Computer Standards & Interfaces 38 (2015) 133–143

Contents lists available at ScienceDirect

Computer Standards & Interfaces

journal homepage: www.elsevier.com/locate/csi

Message-oriented middleware for smart grids

Michele Albano [*], Luis Lino Ferreira, Luís Miguel Pinho, Abdel Rahman Alkhawaja

CISTER/INESC-TEC, ISEP, Polytechnic Institute of Porto, Rua Dr. António Bernardino de Almeida, 431, 4200-072 Porto, Portugal

ARTICLE INFO

Article history:
Received 30 April 2013
Received in revised form 6 August 2014
Accepted 12 August 2014
Available online 21 August 2014

Keywords:
AMQP
RabbitMQ
DDS
XMPP
Publish–subscribe

ABSTRACT

In order to increase the efficiency in the use of energy resources, the electrical grid is slowly evolving into a smart(er) grid that allows users' production and storage of energy, automatic and remote control of appliances, energy exchange between users, and in general optimizations over how the energy is managed and consumed. One of the main innovations of the smart grid is its organization over an energy plane that involves the actual exchange of energy, and a data plane that regards the Information and Communication Technology (ICT) infrastructure used for the management of the grid's data.

In the particular case of the data plane, the exchange of large quantities of data can be facilitated by a middleware based on a messaging bus. Existing messaging buses follow different data management paradigms (e.g.: request/response, publish/subscribe, data-oriented messaging) and thus satisfy smart grids' communication requirements at different extents.

This work contributes to the state of the art by identifying, in existing standards and architectures, common requirements that impact in the messaging system of a data plane for the smart grid. The paper analyzes existing messaging bus paradigms that can be used as a basis for the ICT infrastructure of a smart grid and discusses how these can satisfy smart grids' requirements.

1. Introduction

The energy grid has evolved from a unidirectional production/transmission/distribution/consumption pipeline to a complex system where every level of the pipeline comprises multiple actors that can produce energy, as well as store it and exchange it with many other actors. Different architectural solutions have been proposed, with the goal of facilitating the operational control of such increasingly complex system. The energy grid can now interact with the final user to control his energy consumption, by either direct control on some of his appliances (for example, the washing machine) or indirect control, by providing fine grain resolution on the cost of the energy at a given day and time, such that the final user tunes up his own schedule for the energy consumption. The grid can also promote cooperation among different prosumers (both producers and consumers of energy) to enable more efficient energy usage, particularly in what concerns consuming on the spot for renewable energies.

Traditional techniques cannot cope with the design of energy grids, since these are characterized by a large number of actors and mechanisms, controlled by many different entities, which are kept together by a plethora of connections to exchange energy and data. Thus, the paradigm of the "smart grid" has emerged, in which the interaction between the involved actors is articulated into an energy plane and a data plane, where the latter provides the required information used to orchestrate the efficient allocation of energy to different energy-consuming actors as well as to different storage units.

This smart grid paradigm led to the emergence of a plethora of systems and architectures, with many common points as well as many differences. One of the common points is related to the size and complexity of smart grid systems. In fact, an energy grid usually serves a large number of users by providing them the energy they consume. This characteristic, together with the fact that each actor is controlled by an independent entity, leads to organize smart grids using loosely-connected, service-oriented, scalable architectures, communicating via standard protocols [1] and the introduction of a messaging bus [2] can limit the complexity of the system.

The smart grid can and must adhere to standards to pursue the three goals [3] of: i) improving interoperability between neighboring systems; ii) limiting the complexity of the system when it scales to a large user base; and iii) opening new markets to technology providers and utilities companies. Currently there are (too) many standards that address the smart grid area, focusing on different components or layers of the grid and providing different views on the system, but the latest standardization activities are leading different approaches to convergence on a common semantics.

While adhering to standards is useful to normalize "what" is communicated in the system, the introduction of a messaging bus takes care of normalizing "how" the data is exchanged. The communication functionalities of the messaging bus, and the services supporting it, can be entrusted to a middleware located over the communication

---

[*] Corresponding author.
E-mail addresses: Mialb@isep.ipp.pt (M. Albano), Llf@isep.ipp.pt (L.L. Ferreira), lmp@isep.ipp.pt (L.M. Pinho).

http://dx.doi.org/10.1016/j.csi.2014.08.002
0920-5489/© 2014 Elsevier B.V. All rights reserved.

stacks but under the business logic of the applications. The middleware abstractions facilitate the interaction between different components, and also between the "mechanisms" elements and the "politics" elements of the smart grid, which are the traditional categories used to divide the system components into two sets performing different functions. The mechanisms collect data from the surrounding environment, and actuate on the physical world. The politics contain logic to perform computations based on the information received by the underlying mechanisms. After retrieving data from mechanisms, and processing the data, the politics send commands back to the mechanisms, to perform energy-efficient and business-efficient actions. Fig. 1 highlights the duality between politics and mechanism components.

In the most common type of smart grid, the sensors and actuators are too limited in computational power to be able to support a complex protocol, like the ones used in the middleware. The topology is centered on a gateway installed in the users' houses (e.g. the Energy Service Interface (ESI) in the National Institute of Standards and Technology (NIST) vision [4], which will be described in Subsection 2). The gateway manages a subset of the sensors and actuators deployed in the house, and it is connected to the internet to interact with energy services via a data plane. This topology carries the name of Home Area Network (HAN), and in the rest of this work the gateway installed in the user's HAN will be called HAN Gateway, or HAN GW.

As far as current smart grids are concerned, a user's house usually hosts a number of HANs, one per each vendor of technology, e.g. one for the solar panels and one for controlling the Heating, Ventilation and Air Conditioning (HVAC) system. In this case, the middleware would extend itself only up to the HAN Gateway; the latter would decode the protocol used in the middleware, and then interact with the sensors and actuators associated with it. The middleware supports multiple event processing agents that exchange information between event producers, event consumers, and other agents.

In this paper, we focus on the approaches for supporting the data plane dimension of the smart grid, and in particular the deployment of message-oriented middleware. The remainder of the paper is organized as follows. Section 2 analyzes current standardization efforts and technical initiatives for smart grids and collects the architectural and technological requirements. Section 3 presents messaging bus paradigms and architectures that can potentially satisfy these requirements. Section 4 then provides some use cases, while Section 5 discusses how to select the middleware to be employed to support the functionalities of a particular standard. Section 6 draws some conclusions and wraps up the paper.

2. Standardization efforts for smart grids

In the past few years a number of companies, research centers and standardization bodies worked toward facilitating the design and implementation of smart grids. A number of legacy and closed technologies have created parallel subsystems in the HANs of final users, and then have been refined into standards. Afterwards standardization activities had the goal of organizing existing standards and produce best practices to select the right approach to be used in a given smart grid design.

This work is centered on ICT middleware that can support the smart grid's data plane, and thus the analysis of the smart grid use case was instrumental for eliciting the requirements for middleware for the smart grid. Not to be lost in systems' details, the internals of existing approaches were disregarded, and instead the focus has been on intended scenarios and requirements of the smart grid.

An analysis of existing standards for smart grids can be driven, at top level, by the vision of system engineering, which considers building systems by first providing system architecture, and then refining it into a system design by adding details such as data encoding, and protocols. We consider that existing standards on smart grids can be categorized in three sets, depending on the level of detail they provide such as:

Meta-architectures expand the architectural analysis toward embracing different architectures, with the goal of proposing an abstract model which can be mapped onto a family of architectures. A particular architecture is identified as an instance of the family.

Architectures limit the content of the standards to the proposed smart grid architecture and to the functionalities that must be supported.

Design standards go deep into low-level details, like data encoding and protocols to be employed in the smart grid.

Two examples of meta-architectures are the NIST Canonical Data Model (CDM), which proposed a reference model in "NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 2.0" [4], and the joint effort of CEN (European Committee for Standardization), CENELEC (European Committee for Electrotechnical Standardization) and ETSI (European Telecommunications Standards Institute), which led to a meta-model called Smart Grid Architecture Models (SGAM) [5]. Meta-architectures are too general to draw clear requirements for the ICT middleware that can support it. Anyway, the meta-architectures agree regarding the large scale of the proposed deployments, which leads to the requirement of scalability. Moreover, the actors in the scenario must be able to associate different levels of urgency to their messages, thus the requirement of providing prioritization in the underlying messaging bus.

Two important design standards are the Common Information Model (CIM) [6] [7] by the International Electrotechnical Commission (IEC), and the Smart Energy Profile version 2.0 (SEP) [8], which is a profile of the ZigBee protocol suite. Both design standards were developed in order to allow effective data exchange among different information systems, and they mainly specify the interfaces between components of an energy grid, therefore establishing a common language and protocol for interoperability between software modules, potentially from different vendors. As an example, SEP has been developed to map directly to the Common Information Model (CIM), and it adheres to the NIST framework, and thus SEP inherits CIM characteristics. The approach considers that some messages require Quality of Service (QoS), both in terms of message prioritization and of delivery semantics (e.g. delivery guarantees). Finally, the solution must support a scalable and dynamic scenario, since the design standards explicitly consider systems where

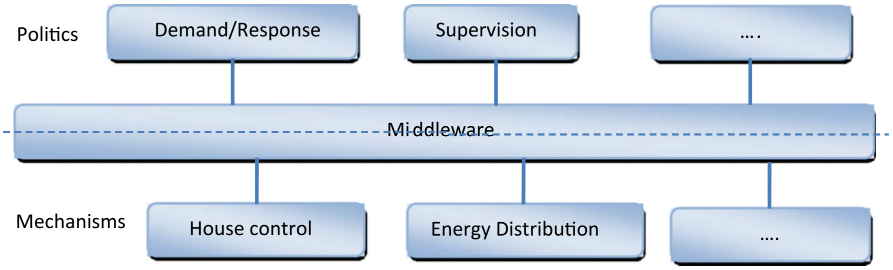

Fig. 1. Politics/mechanisms duality.