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## Review

## Routing in Neighborhood Area Networks: A survey in the context of AMI communications

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## ABSTRACT

Smart Grid is the modern infrastructure of the electric grid, which has the objective to improve efficiency, reliability, and security. This is achieved through the control automation of the transmission and distribution lines, the enhancement of metering technologies, the implementation of 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 metering systems are some of the factors that influence the transit toward a more complex and robust electric grid. A fundamental component of the Smart Grid is an Advanced Metering Infrastructure (AMI), which provides a two-way communication flow between utilities and meters at the customer side. In this survey, we outline the main features of this new infrastructure, including a classification of communication technologies and routing protocols employed in the Neighborhood Area Network domain. We introduce a set of metrics for the AMI network (such as scalability, interoperability, latency, security, and quality of service), and present a full analysis and comparison of AMI-related routing protocols and technologies. Open issues related to wireless and wired technologies, as well as routing for the neighborhood area network domain are also provided.

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## 1. Introduction

Smart Grid is defined as the modern infrastructure of the electric grid, which has the objective 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 the introduction of new energy management techniques (Gungor et al., 2011). 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 toward a more complex and robust electric grid. 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.

The electric grid transformation involves the integration of a bidirectional communication infrastructure. Regarding the distribution component of the electric grid, an advanced metering infrastructure (AMI), which results from the integration of advanced sensors, smart meters, monitoring systems, and energy management systems, has been a focus of interest for governments, utilities, and academia. An initial implementation of the AMI involved the deployment of communication technologies to enable a two-way data flow for sending commands and information in real time to smart meters, as well as the reception of consumption information from the customer premises (Deconinck, 2008). Nowadays, it has been identified that the exchange of information between AMI devices will not be related exclusively to client's consumption, or the sending of control commands to smart meters. The list of applications is expanding to real time pricing, outage management, emergency response, in-home displays, among others (Deconinck, 2013). Therefore, it is critical for the utilities to define the communications requirements and the more suitable technologies for implementing the bidirectional communication system.

In this survey, we first identify the set of design factors that need to be considered in order to support the aforementioned applications in the AMI network. Since both wired and wireless technologies have been proposed for communications in the AMI, we survey the different communication technologies that have been proposed, with a focus on the network segment that connects the smart meters and

data collectors, i.e., the Neighborhood Area Networks (NAN). Additional to communication technologies, we also provide a detailed description of the different routing protocols proposed for the NAN domain. The protocols are compared based on a set of metrics and the performance results reported in the literature. In our survey, we consider the fact that the chosen technology and routing protocol should adapt well to the kind of traffic that will be transmitted.

In general, most previous surveys about networking in Smart Grid consider only a revision of suitable communication technologies for AMI (Gungor et al., 2011; Yan et al., 2013; Namboodiri et al., 2012), or a revision of routing protocols but for a set of specific communication technologies (e.g., wireless) (Iyer, 2011). Our main contribution in this paper corresponds to providing a structured comparison of the routing protocols (regardless of the communication technology) based on well-defined metrics and with a classification of such protocols according to their behavior and reported performance in NAN scenarios. Furthermore, we provide a state of the art review about AMI deployments, and include an identification of issues that are yet to be addressed, which arise from the nature of the communication technologies and the routing processes that are employed in the AMI context.

The remainder of this paper is organized as follows. In Section 2, we describe the AMI network, its evolution regarding the AMI deployments reported around the world, and the design factors to consider at the time of deployment. In Section 3, we classify the communication technologies according to the network segment they fit better, and identify their advantages and disadvantages. Next, in Section 4 we provide the descriptions for the routing protocols proposed for the NAN domain, followed by Section 5 with a qualitative comparison among the routing protocols. The open networking issues are described in Section 6. Concluding remarks are provided in Section 7.

## 2. Advanced metering infrastructure

Smart grid communications 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 (iii) a Wide Area Network (WAN), which communicates data collectors with a utility control center (Tang and Dai, 2010). The Advanced Metering Infrastructure (AMI)

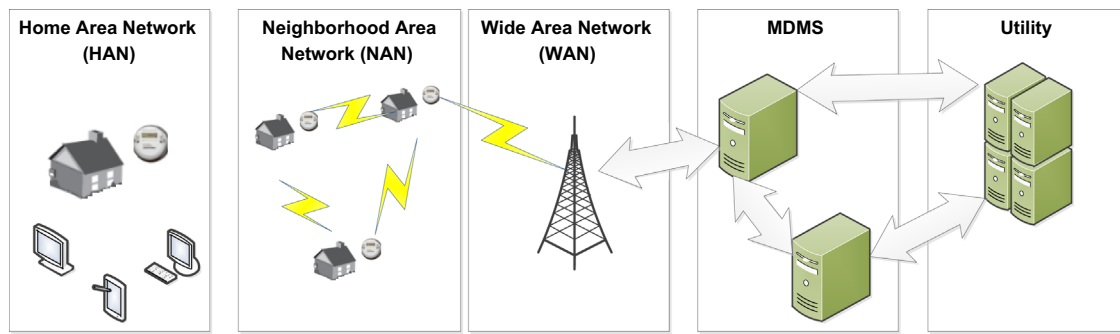


Fig. 1. Basic AMI deployment.

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 (Wang and Leung, 2011; Bennett and Highfill, 2008). An example of a typical AMI deployment is depicted in Fig. 1.

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 by Yan et al. (2013), 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 (Wang and Leung, 2011; Iyer, 2011):

- **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 (Bennett and Highfill, 2008). 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 Section 5, we compare and discuss the routing strategies and protocols that have been adopted in the communications backbone of the AMI context.

### 2.1. Overview of global deployment status of AMI

The advanced metering and demand response survey performed by Federal Energy Regulatory Commission (2012) 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 (Federal Energy Regulatory Commission, 2012).

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 (Nambodiri et al., 2012).

### 2.2. Design factors of the AMI network

Due to the evolution of the electrical grid, specifically electricity metering, a two-way communication network has been required. Applications such as smart metering, demand response (DR) and remote disconnect/reconnect require a communication network that supports them, as well as future application that will become prevalent, such as the sending of information about real time pricing

from the utility to the consumers' homes or electric vehicles charging stations. Aspects regarding the choice of technology in which the AMI will be deployed, the constraints and security of routing protocols (Md Zin et al., 2014), and the system capacity limits are some of the issues to solve through a proper network planning. This plan requires the use of best practice guidelines for the design and deployment of the AMI. The main factors to consider when designing AMI networks are outlined as follows (Leon, 2011):

- Understanding the networking needs and goals of the utility.
- Identifying the main design constraints of the AMI vendor's equipment (in terms of hardware and software capacity).
- Considering the compatibility with AMI communication protocols.
- Planning production costs.
- Design of network topology, considering adaptability with wireless and wired communications.
- Identifying the need for pilot installation, field testing, and site infrastructure exploration.
- Developing a plan for deployment, testing, and post-design adjustments.

Given that each utility has different needs and expectations on the behavior of the AMI network, and considering the varying constraints on performance requirements, a full understanding of these operation needs must be taken into account when designing the AMI.

In relation to the selection of vendors' equipment, the creation of link budgets for the various types of devices that will be used in the network deployment is the first step. In this process, issues such as calculation of hopping limits, battery capacity limits, and transmission power must be considered (Leon, 2011). Also, computer-aided design tools may be required for simulation, dimensioning, and placement of infrastructure equipment purposes. Through this kind of tools, the model of the network is created and then the planning of the whole systems architecture can be deployed in the service area destined for that aim.

Another integral part in the design process is setting up a pilot system. In Leon (2011) a set-up of test transmitters in multiple locations within the service area is recommended. Execution of field measurements by testing the link configurations such as collector-to-meter, collector-to-repeater, and meter-to-meter is also proposed, in order to get a general view of the system performance.

### 3. 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.

#### 3.1. HAN domain

##### 3.1.1. 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). The physical layer is divided into two layers: PHY data service and PHY management. The main function of the physical layer is to transmit and receive messages through the radio medium. MAC layer provides two main services: MAC data service and MAC management service. Both of them allow the transmission and reception of frames through the PHY data service. Functions such as channel switching, energy detection measurement, clear channel assessment, security functions (AES encryption), and quality of service through guaranteed time slots

are some of other features of this standard. Other technical characteristics of the 802.15.4 standard are listed below:

- Frequency bands: 868 MHz/915 MHz and 2.4 GHz.
- Raw data rates: 868 MHz: 20 kbps; 915 MHz: 40 kbps; 2.4 GHz: 250 kbps .
- Channels: 11 in the 868/915 MHz ; 16 in the 2.4 GHz.
- Range: 10–20 m.
- Latency: Down to 15 ms.
- Addressing: Short 8 bit or 64 bit 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 (Understanding ZigBee gateway, 2010). 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. As a result, ZigBee is especially useful in the HAN domain (Sabbah et al., 2014). Many AMI operators prefer smart meters on which the ZigBee protocol can be integrated, embracing the recommendation of the National Institute for Standards and Technology (NIST). Two different ZigBee specifications are available: (i) the one based on the RF4CE specification, which is designed for running in low-power and resource-constrained devices, mostly for control applications. It employs specially developed protocols for network and transport layers; and (ii) the IP-based version, named ZigBee IP, which provides mesh networking and IPv6 connectivity, enabling Internet access from ZigBee devices. The PHY and MAC layers of both specifications are based on the IEEE 802.15.4 standard.

WirelessHART is another technology based on 802.15.4. This technology, however, defines data link, network, and transport layers for deploying real-time industrial control applications (Song et al., 2008). It has become very popular in the electric sector. In the link access, WirelessHART defines a 10 ms time-slot for guaranteed link access. In the upper layers, it designates a centralized network manager in charge of maintaining updated routes. It also employs mesh-networking with self-healing and self-organizing 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 the MAC layer and network layer to enable the transmission of IPv6 packets over IEEE 802.15.4 (Montenegro et al., 2007). 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. Therefore, wireless embedded Internet access is enabled on any device, which provides an option for communications in HAN environments.

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 frequency band, 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 (Lu et al., 2011).

##### 3.1.2. 802.11 and Wi-Fi

The IEEE 802.11 standard (Cali et al., 1998) specifies PHY and MAC layers for Wi-Fi. It operates in the ISM 2.4 GHz and 5 GHz. Other technical specifications of this standard are as follows:

- Frequency bands: 2.4 GHz and 5 GHz ISM bands.
- Maximum data rate: 1 Mbps (802.11b) to 1 Gbps (802.11ac).
- Channels: 13 overlapping 22 MHz wide frequency channels.
- Range: 100 ft at 11 Mbps; 300 ft at 1 Mbps.
- Channel access: CSMA-CA.
- Modulation technique: DSSS

As Wi-Fi is a very mature technology (it is estimated that more than 100 million households worldwide have a Wi-Fi installation for home networking) (Wi-Fi Alliance, 2010), it becomes a suitable communication technology inside the HAN through which devices at home send information to smart meters. Wi-Fi 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.

Among the advantages of Wi-Fi, it operates in unlicensed spectrum, so it is resilient to many types of interference and can coexist with other technologies that share these bands, as it provides mechanisms to deliver robust performance in shared-spectrum and noisy RF environments (Wi-Fi Alliance, 2010). 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 a higher power consumption (when compared with other HAN technologies such as ZigBee).

### 3.1.3. Ethernet

It is a very popular communications technology standard primarily used within the HAN domain, but can also be used in the NAN domain. A variety of speed can be achieved, including 10 Mbps, 100 Mbps, 1 Gbps and 10 Gbps. Main advantages are it being standard-based, easy set up and configuration. Among the drawbacks are that the technology may not be appropriate for connecting all devices in the HAN, due to the high cost and power requirements, plus the need for separate cabling back to a central point.

A comparative summary of the main technologies employed in the HAN domain is presented in Table 1.

## 3.2. NAN domain

### 3.2.1. IEEE 802.15.4 g

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 (Shin et al., 2010):

- Frequency bands: 700 MHz to 1 GHz and the 2.4 GHz band.
- Frame sizes: up to a minimum of 1500 octets.
- It addresses smart grid's geographic requirements by defining appropriate power levels.
- It increases data rates formally to hundreds of kbps, and even Mbps, thus broadening the applicability of mesh systems

**Table 1**  
Comparative summary of main technologies employed in the HAN domain.

Technology	Data rate (Mbps)	Range (m)	Security level	Deployment cost
ZigBee	0.02–0.25	10–20	Low	Low
WiFi	Up to 1000	10–100	Medium	Medium
Ethernet	100–10,000	Up to 100	High	High

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.

It is natural that technologies based on the 802.15.4 standard evolve to support the 802.15.4g technology, in order to provide communications for NAN environments. Such is the case for ZigBee, whose participation in standardization activities for smart grid NANs has been announced in early 2014 (Maley and Renner, 2014). 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. IEEE 802.15.4g addresses reliability in outdoor environments, interference resiliency, and support of high density operation by FHSS techniques. The latter represents a vast improvement over historical not so reliable wireless technologies.

### 3.2.2. 802.11 s

The IEEE 802.11s standard envisions a small-to-medium scale WLAN mesh network configured with a maximum of 32 mesh nodes (called Mesh Points MPs). 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 IEEE 802.11. One of the most important functionalities of the new IEEE 802.11s is the multi-hop routing, which sets up the paths for the wireless forwarding. Mesh capabilities are provided to the mesh points, so they are able to participate in the forwarding process. Regarding the changes in this standard when compared with IEEE 802.11, the amendment is performed only in the MAC layer (modifications to PHY layer are not required) (Bahr, 2006).

### 3.2.3. 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 may be 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. The main technical specifications of this technology are stated below.

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 (from few dozens of kbps to 100 Mbps, respectively) (Sabbah et al., 2014). NBPLC systems generally use the CENELEC (Comité Européen de Normalisation Electrotechnique) bands (3–148.5 kHz). 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. NBPLC generally refers to PLC systems supporting data rates over 1 Mbps.

The main advantage of PLC is associated to the low costs in terms of infrastructure's development. 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,

**Table 2**

Comparative summary of main technologies employed in the NAN domain.

Technology	Data rate (Mbps)	Range (m)	Security level	Deployment cost
PLC	Up to 100	100	High	Medium
WiFi	Up to 1000	100–100	Medium	Medium
IEEE 802.15.4g	Up to 1	10–100	Medium	Medium
DSL	Up to 10	10–100	High	Medium

control, and automation in large systems comprising tens or even hundreds of components spread over relatively wide areas, which contributes to provide scalability. Furthermore, as the power lines are owned by the utility, there is more independence in relation to sending information through third-party networks or operators. 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. The technology is also limited by its low bandwidth, which is why it may not be suitable for more robust applications where large amounts of data need to be transferred. Besides the fact that feeder cables are not designed for data transmission, they are also prone to be interfered by the inverter's outcome.

#### 3.2.4. 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 (Gungor et al., 2011). Commonly, the frequencies on which this technology works are greater than 1 MHz through an ADSL enabled telephone line.

As for the advantages of this technology, one could mention that given a high data transmission rate and the low installation costs for the network deployment, DSL is a good option for the AMI implementation. Regarding the drawbacks, distance dependency is the primary constraint of this technology.

A summary of the technologies used in the NAN domain is depicted in Table 2.

### 3.3. WAN domain

#### 3.3.1. 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. Some of the cellular technologies employed for the long-haul communication are 2G, 2.5G, 3G, and LTE. The latter has a high-capacity of bandwidth and, consequently, can also support several QoS requirements.

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. Data rates for cellular technologies in AMI projects are

now much more competitive. Furthermore, coverage provided by cellular networks is another outstanding advantage, which helps to improve network capabilities. On the contrary, among the identified drawbacks 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. Moreover, transmission through cellular networks still has a high cost, especially when SMS is employed to send information from smart meters to data collectors.

#### 3.3.2. WiMAX

WiMAX (Worldwide Interoperability for Microwave Access) is a wireless broadband technology based on the standard IEEE 802.16 (Marks, 2014). 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 (Aguirre and Magnago, 2013)

- 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 WAN domain, one could focus mainly in 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 (Paolini, 2010). 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.

## 4. Routing for neighborhood area networks in AMI

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. As we mentioned before, different from other surveys, in this paper we consider not only protocols for wireless mesh-based networks but also outline communication protocols for AMI deployed on wired technologies in the NAN domain.

Regarding the traffic involved in the two-way communication channel, different types of traffic can be identified: (i) traffic consisting of data containing the meter-reading, going from homes to utilities' data collectors; (ii) traffic consisting of data containing data going from collectors to substation or the utility itself; and (iii) traffic consisting of data from applications in the Smart Grid. Some of these applications are (Tan et al., 2011) lighting control, heating, ventilation, detection of fluctuations and power outages, switching on and off (remote control of the meter from customer side), demand response, and vehicle charging.

Considering that 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 the routing for the NAN domain in the AMI architecture. Several routing protocols have been classified and evaluated according to a certain set of metrics (Sabbah et al., 2014) that will further be explained. The routing protocols are presented as follows.

#### 4.1. RPL

In an AMI network, the routing protocol must guarantee low energy consumption, assure privacy and information security, as well as support self-organization and self-configuration features. For this purpose, the IETF has proposed the Routing Protocol for Low Power and Lossy Networks (RPL) (Winter et al., 2012). This protocol is of the distance-vector type, and is based on IPv6. It was designed considering the requirements specified in RFC 5826 (Brandt et al., 2010), RFC 5673 (Pister et al., 2009), RFC 5548 (Dohler et al., 2009) and RFC 5867 (Martocci et al., 2010). Some of these requirements include (i) scalability, which refers to the capability of supporting the organization of a large number of nodes into areas of configurable size; (ii) dynamicity, which makes reference to the capability of the routing protocol to support updating mechanisms in order to be informed of changes of connectivity, facilitating reorganization and self-healing features; (iii) latency, which refers to how long it takes for a packet to get from source to destination throughout the network; and (iv) parameter-constrained routing, which has to do with identifying node capabilities that will be used by the routing protocol for forwarding decision (e.g. CPU, memory size, battery level, among others).

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. An objective function (OF) is defined for the purpose of combining a set of metrics. The main idea behind RPL is to maintain information about the network status using one or more directed acyclic graphs (DAGs). A DAG is a directed graph in which all edges are oriented in such a way that no cycles exist. For each DAG created in RPL there is a root. The DAG's root is typically the gateway in the AMI network. All edges in the DAG are contained in the routes oriented to the root node. Each node in the DAG is associated to a rank. For the construction of the DAG, the gateway creates control messages called DIOS (DAG Information Object). The main functions executed by the DIO messages are listed below (Iyer, 2011):

- To identify the DAG from which any root is originated.
- To spread the Rank information of the starting node.
- To define the objective function (OF) that specifies the metric, or the combination of metrics, used to compute the rank in each node.

Once multiple DIO messages have been received, a node computes its own rank and determines its position in the DAG. One way to compute the rank is utilizing the Expected Transmission Count (ETX) as a metric. ETX measures the quality of a route between two nodes, by estimating the average number of required transmissions to send data packets to a neighbor. Since nodes in a network are susceptible to multiples faults, RPL builds a Destination Oriented DAG (DODAG) with several routes from each node. This contributes to enhance the performance and robustness of the network, as well as to guarantee quality of service and to handle traffic in real time (Pavković et al., 2011).

A detailed implementation of RPL for AMI networks is presented in Wang et al. (2010). 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. Once the information that must be stored and maintained by each node is defined, the data traffic forwarding rules are introduced. 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 by Wang et al. aims at providing reliable and low-latency routing support for large-scale AMI networks, through the integration with CSMA-based MAC layer protocols.

#### 4.2. 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 for 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.

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. Three assumptions are required for geographic routing to be performed: (i) a node can determine its own position; (ii) a node is aware of its neighbors' positions; and (iii) the position of the destination is known (Ruhrop, 2009). Among the drawbacks of this protocol, we can mention that GPS devices are costly. In addition, if hard coding of location is employed, the geographic coordinates cannot be changed. This may result in a lack of flexibility when a smart meter is relocated in the premises of a different customer. In general terms, the determination of geographical location is a challenging task (Sabbah et al., 2014).

A performance analysis of geographical routing in AMI networks through a simulation set up is presented in Iyer (2011). 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 were collected, such as the ratio of total transmitted packets to received packets per node, the packet success probability, and the latency.

#### 4.3. AODV

Ad Hoc On-Demand Vector (AODV) routing protocol builds on the Destination-Sequenced Distance-Vector (DSDV) protocol and is based on the RFC 3561 (Perkins et al., 2003). In this protocol, routes are created on demand by minimizing the number of broadcasts (which, unlike DSDV, does not maintain a list of available routes). The routing process in AODV is basically composed of three phases: (i) the discovery phase, whereby a Route Request packet (RREQ) is sent from the source to the destination. Each RREQ has a sequence number that is compared to the sequence number of every intermediate node in the network to determine whether the packet should be forwarded to next hops or whether a Route Reply message (RREP) should be sent instead; (ii) the second phase, which consists of updating the destination sequence numbers in the routing tables of intermediate nodes; and (iii) the third phase,

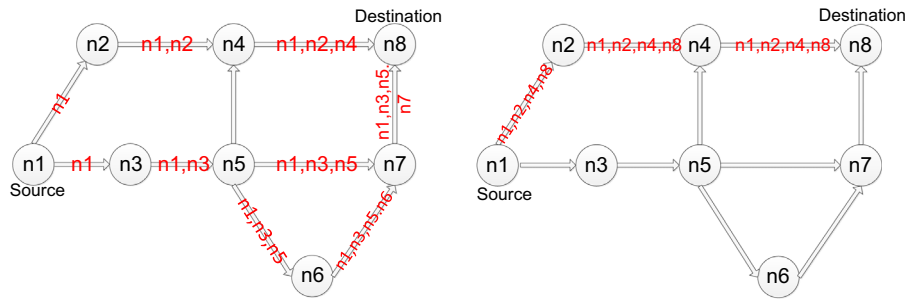


Fig. 2. Dynamic source routing. (a) Route discovery. (b) Route maintenance.

where data sending takes place (Bennett and Wicker, 2010). In the case of AMI only the first phase would be performed once, as the network is stationary, and routes are established in the very beginning.

While AODV was originally designed for Mobile Ad Hoc Networks, it is important to note that the protocol has been modified in previous research works, so it can be used as a routing protocol for NANs in the Smart Grid context, as shown in Farooq and Jung (2013), Baba (2013), and Toimoor (2013). For example, in Toimoor (2013) the authors propose a modification to the protocol, where selected nodes are provided with more intelligence, contributing to lower latency than regular AODV, and making it a useful communication protocol for current and future AMI applications. Among these applications are demand response, remote control of meters (switching on and off of electrical devices), detection of power outages, and electric vehicle charging. In the simulation, the nodes were placed at distances such that the transmitted signal is only received by the neighboring nodes. As the number of hops increased, the throughput decreased, which is the expected behavior due to the routing overhead increment inherent to AODV.

#### 4.4. DSR

Dynamic Source Routing (DSR) protocol is an on-demand routing protocol that follows the concept of source routing. It is based on the RFC 4728 (Johnson et al., 2007). In this protocol, a node maintains a route cache which contains source routes that are known by all other nodes. The route cache is continually updated as new routes to the source are learnt by the nodes. This protocol maintains two major phases: Route discovery and Route maintenance. Whenever a node has to send a packet to some destination, it initially checks the route cache to find out whether the route to the destination is already known. On the one hand, if the route to the destination is already present in the route cache, it uses the same route to transmit the packet. On the other hand, if the route to destination is not present in the route cache, then the node initiates route discovery by broadcasting a route request packet. This route request packet contains a destination address, a source node address, and a unique identification number. Each and every node checks if it has the destination route to the address sent in the route request packet. If the node does not find the destination route in its route cache, it adds its own address to the route record packet and forwards the packet to the nodes among its outgoing links. A route reply is generated only when the route request packet reaches the destination or an intermediate node has the route to the destination in its route cache.

If the route reply is generated by the destination, then the destination places the route record contained in the route request into the route reply packet. If the route request is responded by an intermediate node, then it will append its cache route to the route record to generate the route reply. The responding node must have a route to the initiator in order to send the route reply. If the responding node has the route to the initiator in its route cache,

then it should use that route. Otherwise, if symmetric link is supported, then the node must send the route reply by using the reverse route in the route record. As with the adapted AODV, routes are established only once in DSR, when applied in a Smart Grid scenario. As network topology is not expected to change, maintenance mechanism is not used, and source node utilizes its current route to reach the destination (PratibhaKevre, 2014). An overview of the operation of DSR is provided in Fig. 2.

An evaluation of DSR together with AODV in a grid-based cluster network is performed in PratibhaKevre (2014). 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  $1500 \text{ m} \times 1500 \text{ m}$ . 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 than 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).

#### 4.5. DADR

Distributed Autonomous Depth-First Routing (DADR) (Iwao et al., 2010) 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 (Herberg et al., 2013; Yi et al., 2015). As the data forwarding occurs, all the information learned is used to update the routing table. This happens during periodic Hello Messages exchanged among neighboring nodes, or when the nodes receive a route poisoning message. In order to control and detect loops, a unique Frame ID (FID) is added to a packet. Each time a node forwards a packet, its FID is stored, together with the packet's sender and the packet's next hop. The FID is useful for loop detection, so that when a loop is detected, a poisoning message is generated and the other nodes in the topology are informed about the situation.

A simulation scenario of more than two thousand smart meters is presented in Iwao et al. (2010). 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 that 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.



#### 4.6. HYDRO

Hybrid Routing Protocol (HYDRO) (Dawson-Haggerty et al., 2010) is a link state routing protocol for Low Power and Lossy Networks. It uses DAGs to provide multiple reliable paths to a border router. To this end, each node builds its default route table by adding its neighboring nodes toward a border router. The entries in the route table will be ordered following an ETX metric. According to the top ranked entries of its default table, each node periodically creates a topology report. The nodes piggyback the topology reports on periodic collection traffic, allowing border routers to build and maintain a global view of the topology. The first primitive of HYDRO is the provision of a Default Route Table, which is made of a list of entries (each containing the link-layer address of a node in the direction of a border router). Thus, each node has information about the link-layer packet success rates, so an evaluation of the quality of that link can be performed. This feature is especially important to fulfil the reliability, as multiple routes are provided to a given destination. HYDRO is considered both a centralized and distributed forward mechanism: on the one hand, the low-power nodes maintain a distributed DAG that provides the set of default routes for communicating with border routers; on the other hand, the border routers maintain a global view of the network topology, through the reports sent by each node.

In Dawson-Haggerty et al. (2010), a performance evaluation of HYDRO with different metrics is presented. It involves the implementation of a set of test-beds 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 98.9% in average. As for the scalability, every node's state is bound by the number of destinations it communicates with.

#### 4.7. HWMP

The Hybrid Wireless Mesh Protocol (HWMP) is the multihop default routing protocol for IEEE 802.11 s 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, which, unlike AODV, works on layer 2 and uses a radio-aware routing metric.

When a node needs a path to a given destination, it broadcasts a route request message requesting a route to that destination (Bahr, 2006). This route request message is processed and forwarded by all mesh points to the originator of the route discovery. The destination node, or an intermediate node that owns a path to the destination, answers with a unicast reply message indicating the route requested. After this, the forward path to the destination is set up.

Considering the diverse nature of applications that generate traffic throughout the network, and given that applying a same retransmission mechanism for all packets may reduce the network throughput (Meng et al., 2014), a new method of selective retransmission has been proposed. Jung et al. (2011) 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 for the applications that are part of the smart grid architecture.

### 5. Comparison of routing protocols in AMI networks

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 section we compare, based on a set of selected metrics, the routing protocols for NAN environments in AMI networks introduced in Section 4. We employ the description of operation, as well as the performance results reported in the literature to classify the protocols. In Iyer (2011), 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 160 ms and 173 ms 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% (Iyer, 2011).

Other protocols such as DADR and HYDRO have also been analyzed, considering their behavior in test-beds and real AMI deployments. In Iwao et al. (2010), 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, shown to have a high reliability according to Dawson-Haggerty et al. (2010), as multiple 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 study that summarizes the works in Wang et al. (2010), Ruhrop (2009), Perkins et al. (2003), Toimoor (2013), Johnson et al. (2007), and Dawson-Haggerty et al. (2010) is presented in Table 3. The metrics employed for comparison are described as follows:

#### 5.1. 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 Xu (2011), two limit values for latency are specified on the basis of the components that generate the traffic. As for the Phase Measurement Units (PMU) and Control Centres, 10 ms 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 1 s.

**Table 3**  
Comparison of Routing Protocols in the NAN domain of AMI networks.

	Similar performance for the given network size and traffic scenario. (500 Node Network)		Similar features: Discovery and Maintenance Mechanisms		Sharing distributed forwarding approaches		
	Geo-routing	RPL	AODV	DSR	DADR	HYDRO	HWMP
<b>Latency</b>	End-to-end delay: Avg 173ms	End-to-End Delay: Avg 160ms	High. Great amount of overhead generated (hello messages)	Better than that reached by AODV. Less Overhead	High. Data packets need to travel forward to several hops in order to reach the destination	Better than the reached by DADR. The border router helps to forward packets faster	End to end delay: 300ms for a 300 node network
<b>Reliability</b>	High PDR > 99%	High PDR > 99.9%	High PDR > 91.4%	High PDR > 96%	High PDR > 97.8%. Protocol shows capability of learning new routes when link failures	High PDR > 98.9%. Multiple routes are provided to a destination. Redundancy	High PDR > 96% obtained when 9 nodes were deployed, but the protocol outperform when the number of nodes increase to 25 or more
<b>Scalability</b>	High, more than 2 million metering end points	Implementation specific. (Factors such as trickled timer, operating mode, etc.)	Low. Transmission of hello messages in a large network can become flooding. High cost of processing	Low. Maintenance of routing tables in a large network have a high cost	High. 1500 Node network topology. The protocol doesn't need too much overhead when updating routes	High. As the protocol is defined by both centralized and distributed mechanisms	Low. When 25 or more nodes are in the network, congestions occur
<b>Interoperability</b>	High	High	High	High	High	High	High
<b>Adaptability</b>	Highly adaptable to different network topologies	High. routing paths from the nodes to the central points are constructed according to the deployed architecture	High. Expiration time feature helps to clean up table potential broken and out-of- date links information	High. Any change in the network is detected through the Maintenance Mechanism	High. Routing paths are updated, removed, constructed according to the topology state	High. As the protocol involves the evaluation of links qualities according to topologies changes	Highly adaptable to different network topologies
<b>Data delivery priority</b>	Application dependant	Application dependant	Application Dependand	Application Dependand	Application Dependand	Application Dependand	Application Dependand
<b>Availability</b>	High	High	Medium	Medium	High	High	Low
<b>Ease of deployment</b>	High	High	High	High	Low	High	Low
<b>Routing scheme</b>	Mesh-under	Route-over	Mesh-under	Mesh-under/Route-over	Mesh-under	Mesh-under/Route-over	Mesh-under

## 5.2. 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 (Wang et al., 2011). 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.

## 5.3. Scalability

This metric can be considered as an ability of a system to handle increasing amounts of work in an efficient manner (Zhou et al., 2012). 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.

## 5.4. 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.

## 5.5. Adaptability

This refers to the ability of a routing protocol to adapt to different network topologies, changing link conditions and dynamic processing power and memory overhead. For example, a measure of adaptability refers to how well a protocol performs when nodes lose their transmission power below a given threshold, which results in generation and forwarding of error packets. Considering the vast number of applications and devices that are

expected to emerge in the AMI, the adoption of adaptable routing protocols in the communication backbone is a crucial step to guarantee the self-configurable and self-healing characteristics of the AMI in the NAN domain.

### 5.6. 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 follows: (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.

### 5.7. 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).

### 5.8. Ease of deployment

This metric refers to how well the protocol deals with the network deployment problem. Traditionally, such an issue has been explored as the problem of how or where to place all individual devices and systems that are part of the network, to achieve a good coverage and to meet all communication requirements that the network is intended to address. In order to reach that goal, a generic networking layer and well-tested generic transport protocols are usually needed. Overall, the use of standardized protocols such as IP helps mitigate the network deployment problem, as it provides a generic architecture on the basis of which protocols of higher layers can the network be built (Duquennoy et al., 2011).

### 5.9. 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.

- **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.
- **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.

## 6. Open networking issues

In this section, we identify the challenges related to networking issues in AMI networks. We classify them to separate the challenges inherent to the communications technology from those inherent to the routing process.

### 6.1. Related to communications technologies

When wireless technologies are selected for communications in the AMI, in particular in the NAN domain, aspects such as coverage, reliability, and spectrum management are still open issues (Sun et al., 2012). If coverage is increased, this may have a negative impact in terms of capacity of the wireless network, due to interference and re-transmissions caused by larger wireless links. Also, if coverage is reduced to avoid the interference problem, the number of next-hop candidates gets reduced; hence, the process of finding a path to/from the collector may fail. Relaying techniques are being proposed in order to address this trade-off between coverage and capacity (Sun et al., 2012).

In terms of reliability, the extended list of applications to be supported by the AMI network brings higher standards with variable quality requirements in order to serve such applications. Nonetheless, wireless communications are susceptible to adverse weather conditions and variable propagation patterns, which directly affect the network reliability. Forwarding mechanisms that improve reliability in AMI networks with highly unstable links have been proposed to address this issue (Céspedes et al., 2012; Yi et al., 2015). Spectrum management is another key challenge when more and more wireless technologies over unlicensed bands are deployed. Such is the case for 802.11-based and 802.15-based technologies that are employed in the NAN domain. An efficient use of the spectrum is therefore a critical issue.

If the selection is for a wired technology, such as PLC, then network adaptability is an issue to consider. In the majority of cases, bus or star topologies that connect smart meters to a collector are employed with wired technologies. Thus, a single link failure may represent the complete disconnection of a customer premises since the nature of the technology does not permit to find alternative paths (unless redundant links are employed, which increases the deployment costs). Another issue among the different wired technologies is the interoperability. Since Automatic Meter Reading (AMR) has been present for some time, traditional technologies employed at the time did not consider the possibility to interconnect to other networks. Most solutions are built on top of proprietary stacks of protocols that reduce the chances to re-use such technologies in order to deploy the new IP-based applications expected in the AMI network. Thus, support of IP networking constitutes an issue to be yet addressed in the NAN domain.

### 6.2. Related to the routing process

There are several open issues that need to be addressed together with routing. On the one hand, there is a need for securing the information that is transmitted across the smart grid. Apart from mitigation of cyber-security attacks, a balance between individual energy consumption data for billing purposes and aggregated data for statistical analysis is required from the AMI (Saputro et al., 2012; Md Zin et al., 2014). On the other hand, the different natures of traffic due to an expanded list of applications to be deployed in the AMI raises the need for QoS-aware routing. Hence, routing metrics should adapt to fulfill the QoS requirements. Although complex

combinations of metrics can be achieved through objective functions such as the one proposed in RPL (Dohler et al., 2009), there is still a lack of flexibility for the objective function to adapt “on the fly” according to the type of traffic that is being routed at a certain time.

Moreover, the NAN domain of an AMI network poses a critical challenge: a network with a number of nodes that start from hundreds and may grow to millions. Although scalability is defined as one of the design factors of routing protocols, those employed in the AMI context need to demonstrate that a minimum level of performance can actually be maintained in a very large network.

## 7. Conclusion

In this paper, we have presented a comprehensive survey of communication technologies and routing protocols for Advance Metering Infrastructure deployments, with a special focus on the network domain that connects the smart meters at customer premises and data collectors that connect to the utility, namely the Neighborhood Area Networks (NANs) in AMI. We have described the evolution of the AMI network and the advances in real deployments around the world. As for the communication technologies, we have provided a classification of the different wired and wireless options, identifying the network domain in which each technology fits better. Together with the communication technologies, we have also provided descriptions for the routing protocols proposed for the NAN domain and the set of metrics we have employed for the comparison.

The open networking issues have also been identified and classified depending on whether they are related to the communication technology or the routing process. A proper balance between coverage and capacity are aspects to be investigated when employing wireless technologies for a NAN network with a large number of nodes. Also, while legacy Automated Meter Reading (AMR) systems can be extended to support other AMI applications, interoperability is still an issue, specially when connection to traditional IP networks is expected. Aspects such as secure routing, privacy protection, and QoS capabilities need further study for routing in the NAN domain to support the extended list of applications to be deployed in the AMI network.

As part of our extended work, we will further complement the performance evaluation of all the different routing protocols considered herein. Firstly, we will define a unique AMI scenario, in order to keep the topology conditions uniform. Secondly, we will study the performance of such routing protocols by means of simulations, considering all metrics that we have previously described in this paper.

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