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TESIS DOCTORAL

Contribution to Machine-to-Machine Architectures for Smart Grids

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DEPARTAMENTO DE INGENIERÍA TELEMÁTICA

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A María y a Emma
A mis padres y hermanos

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"Knowing a great deal is not the same as being smart; intelligence is not information alone but also judgment, the manner in which information is coordinated and used."

Dr. Carl Sagan, Cosmos

Abstract

The electrical grid is a huge and complex system which represents a critical infrastructure. Due to this fact, the electric power industry has traditionally adopted a conservative attitude regarding changes. As a result of that, the electrical grid has experienced very few breakthroughs for decades and currently is not prepared to face novel challenges, such as properly integrating DERs (Distributed Energy Resources) or proactively controlling the energy demand by means of the so-called DR (Demand Response) programs, which mainly derive from nowadays society concerns on global warming and climate change.

Upgrading traditional electrical grid to the so-called Smart Grid represents one of the most complex engineering projects ever and will certainly drive the next wave of research and innovation in both the energy and the ICT (Information and Communications Technology) sectors. The road towards the Smart Grid will mean an unprecedented revolution especially at the power distribution and customer domains, since the unpredictable and uncontrollable nature of renewables will impose the coordination of generation and consumption points in almost real time.

M2M (Machine-to-Machine) communications allow networked devices to communicate between them without further human intervention. What in the very beginning seemed to be a tailored solution for telemetry applications, has become a communications paradigm itself, addressing the myriad of applications existing and yet to be in the wide context of the Internet of Things. As a matter of fact, M2M communications represent one of the main pillars of the Smart Grid in that they will enable the bidirectional real-time exchange of information between the consumption and generation facilities to be monitored and controlled, and the information systems where the optimization processes run.

There is a plethora of communications technologies and protocols available within the scope of M2M communications for the Smart Grid. Hence, research is needed in two directions. On the one side, it is required to evaluate how different communications architectures and technologies meet the specific requirements of the Smart Grid before undertaking the important investments needed to deploy this kind of infrastructures on a large scale. On the other side, it is crucial to develop common data models which serve as reference to future horizontal or wide scope protocols which expand across different domains or areas.

This thesis aims to tackle these issues. The main goal of the thesis is to contribute to the area of M2M communications architectures tailored to the power distribution and customer domains of the Smart Grid. In order to achieve this overall objective, first we carry out a survey on the most relevant standardization activities developed in parallel to this thesis and on the most outstanding technological and research trends within the Smart Grid area, identifying gaps and challenges.

Second, we propose a novel M2M communications architecture to support energy efficiency and optimum coordination of DER (Distributed Energy Resources) within the so-called energy-positive neighborhoods, which are neighborhoods which ensure a substantial part of their consumption by local generation based on renewables. The proposed architecture comprises three network segments, for the sake of flexibility and scalability, and combines different communications technologies to meet the specific communications requirements of each of them.

Next, we model formally the domain of knowledge of energy efficiency platforms for energy-positive neighborhoods by means of an ontology developed in OWL (Ontology Web Language), with the aim that it becomes a reference data model for the application of M2M communications to this context. Thus, this ontology has been made public through the EC (European Commission) eeBuildings Data Model community, so that other researches can re-use it and extend it.

We also propose a methodology that can be applied, in general, to characterize any communications overlay deployed on top of an infrastructure devoted to any purpose. Following this methodology, we model the traffic of the proposed M2M communications architecture in realistic large-scale scenarios. The main goal of this model is to ensure that potential works based on it actually mean and bring value to the interested parties. Although the model is tailored to the Portuguese power distribution grid, since it is based on actual data provided by EDP (*Energias de Portugal*), it can be easily adapted to other scenarios by suitably tuning the appropriate parameters.

Taking this model as reference, we finally evaluate the core of the proposed M2M communications architecture twofold. On the one side, we analyze the impact of using IPSec (Internet Protocol Security) or TLS/SSL (Transport Layer Security/Secure Socket Layer) as VPN (Virtual Private Network) technologies on the operational costs of a potential energy efficiency platform which relies on the proposed M2M communications architecture. To the author's best knowledge, no similar studies are available in the state of the art. The main conclusion of this analysis is that using TLS/SSL along with data aggregation is the best option to minimize operational costs at neighborhood level.

On the other side, we evaluate by means of simulations the performance of IEEE 802.11b, using as metric the goodput (i.e., throughput at the application layer), and GPRS (General Packet Radio Service), using as metric the transmission time. The first conclusion of these simulations is along the line that IEEE 802.11b meets the requirements in terms of goodput of the NAN (Neighborhood Area Networks), which is of special interest to the Smart Grid community taking into account the low cost and wide adoption of this technology. The second conclusion of such simulations is that GPRS meets the requirements in terms of bandwidth of the backhaul network, thus confirming that it represents a very attractive technology considering that it is the most mature and widely deployed cellular technology in Europe.

Keywords

Demand Response; Distributed Generation; Electric Vehicle; Energy-positive neighborhoods; Home Area Networks; Home Energy Management Systems; Information and Communications Technologies for Energy Efficiency; Internet of Things; Machine-to-Machine communications; Neighborhood Area Networks; Modeling; Simulation; Smart Grid

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Chapter 1

Introduction

1.1 A new and novel electrical grid paradigm: The Smart Grid

Nowadays we live in such a globalized World driven by such a digital society where everything gets outdated so fast that the Darwinian motto could be rephrased as “update or die”. The electrical grid, however, has remained unchanged, without major architectural improvements, for decades. Is then the electrical grid an exception to the aforementioned motto? The answer is definitely no. The reason why the electrical grid is more resilient to changes has to do with the fact that it is a huge and complex system which represents a key critical infrastructure, so stability and security come first to everything else. However, for some time now, the electrical grid is undergoing slowly but surely its inexorable metamorphosis under the new paradigm of the so-called Smart Grid.

The basic topology of the traditional electrical grid is strictly hierarchical, with clear demarcations between its generation, transmission, and distribution subsystems, as shown in Figure 1-1. The traditional electrical grid is also unidirectional in nature, with an energy flow from the power plant to the customer without any real-time share of information between the consumption and generation points [Farhangi2010]. As a result, it presents quite a few inefficiencies and problems, e.g., the generation capacity is over dimensioned to meet peak demands, which makes the whole system inefficient, or the lack of real-time monitoring and control of critical processes and assets causes blackouts and failures, which is unacceptable for such a critical infrastructure and implies high costs to operators (e.g., to the so-called utilities, which operate at power distribution level). In addition, the traditional electrical grid is not prepared to meet the new requirements and features that nowadays society demands from it.

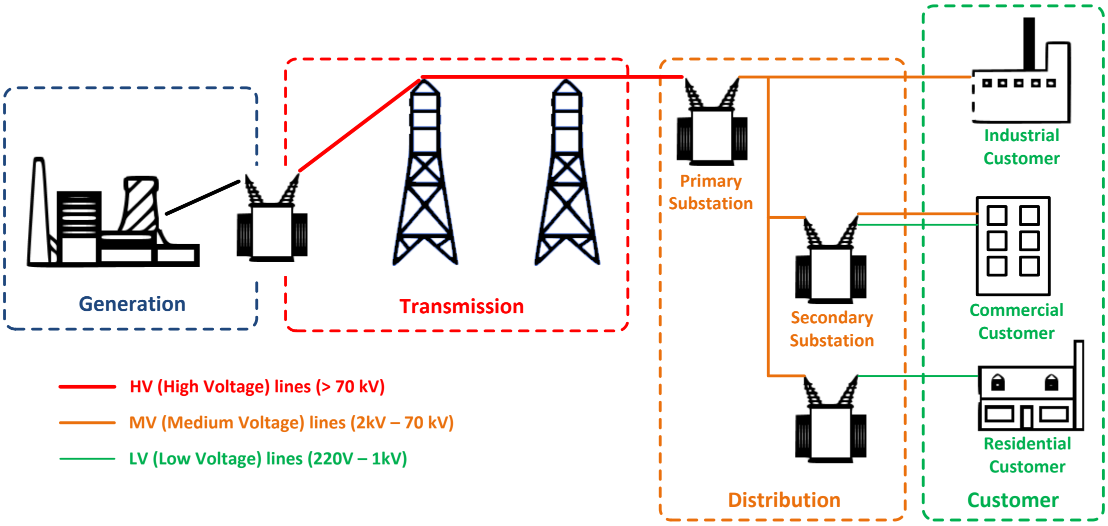


Figure 1-1 – Main subsystems of the traditional electrical grid

During the last decades, social concern about global warming and climate change has dramatically increased. As a token of that, governments worldwide are making great efforts to reduce GHG (Greenhouse Gas) emissions through the reduction of energy consumption and the use of renewable energy. The "Kyoto Protocol"[1] agreed and developed by the UNFCCC (United Nations Framework Convention on Climate Change) [UNKP1997] or the 20-20-20 target of the EU (European Union) climate and energy package[2] [EUCR2008] are two representative examples of the commitments made by developed countries to fight against climate change. However, the defined scenarios for decarbonizing the energy sector will lead to important impacts on the electrical grid, namely due to the high penetration of intermittent renewable technologies, with more reliance on DG (Distributed Generation), and to the proactive control of the demand of electricity [EPIA2012].

The increasing share of variable renewable energy resources (mainly solar photovoltaics and wind power) will lead to major challenges to the electricity system's stability, security and reliability [EURELECTRIC2011]. Moreover, such new generation resources are deployed mostly as DG, creating a more decentralized system, where the figure of the "prosumer"[3] emerges [Toffler1980]. As a result, the scalability of the grid is improved and the energy flows, and so the losses, are reduced, but the complexity of managing such infrastructures increases dramatically.

The increasing electricity consumption in most countries must be also properly addressed by the electrical grid, which must have new tools to optimize it and to promote energy efficiency both in the supply and in the demand sides, such as the monitoring and control infrastructures based on SANs (Sensor and Actuator Networks) or the DR (Demand Response)

[1] The "Kyoto Protocol" is an international treaty wherefore the industrialized countries commit to reduce their GHG emissions.
[2] The 20-20-20 target of the EU climate and energy package sets that the following goals must be achieved in the EU by 2020: 20% reduction of GHG emissions compared to 1990 levels; raising the share of EU energy consumption produced from renewable resources to 20%; 20% of improvement related to energy efficiency.
[3] In the electricity market, the term "prosumer" refers to such a stakeholder that both consumes electricity and produces it.

programs. The electricity consumption will increase even more dramatically with the foreseen wide adoption of EVs (Electric Vehicles) [Faria2012]. However, EVs can be also an important tool to the grid management with the possible control of their charging cycles and the use of their batteries as local energy storage equipment. Thus, the monitoring and control of electricity consumption together with the use of energy storage resources will provide the needed flexibility to ensure the generation/consumption matching.

Therefore, the Smart Grids is expected to address the major shortcomings of the existing electrical grid and to exploit the new resources. Thus, the Smart Grid will no longer be unidirectional, since energy will flow in both directions between the grid and the customers' facilities, and the assumption that the demand for electricity dictates the amount of electricity produced will no longer hold. Although the Smart Grid will still partly rely on large scale generation, the presence of energy storage and renewable energy generation facilities (the so called DERs – Distributed Energy Resources) at the different grid levels will increase dramatically. Furthermore, the Smart Grid will provide the operators of electrical infrastructures (e.g., utilities, aggregators) with enhanced sensory and control capabilities to ensure the full visibility and pervasive control over their assets and services [EPRI2011], [IEA2011].

Hence, the Smart Grid will facilitate the integration of diverse supply-side resources, support the integration of distributed and on-site generation on the customer side, promote more active engagement of demand-side resources and participation of customers' loads, and allow the widespread permeation of dynamic pricing to beyond-the-meter applications [Sioshansi2012].

As Figure 1-2 illustrates, ICT (Information and Communications Technologies) are crucial to upgrade current electrical grid to the Smart Grid, since they will be responsible for providing both the required real-time bidirectional communications among the huge volume of devices involved and the required real-time massive data handling tools.

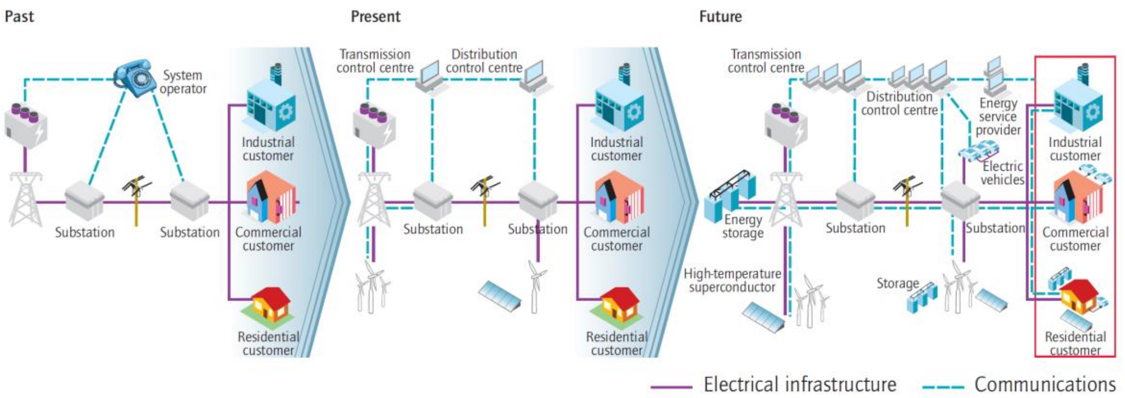


Figure 1-2 – Role of communications in the Smart Grid [IEA2011]

1.1.1 Smart Grid drivers

The increasing penetration of DG, the growing demand of electricity, the large-scale deployment of EVs, and the availability of new energy storage technologies, are the main drivers of the Smart Grid. They do not only introduce new challenges which cannot be solved by the traditional grid, but they do also offer new resources which can be part of the solution.

1.1.1.1 Distributed generation

The already mentioned efforts to reduce GHG emissions related to electricity generation have been leading to a fast increase in the deployment of renewable generation, in particular photovoltaic and wind power. Such renewable energy sources are being deployed not only as bulk generation facilities but also as distributed local generation facilities. These distributed local generation facilities can be connected directly to the power distribution network, as in the so-called VPPs (Virtual Power Plants) [Hernández2013], or to private consumption infrastructures [Claudy2011], enabling self-consumption and leading to the so-called energy-positive neighborhoods[4].

DG has the potential to provide site-specific reliability improvement, as well as transmission and distribution benefits, although it also presents some drawbacks and introduces new challenges.

Electric power systems have been designed for more than a century ago in a top-down perspective, based on highly predictable bulk generation power plants following demand variations. However, the renewable generation resources have characteristics that differ from conventional energy sources. The output of wind and solar power is determined by random meteorological processes, outside the control of the generators or the system operators. Therefore, unlike conventional capacity, wind and solar generated electricity cannot be reliably dispatched or perfectly forecasted and exhibits significant temporal variability [Moura2010a]. In addition, as Figure 1-3 illustrates, renewable energy generation does not typically match the consumption profile of residential buildings and households [Moura2012].

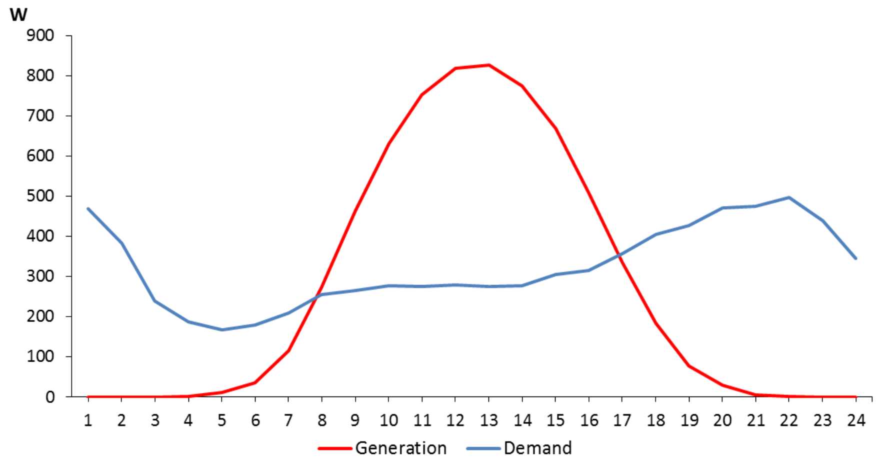


Figure 1-3 – Typical photovoltaic generation and demand profiles in a residential building [Moura2012]

In the EU, the variable generation could represent up to 65% by 2050 according to the EC (European Commission) Energy Roadmap [EC2011a]. As penetration rates of variable generation increase over levels of 15% to 20%, and depending on the electricity system in question, it can become increasingly difficult to ensure the reliable and stable management of electricity systems relying solely on conventional grid architectures with limited flexibility [IEA2011]. Therefore, new monitoring and control tools are crucial to increase the system flexibility and maintain stability and balance at the power distribution grid level.

[4] It should be noted that energy-positive neighborhood is considered to be a neighborhood which ensures a substantial part of its consumption by local generation and not necessarily a neighborhood with more generation than consumption.

1.1.1.2 Electricity demand

Over the last few decades, worldwide energy demand has increased due to industrial development and global economic growth, being the electricity the fastest growing component of the overall energy demand. In the EU, it is expected that electricity will double its share in the final energy demand from the current levels up to 36-39% by 2050, mainly due to its increasing use in transports and buildings [EC2011a].

Buildings, in particular, are the largest electricity consuming sector in the World and account for over one-third of total final energy consumption and an equally important source of GHG emissions [IEA2013]. As Figure 1-4 shows, in the EU in particular, during the last few years the electricity consumption in the industry and transport sectors has kept bounded, whereas the electricity consumption in the building sector has been steadily increasing, becoming a major problem for governments, utilities, customers, and the environment.

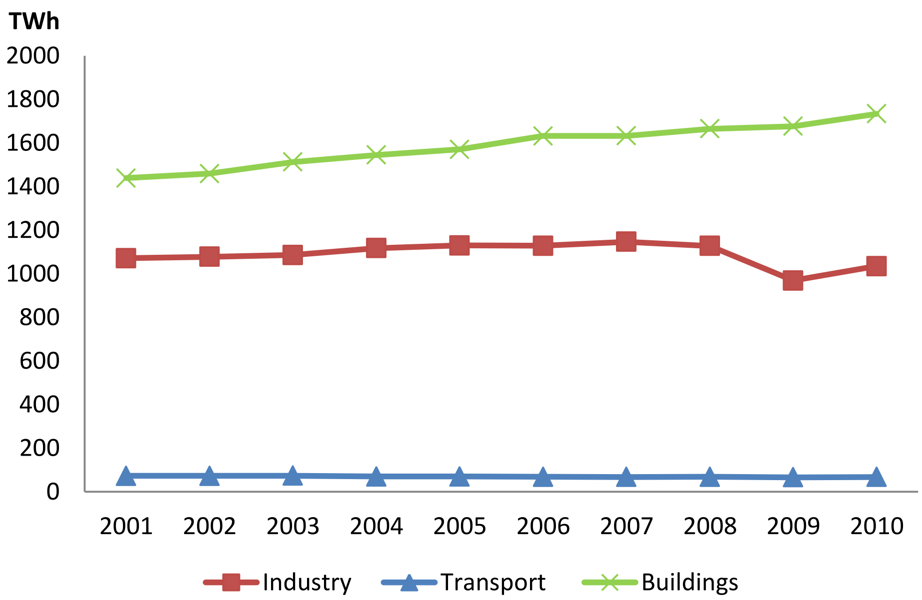


Figure 1-4 – Electricity consumption trends in the EU Industry, Transport, and Buildings sectors until 2010 [Eurostat2013]

The main reasons for these different trends are twofold. On the one hand, electricity consumption has been traditionally a well-identified problem in the industrial sector, since it translates into higher costs. Therefore, huge investments have been devoted to develop EMSs (Energy Management Systems) that reduce dramatically such consumption and, in turn, such costs. On the other hand, electricity consumption in households is not individually very significant; its true impact arises when it is summed up over millions of homes. In addition, the widespread utilization of new types of loads and the requirement of higher levels of comfort and services have also driven such an increase in the electricity consumption in the residential sector [Firth2008].

Indeed, the electricity consumption breakdown in the EU households was recently characterized [De Almeida2011], showing clearly the increasing importance of electronic loads, which represent more than 21% of the overall consumption. Such loads are mostly entertainment and ICT appliances with standby consumptions that represent about 7% of the total annual electricity consumption per household. HVAC (Heating Ventilation and Air Conditioning) loads also show high consumption and an increasing penetration rate. Given such increasing consumptions and the difficulty on identifying the major contributors, in-house monitoring and control systems, with sub-metering capabilities, are needed to make information about unwanted consumptions available to end-users and to give them tools to efficiently control these loads, thus enabling energy efficiency [Moura2013b].

The baseline consumption in an average EU household is fairly high (near 200 W) mostly due to the cold appliances and HVAC loads, as Figure 1-5 shows. However, if properly controlled, such loads can be used as a DR resource. Washing and drying appliances consume more than 16% of the electricity with high consumption at peak hours, while they might be shifted to other periods. Thus, the washing and drying appliances might be rescheduled to periods of lower energy consumption or higher energy production. The cold appliances, HVAC and water heating loads might be also interrupted during short periods of time, without major reduction of service quality, to avoid the most unbalanced situations between generation and consumption.

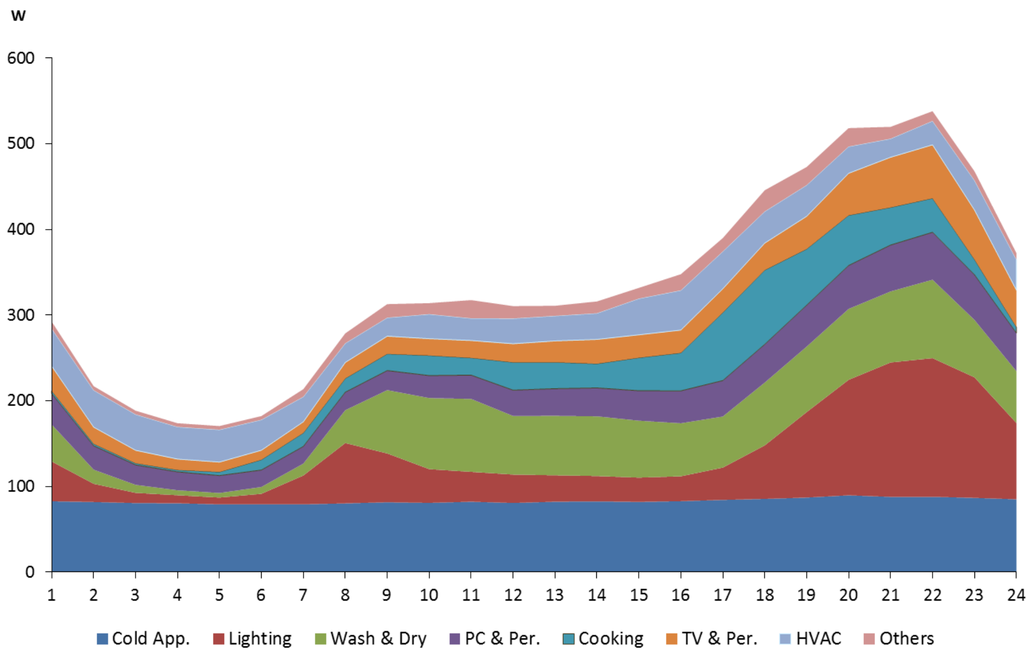


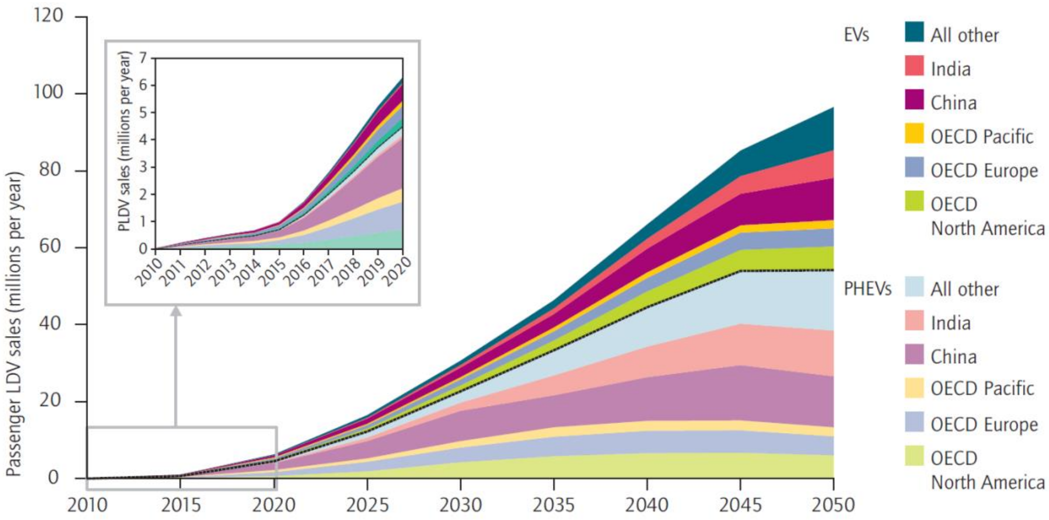
Figure 1-5 – Load profile of an average EU household [De Almeida2011]

In the past, the electrical system was planned and operated under the assumption that the supply system must meet customers' demand of electricity. However, that supposition starts to change in the 1980s with the emergence of a new approach to control a resource traditionally uncontrollable: the load [Gellings2009]. Through the proper application of DSM (Demand-Side Management), and providing incentives to the consumers, it is possible to control the consumption so that it matches shortages in the conventional generation capacity or the uncontrollable dips and peaks of renewable generation.

Thus, using DR programs it is possible to directly or indirectly force a consumption reduction in critical situations in a short period of time, as long as the required communications infrastructure is in place, as it is the case in the Smart Grid. Traditionally DR technologies were typically used to attend upon economic concerns related to balance supply and demand, involving industrial customers which present very high electricity consumption. However, nowadays they can be used to improve the system reliability, reducing or increasing instantaneously the electricity consumption to avoid the problems that result from the intermittence of renewable generation [Moura2010b], and exploiting the great potential of the residential sector [Moura2013a].

1.1.1.3 Electric vehicle and energy storage

The electrification of transport will be responsible for a large increase in the electricity consumption. Europe has a target of 10% share of EV by 2020, which need to be charged by means of the electrical grid [EURELECTRIC2011]. As Figure 1-6 shows, the IEA (International Energy Agency) estimates that the transport sector will make up to 10% of overall electricity consumption by 2050 due to a significant increase in EV and PHEV (Plug-in Hybrid Electric Vehicles) [IEA2011].



LDV: Light Duty Vehicle

Figure 1-6 – Deployment of EVs and PHEVs [IEA2011]

The impact of EV on the distribution network load diagram will require a new approach in load control, since if the vehicle charging is not managed intelligently, it could increase peak load and require major infrastructure investments to ensure the system reliability [Mets2012].

However, the EVs, due to their storage capacity, have a great potential as controllable loads, drawing power and storing energy when not in use (e.g., when they are parked at home or at work, what represents the main part of the day/night) [Pang2012]. Based on these singular characteristics, EV can support the integration of unpredictable intermittent renewable sources and contribute to the system stability, namely by provisioning ancillary services [Goebel2013].

The Smart Grid will allow the smart charging of EV during periods of low demand and/or high generation, thanks to its real-time communications capabilities [López2013b]. Furthermore, over the long term, when V2G (Vehicle-to-Grid) technologies are implemented, it could also allow EVs to feed the electricity stored in their batteries back into the system when needed [Clement2011], [Ma2012]. Additionally, other energy storage technologies, such as batteries and supercapacitors are already available and present increasing performance and decreasing costs.

The need of new energy storage technologies is also due to the alternative planar structure of the Smart Grid. The traditional grid already has energy flexibility (e.g., hydropower dams), but it is in the same place and works in the same manner as the generation, i.e., centralized from top to bottom, which limits the storage capacity. However, the new storage equipment does not need to be located near to the power plants and can be installed in any point of the grid. That choice enables supporting the integration of intermittent energy and the mitigation of congestion.

Therefore, the new energy storage technologies associated with the Smart Grid can ensure the matching between generation and consumption at different grid levels, not only at large-scale but also at neighborhood or building levels.

1.1.2 Smart Grid evolution

Upgrading current electricity grid to the so-called Smart Grid represents one of the major engineering challenges ever. As a result, the road towards the Smart Grid will be long and needs to be paved gradually, certainly driving the next wave of research and innovation in both the energy and the ICT sectors.

The metering side of the distribution system has been the focus of the Smart Grid investments so far, with the initial introduction of the AMR (Automated Meter Reading) systems to read meter data (Figure 1-7). However, AMR systems do not allow the transition to the Smart Grid, due to the absence of control capabilities. In a second stage, the AMI (Advanced Metering Infrastructures) have been used to provide a two-way communication system to the meter as well as the ability to ensure load management and revenue protection. The next step is the leverage of AMI to implement distributed command and control strategies with pervasive control and intelligence across all geographies, components, and functions of the system [Farhangi2010].

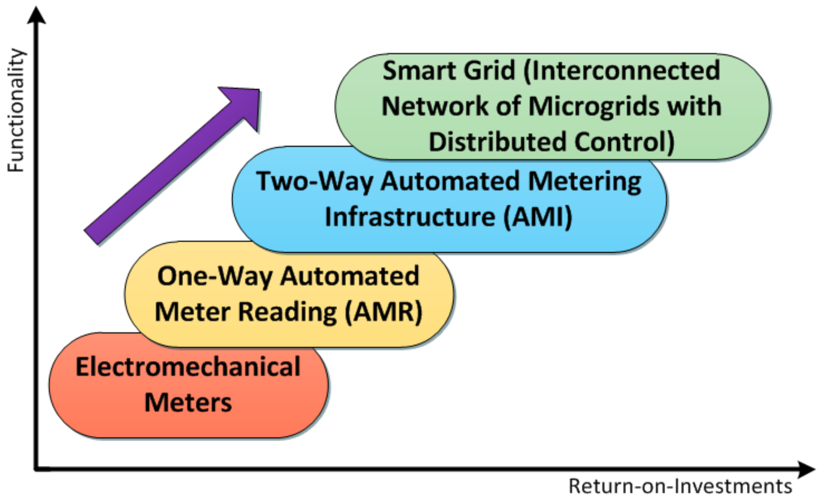


Figure 1-7 – The evolution of the Smart Grid [Farhangi2010]

The evolution of the Smart Grid will then be ensured by the introduction of new layers to enable more advanced functionalities. The basic layer is the already described monitoring and automated infrastructure. The second layer is the connection between participants, integrating customers and energy service providers into the grid. Then, a layer to sense and response is needed to share information, analysing and acting upon it to balance all the resources in real-time. Finally, the layer to analyse and optimize will manage the network using rules, constrains and intelligent agents [IBM2011]. Such layers will enable the development of the different Smart Grid technological areas shown in Figure 1-8, which spread across all the electrical grid domains [IEA2011].

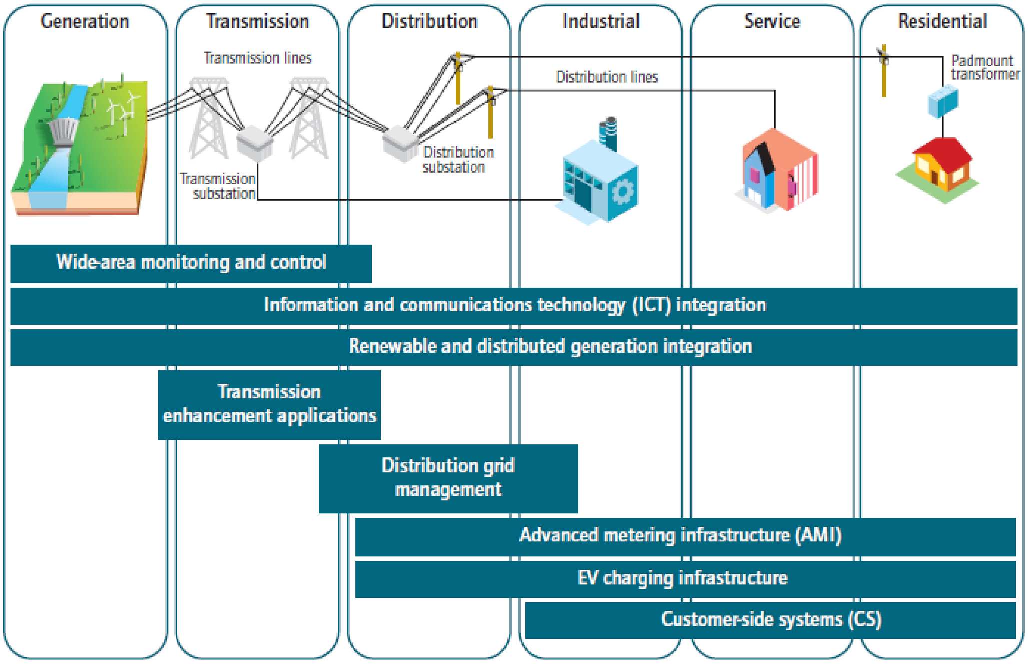


Figure 1-8 – Smart Grid technology areas [IEA2011]

Therefore, the evolution towards the Smart Grid can be divided into the three generations shown in Figure 1-9 [Carvallo2011]. The Smart Grid 1.0 (today's first steps) will be focused on increasing the visibility and awareness of the status of the power distribution network. Thus, throughout this first generation, the existing services will be transformed using advanced communication to offer pre-paid metering, in-home displays, intelligent disconnect, fine-grain load control, advanced outage management, bi-directional metering, and DR.

The Smart Grid 2.0 (grid resident intelligence) will enable future services and foster innovation with applications such as micro-grids and DG, intelligent street lighting, V2G, storage/distribution of renewable generation, fault prediction/outage prevention, energy asset management, and automatic DR.

Finally, the Smart Grid 3.0 (grid leveraged applications) will make the grid completely manageable, extending the applications to take full advantage of the grid resident intelligence. Thus, the Smart Grid of the future will become not just a way to deliver electricity more efficiently, but also an entirely new social and transactional platform with new business models, applications, services, and relationships.

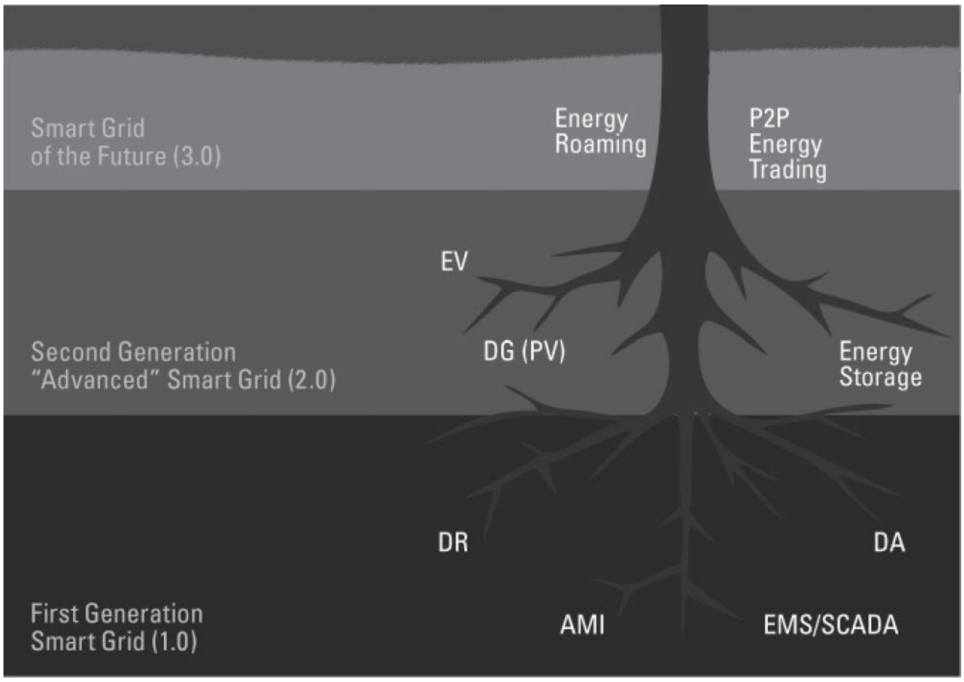


Figure 1-9 – Smart Grid generations [Carvallo2011]

1.2 Thesis motivation

The Smart Grid especially represents a revolution at the distribution and customer domains (notably, at commercial and residential level). The electric power industry has traditionally devoted more attention and resources to power transmission networks and primary power distribution networks (i.e., power networks responsible for transforming high voltage levels to medium voltage levels) rather than to secondary power distribution networks (i.e., power networks responsible for transforming medium voltage levels to the low voltage levels required by commercial and residential customers), since the former ones allowed keeping generation and consumption balanced under the traditional approach.

Therefore, bulk generation plants, power transmission systems and – to some extent - primary power distribution systems, have been traditionally monitored using legacy communications networks which allow a certain level of centralized coordination; whereas secondary power distribution systems have been traditionally passive systems with no or limited communications capabilities. However, as it has been shown throughout this chapter, the impact of the main drivers of the Smart Grid is especially relevant at distribution and commercial and residential customer level (which are connected through secondary power distribution networks), so it is right there where the major breakthroughs are required.

ICT will play a key role on making the Smart Grid a reality at distribution and customer level. On the one side, M2M (Machine-to-Machine) communications will enable the required real-time bidirectional communications between the huge number of devices to be monitored and controlled and the information systems where the optimization processes run. On the other side, advances on data mining, data analytics, the emerging Big Data, and cloud computing, will allow managing, processing and making decisions based on such a huge amount of information [Motamedi2012], [Kezunovic2011], [Miller2013], [Sakr2011].

There is a plethora of communications technologies available for being used in such M2M communications infrastructures for the Smart Grid [Güngör2011], which in practice slows the wide deployment of the Smart Grid down, since this situation introduces uncertainty on the market and so hampers the required investments. Wireless communications technologies are of special interest to the distribution and customer domains of the Smart Grid [Aravinthan2011]. As a token of that, the NIST (National Institute of Standards and Technologies) has launched a specific Working Group within the PAP2 (Priority Action Plan 2) to tackle the challenges and opportunities of wireless communications in this emerging application domain [NIST2011].

Moreover, communications for the Smart Grid present specific requirements from both the technical and economic perspectives, such as [Güngör2013], [Yan2013], [Liu2012]:

- QoS (Quality of Service). The communications infrastructure must provide a given level of QoS that fits the target application. Notably, QoS policies are mainly oriented to traffic prioritization and resource allocation to face congestion situations. Some parameters which are widely used to quantify such QoS level are:
    - Latency. It can be defined as the E2E (End-to-End) delay of the data.
    - Bandwidth. The communications infrastructure must provide an aggregated data rate as high as to carry the traffic associated to the target application. In general, this will depend on the volume of devices as well as on the size of the exchanged packets and the traffic pattern.
    - Reliability. The communications infrastructure must guarantee that it will work correctly during a given percentage of time throughout a year. The more critical the application is, the higher such a percentage will be.
- Interoperability. The communications infrastructure must allow equipment from different manufacturers to interact seamlessly. In order to achieve this goal, the main functional blocks which compose the communications infrastructure as well as the interfaces among them must be defined and standardized. Standardization is crucial to effectively achieve this goal, which eventually fosters competition and thus yields more reliable products at lower cost.
- Scalability. The communications infrastructure must ensure scalability from both the technical and economic perspectives. On the one side, taking into account the huge number of devices this kind of systems involves, the selected communications technologies must minimize the deployment, maintenance and operational costs. On the other side, the communications architecture must be able to incorporate new devices and to accommodate new services.
- Security and privacy. Due to the fact that Smart Grid applications handle sensitive data, security (both physical and cyber-security) and privacy represent key factors for their wide deployment and adoption. If privacy is not guaranteed, many users will not embrace many of the new services. If security is not guaranteed, many service providers will not implement or rely on many of such new services. However, since these two features and cost are usually directly proportional, a trade-off is required in order to obtain feasible solutions.

As a result, it is crucial to evaluate how different communications architectures and technologies meet such requirements before undertaking the important investments needed to deploy this kind of infrastructures on a large scale. Simulations represent a powerful, cost-effective and flexible solution to achieve this goal, although the relevance of their results tightly depends on how accurately the model behind such simulations fits real World scenarios. Therefore, a proper characterization of the communications requirements of the target application is of capital importance in order to obtain meaningful results [López2012a], [ETSI2012], [Khan2013].

At higher levels of the communications stack, there is also a myriad of protocols for every specific application within the Smart Grid, which hampers interoperability both within a given domain or area (e.g., at distribution domain, at customer domain) and across them. In this regard, it is crucial to develop common data models which serve as reference to future horizontal or wider-scope protocols.

1.3 Thesis objectives

This thesis addresses some of the hottest topics - from the communications perspective - introduced by the already presented Smart Grid drivers at distribution and commercial and residential customer level, representing a remarkable contribution to the development of the aforementioned Smart Grid 1.0 and 2.0. Notably, the overall objective of this thesis is to contribute to the area of M2M communications architectures tailored to the power distribution and customer domains of the Smart Grid. Next a breakdown of the specific objectives of this thesis goes:

- Analyze the most relevant standardization activities and research trends within this area, identifying gaps and challenges.
- Design a novel M2M communications architecture for energy-positive neighborhoods that promotes energy efficiency and consumption and generation matching at neighborhood level.
- Formally model the domain of knowledge of the energy efficiency platforms for energy-positive neighborhoods to foster re-using and extending our work, thus increasing its potential impact.
- Model the traffic carried by the proposed M2M communications architecture in realistic large-scale scenarios in order to maximize the impact of potential simulations based on them.
- Evaluate the performance of the proposed M2M communications architecture by means of simulations and draws conclusions that can be valid as guidelines for potential deployments.
- Assess the impact of using different security protocols on the operational costs of a potential energy efficiency platform which relies on the proposed M2M communications architecture.

1.4 Thesis organization

The remainder of this dissertation is organized as follows. Chapter 2 provides an overview of standardization activities, research activities and potential gaps within the Smart Grid area. Chapter 3 describes the M2M communications architecture designed to support energy efficiency and proper integration of local and distributed micro-generation within energy-positive neighborhoods, including the definition of the required functional blocks and the interfaces among them, as well as proposing the communication technologies to be used and an application-layer solution for address management and end-to-end addressability. Chapter 4 presents the ontology that formally defines the vocabulary and taxonomy and captures the engineering and business semantics of the domain of knowledge of the energy efficiency platforms for energy-positive neighborhoods, highlighting how future work can make the most out of it. Chapter 5 maps the proposed M2M communications architecture onto the power distribution network and characterizes the communications requirements and features of our specific target application. Chapter 6 evaluates, from different perspectives, the core of the proposed M2M communications architecture taking Chapter 5 as baseline. Notably, Chapter 6 assesses the operational costs of using different security solutions to establish VPN (Virtual Private Networks) and the performance of the selected communications technologies based on different metrics. Finally, Chapter 7 concludes this dissertation.

The research conducted during this thesis and presented throughout this dissertation has been gradually disseminated and validated in the research community and appropriate standardization organizations, leading to the following publications:

1. G. López, J. I. Moreno, H. Amaris, F. Salazar, “PRICE-GEN: Paving the Road towards Smart Grid through Large-Scale Advanced Metering Infrastructures”, Electric Power Systems Research, Elsevier. (Submitted for publication).

2. G. López, P. Moura, J. I. Moreno, J. M. Camacho, “Multi-faceted Assessment of a Wireless Communications Infrastructure for the Green Neighborhoods of the Smart Grid”, Energies, MDPI. (Submitted for publication).

3. G. López, V. Custodio, J. I. Moreno, M. Sikora, P. Moura, N. Fernández, “Modeling Smart Grid Neighborhoods with the ENERsip Ontology”, Computers in Industry, Elsevier, 2014. (Submitted for publication).

4. G. López, V. Custodio, F. J. Herrera, J. I. Moreno, “Machine-to-Machine Communications Infrastructure for Smart Electric Vehicle Charging in Private Parking Lots”, International Journal of Communication System, Wiley, November 2013.

5. P. Moura, G. López, J. I. Moreno, A. de Almeida, “The role of Smart Grids to foster energy efficiency”, Energy Efficiency, Volume 6, Issue 4, Pages 621-639, November 2013.

6. G. López, J. I. Moreno, “PRICE Project: M2M communications architecture for large-scale AMI deployment”, 4th ETSI M2M Workshop, Mandelieu-la-Napoule, France, November 2013.

7. E. El achab, G. López. J. I. Moreno, “Evaluación de mecanismos de seguridad en entornos de Smart Grid”, JITEL 2013: XI Jornadas de Ingeniería Telemática, Granada, Spain, October 2013.

8. P. Moura, G. López, J. I. Moreno, A. de Almeida, “Impact of Residential Demand Response on the Integration of Intermittent Renewable Generation into the Smart Grid”, EEDAL2013: 7th International Conference on Energy Efficiency in Domestic Appliances and Lighting, Coimbra, Portugal, September 2013.

9. G. López, J. Moreno, P. Moura, A. de Almeida, M. Perez, L. Blanco, “Monitoring System for the Local Distributed Generation Infrastructures of the Smart Grid”, CIRED 2013: 22nd European Conference and Exhibition on Electricity Distribution, Stockholm, Sweden, June 2013.

10. G. López, P. Moura, B. Kantsepolsky, M. Sikora, J. I. Moreno, A. de Almeida, “European FP7 Project ENERsip: Bringing ICT and Energy Together”, Global Communications Newsletter, November 2012.

11. P. Moura, G. López, A. Carreiro, J. I. Moreno, A. de Almeida, “Evaluation Methodologies and Regulatory Issues in Smart Grid Projects with Local Generation-Consumption Matching”, EEMSW2012: International Workshop on Energy Efficiency for a More Sustainable World, São Miguel, Portugal, September 2012.

12. G. López, P. Moura, V. Custodio, J. I. Moreno, “Modeling the Neighborhood Area Networks of the Smart Grid”, IEEE ICC 2012, Ottawa, Canada, June 2012.

13. A. Carreiro, G. López, P. Moura, J. I. Moreno, A. de Almeida, J. Malaquias, "In-house monitoring and control network for the Smart Grid of the future", ISGT Europe 2011: 2nd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies, Manchester, UK, December 2011.

14. G. López, P. Moura, M. Sikora, J. I. Moreno, "Comprehensive validation of an ICT platform to support energy efficiency in future smart grid scenarios", SMFG2011:IEEE International Conference on Smart Measurements for Future Grids, Bologna, Italy, November 2011.

15. G. López, P. Moura, J. I. Moreno, A. de Almeida, "ENERsip: M2M-based platform to enable energy efficiency within energy-positive neighborhoods", IEEE INFOCOM 2011 Workshop on M2M Communications and Networking, Shanghai, China, April 2011.

16. G. López, J. I. Moreno, "Smart Energy-positive Neighbourhoods for the Smart Grid. Architecture, Communications Technologies and Address Management for the ENERsip platform", 2011 ETSI Workshop on "Standards: An Architecture for the Smart Grid". Sophia Antipolis, France, April 2011.

Chapter 2

State of the art

2.1 Introduction

Upgrading current electricity infrastructure to the so-called Smart Grid is one of the most complex engineering projects ever. As a result, there are many challenges to face and problems to overcome, which will certainly drive the next wave of research and innovation in both the energy and the ICT (Information and Communications Technology) sectors.

This chapter provides an overview of the most outstanding standardization and R&D (Research and Development) activities within the distribution and customer domains of the Smart Grid, identifying the gaps and challenges tackled in this thesis. The Smart Grid involves a wide range of technologies and a myriad of standards. Therefore, this chapter does not aim to be exhaustive, but to focus on the most relevant work related to this thesis.

The remainder of the chapter is organized as follows. Section 2.2 outlines the main standardization activities related to this thesis developed by the NIST (National Institute of Standards and Technology), the IEEE (Institute of Electrical and Electronics Engineering), and the ESOs (European Standardization Organizations). Section 2.3 presents the most relevant Smart Grid technologies related to this thesis, paying special attention to communications architectures, technologies, and protocols. Section 2.4 summarizes the main trends in standardization and research within the Smart Grid area from the ICT perspective. Section 2.5 summarizes some relevant European and national R&D projects which tackle the issues previously presented throughout the chapter. Finally, section 2.6 draws conclusions and highlights the gaps and challenges addressed in this thesis.

2.2 Overview of standardization activities

2.2.1 NIST Smart Grid Interoperability Panel

The NIST SGIP (Smart Grid Interoperability Panel) is a private/public partnership funded by different industry stakeholders in cooperation with the US (United States) Federal Government that is aimed at the development of a framework for coordinating all Smart Grid stakeholders in an effort to accelerate standards harmonization and advance in the interoperability of Smart Grid devices and systems.

The SGIP was established by the NIST in late 2009 as part of a broader plan aimed at the coordination of a standards development process for the Smart Grid, in fulfillment of the responsibilities it had been assigned by the EISA (Energy Independence and Security Act of 2007) US law. In 2012, the SGIP was composed of over 780 member organizations representing 22 stakeholder categories, including international organizations, federal agencies, as well as state and local regulators. In January 2013, the SGIP entered a new phase becoming a self-sustaining entity with the majority of funding coming from industry stakeholders, despite NIST still maintains an active role.

The SGIP organizational structure is illustrated in Figure 2-1. The Technical Committees deals with transversal issues and establish guidelines. More specific tasks are carried out by temporary Working Groups belonging either to the DEWGs (Domain Expert Working Groups) or to the PAPs (Priority Action Plans) categories. There are two Technical Committees and a Working Group performing activities in a permanent basis, namely the SGAC (Smart Grid Architecture Committee), the SGTCC (Smart Grid Testing and Certification Committee), and the CSWG (Cyber Security Working Group).

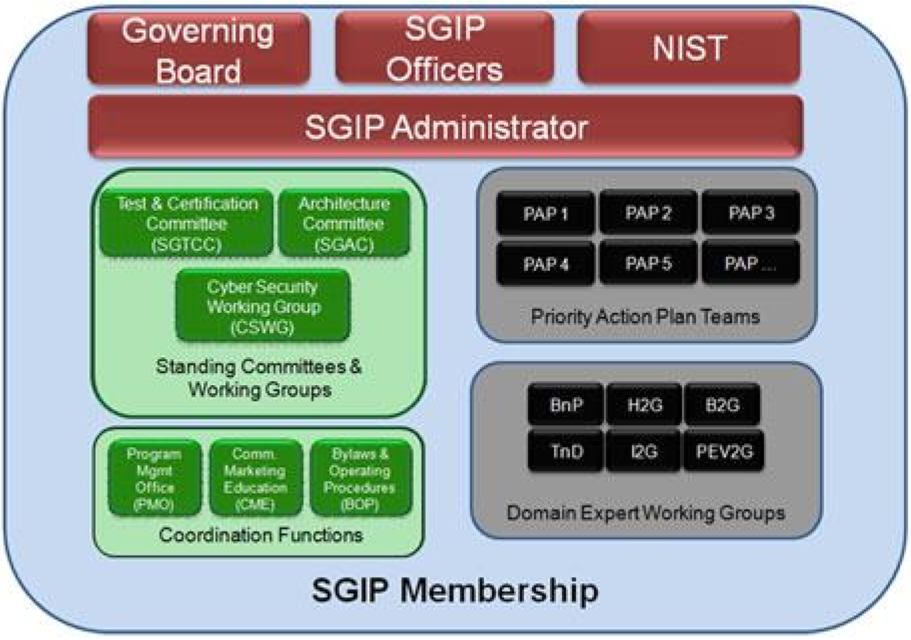


Figure 2-1 - SGIP organizational structure

As a first step towards the harmonization of Smart Grid standards to fully support interoperability, the NIST SGIP developed the Smart Grid conceptual model shown in Figure 2-

2. The first version of this conceptual model was published in January 2010 [NIST2010a] and it was reviewed and updated in February 2012 [NIST2012].

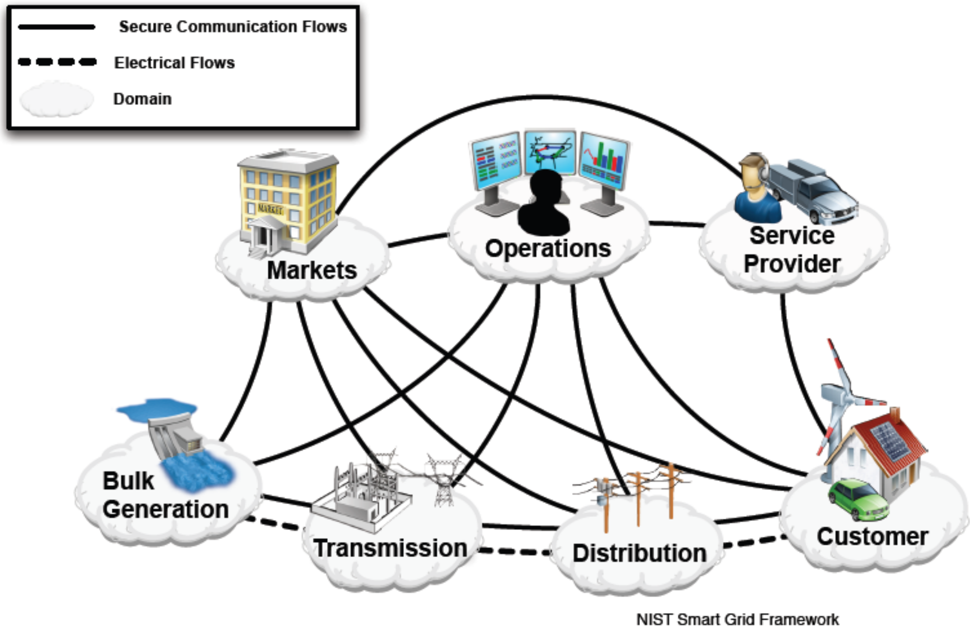


Figure 2-2 – NIST Smart Grid conceptual model [NIST2012]

As Figure 2-2 graphically shows, the NIST Smart Grid conceptual model defines seven domains as well as the electrical and communications flows among them. It can be seen that electrical flows involve the traditional subsystems of the electrical grid; whereas communications flows almost create a mesh topology between every domain, which illustrates the importance of communications in the Smart Grid.

Each domain - and its sub-domains - encompasses Smart Grid actors and applications. Actors include devices, systems, programs, and stakeholders that make decisions and exchange information. Applications are tasks performed by one or more actors within a domain (e.g., home automation). All these pieces can be orchestrated to obtain useful use cases (i.e., select a given domain, a given application, its specific requirements, the actors involve in this application, and describe how they interact). Table 2-1 summarizes the main actors involved in each domain.

Table 2-1 – Domains and Actors in the NIST Smart Grid conceptual model

Domain	**Actor**
Bulk Generation	Generators of electricity in bulk quantities
Transmission	Carriers of bulk electricity over long distances (the so-called TSOs – Transmission System Operators)
Distribution	Distributors of electricity to and from customers (the so-called DSOrs - Distribution System Operators)
Customers	End users of electricity. They may also generate, store, and manage the use of energy. Traditionally, three customer types are considered: home, commercial/building, and industrial
Operations	Managers of the movement of electricity
Markets	Operators and participants in the electricity market
Service Providers	Organizations providing services to electrical customers and utilities (e.g., aggregators, retailers, ESCOs – Energy Services Companies)

Figure 2-3 zooms in every domain and illustrates the main actors involved in each domain as well as the relationships between them from the communications perspective.

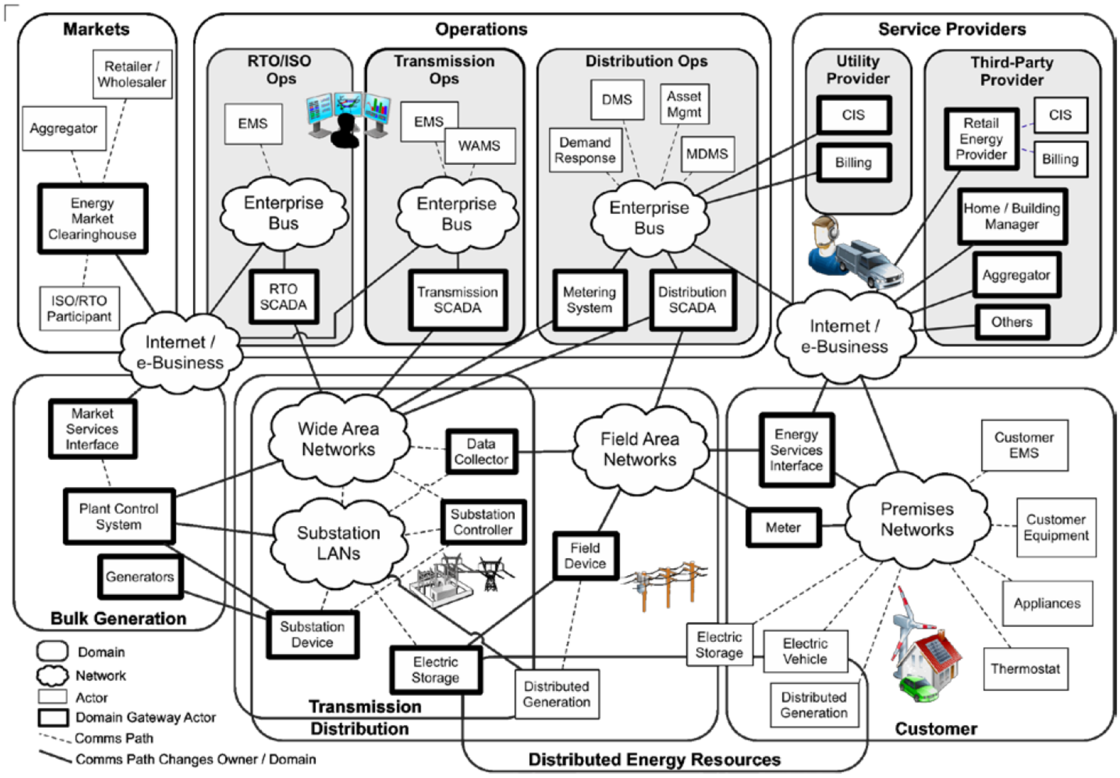


Figure 2-3 – NIST conceptual reference diagram for Smart Grid communications networks [NIST2012]

Although other standardization bodies have also defined their own Smart Grid conceptual models, the NIST Smart Grid conceptual model is the most widely accepted and so it is taken as reference in the remainder of this thesis.

Beside the Smart Grid conceptual model, one of the main outcomes of the SGIP activity is the elaboration of a compendium of standards, practices, and guidelines that allow the development and deployment of a robust and interoperable Smart Grid. As a result, in May 2011 the SGIP Governing Board established the so-called CoS (Catalog of Standards) and the first six standards to be included were approved by the SGIP Plenary in July 2011. This CoS is available on-line through the NIST Smart Grid Collaboration wiki [NIST2014]. As of today, the CoS comprises 20 individual standards and 5 series of standards that in turn contain 36 additional standards, which accounts for a total of 56 standards. The CoS list available in [NIST2014] includes for each standard:

- A brief description.
- Mapping onto functional areas.
- Date in which the standard was included in the CoS.
- Reviews from the SGAC (Smart Grid Architecture Committee), the SGTCC (Smart Grid Testing and Certification Committee), and the CSWG (Cyber Security Working Group).
- Mapping onto the Smart Grid conceptual model domains.

2.2.2 IEEE 2030

Once a conceptual model of the Smart Grid is defined, a reference architecture which works such a conceptual model out by defining functional blocks and interfaces, thus bringing it closer to implementation and so to developers, is required.

The IEEE project 2030 was pioneer on developing such reference architecture, leading to the so-called SGIRM (Smart Grid Interoperability Reference Model). The SGIRM extends the NIST Smart Grid conceptual model and defines three IAPs (Interoperability Architectural Perspectives), which represent the main areas of expertise involved in the Smart Grid [IEEE2011]:

- Power Systems (PS-IAP);
- Communications Technologies (CT-IAP);
- Information Technology (IT-IAP).

Each IAP defines the main functional blocks required in each domain of the NIST Smart Grid conceptual model from the appropriate perspective, as well as the interfaces between functional blocks (intra-domain interfaces), and the interfaces between domains (inter-domain interfaces). The defined IAPs are further particularized for the most important applications in the Smart Grid area, such as AMI (Advanced Metering Infrastructure) or PEV (Plug-in Electric Vehicle). Figure 2-4 illustrates the IEEE 2030 standardization process and overall reference architecture.

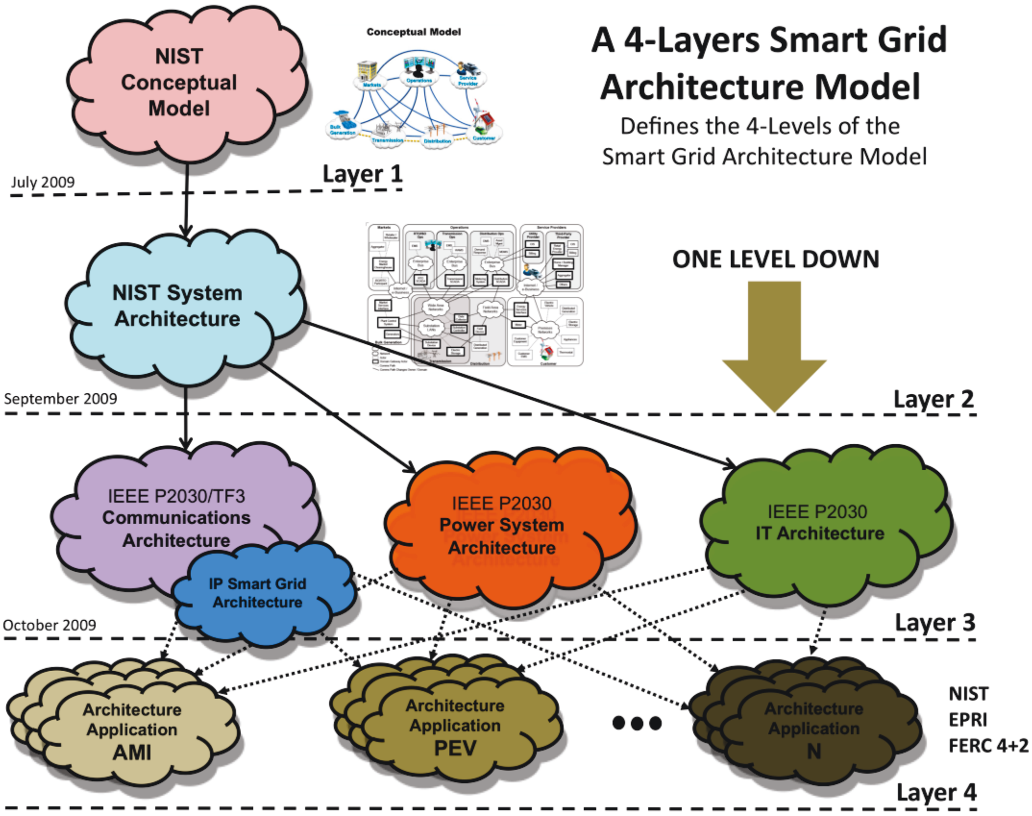


Figure 2-4 – Evolution and scope of IEEE 2030 standardization process[1] [IEEE2011]

[1] It should be noted that dates refer to when the work was developed, but do not represent when the work was published.

The most relevant IAPs to this thesis are the IT-IAP and the CT-IAP. The IT-IAP deals – among other topics – with data modeling. The CT-IAP defines the communications networks that may be used in every domain. Figure 2-5 illustrates the defined communications networks or segments as well as the interfaces among them. Table 2-2 describes briefly the communications networks defined within distribution and customer domains which are of special interest to this thesis.

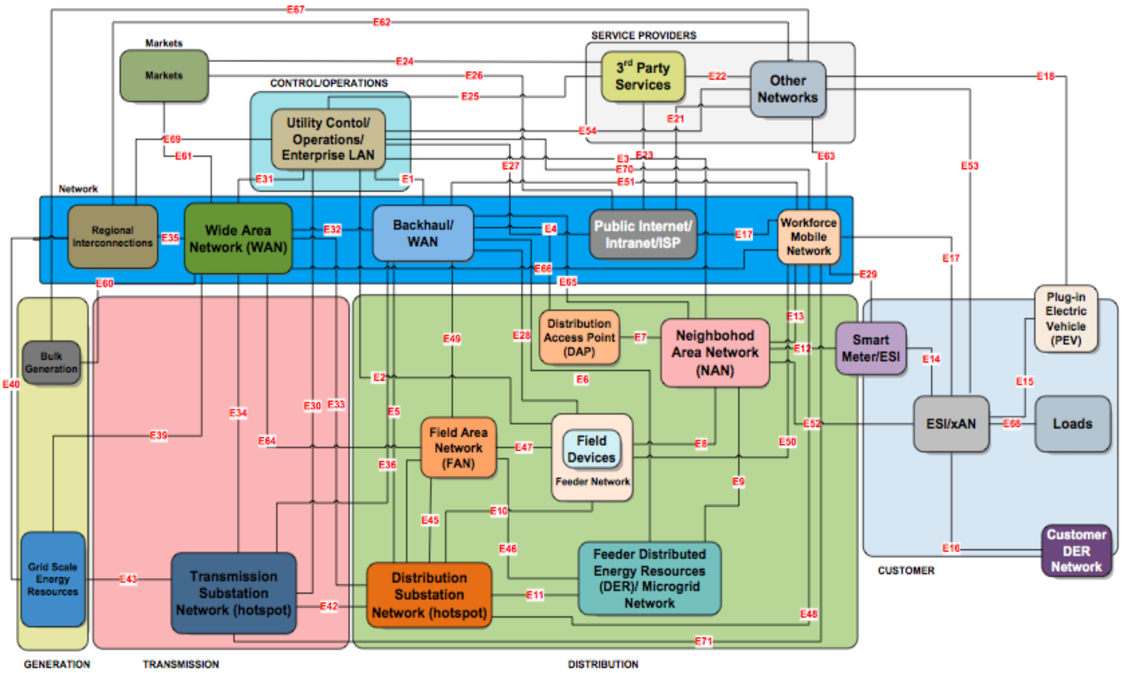


Figure 2-5 – IEEE 2030 Smart Grid communications architecture [IEEE2011]

Table 2-2 – Communications networks defined in the IEEE 2030 CT-IAP of special interest to this thesis

Communications network	Description
xAN/ESIs	xAN represents HAN (Home Area Network), BAN (Building Area Network), and IAN (Industrial Area Network), which encompass all the IEDs (Intelligent Electronic Devices) that allow monitoring and controlling energy status and patterns within each context. ESIs (Energy Services Interfaces) represent logical gateways
NAN	NAN (Neighborhood Area Network) is a last mile communications network that connects ESIs and smart meters as well as DER s(Distributed Energy Resources) and microgrids to the utility control and operation center through the backhaul network
Backhaul	Backhaul network provides connectivity between the utility control and operation center and any communications network within the distribution and customer domains

Based on this reference architecture, the IEEE has sorted their own catalogue of standards and has identified the functional blocks and interfaces where they can be applied, as well as the standardization gaps where new standards are required [IEEE2014].

2.2.3 European Standardization Organizations

The three main ESOs (European Standardization organizations) – namely CEN (European Committee for Standardization), CENELEC (European Committee for Electrotechnical Standardization), and ETSI (European Telecommunications Standards Institute) - are working together on the Smart Grid standardization process. This collaborative work is being driven by the following EC mandates:

- Standardization mandate M/441 to develop an open architecture for utility meters involving communications protocols enabling interoperability (March 2009) [EC2009].
- Standardization mandate M/468 concerning the charging of EVs (June 2010) [EC2010].
- Standardization mandate M/490 to support European Smart Grid deployment (March 2011) [EC2011b].

In response to such mandates, three working groups, involving the participation of the three ESOS, have been created:

- SM-CG (Smart Metering - Coordination Group) in response to M/441.
- Focus Group on European Electro-Mobility in response to M/468.
- SG-CG (Smart Grid – Coordination Group) in response to M/490.

Through the EC standardization mandate M/490 and the corresponding SG-CG, the CEN/CENELEC/ETSI strategic partnership has further developed the NIST Smart Grid conceptual model, adapting it to the specific requirements of the European electricity grid. As a result, a new domain related to DERs has been added, reflecting the importance and high penetration of renewables generation in European power distribution networks [SGCG2012a]. As Figure 2-6 shows, the CEN/CENELEC/ETSI Smart Grid conceptual model considers that DERs are electrically connected to the power distribution network and communicate with it, as well as with the Markets, Operations and Service Provider domains. Nevertheless, it should be noticed that the Customer domain encompasses both DG and energy storage at small scale (see Figure 2-3).

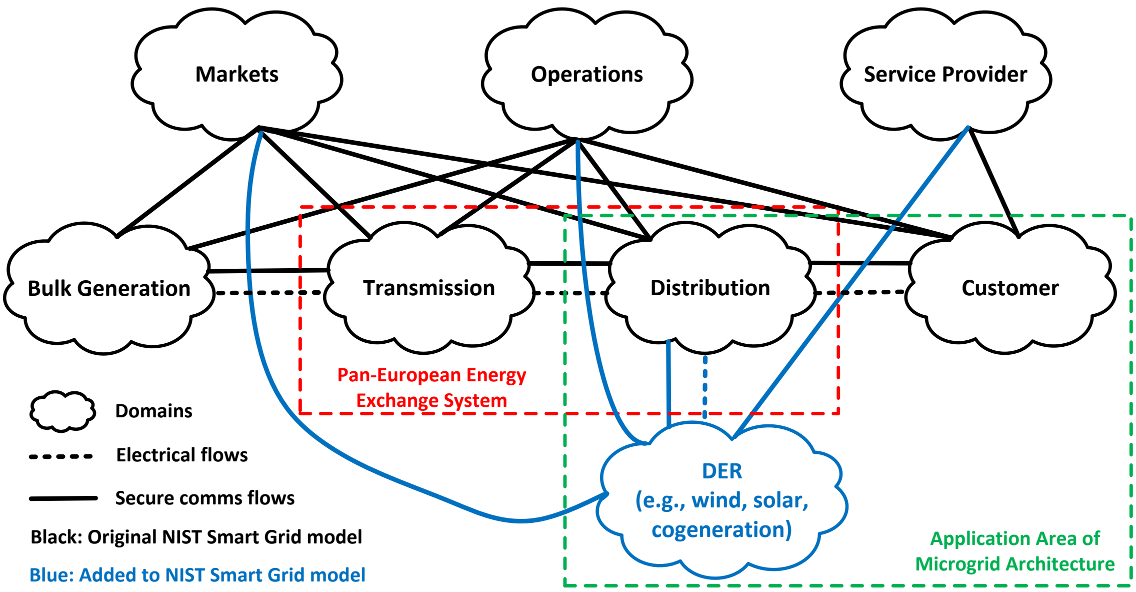


Figure 2-6 –CEN/CENELEC/ETSI Smart Grid conceptual model

The SG-CG has also developed the so-called SGAM (Smart Grid Architecture Model) tailored to the requirements of the European electricity grid. As a result, the three-dimensional architectural model comprising the domains, zones, and layers shown in Figure 2-7, has been defined [SGCG2012a]. The SGAM allows a technologically neutral representation of all the interoperability cases of the Smart Grid. The five defined layers represent – top to bottom - the business objectives and processes, the functions, information exchange and data models, communications technologies and protocols, and the physical and logical components. As a token of the volume and importance of the Communication Layer, it is developed in a separate document [SGCG2012b]. [SGCG2012b] defines the communications networks and their deployment at the Component Layer and maps the identified communications technologies and protocols onto the defined communications networks. This thesis is specially focused on the Communications Layer, addressing also the Information Layer.

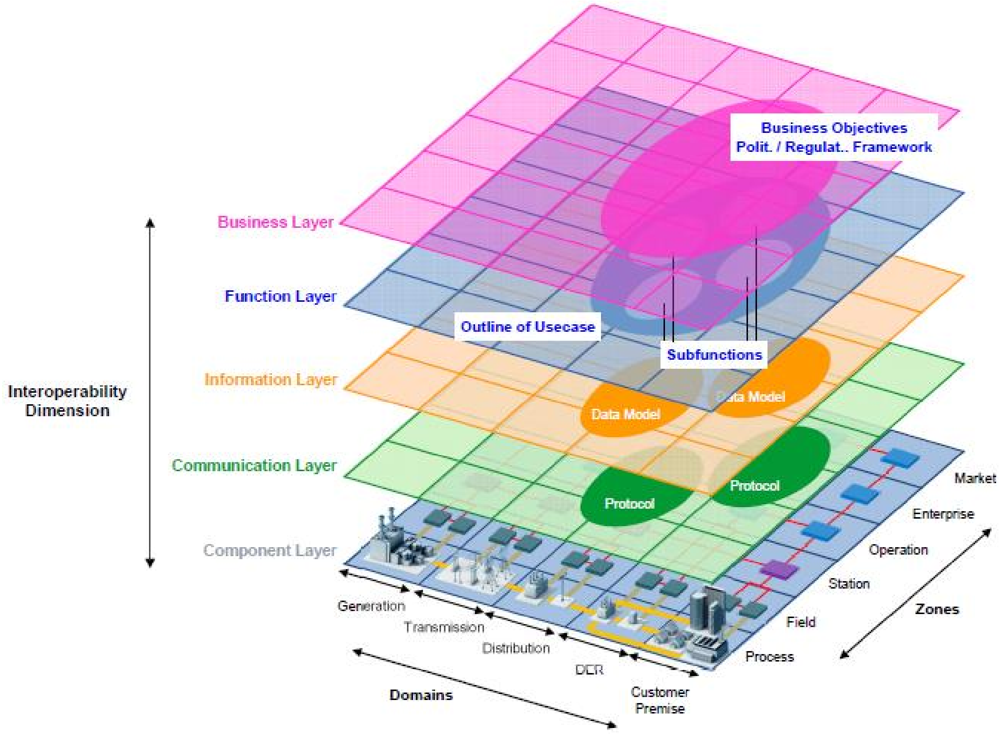


Figure 2-7 – CEN/CENELEC/ETSI SGAM [SGCG2012a]

In addition, another outstanding outcome of the SG-CG work is the elaboration and classification of a first set of standards for the Smart Grid and the identification of standardization gaps where standards are required [SGCG2012c].

It is also worthwhile to remark upon the work developed by ETSI on the standardization of M2M (Machine-to-Machine) communications. This work has been recently transferred to the partnership project OneM2M [OneM2M2014]. As a result of this work, a complete reference architecture has been defined, including functional blocks and interfaces. Figure 2-8 shows the main domains of the ETSI M2M reference architecture. The M2M Device Domain encompasses the so-called capillary networks (in ETSI terminology), i.e., the SANs (Sensor and Actuator Networks). The Network Domain represents the core of the M2M infrastructure and provides bidirectional bulk data exchange over long distances. Finally, the Application Domain encompasses the services which are delivered on top of the M2M infrastructure.

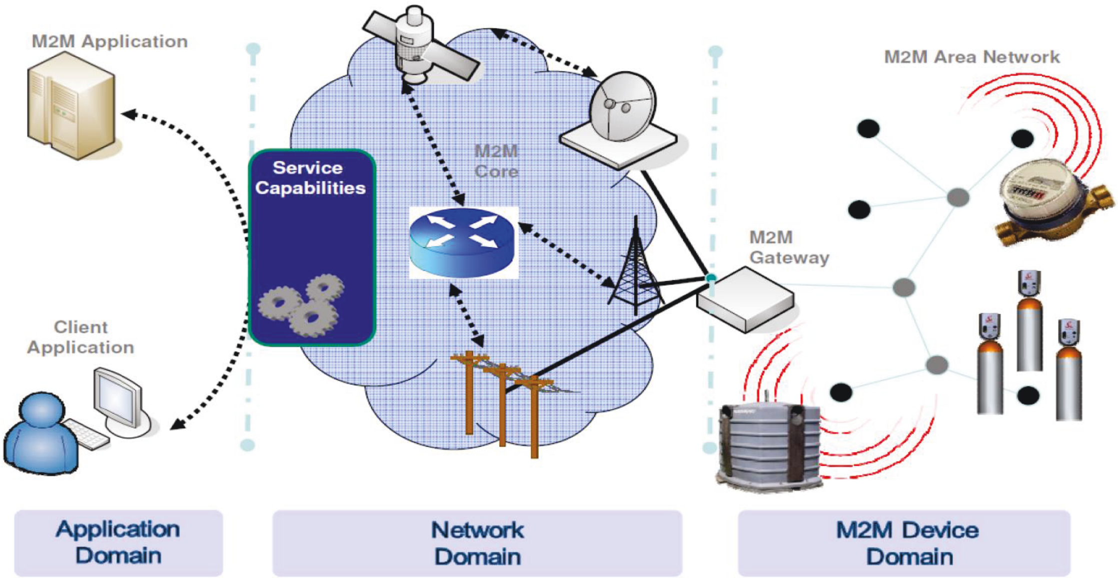


Figure 2-8 – Main domains of the ETSI M2M reference architecture

Figure 2-9 provides a graphical overview of how these three domains can be mapped onto the Smart Grid [ETSI2012].

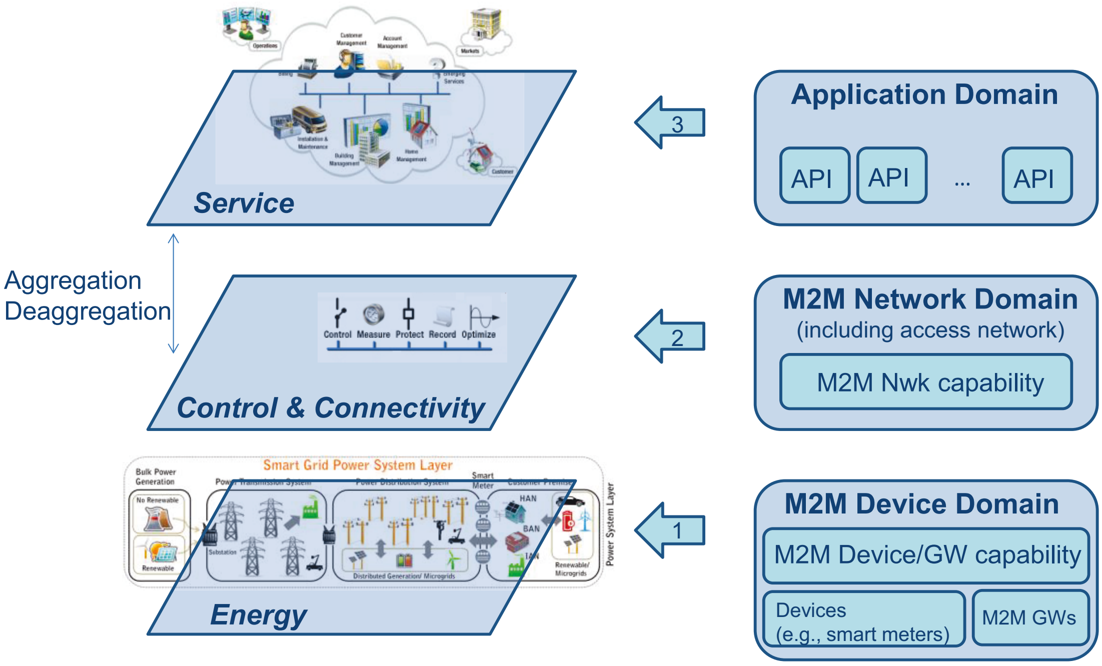


Figure 2-9 – Mapping of ETSI M2M main domains onto the Smart Grid main layers [ETSI2012]

Reference [Lu2012] elaborates on how the ETSI M2M communications architecture can be applied to the Smart Grid, as it is shown in Figure 2-10.

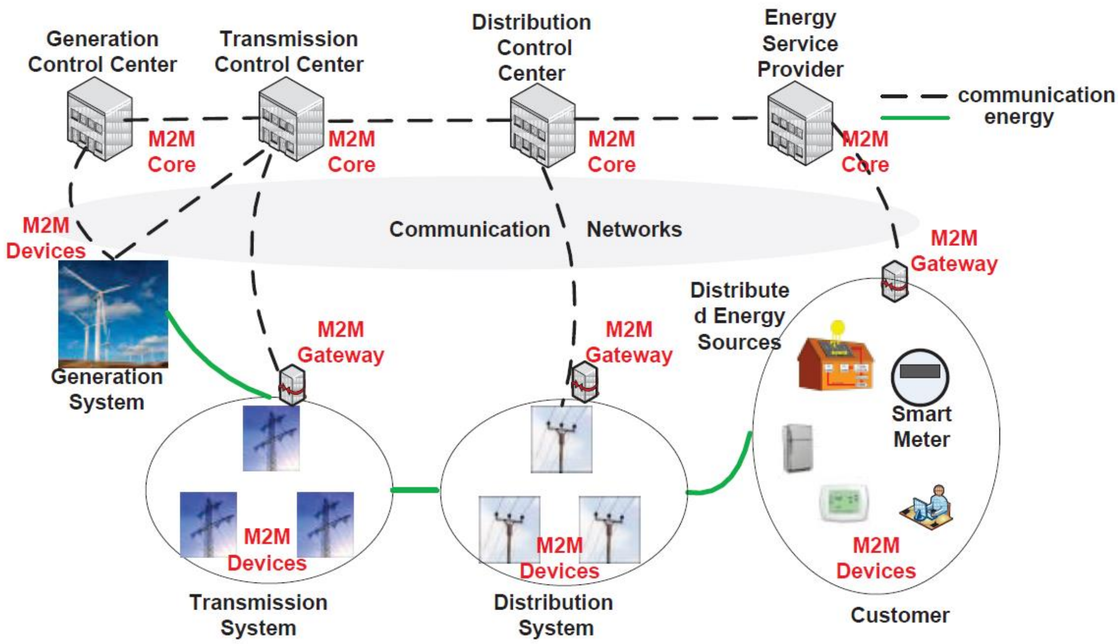


Figure 2-10 –Application of ETSI M2M architecture to Smart Grid sub-systems [Lu2012]

2.3 Overview of related technologies

2.3.1 Smart meters

There is no single definition of smart metering. However, all smart-meter systems comprise an electronic metering box and a communications link. At its most basic form, a smart meter measures electronically how much energy is used and communicate this information to another device which, in turn, allows the customers to view how much energy they are using and how much it is costing to them [ESMA2012].

Smart-meter systems can be classified according to their communications capabilities. The combination of the electronic meters with two-way communications technology is also commonly referred to as AMI. Previous systems, which were limited to one-way communications to collect meter data, are referred to as AMR systems. AMI has developed over time, from its roots as a meter reading substitute to today's two-way communications systems, where smart meters are not just sensors any longer, but they become part of the core of the power distribution network [EEI2011].

In general, AMI bring benefits both to the customers and to the operators or utilities. On the one side, they provide customers with enriched information on their energy usage to aid them in controlling the cost and the environmental impact. On the other side, they provide utilities with very detail data which allow them to perform sophisticated tasks such as load factor control, peak load management, or the development of pricing strategies based on consumption information. In addition, they make the operation and maintenance of the power distribution network easier, allowing enabling or disabling meters, or updating their firmware or settings remotely [López2014c].

AMI are being deployed by utilities to increase operational efficiency (e.g., better pricing information, more accurate bills, or faster outage detection and restoration), to improve energy efficiency (e.g., increasing the user awareness of the energy consumption), and to meet a range of new customer requirements and market opportunities. However, AMI programs are not just a utility operational issue, but they are also a core part of the energy policies of many governmental authorities [Depuru2011].

As a matter of fact, currently AMI deployments are mainly driven by regulation. In the EU (European Union), with the requirements of the article 13 of the so-called Energy Services Directive (2006/32/ED) and the adoption of the Directive on the internal electricity market (2009/72/EC), it became clear that the modernization of the European meter infrastructure and the introduction of intelligent metering systems must become a reality [JRC2012a]. However, this regulatory push meets an actual requirement, since increasing the awareness of the power distribution network is crucial to enable more sophisticated mechanisms, such as DR (Demand Response) or proper EV massive integration.

Nevertheless, the AMI market across Europe remains diverse in terms of maturity, technology preferences, and market drivers. Some countries already have a very high degree of smart meters penetration, e.g., Italy (with 94%) and the Nordic Countries (with 70%), but in general the penetration rate is still medium. EU countries have an overall mandate to deploy smart meters up to 80% of customers by 2020 (namely, directive 2009/73/EC). In some countries the deployment plans are even more ambitious, e.g., the Spanish directive IET/290/2012 forces utilities to renew 100% of their meters to smart meters with telemanagement and ToU (Time of Use) capabilities by the end of 2018. As a result, it is foreseen that 212 million of smart meters will be deployed in Europe between 2011 and 2020 [PR2012].

2.3.2. Smart appliances

The state-of-the-art domestic appliances are not only becoming more and more energy efficient, but they are also offering new important features to achieve lower energy consumption and costs. Smart appliances are household appliances or white goods with monitoring and control capabilities, providing communication with other devices and interfaces.

The AHAM (Association of Home Appliance Manufactures) defines smart appliances as “a modernization of the electricity usage system of a home appliance so that it monitors, protects and automatically adjusts its operation to the needs of its owner” [AHAM2009].

Smart appliances could comprise typical white goods such as refrigerators, freezers, dishwashers, oven and stoves, washing machines and tumble dryers, as well as air conditioners, circulation pumps for heating systems, electric storage heating, and water heaters. The main objective of such appliances is to use an intelligent power management strategy to optimize the load of the power distribution grid responding to utility signals.

Such electric appliances can therefore be used in DR programs (with an override function controlled by the user). This can include rescheduling the operation of washing or dishwashing cycles, interruptions of the operation of appliances, or the use of refrigerators and freezers for temporarily storing energy in order to avoid operation of the compressor during peak times [Timpe2009]. Such DR programs can also detect and react against disturbances in the power frequency of the grid by turning a group of appliances off or on for a few minutes in order to allow the grid to stabilize [Momoh2012].

However, smart appliances are not widely available nor deployed yet, so most current solutions to provide energy efficiency at house and building levels are based on dedicated monitoring and control systems.

2.3.3 Monitoring and control systems

Energy monitoring and control systems have been traditionally used to reduce industrial electricity consumption, but they are being applied more and more to achieve the same goals in corporate office buildings, commercial and service buildings, and even in residential buildings and households.

For the energy consumption monitoring in households there are two main available options with different objectives:

- Whole-house power monitors.

- Power outlet monitors.

Whole-house power monitors have sensor clamps around the incoming power conductors to measure the whole-house consumption. The measured values are sent wirelessly and in real time to a communications gateway, which forwards them either to a home display for direct visualization or to a server so that data can be checked via a computer or smartphone. Thus, whole-house power monitoring systems allow being aware of home energy consumption in real-time as well as double-checking that utility is charging correctly over a given billing period (as long as they provide the required accuracy). In addition, these systems can provide advanced notification of alarms, alerts and advice, using instant text message and email alerts, based on user-defined parameters. Figure 2-11 shows an example of this kind of systems.

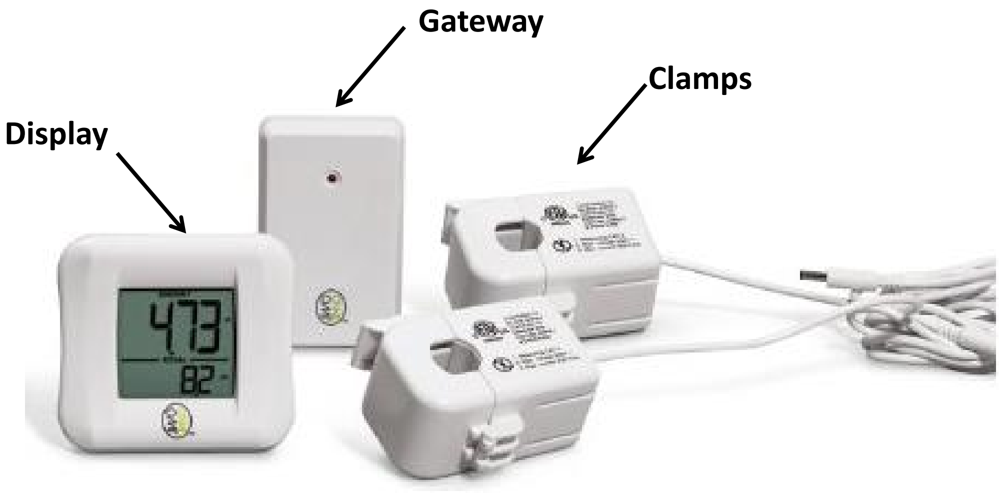


Figure 2-11 –Example of whole-house power monitoring system [OWL2014]

The power outlet monitors is plugged into a power outlet and then the appliance is plugged into it. Such devices can monitor the amount of energy consumed by the appliance and associated costs (as long as the user introduces the prices and tariffs). The most common option includes a display in the socket to show such information, as Figure 2-12 illustrates. Other versions do not have a display in each socket, but they send the data wirelessly to a central display that can receive data from several sockets, creating a kind of monitoring system for the energy consumption of individual appliances.

Figure 2-12 – Example of power outlet monitor [Efergy2014]

The most common devices for the control of energy consumption in households are the remote controlled sockets, which consists of an electrical socket and a remote control. The remote controlled socket is plugged into any normal electrical outlet and can be switched on and off with the remote control. Such devices can bring to normal appliances part of the services provided by smart appliances. Some devices can have a single remote control to several plugs, as shown in Figure 2-13.

Figure 2-13 – Example of remote controlled sockets [Efergy2014]

The capabilities of power outlet monitors and remote controlled sockets can be incorporated in a single device, the so-called smart plugs. Smart plugs represent the cornerstone of the so-called HEMSs (Home Energy Management Systems). Such residential monitoring and control systems for the electricity consumption can also include a whole-house power monitor as well as sensors (e.g., temperature sensor, motion sensor, CO_2 sensor) to measure ambient variables that allow ensuring an agreed level of comfort. All these data are typically sent wirelessly to a gateway that forwards them to a server for their visualization via a computer or smartphone. This gateway also routes commands to the appropriate devices. Figure 2-14 shows a typical configuration of this kind of systems.

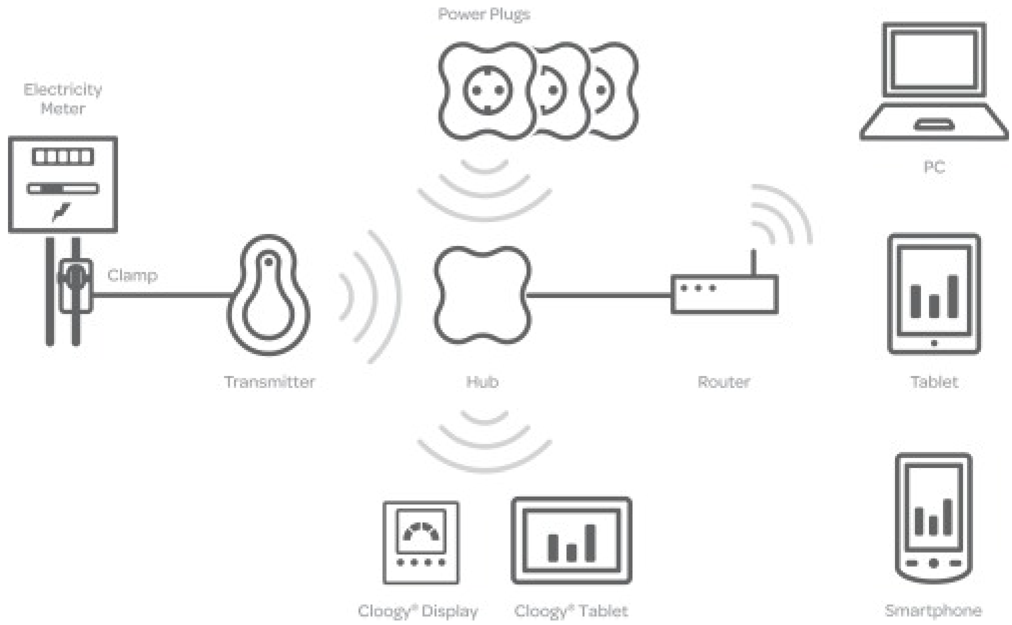


Figure 2-14 – Example of residential monitoring and control system for electricity consumption [Cloogy2014]

Energy generation monitoring systems are also appearing recently in the market, reflecting the increasing penetration of micro-generation at residential level. The energy generation monitoring systems include devices to measure how much energy is being generated as well as the performance of the micro-generation installation (the so-called inverters). The measured values are sent typically wirelessly and in real-time to a gateway that forwards them either to a display for direct visualization or to a server, so that they can be visualized via web applications using any device with Internet connection. Figure 2-15 shows an example of this kind of systems.

Figure 2-15 – Example of monitoring system for residential micro-generation [Enlighten2014]

Finally, with the recent rise of self-consumption and NZEB (Nearly Zero-Energy Buildings), there are also appearing solutions that combine residential electricity consumption monitoring and control systems with residential energy micro-generation monitoring systems in order to optimize and match consumption and generation locally. These systems can be seen as an extension or a more sophisticated version of the aforementioned HEMS. Figure 2-16 shows an example of this kind of systems.

Figure 2-16 – Example of residential monitoring and control system for energy consumption and generation [SHM2014]

As a token of the importance that energy efficiency in the residential sector is winning, much R&D has been carried out in this area during the last few years, which has led to an actual market for such HEMS. Table 2-3 summarizes just a few relevant commercially available solutions which have been developed in parallel to this thesis.

However, such HEMSs currently available in the market, initially tackle the problem of energy efficiency and energy consumption-generation matching locally, without neither taking into account what is going on nearby nor interacting with the energy provider or any other interested third party which operates at broader scope (e.g., at neighborhood or district level), which is the direction most of them are currently heading.

Table 2-3 – Summary of some relevant commercially available HEMSs

Product	Company	Communicatios technologies	Description
Engage [Engage2014]	Efergy	Wireless	Whole-house power monitoring system
eMonitor [eMonitor2014]	Powerhouse Dynamics	Wi-Fi	Whole-house power monitoring system
Enlighten [Enlighten2014]	enphase	Zigbee	Residential PV (photovoltaic) micro-generation monitoring system
Housekeeper [Hk2014]	electronic housekeeper	Z-Wave	Residential monitoring and control system for energy consumption
Cloogy[2] [Cloogy2014]	Intelligent Sensing Anywhere	Zigbee	Initially, residential monitoring and control system for energy consumption. Recently, this solution has incorporated equipment for monitoring of residential PV micro-generation and residential monitoring of gas tanks and meters
Energy Management [EM2014]	greenWave Reality	Zigbee, Z-Wave, Jennet	Initially, residential monitoring and control system for energy consumption. Recently, this solution has been upgraded to monitoring and control system for consumption and generation
Smart Home [SH2014]	fifthplay	Wi-Fi, RF	Modular framework which comprises equipment for residential monitoring and control of energy consumption, as well as for the integration of residential PV micro-generation and EV
OWL Intuition [OWL2014]	OWL	Wireless	Family of products which allow monitor and control of energy consumption as well as energy generation monitoring at residential level
Sunny Home Manager [SHM2014]	SMA	Bluetooth	Solution for monitoring and control of consumption and generation at residential level
Chorus+energynote [Chorus2014]	GEO	Zigbee	Solution for monitoring and control of consumption and generation at residential level

2.3.4 Communications architectures, technologies, and protocols

ICT and M2M communications are crucial in all the aforementioned technologies and represent the key enabler of the Smart Grid at the distribution and customer domains.

When it comes to the required communications infrastructure, the first question that needs to be answered is which the most appropriate communications architecture is. However, there is not a single answer to this question, since this decision depends on multiple factors (e.g., target application, specific features and constraints of the underlying power infrastructure, regulation, etc.).

Reference [Mao2011] analyses the advantages and drawbacks of two communications architectures based on wireless 4G technologies for AMI applications. First, direct communication between the smart meters and the so-called MDMS (Metering Data Management System) is considered, focusing on the main issues that this approach presents

[2] As a matter of fact, Cloogy takes as reference the residential monitoring and control system proposed in this thesis and presented in chapter 3, which was jointly designed with Intelligent Sensing Anywhere.

from the communications point of view. In this regard, the paper highlights the inefficiencies of performing connection establishment and authentication procedures in a per-smart-meter-basis and remarks upon some resultant problems that network operators would have to face in this scenario, such as the required improvement of the RAN (Radio Access Network) to avoid problems related to lack of bandwidth or coverage arising from the huge number of smart meters. To solve these problems, the paper proposes a hierarchical architecture comprising two network segments, where the intermediate device between the smart meters and the MDMS is called AP (Aggregation Point). For the communications between the smart meters and the APs, short range communications technologies (e.g., IEEE 802.15.4/Zigbee or Wi-Fi) can be used; whereas wireless 4G technologies are still used for the communications between the APs and the MDMS.

As a matter of fact, hierarchical heterogeneous communications architectures comprising several network segments and combining different communications technologies present higher flexibility, so they fit a wider range of Smart Grid applications and specific requirements and constraints [Zaballos2011]. Figure 2-17 shows a proposal of this kind of communications architecture for the specific case of the power distribution domain of the Smart Grid [Fadlullah2011].

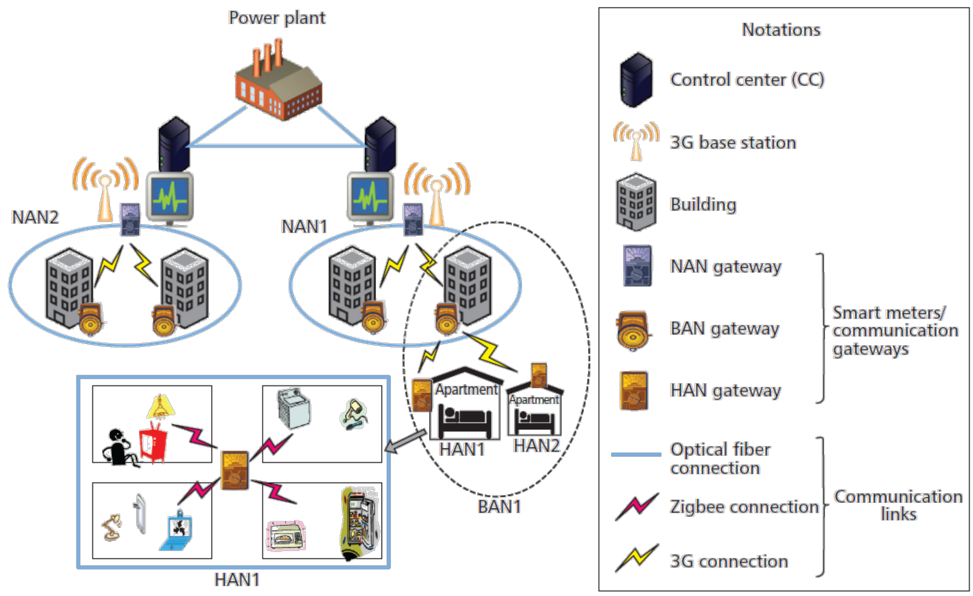


Figure 2-17 – Hierarchical and heterogeneous M2M communications architecture for the power distribution domain of the Smart Grid [Fadlullah2011]

The communications technologies use in the different network segments of such hierarchical heterogeneous M2M communications architectures may vary depending on the country or region. Although this thesis is mainly focused on the EU, Table 2-4 illustrates such different trends in NA (North America), the EU, and AU (Australia) [Lo2012], for the HAN and NAN as defined in [IEEE2011].

Table 2-4 – Summary of some of the communications technologies likely to be deployed in HAN and NAN in different countries [Lo2012]

					PLC		Sub-GHz			
		Wi-Fi	**Zigbee**	**15.4g**	**HomePlug**	**Other**	**ISM**	**Proprietary.**	**WiMAX**	**GPRS**
HAN	**NA**	X	X		X		X			
	EU		X			X	X			
NAN	**NA**			X				X	X	
	EU					X		X		X
	Asia							X		
	AU								X	

However, the Smart Grid at the distribution and customer domains represents such a hot and emerging market that Table 2-4 is far away from including all the available options. Table 2-5 aims to be more exhaustive, mapping the most relevant communications technologies onto the most appropriate network segments defined in [IEEE2011], paying special attention to the EU market [Güngör2011], [Fang2013], [Ancillotti2013], [Usman2013].

Table 2-5 – Summary of communications technologies and their scope

Communications Technologies		HAN	NAN	Backhaul
Wireless	**Zigbee** (Initially based upon IEEE 802.15.4)	X	(Occasionally, using mesh topology)	
	Bluetooth	X		
	Z-Wave	X		
	EnOcean (ISO/IEC 14543-3-10) [EnOcean2014]	X		
	Wi-Fi (IEEE 802.11)	X	X	
	WiMAX (IEEE 802.16)		X	X
	White Spaces		X	X
	Satellite			X
	Cellular			X
Wired	**Insteon** [Insteon2014]	X		
	KNX	X		
	LonWorks	X		
	PLC-based	X (e.g., BACnet, HomePlug)	X (e.g., PRIME, G3-PLC, G.hnem)	
	Ethernet	X (e.g., Fast Ethernet)		X (e.g., 1G/10G Ethernet)
	DSL		X	
	Cable (DOCSIS)		X	
	Fiber		X (e.g., FTTH)	X (e.g., SONET/SDH)

Due to the huge number of devices that Smart Grids involve, cost and energy consumption are two key constraints to be taken into consideration when deciding the most appropriate technology for a given communications segment. On the one side, the cost of deploying and managing the required monitoring and control infrastructure has to be lower than the cost of building and maintaining new peak power plants and of increasing the T&D (Transmission and Distribution) grid capacity. On the other side, the energy consumption of such monitoring and control infrastructure has to be lower than the energy savings ensured by the system itself. In addition, some other features, such as data rate or range, need to be considered depending on the specific requirements of each communications segment.

Based on these considerations, there are some communications technologies that fit specific communications segments better than others. In general, wireless communications technologies are of special interest due to the well-known advantages that they present (e.g., flexibility or ease of deployment).

Standing out among the wireless communications technologies for HAN are IEEE802.15.4/Zigbee and Bluetooth, since they are low-power communication technologies that fit the range and data rate requirements of this network segment. As a token of that, several of the commercial energy management platforms currently available in the market for dwellings and SOHO (Small Office Home Office) presented in section 2.3.3 used Zigbee (e.g., Cloogy [Cloogy2014], GreenWave Reality Energy Management [EM2014]) and Bluetooth (e.g., Sunny Home Manager [SHM2014]).

IEEE802.15.4/Zigbee mesh networks can be also used as last mile solution [Kulkarni2012]. This approach presents advantages from the point of view of the management and maintenance of the infrastructure, although it may also present higher security risks. In practice, this option presents fairly high adoption in areas such as California (US).

Standing out among the wired communications technologies for HAN and NAN are the PLC (Power Line Communications)-based solutions, mainly due to the fact that they present very low deployment costs, since in this case the power infrastructure represents also the communications infrastructure. There are two different types of PLC communications, namely broadband (B-PLC or BPL) and narrowband (NB-PLC). NB-PLC communications were developed to mitigate some problems of BPL related to EMI (Electromagnetic Interference) [Bartak2013] and to crossing from LV (Low Voltage) to MV (Medium Voltage) networks. Currently, the second generation of NB-PLC technologies is already available in the market.

NB-PLC technologies represent the preferred solution of utilities for AMI applications [Aidine2013]. The most relevant NB-PLC technologies for AMI are:

- Meters & More, which is promoted by the Enel Group. Its lower layers are being standardized by the IEC (International Electrotechnical Commission). Meters & More is being widely deployed in those countries where the Enel Group presents high market share (e.g., Italy).

- OSGP (Open Smart Grid Protocol), which is promoted by Echelon. Its lower layers are being also standardized by IEC. OSGP presents its higher penetration rates in the Nordic countries.

- G3, which is promoted by EDF and Maxim. Its PHY and MAC layers have already been published as standard by ITU-T (International Telecommunication Union - Telecommunication Standardization Sector) [ITU2012a]. G3 shows the highest penetration rates in those countries where EDF presents high market share (e.g., France).

- PRIME (PoweRline Intelligent Metering Evolution), which is promoted by the PRIME Alliance, led by Iberdrola. Its PHY and MAC layers have been also published as standard by ITU-T [ITU2012b]. PRIME is being widely deployed in Spain, Portugal, UK (United Kindom), Poland, Brazil, or Australia.

Table 2-6 summarizes the main features of some of these PLC-based communications technologies [Güngör2011], [De Craemer2010], [Ekanayake2012], [Aidine2013].

Table 2-6 –Summary of PLC communications technologies

Name	Type	Details	Scope/App
IEEE 1901	BPL	High speed PLC. Up to 100 Mbps	HAN/In-home multimedia networks
BACnet	NB 1G	ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) standard for building automation and control networks	HAN
HomePlug	BPL	Non-standardized technology specified by the HomePlug Powerline Alliance to interconnect smart appliances using home electricity network	HAN
HomePlug Green PHY	NB 1G	Low-power, cost-optimized PLC networking specification. Tested by American utilities such as Duke Energy, Pacific Gas & Electric, and Southern California Edison	HAN
G3-PLC	NB 2G	Launched by ERDF and Maxim. Aim at providing interoperability, cyber security and robustness while reducing costs	NAN/AMI
PRIME	NB 2G	Open, global standard for multi-vendor compatibility	NAN/AMI
G.HNEM	NB 2G	ITU-T standard which aims at harmonizing G3 and PRIME	NAN/AMI
Meters&More	NB 2G	NB-PLC technology promoted by the Enel group as communications standard for AMI	NAN/AMI
OSGP	NB 2G	NB-PLC technology promoted by Echelon as communications standard for AMI	NAN/AMI

Wi-Fi represents an interesting wireless option for the NAN especially for entities potentially interested on providing energy services without owning the electrical infrastructure, taking into account the fairly low cost and consumption and the high penetration of this communications technology.

Regarding the backhaul, GPRS (General Packet Radio Service) seems to be the cellular technology that better fits the specific requirements of this communications segment and is widely used in the vertical solutions which are more and more being deployed nowadays. Although it is not clear yet whether utilities will outsource the management of such communications infrastructure or will operate it themselves as MVO (Mobile Virtual Operators), utilities seem to prefer the first option. Wired broadband technologies, e.g., DSL (Digital Subscriber Line), cable, or even fiber-based solution such as FTTH (Fiber To The Home), represent appropriate technologies for approaches involving non-dedicated communications infrastructures. In rural environments, WiMAX (Worldwide Interoperability for Microwave Access), satellite communications, and White Spaces [Brew2011] represent interesting technologies.

Reference [Robichon2013] proposes deploying an entirely new cellular network based on CDMA-450 (Code Division Multiple Access at 450 MHz) exclusively devoted to the Smart Grid applications provided by a given DSOr (Distribution System Operator). In this case, the DSOr would be the owner of the communications infrastructure, but a telecom operator would be responsible for running it. The paper claims that this is a suitable solution from both technical and economic perspectives for the specific boundary conditions of the Netherlands, where the 450 Mhz band is unlicensed. However, this would not be the case in those countries where this frequency band is licensed or it would be even impossible in those countries where it is already allocated for any other use.

The aforementioned communications technologies address either the lower communications layers or the whole stack. However, at the application layer in particular, there are also many available standards and protocols, most of them not being bounded to a single network segment, but expanding across them. Table 2-7 summarizes the most relevant ones [Güngör2011], [De Craemer2010], [Ekanayake2012].

Table 2-7 - Summary of higher layers standards and protocols

Name	Details	Scope/App
USNAP	Standard to enable interoperability in HAN	HAN
M-Bus	European standard providing the requirements for remotely reading all kind of utility meters. Wireless M-Bus has been also specified recently	AN/AMI
DLMS/COSEM (IEC 62056)	Application standard for data exchange of meter readings, tariffs, and load control. Work over all the aforementioned 2nd generation NB-PLC solutions	AMI
ANSI C12.19	Flexible metering model for common data structures and industry vocabulary for meter data communications	AMI
OpenADR	Originally developed by Lawrence Berkeley Labs. Open, platform-independent, and transparent E2E standard for demand response	DR, DSM
DNP3	Standard for communications between Control Centers, RTUs (Remote Terminal Units), and IDEs (Intelligent Electronic Devices). Widely used in the US and Canada	SCADA
IEC 60870-5-101	Standard for communications between Control Centers, RTUs, and IDEs. Widely used in Europe	SCADA
IEC 60870-5-104	Include enhancements to 101 at every communications layer	SCADA
IEC 61970/61969	Define a CIM which is necessary for exchanging information between devices and networks. IEC 61970 works in the transmission domain; whereas IEC 61969 works in the distribution domain	Energy Management Systems
IEC 61850	Flexible open standard for communications between and within substations	Substation Automation
MODBUS	Messaging protocol in the application layer that provides communication between devices connected over several buses and networks. It can be implemented through Ethernet or using asynchronous serial transmission over EIA 232, EIA 422, EIA 485	Substation Automation
IEC 60870-6	Protocol for data exchange between utility Control Centers.	Inter-Control Centre Communications

Figure 2-18 provides an overview of where some of the analyzed protocols and standards are placed in the OSI (Open System Interconnection) model.

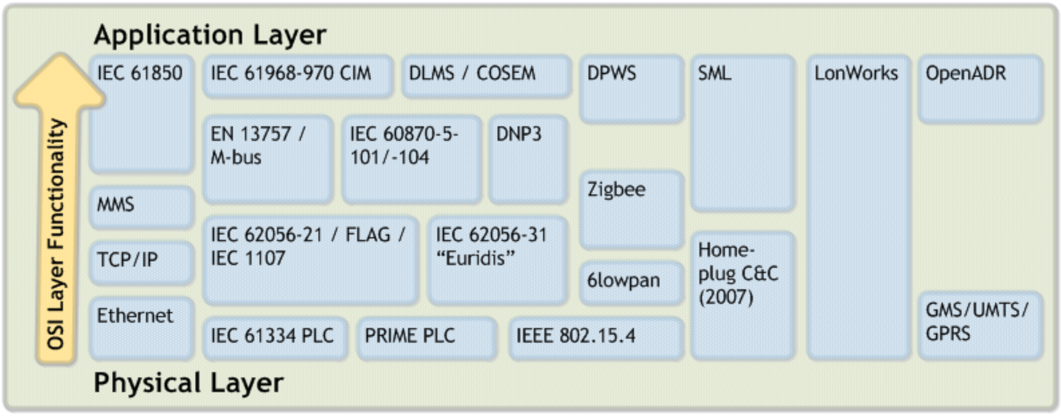


Figure 2-18 – OSI layer placement of most of the analysed standards [Moura2013b], [De Craemer2010]

2.4 Main trends on standardization and research

From the ICT perspective, standardization represents a key issue to foster the effective deployment of Smart Grids, since it allows equipment from different vendors to interoperate and it encourages competition, creating a global market and thus reducing costs. However, in such an emerging market, standardization has to be managed carefully, so that it leaves room for research and innovation. As a result, an optimum balance between standardization and R&D is critical to maximize Smart Grid potential [Yan2013]. Efforts for standardization and R&D need to be undertaken at every layer, homogenization and interoperability being the key issues in this context [Moura2013b].

As it has already been presented, there is a plethora of available specifications and standards at the HAN and NAN level, which actually hampers potential deployments, instead of promoting them, since they introduce uncertainty in the market, instead of reinforcing investments.

The matter of the most appropriate communications architecture and technologies eventually depends on the specific business case behind the target application, which in turn depends on many factors, such as the special features of the target application itself or the special features and the specific regulation of each country (which varies, e.g., even among EU countries). As a result, effective methods to evaluate different options and select the most appropriate ones before undertaking the important investments needed to deploy this kind of infrastructures on a large, are required.

Simulations represent a powerful, flexible, and cost-effective solution to achieve this goal. The research in this area can be classified depending on where it is focused. Thus, some research efforts are mainly focused on evaluating the behavior and performance of the lower layers of the communications protocols [Matanza2013], [Papadopoulos2013]. There are also research works focused on evaluating some figures of merit of the communications infrastructures themselves [Abdul Salam2012]. In this case, it is crucial to appropriately characterize the traffic of the target application [Khan2013] in order to obtain meaningful results. Finally, as the Smart Grid brings energy and ICT together, co-simulation of energy and ICT infrastructures represents a very promising and challenging research area [Anderson2012a], [Mets2011], [Lin2011], [Lévesque2012], [Celli2013], [Majumder2013].

Outstanding efforts are also being carried out by projects in Europe and the US to develop a common language which enables interoperability at HAN level. Notably, two objectives are set with regard to this within the scope of the EU eeBuilding Data Model collaboration (also called as eeSemantics) space:

- The objective in the medium to long term is to develop a common protocol which allows “Plug-and-Play" integration and interoperation of so-called EupP (Energy using and producing Products) from different manufacturers. In order to achieve this goal, a common data model needs to be developed first. In this sense, ontologies are becoming an increasingly popular way of defining machine-readable data models within the Smart Grid area [Grassi2011], [Santodomingo2012], [Wicaksono2012], in particular, and the M2M area [Gyrard2013], in general.

- The objective in the short to medium term is to use middleware (e.g., the SmartLink middleware platform developed under the scope of the EU FP6 project HYDRA and enhanced under the scope of the EU FP7 project SEEMPubS [Osello2013]) which allows managing devices from different vendors using different physical media and communications protocols.

Examples of this trend towards interoperability in the HAN are found in Zigbee and second-generation NB-PLC communications technologies. The Zigbee SEP (Smart Energy Profile) 2.0 puts special emphasis on interoperability, working not only over IEEE 802.15.4 but also over Wi-Fi and PLC, and incorporating 6LoWPAN (IPv6 over Low Power Wireless Personal Area Network) in the Zigbee stack. In the case of NB-PLC technologies, the ITU-T is making remarkable efforts to homogenize second-generation NB-PLC technologies, such as PRIME or G3-PLC, under the standard G.HNEM [Oskman2011]. As a token of this, there are already hardware equipped with both IEEE 802.15.4 and NB-PLC chipsets commercially available [Greenvity2014].

Interoperability between heterogeneous systems (e.g., utilities and home/building energy management systems), allowing holistic energy management, is also critical. As it has already been pointed out, there are also many different protocols developed for specific purposes at the application layer. Homogenization at the data structure level would allow such protocols to interoperate (if required) and would encourage third parties to come up with a wide variety of value-added services that would enrich and energize the Smart Grid market.

The US Green Button Data initiative represents an interesting example of this. Within the Green Button Data approach, the utilities provide their customers with their energy-related information in a standard machine-readable format. Since such information is in standard format, third parties (e.g., ESCOs) will be able to offer added-value services by processing it somehow. Then, the customers will allow those ESCOs whose services are of their interest, to get access to their energy-related information in order to enjoy the services they offer, thus partly solving privacy issues [GBD2014].

2.5 Overview of related projects

During the last few years, many R&D projects have been undertaken both at national and European level to tackle the issues presented throughout this chapter. As a matter of fact, a review recently published by the EU JRC (Joint Research Center) shows that, up to September 2012, a total of 281 Smart Grid projects and around 90 smart metering pilots and rollouts were made across 30 countries in Europe, accounting for total investments of at least €5 billion and €1.8 billion respectively [JRC2012b]. Based on this inventory of Smart Grid projects, the European electricity union Euroelectric has recently launched an online platform on Smart Grid activity in Europe, which includes an interactive, fully searchable map of Smart Grid projects and the detailed project pages [SGprojects2014].

Next, some EU R&D projects of special relevance to this thesis are summarized:

- The REViSITE (Roadmap Enabling Vision and Strategy for ICT-enabled Energy Efficiency) project [REViSITE2012] aims to contribute to the formation of a European multidisciplinary "ICT for energy-efficiency" research community by bringing together the ICT community and important and complementary application sectors, such as grids, building/construction, manufacturing and lighting.

- The IREEN (ICT Roadmap for Energy Efficient Neighborhoods) project [IREEN2013] is a strategic project which examines the ways that ICT for energy efficiency can be extended beyond individual homes and buildings to the wider context of neighbourhoods and communities.

- The Energy Warden (Renewable Energy Sourcing Decisions and Control in Buildings) project [EW2012] aims at developing and marketing a simulator and modeling tool which includes dynamic models for energy producing, storing and using units. The resulting tool aims to provide decision aid in designing or retrofitting energy infrastructures at the building domain.

- The main objective of the HESMOS (ICT Platform for Holistic Energy Efficiency Simulation and Lifecycle Management Of Public Use FacilitieS) project [HESMOS2013] is to allow complex lifecycle simulations to be done during design, refurbishment and retrofitting phases, where the largest energy saving potentials exist.

- The SEEMPubS (Smart Energy Efficient Middleware for Public Spaces) [Osello2013] project specifically addresses reduction in energy usage and CO_2 footprint in existing public buildings and spaces without significant construction works, by an intelligent ICT-based service monitoring and managing of the energy consumption.

- The Adapt4EE project [Adapt4EE2014] aims at providing a holistic approach to the design and evaluation of the energy performance of construction products at an early stage and prior to their realization. The Adapt4EE project is currently responsible for hosting and managing the EC eeSemantics collaboration space.

- The IntUBE (Intelligent use of buildings' energy information) project [IntUBE2011] aims to develop tools for measuring and analyzing building energy profiles based on user comfort needs.

- The main objective of the AIM (A novel architecture for modelling, virtualizing and managing the energy consumption of household appliances) project [AIM2010] is to foster a harmonized technology for profiling and managing the energy consumption of appliances at home.

- The DEHEMS (Digital environment home energy management system) project [DEHEMS2011] aims to bring together sensor data in areas such as household heat loss and appliance performance as well as energy usage monitoring in order to give real-time information on emissions and energy performance of appliances and services.

- The PEBBLE (Positive-energy buildings thru better control decisions) project [PEBBLE2012] aims to optimize loads to achieve generation-consumption matching.

- The FIEMSER (Friendly Intelligent Energy Management System for Existing Residential Buildings) project [FIEMSER2013] addresses the need of achieving energy positive buildings through solutions based on a rational consumption of energy, local generation, and an increase in the consciousness of the building owners towards their energy consumption habits.

- The ENCOURAGE (Embedded iNtelligent COntrols for bUildings with Renewable generAtion and storaGE) project [ENCOURAGE2014] aims to develop embedded intelligence and integration technologies that will directly optimize energy use in buildings and enable active participation in the future smart grid environment.

- The BEyWatch (Building Energy Watcher) project [BeyWatch2011] aims to develop an energy-aware and user-centric solution, able to provide intelligent energy monitoring/control for white goods and power demand balancing at home/building and neighbourhood level.

- The objective of SmartCoDe (Smart Control of Demand for Consumption and Supply to enable balanced, energy-positive buildings and neighbourhoods) project [SmartCoDe2012] is to enable the application of advanced techniques for energy management in private and small commercial buildings and neighbourhoods.

- The ENERsip (ENERgy Saving Information Platform for Generation and Consumption Networks) project [López2012b] aims to create an adaptive, customizable and service-oriented energy monitoring and control system for near real-time generation and consumption matching in residential, commercial buildings and neighborhoods by active and proactively coordinating energy, communications, control, and computing.

- The main target of the ADDRESS (Active Distribution network with full integration of Demand and distributed energy RESourceS) [Belhomme2008] project is to enable the active participation of small and commercial consumers in power system markets and provision of services to the different power system participants.

- The SmartHouse/SmartGrid project [SHSG2011] aims to validate and test how ICT-enabled collaborative technical-commercial aggregations of smart houses provide an essential step to achieve the needed radically higher levels of energy efficiency in Europe.

- The NOBEL (Neighbourhood Oriented Brokerage Electricity and monitoring system) project [NOBEL2012] aims to build an energy brokerage system that allows individual energy consumers to communicate their energy needs directly to both large-scale and small-scale energy producers, thereby making energy use more efficient.

- The MIRABEL (Micro-Request-Based Aggregation, Forecasting and Scheduling of Energy Demand, Supply and Distribution) project [MIRABEL2013] is dedicated to develop an approach on a conceptual and an infrastructural level that allows DSOs to balance the available supply of renewable energy sources and the current demand in ad-hoc fashion.

- The INTEGRIS (INTelligent Electrical Grid Sensor communications) project [Della Giustina2011] proposes the development of a novel and flexible ICT infrastructure based on a hybrid PLC-wireless integrated communications system able to completely and efficiently fulfill the communications requirements foreseen for the Smart Grids of the future.

- The PowerUp project [Caldevilla2013] aims to develop the V2G (Vehicle-to-Grid) interface which ensures the seamless integration of EVs into the Smart Grid.

At national level, some Spanish R&D projects of special relevance to this thesis are summarized next:

- The main objectives of the GAD (Active Demand Side Management Project) project [GAD2010] are to develop: 1) tools to optimize electricity consumption in households, thus reducing electricity cost and environmental impact; 2) devices to show the price and origin of the energy to the customer; 3) technologies that improve power quality while aiding in the integration of renewables.

- The main objectives of the PRICE-GEN project [López2014c] are to: 1) design an optimal and interoperable communications network architecture; 2) develop novel and smart sensing and actuating equipment, which provide information on consumption and generation that allows having a more accurate picture of the power distribution network in almost real-time; 3) validate this platform by means of a pilot scheme which involves the deployment of over 200,000 smart meters and their integration into the operational power distribution infrastructure of a geographical area close to Madrid (Spain).

- The DOMOCELL project [López2013b] aims to design and develop a smart charging infrastructure to seamlessly integrate EV into the Smart Grid at residential level.

Table 2-8 summarizes, classifies and compares the considered R&D projects.

Table 2-8 – Summary and comparison of considered R&D projects

	Projects	**Scope**			**ICT4EE**			**AMI**	**DER**	**EV**	**DR**	**M2M comms**
		H	**B**	**N**	**Guidelines**	**Sim tools**	**DA&V tools**					
1	**REViSITE**		X		X							
2	**IREEN**	X	X	X	X							
3	**Energy Warden**		X			X			X			
4	**HESMOS**		X			X						
5	**SEEMPubS**		X			X						
6	**Adapt4EE**		X			X						
7	**IntUBE**		X				X					
8	**AIM**	X					X					
9	**DEHEMS**	X					X					
10	**PEBBLE**		X				X		X		X	
11	**FIEMSER**	X	X				X		X		X	
12	**ENCOURAGE**		X						X		X	
13	**BEyWatch**	**X**	**X**	**X**			**X**		**X**		**X**	
14	**SmartCoDe**	**X**	**X**	**X**			**X**		**X**		**X**	
15	**ENERsip**	**X**	**X**	**X**			**X**		**X**		**X**	**X**
16	**ADDRESS**	X		X							X	
17	**Smart House/ Smart Grid**	X	X	X							X	
18	**NOBEL**	X	X	X					X		X	
19	**MIRABEL**			X					X		X	
20	**INTEGRIS**			**X**				**X**	**X**	**X**	**X**	**X**
21	**PowerUp**								X	X	X	
22	**GAD**	X									X	
23	**PRICE-GEN**							X				X
24	**DOMOCELL**		X	X					X	X	X	X

H: Home; B: Building; N: Neighborhood; ICT4EE: ICT for Energy Efficiency; Sim: Simulation; DA&V: Data Analysis and Visualization

As Table 2-8 shows, the considered projects approach the overall problem (i.e., energy efficiency and integration of renewable micro-generation at the distribution and customer domains of the Smart Grid) from different perspectives. There are some projects, such as REViSITE and IREEN, whose main goal is to define guidelines and provide tools for effective collaboration. These projects work at a high level of abstraction and present a wide scope, but they do not get into the details of how to solve the specific problems. Regarding the projects that do so, most of them deal with very specific pieces of the overall issue.

The projects BEyWatch, SmartCoDe, ENERsip, and INTEGRIS, excel at presenting the most comprehensive proposals. The ENERsip project differentiates itself from the BEyWatch project and the SmartCoDe project because it explicitly deals with the core M2M communications infrastructure required to tackle the aforementioned overall problem at neighborhood level. The INTEGRIS project also does it. However, the INTEGRIS project approaches the problem from the DSO perspective; whereas the projects BEyWatch, SmartCoDe, and ENERsip are more focused on the customer, leaving the door open for any interested party to run and operate the proposed platforms (e.g., the former project does not consider HEMS nor BEMS; whereas the latter ones do so).

This thesis has been partly developed under the scope of the ENERsip project. As a matter of fact, one of the main objectives of this thesis is to propose a M2M communications architecture that supports energy efficiency and integration of renewable micro-generation within the so-called energy-positive neighborhoods of the Smart Grid. In addition, the research work carried out in this thesis has been taken as reference while being also influenced by the Spanish projects DOMOCELL and PRICE-GEN.

2.7 Conclusions

The review of the state of the art presented throughout this chapter shows the efforts carried out by the main standardization bodies and by the research community to tackle the issues associated to the design and development of the Smart Grid from different perspectives, such as the need for conceptual models and references architectures, the issue of selecting the most suitable communications architectures and technologies, or the trend towards homogenization and interoperability in ICT.

Regarding standards in particular, there are a myriad of them for Smart Grids, but this chapter is focused on the most relevant ones to this thesis. To effectively look for any other standard, the IEC has recently created a free Smart Grid Standards Mapping Tool that allows easily identifying the standards that are needed for any part of the Smart Grid, including not only IEC standards but also standards from other organizations [IEC2014].

This thesis has contributed to some of the aforementioned efforts in parallel with the standardization and R&D works presented throughout this chapter. Figure 2-19 illustrates this fact, showing a timeline of the most relevant milestones of this thesis along with the most relevant standardization and research milestones[3]. Notably, the main contributions of this thesis to the state of the art, as it will be described in detail in the next chapters, are:

- We propose a novel M2M communications architecture to support energy efficiency and energy consumption and generation optimization at neighborhood level, going beyond the meters down to the consumption and generation monitoring and control networks.

- We formally model the domain of knowledge of energy efficiency platforms for the so-called energy-positive neighborhoods by means of an ontology developed in OWL (Ontology Web Language), with the aim that it becomes a reference data model for the application of M2M communications to this context.

- We characterize the traffic carried by the core of the designed M2M communications architecture in realistic large-scale scenarios.

[3] [Fadlullah2011] and [Zaballos2011] are included as remarkable proposals of M2M communications architectures within the same scope of this thesis. [Khan2013] is included as a comprehensive work on characterizing traffic requirements depending on the target application.

- Based on this traffic modeling, we evaluate the core of the proposed M2M communications architecture from both economic and technical perspectives by means of theoretical analysis and simulations.

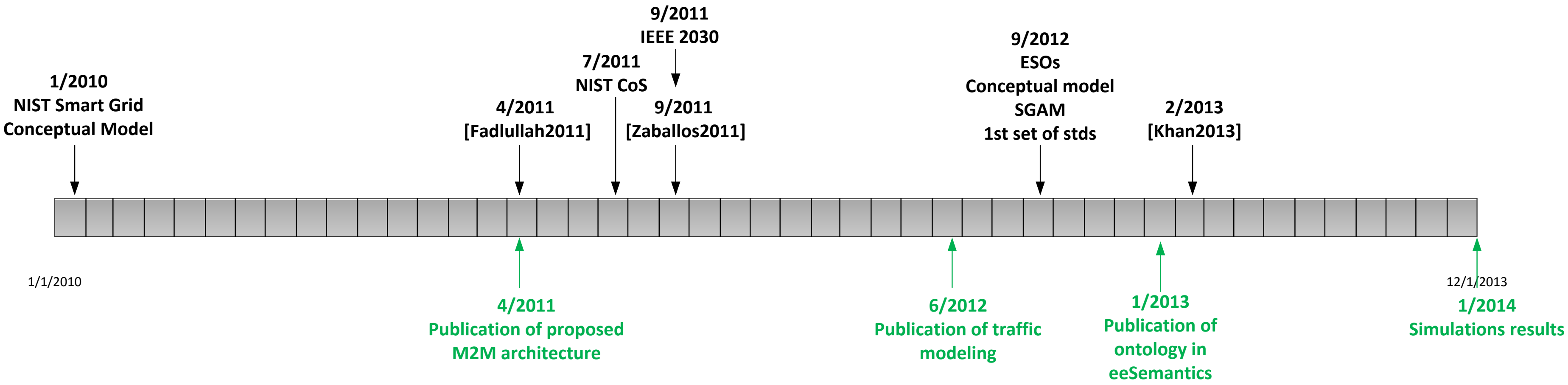


Figure 2-19 – Timeline of the most relevant milestones of this thesis along with the most relevant standardization and research milestones

Chapter 3

Network Architecture

3.1 Introduction

The main drivers of the Smart Grid presented in chapter 1 (namely, energy efficiency and the increasing penetration of DERs – Distributed Energy Resources – including renewable generation and EVs – Electric Vehicles) have special impact on the power distribution domain and on the customer domain (in particular, at residential level). The so-called energy-positive neighborhoods, buildings, and households appear in this context as if such a "divide and conquer" approach was applied to tackle the problem, in that it is addressed at these three levels.

This chapter is focused on addressing such Smart Grid drivers at neighborhood level. To be more precise, the main goal of this chapter is to design a M2M (Machine-to-Machine) communications architecture which supports energy efficiency within energy-positive neighborhoods by enabling electricity consumption reduction at residential level and matching the electricity consumption within a given neighborhood with the generation coming from the local renewable sources distributed along the same neighborhood.

The remainder of the chapter is structured as follows. Section 3.2 presents the overall system architecture, paying special attention to the M2M communications infrastructure. Section 3.3 explains how our proposal is aligned with the standardization work reviewed in chapter 2. Section 3.4 proposes the communications technologies to be used in each network segment. Section 3.5 outlines the most relevant security features of the selected communications technologies and proposes the most appropriate solution in each case. Section 3.6 describes an application-layer solution to provide E2E (End-to-End) addressability throughout the platform and explains how it would work during deployment and operation. Finally, section 3.7 summarizes this chapter and draws conclusions.

3.2 System description

Figure 3-1 shows the overall system architecture of the proposed ICT (Information and Communications Technologies) system to enable electricity consumption reduction and proper integration of DER (Distributed Energy Resources) at neighborhood level. It can be seen that the system is divided into four domains, which represents its main pillars from the ICT perspective. The Building Domain comprises the physical infrastructures owned by the commercial and residential customers of the power distribution network of the Smart Grid, including consumption and generation equipment and the SANs (Sensor and Actuator Networks) to monitor and control them. The User Domain encompasses everything related with making the interaction of the users and the system as fruitful as possible. The Information System Domain represents the "brain" of the system from the energy perspective, comprising the logic that allows the optimal use of the available resources at neighborhood level at any time. Finally, the Neighborhood domain encompasses the core communications infrastructure that carried data and command back and forward, allowing that everything work correctly.

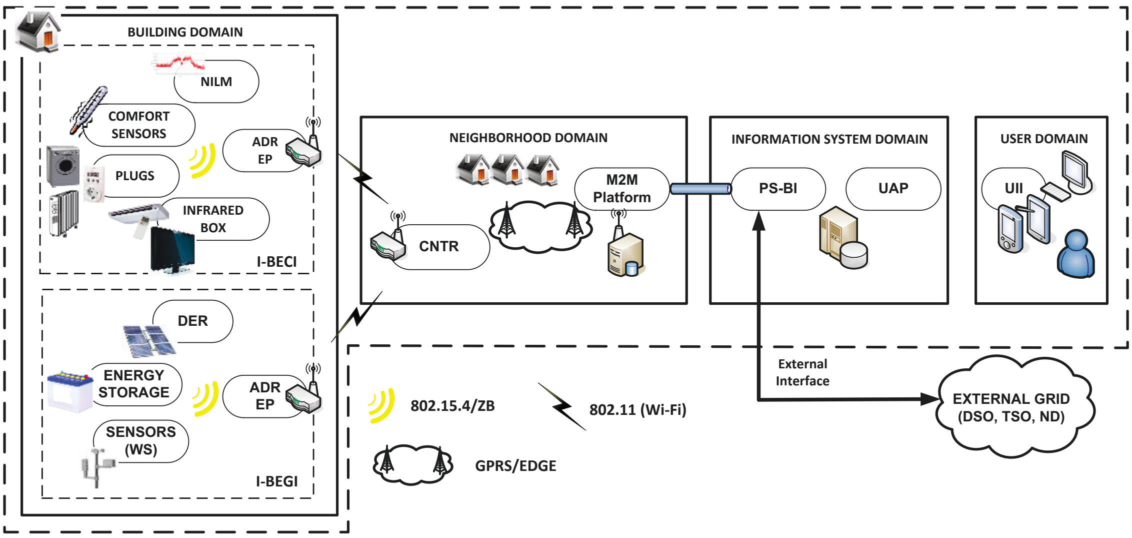


Figure 3-1 – Overall system architecture

Thus, the Information System Domain and the User Domain are indeed related with IT (Information Technology); whereas the Building Domain and the Neighborhood Domain are tightly related with communications. As a matter of fact, the M2M communications architecture proposed in this chapter is spread across these domains, as shown in Figure 3-1. This architecture illustrates how the aforementioned "divide and conquer" approach is applied to communications, in that it is a hierarchical architecture which comprises specific network segments for households, buildings or group of households, and neighborhoods. This approach makes the communications infrastructure more flexible and adaptive, and boosts scalability. The proposed communications architecture is also heterogeneous in that it involves different communications technologies in order to meet the specific communications requirements of each network segment.

3.2.1 Building domain

As it has already been mentioned, the Building Domain encompasses the physical infrastructure (both electrical and ICT) owned by the commercial and residential customers of the power distribution network of the Smart Grid. It is further divided into:

- The so-called I-BECIs (In-Building Energy Consumption Infrastructures), which represent the consumption infrastructures along with the SANs to smartly manage them;
- And the so-called I-BEGIs (In-Building Energy Generation Infrastructures), which represent the local generation facilities along with the SANs to smartly manage them.

I-BECIs and I-BEGIs can be combined or not, giving rise to different profiles of customers:

- Consumers: customers whose households or buildings are only composed of I-BECIs.
- Producers: customers whose infrastructures comprise only I-BEGIs connected to the grid.
- Prosumers: customers that own the so-called energy-positive households or buildings, also known as ZEBs (Zero-Energy Buildings) or NZEBs (Net-Zero Energy Buildings), which integrate both I-BECIs and I-BEGIs.

Every I-BECI or I-BEGI or combination of I-BECI and I-BEGI needs a device that manages the communications inside the SAN or HEMS (Home Energy Management System) and with the Information System where the overall optimization processes run. This device is the so-called ADR EP (Automated Demand Response End Point). Apart from the already said duties, the ADR EP also aims to allow managing in a uniform way the wide variety of devices within the I-BECIs and I-BEGIs, hiding this complexity and heterogeneity to the Information System. In order to achieve this goal, the ADR EP needs to be equipped with multiple hardware interfaces and to support multiple communications protocols, including the potentially different communications protocols within the I-BECIs/I-BEGIs and a common application protocol for the communication with the Information System (e.g., an extension to IEC61850 [Apostolov2013]). Therefore, a star topology controlled by the ADR EP is proposed for the HEMS (i.e., I-BECIs or I-BEGIs or both).

Regarding the SANs for the I-BECIs, taking into account that – as it was pointed out in chapter 2 – smart appliances represent a solution in the long run, the so-called smart Plugs need to be used both to monitor the consumption of the appliances and to control it accordingly to the commands sent by the customer or automatically generated by the Information System. Thus, such smart Plugs allow, e.g., cutting standby consumptions, which may account for up to the 7% of the total annual electricity consumption per household [De Almeida2011].

However, there is a group of devices that are of special interest for energy efficiency and consumption-generation matching which may require a more sophisticated control via IR (Infrared) communications: the HVAC (Heating Ventilating Air Conditioning) loads, which present high consumption and high penetration at households. Therefore, a specific device, the so-called IR Box or GW (Gateway), needs to be placed between this kind of equipment and the ADR EP in order to allow managing them appropriately. The IR GW also allows seamless integration of widely used devices such as TVs or DVDs into the HEMS.

The NILM (Non-Intrusive Load Monitoring) or NIALM (Non-Intrusive Appliance Load Monitoring) [Zeifman2011] represents a very promising technology to enable backward compatibility and to reduce the cost of the HEMS. The NILM is a technology that has been around for a long while [Warren1989]. It allows identifying (based on electrical signature) the appliances which are running, even if they are not equipped with a smart plug with sensor and communication capabilities. In order to achieve this goal, the theoretical NILM approach determines when a specific appliance is turned ON based just on its electrical signature by applying non-supervised DSP (Digital Signal Processing) methods to the overall electrical signal. However, due to the complexity of such methods, a more straightforward approach entails that the customer informs the NILM module about the appliance which has just been turned ON in order to help it learn its electrical signature. As a result, this NILM module allows disaggregating household energy consumption into individual appliances without the need of using smart plugs for every single appliance; only those appliances susceptible to be controlled (e.g., by participating in DR –Demand Response – programs) would need to be plugged in the socket through smart plugs.

To complete the SANs of the I-BECIs, comfort is a keyword when talking about energy efficiency, in that achieving energy efficiency may never compromise the basic comfort level established by the customer. Therefore, the so-called comfort sensors are required to measure different environmental variables, such as temperature, relative humidity or CO_2 concentration, which are taken into account when running the optimization algorithms in order to avoid compromising the customers' basic comfort levels. For instance, the data acquired by a CO_2 concentration sensor can be used to control the AC (Air Conditioning) equipment in order to reduce its electricity consumption as follows. When the CO_2 concentration in a room is below a maximum acceptable value, the AC can cool the air from inside the room, which requires much less electricity than taking it from outside, since it is not so hot. Only when the CO_2 concentration is above such a threshold, the AC will cool the air from outside, until CO_2 concentration goes below the maximum acceptable value again. A temperature sensor can be also used to control the AC equipment efficiently and to integrate it into DR programs by providing feedback on the actual temperature in a room, allowing actuating on the AC consequently.

Regarding the I-BEGIs, photovoltaic panels and µwind turbines represent the most extended technologies in buildings [Jellea2012], [Ayhana2012]. Both the photovoltaic panels and the µwind turbines are equipped with Inverters, which play a double role: on the one side, they adapt the electrical signal (i.e., converting DC into AC); on the other side, they work as RTU (Remote Terminal Units), measuring some key parameters associated to the generation equipment and sending them to the ADR EP. The photovoltaic panels may be also equipped with panel temperature sensors, since this parameter influences their performance. In addition, the so-called energy meters are needed to measure the energy that the installation is generating.

The SANs of the I-BEGIs need to be equipped with sensors to measure variables related to weather conditions (e.g., temperature, humidity, wind direction and speed, solar irradiation) and electrical variables (e.g., DC current or voltage, AC current or voltage) and to send them to the Information System in order to allow accurate status monitoring and accurate generation forecast, which are two key parameters when operating DR events. The set of sensors in charge of monitoring weather conditions can be integrated all together into the same Weather Station and the set of sensors in charge of measuring electrical variables are usually integrated into the same Network Analyzer.

The I-BECI and I-BEGI presented in this section have been taken as reference in the EU FP7 project ENERsip to develop the prototype networks shown in Figure 3-2 and Figure 3-3.

Figure 3-2 – Prototype network for the monitoring and control of I-BECI [Carreiro2011]

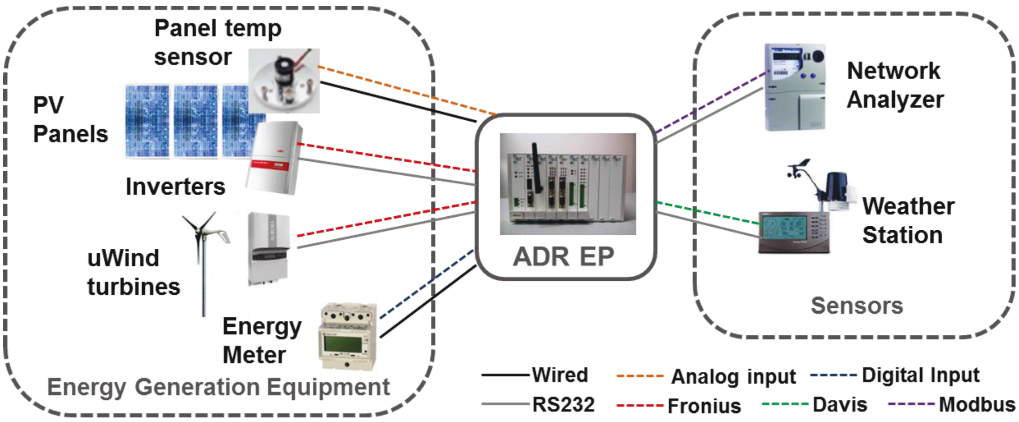


Figure 3-3 – Prototype network for the monitoring and control of I-BEGIs [López2013a]

As it can be seen, the approach in this project was to develop independent ADR EPs for the I-BECIs and for the I-BEGIs. In addition, the I-BECIs rely on wireless short distance communications (IEEE 802.15.4/Zigbee [IEEE2006]); whereas the I-BEGIs rely on wired communications which are currently widely used in these environments. However, the I-BEGI shown in Figure 3-3 can be easily upgraded to support the same wireless protocol as in the I-BECI - thus facilitating their integration – by using off-the-shelf RS-232-Zigbee modems (also known as “Zigbee dongles”).

3.2.2 User domain

The User Domain encompasses the means through which the users and the system interact. It is worthwhile mentioning at this point that energy efficiency is achieved both through automated actions (e.g., DR event) and by influencing users’ behaviors. This is why is so important the way in which the information is presented to the user, so that it is easily understandable, as well as the tools that are provided to the users for them to make decisions, which should be as human-friendly as possible.

This functionality is provided to users via the so-called UII (User Intuitive Interfaces). The UII are applications that allow interacting with the platform in a human-friendly manner. Such applications may run in smartphones or tablets or even in Smart TVs, since this technology is gaining significance and represent a great mean to reach people massively. It is also important that such applications are somehow connected to social networks [Mankoff2010], [Anderson2012b], in order to encourage the users to follow the recommendations proposed by the system. In this way, social games could be presented to the users to try to motivate them to be “greener”.

3.2.3 Information System domain

Gathering the consumption and generation data of the same district at a given moment of time and processing them all together allow reaching global optimizations at neighborhood level, instead of just local optimizations at household level, as it is the case in state-of-the-art HEMS. In addition, since the customers are still allowed to configure a set of parameters and thresholds and they are taken into account when running the optimization algorithms, local optimizations can be also reached, whereas this is impossible the other way around.

However, the Information System is responsible not only for processing the data and making the appropriate decisions, but also for making the appropriate information available to the customers through the UIIs, as well as for dealing with the commands sent and configurations made by the customers.

As a result, the Information System is further divided into two modules: the so-called PS-BI (Power Saving Business Intelligent) and the so-called UAP (User Application Platform). The PS-BI is the one responsible for collecting (through the M2M communication infrastructure) all the data regarding both energy generation and consumption, processing them, and enabling an efficient use of available resources anytime; whereas the UAP works as interface between the PS-BI and the UII, enabling the provision of a whole set of value-added energy efficiency, comfort monitoring and optimization services based on the user profile and the information provided by the PS-BI.

In addition, the Information System may implement a standard interface to allow a system running in a given neighborhood to interact with other relevant stakeholders of the electricity market, such as aggregators, DSOrs (Distribution System Operators) or TSO (Transmission System Operators), so that it may be managed and coordinated with other neighborhood grids, thus providing interoperability and scalability.

3.2.4 Neighborhood domain

The Neighborhood Domain represents the core M2M communications infrastructure which allows controlling, monitoring, and managing such a high volume of generation and consumption devices spread over a wide area remotely. Therefore, it is responsible for carrying, in a reliable manner, data coming from the Building Domain to the Information System Domain and control and management commands going from the Information System Domain to the Building Domain.

For the sake of scalability and flexibility, this core communications infrastructure comprises two network segments. In the first hierarchical level, a group of ADR EPs are managed by the so-called CNTR (Concentrator). In the second hierarchical level, the network of CNTRs is managed by the so-called M2M Platform.

The CNTRs perform management tasks such as ID assignment, IP assignment, or enabling/disabling ADR EPs. In addition, the CNTRs aggregate and forward the data coming from the ADR EPs to the Information System through the M2M Platform and route the commands coming from the Information System to the appropriate ADR EP. In this way, the problems reported in [Mao2011], which were discussed in chapter 2, are avoided.

The M2M Platform works both as OSS (Operation Support System) and as communications gateway. On the one side, the M2M Platform is responsible for performing typical OSS tasks, such as network inventory, network components configuration, fault management, and service provisioning. On the other side, it forwards all the data coming from the CNTRs to the Information System and routes the commands coming from the Information System to the appropriate CNTR.

3.3 Relation to standardization activities

This section explains the relationships of the proposed system and M2M communications architecture with the standardization work presented in chapter 2.

Firstly, taking into account the main goals and functionalities of the system explained in section 3.2 and the summary of the domains defined in the NIST Smart Grid conceptual model shown in the table 2-1 of chapter 2, the scope of the proposed system is bounded to the Customer, Distribution, Service Provider, and Operations domains, as Figure 3-4 illustrates.

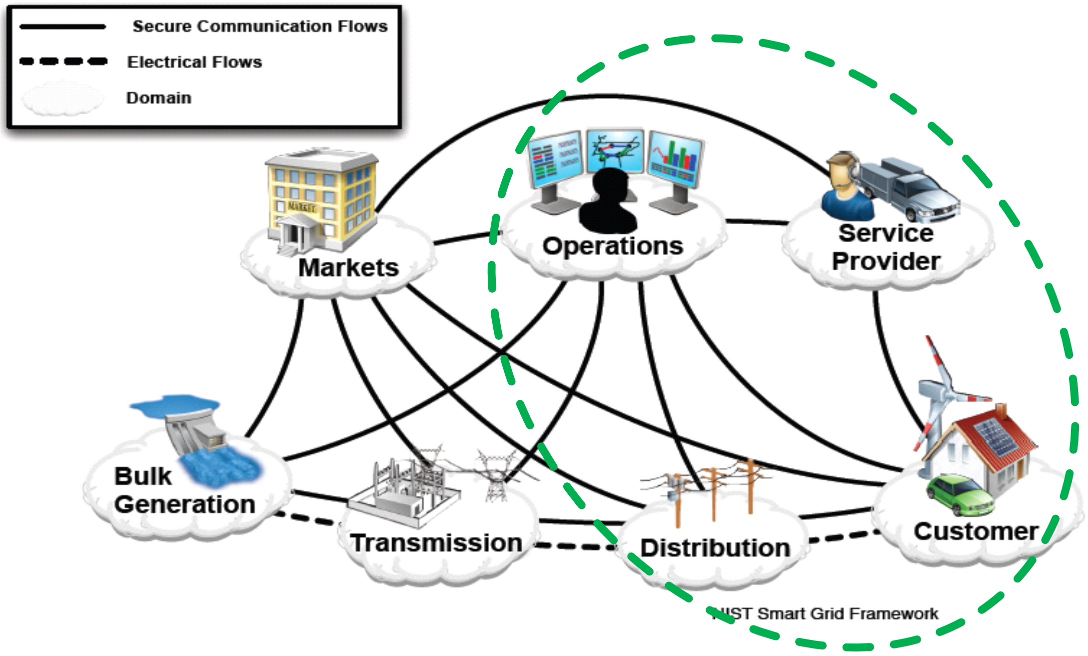


Figure 3-4 – Mapping of the scope of the target platform onto the NIST Smart Grid conceptual model

Secondly, the proposed M2M communications architecture can be mapped onto the CT-IAP (Communications Technologies – Interoperability Architectural Perspective) of the overall IEEE 2030 SGIRM (Smart Grid Interoperability Reference Model) [IEEE2011] as follows:

- The I-BECIs and the I-BEGIs represent the HANs (Home Area Networks) in IEEE 2030 terminology. The ADR EP provides the functionality of ESI (Energy Service Interface).

- The communications segment comprising the ADR EPs and the CNTRs represents the NAN (Neighborhood Area Network) of the M2M communications infrastructure, as defined in the CT-IAP of the IEEE 2030 SGIRM.

- The communications segment composed by the CNTRs and the M2M Platform represents the Backhaul of the M2M communications infrastructure, as defined in the CT-IAP of the IEEE 2030 SGIRM.

Figure 3-5 graphically identifies the HAN, NAN, and Backhaul network in the proposed M2M communications architecture. It should be noted that the remainder of this dissertation will refer to the IEEE 2030 terminology.

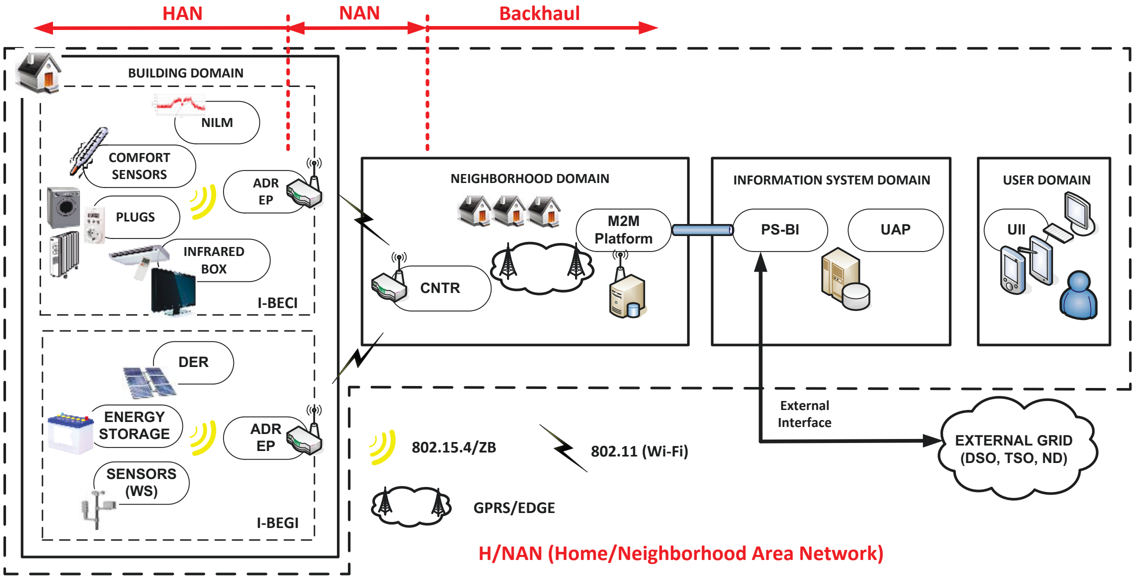


Figure 3-5 – Mapping of the proposed M2M communications architecture onto the IEEE 2030 SGIRM

Regarding the standardization work carried out by the ESOs (European Standardization Organizations), the comparison is focused on the work developed by ETSI on M2M (recently transferred to the partnership project OneM2M [OneM2M2014]), since the conceptual model and the SGAM (Smart Grid Architectural Model) defined by the SG-CG (Smart Grid – Coordination Group) take into account and present many similarities to the already considered standardization work. Figure 3-6 graphically shows the relationship between the M2M domains defined by ETSI and the domains presented in section 3.2.

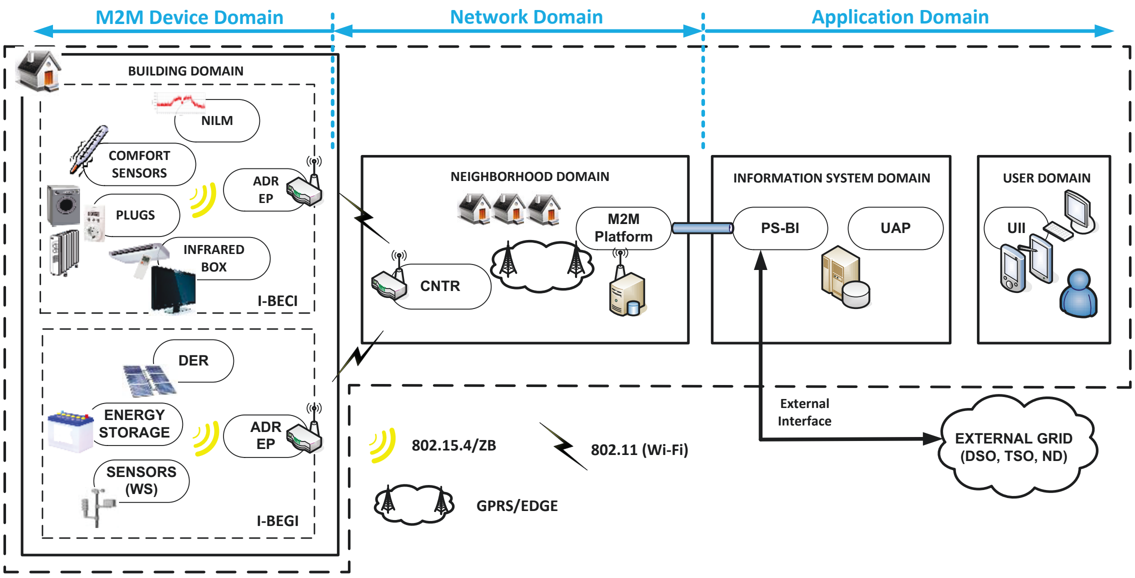


Figure 3-6 – Mapping of the proposed M2M communications architecture onto the ETSI M2M domains

Our M2M communications architecture can be also mapped onto the ETSI M2M architecture applied to the Smart Grid presented in [Lu2012]. The SANs within the I-BECI and

I-BEGI can be seen as capillary networks at the Customer Domain. Regarding the remainder of the M2M communications architecture, there are two possible options, as shown in blue in Figure 3-7:

- If the proposed platform were run by an Energy Service Provider, an additional nesting level to represent the CNTR would be missing in the ETSI M2M architecture proposed in [Lu2012].
- However, if the proposed platform were run by a DSOr, the Customer Domain would be embedded into the Distribution Domain, following the hierarchy of the electricity infrastructure itself. Thus, the ADR EPs and CNTRs could be considered as ETSI M2M GWs at Customer and Distribution Domains respectively, and our M2M Platform could be seen as the ETSI M2M Core of the Distribution Domain.

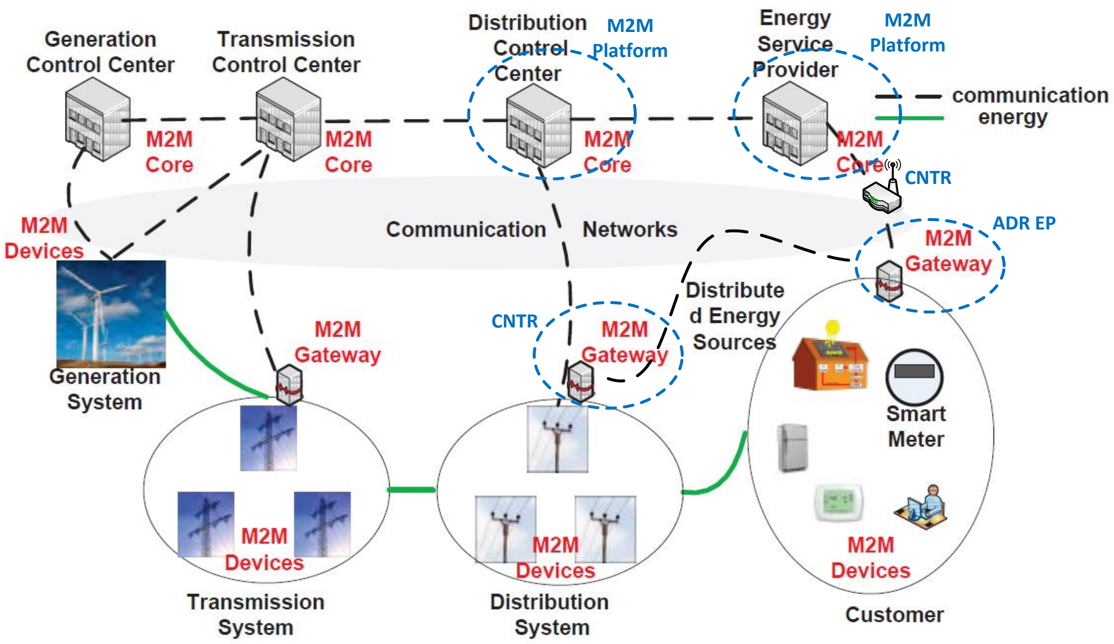


Figure 3-7 – Mapping of the proposed M2M communications architecture onto the ETSI M2M architecture applied to the Smart Grid [Lu2012]

3.4 Communications technologies

As it has already been mentioned, cost and power consumption are two key constraints to be taken into account when deciding the most appropriate technologies for this kind of systems, due to the huge number of devices they involve. Furthermore, some other features, such as data rate or range, which depend on the specific requirements of each communication segment, are also relevant and need to be considered.

Reflecting the outstanding importance of wireless communications in the distribution and customer domains of the Smart Grid [NIST2011], this thesis is specially focused on them.

3.4.1 Home Area Network

There is a plethora of communications standards for smart metering and sub-metering (i.e., HAN/HEMS) [Güngör2011]. In general, wireless solutions are preferred *vis-à-vis* wired ones, since they reduce deployment and maintenance costs and allow higher flexibility. This is not the case for PLC, since PLC does not require the deployment of additional infrastructure. However, by the time the communications technology for this network segment was proposed, PLC was not as technically mature as some of its market competitors, and thus it was not such a cost competitive technology. In addition, PLC communications performance is very sensitive to connecting/disconnecting electrical loads and to EMI (Electromagnetic Interference) [Bartak2013].

The most relevant wireless technologies for this network segment are: Bluetooth (IEEE 802.15.1), Wi-Fi (IEEE 802.11), and IEEE 802.15.4 [Drake2010]. Bluetooth is a communication technology designed to replace wires in the communication of multimedia contents between devices. Although it is a quite inexpensive technology, it presents some drawbacks, such as it provides limited range (very few meters) and too high data rates at the expense of too high power consumption, which make it not appropriate for this kind of applications[1]. IEEE 802.11 is a widely deployed and cheap technology. However, IEEE 802.11 is designed to transmit multimedia contents at high data rate. Therefore, its energy consumption is optimized for transmitting and not for idling; whereas the monitoring sensors of the I-BECIs/-I-BEGIs transmit few data from time to time and are in idle mode most of the time. As a result, it is concluded that the most appropriate communication technology for this network segment is IEEE 802.15.4 [IEEE2006], since it is defined to minimize power consumption and cost in applications with low data rates and no latency constraints.

There are two main technologies that rely on PHY/MAC IEEE 802.15.4 standard: 6LoWPAN (IPv6 over Low power Wireless Personal Area Networks) and Zigbee. 6LoWPAN is an open standard defined by the IETF (Internet Engineering Task Force) [IETF2007]. Its main advantage is that it allows using IPv6 between wireless IEEE 802.15.4-compliant devices, facilitating their integration into an IPv6-based Internet. However, in an IPv4- based Internet scenario, such as the current one, this fact does not add much value to 6LoWPAN. In addition, by the time this decision was made, 6LoWPAN was in the very early development phase.

Zigbee is an open industrial standard developed by the Zigbee Alliance [Zigbee2014]. It had been around in the market for longer time than 6LoWPAN, so it was much more mature. As a matter of fact, the most important hardware and appliance manufacturers, such as Freescale or Texas Instruments, already commercialized Zigbee-capable chips and equipment. In addition, the Zigbee Alliance had just launched the Zigbee SEP (Smart Energy Profile), which is specially designed to meet energy efficiency scenarios' requirements and it also incorporates the IP into Zigbee (actually, it incorporates 6LoWPAN into the Zigbee stack). Therefore, the Zigbee PRO feature set [Zigbee2007] is selected on top of 802.15.4.

3.4.2 Neighborhood Area Network

For the communication between the ADR EPs and the CNTRs, two technologies are considered: IEEE 802.15.4/Zigbee (taking advantage of its mesh topology) and IEEE 802.11. In this case, IEEE 802.11 is chosen over Zigbee since it clearly fits the requirements of this communication segment better (i.e., IEEE 802.11 provides higher bandwidth and coverage). In addition, IEEE 802.11 is considered as a potential cost-effective solution for the NAN due to its massive use.

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[1] This analysis does not take Bluetooth Low Energy into account, since Bluetooth 4.0 was not released by the time it was carried out.

Since it is a quite static and star topology network, the most appropriate IEEE 802.11 working mode is the infrastructure mode, the CNTRs working as APs (Access Points) and the ADR EPs being the clients.

3.4.3 Backhaul

For the communication between the CNTRs and the M2M Platform, the following communication technologies were considered. ADSL (Asymmetric Digital Subscriber Line) is considered not to be appropriate due to neighborhood's network infrastructure installation requirements. The LTE (Long Term Evolution), HSPA+ (High Speed Packet Access) and WiMAX (Worldwide Interoperability for Microwave Access) technologies are not considered appropriate mainly because they are not widely deployed yet and so they are not mature enough. HSxPA (WCDMA - Wideband Code Division Multiple Access) presents some advantages, e.g., it offers increased peak data rates and reduced latency. However, its main problem is that it requires some enhancements inside of the infrastructure that were not yet fully spread in Europe by the time this analysis was performed. Therefore, GPRS/EDGE is considered the most appropriate technology for this communication segment because it is widely deployed and mature, so that cost is kept low and interoperability is boosted. In addition, GPRS/EDGE is considered to be the available technology that fits the requirements of this kind of systems in terms of data rate better.

The communication between the M2M Platform and the Information System will be based on broadband wired technologies (e.g., fiber). Indeed, these pieces of equipment may be located in the same site.

3.5 Security

Security and privacy are two key challenging issues for this kind of systems [McDaniel2009], [Liu2012]. As a result, the main security features of the selected communication technologies are outlined next, proposing also the most appropriate solution in each case.

3.5.1 Home Area Network

As it has already been mentioned, Zigbee specification only addresses the network and application layers. Although latest versions of Zigbee support several options at lower layers, we assume IEEE 802.15.4 at PHY and MAC layers. Therefore, some IEEE 802.15.4 security features and issues are listed first [Sastry2004]:

- AES (Advance Encryption Standard) link layer security for authentication or encryption of IEEE 802.15.4 frames is provided. AES is a block cipher operating on blocks of fixed length (128 bits, in this case). To encrypt longer messages, several modes of operation may be used. The earliest modes described, such as ECB, CBC, OFB and CFB, provide only confidentiality, but they do not ensure message integrity. Other modes, such as the CCM* mode, do ensure both confidentiality and message integrity.

- Key management is not specified.

- A sequential number (the so-called Sequential Freshness) is used to prevent from insertion attacks.

- Integrity is checked by using a Hash code (the so-called MIC - Message Integrity Code). Zigbee allows choosing whether to use it or not. It also allows to configure the length of such a Hash code (32, 64 and 128 bits), being 64 bits the default MIC length.

Regarding Zigbee itself, Zigbee-2007 defines two different feature sets: Zigbee and Zigbee PRO. In general, both Zigbee and Zigbee PRO provide:

- Authentication and encryption at network and application layers by using an AES-128 symmetric key. To be more precise, authentication is based on symmetric keys and Trust Center. The Trust Center is in charge of authenticating devices that want to join the network, managing and distributing the symmetric keys and activating point-to-point security between devices.

- Network layer security for network command frames (route request, route reply, route error) and application security for APS (Application Support Sub-layer) frames.

- Freshness by using frame counters.

- Message integrity.

Zigbee PRO defines two additional security modes [Gislason2008]:

- Standard Security. This security mode is compatible with the basic Zigbee feature set, so Zigbee and Zigbee PRO devices fully interoperate if this security mode is used. It is focused on avoiding devices that do not belong to a given Zigbee network to access it. In order to do so, every single message exchanges within the Zigbee network is encrypted using AES-128 symmetric keys which are only known by the devices that are authenticated in the network. It uses two different sorts of keys: a Network Key, which is used for all network commands from any device and for APS messages, and Link Keys, which are used for each pair of communicating devices. The Network Key could be either provided (in clear) by the Trust Center or programmed on the device. Figure 3-8 illustrates how Standard Security mode works.

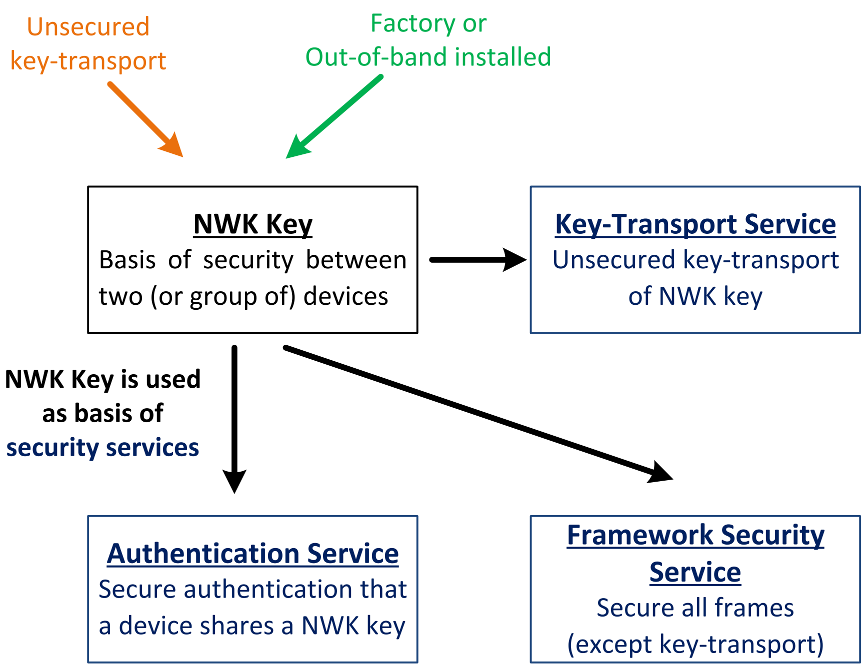

Figure 3-8 – Zigbee PRO Standard Security Mode [Gislason2008]

- High Security. This security mode is only available for the Zigbee PRO feature set. It prevents both from external and internal attacks. In order to do so, every single message exchanges within the Zigbee network is encrypted using a key which is only known by the sender and the receiver of the message. It uses the two keys explained in the Standard Security Mode (i.e., Network Key and Link Keys) together with an additional Master Key. The Master Key could be either provided (in clear) by the Trust Center or programmed on the device. Figure 3-6 illustrates how High Security Mode works.

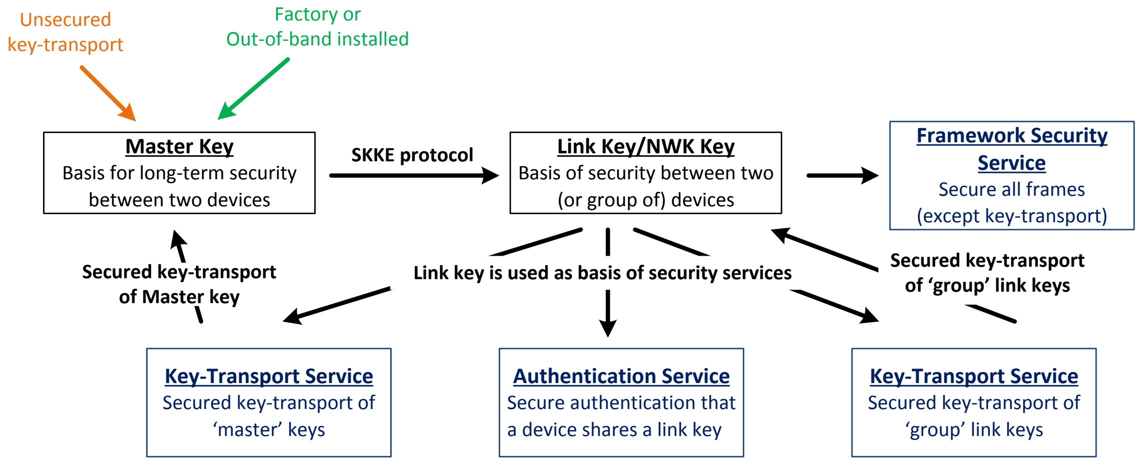

Figure 3-9 – Zigbee PRO High Security Mode [Gislason2008]

Taking into account the relevance of the information managed by this kind of systems, the Zigbee PRO High Security Mode is recommended, despite of the fact that it penalizes backwards compatibility. In addition, following the same reasoning, it is strongly recommended to use Master Keys factory installed on the devices, since this avoids the key distribution mechanism and so reduces dramatically the vulnerability of the wireless network.

3.5.2 Neighborhood Area Network

IEEE 802.11 considers three different layer-2 encryption systems:

- WEP (Wired Equivalent Privacy) is based on RC4 (Rivest Cipher 4). It allows using 64 bits-length keys or 128 bits-length keys, providing the latter higher level of security than the former. Nowadays WEP encryption can be broken in just few minutes by software. Therefore, it does not meet the security requirements of this kind of systems.

- WPA (Wi-Fi Protected Access) introduces enhancements to WEP. Although data is still ciphered using RC4 and 128 bits-length keys, WPA allows changing such keys dynamically over the time (by means of the so-called TKIP - Temporal Key Integrity Protocol). WPA with TKIP uses 48 bits IV (Initialization Vectors) to generate such keys, so the possibilities of collecting sufficient number of 802.11 frames to crack the encryption are reduced. WPA also allows using an Authentication Server (namely a RADIUS server) to distribute different keys to each terminal in the network (using 802.1x/EAP – Extensible Authentication Protocol). However, a less secure operation mode is also available, where all the devices within the same Wi-Fi network share the same encryption key (PSK - Pre-Shared Key). For the time being, some vulnerabilities have been already detected when the shared key is too simple in PSK and in some messages exchange between the AP (Access Point) and the terminals in TKIP.

- WPA2 (Wi-Fi Protected 2) fixes the vulnerabilities detected on WPA. It is fully compliance with IEEE 802.11i standard and it represents the most secure encryption system currently available for Wi-Fi networks.

Other available security solutions for Wi-Fi networks which are fully compatible with the encryption systems described above are:

- MAC filtering policies can be applied in Wi-Fi networks to allow only those devices whose MAC addresses are well-known to access them. However, this mechanism is not very effective since it can be easily cracked just by sniffing traffic for a while and then changing the MAC address to such a well-known one (MAC spoofing).

- In Wi-Fi networks working in infrastructure mode, AP can also be hidden in order to be visible only for authorized devices.

- Additional security at higher layers can be provided by setting VPN (Virtual Private Networks) up [Khanvilkar2004].

In this case, IEEE 802.11 using WPA2 is recommended. MAC filtering or AP hiding can be also applied to increase security. VPNs may be used to provide additional data protection at network layer and above. However, the overhead as well as the increase of complexity (and its potential impact on costs) introduced by this security mechanism have to be carefully analyzed.

3.5.3 Backhaul

Connectivity through cellular technologies requires complex and expensive infrastructures that are going to be provided by a given NO (Network Operator)/SP (Service Provider). Therefore, the operator of the platform will have to pay to such a NO/SP for using this service (i.e., cellular connectivity) and the NO/SP will be responsible for providing robust security mechanisms that ensure –at least - confidentiality, integrity and authentication. In fact, security mechanisms in cellular technologies are standardized by the appropriate standardization bodies (namely, 3GPP – 3rd Generation Partnership Project) and they are heavier and more robust than the ones provided by the rest of the considered wireless technologies.

However, due to the highly sensitive data this kind of systems manages, they cannot rely solely on the security provided by a 3rd party, but they must guarantee the privacy and confidentiality of the sensitive information it carries. Therefore, additional encryption mechanisms at higher layers (e.g., VPNs [Khanvilkar2004]) may be implemented. Nevertheless, this decision has to be analyzed in detail, since encryption means redundancy and so more bits to be transmitted, which in turn in this case means more money to be paid to the NO/SP. Therefore, a trade-off between security and cost is needed.

3.6 Address management and end-to-end addressability

Due to the facts that M2M systems involve a huge amount of devices, that the deployment of this kind of systems is growing really fast, and that predictions point they will grow even faster, efficient numbering and addressing represents definitely a major challenge in M2M communications. The main trends to tackle this problem are: using E.164 numbers and using IP addresses [ECC2010].

E.164 is an ITU-T (International Telecommunications Union - Telecommunication Standardization Sector) recommendation which defines the international public communication numbering plan used in the PSTN (Public Switched Telephone Network) and other data networks. E.164 numbers are needed in practice in order to deliver M2M services on top of existing mobile infrastructures which are not capable to support IP-based mobile access. This family of addressing solutions is based on the phone number associated to the GPRS SIM (Subscriber Identity Module) card (i.e., the MSISDN - Mobile Station Integrated Services Digital Network). The MSISDN, according to ITU-T Recommendation E.164, has 15 digits and is composed of three fields:

- CC: Country Code
- NDC: National Destination Code
- SN: Subscriber Number

There are different proposals on how to use such fields for M2M applications, each one having its pros and cons [ECC2010].

However, as long as mobile networks are being upgraded to embrace IP as common network protocol, IP addresses seem to be the most likely addressing solution for M2M applications in the medium to long run. IPv4 addresses, which are 32-bits long, are the closest solution in time, since IPv4 is the most used network protocol nowadays. IPv6 addresses, which are 128-bits long, will be the solution of the future, since they better fit the requirements of M2M applications in terms of number of devices, but IPv6 is not widely adopted nor used in the target kind of applications yet [López2013c].

In this thesis, we assume IPv4 as network protocol down to the ADR EPs, which are responsible for routing incoming packets to the appropriate consumption/generation device by mapping the IPv4 address associated to their IEEE 802.11 interface onto the address space of their HANs. This is a quite common situation until IPv6 is widely adopted, since there are not enough IPv4 addresses available to be assigned to the huge number of devices that emerging M2M applications entail.

As a result, IPv4 does not provide E2E addressability, so an additional mechanism is needed for this purpose. In this section, an addressing solution at application layer is proposed to allow identifying univocally and addressing every single communications device of the designed M2M communications infrastructure taking advantage of its hierarchical structure. Anyway, this addressing solution is independent of the underlying network protocol, so it would work on top of either IPv4 or IPv6.

In such an application-layer addressing solution, each communications device is assigned a 16-bits ID. The scope of this ID is bounded to the communications element which is right above in the hierarchical communications architecture. Thus, each M2M Platform has a pool of 2^{16} IDs, so it can address univocally up to 2^{16} CNTRs; every single CNTR, in turn, can manage up to 2^{16} ADR EPs; and, finally, every single ADR EP can manage up to 2^{16} consumption/generation devices. Therefore, each consumption/generation device is globally univocally identified by the 8-bytes ID which results from concatenating its own 2-bytes ID with its associated ADR EP, CNTR and M2M Platform IDs. Figure 3-10 illustrates this idea.

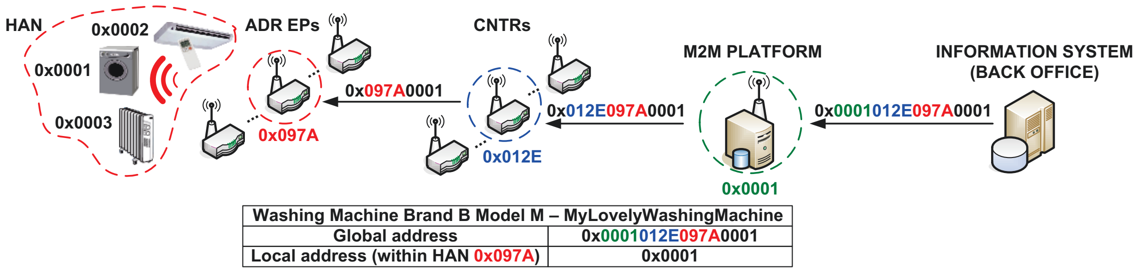

Figure 3-10 – E2E addressability in the proposed addressing solution

The ID distribution and management as well as the routing mechanisms of the proposed addressing solution are described in the next sub-sections.

3.6.1 ID distribution and management

Although one M2M Platform is assumed per neighborhood (as a logical entity, since physically it is advisable to have more than one for reliability and backup purposes), a potential operator of this platform may manage more than one neighborhood. In such a case, each M2M Platform is assigned a 2-bytes ID, which is stored in the Information System together with its associated IMSI (International Mobile Subscriber Identity). It should be noted that if the operator managed a single neighborhood, it would be optional to use a 2-bytes ID to univocally identify the M2M Platform.

Each M2M Platform is equipped with a GPRS SIM card which contains the IMSI and a 128-bits authentication key. These two parameters represent the golden key that allow authenticating and univocally identifying each M2M Platform in the very beginning, i.e., at least, the first time it is switched on (1). If this procedure is successful (2), the Information System assigns the M2M Platform its 2-bytes ID and an IP address (3). The 2-bytes ID is fixed and it will never change. The IP address is assigned dynamically, so it may change. Figure 3-11 illustrates this mechanism.

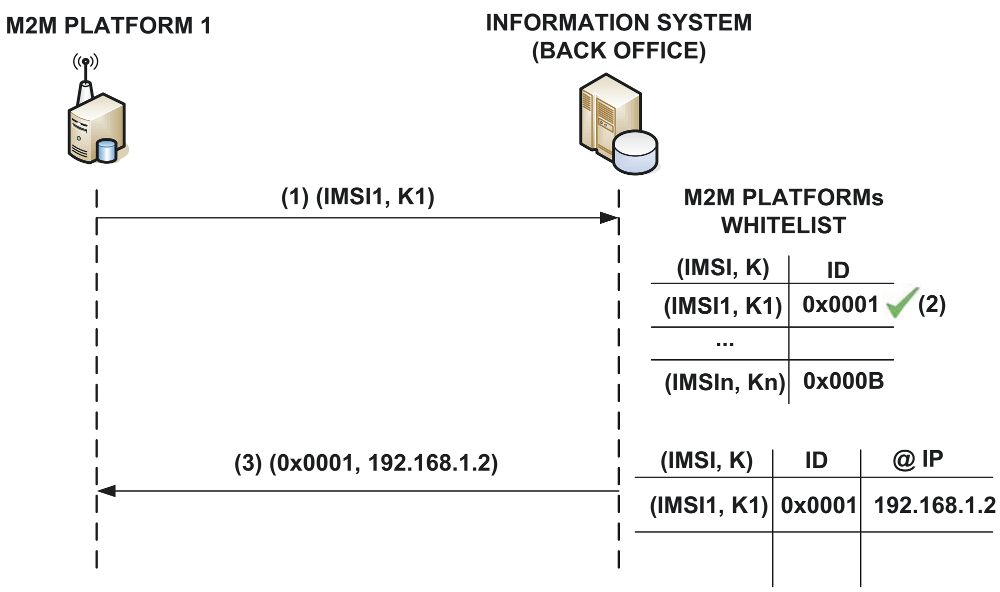

Figure 3-11 – M2M Platforms ID distribution and management

When deploying this kind of platform on a large scale, the CNTRs are provisioned in the appropriate M2M Platform in advance, i.e., the system administrator provides the M2M Platform with a table that contains the IMSI and 128-bits keys of all the CNTRs which are planned to be deployed as well as their associated 2-bytes IDs (1). It should be noted that this table is also stored in the Information System. When a new CNTR is switched on, it authenticates itself in the appropriate M2M Platform using its IMSI and the 128-bits key (2). If this procedure is successful (i.e., it is not a fake CNTR) (3), the M2M platform assigns the CNTR its 2-bytes ID and an IP address (4). Again, the 2-bytes ID is fixed and it will never change, unless the CNTR is not valid anymore. However, the IP address is assigned dynamically, so it may change from time to time or after rebooting the CNTR. Figure 3-12 illustrates such procedure.

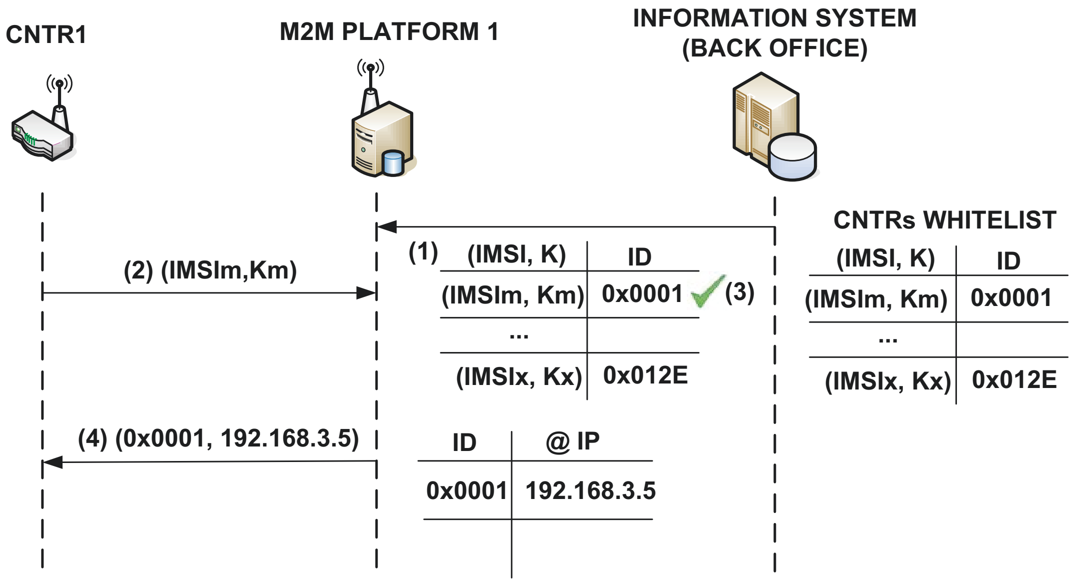

Figure 3-12 – CNTRs ID distribution and management

If a single CNTR is to be installed (e.g., because a new geographical area needs to be covered), the system administrator has to update the table of CNTRs in the appropriate M2M Platform with this new entry. Otherwise, the new CNTR would try again and again without success until this is done.

When deploying this kind of platform on a large scale, the ADR EPs are also pre-provisioned in the appropriate CNTRs. Thus, the system administrator provides every single CNTR with a table that contains the golden key to authenticate and identify univocally the ADR EPs and their associated 2-bytes ID (1). The ADR EPs may be equipped with multiple communication interfaces (e.g., IEEE 802.11, IEEE 802.15.4, IEEE 802.3, RS232, RS485 or PLC). However, they use their IEEE 802.11 MAC address together with a key (which may be pre-programmed on it) to authenticate themselves in the appropriate CNTR (2), because it is mandatory for the ADR EPs to be equipped with an IEEE 802.11 for the communication with the CNTR. If this procedure is successful (3), the CNTR assigns the ADR EP its fixed 2-bytes ID and an IP address which may change dynamically (4). It should be noted that, since every single ADR EP is associated to a given customer, in this case the Information System stores the Customer ID together with all the communication nodes' IDs which lead to its ADR EP (i.e., M2M Platform's ID, CNTR's ID, and ADR EP's ID) (5). Figure 3-13 illustrates such a procedure.

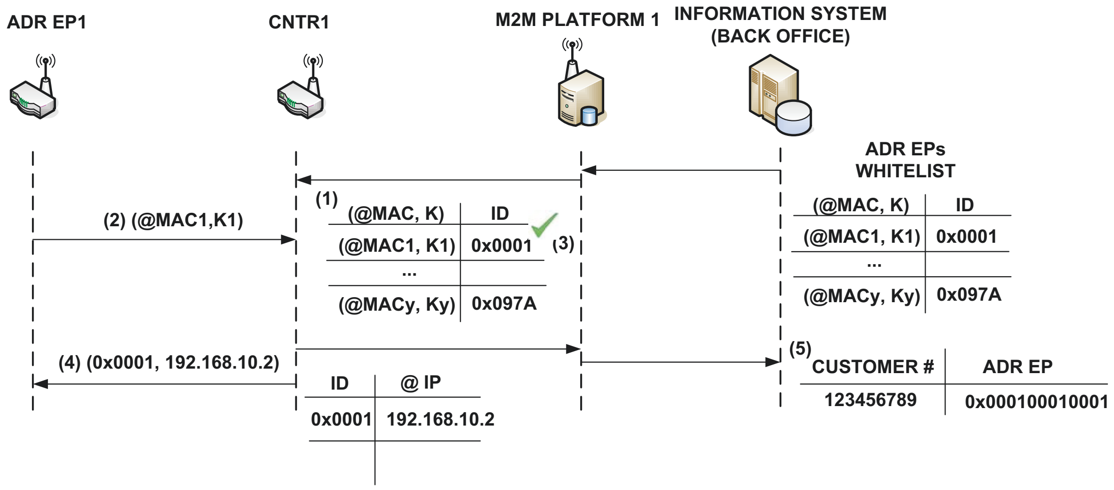

Figure 3-13 – ADR EPs ID distribution and management

Again, if a single ADR EP is to be installed (e.g., because a new customer is registered in the system) the system administrator has to update the table of ADR EPs in the appropriate CNTR with this new entry for the new ADR EP to get connected.

The procedure for registering new consumption/generation devices is sketched in Figure 3-14. First, the user has to register the new device in the platform (i.e., in the Information System) through UIIs and UAP. The user will have to fill some information about the new device, such as the type of device (e.g., washing machine, TV, air conditioning, photovoltaic panel), the brand, the model, the location of the device within the house, and a human-friendly name, along with a code which univocally identifies this device within the whole platform (1). This code will be, in general, the physical/MAC address of the communication interface the device will use to communicate with the ADR EP and it will be provided to the user attached to the device itself. For additional security, this code may be the hash of the physical/MAC address of the device and a random number.

Once the user has registered the new device in the Information System, the Information System will provision this new device in the ADR EP associated to that user, i.e., the Information System will send the new device’s code to the appropriate ADR EP (2). Then, the new device can be turned on and start working without problems.

When the new device is turned on, first it authenticates itself in the ADR EP using its associated code (3). Then, the ADR EP assigns a 2-bytes ID from its own pool of IDs to this device (4) and it stores on its translation table not only the pair [code, 2-bytes ID] but also the appropriate interface (5). Finally, the ADR EP advertises the pair [code, 2-bytes ID] to the Information System (6).

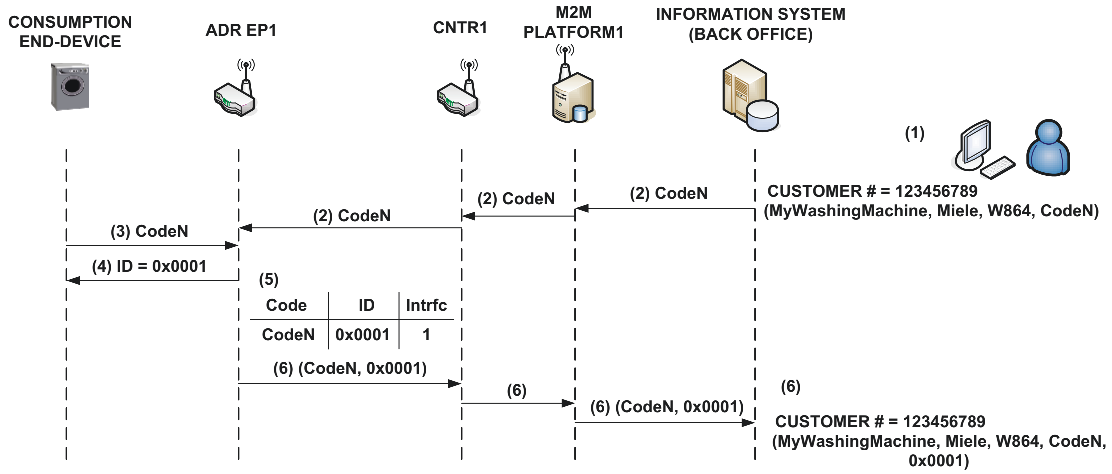

Figure 3-14 – Device ID distribution and management

3.6.2 Routing

When the data flow from the Building Domain to the Information System Domain/User Domain (e.g., sensor reporting a periodic measurement), the procedure is straightforward since every single device in the communication chain has only one option as NH (Next Hop). The device sends the data to its associated ADR EP. The ADR EP concatenates its 2-byte ID to the device's ID as the source of the data and forwards them to its associated CNTR. The CNTR concatenates its 2-bytes ID to the ADR EP's and the device's IDs, as the new source of the data, and forwards them to the appropriate M2M Platform. Finally, the M2M Platform forwards the packet to the Information System (namely, to the Back Office Server) [López2011c]. Figure 3-15 shows such a data flow.

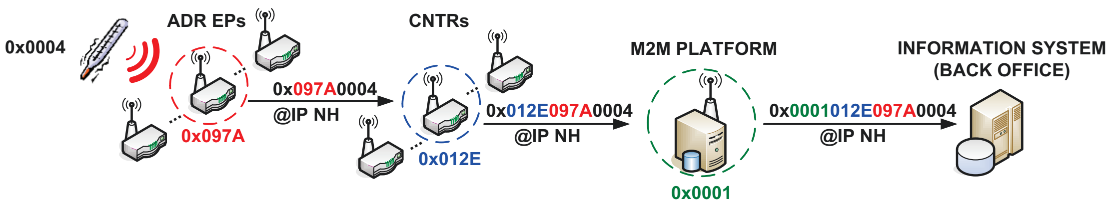

Figure 3-15 – Forwarding of data in the uplink

When the data flow from the User Domain/Information System Domain to the Building Domain, the procedure is a bit more complex. If, for instance, a given user wants to send a request to a specific appliance, first, the Information System will traverse the tree associated to this Customer ID, it will fetch the appropriate sequence of 2-bytes IDs which represent this appliance univocally, and it will send the request to the appropriate M2M Platform, as it is the NH. The M2M Platform will check its table that maps CNTR 2-bytes IDs with IP addresses, it will fill the destination IP address properly and it will route the packet to the appropriate CNTR. The CNTR will perform exactly the same procedure to route the packet to the appropriate ADR EP. Finally, the ADR EP will check its table that maps device 2-bytes IDs with HAN-valid addresses and it will route the packet to the appropriate appliance [López2011c]. Figure 3-16 illustrates this procedure.

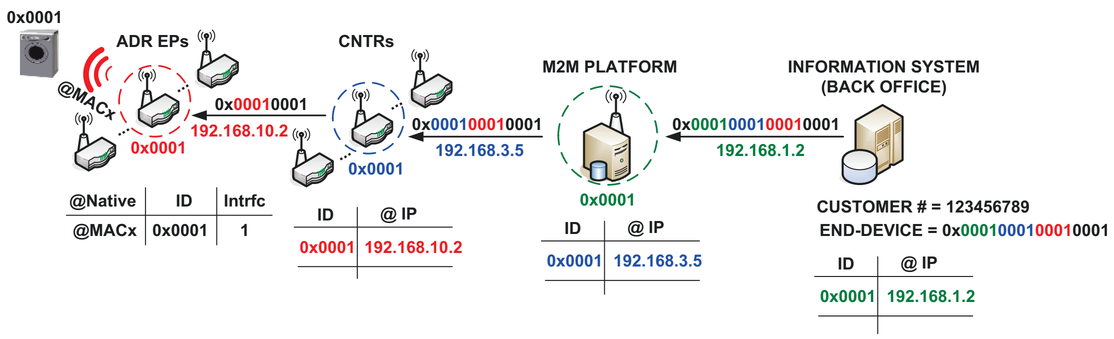

Figure 3-16 – Routing of commands in the downlink

It should be noted that within this approach, the use of IPv4 public addresses (which represent a scarce resource) is not required, but everything can be managed by means of IPv4 private addresses.

3.7 Conclusions

In this chapter we propose a M2M communications architecture to support energy efficiency and integration of renewable micro-generation within the so-called energy-positive neighborhoods of the Smart Grid, which represents one of the main contributions of this thesis.

The proposed M2M communications architecture comprises three network segments, for the sake of flexibility and scalability. It is also a heterogeneous communications infrastructure in that different communications technologies are combined to meet the specific communications requirements of each network segment. In addition, it is compared with the most relevant standardization work presented in chapter 2, identifying how they are related.

Reflecting the outstanding importance of wireless communications in the distribution and customer domains of the Smart Grid [NIST2011], the proposed M2M communications architecture is fully based on wireless communications technologies, such as IEEE802.15.4/Zigbee, 802.11, and GPRS. Throughout the chapter, the most relevant security features of such communications technologies are outlined and the most appropriate solution is proposed in each case.

As an end to the chapter, we also propose an application-layer solution to provide E2E addressability throughout the platform.

The performance of the proposed communications technologies in large scale scenarios is evaluated by means of simulations in chapter 6. The security concerns brought in section 3.5.2 and 3.5.3 related to the impact of using VPN on the performance and operational costs of the platform are also addressed in chapter 6.

Chapter 4

Formal Modeling

4.1 Introduction

As it has been shown in Chapter 3, the so-called smart energy-positive neighborhoods represent complex infrastructures which involve huge number of devices of different nature and with different functionalities. In addition, their communications capabilities enable delivering a wide variety of services which bring into play a wide variety of interested parties or stakeholders. The IT-IAP (Information Technology - Interoperability Architectural Perspective) of the SGIRM (Smart Grid Interoperability Reference Model) defined in IEEE 2030 [IEEE2011] remarks upon the importance of well-defined data models in such complex scenarios in order to:

- Avoid data inconsistency and duplication.
- Make exchange of data and updates of legacy software easier.
- Enhance the ROI (Return On Investment) by enabling more applications to use the data and improve their value through novel analytics.

Therefore, the main goal of this chapter is to formally define the vocabulary and taxonomy and capture the engineering and business semantics of the domain of knowledge of the energy efficiency platforms for energy-positive neighborhoods. To be more concrete, this chapter aims to formally represent the main architectural entities and interfaces of energy efficiency platforms for energy-positive neighborhoods, as well as their potential services and stakeholders, and the relationships between them.

The ISO/IEC/IEEE 42010 [ISO2011] is an international standard for architecture description of systems and software engineering, so it fits the initial aforementioned scope of our target model. UML (Unified Modeling Language) is one of the ADL (Architecture Description Language) considered by ISO/IEC/IEEE 42010. UML is an object modeling and specification language widely used in software engineering. It is used to visually express use cases, hierarchy and composition relationships or sequences of events, and it allows some automatic programming code generation.

Ontologies and OWL (Ontology Web Language) represent another option to define our target model. OWL is an ontology language based on RDF (Resource Description Framework) [Manola2004] that allows the expression of classes and sub-classes, properties with their domains and ranges, and other features such as symmetry, disjointedness, or transitivity (e.g., if a is b and b is c, then a is c). Hence, OWL also allows formally representing real-world systems, the architectural entities composing those systems, and the relationships between them, so it fits the initial scope of our target model as well.

However, OWL presents some advantages compared to UML, namely [Gómez2007], [Witte2007], [Pan2012]:

- The expressiveness of OWL is higher, allowing robust specification of complex relationships among structural entities.
- OWL allows knowledge reusability.
- OWL allows automated reasoning (i.e., inferring information from the existing knowledge without it having to be explicitly expressed).
- The so-called ontology queries allow software applications to load the ontology from the OWL file dynamically while running. Therefore, if the ontology changes, there is no need to recompile the application.

As a result, although both ISO/IEC/IEEE 42010 along with UML and OWL are equally valid for the purpose of our target model, in this thesis we have chosen OWL due to its greater potential, which in turn increases the impact of the thesis itself. As a matter of fact, OWL-based ontologies are becoming an increasingly popular way of defining machine-readable data models within the Smart Grid area [Grassi2011], [Santodomingo2012], [Wicaksono2012], in particular, and the M2M area [Gyrard2013], in general.

The remainder of the chapter is structured as follows. Section 4.2 presents the ontology proposed in this thesis. Section 4.3 illustrates our ontology through a specific use case. Finally, section 4.4 compares the ontology proposed hereby with some related works, discusses how future work can make the most out of our ontology, and draws conclusions.

4.2 Ontology description

Figure 4-1 shows the taxonomy of energy efficiency platforms for energy-positive neighborhoods which results from our ontology. This taxonomy includes the hierarchical levels of the system architecture presented in Chapter 3, from the domains down to the functional blocks. However, in this case the functional blocks are particularized in devices, which are classified depending on their nature. In addition, beside the main architectural concepts, stakeholders, and services, a concept to represent different sites is considered with the aim of making the ontology closer to implementation and real-world scenarios.

As it has been mentioned is section 4.1, the ontology is developed using OWL as modeling language. From the three variants of OWL (on increasing order of expressiveness: OWL Lite, OWL DL – Description Logic -, and OWL Full), OWL DL is used and FaCT++ [Tsarkov2006] is used as reasoner. The free and open source OWL editor Protégé [Protégé2013] is used as development environment. The Protégé Onto-Graph plug-in allows visualizing graphically and in a hierarchical way the defined classes and properties. In addition, the Protégé editor allows attaching descriptions of the defined classes and properties, so that all the information presented hereby is available at the editor and can be consulted easily and in a human-friendly manner.

4.2.1 Classes

The classes that are defined in our model and that will be described throughout this section are (see Figure 4-1):

- Domain
- Subsystem
- Device
- Site
- Stakeholder
- Service

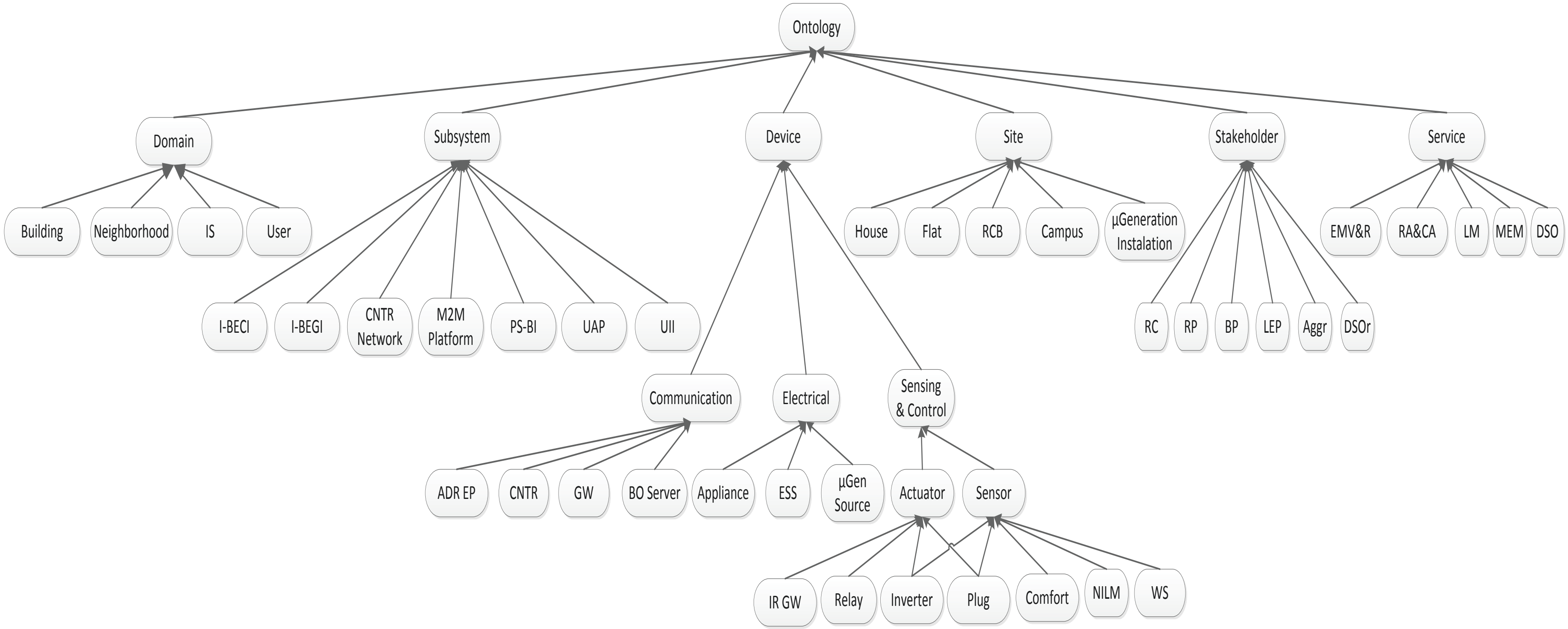

Figure 4-1 – Taxonomy of an energy efficiency platform for energy-positive neighborhood

4.2.1.1 Domain

This class represents the highest level of abstraction in the proposed hierarchical architecture. As it was described in chapter 3, in this thesis we divide a typical energy efficiency platform for energy-positive neighborhoods into the following domains:

- Building domain;
- Neighborhood domain;
- Information System domain;
- User domain.

The Building domain encompasses the consumption and generation infrastructures, along with the SANs (Sensor and Actuator Networks) to monitor and control them, typically associated to smart homes and buildings. The Neighborhood domain encompasses the core of the M2M communications infrastructure, responsible for enabling the required bulk data exchange. The Information System domain represents the intelligence of the platform from the energy perspective. Finally, the User domain encompasses everything related to the interaction of the stakeholders with the platform (e.g., presentation of data, sending of commands).

4.2.1.2 Subsystem

Going deeper into the proposed hierarchical architecture, the Subsystems are found. The Subsystems encompass a group of functional blocks whose duties are tightly related and share some common features. The I-BECI (In-Building Energy Consumption Infrastructure) and the I-BEGI (In-Building Energy Generation Infrastructure) comprise a set of consumption and generation devices respectively, along with their associated SAN and communications gateway (so-called ADR EP – Automated Demand Response End Point). The CNTR (Concentrator) Network encompasses a group of CNTRs that manage the access to the core of the M2M communications infrastructure. The M2M Platform represents the “brain” of the entire M2M communications network, working both as OSS (Operations Support System) and as gateway to the PS-BI (Power-Saving – Business Intelligence). The PS-BI represents the “brain” of the system from the energy perspective and includes extensible set of software services dealing with energy use optimization. The UAP (User Application Platform) encompasses the set of pieces of software that work as interface between the PS-BI and the UIIs (User Intuitive Interfaces), adapting contents appropriately. Finally, the UIIs include the set of front-end applications that interact directly with the stakeholders of the platform.

4.2.1.3 Device

This class represents the lowest level of abstraction in the proposed hierarchical architecture. Thus, if Domain is the class closer to the conceptual model, then Device is the class closer to the development and implementation issues (i.e., to the software and hardware).

According to their nature, the Devices are classified into the following categories:

- Communication Device;
- Electrical Device;
- Sensing and Control Device.

Communication Device represents those devices whose main objective is to enable the bidirectional communication between the Building Domain and the Information System and User Domains. Two attributes are defined to all the Communications Devices: IP address and 16-bits ID (Identifier) [López2011a]. Note that the Protégé editor allows specifying the type of every attribute, e.g., Boolean, Integer, Double, or String, which is the case for these two attributes. The Communication Devices are:

- ADR EP;
- CNTR;
- GW (Gateway);
- BO (Back-Office) Server.

The functionality of ADR EPs and CNTRs has already been explained in Chapter 3. The GW represents the implementation of the M2M Platform as a physical piece of equipment. Therefore, the GW performs the typical tasks of OSS (Operation Support System), e.g., network inventory, network components configuration, fault management, or service provisioning, and is also responsible for enabling the bidirectional communication between the CNTRs and the BO Server.

The BO Server represents the piece of software responsible for the communications within the PS-BI. The BO Server is responsible for sending the commands generated by the business and energy-related processes of the PS-BI to the GW and for receiving the data coming from the GW and making them available to such processes (e.g., by storing them in a database).

Electrical Device represents the pure energy consumption and generation devices considered as the most representative equipment in this kind of platforms. The Electrical Devices are:

- Appliance;
- ESS (Energy Storage System);
- µGeneration Source.

Some attributes that are defined as common to all the Appliances are: Average Consumption, Standby Consumption, and Power (all them are Double). In addition, there are also attributes associated with specific Appliances. For instance, ON/OFF (Boolean) and Temperature Set Point (Double) are attributes of Air Conditioning and Heating. Note that these two attributes are important for DR (Demand Response) events, allowing a coarse (ON/OFF) and a fine (Temperature Set Point) adjustment. ON/OFF/Standby (Integer) is a specific attribute of TV and DVD. In this case, Standby consumption is considered due to the aforementioned importance of such a working mode in ICT (Information and Communications Technologies) equipment when it comes to energy efficiency. ON/OFF (Boolean), Starting Hour and Deadline (Integers) are attributes of Dishwasher and Washing Machine. In this case, Starting Hour and Deadline represent two key parameters to perform load shifting by means of DR events without compromising the agreed level of comfort.

The ESSs are key elements to handle efficiently the energy generated by µGeneration Sources as well as to match generation with consumption in near-future scenarios. Some attributes that are defined as common to all the ESSs are: Is Charging (Boolean), Is Releasing Energy (Boolean), Storage Energy (Double), and Connection Power (Double). The most relevant ESSs in near future scenarios are Battery and EV (Electric Vehicle) [Pang2012], the latter having specific attributes such as Charging Rate (Double), Starting Hour, and Deadline (Integers). Charging Rate deals with the charging mode of the EV (e.g., fast and slow); whereas Starting Hour and Deadline are again key parameters for DR and V2G [Ma2012].

Some attributes that are defined as common to all the µGeneration Sources are: Is Generating (Boolean), Rated DC Voltage and Current (Double), Rated AC Voltage and Current (Double), and Power Factor (Double). As it was already pointed out in Chapter 3, Photovoltaic Panels and µWind Engines are considered as the most extended µGeneration Sources in the building sector [Jellea2012], [Ayhana2012].

Sensing and Control Device represents the Actuators and Sensors considered as the most relevant ones for this kind of systems. Since the Sensing and Control Devices send data and receive commands, they are also assigned an IP address and an ID as attributes. The considered Actuators are: the Relay and the IR (Infrared) GW. The considered Sensors are: the WS (Weather Station), the Comfort Sensor, and the NILM (Non-Intrusive Load Monitoring) Sensor (also known as NIALM - Non-Intrusive Appliance Load Monitoring - in this specific domain [Zeifman2011]). In addition, the Plug and the Inverter works both as an Actuator and as a Sensor.

The Inverters receive commands to control their associated µGeneration Source. In addition, they measure the energy generated by such a µGeneration Source and transmit it either periodically or on-demand. The Plugs act on the power supply of the Appliances by cutting it OFF or ON. In addition, the Plugs measure the electricity consumption of those appliances and send it to the PS-BI, allowing accurate monitoring and abnormal behavior identification.

The NILM Sensor allows identifying (based on electrical signature) the appliances which are running, even if they are not equipped with a Plug with sensor and communication capabilities. The Comfort Sensors measure different environmental variables, such as temperature, relative humidity or CO_2 concentration, which are taken into account when achieving energy savings without compromising the agreed comfort levels. The WS measures variables related to weather conditions in order to provide the PS-BI with relevant parameters for accurate energy generation forecast.

The IR GWs enable managing the IR-controlled appliances, such as HVAC, TVs or DVDs, remotely. Finally, the Relays receive commands targeting their associated ESSs and acts on them consequently, allowing controlling them remotely.

4.2.1.4 Site

This class aims at modeling the most relevant profiles of consumption and generation infrastructures present in energy-positive neighborhoods. Flat represents a flat belonging to a block of flats, so it only has a consumption infrastructure. House represents a house belonging to a housing development, so beside the typical consumption infrastructure, it may have a µgeneration infrastructure (e.g., small photovoltaic installation in the roof). RCB (Residential Commercial Building) represents, for instance, a building of offices, the headquarters of a company, or a shopping center. This kind of buildings may comprise many rooms, several floors, a basement, a roof, and a facade. The RCB has a consumption infrastructure and are assumed to always have a µgeneration infrastructure (e.g., BIPV – Building-integrated Photovoltaics). µGeneration Installation represents an installation composed by Photovoltaic Panels and/or µWind Engines. Finally, Campus represents a set of buildings, which are managed or belong to the same entity (e.g., a university campus comprising several buildings).

4.2.1.5 Stakeholder

This class represents the user segments that may play a role in the energy-positive neighborhoods.

The RC (Residential Consumer) is connected to the low voltage grid and only has energy consuming devices. Their goals include increasing energy efficiency (which means reduction of energy costs) while maintaining a certain level of comfort. They are also willing to participate in a dynamic market, e.g., through DR programs, if properly motivated and rewarded.

The RP (Residential Prosumer) not only has energy consuming devices but also energy producing equipment. Besides the goals mentioned previously for the RC, the RP are also interested in taking maximum economic advantage of their production capabilities.

The BP's (Building Prosumer) main objectives are: to manage their building with certain contractually agreed service level at minimal cost; to contribute to a reduction of the environmental impact of the building operation; and to integrate their BEMS (Building Energy Management System) already deployed – if any – with the energy efficiency platform targeting the whole energy-positive neighborhood.

The LEP (Local Energy Producer) manages a local microgrid, which may include generation and storage equipment. Their goals include the selling of the produced energy, as well as the operation of their energy production devices at minimal cost.

The DSOr (Distribution System Operator) task is to optimize the operation of the power distribution network, which means to anticipate and prevent any abnormal situation possibly resulting in electricity blackouts. The DSOr needs to control the power quality in the network by balancing electricity generation and consumption at any time and is willing to reward Prosumers who actively contribute to this goal. Although the balancing of electricity supply and demand can be managed not only by DSOr but also by other entities, within the scope of our ontology the DSOr is kept as the only user in charge of such operations.

The Aggr (Aggregator) is an intermediary that ensures services to the DSOr (e.g., integration of DER, DR), grouping contracts with individual consumers and managing them. Aggr boosts scalability and increase the system impact by allowing a larger level of energy consumption and production that can be regulated by the DSOr.

4.2.1.6 Service

This class models the services this kind of platforms will potentially offer through the Information System (mainly based on PS-BI).

RA&CA (Remote Access and Control of Appliances) includes a group of services that will allow creating an initial configuration of the network of energy consuming devices, turning a selected device ON or OFF, or changing its properties (e.g., the HVAC system operating temperature).

EMV&R (Energy Monitoring Visualization and Reporting) encompasses a range of services that will provide users with near real-time/periodic/on-demand information about their energy consumption or generation and the associated economic and environmental impact.

The LM (Load Management) category of service will allow users to specify individual devices or groups of devices to be included in the automated load management program. Consequently, those devices will be directly controlled by the platform, ensuring the minimization of costs to the end users, by shifting loads to periods with lower tariffs.

The MEM (Microgrid Energy Management) category of services will provide the appropriate Stakeholders with near real-time monitoring data from the consumption and generation sites, at the local communities' and neighbourhoods' level, improving the balance between generation and consumption in the microgrids.

The DSO (Distribution System Operation) category of services will provide DSOr with near real-time information about distributed generation and consumption of electricity in a given location, highlighting the deviations from the expected energy consumption behavior and providing accurate short-term forecasts of the energy generation. This group of services will also provide the DSOr with the required conditions to operate DR programs.

4.2.2 Properties

Table 4-1 summarizes the features of the defined properties, which are described next. It should be noticed that sub-classes of a given class (i.e., parent class) inherit the properties and attributes from it. Likewise, implicit logical rules hold by the concatenation of explicit relationships (e.g., a Flat cannot have a Photovoltaic Panel, since Photovoltaic Panel is a sort of µGeneration Source which is part of the I-BEGI and Flat is only equipped with I-BECI).

Table 4-1 - Summary of the properties defined in our ontology

Property	Domain	Range	Features	Expression
Is Composed Of	Domain	Subsystem	1:N	Domain → Subsystem
Composes	Subsystem	Domain	Inverse of *Is Compose Of*	Subsystem → Domain
Interacts With	{Subsys|Stkhld}	{Subsys|Stkhld}	Symmetric	{Subsys|Stkhld} ↔ {Subsys|Stkhld}
Supports	PS-BI	Service	1:N	PS-BI → Service
Is Equipped With	Site	I-BE{C|G}I	-	Site → I-BE{C|G}I
Is Owned By	Site	Stakeholder	-	Site → Stakeholder
Owns	Stakeholder	Site	Inverse of *Is Owned By*	Stakeholder → Site
Is Addressed To	Service	Stakeholder	-	Service → Stakeholder
Is Located In	{Device|Site}	Site	-	{Device|Site} → Site
Is Part Of	Device	{Device|Subsystem}	Transitive	Device → {Device|Subsystem}
Communicates With	Device	Device	Symmetric	Device ↔ Device

4.2.2.1 Is Composed Of

The domain of this property is the class Domain and its range is Subsystem. I.e., one Domain is composed of one or more Subsystems. Thus, the Building Domain is composed of the I-BECI and the I-BEGI; the Neighborhood Domain is composed of the CNTR Network and the M2M Platform; the Information System Domain is composed of the PS-BI and the UAP; and the User Domain is composed of the UII.

4.2.2.2 Composes

This is the inverse property of Is Composed Of, so its domain is the class Subsystem and its range is Domain.

4.2.2.3 Interacts With

This is a symmetric property that models the interaction between Subsystems themselves as well as Subsystems and Stakeholders. As for being symmetric, e.g., if the property "Subsystem A interacts with Subsystem B" is defined, then the property "Subsystem B interacts with Subsystem A" is also implicitly defined. In most of the cases, this property is defined between Subsystems themselves. However, the Stakeholders can also interact with the UIIs.

4.2.2.4 Supports

This property models the fact that the considered Services rely on the PS-BI. As a result, its domain is the PS-BI Subsystem and its range is the class Service.

4.2.2.5 Is Equipped With

The domain of this property is the class Site and its range covers the I-BECI and I-BEGI Subsystems. It is used to specify if a given Site is equipped with one or more I-BECIs or with one or more I-BEGIs, or both, which eventually will determine the potential owners of this Site. Thus, it is considered that: a Flat is equipped with exactly 1 I-BECI and exactly 0 I-BEGI, since a flat belongs to a block of flats and photovoltaic windows are not considered (although they may be relevant in the mid-term once they reach a competitive price); a House is equipped with exactly 1 I-BECI and with min 0 I-BEGI; a RCB is equipped with exactly 1 I-BECI and exactly 1 I-BEGI; a µGeneration Installation is equipped with exactly 0 I-BECI and with exactly 1 I-BEGI; and a Campus is equipped with min 1 I-BECI and 1 I-BEGI, since it is assumed to be composed of at least one building (i.e., RCB).

4.2.2.6 Is Owned By

This is a unidirectional property to state what Sites can be owned by which Stakeholders, based on the energy consumption/generation infrastructures of the given Site.

4.2.2.7 Owns

This is the inverse property of Is Owned By. The RC may own a Flat or a House (if not equipped with I-BEGI). The RP owns a House. The BP may own a RCB or a Campus. The LEP owns a µGeneration Installation. The DSO cannot own any Site, but it actually manages and controls the energy consumption and generation within a district composed of hundreds or thousands of Sites. Finally, the Aggr does not own any Site either, but they manage the consumption/production data associated to a group of Sites.

4.2.2.8 Is Addressed To

This is a unidirectional property to map the Services onto the Stakeholders. Table 4.2 shows such a mapping.

Table 4-2 - Mapping of the Services onto the Stakeholders they are addressed to

	RC	RP	BP	LEP	Aggr	DSOr
RA&CA	X	X	X	X		
EMV&R	X	X	X	X	X	X
LM	X	X	X			X
MEM		X	X	X	X	
DSO						X

4.2.2.9 Is Located In

This is a unidirectional property to formally state that the Devices are located physically in the Sites. In addition, some Sites may be located in other Sites (e.g., Flat may be located in RCB, if it is a Residential Building, RCB may be located in Campus). As a result, the domain of this property is Device or Site and its range is Site.

4.2.2.10 Is Part Of

This is a transitive property to formally bind the Devices to the Subsystems. Thus, the Appliances, the Comfort Sensors, the NILM Sensor, and the IR GW are part of the I-BECI; the µGeneration Sources, the ESS, and the WS are part of the I-BEGI; the ADR EP is part of both the I-BECI and the I-BEGI; the CNTR is part of the CNTR Network; the GW is part of the M2M Platform; and the BO Server is part of the PS-BI.

However, there are some special Devices, such as the Inverter, the Relay, and the Plug, which are part of other devices, namely the µGeneration Source, the ESS, and the Appliance, respectively. As for being transitive, if the Inverter is part of the Appliance and the Appliance is part of the I-BECI, the Plug is part of the I-BECI.

4.2.2.11 Communicates With

This is a symmetric property between Devices with communication capabilities (i.e., Communication Devices and Sensor and Actuator Devices). Thus, the Sensors and Actuators communicate with the ADR EP; the ADR EP communicates with the CNTR; the CNTR communicates with the GW; and the GW communicates with the BO Server. As for being symmetric, the communication is bidirectional.

4.3 Use Case

One of the additional advantages of using OWL and Protégé as editor is that they allow defining not only the architecture in a form of a schema, but also creating instances of the classes defined in this schema. This in turn allows for better understanding of the system in the early design stages as well as for clear description of the use cases.

Thus, the main objective of this section is to illustrate the dynamics of this kind of platforms by means of a use case derived from the presented ontology. The use case involves a RP (*John Residential Prosumer*) who subscribes one of the services offered by the platform from the category RA&CA.

Figure 4-2 shows the overall picture of the use case. First, it can be checked that the developed ontology captures not only engineering issues but also business and human-interaction aspects. Furthermore, the main Domains and Subsystems, as well as the relationships between them, are clearly identified. It can be seen that *John Residential Prosumer* owns a House (*House_UC1*). As his name suggests, *John Residential Prosumer* is a prosumer, so the *House_UC1* is equipped with a consumption infrastructure (*I-BECI_UC1*) and a µgeneration installation (*I-BEGI_UC1*). The *I-BECI_UC1* and the *I-BEGI_UC1* are specific Subsystem instances that compose the conceptual Building Domain of the use case. The *I-BECI_UC1* and the *I-BEGI_UC1* interact with the *Concentrator_Network_UC1*, which in turn interacts with the *M2M_Platf_UC1*. Again, the *Concentrator_Network_UC1* and the *M2M_Platf_UC1* are specific Subsystem instances that compose the conceptual Neighborhood Domain of the use case. The *M2M_Platf_UC1* interacts with the *PS-BI_UC1*, which in turn interacts with the *UAP_UC1*, both Subsystem instances composing the conceptual Information System Domain of the use case. Finally, the *UAP_UC1* interacts with the *UII_UC1* (that compose the conceptual User Domain of the use case), which interacts with John in order to allow him to monitor and control his in-house devices.

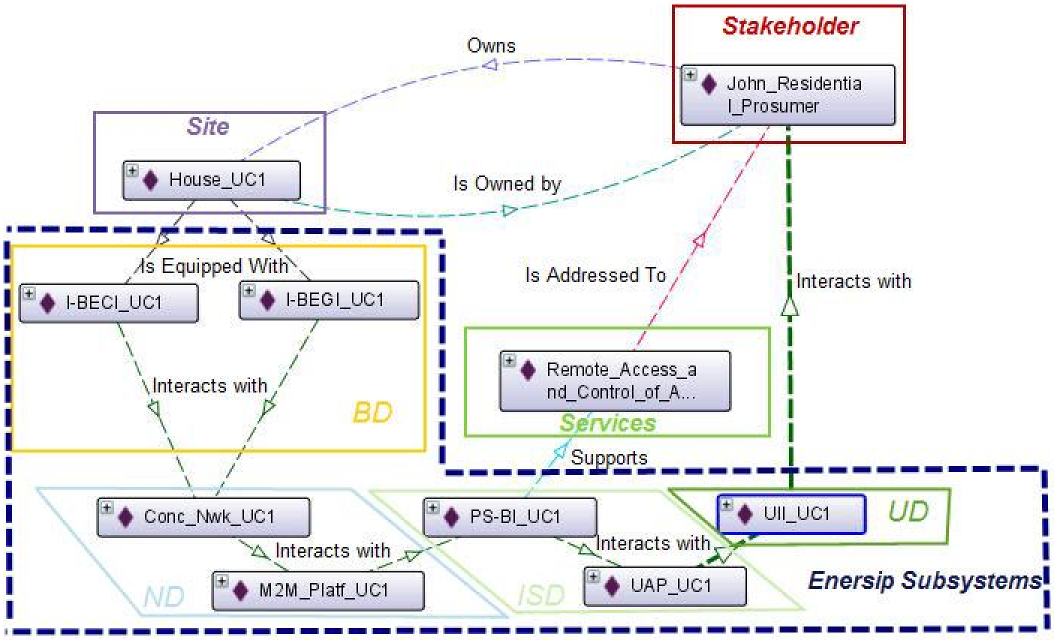

Figure 4-2 – Overall picture of the use case

Note that if the use case considered many Stakeholder instances (e.g., hundreds of RPs), the conceptual Building Domain would be composed of many I-BECI and I-BEGI instances and the conceptual User Domain would be composed of many UII instances; whereas the conceptual Neighborhood and Information System Domains would be still composed of one instance of the appropriate Subsystems. This is because the Subsystems that compose the conceptual Neighborhood and Information System Domains represent a common infrastructure (communications infrastructure and IT infrastructure respectively) shared within a given district running on this platform. Thus, in a use case that considered two different districts running on a platform like this (either managed by the same DSOr or not), there would be two different instances of the Neighborhood and Information System Domains, and so the Subsystems that compose them would be also duplicated.

Figure 4-3 shows the elements that compose the *I-BEGI_UC1* and the *I-BECI_UC1* as well as how they communicate with each other. The *I-BEGI_UC1* represents a small photovoltaic installation comprising the *Solar_Panel_UC1* and the *ADR_End_Point_G_UC1*. The *Solar_Panel_UC1* incorporates the *Inverter_UC1*, which allows monitoring and controlling it and is responsible for communicating with the *ADR_End_Point_G_UC1*. The *I-BECI_UC1* is composed of the *Infrared_GW_UC1*, the *Air_Conditioning_UC1*, the *Washing_Machine_UC1*, and the *ADR_EP_C_UC1*. The *Infrared_GW_UC1* communicates with both the *ADR_End_Point_C_UC1* (e.g., to receive commands) and the *Air_Conditioning_UC1* (e.g., to forward the received commands to the appliance). The *Washing_Machine_UC1* incorporates the *Plug_UC1*, which allows monitoring its consumption and controlling it and is responsible for communicating with the *ADR_End_Point_C_UC1*. Both the *ADR_End_Point_C_UC1* and the *ADR_End_Point_G_UC1* communicate with the *Concentrator_UC1*, which is part of the *Concentrator_Network_UC1*.

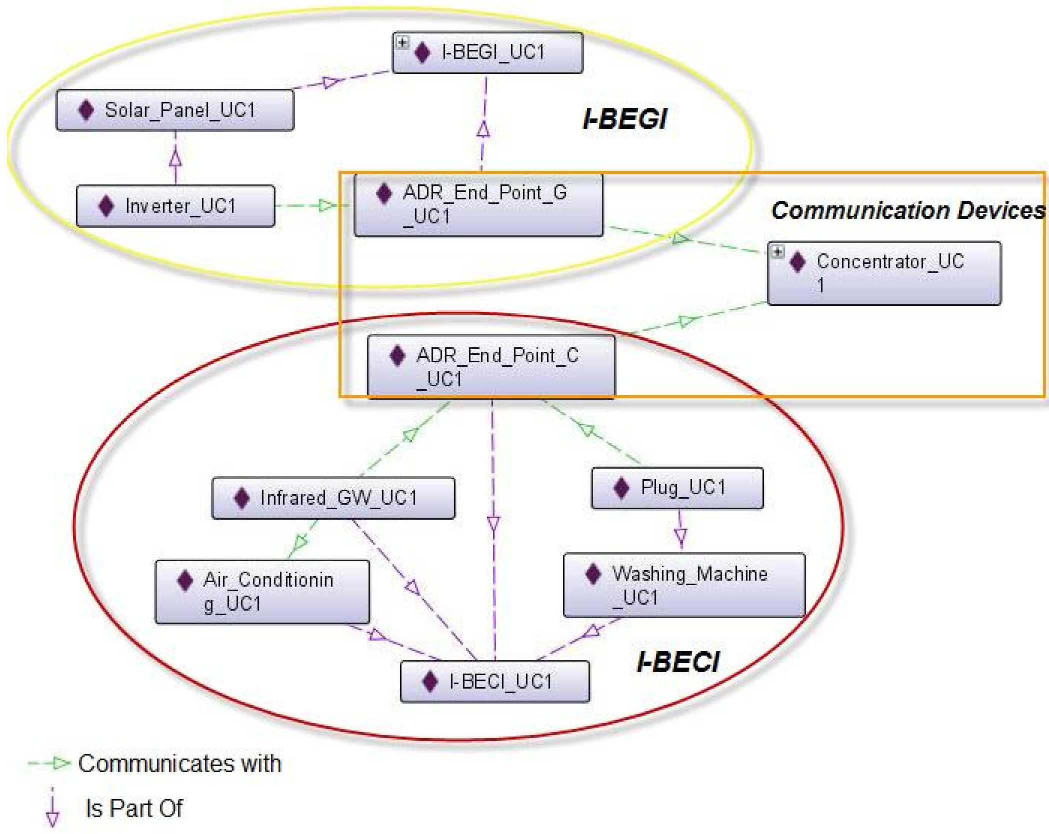

Figure 4-3 – Instances of the I-BECI and I-BEGI in the use case

Finally, Figure 4-4 shows how the different elements of the architecture interact (at different level of abstraction) in order to enable the service. Let us assume that *John Residential Prosumer* wants to know whether he forgot to turn the air conditioning off or not. In order to do so, *John* will send a query to the *Air_Conditioning_UC1* and it will receive an answer. At a high level of abstraction, *John* will interact with his *UII_UC1*, which in turn will interact with the *UAP_UC1*, and so on and so forth until the query reaches the *I-BECI_UC1*. The interaction will be the other way around when the answer comes back to *John*. At a low level of abstraction, the *BO_Server_UC1* will send the query to the *Gateway_UC1*, which in turn will route the query to the *Concentrator_UC1*, which in turn will route the query to the *ADR_End_Point_C_UC1*, which will route the query to the *Infrared_GW_UC1*, which will finally forward it to the *AC_UC1* (see Figure 4-4). The answer will follow the opposite direction until the *BO_Server_UC1*, although in the uplink the Communication Devices will always forward it instead of routing it, since the next hop is well-known. The *BO_Server_UC1* will deliver the answer to the *PS-BI_UC1*. The *PS-BI_UC1* and the *UAP_UC1* will process it and the result will be shown to *John* through his *UII_UC1*. If he checks that the *Air_Conditioning_UC1* is on, *John* will be able to send a command to turn it off and he will receive an acknowledgement, following the same aforementioned procedure.

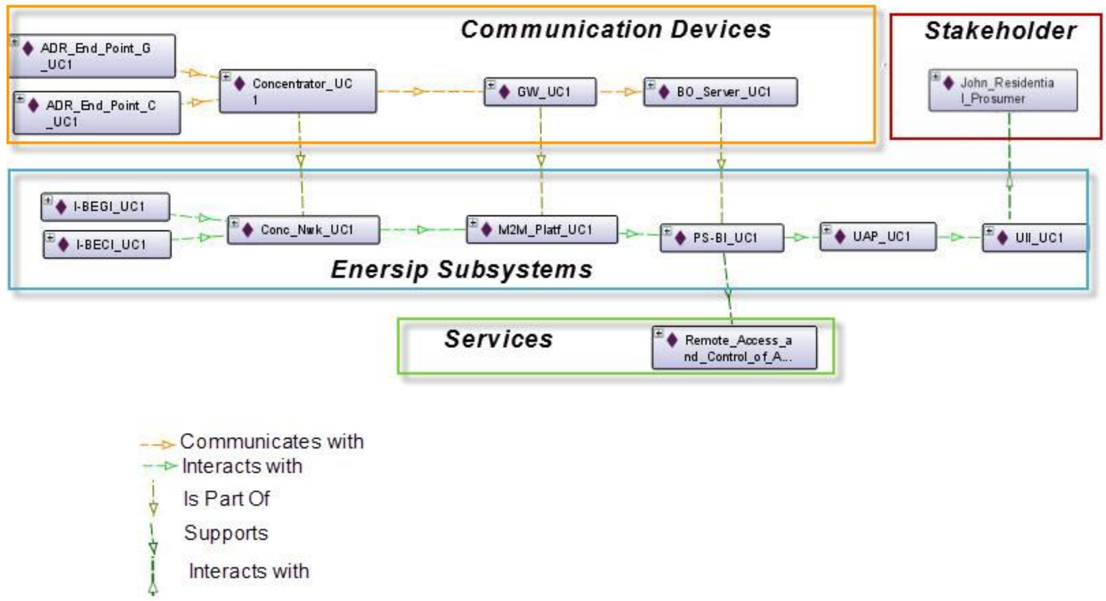

Figure 4-4 – Use case interaction at different levels of abstraction

Many other use cases can be derived from current version of the ontology, illustrating, e.g., the dynamics of different services or the end-to-end addressing solution presented in Chapter 3 in large-scale scenarios [López2012a]. The defined ontology will ensure that the defined rules hold in such use cases, avoiding incongruities.

4.4 Conclusions

There are some recent research works that use ontologies to improve energy efficiency in buildings and households, encouraged by the fact that energy efficiency has become a mandatory requirement in buildings as well as by the fact that NZEB (Nearly Zero-Energy Buildings) and self-consumption seem to be the future in this sector. The works reported in [Wicaksono2012] and [Grassi2011] are the most tightly related to our ontology.

Reference [Wicaksono2012] combines a Building Automation System with an OWL ontology to improve energy efficiency in buildings. However, µgeneration facilities are not considered. Thus, the services offered by the Building Automation System are mainly related to RA&CA and EMV&R. The ontology is generated in two stages. The base ontology representing terminological knowledge in building automation is created manually by experts. This fits the approach of our ontology, which is focused on rendering the shared vocabulary and taxonomy of energy efficiency platforms for energy-positive neighborhoods and is also generated manually. Such a base ontology can be automatically extended through the interpretation of 2D-AutoCAD-drawings of the buildings and data mining approaches. Novel knowledge-driven energy analysis based on the ontology is used to understand energy usage patterns and notify users about any energy inefficiency.

Reference [Grassi2011] proposes the definition of an OWL-based ontology framework for modeling several aspects such as operative scenario, context, QoS (Quality of Service), user preferences, and energy production and consumption in a unique global knowledge base used to support the implementation of efficient control logics. Five ontologies are defined, namely the Context Ontology, the Service Ontology, the User Ontology, the Device Ontology, and the Energy Ontology, all them being covered by our ontology. However, [Grassi2011] is focused just on households, although extending the scope of the ontology to wider application scenarios, such as the ones considered in this thesis (i.e., energy-positive buildings and districts), is pointed out as future work due to their higher potential.

Therefore, the ontologies presented in [Wicaksono2012] and [Grassi2011] are mainly focused on buildings and [Wicaksono2012] does not consider micro-generation; whereas our ontology represents a holistic approach to energy efficiency in buildings, formally defining the vocabulary and taxonomy and capturing the engineering and business semantics from the energy-positive neighborhood perspective.

The ontology developed in this thesis was applied in the EU FP7 project ENERsip [López2012b], bringing many benefits to effectively manage all the phases of the project life cycle. First, it allowed defining the common terminology of the project. This is especially important in Smart Grid related projects, since they involve engineers coming from different fields with different background (e.g., ICT and energy), and it becomes even more important if such projects involve medium to large development teams from different countries. Secondly, this ontology allowed wrapping the platform specifications up in a single model which can be graphically visualized. As a result, it also served as a valuable reference during the development and validation phases of the project. In addition, the obtained formal model facilitates sharing information and knowledge with projects and standardization bodies working on the same or closely related topics.

Our ontology has been also made public through the EC (European Commission) eeBuildings Data Model community (also called as eeSemantics), so that other researches can re-use it and further improve it. Our ontology can be extended and improved and can be useful to other researches in many different ways. An inexperience researcher in this area can use it to get started and get a clear idea of its main elements and the relationships among them at a glance. It can be also taken as basis for developing software to simulate and evaluate either the performance of the platform as a whole or the performance of some specific sub-system or domain (e.g., the Building Domain in self-consumption scenarios) [Stecher2008], [Anjum2012]. It can bring context to generic services or applications, so that they can run seamlessly over the modeled domain (or a part of it) once they are connected to the ontology and understand it. In addition, services and applications developed based on our ontology (or connected to it) can also take advantage of typical software maintenance tasks, such as architectural evolution, which are supported by ontologies through ontology queries and DL reasoning [Gómez2007], [Witte2007].

As a matter of fact, our ontology has been already proposed, with other related works, as starting point for the study on “Available semantics assets for the interoperability of SMART APPLIANCES. Mapping into a common ontology as a M2M application layer semantics”, launched as invitation to tender by the EC in June 2013 [EC2013].

Finally, within the scope of the standard IFC (Industry Foundation Classes) data model for data sharing in the construction and facility management industries [ISO2013], it is currently being considered to convert IFC architecture to OWL. If this is finally the case, our ontology (or part of it) could be considered to be reused and included in such a standard.

Chapter 5

Practical Modeling

5.1 Introduction

Choosing the most suitable communications technologies for a given combination of communications architecture and application represents a challenging task in Smart Grid scenarios, due to the wide range of available options and to the specific requirements from both technical and economic perspectives that need to be met [Güngör2013], [Yan2013], [Liu2012]. As a result, effective methods to evaluate and compare how such available communications technologies meet these specific requirements are crucial in order to select the most appropriate ones before undertaking the important investments needed to deploy this kind of infrastructures on a large scale.

This evaluation may be carried out by deploying real pilot schemes involving high volume of devices. Although this approach may yield the most accurate results, it implies high costs and lacks of flexibility, in that only the deployed technologies can be evaluated. However, such evaluation can be also approached by means of simulations, which represent a powerful, flexible and cost-effective solution to achieve the same goal.

A crucial consideration when it comes to simulations is that they are based on a model of the actual issue under study. Therefore, the better that model fits the actual issue, the more relevant and meaningful the results obtained from the simulations will be.

This chapter is focused on modeling real world scenarios of the energy-positive neighborhoods of the Smart Grid which allow obtaining meaningful results from potential works based on them. The model considers near real-time bidirectional communications in realistic scenarios. In addition, in order to maximize the impact on the Smart Grid area, it not only considers current or short-term scenarios, but also foreseen medium to long-term ones. Thus, the conclusions from potential works based on this model will be valid for a longer period of time and they will allow making appropriate decisions in advance [López2012a].

The model presented in this chapter is mainly based on data from actual power distribution infrastructures and it is customized for the EU FP7 project ENERsip, since it was taken as reference in part of the comprehensive evaluation plan of this project [López2011b]. However, the characterized scenarios are valid for any energy-positive neighborhood and can be easily adapted just by suitably tuning the identified parameters.

The remainder of the chapter is structured as follows. Section 5.2 outlines the methodology we propose to properly model any communications overlay which works on top of an infrastructure devoted to any purpose. Section 5.3 presents the context and scope of the model developed in this thesis along with the characterized scenarios. Finally, section 5.4 draws conclusions highlighting for what purposes this model can be used, in general, as well as how it is used in this thesis.

5.2 Methodology

The methodology followed throughout this chapter can be applied to characterize in practice not only the communications infrastructure required to meet the requirements and achieve the goals of the so-called energy-positive neighborhoods, but also any communications overlay deployed on top of an infrastructure devoted to any purpose. The main steps of such a methodology are:

1. Map the communications overlay onto the underlying infrastructure. This step allows extrapolating well-known information of the underlying infrastructure (e.g., how it is physically or geographically deployed and organized) to the communications infrastructure.

2. Set the scope of the target model (i.e., which parts of the communications infrastructure are going to be considered and which parts are not going to be considered).

3. Identify parameters that can be relevant to properly characterize how the communications infrastructure works.

4. Cluster such parameters in relevant scenarios and quantify them given certain boundary conditions. In our case, for instance, the model is bounded to the Portuguese power distribution network (since it is based on data provided by EDP – *Energias de Portugal*) and the ENERsip specifications and implementation.

As main outcome of applying this methodology, a set of more sophisticated scenarios resulting from combining the basic ones is obtained. Each of those more sophisticated scenarios models the communications infrastructure in realistic situations which are characterized by the specific values the considered parameters take.

5.3 Communications infrastructure modeling

5.3.1 Context and scope

This section covers the steps 1 and 2 of the already presented methodology. First, the proposed M2M communications architecture is going to be mapped onto the typical power distribution infrastructure, which is shown in Figure 5-1.

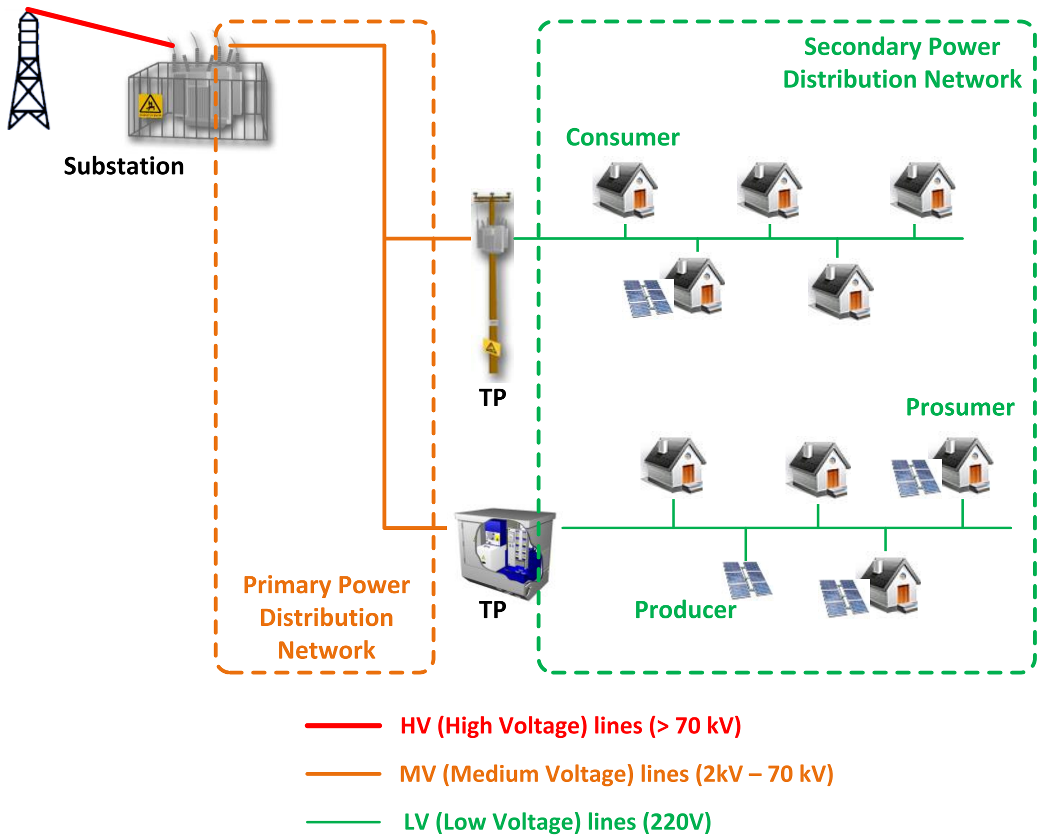

Figure 5-1 – Typical electricity distribution infrastructure

Such typical power distribution network is mainly composed of:

- Customers, which in the case of energy-positive neighborhoods can be either Consumers or Producers or Prosumers;
- TPs (Transformer Points)[1], which are dedicated to transforming the voltage supplied by the medium voltage distribution grid into voltage values suitable for supplying low voltage Customers (e.g., residential customers);
- Substation, which is dedicated to transforming the voltage supplied by the high voltage distribution grid, used to carry electricity throughout long distances, into voltage values suitable for supplying medium voltage lines.

The TPs are responsible for supplying low voltage to clusters of Customers; whereas the Substation is in charge of many TPs, and thus, of a high number of Customers. Thus, the scope

[1] They are also known as Transformation Centers or Feeders.

of the TPs is bounded to a group of Customers; whereas the scope of the Substation is bounded to big neighborhoods or small cities.

There is a clear correspondence between the designed M2M communications architecture and the power distribution grid, as Figure 5-2 shows. Thus, the ADR EPs (Automated Demand Response End Points) are associated to the Customers and the CNTRs (Concentrators) are associated to the TPs. The M2M GW (Gateway) is logically associated to the Substation that manages the target neighborhood. However, using a backhaul network allows the M2M GW to be physically located at the Substation or wherever else the data centers of the entity operating the system (e.g., DSOr – Distribution System Operator -, retail electric provider, aggregator, ESCO – Energy Service COmpany) are.

As it is highlighted in continuous green line in Figure 5-2, our model will be focused on the core of the designed M2M communications architecture, which comprises the wireless communications segments from the ADR EPs to the M2M GW, i.e., the NANs (Neighborhood Area Networks) and the Backhaul network as defined in the CT-IAP (Communications Technologies – Interoperability Architectural Perspective) of the IEEE 2030 SGIRM (Smart Grid Interoperability Reference Model) [IEEE2011]. The communications technologies considered for these communications segments are IEEE 802.11 and GPRS (General Packet Radio Service), respectively.

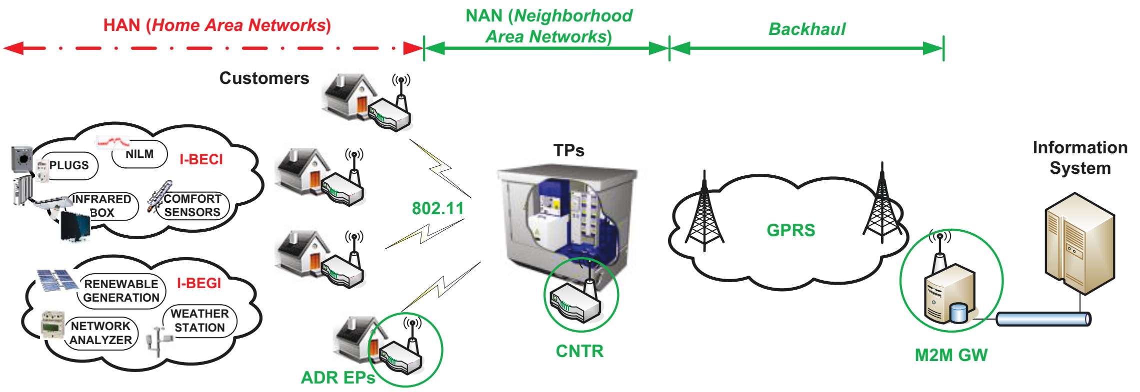

Figure 5-2 – Mapping of the designed M2M communications architecture onto the power distribution infrastructure

5.3.2 Characterized scenarios

This section covers steps 3 and 4 of the methodology presented in section 5.2. In order to actually identify relevant parameters, first the traffic patterns of the M2M communications infrastructure (both for the uplink and for the downlink) need to be characterized as statistical distributions. Regarding the downlink, the users' behaviors and the outputs of the decision maker module of the Information System (i.e., the PS-BI – Power Saving Business Intelligence - module) are considered to be random and memoryless, so they can be characterized as exponential distributions. Consequently, the aggregated downlink traffic can be characterized as Poisson distributions. Therefore, the following parameters need to be estimated in order to properly model the downlink traffic:

- μ_{IS}: Average periodicity of sending requests either by the users or automatically generated by the PS-BI module.
- S_{IS}: Size of the application messages sent either by the users or automatically generated by the PS-BI module (the size of the acknowledgement can be assumed to be the same).

Regarding the uplink, the consumption and generation data are sent periodically. Thus, every uplink stream can be characterized as a uniform distribution during the first sending period and, from then on, as a deterministic distribution with a given sending periodicity. Therefore, the following parameters need to be estimated in order to properly model the uplink traffic:

- A_C and A_G: number of ADR EP-C (Consumption) and ADR EP-G (Generation) per CNTR, respectively.
- S_C and S_G: size of the consumption and generation data at the application layer, respectively.
- ***T***: periodicity which ADR EPs send data with.
- ***C***: number of CNTRs per M2M GW.

It is worthwhile to remark upon the fact that downlink traffic may influence uplink traffic by means of the acknowledgements. However, they can be decoupled in practice by using a specific module at the ADR EPs – independent of the module responsible for generating uplink traffic - responsible for echoing the received messages.

Several scenarios are considered in order to assign values to such parameters appropriately. First, it is distinguished between Urban (***U***) and Rural (***R***) scenarios, since in the power distribution grid the number of Customers/TP (***Cust/TP***), the number of TPs/Substation (***TP/Subs***) and the maximum acceptable distance between Customers and TPs (D_{max}) vary remarkably between both. Based on the mapping presented in section 5.3.1, ***Cust/TP*** is related to the number of ADR EPs/CNTR and ***TP/Subs*** is directly the number of CNTRs/M2M GW (***C***). D_{max} is relevant in order to figure out whether IEEE 802.11 coverage is enough or not. Finally, for the sake of comprehensiveness, the minimum density of Customers per TP (d_{min}), computed as shown in (1), may be also of interest.

$$dmin = \frac{Cust/_{TP}}{\pi \cdot Dmax^2} \left[\frac{Cust/_{TP}}{km^2}\right] \qquad (1)$$

Table 5-1 summarizes the values of such parameters for each of these scenarios.

Table 5-1 - Main parameters for Urban and Rural scenarios

Parameter	Urban	Rural
Cust/TP	360 (1)	100 (1)
Dmax (m)	500 (1)	700 (1)
dmin (Cust/km^2)	458.36	64.96
C	150 (1)	220 (1)

(1) Data provided by EDP

As it was already motivated in section 5.1, current or short-term (***ST***) scenarios and medium to long-term (***LT***) scenarios are also considered. The main parameters that vary from one of these scenarios to another are:

- ***T***: Periodicity of sending consumption and generation data of the ADR EPs.
- Type of appliances.
- ***Plugs/I-BECI***: Number of appliances per I-BECI. For the purpose of the model, the I-BECI architecture presented in Chapter 3 is simplified by assuming that every appliance is monitored and controlled by a Plug.

- $\boldsymbol{S_C}$ and $\boldsymbol{S_G}$: size of the consumption and generation data at the application layer, respectively.

- Penetration of micro-generation (***(I-BECI|I-BEGI)/Cust***). This parameter varies also from Urban to Rural scenarios. It will be always higher in the Rural scenarios than in the Urban ones due to the type of dwellings (e.g., houses where photovoltaic panels can be installed in the roof are more common in the former; whereas buildings of flats are more common in the latter). It will be also higher in the long-term than in the short-term, since the penetration of micro-generation and self-consumption is foreseen to increase in the forthcoming years.

- $\boldsymbol{A_C}$ and $\boldsymbol{A_G}$: number of ADR EP-C and ADR EP-G per CNTR, respectively. In this chapter, it is assumed that there are independent communications gateways for the I-BECI (ADR EP-C) and for the I-BEGI (ADR EP-G). Thus, $\boldsymbol{A_C}$ is equal to ***Cust/TP***, since it is assumed that every Customer is equipped with an I-BECI; whereas $\boldsymbol{A_G}$ is computed by multiplying $\boldsymbol{A_C}$ by the estimation of the penetration of micro-generation (assumed always < 1).

T is estimated as 15 minutes, for the short-term scenario, and 5 minutes, for the long-term scenario. In addition, in order to evaluate somehow the impact of DR (Demand Response) events on the communications infrastructure performance, it might be considered that a given percentage of the overall ADR EP-C send information every minute (***T*** = 1 minute) during a given period of time (prior to the DR event). The latter assumption holds both for short-term and long-term scenarios.

Regarding the number of appliances per I-BECI, in principle one appliance per type of appliance is considered. The number of appliances per I-BECI as well as the type of the appliances is determined by coupling those appliances with higher impacts on energy efficiency and DR with those appliances which present higher ownership rate. Based on the data collected in the project REMODECE (Residential Monitoring to Decrease Energy Use and Carbon Emissions in Europe) [De Almeida2011], 5 appliances per I-BECI are considered for the short-term scenario, such appliances being refrigerator, washing machine, dishwasher, air conditioning, and water heater; whereas 10 appliances per I-BECI are considered for the long-term scenario, such appliances being refrigerator, freezer, washing machine, clothes dryer, dishwasher, router, TV, DVD player, air conditioning, and water heater.

$\boldsymbol{S_G}$ and $\boldsymbol{S_C}$ are taken from the actual implementation of ENERsip. In the case of $\boldsymbol{S_G}$, the following information is provided:

- An Inverter sends 520 Bytes periodically.

- A Counter (used to measure the energy generated by a given µGeneration Source) sends 150 Bytes periodically.

- A WS (Weather Station) sends 360 Bytes periodically.

As it has already been explained throughout this dissertation, both the Inverter and the Counter are associated to a µGeneration Source. The most relevant µGeneration Sources are photovoltaic panels and µwind turbines. Since the penetration of photovoltaic panels is foreseen to be much higher than the penetration of µwind turbines, the configuration of the I-BEGI considered for the short-term scenario comprises 1 photovoltaic panel installation (i.e., 1 Inverter and 1 Counter) and 1 WS. However, the configuration of the I-BEGI considered for the long-term scenario comprises 1 photovoltaic panel installation, 1 µwind turbine installation (i.e., 2 Inverters and 2 Counters) and 1 WS. As a result, assuming that the ADR EP-G aggregates the outgoing traffic, the following values are obtained:

- $\boldsymbol{S_G|_{ST}}$ = 1030 Bytes

- $\boldsymbol{S_G}|_{LT}$ = 1700 Bytes

In the case of the I-BECI, it is assumed that the sampling periodicity in the Plugs is the same as the sending periodicity in the ADR EP-C (i.e., one sample per plug is sent by the ADR EP-C at a time) and that the ADR EP-C aggregates the outgoing traffic. The number of bytes varies depending on the number of samples aggregated in the message, being approached by the straight line formula shown in (2).

$$Sc = 71 * Plugs + 185 \ (2)$$

As a result, the following values are obtained:

- $\boldsymbol{S_C}|_{ST}$ = 540 Bytes
- $\boldsymbol{S_C}|_{LT}$ = 895 Bytes

The estimation of the penetration of micro-generation is based on the know-how of the ENERsip consortium. Table 5-2 summarizes the main parameters for both short and long-term scenarios:

Table 5-2 - Main parameters for Short-term and Long-term scenarios

Parameter	Short-term	Long-term
T (min)	15	5
Plugs/I-BECI	5	10
S_C (Bytes)	540	895
S_G (Bytes)	1030	1700
I-BECI/Cust	1	1
I-BEGI/Cust	U: 0.1	U: 0.4
	R: 0.4	R: 0.8
A_C	U: 360	U: 360
	R: 100	R: 100
A_G	U: 36	U: 144
	R: 40	R: 80

The intensity of usage of the platform is tuned in order to model the downlink traffic, giving rise to three scenarios more:

- Low usage
- Medium usage
- High usage

Such scenarios model, e.g., peaks and dips on the intensity of usage of the platform. The main parameters estimated for these scenarios are summarized in Table 5-3.

Table 5-3 - Main parameters in Low usage, Medium usage and High usage scenarios

Feature	Low usage	Medium usage	High usage
μ_{IS}	1 day	2 hours	5 minutes
S_{IS} (Bytes)	256	256	256

As a result, at a first glance, the model presented throughout this chapter comprises 12 different scenarios, as Table 5-4 shows, which still can be tuned to evaluate different *figures-of-merit* of the proposed M2M communications architecture.

Table 5-4 - Scenarios considered in the model presented in this chapter

	Short-term	**Long-term**
Urban	1) Low usage 2) Medium usage 3) High usage	4) Low usage 5) Medium usage 6) High usage
Rural	7) Low usage 8) Medium usage 9) High usage	10) Low usage 11) Medium usage 12) High usage

5.4 Conclusions

This chapter presents a methodology that can be applied to characterize in practice not only the communications infrastructure required to meet the requirements and achieve the goals of the so-called energy-positive neighborhoods, but also any communications overlay deployed on top of an infrastructure devoted to any purpose. As a matter of fact, this methodology is also applied in the on-going Spanish R&D (Research and Development) project PRICE to obtain guidelines for proper design and deployment of AMI (Advanced Metering Infrastructures) [López2013c], [López2014c].

As a result of applying this methodology, the proposed M2M communications architecture is modeled in practice, as it is explained throughout the chapter. This model considers near real-time bidirectional communications both in short-term and in long-term scenarios. Although this model is customized for the Portuguese power distribution infrastructures and the EU FP7 project ENERsip, it can be easily adapted to any other situation just by suitably tuning the appropriate parameters.

Power distribution networks are quite similar throughout Europe. Therefore, the typical values of *Cust/TP*, *TP/subs*, and D_{max} of the Portuguese power distribution networks are representative for the rest of Europe. However, they are not representative in North America.

First, European transformers are larger and there are more *Cust/TP* and *TP/Subs*. Hence, A_C and *C* would be lower in North America than the values considered in this chapter. Second, North American secondary power distribution networks are single-phase and are standardized on 120/240V; whereas European secondary power distribution networks are three-phase and are standardized on 220, 230, or 240 V, which represent twice the North American standard. With twice the voltage, a circuit feeding the same load can reach four times the distance. And because three-phase secondary can reach over twice the length of a single-phase secondary, a European secondary can reach 8 times the length of a North American secondary for a given load and voltage drop [Short2005]. As a result, D_{max} could be up to 8 times lower in North America than the value considered in this chapter, which indeed is good news for using Wi-Fi in this network segment.

Regarding micro-generation and self-consumption, the situation in term of total installed capacity is not the same in all the countries of the EU. Regarding residential PV in particular [EPIA2013], the top 5 European markets in term of overall installed capacity are Italy, Germany, Belgium, UK, and Denmark. However, our model considers the penetration rate of these technologies as a percentage of the overall number of households/buildings with the aim that the estimated values are as representative as possible. Nevertheless, countries like Belgium, Denmark or the Netherlands still stand out when talking about penetration rates of residential PV. In the US, the differences are also remarkable, standing out states like California.

Since this model has been carefully developed to fit real-world scenarios, potential works based on it will provide meaningful results to any entity interested on operating this kind of platforms, avoiding one of the main problems identified in the state-of-the-art when it comes to simulating or testing communications infrastructures for the Smart Grid [Abdul Salam2012], [Shrestha2012].

Thus, in general potential simulations based on this model may yield results along the lines of, e.g.:

- Evaluate how the communications infrastructure performs (e.g., in terms of percentage of available resources consumed) under the characterized scenarios.

- Evaluate the maximum number of users that can be handled in each of such scenarios assuming full availability of communications resources (i.e., the communications infrastructure is exclusively devoted to carry traffic from a given energy efficiency platform).

- Identify possible bottlenecks in the communications architecture.

- Evaluate whether a public communications network, or a private communications network, or a hybrid solution, is the best approach for this kind of systems.

- Evaluate the performance of the system under different design decisions or different network conditions (e.g., with and without data aggregation, during a DR event).

- Evaluate the performance of the selected communications technologies in the aforementioned scenarios

- Evaluate the performance of other alternative communications technologies, such as NB-PLC (Narrow-Band Power Line Communications) solutions, WiMAX (Worldwide Interoperability for Microwave Access), or UMTS (Universal Mobile Telecommunications System), in such scenarios.

This model is taken as reference in chapter 6 to assess the operational costs of using different security solutions in the backhaul network as well as to evaluate the performance of the selected communications technologies based on different metrics.

Chapter 6

Evaluation

6.1 Introduction

As it has been already highlighted throughout this dissertation, communications for the Smart Grid need to meet specific requirements from both the technical and economic perspectives, such as throughput, reliability, scalability, security, or low deployment and operational costs [Güngör2013], [Yan2013], [Liu2012]. Hence, it is crucial to evaluate how different communications technologies meet such requirements before undertaking the important investments needed to deploy this kind of communications infrastructures on a large scale.

This chapter aims to shed some light on this issue. In particular, the main goal of this chapter is to evaluate, from both the technical and economic perspectives, the core of the M2M (Machine-to-Machine) communications architecture proposed in chapter 3 taking as reference the model presented in chapter 5. Such a core communications infrastructure is fully based on widely deployed wireless communications technologies, such as IEEE 802.11 and GPRS (General Packet Radio Service).

The remainder of the chapter is structured as follows. Section 6.2 outlines the general considerations and assumptions made in this chapter regarding the model presented in chapter 5. Section 6.3 analyzes and compares IPSec (Internet Protocol Security) and TLS/SSL (Transport Layer Security / Secure Socket Layer) both from the technical point of view and in terms of the potential impact on operational costs of using them as VPN (Virtual Private Network) technologies. Section 6.4 evaluates by means of simulations the performance of IEEE802.11b, in terms of goodput (i.e., throughput at the application layer), and the performance of GPRS, in terms of transmission time (which is in turn related to bandwidth).

6.2 General considerations and assumptions

The model presented in chapter 5 is focused on the core of the M2M communications architecture proposed in chapter 3, which encompasses from the ADR EPs (Automated Demand Response End Points) up to the M2M GW (Gateway), and considers near real-time bidirectional communications in realistic large-scale scenarios.

However, decoupling the uplink and the downlink reduces the complexity and increases the granularity of potential assessments, allowing addressing them separately as well as putting them eventually together to double-check the results obtained previously. In particular, this chapter is focused on the uplink (i.e., consumption and generation data flowing from the ADR EPs to the M2M GW), because the uplink traffic may be so high as to challenge the communications infrastructure itself, thus representing the major concern for the entities interested on operating this kind of platforms (e.g., DSOr – Distribution System Operator -, retail electric provider, aggregator, ESCO – Energy Service COmpany) in the short to medium term.

In addition, we assume that data reach the application layer at the CNTR (Concentrator), which implies some advantages:

- Relevant functionalities, such as data aggregation, can be evaluated at the CNTR.
- The NAN (i.e., ADR EPs – CNTR) and the Backhaul network (CNTRs – M2M GW) can be addressed separately.

Thus, in this chapter we distinguish between Urban (*U*) and Rural (*R*) scenarios, since - based on the data from real power distribution infrastructures provided by EDP (*Energias de Portugal*) - the number of customers/TP (*Cust/TP*), the number of TPs/Substation (*TP/Subs*), and the maximum acceptable distance between customers and TPs (D_{max}), vary remarkably between both.

In addition, we consider not only current or short-term (*ST*) scenarios but also medium to long-term (*LT*) scenarios, so that the obtained conclusions are valid for a longer period of time and are used to take the appropriate decisions in advance. The main differences between short-term and long-term scenarios have to do with:

- The periodicity which ADR EPs send data with (*T*) and the size of such data (*S*). *T* will be lower in the long-term, thus being closer to real-time. *S* will be higher in the long-term, since more devices with communications capabilities are assumed both in the I-BECIs (In-Building Energy Consumption Infrastructures) and in the I-BEGIs (In-Building Energy Generation Infrastructures). In addition, *S* is also different for I-BECIs and I-BEGIs (S_C and S_G, respectively), since the sensors and actuators networks within them are composed of different devices.
- The penetration of micro-generation. This parameter will be always higher in the rural scenarios than in the urban ones due to the type of dwellings (e.g., houses where photovoltaic panels can be installed in the roof are more common in the former; whereas buildings of flats are more common in the latter). Furthermore, it will be also higher in the long-term than in the short-term scenarios, since the penetration of micro-generation and

self-consumption is foreseen to increase in the forthcoming years. In this chapter we assume independent communications gateways for the I-BECI (ADR EP-C) and for the I-BEGI (ADR EP-G). Thus, the number of ADR EP-C (A_C) is equal to the number of *Cust/TP*; whereas the number of ADR EP-G (A_G) is computed by multiplying A_C by the estimation of the micro-generation penetration (always lower than 1).

Table 6-1 summarizes the values of the aforementioned parameters in the four scenarios considered in this chapter, where *C* refers to the number of CNTRs/M2M GW (i.e., *TP/Subs*) and *D* refers to the maximum acceptable distance between customers and TPs (D_{max}).

Table 6-1 - Summary of the parameters relevant to the scenarios considered in Chapter 6

Scenarios	**Short-term (ST)**	**Long-term (LT)**
Urban (U)	A_C/A_G = 360/36 S_C/S_G = 540B/1030B T/D/C = 15'/500m/150	A_C/A_G = 360/144 S_C/S_G = 895B/1700B T/D/C = 5'/500m/150
Rural (R)	A_C/A_G = 100/ 40 S_C/S_G = 540B/ 1030B T/D/C = 15'/700m/220	A_C/A_G = 100/80 S_C/S_G = 895B/1700 B T/D/C = 5'/700m/220

Figure 6-1 illustrates the model considered in this chapter and highlights its scope in continuous green line.

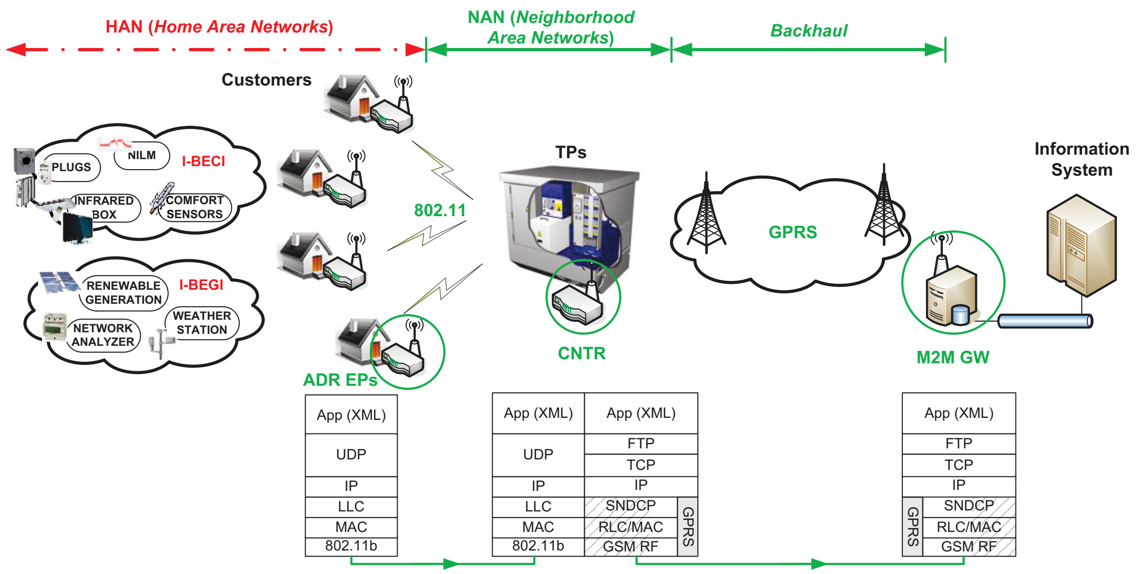

Figure 6-1 – Details of the model considered in chapter 6

6.3 Evaluation of end-to-end security protocols

The main goal of this section is to assess the impact of using security protocols which support VPNs on the operational costs of an energy-efficiency platform for energy-positive neighborhoods which relies on the M2M communications architecture proposed in chapter 3. Thus, secure communications channels are to be established between pairs of entities of this communications architecture. Therefore, bearing in mind that this chapter is focused on the core of the already mentioned communications architecture, such secure channels can be established from the ADR EPs directly to the M2M GW or from the CNTRs to the M2M GW, as Figure 6-2 (a) and (b) illustrates.

If the secure tunnels were established from the ADR EPs straight to the M2M GW, the CNTRs would not be able to aggregate data, which would affect negatively the scalability and operational costs of the platform. Thus, this case is actually divided into establishing secure tunnels from the ADR EPs to the CNTR and from the CNTRs to the M2M GW, which implies the highest numbers of tunnels and so the most complex scenario to manage, as Figure 6-2 (c) shows.

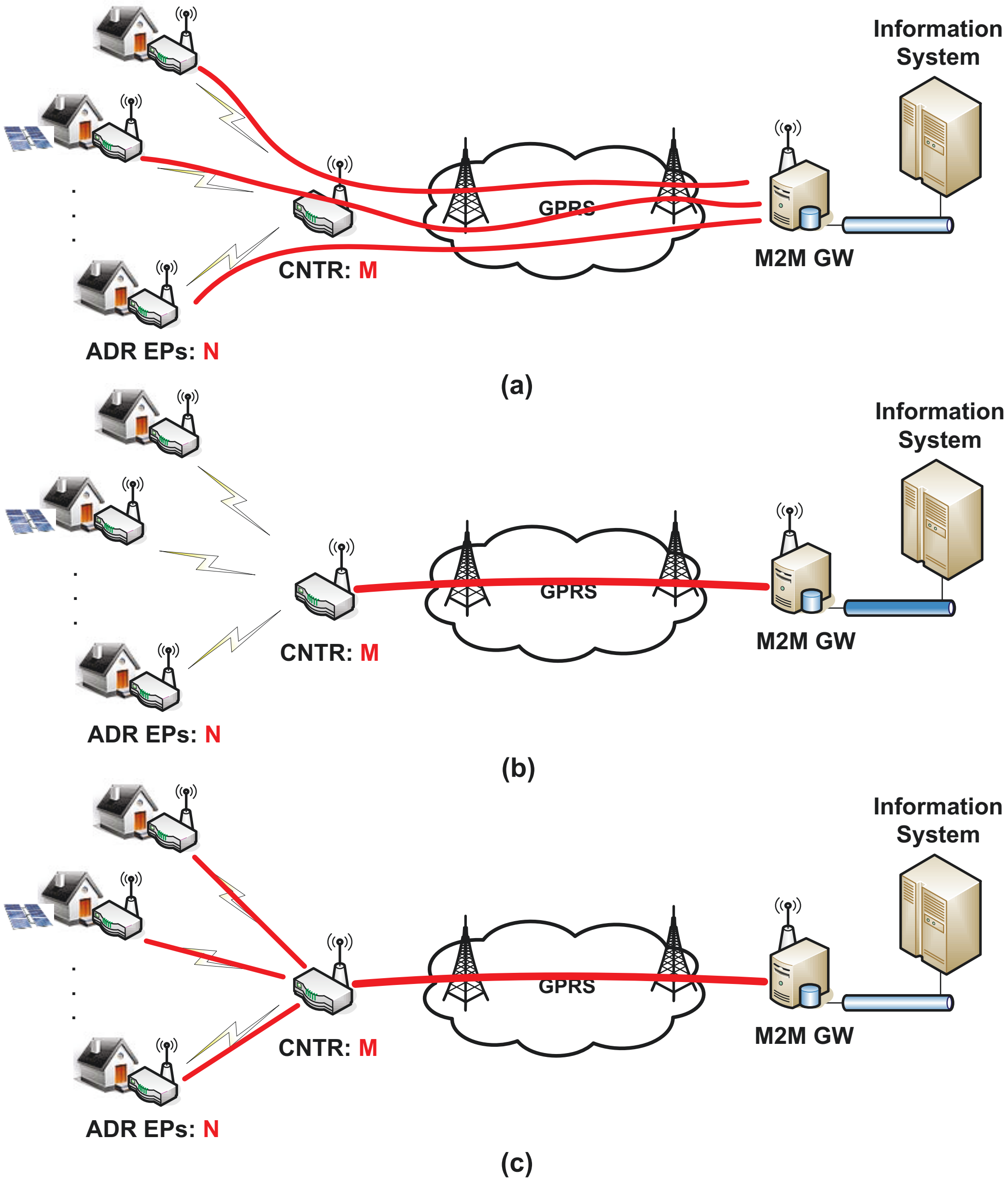

Figure 6-2 – (a) *NxM* direct secure tunnels from the ADR EPs to the M2M GW; (b) *M* secure tunnels from the CNTRs to the M2M GW; (c) *NxM* secure tunnels from the ADR EPs to the CNTRs + *M* secure tunnels from the CNTRs to the M2M GW

Regarding the secure tunnels from the ADR EPs to the CNTRs, it might be interesting to evaluate the impact of the overhead introduced by the security protocol on the performance of the wireless link. This overhead will not increase the operational costs though, since in principle it is assumed that the operator of the platform will be responsible for this network segment. Hence, the operator itself will be also responsible for configuring the basic security mechanisms within this network segment (i.e., WPA2 – Wi-Fi Protected Access 2).

Regarding the secure tunnels from the CNTRs to the M2M GW, the overhead introduced by the security protocol does have an impact on the operational costs, since the backhaul connectivity will be a service offered by a 3rd party (e.g., a telecom operator). In addition, in this case the operator of the platform must use such security mechanisms at higher layers, since the basic security mechanisms are out of its scope and it cannot rely solely on the security provided by such a 3rd party.

This section is focused on the case of establishing VPNs from the CNTRs to the M2M GW. Two scenarios are in turn considered within this specific case:

- Fast Forwarding (*FF*): the CNTRs forward the packets coming from the ADR EPs to the M2M GW on a per-packet basis, using a TCP (Transport Control Protocol) connection for this purpose.

- Aggregation (*Aggr*): the CNTRs store all the packets received from the ADR EPs throughout a given period and send them all together using a FTP (*File Transfer Protocol*) connection.

Regarding the security protocols themselves, there are many mechanisms to provide E2E (End-to-End) security at the different layers of the protocol stack [Khanvilkar2004], [Berger2006]. VPN can be implemented at the link layer using L2TP (Layer 2 Tunneling Protocol). IPSec represents the most widely deployed solution to do so at the network layer. TLS/SSL is the most widely used protocol for this purpose at the transport layer. And SSH (Secure Shell) is widely used at the application layer for secure remote access. In this chapter, we analyze and compare IPSec and TLS/SSL.

6.3.1 Technical comparison

Table 6-2 summarizes and compares some relevant technical features of IPSec and TLS/SSL. It can be seen that both IPSec and TLS/SSL provides the basic security features required by our target application (i.e., authentication, trustworthiness, and confidentiality). The main drawbacks of IPSec are the complexity of configuration and the NAT (Network Address Translation) incompatibility; whereas one of the main drawbacks of TLS/SSL is the complexity of using PKI (Public Key Infrastructure). Regarding the fact that TLS/SSL only supports some TCP applications, there is no problem in our case, since FTP is one of the TCP applications supported by TLS/SSL. As result, it is concluded that, from a technical point of view, there is no compelling reason to rule one of these protocols out.

Table 6-2 - Summary of IPSec and TLS/SSL technical comparison

Feature	**IPsec**	**TLS/SSL**
Authentication	Yes	Yes
Trustworthiness	Yes	Yes (More robust, since the HMAC is longer)
Confidentiality	Yes (if ESP)	Yes
Configuration	Complex	Straightforward
Interoperability problems	Yes (NAT)	No
TCP apps support	All	Some
UDP support	Yes	Only DTLS
PKI	No	Yes
Compression	Yes	Only OpenSSL
Client-specific software	Yes	No
Multi-environment support	Some times	Yes
Apps filter	No	Yes (VPN support to specific apps)

6.3.2 Economic comparison

This section analyses the impact of using IPSec or TLS/SSL on the operational costs of a potential energy efficiency platform which relies on the proposed M2M communications architecture.

In order to do so, first the MSS (Maximum Segment Size) of TCP needs to be determined, since this influences the number of packets sent through the GPRS link and the ratio of data vs. control headers (i.e., overhead). There are quite a few papers on the use of TCP over GPRS. Initially, the trend was to use low MSS (e.g., 512 B [Meyer1999] and 413 B [Rendón2001]). However, although low MSS may be appropriate for interactive applications, [Benko2004] proves that using high MSS (1400-1600 B) maximizes the goodput in applications of massive data exchange, as it is our case.

Taking this range of TCP MSS as reference, we compute the MSS used in this chapter by subtracting from the 1482 B pointed out in [Aschenbruck2004] as optimum MTU (Maximum Transmission Unit) of the SNDCP (Sub Network Dependent Convergence Protocol) layer of GPRS, the size of the headers up to the transport layer. Table 6-3 summarizes the overhead introduced by IPSec and TLS/SSL [Alshamsi2005]. We consider always the worst case for the analysis carried out in this section, i.e., 44 B for IPSec (plus the 20 B of the additional header introduced in the tunnel mode) and 25 B for TLS/SSL.

Table 6-3 - Overhead introduced by IPSec and TLS/SSL [Alshamsi2005]

Protocol	Mode	Size (Bytes)
IPSec tunnel mode	ESP	32
	ESP y AH	44
IPSec transport mode	ESP	36
	ESP y AH	48
TLS/SSL	HMAC-MD5	21
	HMAC-SHA-1	25

Figure 6-3 shows the protocol stack that implements both the CNTRs and the M2M GW in each of the considered cases, specifying the size of the headers in bytes. The layers considered in this section to compute the number of bytes carried by GPRS are marked in Figure 6-3 with forward slash.

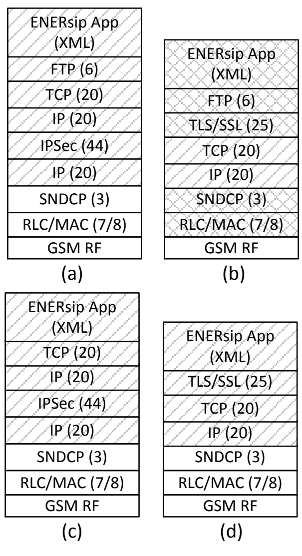

Figure 6-3 – Protocol stack at CNTR and M2M GW for: (a) IPSec &Aggr. (b) TLS/SSL & Aggr. (c) IPSec & FF. (d) TLS/SSL & FF

In order to translate the volume of traffic onto cost, two commercial Spanish M2M tariffs are used: 1) 100 MB/10 €/month, and 2) 20 MB/3 €/month.

Next, we evaluate the impact of IPSec and TLS/SSL on the operational cost following these steps: 1) the volume of bytes carried by GPRS is computed per a single CNTR and per month for each scenario; 2) the obtained bytes are translated onto cost using the aforementioned M2M tariffs; 3) the cost per neighborhood and per year is computed by multiplying the cost per CNTR and per month by C (*cf.* Table 6-1) and by 12 [El achab2013].

Table 6-4 details the results of our analysis for each of the considered scenarios. V_{NS} represents the volume of traffic (in MB) carried by the GPRS network in one month without using any security protocol. V_S represents the volume of traffic (in MB) carried by the GPRS network in one month using the corresponding security protocol. R_{NS} represents the ratio between the application-layer data and V_{NS} (in %). R_S represents the ratio between the application-layer data and V_S (in %). O_S is computed as the difference between V_S and V_{NS}, so it represents the overhead introduced by the security protocol (in %). C_{NS} represents the monthly cost of carrying V_{NS} (in €). C_S represents the monthly cost of carrying V_S (in €). Finally, D_C is computed as the difference between C_S and C_{NS}, so it represents the cost of using the corresponding security solution in a given scenario.

Table 6-4 - Summary of the results of the analysis of the impact on the operational costs of using IPSec or TLS/SSL

		Short-term (SL)		**Long-term (LT)**	
		IPSec	**SSL/TLS**	**IPSec**	**SSL/TLS**
Urban (U)	**Aggr**	V_{NS} =656,25 V_S =686,74 R_{NS} =96.88 % R_S =92.58 % Os = 4.3 % C_{NS} = 69 C_S = 70 D_C = 1	V_{NS} = 656,25 V_S = 667,96 R_{NS} =96.88 % R_S =95.18 % Os =1.7% C_{NS} = 69 C_S = 70 D_C = 1	V_{NS} =4821,65 V_S =5047,17 R_{NS} =96.895 % R_S =92.56 % Os =4.335 % C_{NS} = 486 C_S =509 D_C = 23	V_{NS} = 4821,65 V_S =4907,11 R_{NS} = 96.895 % R_S = 95.207% Os = 1.688 % C_{NS} = 486 C_S =493 D_C = 7
	FF	V_{NS} =679,28 V_S =748,89 R_{NS} =93.6 % R_S =84.89 % Os =8.71 % C_{NS} = 70 C_S =79 D_C = 9	V_{NS} =679,28 V_S =706,48 R_{NS} =93.6 % R_S =90 % Os =3.6% C_{NS} = 70 C_S =73 D_C = 3	V_{NS} =4885,51 V_S =5227,23 R_{NS} =95.628 % R_S =89.38 % Os =6.248 % C_{NS} = 490 C_S =526 D_C = 36	V_{NS} =4885,51 V_S =5018,99 R_{NS} = 95.628 % R_S =93.085 % Os =2.543 % C_{NS} = 490 C_S =500 D_C = 10
Rural (R)	**Aggr**	V_{NS} =269,94 V_S =282,62 R_{NS} =96,86% R_S =92.5 % Os =4.36 % C_{NS} = 30 C_S = 30 D_C = 0	V_{NS} =269,94 V_S =274,74 R_{NS} =96,86% R_S =95,17 % Os =1.69 % C_{NS} = 30 C_S = 30 D_C = 0	V_{NS} =1917,95 V_S =2007,61 R_{NS} =96.877 % R_S =92.55 % Os =4.327 % C_{NS} = 193 C_S = 203 D_C = 10	V_{NS} =1917,95 V_S =1951,67 R_{NS} =96.877 % R_S =95.2 % Os =1.67 % C_{NS} = 193 C_S = 199 D_C = 6
	FF	V_{NS} =276,86 V_S =301,46 R_{NS} =94.4 % R_S =86.7 % Os =7.7 % C_{NS} = 30 C_S = 33 D_C = 3	V_{NS} =276,86 V_S =286,47 R_{NS} =94.4 % R_S =91.27 % Os =3.6 % C_{NS} = 30 C_S = 30 D_C = 0	V_{NS} =1943,76 V_S =2080,87 R_{NS} =95.59 % R_S =89.29% Os =6.3 % C_{NS} = 199 C_S = 210 D_C = 11	V_{NS} =1943,76 V_S =2021,04 R_{NS} =95.59 % R_S =91.9 % Os =3.69 % C_{NS} = 199 C_S = 206 D_C = 7

Table 6-5 shows the difference between the annual cost of using *Fast Forwarding* and the annual cost of using *Aggregation* ($C_S|_{FF} - C_S|_{Aggr}$) in each scenario for a single CNTR. Table 6-5 also shows this difference in each scenario for the whole district/neighborhood[1].

Table 6-5 - Difference in terms of cost (in €) per CNTR and per district during one year between using *Fast Forwarding* and using *Aggregation* in each scenario

	Short-term (ST)		**Long-term (LT)**	
	IPSec	**TLS/SSL**	**IPSec**	**TLS/SSL**
Urban (U)	9*12=**108** 108*150= **16200**	3*12=**36** 36*150= **5400**	17*12=**204** 204*150= **30600**	7*12=**84** 84*150= **12600**
Rural (R)	3*12=**36** 36*220= **7920**	0	7*12 = **84** 84*220= **18480**	7*12=**84** 84*220= **18480**

In order to facilitate the understanding of the impact of using *Fast Forwarding* or *Aggregation* on the operational costs of the platform, Figure 6-4 graphically shows the difference between the annual cost of using *Fast Forwarding* and the annual cost of using *Aggregation* in each scenario for a whole district. It can be seen that the difference of cost – although almost negligible for a single CNTR - can be appreciable at neighborhood level, notably in urban and long-term scenarios. In addition, it can be also checked that the difference is always higher when using IPSec, since it introduces higher overhead. In conclusion, Figure 6-4 illustrates the savings that can be achieved by using *Aggregation*. Nevertheless, it is worthwhile to remark that the results obtained in this analysis represent a lower bound of the savings that *Aggregation* could bring, since we just aggregate data during one period.

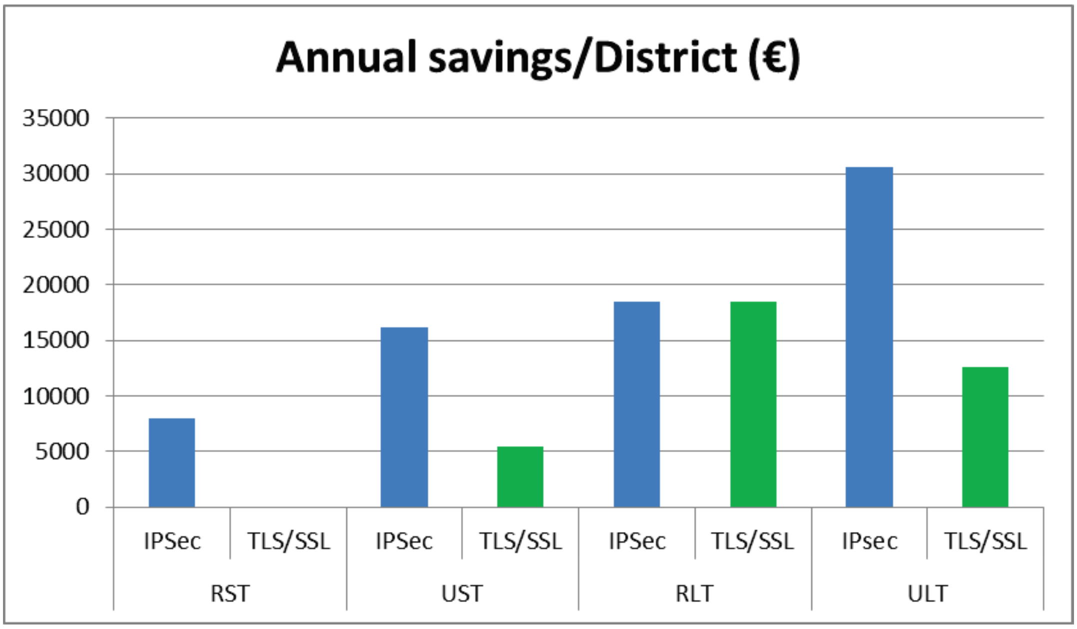

Figure 6-4 – Annual savings per district between implementing *Fast Forwarding* or *Aggregation* at CNTRs for each security protocol in each scenario

Table 6-6 shows the difference between the annual cost of using IPSec and the annual cost of using TLS/SSL ($C_S|_{IPSec} - C_S|_{TLS/SSL}$) in each scenario for both a single CNTR and the whole district/neighborhood.

[1] It should be noted that District is used to refer to the whole power infrastructure managed by a given Substations, where the consumption-generation optimization algorithms run.

Table 6-6 - Difference in terms of cost (in €) per CNTR and per district during one year between using IPSec and TLS/SSL in each scenario

		Short-term (ST)	Long-term (LT)
Urban (U)	**Aggr**	0	16*12 = **192** 192*150= **28800**
	FF	6*12 = **72** 72*150=**10800**	26*12 = **312** 312*150=**46800**
Rural (R)	**Aggr**	0	4*12 = **48** 48*220=**10560**
	FF	3* 12=**36** 36*220=**7920**	4*12 = **48** 48*220=**10560**

Again, to aid understanding the impact of using IPSec or TLS/SSL on the operational costs, Figure 6-5 graphically shows this difference in each scenario for a whole district. It can be checked that the difference of costs between using IPSec or TLS/SSL is always higher when using *Fast Forwarding*, since data sending is very inefficient in this situation, so the difference between the overhead introduced by IPSec and by TLS/SSL is even higher. It can be also checked that, in the case of using *Aggregation*, the potential savings of using TLS/SSL instead of IPSec are especially relevant in long-term scenarios.

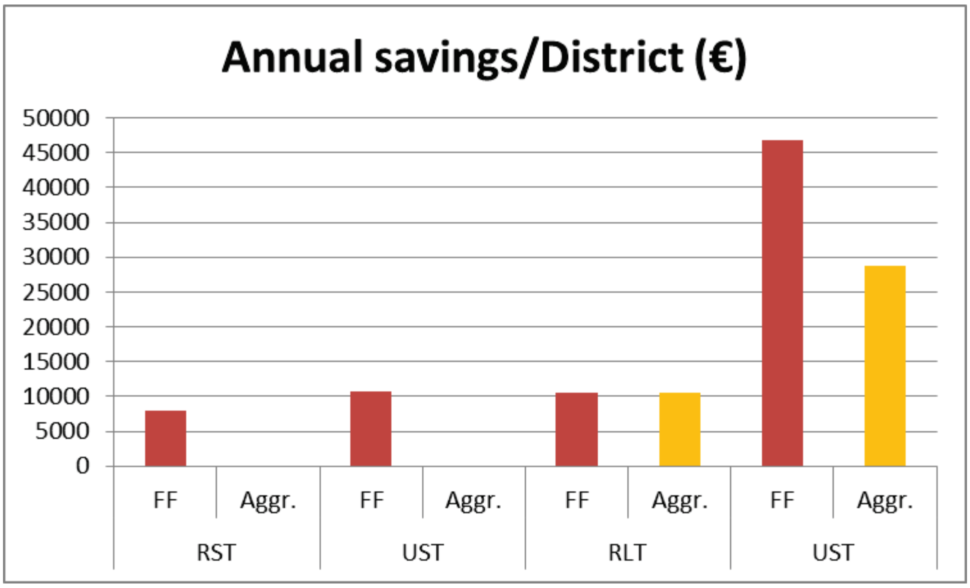

Figure 6-5 –Annual savings per district between implementing IPSec and TLS/SSL at CNTRs in each scenario depending on whether *Fast Forwarding* or Aggregation is used

Therefore, it can be concluded that *Aggregation* and TLS/SSL as VPN technology is the best combination in order to minimize the operational costs of the platform. Hence, such a combination will be assumed in the next section [López2014b].

Nevertheless, it should be noticed that the overhead – and so the costs - can be lower by implementing compression mechanisms (in the case of TLS/SSL, only OpenSSL supports it) and that the volume of data sent through the GPRS network – and so the costs – can be lower if only the data that change compared to the previous period are sent, which can be implemented, e.g., using JSON (JavaScript Object Notation).

6.4 Evaluation of communications infrastructure performance

This section evaluates the performance of IEEE 802.11 and GPRS using goodput and transmission time as metrics, respectively.

6.4.1 Simulation setup

The simulations were run using OMNeT++ 4.2.2 as network simulation framework [Varga2008]. Notably, the models and network components available in the INET framework 4 were used and modified when needed.

The simulations were run in a laptop equipped with a microprocessor Intel Core 2 Duo T7250 at 2 GHz, 1 Gb of RAM (Random Access Memory), and 2 Mb of cache memory, using Ubuntu 10.04 as OS (Operating System). The simulation time was set to 1 hour after checking that simulations converge after one period (i.e., 15 minutes in short-term scenarios and 5 minutes in long-term scenarios). Each scenario was simulated 100 times for both the NAN and the backhaul network in order to get statistically meaningful results. Therefore, the obtained data were considered to fit a Gaussian distribution based on the central limit theorem and hence (1) can be used to compute 95% confidence intervals, μ being the mean, σ being the standard deviation, and n being the length of the data (i.e., n=100). Octave 3.2 was used to process the data.

$$(\mu - 1.96 \cdot \frac{\sigma}{\sqrt{n}}, \mu + 1.96 \cdot \frac{\sigma}{\sqrt{n}}) \qquad (1)$$

Figure 6-6 shows the network used to simulate the NAN.

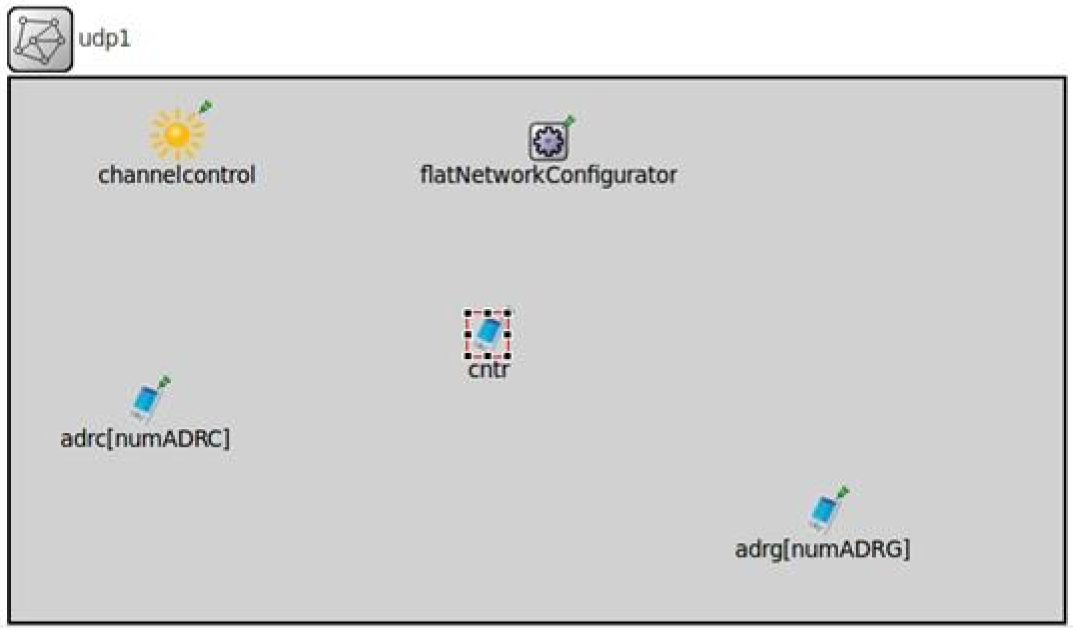

Figure 6-6 – Network used to simulate the NAN

The functionalities of the modules shown in Figure 6-6 are outlined next:

- *channelcontrol*: this module manages the PHY (PHYsical) and MAC (Media Access Control) layer of IEEE 802.11.

- *flatNetworkConfigurator*: this module assigns IP addresses within the same network segment.

- *MobileHost*: this module is taken as reference to implement the functionalities of ADR EP-Cs, ADR EP-Gs, and CNTR. Figure 6-7 shows the internal structure of the *MobileHost*. It can be seen that this module implements from an IEEE 802.11 interface in ad-hoc mode up to a set of UDP (User Datagram Protocol) applications. From such a set of UDP applications, *UDPBasicApp* is used to implement the ADR EPs, since *UDPBasicApp* allows fixing the sending periodicity and length of the messages; whereas a passive UDP socket (*UDPSink*) is used to implement the CNTR. In addition, a *DatarateChannel* was included between the UDP layer and the application layer in the upper direction in order to measure the aggregate throughput at the application layer in the CNTR (i.e., the so-called goodput).

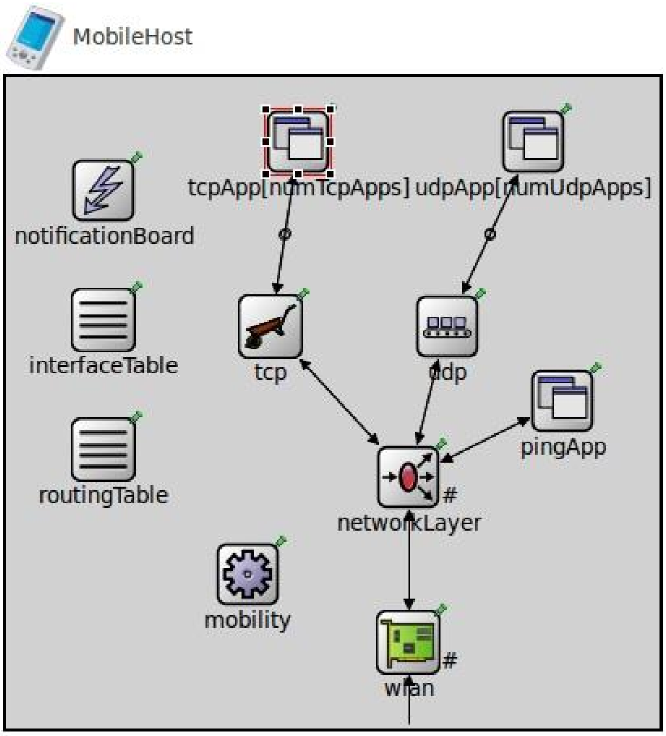

Figure 6-7 – Internal structure of the module *MobileHost*

The wireless router Linksys WRT160NL [WRT160NL] from Cisco is taken as reference for configuring the PHY and MAC parameters of the 802.11 link, since this device was actually used to implement the prototype of the ADR EP in the ENERsip project. The family of standards 802.11 encompasses many protocols [Hiertz2010]. The Linksys WRT160NL, in particular, supports 802.11b/g/n. In this work, we focus on 802.11b and g. Table 6-7 summarizes the most relevant parameters of IEEE 802.11b and g in the Linksys WRT160NL.

Table 6-7 - Summary of Linksys WRT160NL datasheet

	802.11b		**802.11g**	
	1 Mb	**11 Mb**	**6 Mb**	**54 Mb**
EIRP	19 ± 1.5 dBm Min = 56.2 mW Max = 112.2 mW		15 ± 1.5 dBm Min = 22.387 mW Max = 44.67 mW	
Sensitivity	- 92 dBm	- 86 dBm	-84 dBm	-74 dBm

In order to check whether all these protocols provide the range required by our target application (*D*) or not, the well-known Friis equation (2) with $\alpha=2$ is applied, since Free-Space is used as propagation model in OMNeT++ [Khosroshahy2007].

$$receivedPower = \frac{powerSend * \lambda^2}{16 * \pi^2 * dist^{\alpha}} \qquad (2)$$

Table 6-8 summarizes the minimum transmission power (*powerSend*) required to reach *D* with a received power equals to the sensitivity. If *powerSend* is higher than the maximum EIRP (Effective Isotropic Radiated Power), the protocol under question cannot be used in our target application, as it is the case of 802.11g at 54 Mb.

Table 6-8 - Summary of minimum transmission powers required for our target application

Scenarios	Distance (m)	*powerSend* (mW)			
		802.11b 1 Mb	**802.11b 11 Mb**	**802.11g 6 Mb**	**802.11g 54 Mb**
Urban (U)	500	**1.59 < EIRP**	**6.35 < EIRP**	**10.056 < EIRP**	**100.56 > EIRP**
Rural (R)	700	**3.125 < EIRP**	**12.44 < EIRP**	**19.71 < EIRP**	**197.1 > EIRP**

Finally, IEEE 802.11b at 11 Mb was selected for our simulations. Table 6-9 shows the configuration of the PHY and MAC parameters of IEEE 802.11b used in such simulations.

Regarding the Backhaul network, when developing the simulations, we realized that in practice there cannot be interferences in the GPRS links, since GPRS uses dedicated channels, instead of shared medium. As a result, the parameter *C* from Table 6-1 is not needed in these simulations. This reduces the complexity of them, since instead of having to simulate *C* GPRS connections; it is enough to simulate just one. Figure 6-8 shows the network used to simulate the backhaul communications.

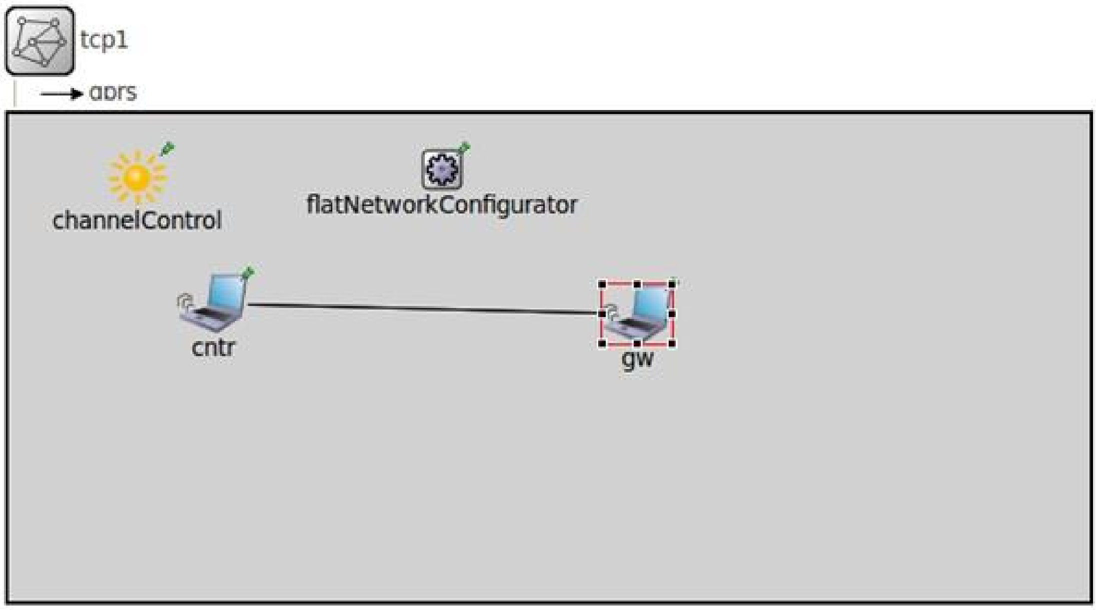

Figure 6-8 – Network used to simulate the Backhaul

From the modules shown in Figure 6-8, only the functionalities of the *WirelessHostSimplified* need to be described, since the functionalities of the *channelcontrol* and the *flatNetworkConfigurator* have already been presented. *WirelessHostSimplified* is taken as reference to implement the functionalities of the CNTRs and the M2M GW. Figure 6-9 shows the internal structure of this module. As it can be seen, the *WirelessHostSimplified* implements three different PHY/MAC layers, namely *wlan* (i.e., IEEE 802.11 in infrastructure mode), *eth* (i.e., Ethernet), and *ppp* (i.e., Point-to-Point). The *ppp* module is selected to model the GPRS link. At the application layer, the *WirelessHostSimplified* implements a set of TCP applications. *TCPBasicClientApp* and *TCPGenericSrvApp* are the most suitable applications to implement an FTP application. *TCPBasicClientApp* allows specifying the time gap between requests (i.e., sending periodicity) and the size of the reply (i.e., size of data). Thus, once a *TCPGenericSrvApp* receives a request, it just replies a message with the size specified in that request.

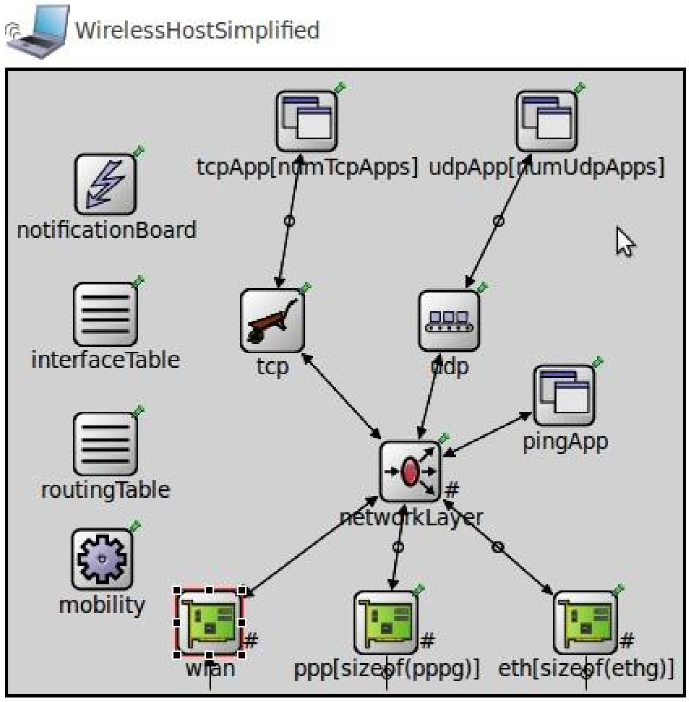

Figure 6-9 – Internal structure of the module *WirelessHostSimplified*

As a result, despite the fact that in practice the M2M GW works as FTP server and the CNTRs work as FTP clients, in our simulations the *TCPBasicClientApp* was used to implement the M2M GW and the *TCPGenericSrvApp* was used to implement the CNTR. Thus, the time that the CNTR needs to send the data to the M2M GW can be computed as the difference between the time when they are received at the M2M GW and the time when the request is received at the CNTR (since the parameter *ReplyDelay* of *TCPGenericSrvApp* is set to 0). A *DatarateChannel* was included between the TCP layer and the application layer in the upper direction indeed to measure the bytes received at the application layer in the M2M GW and in the CNTR.

The GPRS link itself is modeled as a *DatarateChannel* with the following features, which are also summarized in Table 6-9:

- Delay = 1 μs.
- Data rate = 26.8 kbps. This parameter is set based on the uplink data rate of an actual GPRS network reported in [Shrestha2012]. A dedicated infrastructure is assumed, i.e., the GPRS link only carries data associated to our application.
- Probability of error = 0.001, based on the theoretical availability of the channel [NIST2010b].

Table 6-9 - Summary of the most important parameters for each communications technology

		Parameter	Value
GPRS		Delay	1 μs
		Uplink data rate	26.8 Kbps
		Probability of error	0.001
802.11b	**PHY**	Carrier frequency	2.4 GHz
		Transmitter power	79.43 mW
		Path loss (α)	2
		Sensitivity	-86 mW
		Bit rate	11 Mbps
	MAC	Retry limit	7
		Contention window	32

6.4.2 Performance evaluation

Table 6-10 summarizes the goodput measured at the CNTR in the four simulated scenarios and compares it with the theoretical approximation computed using (3).

$$TheoreticalGoodput = \frac{Ac * Sc * 8 + Ag * Sg * 8}{T} \qquad (3)$$

Table 6-10 - Summary of NAN results (Goodput in bps)

		Short-term (ST)	Long-term (LT)
Urban (U)	**Theoretical**	2057.6	15120
	Simulated	(2043.94 , 2048.05)	(15070.09 , 15077.91)
Rural (R)	**Theoretical**	846.22	6013.3
	Simulated	(843.54 , 845.79)	(6011.81 , 6012.32)

It can be checked that the obtained results fit the expected results in every scenario[2]. Figure 6-10 shows the goodput for just one simulation run in every scenario. It can be observed that the simulated goodput converges to a value which is close to the theoretical one in each scenario. As a result, it can be concluded that the protocol IEEE802.11b at 11 Mb meets the requirements (in terms of goodput) of the NAN in all the considered scenarios. Due to the fact that the maximum goodput is in the order of tens of Kb, IEEE 802.11b at 1 Mb or IEEE802.11g at 6 Mb could also be used.

[2] In order to avoid simulation problems in the worst case scenario (i.e., ULT), explicit memory deallocation at MAC layer is needed.

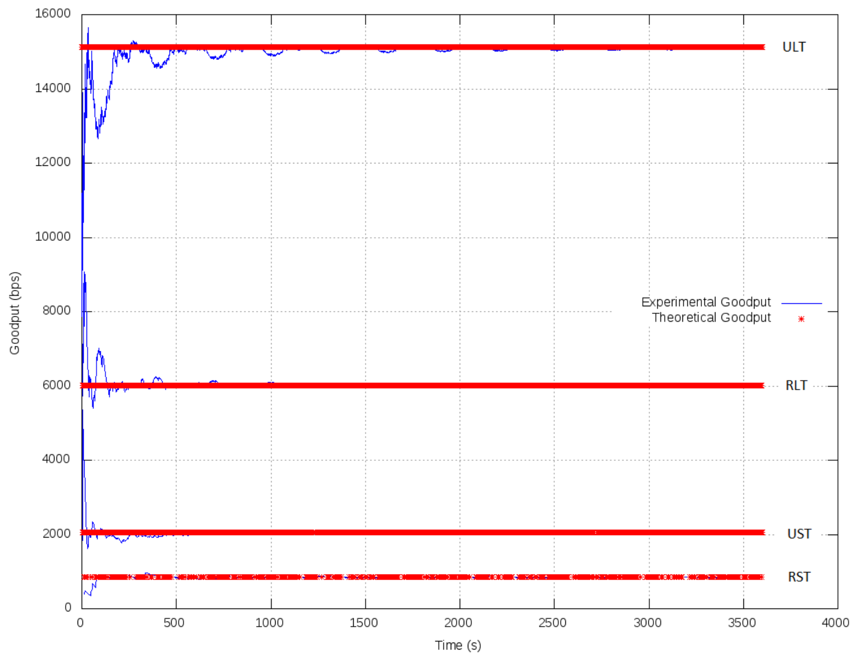

Figure 6-10 – NAN results for each scenario for a simulation time of 3600 s

Table 6-11 summarizes the time that the CNTR spends to transfer the data to the M2M GW (T_{CNTR}) in the four simulated scenarios and compares them with the time computed theoretically using the fragmentation criteria reported in [Aschenbruck2004] and the bytes of the layers marked in Figure 6-3 with back slash.

Table 6-11 - Summary of Backhaul network results (Transmission Time in s)

		Short-term (ST)	Long-term (LT)
Urban (U)	**Theoretical**	T_{CNTR} = 73.477 < 900	T_{CNTR} = 179.93 < 300
	Simulated	(77.41 , 78.93)	(190.18 , 191.28)
Rural (R)	**Theoretical**	T_{CNTR} = 30.224 < 900	T_{CNTR} = 71.564 < 300
	Simulated	(31.67 , 32.37)	(75.47 , 76.12)

It can be checked that the simulated T_{CNTR} is always slightly higher than the theoretical value, mainly due to the probability of error and to slightly different fragmentation policies. In addition, T_{CNTR} is always lower than the sending period, which means that GPRS meets the requirements (in terms of bandwidth) of the Backhaul network in all the considered scenarios.

6.5 Conclusions

This chapter evaluates some features of such widely used wireless communications technologies as IEEE 802.11 and GPRS in a Smart Grid application which consists of gathering consumption and generation data periodically in order to reduce electricity consumption and to maximize consumption-generation matching at neighborhood level. This assessment is carried out analytically and by means of simulations considering realistic large-scale scenarios, so the obtained results are valid to be taken into account as guidelines for potential deployments.

The chapter analyses the impact of using IPSec and TLS/SSL as VPN technologies on the operational costs of the platform. The main conclusions of such analysis are: 1) that TLS/SSL minimizes the operational costs, the difference being especially remarkable in Long-term scenarios; and 2) that using *Aggregation* at the CNTR also allows reducing the operational costs of the platform at neighborhood level considerably.

In addition, it is worthwhile to remark that the overhead – and so the costs - can be lower by implementing compression mechanisms (in the case of TLS/SSL, OpenSSL should be used) and that the volume of data sent through the GPRS network – and so the costs – can be lower if only the data that change compared to the previous period are sent, which can be implemented, e.g., using JSON (JavaScript Object Notation).

The main conclusion of the simulations with regards to the NAN is that IEEE 802.11b meets the requirements in terms of goodput of this network segment in all the considered scenarios. This conclusion is of special interest to the Smart Grid community taking into account the low cost and wide adoption of IEEE 802.11b. However, this still needs to be checked in practice, since the simulations do not take into account the effects of interferences nor complex propagation models.

In addition, in order to avoid potential problems related to the coverage of IEEE 802.11, sub-GHz Wi-Fi (IEEE 802.11AH) [Aust2012] may be also considered in the future for the NAN in rural scenarios, where distances are higher, but data rates are lower. In such rural scenarios, it is also worth considering White Spaces [Brew2011].

Regarding the Backhaul network, it was proved that GPRS meets the requirements in terms of bandwidth of this network segment in all the considered scenarios. Therefore, GPRS represents a very attractive technology considering that it is the most mature and widely deployed cellular technology in Europe.

However, the relevance of the obtained results can be improved by using a more accurate model for the GPRS link or by testing the considered scenarios in a real GPRS network.

Chapter 7

Conclusions

7.1 Introduction

This chapter is structured as follows. Section 7.2 summarizes the main contributions and conclusions of this thesis. Section 7.3 highlights the most outstanding contributions of this thesis to the state of the art and the synergies with R&D (Research and Development) projects, EC (European Commission) initiatives, standardization activities, and industry. Finally, section 7.4 outlines potential research lines that can be undertaken using the work developed in this thesis as baseline.

7.2 Conclusions

Broadly speaking, this thesis represents a remarkable contribution to the area of tailored M2M (Machine-to-Machine) architectures that meet the specific requirements of the power distribution and customer domains of the Smart Grid, supporting energy efficiency and proper integration of DG (Distributed Generation) and EVs (Electric Vehicles) by enabling sophisticated mechanisms such as DR (Demand Response). The specific contributions of this thesis are summarized as follows:

- In chapter 2 we carry out a survey on the most relevant standardization activities developed in parallel to this thesis and on the most outstanding R&D trends within the Smart Grid area, identifying gaps and challenges [Moura2013b].

- In chapter 3 we propose a novel M2M communications architecture to support energy efficiency and optimum coordination of DER (Distributed Energy Resources) within the so-called energy-positive neighborhoods (i.e., neighborhoods which ensure a substantial part of their consumption by local generation) [López2011a], and we map it onto the standardization work presented in chapter 2. The proposed M2M communications architecture aims to meet Smart Grid specific requirements such as scalability, interoperability, or low deployment and operational costs. Reflecting the outstanding importance of wireless communications in the Smart Grid, such M2M communications architecture is fully based on well-known and widely adopted wireless communications technologies, such as IEEE802.15.4/Zigbee, IEEE 802.11, and GPRS (General Packet Radio Service). This network architecture is taken as reference to design M2M communications infrastructures for related applications such as smart EV charging [López2013b].

- In chapter 4 we formally model the domain of knowledge of energy efficiency platforms for energy-positive neighborhoods by means of an ontology developed in OWL (Ontology Web Language). This ontology not only represents the main architectural entities and interfaces of such energy efficiency platforms for energy-positive neighborhoods but also their potential services and stakeholders, and the relationships between them [López2014a]. The developed ontology has been made public through the EC eeBuildings Data Model community (also called eeSemantics) so that the research community can make the most out of it.

- In chapter 5 we characterize the core of the M2M communications architecture presented in chapter 3 in realistic large-scale scenarios. The scenarios modeled in this chapter are customized for the Portuguese power distribution infrastructure and for the EU FP7 project ENERsip [López2012a]. However, they can be adapted to any other electricity distribution infrastructure and energy efficiency platform just by suitably changing the values of the identified parameters. As a matter of fact, the methodology followed in this chapter can be applied to characterize in practice any communications overlay deployed on top of an infrastructure devoted to any purpose and it ensures obtaining results that actually mean and bring value to the interested parties.

- Finally, in chapter 6 we evaluate the core of the M2M communications architecture proposed in chapter 3 taking as reference the model presented in chapter 5. This evaluation is twofold. On the one side, we analyze and compare IPSec (Internet Protocol Security) and TLS/SSL (Transport Layer Security/Secure Socket Layer) from both technical and economic perspectives [El achab2013]. The main outcome of this analysis is that using TLS/SSL as VPN (Virtual Private Network) technology along with data aggregation at the CNTR (Concentrator) is the best option to minimize operational costs at neighborhood level. On the other side, we evaluate by means of simulations the performance of the selected communications technologies using as metrics the goodput (i.e., throughput at the application layer), in the case of IEEE 802.11b, and the transmission time (which is in turn related to bandwidth), in the case of GPRS (General Packet Radio Service). Standing out as main outcome of these simulations is that IEEE 802.11b meets the requirements in terms of goodput of the NAN (Neighborhood Area Networks), which is of special interest to the Smart Grid community taking into account the low cost and wide adoption of this technology, and that GPRS meets the requirements in terms of bandwidth of the backhaul network, thus confirming that it represents a very attractive technology considering that it is the most mature and widely deployed cellular technology in Europe [López2014b].

As a result, this thesis adds value to the emerging Smart Grid universe, notably as regards communications architectures and technologies and common data models. Much R&D activities are still on-going with the aim of determining the most appropriate communications architectures and technologies, involving both simulations and actual deployments. In truth and in fact this will eventually depend on the specific business case behind the target application, which in turn may depend on many factors, such as the special features of the target application itself or the special features and the specific regulation of each country (which varies even among EU countries) [Moura2012].

Beside the underlying communications technologies, application protocols are also crucial to push the Smart Grid forward in the distribution and customer domains. In particular, common data models which can be further developed down to standard application protocols would enable moving beyond current vertical solutions and systems and reaching a level of interoperability that allows heterogeneous devices from different vendors relying on different communications technologies but targeting the same application to interact seamlessly. This would give rise to a more stable and wider market that would foster investments and economies of scale, which in the end imply more reliable products at lower costs.

This brings us to the key piece of the Smart Grid puzzle: the customers. Customer engagement is definitely crucial for the Smart Grid to become a reality at distribution level and this is far away from being just a matter of technology. As it has been made clear throughout this dissertation, customer involvement is mandatory to properly operate the Smart Grid and the Smart Grid brings benefits to customers. However, in this respect the power distribution industry needs to undertake a revolution like the one the telecom industry underwent with cellular communications. Nowadays most of us cannot live without them because they also bring many benefits to our day-to-day. But did not we live without being always connected a couple of decades ago? We did it without problems. Such a need was artificially created in us. In the case of the telecom industry, the telecom operators were responsible for this. In the case of the power distribution industry, who will lead the change that converts the Smart Grid into a mass phenomenon?

7.3 Thesis impact

The main results from the research work presented throughout this dissertation have been disseminated by means of the following publications:

- Top-tier journals:
    - G. López, P. Moura, J. I. Moreno, J. M. Camacho, “Multi-faceted Assessment of a Wireless Communications Infrastructure for the Green Neighborhoods of the Smart Grid”, Energies, MDPI. (Submitted for publication). Impact Factor: 1.844. JCR (38/81), category: Energy & Fuels.
    - G. López, J. I. Moreno, H. Amaris, F. Salazar, “PRICE-GEN: Paving the Road towards Smart Grid through Large-Scale Advanced Metering Infrastructures”, Electric Power Systems Research, Elsevier. (Submitted for publication). Impact Factor: 1.679. JCR (70/243), category: Engineering, Electrical & Electronic.
    - G. López, V. Custodio, J. I. Moreno, M. Sikora, P. Moura, N. Fernández, “Modeling Smart Grid Neighborhoods with the ENERsip Ontology”, Computers in Industry, Elsevier. (Submitted for publication). Impact Factor: 1.709. JCR (34/100), category: Computer Science, Interdisciplinary Applications.

   - G. López, V. Custodio, F. J. Herrera, J. I. Moreno, "Machine-to-Machine Communications Infrastructure for Smart Electric Vehicle Charging in Private Parking Lots", International Journal of Communication System, Wiley, November 2013. DOI: 10.1002/dac.2705. Impact Factor: 0.712. JCR (48/78), category: Telecommunications.

   - P. Moura, G. López, J. I. Moreno, A. de Almeida, "The role of Smart Grids to foster energy efficiency", Energy Efficiency, Volume 6, Issue 4, Pages 621-639, November 2013. Impact Factor: 1.150. JCR (47/81), category: Energy & Fuels.

- Top-tier conferences:

   - G. López, P. Moura, V. Custodio, J. I. Moreno, "Modeling the Neighborhood Area Networks of the Smart Grid", IEEE ICC 2012, Ottawa, Canada, June 2012. Microsoft Academic Search (5/247), category: Networks & Communications.

   - G. López, P. Moura, J. I. Moreno, A. de Almeida, "ENERsip: M2M-based platform to enable energy efficiency within energy-positive neighborhoods", IEEE INFOCOM 2011 Workshop on M2M Communications and Networking, Shanghai, China, April 2011. Microsoft Academic Search (1/247), category: Networks & Communications.

- Conferences in the area of Smart Grids or M2M communications:

   - E. El achab, G. López. J. I. Moreno, "Evaluación de mecanismos de seguridad en entornos de Smart Grid", JITEL 2013: XI Jornadas de Ingeniería Telemática, Granada, Spain, October 2013.

   - P. Moura, G. López, J. I. Moreno, A. de Almeida, "Impact of Residential Demand Response on the Integration of Intermittent Renewable Generation into the Smart Grid", EEDAL2013: 7th International Conference on Energy Efficiency in Domestic Appliances and Lighting, Coimbra, Portugal, September 2013.

   - G. López, J. Moreno, P. Moura, A. de Almeida, M. Perez, L. Blanco, "Monitoring System for the Local Distributed Generation Infrastructures of the Smart Grid", CIRED 2013: 22nd European Conference and Exhibition on Electricity Distribution, Stockholm, Sweden, June 2013.

   - P. Moura, G. López, A. Carreiro, J. I. Moreno, A. de Almeida, "Evaluation Methodologies and Regulatory Issues in Smart Grid Projects with Local Generation-Consumption Matching", EEMSW2012: International Workshop on Energy Efficiency for a More Sustainable World, São Miguel, Portugal, September 2012.

   - A. Carreiro, G. López, P. Moura, J. I. Moreno, A. de Almeida, J. Malaquias, "In-house monitoring and control network for the Smart Grid of the future", ISGT Europe 2011: 2nd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies, Manchester, UK, December 2011.

   - G. López, P. Moura, M. Sikora, J. I. Moreno, "Comprehensive validation of an ICT platform to support energy efficiency in future smart grid scenarios", SMFG2011:IEEE International Conference on Smart Measurements for Future Grids, Bologna, Italy, November 2011.

Additionally, the research conducted throughout this thesis takes as baseline previous research on the application of M2M communications and WSNs (Wireless Sensor Networks) to e-health. Such previous work was published in the following top-tier journals and conferences:

- V. Custodio, F. J. Herrera, G. López, J. I. Moreno, “A Review on Architectures and Communications Technologies for Wearable Health-Monitoring Systems” Sensors, Pages 13907-13946, October 2012. Impact Factor: 1.953. JCR (8/57), category: Instruments & Instrumentation

- G. López, V. Custodio, J. I. Moreno, “LOBIN: E-Textile and Wireless-Sensor-Network-Based Platform for Healthcare Monitoring in Future Hospital Environments”, IEEE Transactions on Information Technology in Biomedicine, Volume 14, Issue 6, Pages 1446-1458, November 2010. Impact Factor: 1.978. JCR (21/132), category: Computer Science, Information Systems.

- G. López, V. Custodio, J. I. Moreno, “Location-Aware System for Wearable Physiological Monitoring Within Hospital Facilities”, IEEE PIMRC 2010: 21st Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Istanbul, September 2010. Microsoft Academic Search (18/247), category: Networks & Communications.

This thesis has been carried out under the scope and influence of the R&D projects summarized in Table 7-1.

Table 7-1 - R&D projects related to this thesis

Name	Funding scheme	Topic	Duration	Consortium
PRICE-GEN	INNPACTO (IPT-2011-1507-920000)	AMI	2011-2014	Iberdrola, Unión Fenosa Distribución, ZIV, Arteche, Current, CIRCE, UC3M
ENERsip	FP7 (Grant agreement n° 247624)	EE DG	2010-2012	Tecnalia, Israel Electric Corp., Motorola Solutions Israel Ltd., Honeywell Prague Laboratory, AMPLIA, Intelligent Sensing Anywhere, ISASTUR, VITO, ISR-UC, UC3M
DOMOCELL	AVANZA2 (TSI-020100-2009-849)	EV	2009-2011	Unión Fenosa Distribución, Red Eléctrica Española, Amplía, Nlaza, Neoris, CITEAN, UPV, UC3M

EE: Energy Efficiency

During the development of the thesis, I have also carried out two internships at ISR-UC (Institute of System and Robotics – University of Coimbra), in particular at the "Intelligent Energy Systems " research group led by Dr. Aníbal de Almeida, working close together with Dr. Pedro Moura. As a result of such internships, our expertise on ICT has been complemented with their expertise on energy and the link between the Telematics Engineering Department of the UC3M and the ISR-UC has been strengthened. In addition, the research conducted during these internships has led to the publication of several papers and the internships themselves allow this thesis to be awarded with the International Doctorate certification.

Finally, the main synergies between this thesis and EC initiatives, standardization activities and industry, are summarized next:

- Participation in EC initiatives. As it has already been mentioned in section 7.2, the ontology developed under the scope of this thesis has been inputted to the eeBuildings Data Model community (also called as, eeSemantics). As a first impact of this, our ontology was proposed with other related works as starting point for the study on “Available semantics assets for the interoperability of SMART APPLIANCES. Mapping into a common ontology as a M2M application layer semantics”, launched as invitation to tender by the EC in June 2013 [EC2013].

- Participation in standardization activities. Part of the research work carried out under the scope of this thesis has been presented in the following workshops organized by ETSI:

  - G. López, J. I. Moreno, "PRICE Project: M2M communications architecture for large-scale AMI deployment", 4th ETSI M2M Workshop, Mandelieu-la-Napoule, France, November 2013.

  - G. López, J. I. Moreno, "Smart Energy-positive Neighbourhoods for the Smart Grid. Architecture, Communications Technologies and Address Management for the ENERsip platform", 2011 ETSI Workshop on "Standards: An Architecture for the Smart Grid", Sophia Antipolis, France, April 2011.

  In addition, the knowledge acquired during this thesis has enabled me to be promoted as representative of the COIT (Spanish Official Professional Association of Telecommunications) in AENOR (Spanish Association for Standardization and Certification), participating on a regular basis in the AEN/CTN 207/SC 13 "*Aparatos de medida de la energía eléctrica y del control de cargas*". As a remarkable impact of my participation in AENOR as representative of the COIT so far, we have recently inputted our proposal of priority ranking for the new standardization gaps identified in the second phase of the standardization mandate M/490, which will be addressed by the SG-CG (Smart Grid – Coordination Group) during 2014.

- Knowledge transferred to industry. The I-BECI (In-Building Energy Consumption Infrastructure) presented in chapter 3 of this dissertation, which was designed jointly with ISA (Intelligent Sensing Anywhere) [Carrerio2011], has been further developed by this company, becoming a commercial product which is already available in the market [Cloogy2014].

7.4 Future work

Next, we outline some future research lines that result from this thesis:

- In this thesis, the evaluation of the performance of the proposed M2M communications architecture is focused on the uplink, since the importance of the uplink is higher in the short term and the uplink traffic pattern is well-known and may be so high as to challenge the communications infrastructure itself. Therefore, this work can be further developed by including the downlink, putting special emphasis on evaluating the impact of DR events on the performance of the M2M communications infrastructure.

- This thesis is especially focused on wireless communications technologies, reflecting their outstanding importance within the Smart Grid area. Notably, IEEE 802.11 and GPRS are considered and evaluated, since they represent two of the most widely adopted wireless communications technologies nowadays. As result, this work can be extended by evaluating other communications technologies (e.g., PRIME, UMTS, LTE or WiMAX) either for the application considered in this thesis or for any other Smart Grid application (by suitably tuning the parameters identified in the practical model developed as part of this thesis).

- Taking the network simulation framework used in this thesis (i.e., OMNeT++) as reference, it can be investigated how it could be coupled with other power network simulator (e.g., PSLF) to enable co-simulations (i.e., simulate power networks and their associated communications overlay at the same time), which definitely represents a very hot topic within the Smart Grid area currently and in the forthcoming years.

Table of Acronyms

AC	Air Conditioning
AC	Alternating Current
ADDRESS	Active Distribution network with full integration of Demand and distributed energy RESourceS
ADL	Architecture Description Language
ADR	Automated Demand Response
ADR EP	Automated Demand Response End Point
ADR EP-C	Automated Demand Response End Point – Consumption
ADR EP-G	Automatic Demand Response End Point – Generation
AENOR	Spanish Association for Standardization and Certification
Aggr	Aggregator
AHAM	Association of Home Appliance Manufactures
AIM	A novel architecture for modelling, virtualizing and managing the energy consumption of household appliances
AMI	Advanced Metering Infrastructure
AMR	Automated Meter Reading
ANSI	American National Standard Institute
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BEMS	Building Energy Management System
BEyWatch	Building Energy Watcher
BIPV	Building-integrated Photovoltaics
BO	Back-Office
BP	Building Prosumer
BPL	Broadband Power Line Communications
CDMA	Code Division Multiple Access
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CNTR	Concentrator
COIT	Spanish Official Professional Association of Telecommunications
COSEM	Companion Specification for Energy Metering
CSWG	Cyber Security Working Group
CT-IAP	Communications Technologies – Interoperability Architectural Perspective
DC	Direct Current
DER	Distributed Energy Resource
DEWG	Domain Expert Working Group
DG	Distributed Generation
DEHEMS	Digital environment home energy management system
DL	Description Logic

DLMS	Device Language Message Specification
DNP	Distributed Network Protocol
DOCSIS	Data Over Cable Service Interface Specification
DR	Demand Response
DSL	Digital Subscriber Line
DSM	Demand-Side Management
DSO	Distribution System Operation
DSOr	Distribution System Operator
DSP	Digital Signal Processing
EAP	Extensible Authentication Protocol
EC	European Commission
ECC	Electronic Communications Committee
EIRP	Effective Isotropic Radiated Power
EISA	Energy Independence and Security Act of 2007
EMC	Electromagnetic Compatibility
EMS	Energy Management System
EMV&R	Energy Monitoring Visualization and Reporting
ENCOURAGE	Embedded iNtelligent COntrols for bUildings with Renewable generAtion and storaGE
Energy Warden	Renewable Energy Sourcing Decisions and Control in Buildings
ENERsip	ENERgy Saving Information Platform for Generation and Consumption Networks
EPIA	European Photovoltaic Industry Association
EPRI	Electric Power Research Institute
ESCO	Energy Service Company
ESO	European Standardization Organization
ESS	Energy Storage System
ETSI	European Telecommunications Standards Institute
EU	European Union
EupP	Energy using and producing Products
EV	Electric Vehicle
E2E	End-to-end
FIEMSER	Friendly Intelligent Energy Management System for Existing Residential Buildings
FP7	Seventh Framework Programme
FTP	File Transfer Protocol
FTTH	Fiber To The Home
GAD	Active Demand Side Management Project
GHG	Greenhouse Gas
GPRS	General Packet Radio Service
GW	Gateway
HAN	Home Area Network
HEMS	Home Energy Management System
HESMOS	ICT Platform for Holistic Energy Efficiency Simulation and Lifecycle Management Of Public Use FacilitieS
HVAC	Heating Ventilation and Air Conditioning
I-BECI	In-Building Energy Consumption Infrastructure
I-BEGI	In-Building Energy Generation Infrastructure
ICT	Information and Communications Technologies
ID	Identifier
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IEEE	Institute of Electrical and Electronics Engineering
IFC	Industry Foundation Classes
IMSI	International Mobile Subscriber Identity
INTEGRIS	INTelligent Electrical Grid Sensor communications
IntUBE	Intelligent use of buildings' energy information
IP	Internet Protocol
IPSec	Internet Protocol Security

IR	Infrared
IREEN	ICT Roadmap for Energy Efficient Neighborhoods
ISO	International Organization for Standardization
IT-IAP	Information Technology – Interoperability Architectural Perspective
ITU-T	International Telecommunication Union - Telecommunication Standardization Sector
IV	Initialization Vector
JSON	JavaScript Object Notation
LDV	Light Duty Vehicle
LEP	Local Energy Producer
LM	Load Management
LTE	Long Term Evolution
LV	Low Voltage
L2TP	Layer 2 Tunneling Protocol
MAC	Medium Access Control
MDMS	Metering Data Management System
MEM	Microgrid Energy Management
MIRABEL	Micro-Request-Based Aggregation, Forecasting and Scheduling of Energy Demand, Supply and Distribution
MSISDN	Mobile Station Integrated Services Digital Network
MSS	Maximum Segment Size
MTU	Maximum Transfer Unit
MV	Medium Voltage
MVO	Mobile Virtual Operator
M2M	Machine-to-Machine
NAN	Neighborhood Area Network
NAT	Network Address Translation
NB-PLC	Narrow Band - Power Line Communications
ND	National Dispatcher
NH	Next Hop
NILM	Non-Intrusive Load Monitoring
NIALM	Non-Intrusive Appliance Load Monitoring
NIST	National Institute of Standards and Technologies
NZEB	Nearly Zero-Energy Buildings
OS	Operating System
OSGP	Open Smart Grid Protocol
OSI	Open Systems Interconnection
OSS	Operation Support System
OWL	Ontology Web Language
PAP	Priority Action Plan
PEBBLE	Positive-energy buildings thru better control decisions
PHEV	Plug-in Hybrid Electric Vehicle
PHY	PHYsical
PKI	Public Key Infrastructure
PLC	Power Line Communications
PRICE	Joint Project of Intelligent Networks in the Henares Corridor
PRIME	PoweRline Intelligent Metering Evolution
PS-BI	Power Saving – Business Intelligence
PS-IAP	Power Systems – Interoperability Architectural Perspective
PSK	Pre-Shared Key
PSTN	Public Switched Telephone Network
QoS	Quality of Service
RAM	Random Access Memory
RAN	Radio Access Network
RA&CA	Remote Access and Control of Appliances
RC	Residential Consumer
RCB	Residential Commercial Building
RC4	Rivest Cipher 4
RDF	Resource Description Framework

REMODECE	Residential Monitoring to Decrease Energy Use and Carbon Emissions in Europe
REViSITE	Roadmap Enabling Vision and Strategy for ICT-enabled Energy Efficiency
ROI	Return On Investment
RP	Residential Prosumer
RTU	Remote Terminal Unit
R&D	Research and Development
SAN	Sensor and Actuator Network
SDH	Synchronous Digital Hierarchy
SEEMPubS	Smart Energy Efficient Middleware for Public Spaces
SEP	Smart Energy Profile
SGAC	Smart Grid Architecture Committee
SGAM	Smart Grid Architecture Model
SGIP	Smart Grid Interoperability Panel
SGIRM	Smart Grid Interoperability Reference Model
SGTCC	Smart Grid Testing and Certification Committee
SIM	Subscriber Identity Module
SmartCoDe	Smart Control of Demand for Consumption and Supply to enable balanced, energy-positive buildings and neighbourhoods
SNCDP	Sub Network Dependent Convergence Protocol
SOHO	Small Office Home Office
SONET	Synchronous Optical Networking
SSH	Secure Shell
SSL	Secure Socket Layer
TC	Technical Committee
TCP	Transmission Control Protocol
TKIP	Temporal Key Integrity Protocol
TLS	Transport Layer Security
ToU	Time of Use
TP	Transformation Point
TSO	Transmission System Operator
T&D	Transmission & Distribution
UAP	User Application Platform
UDP	User Datagram Protocol
UII	User Intuitive Interface
UK	United Kingdom
UML	Unified Modeling Language
UMTS	Universal Mobile Telecommunications System
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USNAP	Universal Smart Network Access Port
V2G	Vehicle-to-Grid
VPN	Virtual Private Network
VPP	Virtual Power Plan
WEP	Wired Equivalent Privacy
WG	Working Group
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WPA	Wi-Fi Protected Access
WPA2	Wi-Fi Protected Access 2
WS	Weather Station
WSAN	Wireless Sensor and Actuator Network
WSN	Wireless Sensor Network
ZEB	Zero Energy Building
3GPP	3rd Generation Partnership Project
6LoWPAN	IPv6 over Low Power Wireless Personal Area Network

Table of Symbols

A_C	Number of ADR EP-C (Consumption) per CNTR
A_G	Number of ADR EP-G (Generation) per CNTR
Aggr	Aggregation
B	Byte
C	Number of CNTRs per M2M GW
C_{NS}	Cost of carrying V_{NS} through the GPRS network (in €)
C_S	Cost of carrying V_S through the GPRS network (in €)
$C_S\|_{Aggr}$	Cost of carrying V_S through the GPRS network (in €) using *Aggregation*
$C_S\|_{FF}$	Cost of carrying V_S through the GPRS network (in €) using *Fast Forwarding*
$C_S\|_{IPsec}$	Cost of carrying V_S through the GPRS network (in €) using IPSec
$C_S\|_{TLS/SSL}$	Cost of carrying V_S through the GPRS network (in €) using TLS/SSL
Cust/TP	Number of Customers per TP
D_C	Cost of using the corresponding security solution
D_{max}	Maximum acceptable distance between Customers and TPs
d_{min}	Minimum density of Customers per TP
FF	Fast Forwarding
(I-BECI|I-BEGI)/Cust	Penetration of micro-generation
Kb	Kilobits per second
LT	Long-term scenario
Mb	Megabits per second
MB	MegaByte
O_S	Overhead introduced by the security protocol (in %)
Plugs/I-BECI	Number of appliances per I-BECI
R	Rural scenario
R_{NS}	Ratio between the application-layer data and V_{NS} (in %)
R_S	Ratio between the application-layer data and V_S (in %)
S_C	Size of the consumption data at the application layer
$S_C\|_{LT}$	Size of the consumption data at the application layer in long-term scenarios
$S_C\|_{ST}$	Size of the consumption data at the application layer in short-term scenarios
S_G	Size of the generation data at the application layer
$S_G\|_{LT}$	Size of the generation data at the application layer in long-term scenarios
$S_G\|_{ST}$	Size of the generation data at the application layer in short-term scenarios
S_{IS}	Size of the application messages sent either by the users or automatically generated by the PS-BI module
ST	Short-term scenario
T	Periodicity which ADR EPs send data with
T_{CNTR}	Time that the CNTR spends to transfer the data to the M2M GW
TP/Sub	Number of TPs/Substation
U	Urban scenario

V_{NS}	Volume of traffic (in MB) carried by the GPRS network in one month without using any security protocol
V_S	Volume of traffic (in MB) carried by the GPRS network in one month with using the corresponding security protocol
μ	Mean
μ_{IS}	Average periodicity of sending requests either by the users or automatically generated by the PS-BI module
σ	Standard deviation

References

[Abdul Salam2012] S. Abdul Salam, S. Mahmud, G. Khan, H. Al-Raweshidy, "M2M communication in Smart Grids: Implementation scenarios and performance analysis", IEEE Wireless Communications and Networking Conference Workshops, Paris, France, 2012

[Adapt4EE2014] Adapt4EE project Official Web Site: http://www.adapt4ee.eu/adapt4ee/ [Accessed 2014/1/5]

[AHAM2012] "Smart Grid White Paper: The Home Appliance Industry's Principles & Requirements for Achieving a Widely Accepted Smart Grid", AHAM, 2009

[Aidine2013] A. Aidine, A. Tabone, J. Muller, "Deployment of Power Line Communication by European Utilities in Advanced Metering Infrastructure", IEEE ISPLC 2013, Johannesburg, South Africa, 2013

[AIM2010] AIM project Official Web Site: http://www.ict-aim.eu/ [Accessed 2014/1/5]

[Ancillotti2013] E. Ancillotti, R. Bruno, M. Conti, "The role of communication systems in smart grids: Architectures, technical solutions and research challenges", Computer Communications, Vol. 36, Issues 17-18, pp. 1665-1697, 2013

[Anderson2012a] D. Anderson, Z. Chuanlin, C. Hauser, V. Venkatasubramanian, D. Bakken, A. Bose, "Real-Time Simulation for Smart Grid Control and Communications Design", IEEE Power&Energy Magazine, 10 (1), pp. 49-57, Jan. 2012

[Anderson2012b] K. Anderson, S. Lee, C. Menassa, "Effect of social network type on building occupant energy use", BuildSys 2012: Fourth ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings, Pages 17-24, 2012

[Anjum2012] N. A. Anjum, J. A. Harding, R. I. Young, K. Case, "Mediation of foundation ontology based knowledge sources", Computers in Industry, Volume 63, Pages 433-442, 2012

[Apostolov2013] A. Apostolov, "Integration of Distributed Energy Resources in Smart Grids", CIRED 2013: 22nd European Conference and Exhibition on Electricity Distribution, Stockholm, Sweden, June 2013

[Aravinthan2011] V. Aravinthan, B. Karimi, V. Namboodiri, W. Jewell, "Wireless Communication for Smart Grid Applications at Distribution Level – Feasibility and Requirements", IEEE PES GM: Power and Energy Society General Meeting, Detroit, MI USA, July 2011

[Aschenbruck2004] N. Aschenbruck, M. Frank, W. Hansmann, P. Martini, C. Scholz, J. Tölle, "Integration of 3G Protocols into the Linux Kernel to Enable the Use of Generic Bearers", High Speed Networks and Multimedia Communications, Pages 533-544. Springer Berlin Heidelberg, 2004

[Aust2012] S. Aust, R. Prasad, I. Niemegeers, "IEEE 802.11ah: Advantages in standards and further challenges for sub 1 GHz Wi-Fi", IEEE International Conference on Communications, Ottawa, Canada, 2012, Pages 6885-6889

[Ayhana2012] D. Ayhana, S. Sağlam, "A technical review of building-mounted wind power systems and a sample simulation model", Renewable and Sustainable Energy Reviews, Volume 16, Issue 1, Pages 1040–1049, 2012

[Bartak2013] G. F. Bartak, A. Abart, "EMI of emissions in the frequency range 2 kHz - 150 kHz", CIRED 2013: 22nd European Conference and Exhibition on Electricity Distribution, Stockholm, Sweden, June 2013

[Belhomme2008] R. Belhomme, R. Cerero, G. Valtorta, A. Paice, F. Bouffard, R. Rooth, "ADDRESS – Active Demand for the Smart Grid of the Future", CIRED seminar 2008: Smart Grids for Distribution, Frankfurt, Germany, June 2008

[Benko2004] P. Benko, G. Malicsko, A. Veres, "A Large-scale, Passive Analysis of End-to-End TCP Performance over GPRS", IEEE INFOCOM 2004, Hong-Kong, 2004

[Berger2006] T. Berger, "Analysis of current VPN technologies", IEEE ARES 2006: 1st International Conference on Availability, Reliability and Security, 2006

[BEyWatch2011] BEYWatch project summary: http://www.innovationseeds.eu/Virtual_Library/Results/BEYWATCH.kl#.Us8-ubS0aQY [Accessed 2014/1/5]

[Brew2011] Brew M., Darbari F., Crockett L.H., Waddell M.B., Fitch M., Weiss S., Stewart R.W., "UHF White Space Network for Rural Smart Grid Communications", IEEE SmartGridComm: International Conference on Smart Grid Communications, October 2011

[Caldevilla2013] A. Caldevilla, "EU FP7 project PowerUp and Beyond", 4th ETSI M2M Workshop, Mandelieu-la-Napoule, France, November 2013

[Carreiro2011] A. Carreiro, G. López, P. Moura, J. I. Moreno, A. de Almeida, J. Malaquias, "In-house monitoring and control network for the Smart Grid of the future", ISGT Europe 2011: 2nd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies, Manchester, UK, December 2011

[Carvallo2011] A. Carvallo, J. Cooper, "The Advanced Smart Grid Edge Power Driving Sustainability", Artech House, 2011. ISBN-13: 978-1608071272

[Celli2013] G. Celli, E. Ghiani, F. Pilo, G. G. Soma, "Reliability assessment in smart distribution networks", Electric Power Systems Research, Vol. 104, pp. 164-175, 2013

[Chorus2014] Chorus Official Web Site: http://store.greenenergyoptions.co.uk/dp/B00CFNAXVG [Accessed 2014/1/5]

[Claudy2011] M. C. Claudy, C. Michelsen, A. O'Driscoll, "The diffusion of microgeneration technologies – assessing the influence of perceived product characteristics on home owners' willingness to pay", Energy Policy, Volume 39, Issue 3, Pages 1459-1469, March 2011

[Clement2011] K. Clement-Nyns, E. Haesen, J. Driesen, "The impact of vehicle-to-grid on the distribution grid", Electric Power Systems Research, Volume 81, Issue 1, Pages 185-192, 2011

[Cloogy2014] Cloogy Official Web Site: http://www.cloogy.com/en/ [Accessed 2014/1/5]

[De Craemer2010] K. De Craemer, G. Deconinck, "Analysis of State-of-the-art Smart Metering Communications Standards", Proceedings of the 5th Young Researchers Symposium, 2010

[DEHEMS2011] DEHEMS project Official Web Site: http://www.dehems.eu/ [Accessed 2014/5/1]

[Della Giustina2011] D. Della Giustina, S. Zanini, S. Pugliese, L. Cremaschini, "The role of INTEGRIS in the A2A Reti Elettriche's roadmap toward the smart grid ", SMFG2011:IEEE International Conference on Smart Measurements for Future Grids, Bologna, Italy, November 2011

[Depuru2011] S. S. S. R. Depuru, L. Wang, V. Devabhaktuni, "Smart meters for power grid: Challenges, issues, advantages and status", Renewable and Sustainable Energy Review, Volume 15, Issue 6, Pages 2736-2742

[Drake2010] J. Drake, D. Najewicz, W. Watts, "Energy Efficiency Comparisons of Wireless Communication Technology Options for Smart Grid Enabled Devices", General Electric, December 2010

[EC2009] Standardization mandate M/441, "Standardisation mandate to CEN, CENELEC and ETSI in the field of measuring instruments for the development of an open architecture for utility meters involving communications protocols enabling interoperability", EC, March 2009. On-line: http://www.etsi.org/images/files/ECMandates/m441%20EN.pdf [Accessed 2014/1/5]

[EC2010] Standardization mandate M/468, "Standardisation mandate to CEN, CENELEC and ETSI concerning the charging of electric vehicle, EC, June 2010. On-line: http://ec.europa.eu/energy/gas_electricity/smartgrids/doc/2010_06_04_mandate_m468_en.pdf [Accessed 2014/1/5]

[EC2011a] "Energy Roadmap 2050", Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, 2011

[EC2011b] Standardization mandate M/490, "Standardization Mandate to European Standardisation Organisations (ESOs) to support European Smart Grid deployment", EC, March 2011. On-line: http://ec.europa.eu/energy/gas_electricity/smartgrids/doc/2011_03_01_mandate_m490_en.pdf [Accessed 2014/1/5]

[EC2013] "Study on the available semantics assets for the interoperability of Smart Appliances. Mapping into a common ontology as a M2M application layer semantics" EC Tender Specifications, SMART 2013/0077. On-line: http://ec.europa.eu/digital-agenda/en/news/invitation-tender-study-available-semantics-assets-interoperability-smart-appliances-mapping [Accessed 2014/1/5]

[ECC2010] "Numbering and Addressing in M2M Communications", Draft ECC Report 153, Vilnius, June 2010

[EEI2011] "Smart Meters and Smart Meter Systems: A Metering Industry Perspective"; An EEI-AEIC-UTC White Paper Smart Grid white paper; March 2011

[Efergy2014] Efergy Official Web Site: http://efergy.com/eu/ [Accessed 2014/1/5]

[Ekanayake2012] Ekanayake J., Liyanage K., Wu J., Yokoyama A., Jenkins N., "Smart Grid: Technology and Applications", IEEE Press, 2012. ISBN-13: 978-0470974094

[El achab2013] E. El achab, G. López. J. I. Moreno, "Evaluación de mecanismos de seguridad en entornos de Smart Grid", JITEL 2013: XI Jornadas de Ingeniería Telemática, Granada, Spain, October 2013

[EM2014] GreenWave Reality Energy Management solution Official Web Site: http://www.greenwavereality.com/solutions/energymgmt/ [Accessed 2014/1/5]

[eMonitor2014] eMonitor Official Website: http://www.powerhousedynamics.com/residential-energy-efficiency/ [Accessed 2014/1/5]

[ENCOURAGE2014] ENCOURAGE Project Official Web Site: http://www.encourage-project.eu/ [Accessed 2014/1/5]

[Engage2014] Engage Official Website: http://engage.efergy.com/ [Accessed 2014/1/5]

[Enlighten2014] Enlighten Official Website: http://enphase.com/enlighten/ [Accessed 2014/1/5]

[EnOcean2014] EnOcean Official Website: http://www.enocean.com/en/home/ [Accessed 2014/1/5]

[EPIA2012] "Connecting the Sun: Solar Photovoltaics on the road to large-scale grid integration", European Photovoltaic Industry Association, September 2012

[EPIA2013] "Global Market Outlook for Photovoltaics 2013-2017", European Photovoltaic Industry Association, September 2012, May 2013

[EPRI2011] "Estimating the Costs and Benefits of the Smart Grid – A Preliminary Estimate of the Investment Requirements for a Fully Functioning Smart Grid", Electric Power Research Institute, 2011

[ESMA2012] ESMA, "What is Smart Metering?", European Smart Metering Alliance, 2012

[ETSI2012] "Machine-to-Machine communications (M2M); Applicability of M2M architecture to Smart Grid Networks; Impact of Smart Grids on M2M platform", ETSI Technical Report 102 935, September 2012.

[EUCR2008] "20 20 by 2020: Europe's climate change opportunity", EU Communication Report, 2008

[EURELECTRIC2011] "10 Steps to Smart Grids", Union of the Electricity Industry – EURELECTRIC, 2011

[Eurostat2013] Eurostat Energy Statistics: http://epp.eurostat.ec.europa.eu/portal/page/portal/energy [Accessed 2013/11/12]

[EW2012] Energy Warden project Official Web Site: http://buildingwarden.com/energywrdn/ [Accessed 2014/1/5]

[De Almeida2011] A. De Almeida, P. Fonseca, B. Schlomann, N. Feilberg, "Characterization of the Household Electricity Consumption in the EU, Potential Energy Savings and Specific Policy Recommendations", Energy and Buildings, Volume 43, Issue 8, Pages 1884–1894, August 2011

[Fadlullah2011] Z. Fadlullah, M. Fouda, N. Kato, A. Takeuchi, N. Iwasaki, Y. Nozaki, "Towards Intelligent Machine-to-Machine Communications in Smart Grid", IEEE Communications Magazine, Volume 49, Issue 4, Pages 60-65, April 2011

[Farhangi2010] H. Farhangi, "The Path of the Smart Grid", IEEE Power and Energy Magazine, Volume 8, Issue 1, Pages 18 – 28, January-February 2010. ISSN: 1540-7977

[Faria2012] R. Faria, P. Moura, J. Delgado, A. de Almeida, "A sustainability assessment of electric vehicles as a personal mobility system", Energy Conversion and Management, Volume 61, Issue 1, Pages 19 – 30, 2012. ISSN: 0196-8904

[FIEMSER2013] FIEMSER project summary: http://www.ice-wish.eu/uk/ec-cofunded-projects-related-to-ict-and-building/fiemser.asp [2014/1/5]

[Firth2008] S. Firth, K. Lomas, A. Wright, R. Wall, "Identifying trends in the use of domestic appliances from household electricity consumption measurements", Energy and Buildings, Volume 40, Issue 5, Pages 926–936, 2008

[GAD2010] GAD project Official Web Site: http://gad.ite.es/index_en.html [Accessed 2014/1/5]

[Gellings2009] C. Gellings, "The Smart Grid: enabling energy efficiency and demand response", CRC, New York, 2009. ISBN-13: 978-1439815748

[Gislason2008] D. Gislason, "Zigbee Technical Overview", Wireless Japan, Tokyo, Japan, 2008

[Goebel2013] C. Goebel, D. Callaway, "Using ICT-controlled plugin electric vehicles to supply grid regulation in California at different renewable integration levels", IEEE Transactions on Smart Grid, Volume 4, Issue 2, Pages 729-740, June 2013. ISSN: 1949-3053

[Gómez2007] A. Gómez-Pérez, M. Fernández-López, O. Corcho, "Ontological Engineering: With Examples from the Areas of Knowledge Management, E-Commerce and the Semantic Web", Advanced Information and Knowledge Processing, Springer-Verlag, 2007. ISBN 978-1-85233-551-9

[Grassi2011] M. Grassi, M. Nucci, F. Piazza, "Towards an ontology framework for intelligent smart home management and energy saving", IEEE International Symposium on Industrial Electronics, Pages 1753–1758, 2011

[GBD2014] Green Button Data Official Website: http://www.greenbuttondata.org/ [Accessed 2014/1/5]

[Greenvity2014] Greenvity Official Website: http://www.greenvity.com/products-gv7011.htm [Accessed 2014/1/5]

[Güngör2011] V. C. Güngör, D. Sahin, T. Kocak, S. Ergüt, C. Buccella, C. Cecati, G. P. Hancke, "Smart Grid Technologies: Communication Technologies and Standards", IEEE Transactions on Industrial Informatics, Volume 7, Issue 4, Pages 529-539, November 2011

[Güngör2013] V. C. Güngör, D. Sahin, T. Kocak, S. Ergüt, C. Buccella, C. Cecati, G. P. Hancke, "A Survey on Smart Grid Potential Applications and Communication Requirements", IEEE Transactions on Industrial Informatics, Volume 9, Issue 1, Pages 28-42, February 2013

[Gyrard2013] A. Gyrard, C. Bonnet, K. Boudaoud, "A Machine-to-Machine Architecture to Merge Semantic Sensor Measurements", WWW2013, Rio de Janeiro, Brazil, 2013.

[Hernández2013] L. Hernández, C. Baladron, J. M. Aguiar, B. Carro, A. Sánchez-Esguevillas, J. Lloret, D. Chinarro, J. J. Gómez-Sanz, D. Cook, "A Multi-Agent System Architecture for Smart Grid Management and Forecasting of Energy Demand in Virtual Power Plants", IEEE Communications Magazine, Volume 51, Issue 1, Pages 106-113, January 2013. ISSN: 0163-6804

[HESMOS2013] HESMOS project Official Website: http://hesmos.eu/ [2014/1/5]

[Hiertz2010] G. R. Hiertz, D. Denteneer, L. Stibor, Y. Zang, X. Pérez-Costa, B. Walke, "The 802.11 Universe", IEEE Communications Magazine, Volume 48, Issue 1, January 2010

[Hk2014] electronic Housekeeper Official Web site: http://www.electronichousekeeper.com/ [Accessed 2014/1/5]

[IBM2011] "The Value of Smarter Energy: Orchestrating the Network End-to-End", IBM Center for Applied Insights

[IEA2011] "Technology Roadmaps: Smart Grids", International Energy Agency, 2011

[IEA2013] "Transition to Sustainable Buildings: Strategies and Opportunities to 2050", International Energy Agency, 2013

[IEC2014] IEC Smart Grid Standards Mapping Tool Official Web Site: http://smartgridstandardsmap.com/ [Accessed 2014/1/5]

[IEEE2006] "Wireless Medium Access Control and Physical Layer Specifications for Low-Rate Wireless Personal Area Networks," IEEE Std 802.15.4-2006

[IEEE2011] "Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), and the End-Use Applications and Loads", IEEE standard 2030, September 2011

[IEEE2014] Approved & Proposed IEEE Smart Grid standards: http://smartgrid.ieee.org/standards/ieee-approved-proposed-standards-related-to-smart-grid [Accessed 2014/1/5]

[IETF2007] G. Montenegro, K. Kushalnagar, J. Hui, D. Culler, "Transmissions of IPv6 packets over IEEE 802.15.4 Networks", RFC 4944, September 2007. Online: http://www.rfc-editor.org/rfc/rfc4944.txt [Accessed 2014/1/10]

[Insteon2014] Insteon Official Website: http://www.insteon.com/ [Accessed 2014/1/5]

[IntUBE2011] INTUBE project summary: http://cordis.europa.eu/projects/rcn/86722_en.html [Accessed 2014/1/5]

[IREEN2013] IREEN project Official Web Site: http://www.ireenproject.eu/ [Accessed 2014/1/5]

[ISO2011] ISO/IEC/IEEE 42010 Official Website: http://www.iso-architecture.org/42010/ [Accessed 2013/11/10]

[ISO2013] ISO/PRC 16739. Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries. On-line: http://www.iso.org/iso/home/store/catalogue_ics/catalogue_detail_ics.htm?csnumber=51622 [Accessed 2013/11/18]

[ITU2012a] ITU-T standard G.9903, "Narrowband orthogonal frequency division multiplexing power line communication transceivers for G3-PLC networks", 2012

[ITU2012b] ITU-T standard G.9904, "Narrowband orthogonal frequency division multiplexing power line communication transceivers for PRIME networks", 2012

[Jellea2012] B. Jellea, C. Breivikb, H. Røkenes, "Building integrated photovoltaic products: A state-of-the-art review and future research opportunities", Solar Energy Materials and Solar Cells, Volume 100, Pages 69–96, May 2012

[JRC2012a] "Guidelines for Cost Benefit Analysis of Smart Metering Deployment", JRC Scientific and Technical Research, 2012

[JRC2012b] "Smart Grid projects in Europe: Lessons learned and current developments", JRC Scientific and Policy Report, 2012. On-line: http://ses.jrc.ec.europa.eu/sites/ses.jrc.ec.europa.eu/files/documents/ld-na-25815-en-n_final_online_version_april_15_smart_grid_projects_in_europe_-_lessons_learned_and_current_developments_-2012_update.pdf [Accessed 2014/1/5]

[Kezunovic2011] M. Kezunovic, "Translational Knowledge: From Collecting Data to Making Decisions in a Smart Grid" Proceedings of the IEEE, Volume 99, Issue 6, Pages 977-997, 2011

[Khan2013] R. H. Khan, J. Y. Khan, "A comprehensive review of the application characteristics and traffic requirements of a smart grid communications network", Computer Networks, Volume 57, Issue 3, Pages 825–845, 2013

[Khanvilkar2004] S. Khanvilkar, A. Khokhar, "Virtual Private Networks: An Overview with Performance Evaluation", IEEE Communications Magazine, Volume 42, Issue 10, Pages 146-154, 2004

[Khosroshahy2007] M. Khosroshahy, T. Turletti, K. Obraczka, "Snapshot of MAC, PHY and Propagation Models for IEEE 802.11 in Open-Source Network Simulators", INRIA Research Report, September 2007. Online: http://hal.inria.fr/inria-00175359/en/ [2014/1/12]

[Kulkarni2012] P. Kulkarni, S. Gormus, F. Zhong, F. Ramos, "AMI Mesh Networks—A Practical Solution and Its Performance Evaluation", IEEE Transactions on Smart Grid, Vol 3. No. 3, pp. 1469-1481, 2012

[Lévesque2012] M. Lévesque, D. Q. Xu, G. Joós, M. Maier, "Communications and power distribution network co-simulation for multidisciplinary smart grid experimentations", ANSS 2012, San Diego, USA, 2012

[Lin2011] H. Lin, S. Sambamoorthy, S. Shukla, J. Thorp, L. Mili, "Power system and communication network co-simulation for smart grid applications", in IEEE PES Innovative Smart Grid Technologies, 2011, Hilton Anaheim, CA, Pages 1-6

[Liu2012] J. Liu, Y. Xiao, S. Li, W. Liang, C. L. Chen, "Cyber Security and Privacy Issues in Smart Grids", IEEE Communications Surveys and Tutorials, Volume 14, Issue 4, Pages 981-997, 2012

[Lo2012] C.-H. Lo, N. Ansari, "The Progrssive Smart Grid System from both Power and Communications Aspects", IEEE Communications Surveys & Tutorials, Volume 14, Issue 3, Pages 799-821, 2012

[López2011a] G. López, P. Moura, J. I. Moreno, A. de Almeida, "ENERsip: M2M-based platform to enable energy efficiency within energy-positive neighborhoods", IEEE INFOCOM 2011 Workshop on M2M Communications and Networking, Shanghai, China, April 2011

[López2011b] G. López, P. Moura, M. Sikora, J. I. Moreno, "Comprehensive validation of an ICT platform to support energy efficiency in future smart grid scenarios", SMFG2011:IEEE International Conference on Smart Measurements for Future Grids, Bologna, Italy, November 2011

[López2011c] G. López, J. I. Moreno, "Smart Energy-positive Neighbourhoods for the Smart Grid. Architecture, Communications Technologies and Address Management for the ENERsip platform", 2011 ETSI Workshop on "Standards: An Architecture for the Smart Grid". Sophia Antipolis, France, April 2011.

[López2012a] G. López, P. Moura, V. Custodio, J. I. Moreno, "Modeling the Neighborhood Area Networks of the Smart Grid", IEEE ICC 2012, Ottawa, Canada, June 2012

[López2012b] G. López, P. Moura, B. Kantsepolsky, M. Sikora, J. I. Moreno, A. de Almeida, "European FP7 Project ENERsip: Bringing ICT and Energy Together", Global Communications Newsletter, November 2012

[López2013a] G. López, J. Moreno, P. Moura, A. de Almeida, M. Perez, L. Blanco, "Monitoring System for the Local Distributed Generation Infrastructures of the Smart Grid", CIRED 2013: 22nd European Conference and Exhibition on Electricity Distribution, Stockholm, Sweden, June 2013

[López2013b] G. López, V. Custodio, F. J. Herrera, J. I. Moreno, "Machine-to-Machine Communications Infrastructure for Smart Electric Vehicle Charging in Private Parking Lots", International Journal of Communication System, Wiley, 2013. DOI: 10.1002/dac.2705

[López2013c] G. López, J. I. Moreno, "PRICE Project: M2M communications architecture for large-scale AMI deployment", 4th ETSI M2M Workshop, Mandelieu-la-Napoule, France, November 2013

[López2014a] G. López, V. Custodio, J. I. Moreno, M. Sikora, P. Moura, N. Fernández, "Modeling Smart Grid Neighborhoods with the ENERsip Ontology", Computers in Industry, Elsevier, 2013. (Submitted for publication)

[López2014b] G. López, P. Moura, J. I. Moreno, J. M. Camacho, "Multi-faceted Assessment of a Wireless Communications Infrastructure for the Green Neighborhoods of the Smart Grid", IEEE ICC 2014, Sydney, Australia, June 2014. (Submitted for publication)

[López2014c] G. López, J. I. Moreno, H. Amaris, F. Salazar, "PRICE-GEN: Paving the Road towards Smart Grid through Large-Scale Advanced Metering Infrastructures", Electric Power Systems Research, Elsevier. (Submitted for publication)

[Ma2012] Y. Ma, T. Houghton, A. Cruden, D. Infield, "Modeling the Benefits of Vehicle-to-Grid Technology to a Power System", IEEE Transactions on Power Systems, Volume 27, Issue 2, Pages 1012-1020, 2012

[Majumder2013] R. Majumder, G. Bag, G. Velotto, A. Marinopoulos, "Closed loop simulation of communication and power network in a zone based system", Electric Power Systems Research, Vol. 95, pp. 247-256, 2013

[Mankoff2010] J. Mankoff et al, "StepGreen.org: Increasing energy saving behaviors via social networks", Proceedings of the 4th International AAAI Conference on Weblogs and Social Media, May 2010

[Manola2004] F. Manola, E. Miller, B. McBride. RDF Primer. W3C Recommendation 2004. On-line: http://www.w3.org/TR/2004/REC-rdf-primer-20040210/ [Accessed 2013/6/10]

[Mao2011] R. Mao, V. Julka, "Wireless Broadband Architecture Supporting Advanced Metering Infrastructure", IEEE VTC Spring, Budapest, Hungary, 2011

[Matanza2013] J. Matanza, S. Alexandres, C. Rodríguez-Morcillo, "Performance evaluation of two narrowband PLC systems: PRIME and G3", Computer Standards & Interfaces, Vol. 36, Issue 1, pp. 198-208, 2013

[McDaniel2009] P. McDaniel, S. McLaughlin, "Security and Privacy Challenges in the Smart Grid", IEEE Security and Privacy, Volume 7, Issue 3, Pages 75-77, May/June 2009

[Mets2011] K. Mets, T. Verschueren, C. Develder, T. Vandoorn, L. Vandevelde, "Integrated simulation of power and communication networks for smart grid applications", in IEEE CAMAD 2011 International Workshop on Computer Aided Modeling and Design of Communication Links and Networks, 2011, Kyoto, Japan, pp. 61-65

[Mets2012] K. Mets, R. D'hulst, C. Develder, "Comparison of intelligent charging algorithms for electric vehicles to reduce peak load and demand variability in a distribution grid", Journal of Communications and Networks, Volume 14, Issue 6, Pages 672-681, 2012

[Meyer1999] M. Meyer, "TCP Performance over GPRS", IEEE WCNC 1999, New Orleans, USA, 1999

[Miller2013] H. G. Miller, P. Mork, "From Data to Decisions: A Value Chain for Big Data", IT Professional, Volume 15, Issue 1, Pages 57-59, 2013

[MIRABEL2013] MIRABEL project Official Web Site: http://www.mirabel-project.eu/ [Accessed 2014/1/5]

[Momoh2012] J. Momoh, "Smart Grid: Fundamentals of Design and Analysis", IEEE Press, 2012. ISBN-13: 978-0470889398

[Motamedi2012] A. Motamedi, H. Zareipour, W. D. Rosehart, "Electricity Price and Demand Forecasting in Smart Grids" IEEE Transactions on Smart Grid, Volume 3, Issue 2, Pages 664-674, 2012

[Moura2010a] P. Moura, A. de Almeida, "Multi-Objective Optimization of a Mixed Renewable System with Demand-Side Management", Renewable & Sustainable Energy Reviews, Volume 14, Issue 5, Pages 1461-1468, 2010

[Moura2010b] P. Moura, A. de Almeida, "The Role of Demand-Side Management in the Grid Integration of Wind Power", Applied Energy, Volume 87, Issue 8, Pages 2581 - 2588, 2010

[Moura2012] P. Moura, G. López, A. Carreiro, J. I. Moreno, A. de Almeida, "Evaluation Methodologies and Regulatory Issues in Smart Grid Projects with Local Generation-Consumption Matching", EEMSW2012: International Workshop on Energy Efficiency for a More Sustainable World, São Miguel, Portugal, September 2012

[Moura2013a] P. Moura, G. López, J. I. Moreno, A. de Almeida, "Impact of Residential Demand Response on the Integration of Intermittent Renewable Generation into the Smart Grid", EEDAL2013: 7th International Conference on Energy Efficiency in Domestic Appliances and Lighting, Coimbra, Portugal, September 2013

[Moura2013b] P. Moura, G. López, J. I. Moreno, A. de Almeida, "The role of Smart Grids to foster energy efficiency", Energy Efficiency, Volume 6, Issue 4, Pages 621-639, November 2013

[NIST2010a] "NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0", NIST Special Publication 1108, January 2010

[NIST2010b] "Wireless Functionality and Characteristics Matrix for the Identification of Smart Grid Domain Application", NIST PAP2, January 2010

[NIST2011] "Guidelines for Assessing Wireless Standards for Smart Grid Applications", NIST PAP2, February 2011

[NIST2012] "NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 2.0", NIST Special Publication 1108R2, February 2012

[NIST2014] NIST Smart Grid Collaboration Wiki for Smart Grid Interoperability Standards: http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/SGIPCatalogOfStandards [Accessed 2014/1/5]

[OneM2M2014] OneM2M Official Website: http://www.onem2m.org/ [Accessed 2014/1/5]

[Osello2013] A. Osello *et al*, "Energy saving in existing buildings by an intelligent use of interoperable ICTs", Energy Efficiency, Volume 6, Issue 4, Pages 621-639, November 2013

[Oksman2011] V. Oksman, J. Zhang, "G.HNEM: the new ITU-T standard on narrowband PLC technology", IEEE Communications Magazine, Vol. 49, No. 12, pp. 36-44, 2011

[OWL2014] OWL Official Web Site: http://www.theowl.com/ [Accessed 2014/1/5]

[Pan2012] J. Z. Pan, S. Staab, U. Assman, J. Ebert, Y. Zhao, "Ontology-Driven Software Development", Springer, 2012, ISBN: 978-3-642-31226-7

[Pang2012] C. Pang, P. Dutta, M. Kezunovic, "BEVs/PHEVs as Dispersed Energy Storage for V2B Uses in the Smart Grid", IEEE Transactions on Smart Grid, Volume 3, Issue 1, Pages 473-482, 2012

[Papadopoulos2013] T. A. Papadopoulos, A. I. Chrysochos, G. K. Papagiannis, "Narrowband power line communication: Medium voltage cable modeling and laboratory experimental results", Electric Power Systems Research, Vol. 102, pp. 50-60, 2013

[PEBBLE2012] PEBBLE project Official Web Site: http://www.pebble-fp7.eu/ [Accessed 2014/1/5]

[PR2012] "Smart Meters in Europe - Advanced Metering Infrastructure for Electric Utilities in Europe: Business and Technology Issues, Country Profiles, Key Industry Players, and Market Forecasts", Pike Research, 2012.

[Protégé2013] Protégé Official Website: http://protege.stanford.edu/ [Accessed 2013/11/18]

[Rendón2001] J. Rendón, F. Casadevall, D. Serarols, "Snoop TCP Performance over GPRS", IEEE VTC Spring 2001, Rhodes, Greece, 2001

[REViSITE2012] REViSITE project Official Web Site: http://www.revisite.eu/ [Accessed 2014/1/5]

[Robichon2013] G. Robichon, "CDMA-450: a new approach for DSO's in Europe", 4th ETSI M2M Workshop, Mandelieu-la-Napoule, France, 2013

[SGprojects2014] EU Smart Grids Projects Portal: https://portal.smartgridsprojects.eu/Pages/default.aspx [Accessed 2014/1/5]

[SmartCoDe2012] SmartCoDe project Official Web Site: https://www.fp7-smartcode.eu/overview [Accessed 2014/1/5]

[Sakr2011] Z. Sakr, A. Liu, D. M. Batista, M. Alomari, "A Survey of Large Scale Data Management Approaches in Cloud Environments", IEEE Communications Surveys and Tutorials, Volume 13, Issue 3, Pages 311-336, 2011

[Santodomingo2012] R. Santodomingo, J. A. Rodríguez-Mondéjar, M. A. Sanz-Bobi, "Using Semantic Web Resources to Translate Existing Files Between CIM and IEC 61850", IEEE Transactions on Power Systems, Volume 27, Number 4, 2012

[Sastry2004] N. Sastry, D. Wagner, "Security Considerations for IEEE 802.15.4 Networks", WiSE'04: ACM Workshop on Wireless Security 2004

[SGCG2012a] "Smart Grid Reference Architecture", SG-CG, November 2012

[SGCG2012b] "Smart Grid Reference Architecture – Annex K", SG-CG, November 2012

[SGCG2012c] "First Set of Standards", SG-CG, November 2012

[SH2014] Fifthplay Smart Home solution Official Web Site: http://www.fifthplay.com/en/smart-homes/the-solution [Accessed 2014/1/5]

[SHM2014] Sunny Home Manager Official Web Site: http://www.sma.de/en/produkte/monitoring-systems/sunny-home-manager.html [Accessed 2014/1/5]

[Short2005] T. A. Short, "Electric Power Distribution Equipment and Systems", CRC Press, November 2005. ISBN-13: 978-0849395765

[Shrestha2012] G. M. Shrestha, J. Jasperneite, "Performance Evaluation of Cellular Communication Systems for M2M Communication in Smart Grid Applications", Computer Networks, Pages 352-359. Springer Berlin Heidelberg, 2012

[SHSG2011] Smart House/Smart Grid project Official Web Site: http://www.smarthouse-smartgrid.eu/ [2014/1/5]

[Sioshansi2012] F. Sioshansi, "Smart Grid: Integrating Renewable, Distributed and Efficient Energy", Elsevier, 2012. ISBN-13: 978-0123864529

[Stecher2008] R. Stecher, C. Niederée, Nejdl, P. Bouquet, "Adaptive ontology re-use: finding and re-using sub-ontologies", International Journal of Web Information Systems Volume 4, Issue 2, Pages 198-214, 2008

[Timpe2009] C. Timpe, “Smart Domestic Appliances Supporting the System Integration of Renewable Energy, SMART-A project, 2009

[Toffler1980] A. Toffler, “The Third Wave”, Bantam, 1980. ISBN-13: 978-0553246988

[Tsarkov2006] D. Tsarkov, I. Horrocks, “FaCT++ Description Logic Reasoner: System Description”, Automated Reasoning, Lecture Notes in Computer Science, 4130, Pages 292-297, Springer, 2006

[Usman2013] A. Usman, S. H. Shami, “Evolution of Communication Technologies for Smart Grid applications”, Renewable and Sustainable Energy Reviews, Volume 19, Pages 191-199, March 2013

[UNKP1997] “Kyoto Protocol”, United Nations Framework Convention on Climate Change, 2009

[Varga2008] A. Varga, R. Hornig, “An overview of the OMNeT++ simulation environment”, Simutools08 1st International Conference on Simulation tools and Techniques for Communications, Networks and Systems & Workshops, 2008, Brussels, Belgium, Pages 1-10. On-line: http://www.omnetpp.org/doc/workshop2008/omnetpp40-paper.pdf. [Accessed 2014-1-12]

[Warren1989] S. D. Warren, L. D. Brandeis, “Residential Energy Monitoring and Computerized Surveillance via Utility Power Flows”, IEEE Technology and Society Magazine, June 1989

[Wicaksono2012] H. Wicaksono, K. Aleksandrov, S. Rogalski, “An Intelligent System for Improving Energy Efficiency in Building Using Ontology and Building Automation Systems. Automation”, InTech, 2012. ISBN: 978-953-51-0685-2

[Witte2007] R. Witte, Y. Zhang, J. Rilling, “Empowering Software Maintainers with Semantic Web Technologies”, ESWC'07: 4th European Conference on The Semantic Web: Research and Applications, Pages 37-52, 2007

[WRT160NL] Cisco Linsys WRT160NL Datasheet. 2009

[Yan2013] Y. Yan, Y. Quian, H. Sharif, D. Tipper, “A Survey on Smart Grid Communication Infrastructures: Motivations, Requirements and Challenges”, IEEE Communications Surveys and Tutorials, Volume 15, Issue 1, Pages 5-20, 2013

[Zaballos2011] A. Zaballos, A. Vallejo, J. M. Selga, “Heterogeneous communication architecture for the smart grid”, IEEE Network, Vol. 25, No. 5, pp. 30-37, 2011

[Zeifman2011] M. Zeifman, K. Roth, “Nonintrusive Appliance Load Monitoring: Review and Outlook”, IEEE Transactions on Consumer Electronics, Volume 57, Issue 1, Pages 76-84, 2011

[Zigbee2007] “Zigbee 2007/PRO specification”, Zigbee Alliance, October 2007

[Zigbee2014] Zigbee Alliance Official Web Site: http://www.zigbee.org/ [Accessed 2014/1/5]

[ZWave2014] Z-Wave Official Web Site: http://www.z-wave.com/ [Accessed 2014/1/5]