Energies **2014**, *7*, 5953-5994; doi:10.3390/en7095953

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Article

A Semantic Middleware Architecture Focused on Data and Heterogeneity Management within the Smart Grid

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Received: 3 June 2014; in revised form: 23 August 2014 / Accepted: 2 September 2014 / Published: 10 September 2014

Abstract: There is an increasing tendency of turning the current power grid, essentially unaware of variations in electricity demand and scattered energy sources, into something capable of bringing a degree of intelligence by using tools strongly related to information and communication technologies, thus turning into the so-called Smart Grid. In fact, it could be considered that the Smart Grid is an extensive smart system that spreads throughout any area where power is required, providing a significant optimization in energy generation, storage and consumption. However, the information that must be treated to accomplish these tasks is challenging both in terms of complexity (semantic features, distributed systems, suitable hardware) and quantity (consumption data, generation data, forecasting functionalities, service reporting), since the different energy beneficiaries are prone to be heterogeneous, as the nature of their own activities is. This paper presents a proposal on how to deal with these issues by using a semantic middleware architecture that integrates different components focused on specific tasks, and how it is used to handle information at every level and satisfy end user requests.

Keywords: middleware; smart grid; semantics; Enterprise Service Bus (ESB); energy optimization

1. Introduction

When considering the risks and opportunities that lie for humanity in the nearest future, it becomes clear that energy is a main topic to discuss. Indeed, human beings on Earth require an ever-rising amount of resources, due to the increase of world population which, not only has already surpassed the 7000 million inhabitants mark [1], but also is expected to become more than 8200 million in 2030 [2] and 9300 million by 2050 [3]. At the same time, there is a gradual shift in the way the Earth is populated, with an ongoing trend of rural exodus and urban migration. This trend has become so noticeable that nowadays there are more people living in cities than in the countryside, something that has never happened before [4]. This change creates new challenges in terms of infrastructures, transport and energy management that must be solved from a sustainability-based point of view. In the end, an optimization of energy usage must be sought so as to guarantee that the needs of present and future populationare covered.

As far as energy and electricity are concerned, one major development to take into account is the "Smart Grid". Although it has been defined in different manners (for example, as "sophisticated, digitally enhanced power systems where the use of modern communications and control technologies allows much greater robustness, efficiency and flexibility than today's power systems" [5] or as an electrical power infrastructure capable of making intelligent decisions about the status of electrical power systems [6]), there are two features that are inherent to it: energy saving as a clear target—using mechanisms that tend to regulate and incentive the reduction of energy usage at peak hours, such as Demand Side Management [7] and an extensive use of Information and Communication Technologies—effectively recognized by several standards, as IEEE P2030, so as to guarantee seamless communication among electricity employment stages [8]. Demand Side Management can also be used for long-term energy consumption planning, as it is likely to establish policies in load balance and load usage for extended periods of time, thus resulting in the ability to forecast energy consumption and deal with it in a less unpredictable manner. From our point of view, the Smart Grid can be defined as a conventional power grid that becomes enhanced by the use of Information and Communication Technologies, allowing it to perform complex and innovative functionalities bent on energy savings and information management platform. Therefore, end users become able to consume electricity in a more efficient manner, stretching the use of energy resources for longer periods of time.

Typically, a Smart Grid will involve different stakeholders. Among them, it is necessary to highlight the importance of the following:

1. Transmission System Operator (TSO): it is the provider of the conventional grid equipment, which is responsible for power transmission, especially when high voltage electricity is transferred;
2. Distribution System Operator (DSO): it is the entity that manages medium voltage transmission. Also, it usually behaves as the mediating actor between the TSO and the aggregator, selling the energy to the latter;
3. Aggregator: this company purchases the electricity that is sold by the DSO, and resells it to the end users that are going to consume it. However, they may be able to collect a share of energy by themselves;
4. "Prosumer": while traditional energy consumers are present in the Smart Grid as well, they are also able to obtain energy from their own equipment (solar panels, small-sized windmills, *etc.*),

thus becoming an actor able to produce and consume energy, hence the term "prosumer" (producer + consumer).

At the same time, there are several differing technologies involved in the Smart Grid; it can be argued that the most notorious ones are:

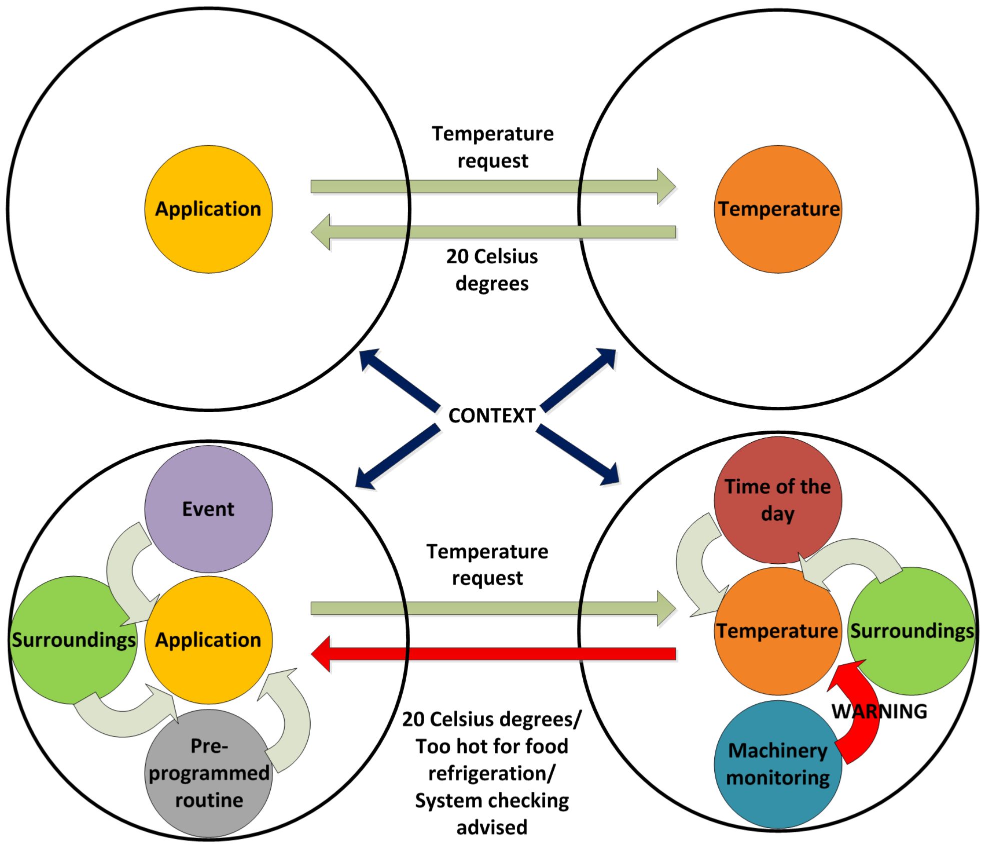
1. Distributed Energy Resources (DERs): they have been previously referred to as the equipment that a prosumer employs in order to obtain energy from its local environment. Commonly, these resources will be located at the user workplace or dwelling;
2. Advanced Metering Infrastructure (AMI): it is the equipment used for energy-related measurements (consumption, costs, *etc.*); it is usually placed at the end user's surroundings;
3. Big Data: rather than being a hardware-based technology, Big Data is about the management and analysis of the significant amount of information that will be required within the Smart Grid, which will be advisable if services and applications are to be implemented satisfactory.

With a grid conceptually as old as one hundred years [8], stakeholders of varying interests and heterogeneous technologies, information interchange at the ICT systems that belong to the Smart Grid becomes the next issue to deal with. Given the different nature of each of the actors, it is likely that information dealing with data requests or event triggering will be transferred in many different formats. Depending on the equipment manufacturer (for example, Siemens [9] and Schneider [10] have independent developments in this area), information may be transferred using one kind of data format (XML, JSON) or another; when used with equipment from other manufacturers, proprietary solutions with a low degree of compatibility and accessibility are prone to appear as well. This interoperability challenge is a major issue in the Smart Grid environment, ranging from what may be found in a microgrid when using power standards (Ustun *et al.* [11]) to a more holistic view comprising the whole Smart Grid [12]. It is also faced when devices from different vendors are just collecting information from the environment [13], something not dissimilar to what AMI is expected to do. We consider that the best way to fix this problem is designing a software layer that abstracts the heterogeneity of the hardware devices that are present in the environment and offer a homogenous-looking appearance to the application layer. This software layer is called "middleware". Middleware has been defined in many ways; its usability ranges from a bridge between a system and an operator, capable of monitoring different pieces of equipment, to a tool employed to couple the functionalities of a Secondary Substation Node with the utility systems of a grid [14]. In any case, the underlying idea is that it will hide the variety of the hardware devices used as part of the Smart Grid to ease the development of the applications handled by end users without expert knowledge of ICTs.

Information management is another major research topic that is critical for the correct performance of the Smart Grid, for it will offer the data that is required both for end user applications and right middleware management. Here, "data semantics" must be pinpointed; although not taking part just in the Smart Grid, it is foreseen to become of major importance for developments in this area. Semantics allows entities to become aware of the transferred data and consequently, knowledge can be inferred from the transmitted information. As a use case, if a request for temperature is made, and the result is "20 °C", it is all the information that can be extracted in a conventional system. However, in a semantic environment, the obtained temperature will be evaluated, and if possible, actions will be considered, behaving as "20 °C is too hot for food refrigeration. It is suggested to check the systems" instead of the isolated temperature value. Commonly, ontologies will be taking great responsibility, as they are in charge of compiling the information about the entities that are part of the system. An ontology can be loosely described as a dictionary containing updated information about all the entities that are part of a system, along with all their interrelations and interactions. They are often represented in RDF standard format, which is not dissimilar to XML [15]. Web Ontology Language is often used as a language to compose them, even when they are developed for a Smart Grid as an element of its architecture [16].

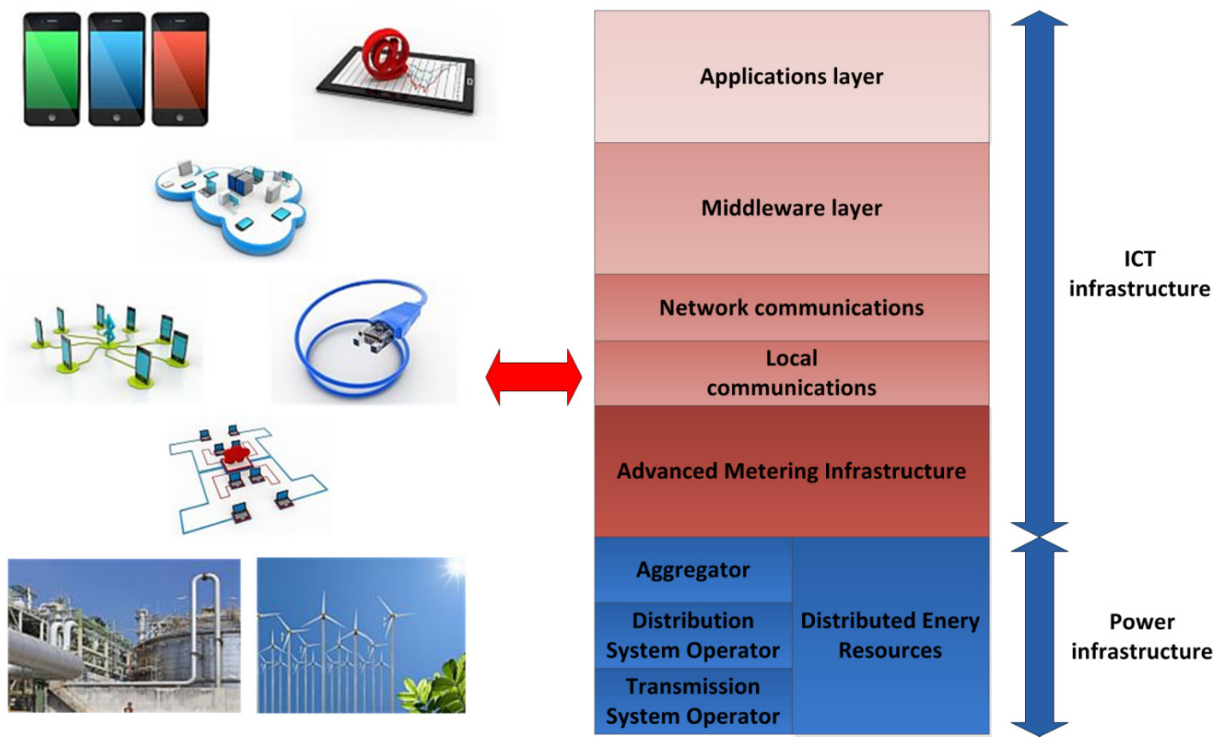
Similarly, other system features come in handy for semantic data, such as "context awareness": if data semantics is awareness of the information inferred from data, then context awareness can be deemed as the information that the system obtains becoming aware of its surroundings; it can also be defined as "the ability of computing systems to acquire and reason about the context information and adapt the corresponding applications accordingly" [17]. In this way, context awareness turns into a facility that is exploited to the system advantage, working closely with semantics in order to infer information from a holistic perspective, as it has been represented in Figure 1.

Figure 1. Differences between a context-aware and a non-context-aware application.



In the end, a Smart Grid system can be organized as the way represented in Figure 2. There are two different areas of knowledge that must be considered according to its subjacent features: one related with power creation and transmission—consisting of all the equipment used to generate electricity, either from regular facilities as power plants, or Distributed Energy Resources—and another one related with Information and Communication Technologies (ICT). Additionally, a middleware layer is a useful optimization for information management in its domains.

Figure 2. Layered overview of the Smart Grid



Although there are a great number of developments involving information management as an unavoidable feature of the Smart Grid, they often fall short in taking into account the three different characteristics—in fact, non-functional requirements—that have been defined as critical in this introduction: Smart Grid focus, prominent information management layer and semantic capabilities for data treatment. There are several major reasons to choose these as the non-functional requirements as the scope of the solution shown in this paper:

1. Smart Grid focus guarantees that an optimized solution has been developed for the specific needs and services of this environment, such as Demand Side Management, Demand Response or energy consumption forecasting. Should an ICT-based architecture be ported from any other environment to the Smart grid, major changes are likely to be required, thus resulting in a more constrained system and additional adaptation efforts;
2. A prominent information management layer is a must-have if information is going to be transferred with efficiency, for it can be charged with the tasks typically related with data (request/response transfers, context awareness, entity registration, *etc.*). Alas, semantic capabilities are more easily added if they become located in a layer or component as this;
3. Semantic capabilities are a compelling addition to a Smart Grid-based architecture because they allow the system to have smarter capabilities: registration can offer more information about the entities involved, applications are able to implement more complex functionalities and the information semantics allows the system to learn new concepts that will improve the future performance of the system.

It should come as no surprise that an implemented proposal fully considering these features has been put forward in this paper, showing how the three defined non-functional requirements have been modeled, implemented and tested with actual devices and applications. The contributions of this paper can be summarized as presented below:

1. **A semantic middleware architecture has been implemented from scratch for a microgrid encased in a Smart Grid.** It does not only abstract hardware heterogeneity for the upper layers, but also has semantic features implemented which are capable of dealing with transmitted information according to its meaning (semantic storage of information, SPAQRL requests, *etc.*). Also, while tests have been done using a microgrid model, it could be installed in several of them that altogether make a Smart Grid, provided that there is a coordination mechanism among the different microgrids (for example, multi-agent coordination for global information discovery [18]);
2. **This semantic middleware architecture has been developed using open software tools.** Fuse ESB and Java programming language have been critical for the architecture implementation. In this way, the architecture can be modified by third party developers and further expanded, and its services can be learnt and utilized for research purposes;
3. **The semantic middleware architecture presented here is distributed.** It can be deployed in most of the devices that would be expected in a microgrid so as to have them cooperating simultaneously in different parts of the system. AMI open enough to have Fuse ESB-like components can have software *bundles* installed, as shown in section 5.

The remaining parts of the paper are organized as follows: a related works section is provided to evaluate the most notorious developments when considering Smart Grid focus, information management and semantics. Challenges found in these architectures, along with their evaluation, are described in Section 3. Section 4 describes thoroughly our proposal, depicting in an accurate manner all the elements that are important in it. Results of the testing activities that have been conducted are shown in section 5. Conclusions and future works have been added in section 6 and, to wrap the whole paper, acknowledgements and references have been added as the last two sections.

2. Related Works

When considering how information is managed in the Smart Grid, there are several facts that must be acknowledged. In spite of having a majority of the solutions created in an "ad hoc" fashion, some other information management platforms make use of a differentiated level that may or may not be shaped as a differentiated layer. In order to accurately evaluate how the studied proposals are matching and fulfilling the non-functional requirements (Smart Grid focus, information management prominence and semantic capabilities) presented here, a classification system has been developed. Depending on the maturity level of those requirements in each of the reviewed proposals, a score is given ranging from 1 to 5. Table 1 is depicting the criteria used to grade how focused the proposals are on the idea of developing a proposal tailored for the needs of the Smart Grid. It has to be considered that, rather than the quality of the related works, what is being taken into account is their suitability to the non-functional requirements defined as of major importance. Therefore, chances are that the presented proposals are successfully matching the requirements that they were conceived with, but they struggle to adapt to the scenario and conditions presented here.

Table 1. Grade description for Smart Grid focus.

Smart grid focus	Grade description
Grade: 5	Information management platform conceived, designed and implemented for the Smart Grid from the beginning. Tests are provided by using a number of actual devices. Extensive information about its features is provided.
Grade: 4	Information management platform conceived, designed and implemented for the Smart Grid almost from scratch. Tests are provided by using simulation tools rather than actual devices.
Grade: 3	The information management platform has used a significant plethora of components prior to its usage in the Smart Grid, although the development has been tested and modified for the latter scenario.
Grade: 2	Information management platform ported from another kind of system alien to the Smart Grid. Important information is missing.
Grade: 1	The information management platform is not related with the Smart Grid / very scarce information is provided about its characteristics.

Furthermore, as depicted in Table 2, information management prominence has been graded as well. In this case, the relevance of any kind of refined procedure used for data collection and transfer able to cope with information of different origins has been considered, taking into account the quantity of detail and practicality of the information management proposals.

Table 2. Grade description for Information Management Prominence.

Information management prominence	Grade description
Grade: 5	Specific components designed and implemented in order to treat and enrich the data that is transferred throughout the system. Extensive information is provided about specific characteristics of the Smart Grid.
Grade: 4	A detailed description about information management is provided, without having specific or prominent components used for them. Information is provided about specific characteristics of the Smart Grid
Grade: 3	Data regarding information management is offered at an acceptable level: overall characteristics of the system (block diagrams, *etc.*) are provided, but there are less data about information treatment and transfer.
Grade: 2	Provided data is a superficial description of the characteristics of information management without profound, detailed description.
Grade: 1	No data available about management procedures or very scarce information is provided about its characteristics.

Finally, as shown in Table 3, the implementation of semantic capabilities has been graded as well, taking into account the information that was presented about them, as well as the depth of semantics and ontologies usage in the proposal.

Among the available information management platforms, the most relevant and updated are described and review in the following subsections.

Table 3. Grade description for Semantic Capabilities.

Semantic capabilities	Grade description
Grade: 5	Semantic capabilities have been made part as part of the proposal since the first design stages and are used extensively as part of the proposal. Descriptions regarding used ontologies or ontology languages provided.
Grade: 4	Semantic capabilities are added for prominent services. The amount of functionalities using them is significant. Detailed information provided about their characteristics and usage.
Grade: 3	Semantics are used for a small set of functionalities. Information regarding semantics is offered at an intermediate level (theoretical concepts, description of the ontology).
Grade: 2	Information regarding semantics is treated at a superficial level (theoretical concepts). Few information is provided about semantic capabilities
Grade: 1	No semantic capabilities are provided in the proposal / very scarce information is provided about its characteristics.

2.1. A Cloud Optimization Perspective

Xi Fang *et al.* put forward an information management platform strongly based on cloud computing devoted to Smart Grid systems [19]. Their proposal covers four different domains, namely "Smart Grid domain", "cloud domain", "broker domain" and "network domain". Smart Grid domain deals with three concepts: "Data Item" as an information object generated by some information sources, "Computational Project" as the component that uses Data Items and output information from previously finished tasks as inputs, and a "User" willing to access to the information related to Data Items or the outputs generated by the Computational Projects. Additionally, cloud domain consists of one or several clouds used for storage and computational services; different clouds may have different pricing policies depending on their particular needs. Broker domain will be the one responsible for mediation between the Smart Grid domain and the cloud domain whenever there are facilities that have to be interchanged. Finally, the network domain is involved with the network infrastructure and data transmission between any two former domains. The leading idea of this proposal is that the pricing policies of the Smart Grid, information provisioning and information storage will be offered as transparent facilities.

As far as cloud computing is concerned, it is a way to have a distributed solution that allows to store and execute complex and heavier operations than a standalone system would be able to perform. However, cloud computing systems tend to be more vulnerable in terms of security than other systems and must be equipped with extra mechanisms as Intrusion Detection Systems (IDSs) [20]. Besides, little information is provided about how to deal with peripheral devices as AMIs or high level applications, and semantic treatment of data takes not part in the proposal.

Smart Grid focus: 4 (detailed description, simulated results). Information Management Prominence: 4 (detailed description). Semantic capabilities: 1 (no semantic capabilities).

2.2. Stochastic Information Management in Smart Grid

Hao Liang *et al.* offer a different view as an information management platform in the Smart Grid, emphasizing the stochastic procedures to deal with data [21]. Great care is put on the applications that the Smart Grid is expected to tackle, as Demand Side Management, conceived as a way to optimize power consumption among prosumers, or electric vehicles that are recharged. The authors stress the stochastic models used for energy-related activities, especially renewable ones: "wind power generation, solar power generation, energy demand, vehicle mobility, component outage and energy storage". They have built a model that considers how information is managed by using a four bus power system that is considering data in each of the buses, such as active and reactive power injections, voltage, and a phase difference between the other generator buses. Further information is offered about "microgrid planning, microgrid operation" and "energy storage management", along with a thorough study on the applications that can be used as part of the Demand Side Management facilities.

This proposal reflects a very clear view of what the services from a Smart Grid look like, but it privileges those specific services rather than a more holistic perspective of the Smart Grid as a whole. Furthermore, there is no information about having a prominent layer that manages all the information in the Smart Grid, rather than scattering the functionalities related to it. Finally, complex treatment of information has not been considered in this proposal.

Smart Grid focus*:* 4 (detailed description, simulated results). Information Management Prominence*:* 2 (little data on information management platforms). Semantic capabilities*:* 1 (no semantic capabilities).

2.3. Smart-Frame

Joonsang Baek *et al.* offer their own ideas about an information management platform for the Smart Grid [22]. As it was done with the first proposal, the authors rely on a cloud computing infrastructure to provide a platform for information management, especially conceived to deal with issues of the front end elements present in the system. The authors' proposal is described according to three different viewpoints: "system architecture", "logical components" and "information management". System architecture explains how the system is divided into different regions that are managed by separated cloud computing centers, each of which can be set up either from a public or a private cloud. What is more, this service architecture exposes four different kinds of cloud computing services: Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS), Data-as-a-Service (DaaS) and Software-as-a-Service (SaaS). Logical Components depict how services are classified according to four different clusters (information storage, general user services, control and management services and electricity distribution services), recognizing at the same time Infrastructure-as-a-Service as the backbone of the system. Information Management is focused on dataflow through the different entities of the proposal; a centralized service deals with the information flow by using a schedule defining particular sources and destinations for the information. In addition to the three different perspectives shown by the authors, an identity-based cryptographic solution is described to have a more trustworthy platform.

The presented proposal takes a more defined view on a platform (the authors refer to it as a "framework") specifically built for a Smart Grid, but focuses primarily on the security functionalities that have been developed. Plus, semantic treatment of data is neglected, with no use of processed information in order to infer knowledge from the transmitted data. Finally, while the cloud computing paradigm offers a series of advantages compared to other distributed solutions, it also poses specific risks (security, accessibility) that must be considered as well.

Smart Grid focus*:* 4 (detailed description, simulated results). Information Management Prominence*:* 3 (proposal dealing mostly with security and cloud capabilities). Semantic capabilities*:* 1 (no semantic capabilities).

2.4. Semantic Information Modeling for Emerging Applications

Qunzhi Zhou *et al.* put forward their own research work about semantic information modeling for Smart Grid-based applications [23]. The authors' contributions are based on the usage of Demand Response (DR) as an emerging application for the Smart Grid, which will make use of a Smart Grid information model compliant with Semantic Web techniques. The authors present how Smart Grid applications are created by using its usual knowledge space, and how a series of contents (real time consumption, infrastructure information, customer behavior, schedule information and natural conditions) can be leveraged as part of the operations of Demand Response optimization. What is more, a semantic Smart Grid information model is put forward, with a model architecture that can be accessed at different levels and makes use of OWL to represent the information model, along with a MySQL database to store it by means of Jena API (often use for semantic data developments [24]). Additionally, component ontologies are treated as well: Common Information Model is the expected choice, as it is used to describe the electric components that are typical of the Smart Grid [25], along with other ontologies used for organization, infrastructure, weather, space, and time.

Unlike the former pieces of work studied, this proposal uses many more vast semantic capabilities than before. However, the bulk of the efforts poured onto a very specific application—as Demand Response is—limits the information about other services and features typical of the Smart Grid. Besides, an information management platform is not extensively studied in this piece of work.

Smart Grid focus*:* 3 (extensive mention to one specific application). Information Management Prominence*:* 2 (mentioned as something aside). Semantic capabilities*:* 4 (semantic capabilities have been added and thoroughly described for one specific application).

2.5. KT's Smart Grid Architecture and Open Platform

Jisun Lee *et al.* offer an example of how to handle information involving Smart Grid applications according to the interests of KT Corp. [26]. According to their point of view, customer needs in terms of Energy Management System imply new functionalities (Demand Response capabilities, Distributed Energy Resources, Electric Vehicle Integration, Energy Management Improvement, Grid Performance Optimization) that must be solved. The authors mention that an energy management platform should be characterized by three different facilities: interoperability of networked communications (no matter whether they are wireless or not), interoperability and scalability for customer services (paving the way for a distributed architecture based on Service Oriented Architecture or web service principles) and finally, since business opportunities are presented for users (prosumers are able not only to pay for the electricity they consume, but also to sell it) a business ecosystem should be presented for them as well. The authors' intention is focusing their proposal on the AMI that is used both to monitor end user behavior and keeping the customer aware about their power usage. Another compelling feature of the proposal is the openness of their platform: labeled as a "KT'S Smart Grid Architecture and Open

Platform", it offers not only communication management technologies, but also customer-oriented services and communications, along with third party applications and energy services.

As far as the proposal is concerned, it has a decisive practical projection that guarantees its usability and feasibility. However, it struggles to describe a broader point of view that implies the Smart Grid beyond the end user applications. Additionally, the proposal does not consider neither a differentiated component for information management (such as a middleware layer placed between the applications and the hardware and communication capabilities), nor how semantics are integrated as part of the information treatment that is done.

Smart Grid focus: 5 (detailed description, demonstration project). Information Management Prominence*:* 3 (overall characteristics of the system). Semantic capabilities*:* 1 (no semantic capabilities).

2.6. Service-Oriented Middleware for the Smart Grid

Liang Zhou *et al.* put forward their own solution, providing a more middleware-oriented implementation [27]. Here, middleware is used as a way to guarantee that the disparity of the underlying devices will not affect the availability of services within the system. What is more, a high degree of flexibility on the provided services is offered as well. The presented architecture is composed of three layers with different functionalities: a "user part" (mostly concerned about Quality of Service features that are going to be provided for the end users, as well as economy-driven applications), a "control part" (equipped with four different functions called fault report, security guarantee, user information management and power allocation that can be used for further developments), and a "transmission layer" (composed by communication, generation and distribution parts; this layer's usual functionality will be power transmission from the generation plants to the distribution facilities through a group of substations).

This proposal is able to provide a clear layer devoted to information management for the Smart Grid that combines the advantages of having a distributed architecture and a dedicated management of the data flow from the applications and end user devices. Unfortunately, there is not a given way to use semantically enriched information; ontologies or mechanisms to provide advanced services, such as context awareness, have not been implemented either.

Smart Grid focus: 4 (detailed description, simulated results). Information Management Prominence: 5 (specific components designed and implemented). Semantic capabilities: 1 (no semantic capabilities).

2.7. Advanced Demand Side Management for the Future Smart Grid

Pedram Samadi *et al.* offer their own work regarding Demand Side Management by using a mechanism design [28]. It is assumed by the authors that end users have been equipped with "Energy Consumption Controllers (ECCs)" that are collecting information about consumer behavior. In this way, it is possible to have a more refined pricing methodology. The idea behind is that a "Vickrey-Clarke-Groves" mechanism can be used to improve the relation between the aggregate utility functions of the users and the total energy cost, which is capital for the performance of Demand Side Management within the Smart Grid. It must be highlighted that the main motivation for this piece of work is this DSM service; thus, the contributions that are claimed by the authors (Vickrey-Clarke-Groves usage for the Smart Grid, optimization problem formulation and its properties, especially truthfulness and efficiency, use case for their algorithm) are conceived entirely for it. Consequently, although this proposal fares fine in the area of DSM one of the most compelling services associated to the Smart Grid is not showing the overall perspective that is expected from an information management platform able to acknowledge data transfer among the different entities of the system. Alas, there is no information about how higher level capabilities (semantic web, context awareness, *etc.*) are offered in this platform.

Smart Grid focus: 3 (extensive description of a single application). Information Management Prominence: 2 (information management as an afterthought). Semantic capabilities: 1 (no semantic capabilities).

2.8. Information Framework of Smart Distribution Grid

Xuejian Shao *et al.* describe the research done on their Information Framework for the Smart Grid [29]. Their work involves different breakthroughs in the field of the Smart Grid, describing in a more specific way how Information and Communication Technologies have become interweaved with standards for electrical installations. The authors explain how IECSA (Integrated Energy and Communication Systems Architecture) was developed in order to create a Reference Architecture Framework. The Smart Grid is considered here as made up by five layers, that is to say, a "Business Process Layer, a Services layer, a Service components layer, an Information service layer" and "an Application service layer". Additionally, it is described how two electrical appliances standards, IEC61968 and IEC61970 share some of their features: a) both of them make use of Common Information Model; b) the concept of integrating an application integration architecture; c) a Components Generic Interface and d) an Information Exchange Model. While this piece of work has its value as a report on what standards and technologies are remarkable for the smart grid, it intends to present a high level perspective of the ICT part and the electrical part of Smart Grid, rather than putting forward a more precise proposal.

Smart Grid focus: 2 (high level, non-detailed descriptions of standards). Information Management Prominence: 1 (little to no information about information management platforms). Semantic capabilities: 1 (no information about semantic capabilities and the Smart Grid).

3. An Evaluation on Information Management Platforms for the Smart Grid

There is a collection of proposals on how to manage information in a Smart Grid to fulfill the main objectives it was conceived with. However, they all seem to have frequent flaws when some appealing features are considered: despite the fact that they all were created with the Smart Grid in mind to a greater or a smaller extent, there are some other characteristics, as having specific solutions for information management, or the implementation of semantic features in order to improve the usability of the data for more elaborated services as context awareness, that are either incomplete or missing.

As an example of how the proposals have been evaluated, if an hypothetic information management subsystem was specifically made for the Smart Grid and tested with actual devices, had differentiated parts of the whole system for information management, but used almost no semantics, it would be evaluated as *Proposal (Smart Grid focus, Information management prominence, Semantic capabilities) = [5 4 1].* Table 4 depicts how the proposals have been graded.

It could be said that although the revised proposals are quite compelling and tend to offer a satisfactory solution for specific goals, they do not provide a solution with complete implementations of information management systems that have semantic features as well. Therefore, the authors of this paper have conceived, developed and tested a proposal that fulfills the requirements that have been identified before. Those requirements are met due to the following reasons:

1. Our proposal has been specifically conceived for a microgrid encased in a Smart Grid from the beginning. Instead of adapting an existing solution, which in fact could end up with a poor port of an earlier development, conceiving a new information management platform with proven software solutions seemed as a better starting ground;
2. It is emphasized how information is managed by means of specific tools. A middleware architecture was the software layer that best could solve issues with hardware and information heterogeneity, rather than trying *ad hoc* solutions that should be changed for different devices;
3. Semantics and smarter data treatment are enabled. As part of the current efforts done in software engineering, information is enriched by using ontologies and semantic features to offer services under a Service-oriented Architecture (SOA) paradigm.

Table 4. Reviewed proposal grading.

Proposal regular name	Smart grid focus	Information management prominence	Semantic capabilities	Total/15 (pts.)
A cloud optimization perspective	4	4	1	9/15
Stochastic information management in smart grid	4	2	1	7/15
Smart-frame	4	3	1	8/15
Semantic information modeling for emerging applications	3	2	4	9/15
KT's smart grid architecture	5	3	1	9/15
Service-oriented middleware for the smart grid	4	5	1	10/15
Advanced demand side management for the future smart grid	3	2	1	6/15
Information framework of smart distribution grid	2	1	1	4/15

4. Description of the Proposal

The architecture described in this document for the middleware uses as inputs the requirements defined in the e-GOTHAM project [30] for a microgrid, and takes into account the IEEE 2030 Guide [31] and CEN-CENELEC-ETSI SGAM [32]. While the latter offers a holistic view of a completed microgrid, dividing its functionalities in five different layers (business, functional, information, computation and communication) it lacks an accurate description of what to use for data and information management, which is the main scope of our proposal.

Rather than being deployed in one single device, the middleware architecture presented here is distributed in several physical elements, as illustrated in Figure 3. These elements represent the ICT components of the microgrid used as part of the Smart Grid. A "Central Controller" (a hardware device involving functionalities that affect the whole microgrid are deployed) connected to several "Local

Controllers" (simpler hardware devices including functionalities that involve one or several devices locally) and full compatible devices can be viewed. Some Local Controllers may act as bridges between legacy (already existing hardware pieces) or project proprietary (specifically developed) devices and the middleware architecture.

Figure 3. System elements and networks

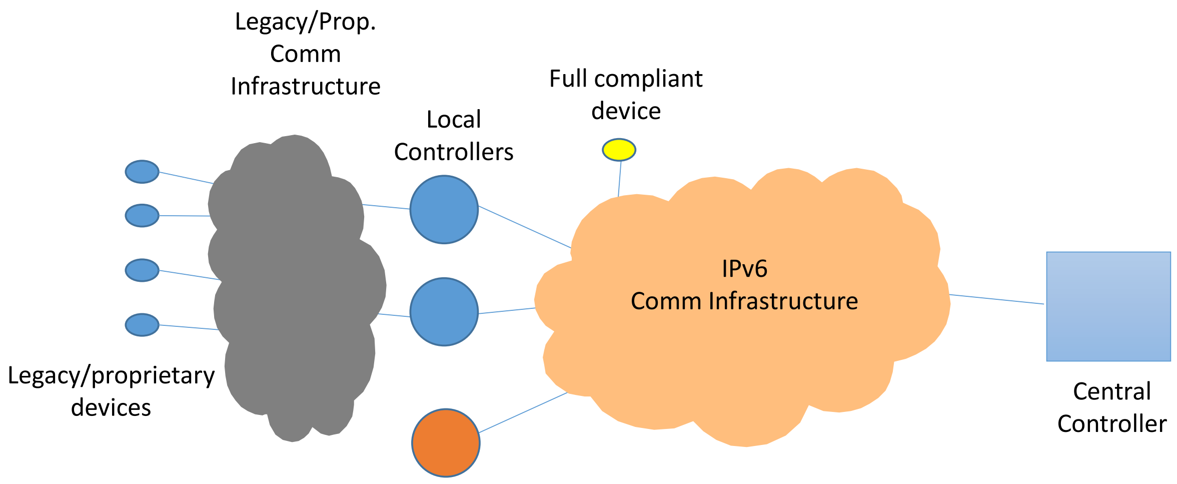
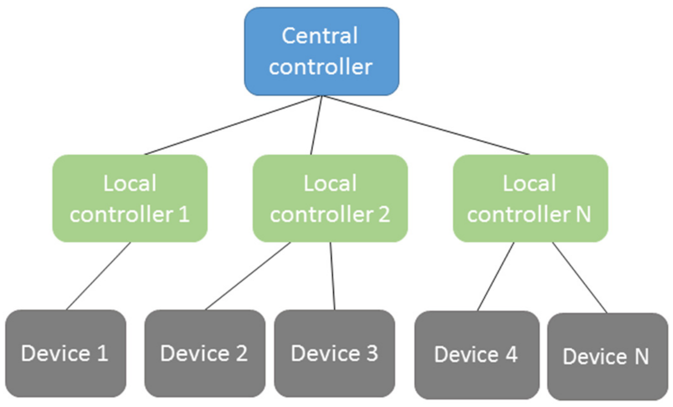


Figure 4 shows the hierarchy existing through the system elements. Usually, there is only one Central Controller; the amount and types of Local Controllers will depend on the scenario where the middleware is deployed. Devices will rely on Local Controllers.

Figure 4. Middleware elements hierarchy.



4.1. Architecture Presentation

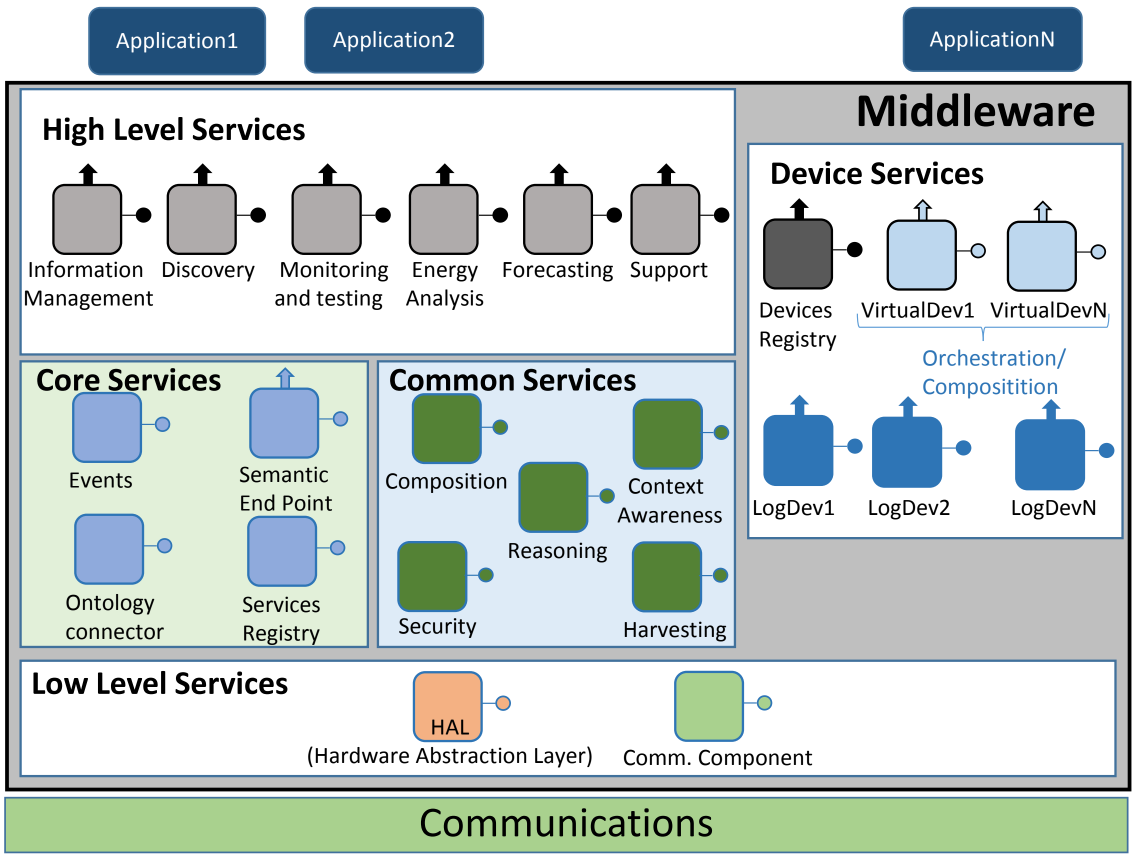
When a middleware architecture had to be conceived for its usage in the Smart Grid, there were three main aspects that had to be considered for the implementation stage:

1. It required both SOA concepts to be used and a layered model for services divided and located in upper and lower levels;
2. It should be a distributed middleware architecture, where different hardware components may have several middleware parts deployed;
3. Semantic characteristics should be included. This was a critical challenge, for a particular ontology that would have the middleware architecture as its domain would be employed for

semantic service and data registration, in order to infer knowledge from the information that is being transferred.

After several preliminary designs, a middleware architecture fulfilling the non-functional requirements defined in previous sections, along with its own major features, was elaborated, as depicted in Figure 5.

Figure 5. Middleware architecture.



Since a Smart Grid may be used for a plethora of different applications, related with data requests or information storage, dividing middleware functionalities by separated blocks—in a divide-and-conquer approach—was something to consider. In fact, it had been done before in the work presented by other authors as Liang *et al.* [33] or Sucic *et al.* [34], which was taking into account standards bound to the conventional power grid. Also, having components inside each of the blocks can be used as objects that manage different middleware functionalities, as described by Jin and Sung [35].

4.1.1. High Level Services

These are the access points for applications at the upper layer that perform actions involving middleware properties. They can be regarded as the very first kind of services that are used in the middleware architecture from an upper point of view. Their functionalities are accessed via Representation State Transfer (REST) interfaces. Six services have been defined:

1. **Information Management.** It checks whether the information that has been retrieved by the middleware as an answer to a request matches the structure of the inner service ontology that the architecture is using;

2. **Discovery.** It is used to let the end user know what services are available, both in the middleware architecture and related to the hardware devices that are part of the system;
3. **Monitoring and testing.** It is used as a way to test the current status of the services that can be employed. Besides, it will be the most usual high level service to be executed when a pilot interface is managed;
4. **Energy analysis.** When requests involving specific data about energy are done, this high level service will come in handy to direct the data request;
5. **Forecasting.** Much like energy analysis, this high level service will be used whenever there is a request related with forecasting information;
6. **Support.** This high level middleware service is conceived for ancillary functionalities that are particular of the hardware device where the middleware architecture is deployed. If the monitoring and testing component is not enough by itself, Support high level service may be used as well.

4.1.2. Core Services

The services that are part of this block are the most critical of the ones taking part in the middleware architecture, as they have functionalities (semantic information treatment, service registry) that middleware cannot do without. The ones that have been identified as mandatory are as follows:

1. **Events.** As the middleware architecture used may use protocols that follow a publish/subscribe paradigm (for example, Advance Message Queuing Protocol or AMQP), it is useful to have a component to handle this sort of communications;
2. **Semantic Endpoint.** It offers compatibility between devices that do not use the middleware ontology and the remaining parts of the middleware architecture;
3. **Ontology connector.** It is used as a way to map the information retrieved from the devices and services into a semantic-compliant data model used within the middleware architecture;
4. **Service Registry.** Its main functionality is the registry of the services that, instead of being obtained from outer devices, are part of the middleware. Besides, they will be semantically registered by means of the operations made by the Ontology Connector.

4.1.3. Device Services

In this middleware block, all the devices (sensors and actuators) connected to the system have a logical representation in the middleware architecture based on their most important features and capabilities. This representation is named “Logical Device”. Logical Devices can be implemented on an IP-connected piece of equipment as long as the device hardware can run a mandatory minimum part of the middleware. For those devices incapable of implementing any part of the middleware (due to their low capabilities or any other constraining reason) the associated Logical Device will be implemented either in the Central or the Local Controller. Creation of Logical Devices allows the usage of the service ontology to describe in a complete manner the physical devices characteristics and to registry these elements in the device semantic database for later discovery and use. Three types of services have been enumerated here:

1. **Devices Registry.** It carries out the actions required to register a Logical Device and integrate it as part of the whole deployment. In addition to that, it will keep an strong connection with the deployed Logical Devices by means of heartbeat messages that will be sent to the Device Registry service. It must be noted that since Device Registry will be used with device services and Service Registry with middleware services, they are using different pieces of information;
2. **Logical Devices.** Used to represent the hardware devices that take part in the whole system. They are also used as service containers, depending on the sensors and capabilities that physical devices are equipped with. In addition to encapsulate hardware device features, they also provide a way to be deployed as compressed files in Fuse ESB-friendly locations, as explained later. The inclusion of Logical Devices in the architecture was decided after considering the Virtual Entities and Services defined in Internet of Things Architecture (IoT-A) [36];
3. **Virtual Devices.** Virtual Devices result by merging two or more Logical Devices into a single one that will offer composed services dependent on the ones provided by Logical Devices. For example, a Logical Device offering a "temperature" service, and another one providing a "humidity" service can be merged into a third, different one named "environmental conditions" service that can be used to evaluate to probability of getting moss plants in one room.

4.1.4. Common Services

While designing this middleware architecture, some common functionalities required for the correct performance of the applications used in the system would sprang up (data gathering, context awareness, service composition, *etc.*) regardless of the differing characteristics of the latter. Thus, a block of services dealing with the ones most usually employed has been created, in order to tackle the functionalities most closely linked to the frequent data transfers and operations required. One major feature of this block is that despite the fact that some components of the other blocks may not be deployed in a particular scenario, all common services are likely to be needed, regardless of the middleware surrounding environment. Five services have been defined as the ones taking part here.

1. **Composition.** It becomes of major importance when Virtual Devices are formed, as it will be the one used for this task;
2. **Context awareness.** It will be responsible for using retrieved information about the current status of the overall system, taking into account if there is any faulty performance so as to fix it;
3. **Reasoning.** When required, it will work jointly with Context Awareness to provide decision making mechanisms;
4. **Security.** It is a component devoted to functionalities and extra needs involving security. It provides features as integrity, privacy or authenticity, albeit the extra features required in this component will have to be met at the application and/or hardware levels;
5. **Harvesting.** This service collects the information obtained from the Low Level services and transfers it to the upper layers of the middleware architecture.

4.1.5. Low Level Services

As opposed to the other services, the ones located at this block are more focused on outer parts of the middleware architecture, such as the communications layer, that are used to either establish connections with other devices or with other components of the distributed middleware. The two entities that have been located here are:

1. **Hardware Abstraction Layer (HAL).** Its main usage point is to abstract all the hardware-specific features that may be found as part of the hardware components of the deployment;
2. **Communications component.** It is the actual interface between the communications layer protocol and the middleware architecture. Depending on the protocol used outside the middleware, it may use interfaces adapted to the communications protocol used (Java Message Service or JMS, AMQP, *etc.*).

4.2. Implementation Software Facilities

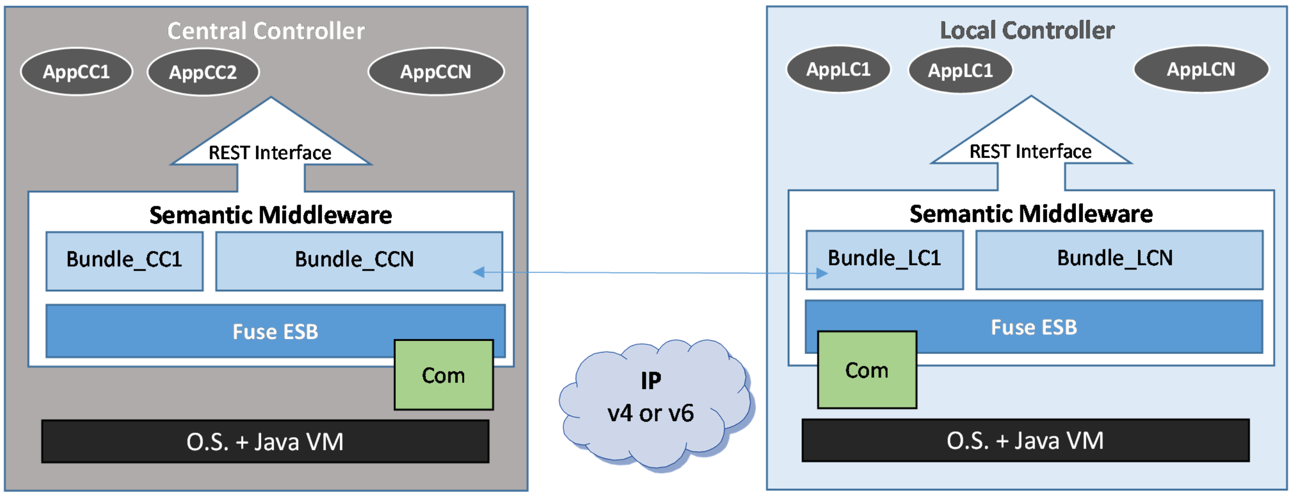
Next subsections deal with the different software tools used to implement the described middleware architecture. Section 4.2.1 is about Enterprise Service Bus; section 4.2.2 offers information about the interfaces that have been used for software bundle communication. Finally, section 4.2.3 describes the messages used for data interchange within the middleware

4.2.1. Fuse Enterprise Service Bus

An Enterprise Service Bus (ESB) was selected to deploy the semantic middleware architecture. ESB is a well-known software architecture that uses the bus as a message system to interchange information between the application components or, in ESB terminology, “bundles”. ESB also allows the implementation and publication of interfaces using several techniques in an affordable way in terms of computational resources. For the deployment that has been tested with real devices, JBoss Fuse ESB has been chosen; its inter-bundle communication capabilities can be used by the different services that are implemented [37]. Another advantage of using Fuse ESB is that it performs its functionalities regardless of the protocols that are used at lower levels. For example, the access to physical devices and Local Controllers may also be driven by AMQP, an open standard application layer protocol for message oriented exchange [38].

Thus, Fuse ESB can be regarded as the place where services are allocated and from where they can be provided. Figure 6 depicts the general schema used for the implementation where the Central Controller and the Local Controller can be distinguished. Each of them is using distributed components that are being shared throughout the system. This structure comes in handy when different components are deployed in the Central (Device registry, Service registry, Ontology Connector, *etc.*) and Local (Logical Device, Virtual Devices, *etc.*) controllers. Applications running in the Central Controller are called AppCC1 (after Application at Central Controller number 1), AppCC2, and so on until AppCN. In the same way, applications belonging to the Local Controller are AppLC1 (after Application at Local Controller number 1), AppLC2, and so on until AppLCN. Both groups of applications use the services provided by the semantic middleware by means of RESTful interfaces.

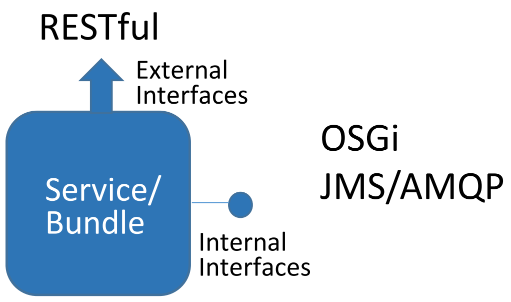
Figure 6. Enterprise Service Bus (ESB) extends the middleware to the Local Controller.



4.2.2. Service Interfaces Types

Figure 7 shows the interfaces offered by the middleware services. Two kinds of interfaces can be highlighted: internal and external. External interfaces are implemented by using a RESTful solution easy to handle with an ESB. Internal interfaces can be implemented using Open Service Gateway initiative (OSGi) interfaces (which are the native ones for Fuse ESB), JMS ones for asynchronous communications or AMQP bridged to the ESB using JMS capabilities. Interchanged messages are semantics-based messages codified in application layer meta-languages and languages as eXtensive Markup Language (XML) or JavaScript Object Notation (JSON).

Figure 7. Interfaces for a high level service bundle.



4.2.3. Operation Protocol Messages

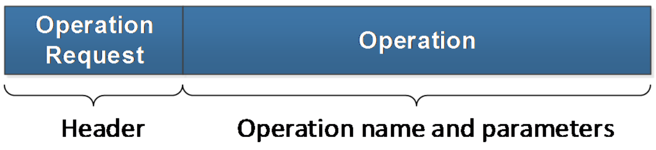
Regardless of the interface type—OSGi, JMS or AMQP—the interchanged messages share the same content and data fields. Two kinds of messages will be used in the operation protocol: operation request and operation response. They have been described in XML and contain the information of the operations. Operation messages are as follows:

1. **Operation Request:** by following a client-server paradigm, they will be sent from a Fuse ESB bundle acting as the client and received by a different bundle acting as the server. This message is made up by two fields:
   a) Message type: it identifies what kind of message is being transferred;

b) Operation: this field encases the operation significant characteristics, namely the operation name and the input parameters. Furthermore, if any precondition is required for the operation to be triggered, it will be included as well.

The message appearance has been depicted in Figure 8.

Figure 8. Operation request message.



An example of the XML-formatted message that is being transmitted looks as presented in Figure 9.

Figure 9. Operation request eXtensive markup language (XML) example.

```
<message>
   <type> OPERATION REQUEST </type>
   <operation>
      <name> getServiceOp1 </name>
      <parameters>
         <input> Units </input>
         <precondition> ON </precondition>
      </parameters>
   </operation>
</message>
```

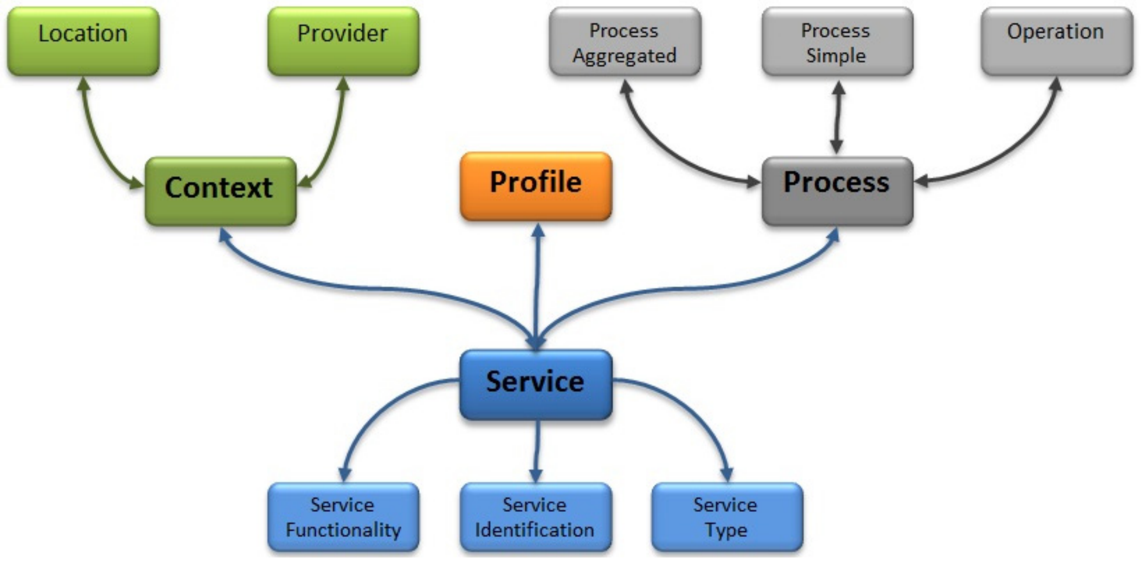
2. **Operation Response:** it is the natural counterpart of the Operation Request message, the one that is sent from the server bundle to the client one as an answer. As the former one, it is divided in two different parameters:
   a) Message type: it identifies the kind of message that is being interchanged between bundles;
   b) Operation: its content resembles Operation Request message, albeit the parameters that are contained are the output returned value instead of the inputs that were sent before.

4.3. Semantic Features

One of the project objectives has been achieving a middleware architecture with the innovative characteristic of inferring semantic knowledge from data. In order to integrate this characteristic in the semantic middleware architecture, a service-oriented ontology, where services from the middleware are semantically annotated in a repository, has been developed. Although the idea of having a "gluing" layer that uses a communication bus with semantic capabilities is not entirely new (Jeroen Famaey *et al.* do indeed put it forward [39]), so far it has not been fully implemented in a middleware architecture for Smart Grid environments. These semantic features allow easy information exchanges between different types of computers, devices or components employing several kinds of operating systems and application languages. Therefore, interoperability of heterogeneous information sources between different middleware components can be enabled by means of this ontology. In addition to that, the ontology provides a knowledge domain where the semantic data reusability becomes plausible.

The service-oriented ontology has been designed in Web Ontology Language (OWL) with the Protégé tool [40] and a general overview is presented in Figure 10.

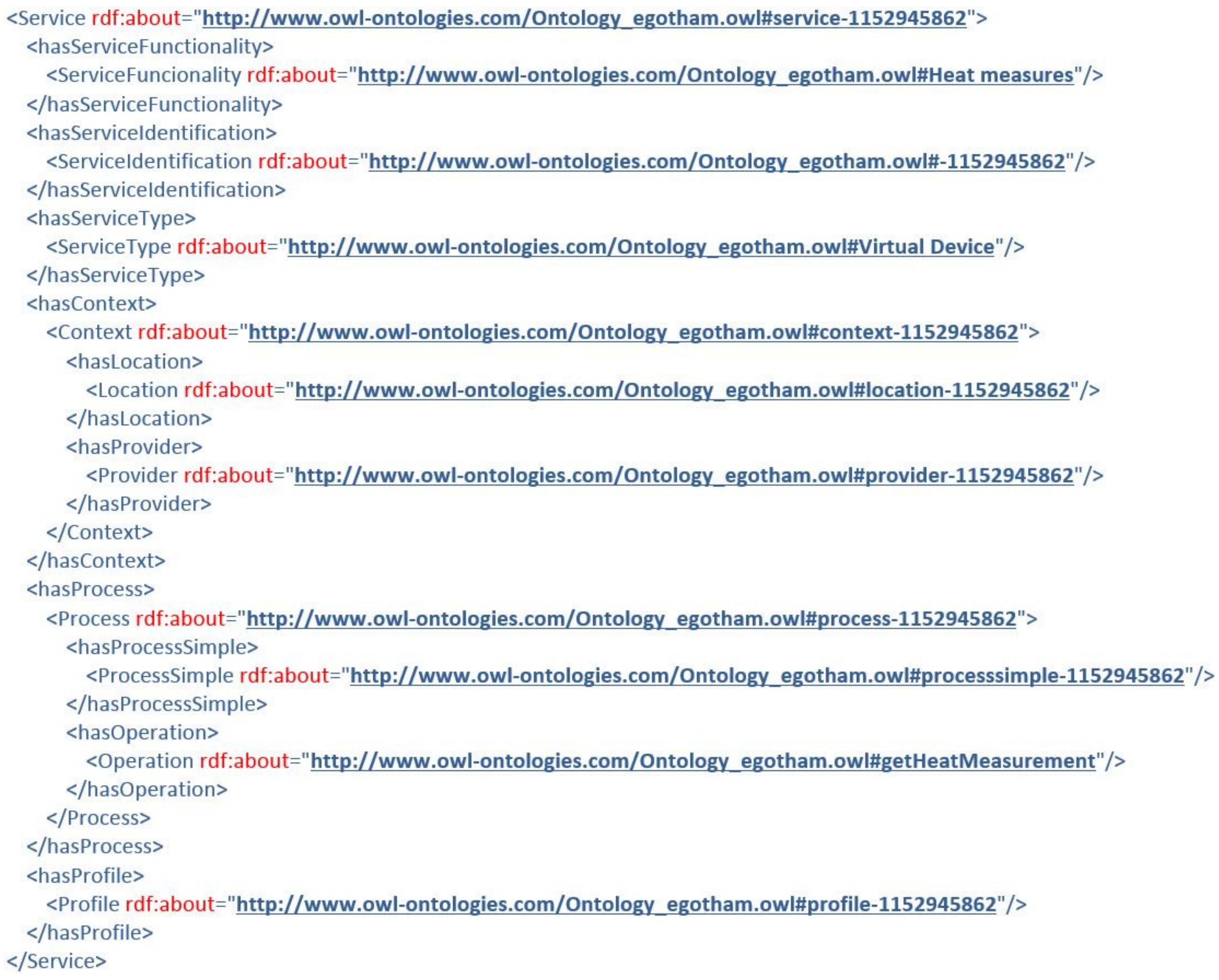
Figure 10. General overview of the service-oriented ontology.



The main class—called "Service"—has, in turn, three subclasses: "ServiceFunctionality", "ServiceIdentification" and "ServiceType". The first one describes the functionality that the service has been designed for. The second subclass identifies uniquely the service inside the middleware architecture, and the third one indicates which sort of service is taking into account the architecture classification (high level services, device services, core services, common services, and low level services). There are three more important classes in the ontology directly related to the "Service" class. The first one is called "Context" which defines the interrelated conditions in which the service exists or occurs. It is able to provide the specific location (class "Location") and inform about the provider of the service using the class "Provider". The second one is the "Process" class. It represents the logic of the service which it can be a simple process (class "ProcessSimple") or an aggregated one (class "ProcessAggregated"). On the one hand, a simple process is a single service that takes the requested information directly and its functionality with the appropriated treatment provides. On the other hand, an aggregated process supplies a new functionality composed by two or more simple process. "Process" class is linked with "Operation" class because one process may have one or more operations associated. Finally, the class named as "Profile" represents the public description of the service; for example, the protocol used between the service and the application that are using it. Figure 11 shows an example of a semantically annotated service represented in RDF; it shows a plethora of semantically annotated information: functionality, type, identification or location are provided, as well as the methods used to achieve the functionality (getHeatMeasurement).

This service-oriented ontology has been managed by means of a Jena API [24] that allows us to control all its classes and relationships using Java language. It offers the possibility of storing all the information in a semantic repository based on RDF triples, thus keeping it available to later consult these data with a particular query language called SPARQL [41].

Figure 11. Example of semantically annotated service.



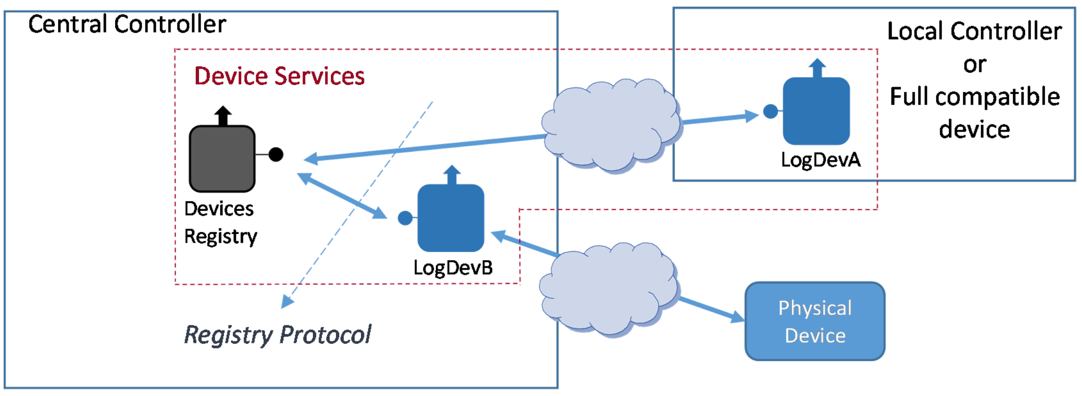
```
<Service rdf:about="http://www.owl-ontologies.com/Ontology_egotham.owl#service-1152945862">
  <hasServiceFunctionality>
    <ServiceFuncionality rdf:about="http://www.owl-ontologies.com/Ontology_egotham.owl#Heat measures"/>
  </hasServiceFunctionality>
  <hasServiceIdentification>
    <ServiceIdentification rdf:about="http://www.owl-ontologies.com/Ontology_egotham.owl#-1152945862"/>
  </hasServiceIdentification>
  <hasServiceType>
    <ServiceType rdf:about="http://www.owl-ontologies.com/Ontology_egotham.owl#Virtual Device"/>
  </hasServiceType>
  <hasContext>
    <Context rdf:about="http://www.owl-ontologies.com/Ontology_egotham.owl#context-1152945862">
      <hasLocation>
        <Location rdf:about="http://www.owl-ontologies.com/Ontology_egotham.owl#location-1152945862"/>
      </hasLocation>
      <hasProvider>
        <Provider rdf:about="http://www.owl-ontologies.com/Ontology_egotham.owl#provider-1152945862"/>
      </hasProvider>
    </Context>
  </hasContext>
  <hasProcess>
    <Process rdf:about="http://www.owl-ontologies.com/Ontology_egotham.owl#process-1152945862">
      <hasProcessSimple>
        <ProcessSimple rdf:about="http://www.owl-ontologies.com/Ontology_egotham.owl#processsimple-1152945862"/>
      </hasProcessSimple>
      <hasOperation>
        <Operation rdf:about="http://www.owl-ontologies.com/Ontology_egotham.owl#getHeatMeasurement"/>
      </hasOperation>
    </Process>
  </hasProcess>
  <hasProfile>
    <Profile rdf:about="http://www.owl-ontologies.com/Ontology_egotham.owl#profile-1152945862"/>
  </hasProfile>
</Service>
```

4.4. Device Registry

One of the most important tasks a semantic middleware must implement is service registration, so that existing services and their capabilities are known. Thus, Logical Devices require to be registered in the middleware to know their presence and their functionality. Logical Devices can be implemented inside the middleware architecture in two ways: Logical Device Type A and Logical Device Type B. Figure 12 represents the scenario where the two types of existing Logical Devices are depicted:

1. Logical Device Type A. It will be implemented as part of the Local Controller. Since the Local Controller will be effectively a device accessible enough to install the Logical Device, it can be regarded as a full middleware-compliant device (e.g., LogDevA in Figure 12);
2. Logical Device Type B. Unlike type A, this Logical Device is implemented outside the device it is bound to; in fact, it will be usually implemented at the Central Controller (e.g., LogDevB in Figure 12). This option will be used, for example, when the physical device is not computationally capable of having a functional middleware installation.

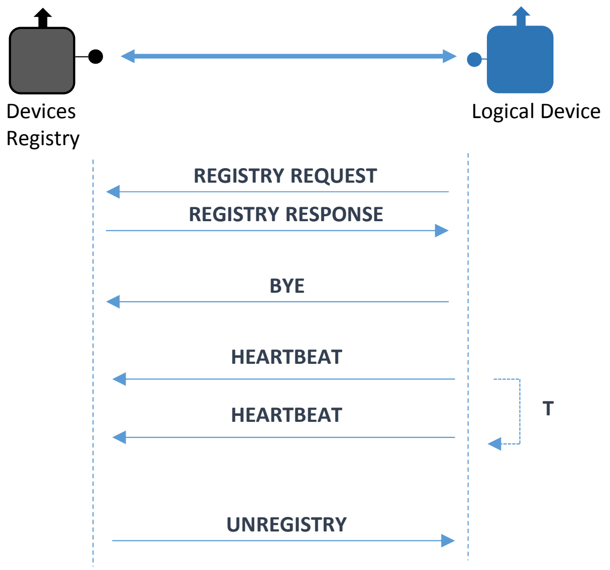
Figure 12. Logical device types.



4.4.1. Registry Protocol

It is mandatory to elaborate a protocol to register the Logical Devices that are mapping physical devices existing throughout the system. The two displayed kinds of Logical Devices will use this protocol in their relations with the Device Registry, as illustrated in Figure 13.

Figure 13. Device registry protocol.



The protocol messages have been defined in the following manner:

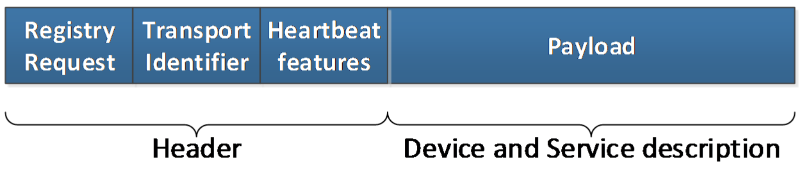
1. **Registry Request.** It is the message used to integrate a Logical Device. In this message there will be data required to send the request. These data are:
    a) Message type: it has the same functionality as before: identifying the kind of message that is being transferred;
    b) Transport identifier: used to particularize a device according to lower layer parameters, such as an IP address. It has been conceived as an optional parameter, as it is used just in case lower layers do not provide a way to get a sender identifier;
    c) Heartbeat features: used so as to confirm that once the registration has taken place, the devices that have been registered will send messages to guarantee that they remain functional

and can perform their assigned tasks. As related in [42], using a dynamic procedure to send these messages that is aware of the success or failure of the device performance is advisable. Consequently, heartbeat messages will be given the opportunity to be sent at a decreasing rate, as long as all the previous ones have reached its destination successfully. Different algorithms can be used as well; if the value field has zero as a value, a constant periodic amount of time will be used between messages, otherwise some other ways of transmitting heartbeat messages can be used;

d) Payload: among the contents of this field there will be a physical device unique identifier (labeled as deviceTypeID in the XML representation of this message) and context sensitive data. By means of deviceTypeID information—which is providing the device manufacturer, model and serial number—one template will be used to complete the semantic registration of the device, as it will be described in section 4.4.3. This template will be filled up with information from the Logical Device and sent to the Ontology Connector so as to have the device semantically stored.

The appearance of this message will be as represented in Figure 14.

Figure 14. Registry request message.



Additionally, the XML representation of the message resembles the ones that were depicted in Figure 15. As it can be noted, heartbeat characteristics have been added as well.

Figure 15. Device registry request XML example.

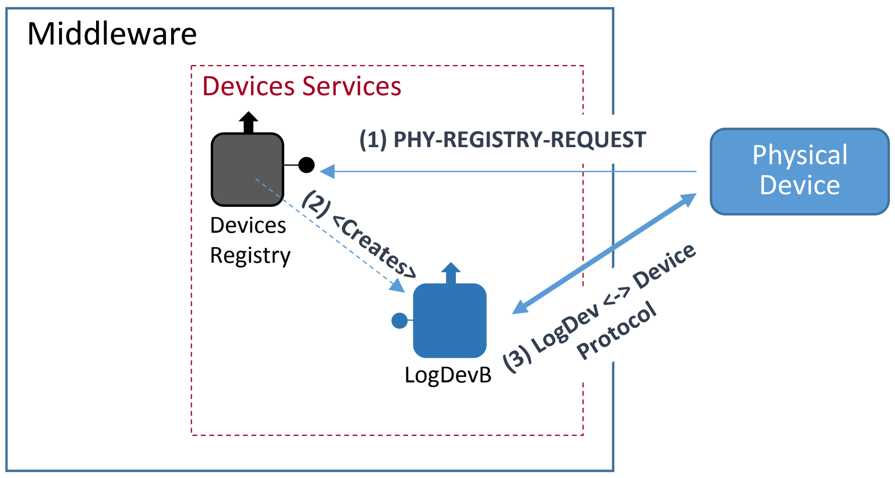
```
<message>
  <type>REGISTRY REQUEST</type>
  <TransportId> Source Identifier</TransportId>
  <heartbeat>
<adaptativeAlgorithm>1</adaptive Algorithm>
    <timelapseUpperThresholdSeconds>300</timelapseUpperThresholdSeconds>
    <timeLapseExtension>100</timeLapseExtension>
        <timelapseLowerThresholdSeconds>3000</timelapseLowerThresholdSeconds>
  </heartbeat>
  <payload>
    <deviceTypeId>
      <manufacturerId> Manufacturer </manufacturerId>
      <modelId> SI8421 </modelId>
      <serialNumber> 0546258 </serialNumber>
    </deviceTypeId>
    <context>
      <location>
        <latitude>12.45</latitude>
        <longitude>13.57</longitude>
      </location>
    </context>
  </payload>
</message>
```

2. **Registry Response**. Used to confirm that the registration process was completed. It is sent from the Device Registry to the Logical Device that sent a Registry request before;
3. **Bye**. This is a message sent when a Logical Device chooses voluntarily to be disconnected from the system (instead of being forced out by an accident or any other malfunctioning issues);
4. **Unregister**. This message is quite similar to Bye with a difference in the direction it is transferred: instead of travelling from the Logical Device to the Device Registry, it will go the other way round, as the action of disconnecting the device from the system will be taken by the Device Registry;
5. **Heartbeat**. This message will be the one that is used by the Logical Device to send a periodical acknowledgment of the good performance of the system.

4.4.2. Registering Physical Devices

As far as logical device creation is concerned there are different procedures to launch Logical Devices, provided that their wanted type of Logical Device (A or B) is taken into account. Logical Devices categorized as type A either run in a Local Controller or are a Local Controller by themselves. In any case, they will be pre-installed Logical Device pre-existing the registration process. Type B Logical Devices must be generated by the Device Registry according to the process described in next lines. Figure 16 shows the steps used to create a Logical Device of type B.

Figure 16. Logical Device B type creation.



This process can be explained as follows:

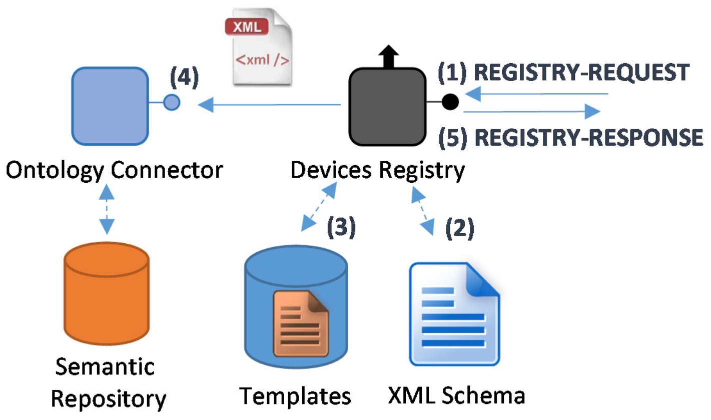
1. The physical device sends a Phy-Registry-Request message to the Devices Registry. This message contains the same physical device unique identifier associated to the label <deviceTypeId> used in the previously described Registry Request message;
2. The Devices Registry service checks if the physical device is correctly formatted and creates, if checking was successful, the right bound Logical Device;
3. Once the logical device is created, it connects with its bound physical device using the appropriate communication protocol that will depend on the physical devices communication

capabilities. The Logical Device will get from the physical device all the information needed to represent it within the middleware architecture.

4.4.3. Registry and Ontology

Up until this point, the procedures and actions related with the registry protocol carried out to register a Logical Device have already been described. However, the semantic registration in the middleware architecture must be explained too, as illustrated in Figure 17.

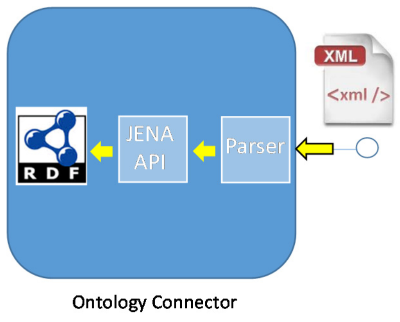
Figure 17. Semantic registry process.



The steps that must be taken for the complete process of a Type A registration device are:

1. A Request Registry for service registration will be received at the Device Registry;
2. This message will have data on its payload part that will have to be validated as any other XML-formatted document. In order to do so, there will be several XMLSchemas that effectively guarantee that the information received by the Device Registry is compliant with the format that is expected from the Logical Devices;
3. Semantic registration requires a template to be filled with the information once the content of the request has been validated. These templates will be pre-installed in the Central Controller with the deployed middleware architecture;
4. When the template fulfilling is finished, it is sent towards the Ontology Connector using the OSGi-based interface for internal middleware communications;
5. The Ontology Connector will collect the information sent by the Device Registry and store it for its future usage. The process has been depicted in Figure 18.

Figure 18. Ontology Connector components.



The role taken by the Ontology Connector will require the usage of three different inner components:

1. Parsing block: when it receives the XML-formatted information it will extract the most relevant fields to have them processed by the next block;
2. JENA API block: it is in charge of turning the attributes that had been collected before into RDF-formatted files that will contain the semantic information;
3. RDF files: they will contain the information related with the middleware ontology. It will usually be dealing with information about the services and their capabilities.

4.5. Middleware Service Registry

Middleware service registry is conceived as the registration of the services that take part in the middleware architecture rather than the devices that connect to the system. Since they are services that do not depend on physical devices, fewer messages are required for the whole process. Specifically, only registry request and registry response are required.

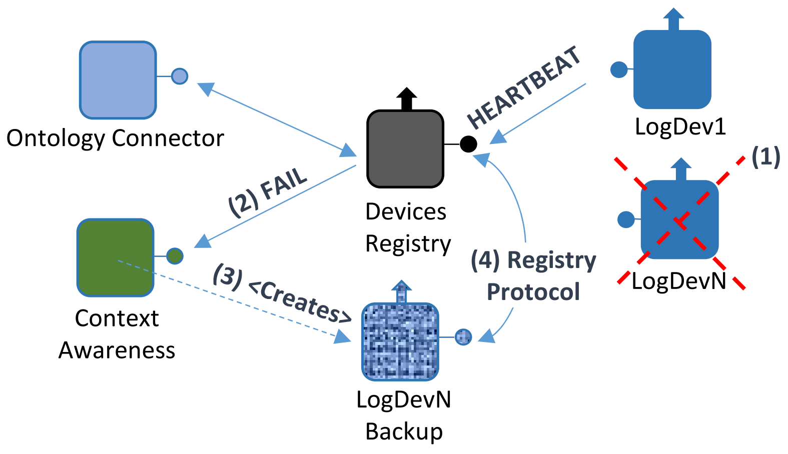
1. Registry Request. It is the message used to start the registration. It has two familiar fields:
   a) Message type: it will identify what kind of message is being sent;
   b) Payload: this field is containing the majority of the information required by the service. They will too make use of templates in order to determine how the content should look like in order to successfully complete the registration process.
2. Registry Response. This message will be sent back to the service that sent the registry request in the first place. The data that is part of the message are:
   a) Message type: it defines the kind of message that is sent from one bundle to another;
   b) Payload: it contains the information related with the result of the registry process.

4.6. Context Awareness

The main concept behind our vision of context awareness is that the system must be able to carry on performing their duties in the best possible way, even if there are malfunctions affecting the system. Therefore, the idea of offering functionalities that guarantee *resilience* has to be included. This scenario is the one that we consider as most important, since it is the one most likely to take place in an extended deployment of the scenario. Resilience is understood in the scope of this project as the ability of the system to carry on performing its functionalities while remaining unaffected to a great extent in case any issue comes up. Adding context aware features to a middleware architecture has been tried before; for example, Di Zheng *et al.* [43] put forward a context aware middleware architecture for Quality Management, albeit it is conceived primarily for mobile devices.

In order to manage all the operations related to context awareness, a specific component was developed for them (Context Awareness service). Heartbeat messages are important for resilience, as it will be acknowledging the presence of the devices taking part in the system and, by proxy, its regular performance as the procedure is represented in Figure 19.

Figure 19. Logical device backing up scenario.



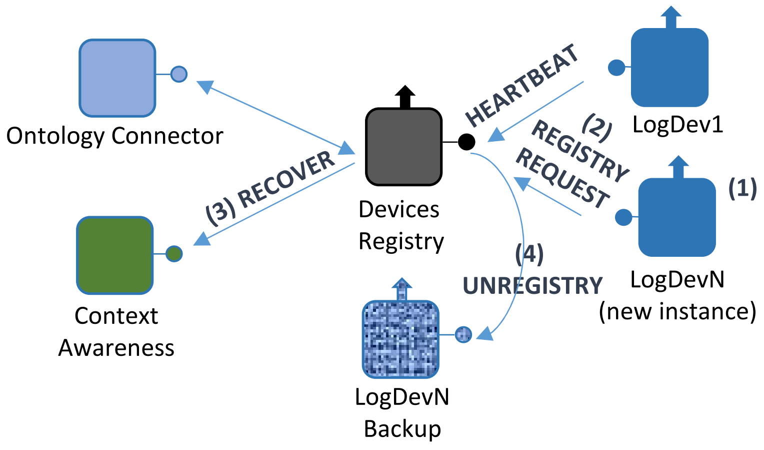
The Logical Device backing up process can be explained as follows:

1. A failure takes place in one of the devices integrated in the system; consequently, it affects the Logical Device that is bound to it (Logical Device N). Therefore, it will not be able to send any Heartbeat messages to the Device Registry;
2. In the absence of Heartbeat messages, Logical Device N will be forced to send a FAIL message, containing the Logical Device N unique identifier, along with the last time when a successful heartbeat message was received;
3. By using the unique identifier, a Logical Device backup will be created by the Context Awareness component, specifically created for this task according to all the functionalities that were previously contained by the Logical Device, thus creating Logical Device N Backup (LogDevN Backup);
4. At this point, a lighter registry request message will be sent by LogDevN Backup to complete the registration process.

After having the former Logical Device replaced by its new LogDevN Backup, the latter will be kept functional until there is a new registry request from the physical device that had previously gone out of order. In that case, the procedure that is used to acknowledge the recovery of the former Logical Device must be foreseen as well. It should be executed following next steps displayed in Figure 20:

1. When the LogDevN gets recovered it will start running again. Since it will have to be notified for the whole middleware architecture, the registry protocol must be initiated;
2. LogDevN will be registered. At this very moment, LogDevN Backup will no longer be necessary; a Recover message will be sent from the Device Registry component to the Context Awareness one so as to notify the changes in the existing Logical Devices;
3. Also, this change is notified at the Ontology Connector. It will edit the ontology contents in order to update it to the new current situation;
4. Finally, the Logical Device that was used as a backup will be unregistered. For this purpose, a message to unregister the backup Logical Device.

Figure 20. Logical Device resume.

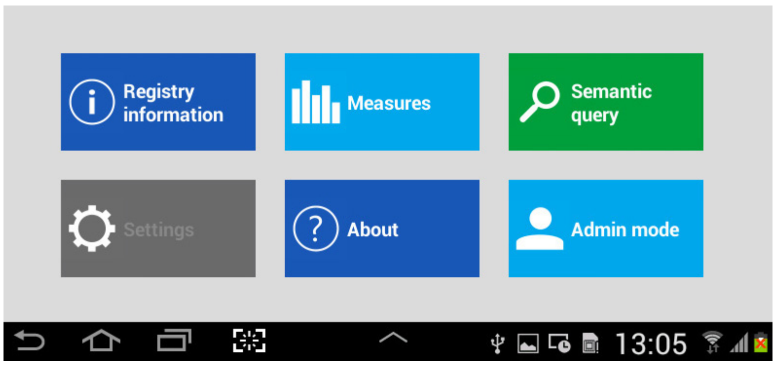


4.7. Service-Related Functionalities

Since the information regarding the services is going to be stored by means of the Ontology Connector, it can be accessed from upper layers that access the middleware architecture from the application level. For instance, Discovery Service may be used with this purpose, and the information that gets retrieved can be shown at a Graphic User Interface (GUI). Based on the results that have been obtained during the testing procedures, and to prove the usability of the middleware architecture that is being described here, an Android application has been developed to ease the evaluation of the middleware performance, as well as using the most frequent use cases that appear in a system.

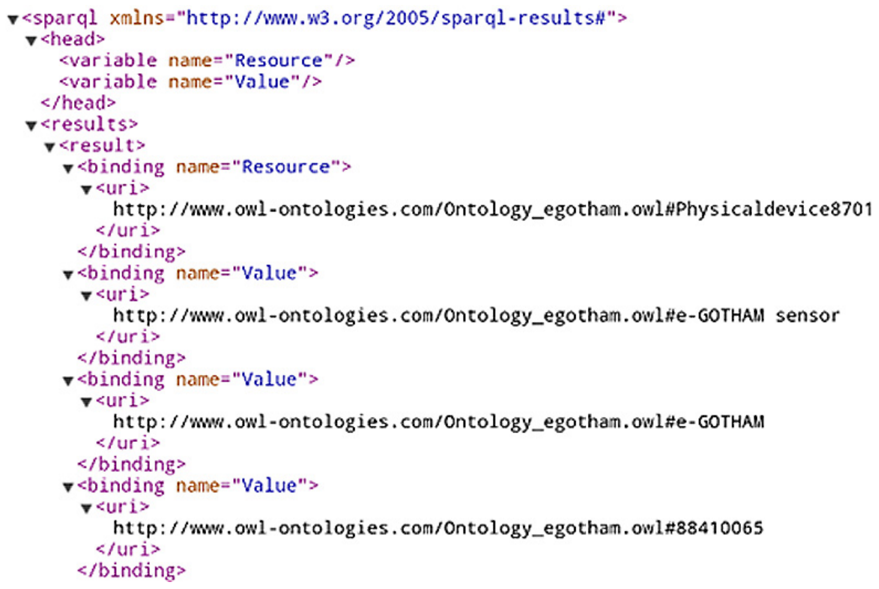
Figure 21 shows the appearance of the main window application. By using this application it is possible to get registry information, collect measures from devices, execute semantic queries or perform administrate tasks. Also, the application settings can be configured to have the device it runs on connected to different REST interfaces.

Figure 21. Application main window.



As the operations are accessed via REST interfaces, any device with the HTTP protocol stack enabled will access them. For example, a SPARQL query requesting a list of all the registered devices could be answered by the Ontology Connector, *i.e.*, with the XML information partially illustrated in Figure 22. Note that it is showing information already included in the semantically stored description of the resource, such as an identifier of the device, its manufacturer or its serial number.

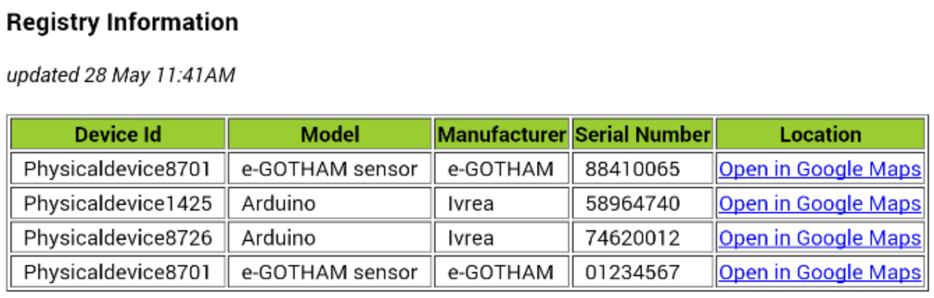
Figure 22. XML-formatted device information.



```
▾<sparql xmlns="http://www.w3.org/2005/sparql-results#">
  ▾<head>
      <variable name="Resource"/>
      <variable name="Value"/>
    </head>
  ▾<results>
    ▾<result>
      ▾<binding name="Resource">
        ▾<uri>
            http://www.owl-ontologies.com/Ontology_egotham.owl#Physicaldevice8701
          </uri>
        </binding>
      ▾<binding name="Value">
        ▾<uri>
            http://www.owl-ontologies.com/Ontology_egotham.owl#e-GOTHAM sensor
          </uri>
        </binding>
      ▾<binding name="Value">
        ▾<uri>
            http://www.owl-ontologies.com/Ontology_egotham.owl#e-GOTHAM
          </uri>
        </binding>
      ▾<binding name="Value">
        ▾<uri>
            http://www.owl-ontologies.com/Ontology_egotham.owl#88410065
          </uri>
        </binding>
```

Other example of a service functionality that can be provided is listing the available devices of the system, as is depicted in Figure 23. It is done so by retrieving RDF-based information that will be employed in a XSLT transformation.

Figure 23. Graphical representation of the existing devices.



Registry Information

updated 28 May 11:41AM

Device Id	Model	Manufacturer	Serial Number	Location
Physicaldevice8701	e-GOTHAM sensor	e-GOTHAM	88410065	Open in Google Maps
Physicaldevice1425	Arduino	Ivrea	58964740	Open in Google Maps
Physicaldevice8726	Arduino	Ivrea	74620012	Open in Google Maps
Physicaldevice8701	e-GOTHAM sensor	e-GOTHAM	01234567	Open in Google Maps

There may even be some other services that can come in handy too, such as monitoring one particular device over other ones by using filtering criteria.

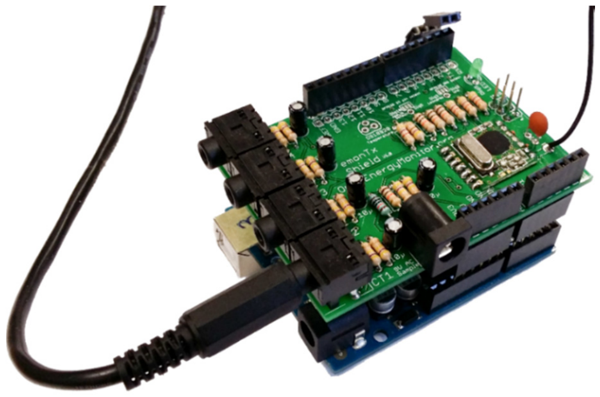
5. Performance Tests and Behavior

Since our proposal has been developed to fulfill the non-functional requirements that were fixed as mandatory, tests were carried out on it in order to determine its performance and behavior, once the proposal was implemented and use cases were offered as functionalities. Among all the involved services of the middleware architecture, the ones that were foreseen as having the greatest share of workload were the ones used to test the reliability and performance of the middleware architecture. The system that was tested was composed by:

1. **Hardware level.** Basically, it represents the hardware elements that make up a Logical Device running in a Local Controller. It has a significant degree of heterogeneity, for the physical devices that make a Logical Device can be varied and there is no direct equivalence between the Logical

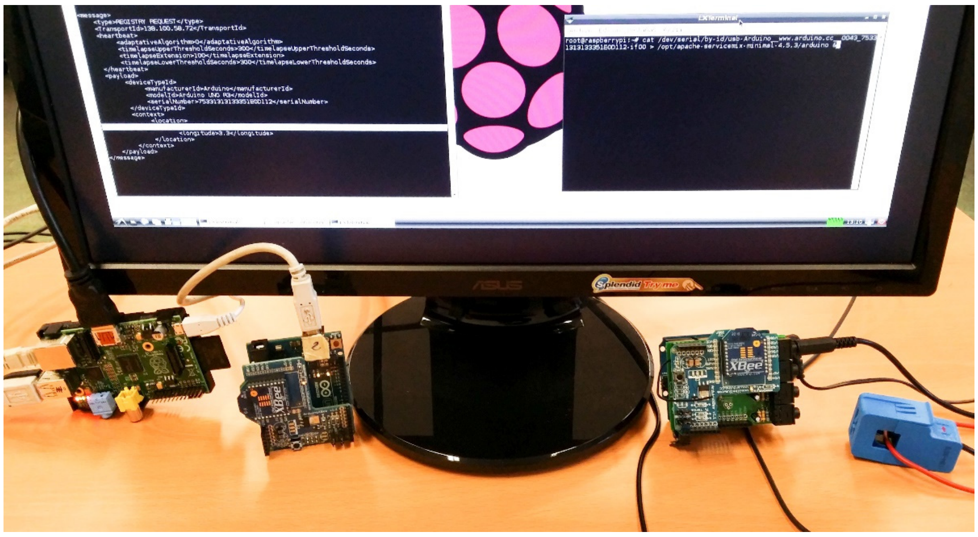
Device and the number of devices involved in this representation. Five pieces of hardware are present here: a) a current sensor that uses Hall effect to its advantage in order to measure power usage; b) an electrical current measurement shield called *EmonTx Arduino shie*ld, manufactured by OpenEnergyMonitor, a company that manufactures electronic devices with a relevant degree of openness and Do-It-Yourself procedures [44] with an appearance as shown in Figure 24; c) two Arduino Uno boards, which provide the required amount of pins and capabilities needed for the information transmission in the prototype, one will be used to attach the shield and receive the data from it to send it via 802.15.4 communications to the other one, which will be gathering the data to send it and d) a Raspberry Pi, which both transfers the gathered data and is used as part of the PC that has installed the middleware architecture as a distributed server, where the most resource-demanding operations will be run in order to keep the Raspberry Pi functional in each moment;

Figure 24. EmonTx Arduino shield mounted over an Arduino Uno.



The overall appearance of the assembly involving the different hardware devices that would be mapped as a Logical Device can be seen in Figure 25. The different wired and wireless protocols were integrated without showing signs of defective performance.

Figure 25. Hardware equipment used for current measurement.



```
<message>
    <type>REGISTRY REQUEST</type>
    <TransportId>138.100.58.72</TransportId>
    <heartbeat>
        <adaptativeAlgorithm>0</adaptativeAlgorithm>
        <timelapseUpperThresholdSeconds>300</timelapseUpperThresholdSeconds>
        <timelapseExtension>100</timelapseExtension>
        <timelapseLowerThresholdSeconds>300</timelapseLowerThresholdSeconds>
    </heartbeat>
    <payload>
        <deviceTypeId>
            <manufacturerId>Arduino</manufacturerId>
            <modelId>Arduino UNO R3</modelId>
            <serialNumber>75331313133351E0D112</serialNumber>
        </deviceTypeId>
        <context>
            <location>
```

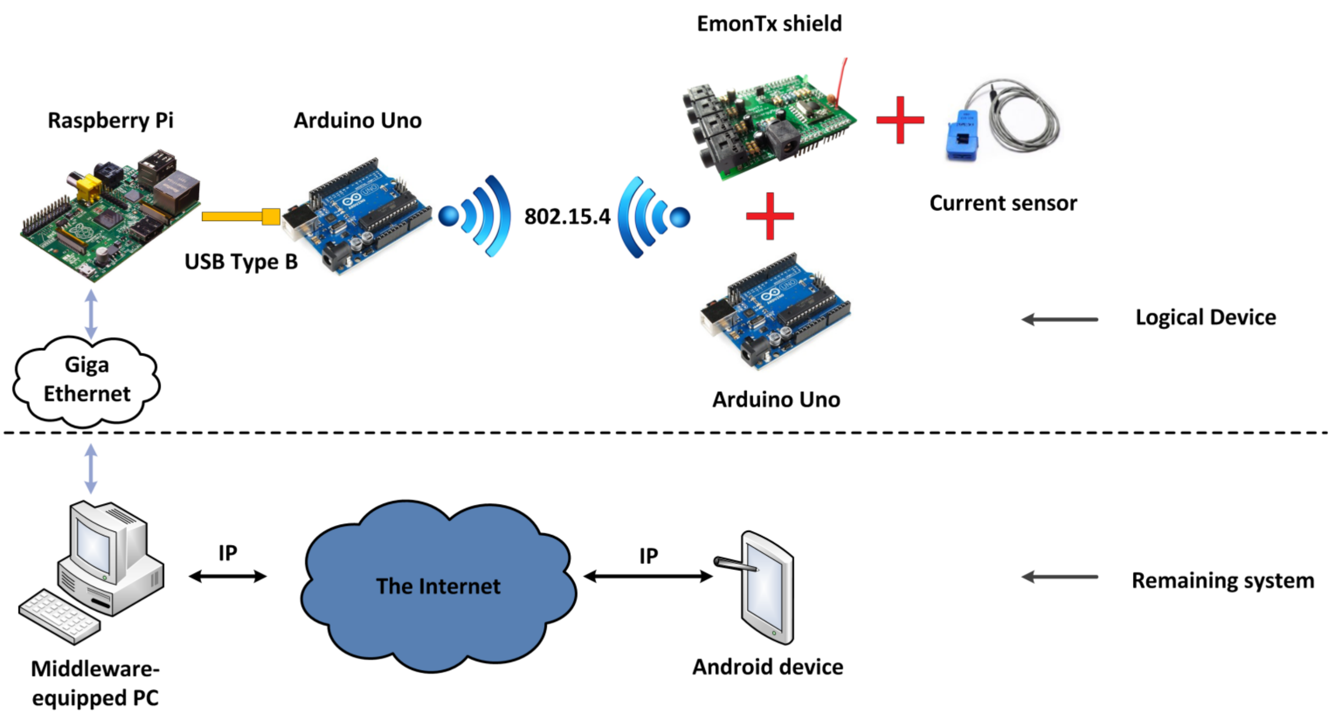
```
                <longitude>3.3</longitude>
            </location>
        </context>
    </payload>
</message>
```

```
root@raspberrypi:~# cat /dev/serial/by-id/usb-Arduino__www.arduino.cc__0043_7533
13131333351E0D112-if00 > /opt/apache-servicemix-minimal-4.5.3/arduino &
```

2. **Communications level.** There are two different kinds of communications: on the one hand, standard IEEE 802.15.4 is used as a local, wireless one to transmit data from the shield-connected current sensor to the Arduino Uno. On the other hand, regular Internet connections will be enabled so as to use them to be accessed via REST interfaces. In a nutshell, the Wireless Sensor Network-like scenario will use IEEE 802.15.4 for communications, and the remaining parts of the deployment use the Internet Protocol;
3. **Middleware level.** A computer is used as the Central Controller with the middleware components already described: a Fuse ESB with several bundles running inside, each of them containing the services that are used, and the Logical Devices representing the hardware pieces that belong to the system;
4. **Application level.** A web browser was used to obtain the information and have it readable. As depicted before, an REST-connected Android application was also employed to monitor which devices are registered, what services they are capable of providing, and regular service requests. Also, the time required to register a device (that is to say, creating a logical device that will become semantically registered) was tested.

The overall appearance of the system that has been tested is shown in Figure 26. While there are several pieces of hardware used to build what represents the Logical Device, the remaining parts of the system are conceptually simple.

Figure 26. Overall view of the used components.



5.1. Measures and Discussion

As soon as the scenario described above was deployed, tests were run. There are several kinds of measures that have been collected. For example, Table 5 depicts some current measures obtained from the current sensor linked to the EmonTx Arduino shield. These measures are taken approximately every

2 seconds and the Logical Device adapts and buffers them, thus leaving them ready to be sent, if previously demanded, to the client.

Table 5. Current measurement values.

Counter	Value	Timestamp
1	71	2014-05-30T15:19:44.029
2	67	2014-05-30T15:19:46.351
3	71	2014-05-30T15:19:48.778
4	82	2014-05-30T15:19:52.25
5	112	2014-05-30T15:19:56.211

Is it necessary to keep in mind that the Logical Device is implemented in an ESB bundle installed in a Raspberry Pi. As the regular Fuse ESB would require too much computational resources, mainly in terms of the amount of memory required (1 GByte is the minimum amount of RAM memory recommended to rub Fuse ESB), the ESB version installed is Apache Servicemix Minimal 4.5.3 [45]. Thus, it can be demonstrated that it is possible to use an ESB distribution for light Logical Device implementations. Table 6 summarizes the main characteristics of the used computers.

Table 6. Equipment characteristics.

	Equipment characteristics
Middleware-equipped personal computer	CPU Intel® Core™ i3-3240 @3,4GHz, RAM 8Gbytes, Ubuntu 12.04 LTS running on VMware Player 4.0.6
Raspberry Pi	Model B, 512 Mbytes.
PC2 used alternatively to Raspberry Pi to run the logical device.	CPU Intel® Core™ 2 6400@2.14GHz, RAM 3Gbytes, Windows 7.

In order to determine the performance that can be obtained using a Raspberry Pi to implement Logical Devices two types of tests have been done: a) required time used to registry a Logical Device and b) required time to collect a data measure. Each measure is repeated changing the computer where the Logical Device is executed from the Raspberry Pi to PC2.

5.1.1 Time to Registry a Logical Service Measurement

With the Devices Registry service running in the Middleware-enabled PC and the Logical Device running in the Raspberry Pi, forty measures of the amount of time needed to register this Logical Device were taken. Time is measured from the instant when a Registry Request is sent to the Devices Registry to the moment when a Registry Response is received. The results are shown in Figure 27.

Overall, measurements are quite regular, expect for the very first one, probably due to the fact that one or more bundles at the Raspberry Pi may have not been fully deployed when the measure was taken. The average time, excluding the first measure, is 719.7 milliseconds, the median is 743.0 milliseconds and the standard deviation 295.1 milliseconds, a value that represents a 41.0% over the average. While these values are valid values for the registry operation, their dispersion is significant, probably because the Raspberry Pi is working at the edge of its possibilities. In any case, the overall results are satisfactory in the sense that in less than one second on average, registration of the hardware components that make up a Local Controller are registered in the middleware architecture of a Central Controller.

On the other hand, Figure 28 illustrates the measures observed in the registration process of the Logical Device when it runs in the PC2. In this case, statistics values are: 128.3 milliseconds as average and 122 milliseconds for median with a standard deviation of 34.8 milliseconds. If compared with the former ones, only a measure is notoriously higher than the majority of values, and the dispersion one is very low. In fact, measured values are dramatically lower for the Personal Computer than for the Raspberry Pi, at the cost of being much less portable than the latter.

Figure 27. Required time to registry a Logical Device located at a Raspberry Pi.

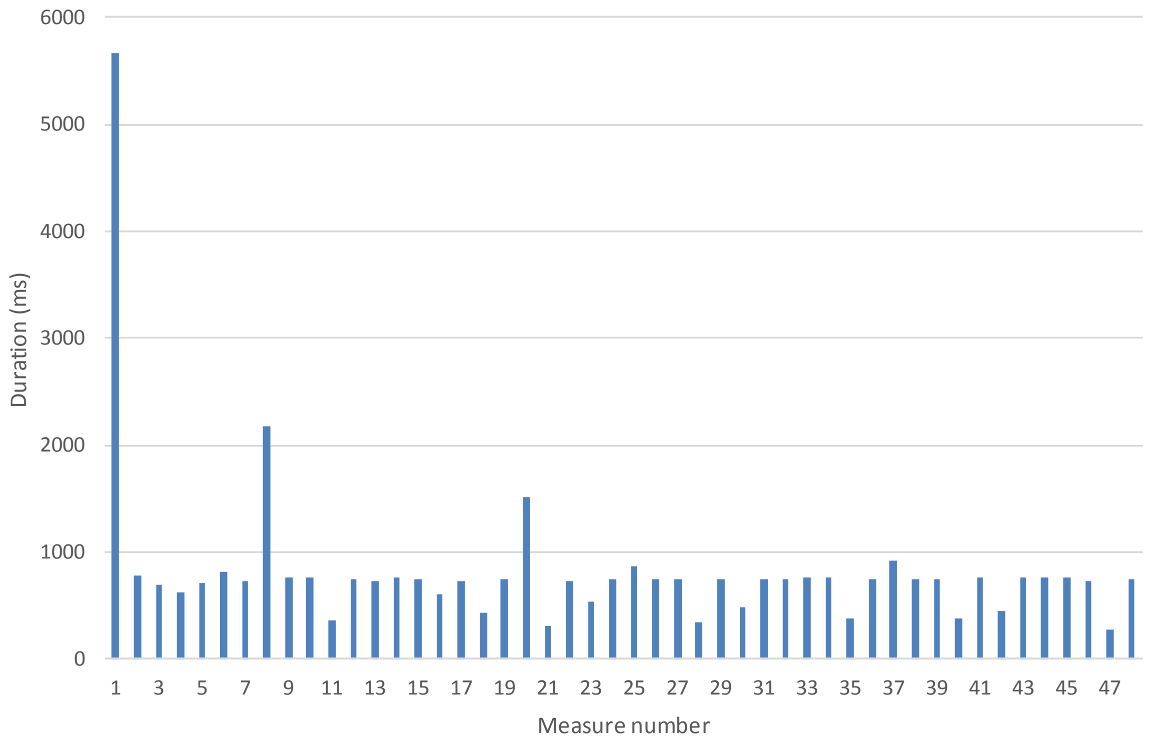
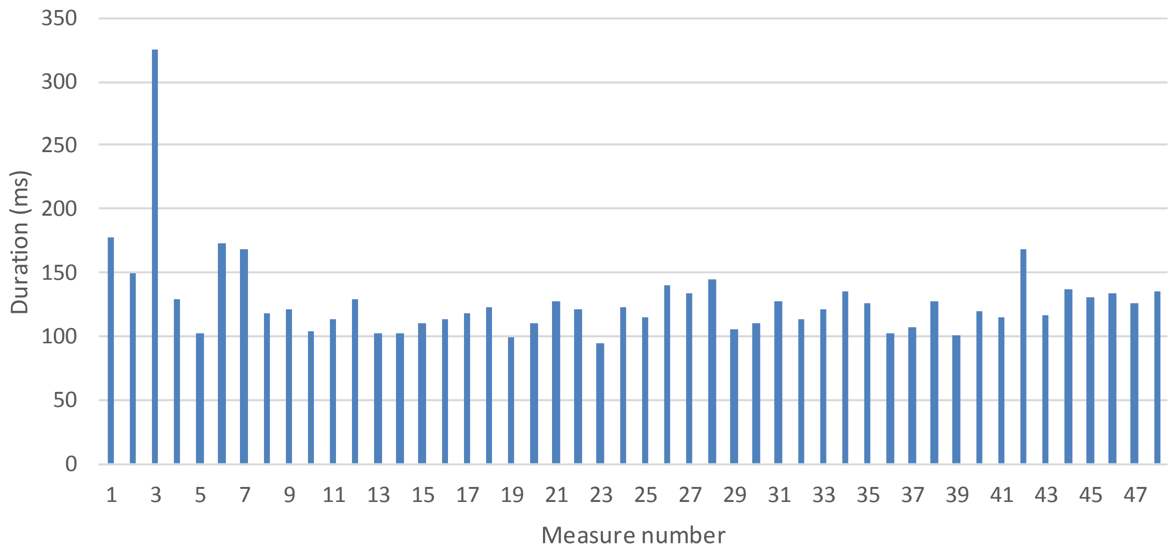


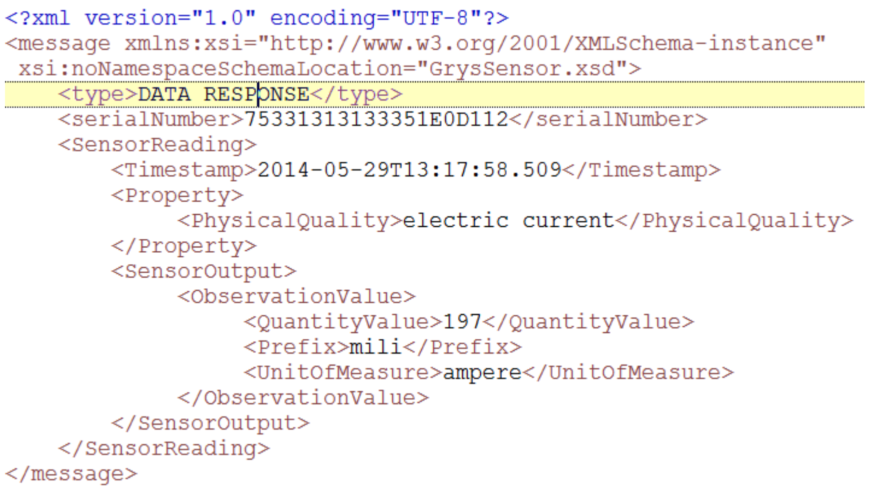
Figure 28. Required time to registry a Logical Device located at a Personal Computer.



5.2.2 Time to Collect One Measurement

The Support service uses the functionalities provided by the Harvesting Common services (see Figure 5) that, so as to reach the Logical Device, employ the ones provided by the Communications Component. These services are running in the middleware-equipped PC shown before. Figure 29 describes the DATA RESPONSE sent from the logical sensor with the electrical current value.

Figure 29. Data response message with a sensor measure.



```
<?xml version="1.0" encoding="UTF-8"?>
<message xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
 xsi:noNamespaceSchemaLocation="GrysSensor.xsd">
    <type>DATA RESPONSE</type>
    <serialNumber>75331313133351E0D112</serialNumber>
    <SensorReading>
        <Timestamp>2014-05-29T13:17:58.509</Timestamp>
        <Property>
             <PhysicalQuality>electric current</PhysicalQuality>
        </Property>
        <SensorOutput>
             <ObservationValue>
                  <QuantityValue>197</QuantityValue>
                  <Prefix>mili</Prefix>
                  <UnitOfMeasure>ampere</UnitOfMeasure>
             </ObservationValue>
        </SensorOutput>
    </SensorReading>
</message>
```

This test aims to determine the maximum possible data collection frequency. For this purpose, one hundred data measurements have been taken using a loop in the Support service. At the same time, the Logical Device has been programmed to return a random current value. In this way, the obtained measures will correspond to the time used by the messages to get transmitted throughout the Ethernet network and cross the software layers of the middleware architecture.

Results when the Logical Device is running in a Raspberry Pi are shown in Figure 30. Statistical values for this measure are: average 63.6 milliseconds, median 54.0 milliseconds and standard deviation 75.9 milliseconds. There are two values quite higher when compared to all the others, probably produced by network or operating system delays. Should these values be eliminated, average is 53.06 milliseconds and the standard deviation 15.1 milliseconds. These values provide a maximum data gathering frequency of 15.7 measures per second. It can be inferred that the required amount of time for data to be collected is almost negligible for an end user, thus proving that the middleware architecture is seamlessly integrated with all the other hardware and software components of the system.

When a Logical Device is installed in PC2 as an alternative to the Raspberry Pi the obtained results will have the appearance shown in Figure 31.

Statistical data for this test are: average 40.6 milliseconds, median: 40.0 milliseconds and standard deviation 5.1 milliseconds. There are two ideas to be extracted from these results: to begin with, the required amount of time to collect the information is lower for the PC than for the raspberry Pi, but not to a great extent, so the used messages are being processed with ease by very different hardware. Additionally, standard deviation is lower, so the required time periods are more similar among each other; this can also be inferred from the very small difference between average and median values. It is possible to get 24.6 measures per second by using PC2.

Finally, in case a Logical Device is storing data that needs to be accessed, Figure 32 depicts an experiment where the Logical Device is running in the Raspberry Pi, and gathered values must be read from a file. This task implies an increment of 127.5 milliseconds over the average obtained when a random data was returned. Average value is 191.1 milliseconds, median 182.5 milliseconds and standard deviation 80 milliseconds. In this chart it is also possible to find two values out of the common band of values that increase the standard deviation. Clearly, accessing a file is a more time consuming task that collecting the information on the fly.

It must be noted that while the information obtained from the tests done is basically about registry time periods and electric current measurements, judging from the obtaining amounts of time and the data itself, it can be regarded as a proof of the viability of adding a middleware architecture to a system deployed in a microgrid: the amount of time needed to obtain the tested functionalities is negligible for a regular user, and the reliability of the whole architecture when requesting measurements or registering Logical Devices is very high.

Figure 30. Data collection time in a Raspberry Pi for random values.

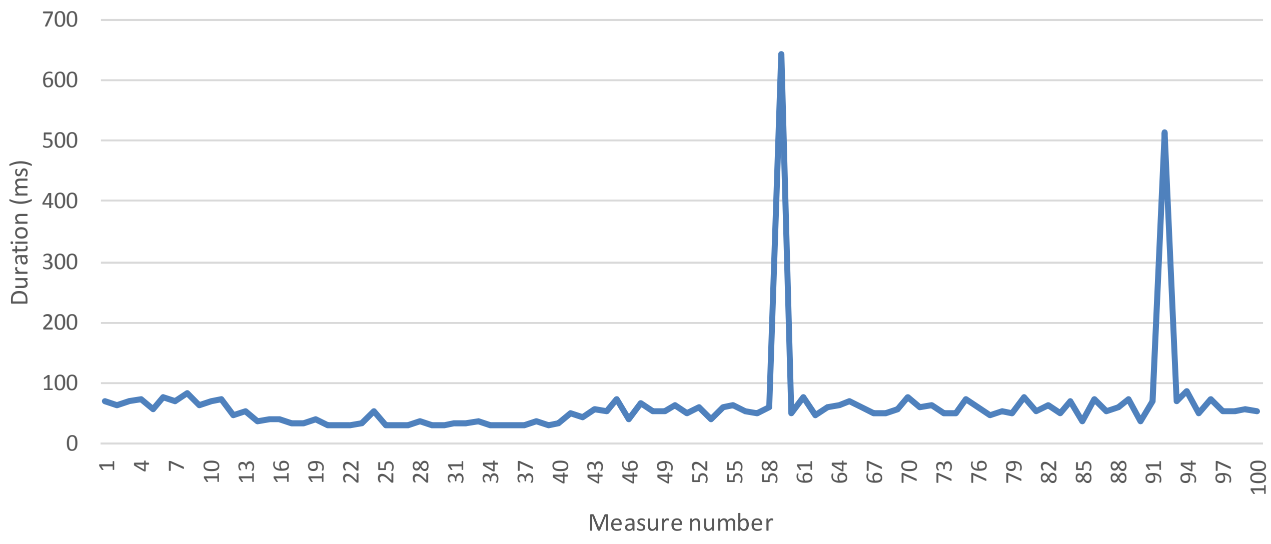


Figure 31. Data collection time in a Personal Computer for random values.

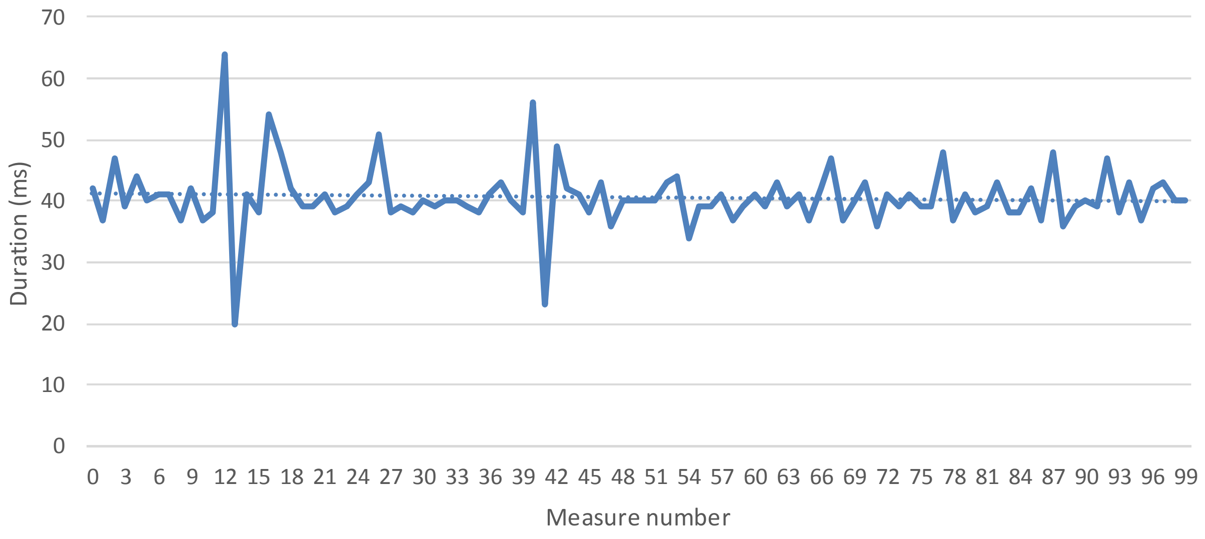
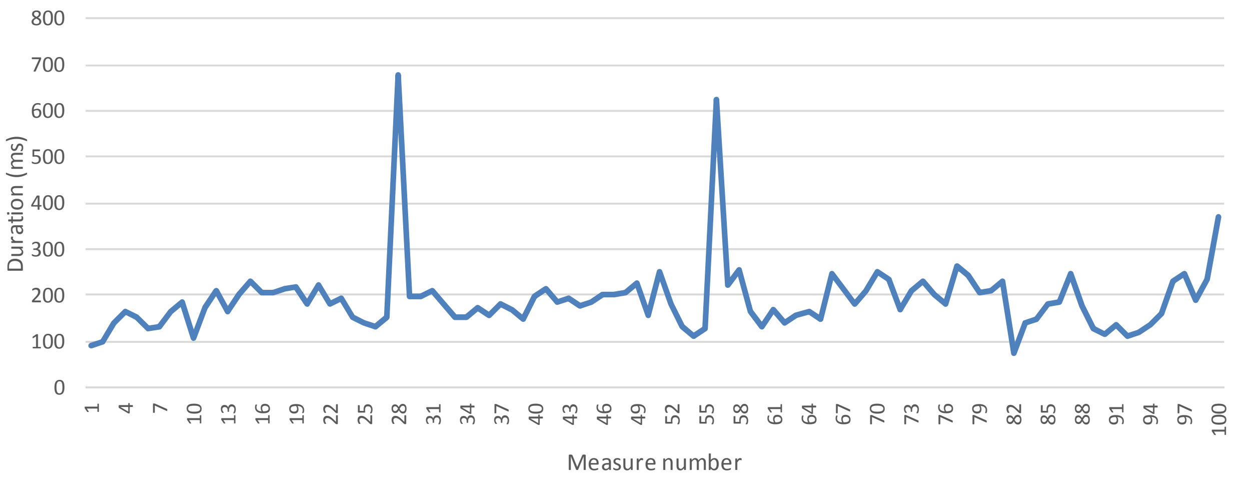


Figure 32. Data collection time for a Raspberry Pi reading data from a file.



6. Conclusions and Future Works

This paper has presented a proposal of a middleware architecture specially designed for a Smart Grid environment compliant with IEEE P2030 guidelines and CEN-CENELEC-ETSI SGAM framework. It provides a holistic solution in middleware architectures designed for the Smart Grid, with a high level of semantic data treatment and context awareness able to provide some advantages over the existing solutions, as the following major characteristics have been integrated in a harmonized way:

1. Semantic data treatment is implemented using a service-oriented ontology that is focused on services and information management regarding devices. This ontology offers smart data treatment specially adapted to the Smart Grid. It has been designed and implemented to describe all the functionalities and characteristics of the existing services in the middleware;
2. A software representation of the existing devices of a system has been achieved by using Logical Devices. This solution grants a more specific device management for operations such as discovery or service registration;
3. A context aware solution for device failures that provides a replacement mechanism for the Logical Device associated has been developed so as to carry on with the usual performance of the system;
4. This middleware proposal follows the Service Oriented Architecture model, which provides flexible design solutions offering support for several communications mechanisms and interface creations, including external RESTful interfaces. In addition to that, the middleware components are highly autonomous, and there is a reasonable degree of portability and scalability among systems;
5. Fuse ESB-based implementation solves service integration issues over a distributed and heterogeneous environment;
6. The different tasks have been distributed among different elements of the layered architecture so that the addition of new Common and High Level services to solve future microgrid challenges will be less troublesome;
7. Logical Devices have been proven to be able to run in medium-to-low capability devices. Since they are not dependent on the hardware that they are installed on (only a functional ESB is required), they can be ported to other devices as BeagleBone boards, *etc.*

Thus, it can be considered that the proposal successfully tackles the previously exposed weaknesses of other related works with regards to the previously inferred non-functional requirements. Nevertheless, there are several future works that will be dealt with in the near future involving this semantic, context-aware middleware architecture for the Smart Grid environment. Portability of the presented services will be further tested in pilots of differing nature, as the final planned target is checking middleware performance under different scenarios to tune up different features if required. The final objective would be obtaining fully portable bundles that require little to no human intervention at all, so as to become integrated in any system, as long as they are running under ESB-friendly environments. Furthermore, context aware capabilities will be expanded; a more advanced engine that will gather information from the contextual conditions of the system and, by doing so, trigger events and actions according to the former is under study. Also, OWL-based reasoning functionalities using the stored knowledge as an information source could be considered. Finally, tests could be expanded to involve more devices of differing natures, such as laptops or small capability devices wirelessly interacting with each other.

Acknowledgments

The research work presented here has been done as part of the duties and tasks of the e-GOTHAM ("Sustainable—Smart Grid Open System for the Aggregated Control, Monitoring and Management of Energy") research project, an ARTEMIS initiative (ART Call 2011 295378, [46]) that has among other objectives creating a new aggregated energy demand model that will integrate renewable energy sources, prioritizing green energy over fossil fuels and improving management of energy demand and supply. The research group belonging to the Technical University of Madrid (UPM) that has undertaken the duties related to the development of this middleware architecture is called Grupo de Redes y Servicios de próxima generación (Next Generation Networks and Services Group, GRyS), integrated as part of the CITSEM (Research Center on Software Technologies and Multimedia Systems for Sustainability, Centro de Investigación en Tecnologías Software y Sistemas Multimedia para la Sostenibilidad). Among the people consulted during the development activities, Luis Aguilar and Luis Manuel Moreno must be mentioned.

Author Contributions

Rubén de Diego has made contributions on the study of the assessed proposals and in the architecture development. He has also been involved in the tests carried out to evaluate the performance of the deployment.

José-Fernán Martínez has made contributions to the study made on the presented Smart Grid proposals and their evaluation. He has also contributed to the development of the middleware architecture described in this manuscript.

Jesús Rodríguez-Molina has contributed to the study of the proposals, their evaluation criteria and the development of the middleware architecture. He has also taken part in the performance tests.

Alexandra Cuerva has made contributions on the semantic features present in the middleware architecture, along with the content related to semantics throughout the whole manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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