An Analysis of Reference Architectures for the Internet of Things

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ABSTRACT

The Internet of Things (IoT) is a paradigm in which smart objects actively collaborate with other physical and virtual resources available in the Internet. IoT environments are characterized by a high degree of heterogeneity, encompassing devices with different capabilities, functionalities, and network protocols. To address such a heterogeneity, some platforms have been proposed aiming at abstracting away the specificities of such devices and promoting interoperability among them. Nevertheless, the lack of standardization in IoT makes these platforms to often not properly address several important requirements in this context. In this context, reference architectures can define an initial set of building blocks for IoT environments and to provide a solid foundation for leveraging its wide adoption. In this paper, we introduce two recent reference architectures for IoT, namely the IoT Architectural Reference Model and the architecture proposed by WSO2. By analyzing the characteristics of these architectures, we intend to shed light on important issues for future research on reference architectures for IoT.

Categories and Subject Descriptors

C.2.4 [**Computer-Communication Networks**]: Distributed Systems—*distributed applications*; D.2.11 [**Software Engineering**]: Software Architectures—*domain-specific architectures*

General Terms

Design, Standardization

Keywords

Internet of Things, IoT, reference architecture

1. INTRODUCTION

The *Internet of Things* (IoT) [1] has rapidly evolved in recent years as an umbrella term for smart objects, services, and applications connected through the Internet. Such smart things can also collaborate with other physical and virtual resources available in the Web, thus providing value-added information and functionalities for end-users and/or applications. Furthermore, the dissemination of the IoT paradigm has a wide potential to produce a considerable impact in the daily lives of human beings with the emergence of new applications and systems from several real-world domains, such as energy, health care, and environmental urban monitoring.

IoT environments are inherently characterized by a high degree of hardware and software heterogeneity, encompassing devices with different capabilities/functionalities and network protocols. In this context, IoT platforms and systems have been recently proposed to abstract away the specificities of such devices from applications and/or end-users, to promote interoperability among them, and to contribute and leverage the development of IoT applications [10]. These architectures are mainly intended to: (i) efficiently support the heterogeneity and dynamics of IoT environments; (ii) provide abstractions over physical devices and services to applications and users; (iii) provide device management and discovery mechanisms; (iv) allow connecting these elements through the network; (v) manage large volumes of data; and (vi) address security and scalability issues [2].

It has been possible to notice that the IoT platforms proposed in the literature mainly focus on the seamless integration of heterogeneous devices and the provision of high-level models for developing applications [2, 9]. However, the lack of standardization in the IoT context leads these solutions to adopt different programming models that are not compatible with each other, thus becoming an obstacle to the full interoperability required by such a paradigm. Moreover, they do not properly cope with scalability issues and neglect important concerns in their conception, e.g., privacy and security. In fact, there is still no complete consensus on which functional elements and non-functional properties must be addressed by platforms targeting IoT.

In order to mitigate the aforementioned limitations, *reference architectures* arise as relevant means of defining an initial set of building blocks for IoT environments and providing a solid foundation to leverage a wider adoption of this paradigm. Nonetheless, reference architectures for IoT are a very recent research topic and few proposals have been introduced so far. In this paper, we introduce and discuss two reference architectures proposed for IoT, namely the IoT Architectural Reference Model (IoT ARM) [3] and the architecture developed by the WSO2 company [5]. Our main goal

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is to analyze these two proposals in terms of their support for addressing the main requirements of the IoT paradigm, thus shedding light on important issues to be addressed in future research on reference architectures for IoT. It is important to highlight that we do not intend to herein present the state of the art on reference architectures for IoT, but to analyze the characteristics of these architectures and discuss some relevant issues in this context.

The remainder of this position paper is organized as follows. Sect. 2 highlights the relevance of reference architectures for IoT and introduces the previously mentioned solutions in this context. Sect. 3 presents a brief discussion built upon an analysis of these reference architectures. Finally, Sect. 4 provides some concluding remarks.

2. REFERENCE ARCHITECTURES FOR IOT

Despite the several definitions found in the literature, reference architectures can be understood as abstract architectures encompassing knowledge and experiences in a given application domain, thus being able to facilitate and guide development, standardization, interoperability, and evolution of software systems in such a domain [8]. Establishing reference architectures is an important issue in IoT as they can describe both essential building blocks as well as design choices for dealing with functional and non-functional requirements in IoT environments. Therefore, directions provided by a reference architecture are important elements to guide and facilitate the development of IoT systems coping with their increasing scale and complexity. Furthermore, reference architectures allow constructing systems able to properly fulfill the existing requirements of IoT by taking into account the set of building blocks provided by such architectures. Finally, considering that developing interoperable solutions is an important concern in the IoT scenario, such an interoperability can be achieved by constructing system architectures founded upon a reference architecture.

In the following, we introduce two recent reference architectures for IoT, namely (i) the IoT Architectural Reference Model (IoT ARM) [3], developed within the Internet of Things Architecture European project[1], and (ii) the architecture proposed by the WSO2 company [5]. The former was established upon a reference model aiming to be a baseline for IoT system architectures, in a top-down manner. In turn, the latter was conceived by following a bottom-up approach based on the expertise of WSO2 in the development of IoT solutions.

2.1 IoT ARM

The IoT ARM proposal is based on the establishment of an architectural reference model encompassing (i) a reference architecture and (ii) a set of key features to construct IoT concrete architectures. As shown in Fig. 1, this reference architecture provides high-level architectural *views* and relevant *perspectives* for constructing IoT systems. Such architectural views offer descriptions that allow viewing an architecture under different angles and can be used when designing and implementing a concrete architecture. In turn, the perspectives represent set of tasks, tactics, directives, and architectural decisions for ensuring that a given concrete system accomplishes one or more quality attributes shared by one or more architectural views. These architectural views and perspectives are briefly described in the following. More details can be found in [3].

[1] Internet of Things Architecture (IoT-A): http://www.iot-a.eu/

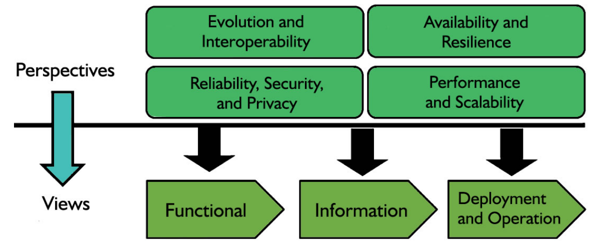

Figure 1: Views and perspectives of the IoT ARM [3].

Functional View. As depicted in Fig. 2, the *Functional View* describes nine functionality groups, each one with one or more functional components. Despite this view specifies the basic functional components, it does not specifies the interactions among such components as they typically depend on design decisions that are not made at this level of abstraction, but when developing the concrete architecture.

Information View. One of the main purposes of connected smart objects in IoT is the exchange of information among each other and also with external systems. Therefore, this view is concerned about how representing relevant information in an IoT system in terms of static information structures. Moreover, it describes the components that handle information, the dynamic information flows through the system, and the life cycle of information within the system. The main element of this view is the *virtual entity*, which models a physical element of interest in the system.

Deployment and Operation View. Connected and smart objects in IoT can be realized in many different ways and can communicate by using many different technologies. In addition, different systems need to communicate with each other in a compliant way. To tackle such issues, this view aims to address how an IoT system can be realized by selecting the proper technologies and making them to communicate and operate, as well as to offer a set of guidelines to drive developers/architects through the different design decisions that they have to face in the system development. Three main elements are encompassed by this view, namely (i) devices, (ii) resources, and (iii) services. Nonetheless, a complete analysis of all technological possibilities and their combinations goes beyond the scope of this view.

Besides the aforementioned views, the IoT ARM offers four perspectives regarded as the most important ones for IoT systems, namely: (i) *Evolution and Interoperability*; (ii) *Availability and Resilience*; (iii) *Reliability, Security, and Privacy*; and (iv) *Performance and Scalability*. Each of these perspectives has more or less impact over each view and contains: (i) the desired *quality* addressed by the perspective; (ii) *requirements* relevant for IoT and related to the perspective; (iii) *applicability* of the perspective to (types of) IoT systems; (iv) *activities* suggested to achieve the desired qualities; and (v) architectural *tactics* related to the perspective and that can be used by an architect when designing the system. This set of perspectives seems to be relevant for system developers as several quality parameters have to be taken into account, even more for the IoT domain. Moreover, these perspectives are intended to provide a framework for reusing knowledge and fostering the application of a systematic approach to ensure that a given system fulfills the required quality attributes.

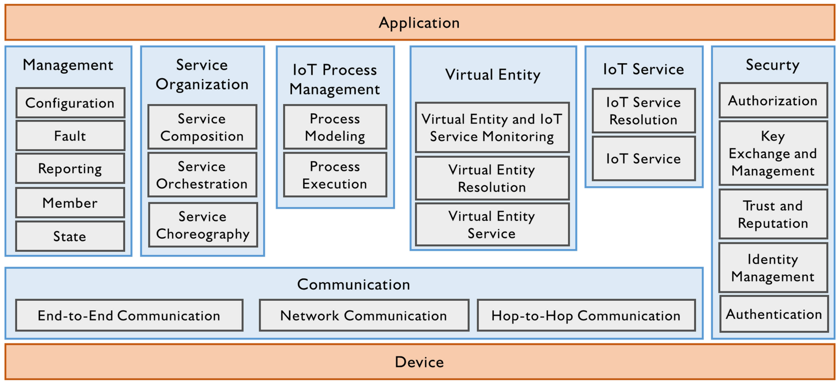

Figure 2: Functional groups and components of the *Functional View* of the IoT ARM [3].

2.2 WSO2's Reference Architecture

The WSO2 company has proposed a reference architecture based on its expertise in the development of IoT solutions [5]. Such a reference architecture encompasses devices and both server-side and cloud architectures required to interact with and manage these devices. The main goal is to provide architects and developers with an effective starting point that is able to cover most of the requirements of IoT systems and development projects. However, it does not focus on detailing how a particular client-server, hardware or cloud architecture should work as the reference architecture is independent on specific providers and it is not bound to a specific set of technologies.

Fig. 3 illustrates the reference architecture proposed by WSO2. This architecture consists of a set of five layers, each one performing a well-defined functionality:

(i) *Device Layer*, in which each device should have a unique identifier and direct or indirect communication with the Internet;

(ii) *Communications Layer*, which supports device connectivity, with multiple potential protocols;

(iii) *Aggregation/Bus Layer*, which supports, aggregates, and combines communications from several devices, as well as bridges and transforms data among different protocols;

(iv) *Event Processing and Analytics Layer*, which processes and reacts upon events coming from the *Aggregation/Bus Layer*, as well as can perform data storage; and

(v) *External Communications Layer*, through which users can interact with devices and access data available at the system.

The WSO2's reference architecture also provides two additional transversal layers, namely: (i) *Device Management Layer*, which communicates with devices through different protocols and allows remotely managing them; and (ii) *Identity and Access Management*, which is responsible for access control and security directives.

It is important to highlight that each of the layers proposed in the WSO2's reference architecture can be instantiated by using specific technologies that better suit the IoT system under construction. For instance, multiple protocols such as the well-known HTTP (*HyperText Transfer Protocol*) and the recent, lightweight CoAP (*Constrained Application Protocol*) can be used to support communication among devices within the *Communications Layer*.

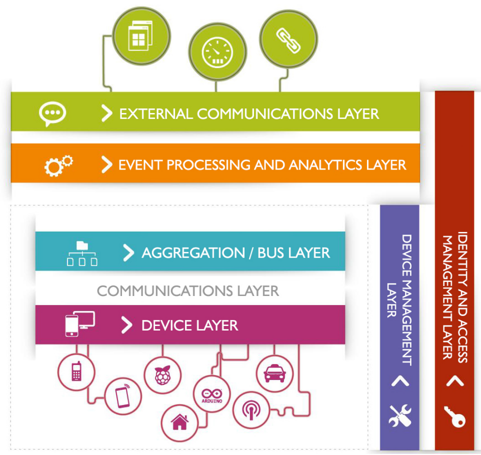

Figure 3: WSO2's reference architecture [5].

3. DISCUSSION

In the IoT context, there is a set of requirements to be fulfilled by platforms and systems aiming at meeting needs of users and applications, as well as addressing the challenges that arise from this scenario. The literature often mentions some requirements regarded as essential for IoT platforms [2, 4, 7]: (i) *interoperability* among the several existing devices, services, and applications; (ii) *device management and dynamic discovery*; (iii) gathering, management, and processing of contextual information, i.e., *context-awareness*; (iv) support to *scalability* to manage the increasing amount of devices; (v) *management of large volumes of data* generated by smart objects and transmitted through the network; (vi) data *security*, *integrity*, and *privacy*; and (vii) *dynamic adaptation* to ensure availability and quality of applications at execution time. Table 1 summarizes how the elements of both IoT ARM and the WSO2's reference architecture encompass these requirements. In this table, the ✓ symbol indicates that the requirement is fulfilled, the ○ symbol indicates that the requirement is partially fulfilled, and the × symbol indicates that the requirement is not fulfilled.

As shown in Table 1, most of the aforementioned requirements are not addressed by the functional components specified by the *Functional View* of the IoT ARM, even though some important components could be considered for a reference architecture for IoT. On the contrary, the WSO2's reference architecture encompasses most of the mentioned requirements. As the layers provided by such a reference architecture do not specifically determines the functional compo-

Table 1: IoT requirements vs. reference architectures

Requirement	IoT ARM	WSO2
Interoperability	✓	✓
Device discovery and management	×	○
Context-awareness	×	○
Scalability	✓	✓
Management of large volumes of data	×	○
Security, privacy, and integrity	✓	✓
Dynamic adaptation	×	×

nents that realize them, the *Event Processing and Analytics Layer* could contain a component responsible for processing contextual information, as well as another component able to manage large volumes of data. Nevertheless, both IoT ARM and the WSO2's reference architecture lack of elements for dynamic adaptation in IoT. This is an essential requirement that must be taken into account by reference architectures in this scenario due to the high dynamicity of IoT environments, in which devices may become unavailable as a consequence of failure, energy, network unavailability, user mobility, etc.

Another important issue related to reference architectures for IoT is the need of a comprehensive *reference model* for this context. A reference model can be defined as an abstract artifact that presents a set of common concepts and relationships between with respect to a specific domain [8]. In addition, reference models can be used when establishing reference architectures as they provide the common ground in terms of the domain elements required to be encompassed by such architectures. Unlike the WSO2's reference architecture, the IoT ARM includes the *IoT Reference Model*, a reference model composed of relevant concepts and definitions on which IoT architectures can be built. Such a reference model is also important to offer a common understanding of the IoT domain and foster development, comparison, and evaluation of architectural solutions. Moreover, reference models are important for IoT as this paradigm already suffers from an inconsistent usage and misunderstanding of the central elements [6].

4. CONCLUSION

The wide variety of requirements to be addressed and devices to be supported in the IoT paradigm results in architectures that are not easy to conceive and handle. In this scenario, it is undeniable the role played by reference architectures as means of guiding the construction of IoT systems and minimizing the existing lack of standardization when developing these solutions.

In this paper, we presented two recent proposals of reference architectures for IoT, namely the IoT ARM and the reference architecture proposed by the WSO2 company. We analyzed both proposals in the light of some well-known requirements for IoT platforms and we concluded that both proposals need to go a step further towards fulfilling the essential requirements for the IoT realm. Despite both initiatives neglect dynamic adaptation (a mandatory requirement in this scenario), we observed that the WSO2's reference architecture offers a more promising approach for IoT development as it supports all requirements in a complete or partial way. Nevertheless, the low maturity of these reference architectures clearly points out the need of more research efforts on reference architectures targeting IoT.

Finally, it is important to highlight the role played by reference models in the IoT context, such as the IoT Reference Model included in the IoT ARM. These reference models should be taken into account to allow a comprehensive understanding of the IoT paradigm and related application domains, as well as to support the establishment of reference architectures. In this perspective, we consider that both high-level and domain-specific reference models are required to provide a better baseline for generic and domain-specific reference architectures for IoT and its wide range of application domains.

5. ACKNOWLEDGMENTS

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