Interoperability in Internet of Things Infrastructure: Classification, Challenges, and Future Work

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Abstract. The Internet of Things (IoT) is an important research area, and substantial developments for a wide range of devices and IoT platforms is evident. However, one of the critical issues in IoT is that the different proprietary IoT platforms and systems are still not interoperable; unable to talk with each other. In this paper, we survey the state-of-the-art on interoperability in IoT. First, we provide a classification of techniques and schemes looking at IoT interoperability from different perspectives. For each category, we present the approaches proposed in the papers. Second, we use the interoperability classification as a baseline to compare some of the existing IoT research projects and identify gaps in the existing solutions. Our findings will help domain experts and professionals to get an overview and categorization of existing interoperability solutions in IoT and select an appropriate approach to help increase the number of interoperable IoT products.

Keywords: Fragmentation · Internet of Things · Interoperability
IoT platforms

1 Introduction

In the past decade, an abundance of IoT devices and platforms have been integrated into a wide range of applications like the market, healthcare, agriculture, utilities, energy, transportation, industrial control, and buildings, etc. Numerous studies forecast the substantial development of the IoT in the coming years. e.g., International Data Center (IDC) predicts that by 2020 the IoT solutions market will grow to $7.1 trillion [1], which will include 50 billion Internet-connected devices [2]. The European project Unify-IoT[1], lately identified that there are more than 300 IoT platforms in the current market.

Those studies are encouraging, since they suggest a tremendous impact of the IoT over the coming years. However, a new McKinsey analysis [3] points out a substantial threat to the predicted economic value: *missing interoperability*. Particularly, the

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[1] http://unify-iot.eu.

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authors state that 40% of the potential benefits of IoT can be obtained with the interoperability between IoT systems, i.e. two or more dissimilar systems are able to work together.

The current IoT market is fragmented due to the extreme degree of heterogeneity in terms of device protocols, controllers, network connectivity methods, application protocols, standards, data formats and so on. The absence of interoperability in IoT is due to a lack of standardisation [4, 5]. Vendors are intentionally defining different IoT platforms, proprietary protocols and interfaces which are incompatible with other solutions. Therefore, these vendors create different verticals and mostly closed ecosystems, which are sometimes called *stove pipes* or *silos*. To be precise, the components in one silo cannot talk to the components in another silo. For example, currently, before customers can access different IoT things they generally need a dedicated application for that particular thing preloaded onto the smartphone, such as the Philips Hue or the Belkin WeMo switch. This way the customer will have many devices, each with their own application, that work independently of each other. Also, there are data interoperability issues when developers want to create an innovative IoT application exploiting resources from different IoT applications and or/services (such as Oral-B or the Apple HealthKit) in heterogeneous domains (e.g., smart health, smart home, etc.). These issues ultimately lead to vendor lock-in of end-users.

Considering the importance of interoperability in IoT, first we need to understand interoperability and the existing solutions to analyze what is needed and identify the platforms that are ahead to help increase the number of interoperable IoT products. A classification of IoT interoperability is provided in Sect. 2. Then, based on the classification, a survey of the existing H2020 IoT research projects is presented in Sect. 3. Finally, the paper concludes in Sect. 4.

2 Interoperability Classification in IoT

Interoperability is a major topic in many different domains and there are several distinct definitions of this term in the literature. Between the diverse definitions for interoperability, we quote the most noteworthy one in our context. The IEEE defines interoperability as "the ability of two or more systems or components to exchange information and to use the information that has been exchanged" [6]. According to this definition, there are many scientific challenges: the ability to get the data, to exchange information, and the ability to use the information once it has been received.

Standard organizations and open source communities have been working to address interoperability issues in different parts or levels. We divide the existing interoperability solutions in the literature according to the level of interoperability that has been achieved between IoT platforms or systems: device level, networking level, syntactic level, semantic level, cross-platform level, and cross-domain interoperability. The categories are described in the following subsections.

Device Level Interoperability. Various communication technologies such as: WiFi, 3G/4G, ANT+, ZigBee have emerged since only one wireless technology cannot support the different requirements of IoT markets. However, in the absence of a de-facto communication standard(s), not all smart devices implement all these communication technologies. Device level interoperability refers to enabling the integration of such heterogeneous communication technologies and standards supported by different IoT devices. This layer should focus on accessing devices through unifying interfaces and the ability to integrate new devices into any IoT platform. For example, consider a smart home scenario where the light bulbs and thermostats use ZigBee, speakers communicate with Bluetooth, and switches communicate through WiF. Interoperability in this example enables different devices to understand and translate between these disparate communication technologies. An ideal IoT platform would offer a pool of standardized communication protocols where the device manufacturers may select the appropriate protocols (e.g. CoAP for constrained devices). In the literature device level interoperability relies either on a gateway solution (sometimes called protocol converters) that can be extended using plug-ins, to support new communication protocols or by instructing the device vendors to only use the protocols that are supported (such as Fosstrak[2]). For example, the Apple HomeKit[3], If-This-Then-That (IFTTT)[4] and Eclipse Ponte[5], Lightweight M2M[6] (LWM2M) are some of the gateway solutions in the literature.

Network Level Interoperability. Network level interoperability deals with mechanisms to exchange messages between systems through different networks (networks of networks) to provide end-to-end communication. To make systems interoperable, each system should be able to exchange messages with other systems through various types of networks. In this level, protocol interoperability is the main focus. At the standardization level, the IETF has developed a set of standards for routing including RPL, CORPL, and CARP and solutions for encapsulation including 6LowPAN, 6TiSCH, 6Lo, and Thread [7]. In addition, the cloud has been used as a medium to address interoperability at this level. This is called Fog of Things [8], where the computing, storage and networking services are placed at the edge of the network rather than centralized cloud servers. Fog of Things aims for providing value to the data before making it available on the web facilitating the interoperability of the devices at the edge and preparing the managed data for further applications to be interoperable. Another new solution to address interoperability in this level is software-based approaches such as Software Defined Networking (SDN) which hides all the control and management operations from the IoT devices by setting them inside a middleware layer [9], which alleviates the dependency from vendors.

Syntactic Level Interoperability. Syntactic level interoperability refers to interoperation of the format as well as the data structure used in any exchanged information or service between heterogeneous IoT system entities. This level of interoperability is important to enable smooth message transition between different IoT systems. Web

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[2] https://fosstrak.github.io/.

[3] www.apple.com/ios/home.

[4] https://ifttt.com.

[5] http://www.eclipse.org/proposals/technology.ponte/.

[6] http://technical.openmobilealliance.org/Technical/technical-information/omna/lightweight-m2m-lwm2m-object-registry.

technologies such as HTTP, JSON, REST and SOAP architecture of the World Wide Web, an approach referred to as the Web of Things (WoT) is proposed to provide greater interoperability. The WoT enables developers to connect things using web technologies and tools to create new applications and mashups. The use of the web provides a one-for-all solution for providing higher degree of interoperability, since there is no need to install/develop specific software and drivers for various devices, enabling the connection of heterogeneous devices in dissimilar domains. The Web supports different content types which resolve the challenge of working with different data formats in different applications across multiple platforms. Some of the most common web-based representations of the resources are plain text, JSON, XML and EXI. XML helps achieve syntactic interoperability by encoding syntactic information into XML documents, providing platform and language independence, vendor neutrality, and extensibility, which are all crucial to interoperability. In addition, JSON is becoming popular in the IoT market, as it is lightweight, simple and offers capabilities close to the XML ones without requiring the overhead (e.g. schema) and processing requirements of XML. Also, the Sensor Web Enablement[7] (SWE) framework provide a standard set of web service interfaces towards making it easier to share sensor data. Moreover, there are many efforts for IoT/Cloud convergence [10], and several IoT cloud-enabled platforms (ThingWorx[8], OpenIoT[9], Xively[10], and ThingsSpeak[11]) are available at the syntactic level to facilitate the aggregation of data and services from heterogeneous IoT devices.

Semantic Level Interoperability. Semantic level interoperability deals with the technologies needed for enabling the meaning of information to be shared by communicating parties. To enable building new innovative, applications which make use of data from multiple existing vertical IoT silos these systems must not only be able to exchange information but also have a common understanding of the meaning of this data. This level is concerned with data and information models which will describe: the things, application functionalities, data modeling and service descriptions, in a uniform way to enable machines to read and understand the data sent and received. For example, consider two smart lightening deployments, which have been planned and implemented independently. There is a need to combine both deployments to calculate the amount of energy gains reached. This is challenging because each deployment speaks diverse languages at the data level. They have different data formats as well as different semantics, such as units of measurement, sensor types and features, mathematic constructs and so on. The technologies from the Semantic Web have been used to address interoperability in this level. Ontologies are used to define a common, machine-readable dictionary that is able to express resources, services, APIs and related parameters (such as Semantic Sensor Network, IoT-Lite, and Architectural Reference Model). Other semantic web techniques such as Resource Description Framework

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[7] www.opengeospatial.org/ogc/markets-technologies/swe.

[8] http://www.thingworx.com.

[9] http://www.openiot.eu.

[10] https://xively.com.

[11] http://thingspeak.com.

(RDF), RDF Schema, Web Ontology Language, Linked Data and SPARQL are used for representing web resources in a uniform form and reasoning over them. In this level, there are issues such as: (1) ontology heterogeneity (e.g., ontology designed by different persons differ in the structure), terms used to describe data (e.g., t, temp and temperature are several terms to describe temperature), and the meaning of data exchanged according to the context (e.g., body temperature differs from room temperature). Semantic interoperability can be achieved through agreed-upon information models of the terms used as part of the interfaces and exchanged data. Moreover, catalog based approaches such as HyperCat[12], allows distributed data repositories to be used jointly by applications.

Cross-platform Interoperability. The Cross-Platform interoperability is the main requirement to have an interoperable IoT system. This interoperability level enables federation across different IoT platforms by integrating data from various platforms specific to one vertical domain such as smart home, smart healthcare, smart garden, etc. For example, assume that a user wants to use a single application to manage the smart lighting at home and in the office. Currently, two different applications are required; one for his home automation system, and the other for the office environment. The cross-platform interoperability level allows managing devices at both home, in the office, and other place.

Cross-domain Interoperability. Cross-Platform solutions focus on specific activities that are limited to one domain. The Cross-domain interoperability enables the federation of different platforms within heterogeneous domains to build horizontal IoT applications. This federation will not try to mandate a specific protocol at any levels of the protocol stack as the only standard across domains. In contrast, it is essential that IoT platforms can choose the desired protocols to control the end-to-end communications and data exchange (from sensors to gateways to cloud-based platforms) based on their requirement and purpose. In the literature, some IoT solution providers wrap and offer their domain-specific platforms in a 'Sensing as a Service' way [11], which provides third parties useful information with respect to a single domain. For example, a smart home platform can provide domain-specific enablers such as air temperature and the lighting conditions. These enablers can then be exploited by other IoT platforms, such as smart healthcare, to provide more innovative applications and scenarios.

3 Analysis of Current IoT Interoperability Platforms

To assess the maturity of IoT interoperability, we determine the features discussed in Sect. 2 that are supported by state-of-the-art IoT platforms. We analysed some of the recent H2020 European research projects as shown in Table 1. These projects are developing interoperability solutions at different interoperability levels. In the following, we discuss the mappings of the interoperability levels and the method and solutions provided by the projects. In addition, we discuss some shortcomings.

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[12] www.hypercat.io.

Table 1. A summary of the IoT platforms supporting interoperability requirements. ✓ = supported; ✗ = not supported

Interoperability Level	TagIt Smart!	Big IoT	SymbIoTe	AGILE	bIoTope	BUTLER	Open-IoT	UniversAAL	FIESTA-IoT	RERUM	VICINITY	VITAL	iCore	FIWARE	Inter-IoT
Device	✗	✗	✗	✓	✗	✓	✗	✓	✗	✓	✓	✓	✓	✗	✓
Network	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✓
Syntactic	✗	✓	✓	✗	✓	✗	✓	✓	✓	✓	✓	✓	✗	✓	✓
Semantic	✗	✓	✓	✗	✗	✓	✓	✗	✓	✗	✓	✓	✗	✓	✓
Cross-Platform	✗	✓	✓	✗	✓	✗	✗	✓	✓	✓	✗	✓	✗	✓	✓
Cross-Domain	✗	✓	✓	✗	✓	✗	✗	✓	✓	✗	✗	✗	✗	✓	✓

3.1 Interoperability Among IoT Platforms

TagItSmart![13] offers a set of tools and enabling technologies integrated into a platform with open interfaces to make mass-market products connected using smart printed QR codes, smartphone, and cloud. However, interoperability support is limited to the device level in this project. Similarly, the AGILE project focuses on the integration of heterogeneous devices by build a modular IoT gateway, which provides RESTful APIs to interact with user devices. The configuration of the gateway is performed automatically based on the hardware configuration, reducing the gateway setup time. The bIoTope[14] provides a platform that enables stakeholders to create new IoT systems and to rapidly harness available information using Systems-of-Systems (SoS) capabilities for connected smart objects by providing standardised open APIs for the interoperability between smart objects of different platforms. Two Open API standards are mentioned Open Messaging Interface and Open Data Format. Different from other projects, the SymbIoTe[15] provides a middleware which focuses on the federation of IoT platforms. Syntactic interoperability is addressed by a high-level API which acts like an adapter to provide a uniform access to resources of all platforms. Semantic interoperability is addressed by semantic mapping between the platform-specific information models, where platform-specific extension of one platform is translated into the platform-specific exaction of the other platform. Similar to SymbIoTe, the Big-IoT[16] project focuses on the federation between IoT platforms, developing a generic, unified Web API for smart object platforms focusing on syntactic and semantic interoperability enabling application developers to interact with different IoT platforms. Vital[17] provides syntactic interoperability using SOA and enables RESTful web services for communication interchange mechanism, and semantic interoperability is

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[13] http://tagitsmart.eu.

[14] www.biotope-project.eu.

[15] http://iot-epi.eu/project/symbiote.

[16] http://big-iot.eu.

[17] http://vital-iot-eu/.

achieved by using a common-data model using Linked Data standards such as RDF (for modelling and accessing metadata and data), JSON-LD, and ontologies. Vital also aims to integrate different IoT platform, but it doesn't address cross-domain mechanisms and is limited to smart city domain. Unlike BigIoT, Vital stores the data coming from IoT systems. The VICINITY[18] platform supports semantic interoperability (building on LinkSmart/Hydra [12]) and the use of existing ontologies (e.g. from Ready4SmartCities[19], oneM2M[20]) to provide “interoperability as a service”. The openIoT project focuses on an open source middleware for creating real-time IoT services on demand. However, it does not address cross-platform and cross-domain mechanisms. The Inter-IoT[21] aims to provide an interoperable and open IoT framework for the integration of heterogeneous IoT platforms with the consideration of cross-domain interoperability. Unlike the other existing projects, this project considers interoperability at all the mentioned levels. The FIESTA-IoT[22] project is considering the semantic interoperability of testbeds regardless of the application domain.

3.2 Interoperability Analysis Results

From the analysis of the approaches taken by different projects shown in Table 1, it is clear that most of the projects address two to five interoperability levels and their focus is providing interoperability solutions to connect existing IoT commercial and open source platforms. It is also clear that there are several efforts towards solving the interoperability issue within the application and data and semantic layer. This is because interoperability at the application level is still not mature since the existing solutions lack information models and have a strong relationship with the underlying communication architecture (RPC or RESTful design). In addition, many of the projects proposing semantic-based components are not interoperable with each other. For instance, the existing projects don't use the same data model to structure the data produced by smart objects or the same reasoning approach to deduce new knowledge from data produced by smart devices. Moreover, current implementations focus on specific IoT application domains neglecting cross-domain interoperability.

To allow the development of applications on top of IoT platforms, the IoT platforms should provide the developers an APIs to their functionality. Further, to enable an efficient development of cross-IoT platform applications, these APIs should be uniform across the platforms to the extent possible. Today's IoT platforms almost all provide a public REST API to access the services. The APIs are usually based on RESTful principles; however, most platforms use custom REST APIs and data models which complicates the mashing up of data across multiple platforms. From our results, using standards such as HyperCat (See footnote 12) should be adopted to address such issues.

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[18] http://vicinity2020.eu/vicinity.

[19] http://www.ready4smartcities.eu.

[20] www.onem2m.org.

[21] www.inter-iot-projects.eu.

[22] http://fiesta-iot.eu.

4 Conclusion

In this paper, we have answered two questions: what are the different categories for an interoperable IoT ecosystem and how interoperability has been addressed in the literature. At the device level gateways and smartphone solutions are the main method to address the connectivity issues. In the networking level, IPv6 and other standard technologies such as SDN, NFV and Fog are promising. From the Syntactic and Semantic perspectives, web technologies (open APIs, RESTful web services, JSON-like dictionary, and mashups) and semantic web technologies provide a high degree of interoperability. Finally, interoperability at the higher levels (cross-platform and cross-domain) can be achieved by the collaboration and agreement between IoT platform owners on many essential issues such as exposing the resources, interfaces, services, and data models. The main results of our research are that we believe that there is not likely a common set of standards that will be universally accepted which will allow IoT devices and platforms to work together. However, by applying some of the presented techniques interoperability can be improved.

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