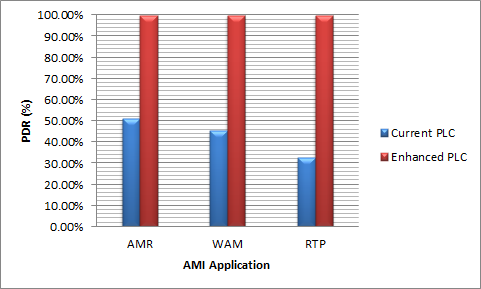


Figure 9.2 Comparison of Current PLC and Enhanced PLC on the basis of PDR for the Best Case

Consequently, through the adoption of technologies that provide higher data rates, a more reliable and robust AMI network can be obtained.

**9.1.2. Performance Analysis of IEEE 802.15.4g**

In order to evaluate the performance of WMN for AMI deployment, we have performed simulations of IEEE 802.15.4g networks to provide an overview of the behaviour of such approach in small and large scale AMI networks. Twenty meters have been randomly deployed in a 50x50m area, and a multihop forwarding mechanism has been implemented in every node for routing purposes. We intend to evaluate the impact of technology data rate in the performance the AMI, taking into account all traffic loads expected in the network. As stated in previous chapters, IEEE 802.15.4g defines a data rate up to 1Mbps. For simulation purposes, we have adopted the same data rate in the AMI communication backhaul. As every meter transmits only to those meters within coverage range (which has been set to 19m), the transmission power required in every node is reduced. Consequently, interference between nodes is also minimized. Parameter set up is displayed in Tables 10.1, 10.2 and 10.3.

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Propagation model | LogNormal |
| Receiver Sensitivity | -94dBm |
| Transmission Power | 0.0020mW |

Table 10.1 Parameters for PHY submodule in the Mesh scenarios

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Transmission power | 0.0020mW |
| Data rate | 1Mbps |

Table 10.2 Parameters for MAC submodule in the Mesh scenarios

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Maximum transmission power | 0.0020mW |
| Minimum signal attenuation | -94dBm |
| Minimum path loss coefficient (alpha) | 2.1 |
| Minimum carrier frequency of the channel | 2.4 GHz |

Table 10.3 Parameters for connection manager in the Mesh scenarios

Similarly to the methodology employed in the previous PLC performance assessment, we have carried out simulations for the worst, intermediate and best cases in WMN environments. Table 10.4 reports the PDR values for both AMR and WAM when running the three different scenarios. PDR exhibits a faster decay when considering the sending of WAM packets at lower frequencies. On the other hand, AMR converges to a PDR of \_\_\_.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Scenario ID | PDR AMR (%) | PDR WAM (%) | EED AMR (s) | EED WAM (s) |
| WCMesh |  |  |  |  |
| ICMesh |  |  |  |  |
| BCMesh |  |  |  |  |

Table 10.4 Summarized results for Mesh AMI network

Since bottleneck of mesh networks is commonly represented by the degradation of the performance with the increasing number of nodes and traffic load, the adoption of lower data packet sending frequencies is recommended in order to limit such impairment. According to simulation results plotted in Figs. 1 and 2, this indeed improves significantly the system’s performance. By decreasing the frequencies to which packets are generated, better values of PDR are obtained for both AMR and WAM applications. We attribute this behaviour to the fact that fewer collisions take place throughout the network, as meters attempt to transmit and forward less number of packets. Nonetheless, as for the advantages of adopting a mesh topology in a NAN environment one could mention: the possibility to expand network density, less energy consumption due to lower transmission power requirements, and the self-healing capabilities of the network (as multiple paths are available to reach the collector).

TO BE COMPLETED

Fig. 1 PDR for AMR in a IEEEE 802.15.4g-based WMN

TO BE COMPLETED

Fig. 2 PDR for WAM in a IEEEE 802.15.4g-based WMN

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**9.2 RECOMMENDATIONS**

In this section we outline important factors to consider when designing and deploying AMI networks. We shall give a full sweep of the actions to be taken by utilities in order to support the vast number of AMI applications that are expected to emerge in the near future. Considering that current infrastructure does not provide a robust communication backhaul for the transmission of information of different nature, which is the case of a full-fledge bidirectional AMI network, a well-structured methodology to roll out AMI pilots for the long term will become of the utmost importance. A set of best practices for the planning and execution of AMI networks will be presented, which are meant to increase the odds of success in their implementation.

**9.2.1 BEST PRACTICES**

1. **Revision of specific utility needs: Vision and business case.**

As many potential benefits are envisioned from the implementation of AMI, it will become important for utilities to determine which of them they will seek to maximize. For this purpose, a clear vision of how the rollout of AMI would impact the company and its primary interests must be built. Such a vision should be aligned to the corporate strategy. Utilities should then create a vision and a road map that includes all available information about the needs that have already been identified, main motivation for the implementation of the AMI and how the company’s goals are linked to the road map defined to fulfill them. This vision should also be communicated to all project’s stakeholders (employees, customers, regulators, vendors, government, etc.) [1].

Once more prevalent applications have been identified from this strategic planning exercise, utilities are recommended to use an iterative process to determine the impact of every single application in the specific domain where utility is expecting to get significant improvements. Overall, this process consists of creating a business case for each application to be run, so a balance between benefits, costs, flexibility and risk management can be obtained. [1]

1. **Planning and execution of the AMI: Selection of the most suitable communication technology according to the context on which the AMI is expected to be deployed.**

Along with integration to their business core systems, utilities should assess how well the chosen technology adapts to the current and long-term communication requirements of all applications expected to be deployed in the AMI backhaul. Future AMI applications will require greater capabilities (for example, lower values of latency for awareness situational communication systems or higher bandwidths for interactive customer applications) [1]. A long term vision in the choice of the technological approach to be implemented, as well as the technology maturity chosen, will be determining factors in the success of the AMI rollout.

Not only are technologies chosen for AMI deployment expected to be integrated with other utility core systems, but with other systems that may not be part of the utility domain [2]. In this regard, technology should also comply with existing and emerging standards to fulfill with the interoperability requirements of the AMI.

1. **Customers : Identifying customers’ needs and expectations about the AMI**

Customer engagement is crucial to succeed in the implementation of the AMI. While potential benefits for consumers derived from the transition towards a Smart grid are well known for all Smart grid players, it becomes crucial that consumers have a full understanding of their role in the whole process [2]. Thus, consumers are given the opportunity to choose their level of involvement in the process, while envisioning all tangible benefits they can get. Hence, utilities are recommended to involve consumers early on trials and first AMI pilots before moving to full scale deployment.

Segmentation of consumers is also another aspect to consider within the process of planning and executing an AMI implementation. Provision of differentiated services according to various customer profiles is a common step. On one hand, by providing tailored energy services, utilities increase their odds to meet customer’s needs, as well as their acceptance of the new structured system and business model. On the other hand, customer segmentation implies the possibility to target both consumers with great purchasing power, and those less well-off [2].

1. **Security and Interoperability**

Addressing security, data privacy and interoperability is a requisite of the utmost importance for a successful AMI deployment. As smart grid is characterized by increased flow of data in a two-way architecture, unauthorized access, disclosure and/or use of sensitive customer information is an issue that must be taken into consideration when designing a road map to implement the AMI network [3].

Along with security requirements and measures, utilities should also consider proven standards and industry best practices used for the integration of the AMI core systems with standard-based communication networks (such as IP). With such an open architecture, applications that are expected to emerge in the future AMI can be integrated in both the demand side and supply side [3].

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**10. OBTAINED RESULTS**

* A survey and comprehensive comparison of available communication technologies and routing protocols for AMI.

* A comprehensive overview of the AMI operation in Colombia. This includes the identification of technologies for AMI deployments, integration of ICT and AMI approach, and the specific needs that must be fulfilled in the Colombian electricity sector.
* An analysis of the performance of popular AMI technologies and communication protocols considering the response to future AMI applications.
* An identification of the most suitable technologies for deployment of future AMI applications within the Colombian electricity sector.

****Conclusions****

In this thesis we have presented a comprehensive review of communication technologies and routing protocols that have been widely adopted for the implementation of AMI networks. We have carried out a study to determine the current status of AMI deployments in Colombia and outlined aspects regarding business model, communication technologies, and communication protocols used in the AMI network backhaul. According to the specific needs of the Colombian Electricity Sector, most prevalent applications to be deployed in the near future AMI have also been identified.

We have also evaluated the performance of two different technologies for the implementation of AMI in Colombia. Power Line Communication (PLC) and IEEE 802.15.4g have been chosen for evaluation purposes. On the one hand, PLC has become one of the most widely adopted technologies for AMI rollout. The possibility to reuse the existing electric grid for data transmission is one of the main advantages that are envisaged by utilities when planning and deploying an AMI pilot. On the other hand, IEEE 802.15.4g is intended to be one of the most promising wireless mesh technologies for AMI, as it supports large and geographically diverse networks with higher data rates. Thus, it broadens the applicability of mesh systems to support future AMI applications.

Overall, simulation results show that current AMI deployments in Colombia fall short of expectations 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 future AMI) in both PLC and IEEE 802.5.4g approaches, 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 when increasing data rate from 128kbps to 1Mbps. Technologies such as PRIME or G3-PLC provide promising solutions for the Smart Grid, as they offer data rates up to 1Mbps [ref].

Results yielded from simulations also show that {TechnologyX} performs better than {TechnologyY}, as higher levels of reliability in the network can be achieved. Considering that packet delivery efficiency is of the utmost importance in the case of transmission of wide-area situational awareness information (such as the one in WAM applications), the choice of the best technology to meet the specific requirements for this application is based on how reliable the packet delivery is in such a case. Regarding AMR and RTP…

Some considerations to take into account when designing the AMI planning process, involve the…

The trade-off between coverage and latency is an issue yet to be investigated when employing wireless technologies in the NAN domain. Interoperability is another issue to be addressed, as legacy AMR systems may be connected to other IP networks, to support future AMI applications. Communication requirements such as secure routing, cyber security and QoS capabilities need further study, when considering the extended list of applications that may be part of future AMI systems.

****Future work****

While PLC has been widely adopted for AMI rollouts, and wireless mesh networks such as the ones based on IEEE 802.15.4g have also arisen as an appealing alternative for the deployment of AMI, the performance of other communication technologies needs further study. A performance evaluation of DSL and Wi-Fi is yet to be shown, in order to cover all proposed communication technologies in the NAN domain for AMI network deployment in Colombia. The analysis of the suitability of these communication technologies for the implementation of AMI is application dependant, according to the specific needs of utilities, and will be open to improvements as actual data from field measurements emerge. The future work will be to evaluate the performance of such technologies with more applications running in the grid. Based on such long term analysis, the odds of success in the selection of particular communication technologies for the AMI rollout can be improved.

There are also open networking issues related to the routing process in the NAN domain for the AMI backbone. On the one hand, security across the smart grid is a critical issue to be considered when designing and deploying the AMI. On the other hand, the different natures of traffic that will be transported throughout the network entails the need to implement routing protocols that are both cost-effective and QoS-aware. As it is expected for the smart grid to be expanded vastly, scalability of the AMI network will become an issue to be addressed. Trade-off between network density and latency is yet to be analyzed, as an increase in coverage implies an increase in number of hops to reach the final destination (and thus, a more reliable network by having more available paths), but also adds delay to the end-to-end communication.

Further study should also be devoted to the interoperability issues that implies the adoption of proprietary protocols in the majority of utilities premises. The integration of legacy AMR systems to IP-based networks in a standardized architecture becomes a critical issue to be addressed, as not only new applications are expected to emerge in the grid, but also security issues must be considered in such integration of devices and systems. In this perspective, open standards are required to update and upgrade the security mechanisms of such devices, and thus hedge the risks as they evolve [2].

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