Interoperability in IoT: A Vital Key Factor to Create the "Social Network" of Things.

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Abstract— **The Internet of Things (IoT) is a concept that describes the connection of various devices with built-in sensors and communication equipment to achieve the collection and transmission of data in a network. IoT devices are increasing with geometric progress, and ensuring interoperability and handling of the enormous heterogeneous data generated is of major importance for the creation of intelligent applications and services. This paper presents the state of art and current solutions on the issues of interoperability in the IoT domain, as well as the challenges and open issues. Finally, a discussion is provided on what future research should focus on and solutions are outlined to achieve interoperability in IoT systems that can lead to a "Social Network" of Things.**

Keywords- Internet of Things; Interoperability; Semantic Web Technologies; IoT platforms; ontologies; Social Network of Things; middleware; Open Linked Data, ontology alignment; reasoning mechanisms.

I. INTRODUCTION

The Internet of Things (IoT) is the next big step in the field of technology. New technologies are being developed to meet the ever-increasing demands of a new digital world where heterogeneous devices will be connected, forming a part of an IoT ecosystem [1]. IoT has the potential to bring out many possibilities of natural objects, which until recently were considered impossible. This has a significant impact on society, economic growth and in the informatics sector.

The IoT devices collect a huge amount of data using microcontrollers and sensors embedded in them connecting home users, businesses, public facilities, and business systems. These data are multimodal including video streams, images, and text data. The density of systems and technologies is becoming increasingly high and ensuring interoperability and handling of such large scale heterogeneous data will be a key factor in the development of smart applications in several areas, such as Smart Cities, Smart Homes, Smart Health, Smart Agriculture, etc. [2].

According to Noura et al. [3], the interoperability on the Internet of Things relates to the layers below: 1) Device, 2) Syntactic, 3) Networks, 4) Semantic and 5) Platform architecture. The difficulty in the communication between the various devices is not only related to the diversity of devices but also is about the way data is labelled, how devices are represented and modelled, as well as, it is about the architecture type of the different systems.

There are several definitions in the literature for interoperability. From all these definitions, we will focus on the one that is most important about our context. The IEEE defines interoperability as "the ability of two or more systems or components to exchange information and use the information exchanged" [4]. Moreover, we can define interoperability as a measure of the degree to which diverse systems, organizations, and/or individuals are able to work together to achieve a common goal [5].

The "Internet of Things" concept implies that all Things are harmoniously connected so they can communicate and they are also easily accessible from the Internet to deliver services to end-users [6]. But, to create a new "Social Network" of Things, a truly connected world, that harmoniously connects applications to Smart Homes, Smart Cities, Smart Agriculture, Smart Health, etc., it will require a real horizontal integration of devices, applications, systems and platforms.

Firstly, in this work, we attempt to define the problem of interoperability in IoT systems and then we report the current developments on this issue (Section II). Following the challenges and open issues (Section III) and existing solutions (Section IV) are discussed. As a contribuiton, solutions are proposed to enhance interoperability in the IoT field and ideas are presented on what future research should focus on (Section V) before our conclusion (Section VI).

II. INTEROPERABILITY LEVELS IN IOT

IoT interoperability is a multifaceted issue and the solutions to be addressed must be in line with many factors that are also referred to the literature as interoperability levels. A taxonomy of interoperability for IoT is based on four levels: technical, syntactical, semantic and organizational interoperability [3][7]. Below we will analyze each level individually.

A. Technical Interoperability

Technical Interoperability includes the first three levels of classification, as proposed by Noura et al. and it includes the interoperability of devices, the interoperability of networks and the interoperability of platforms.

a) Device Interoperability

Devices that are integrated into the world of IoT are becoming more and more ubiquitous. These Smart Devices / Things are either devices with a lot of computing power like smartphones and Raspberry Pi, or devices with built-in microswitches and low-power actuators, such as Arduino, Wispmote, Libelium, and others [7]. The problem of interoperability at this level is due to the inability of all these devices with different architectures and power levels to interact properly.

b) Network Interoperability

Moreover, due to the variety and heterogeneity of IoT devices, many communication protocols have been developed to cover all requirements in the IoT market. Home appliances, such as smart air conditioners, refrigerators, televisions, etc., use Wifi and 2G / 3G / 4G cellular communications. Other mobile devices use more low-power and short-range wireless technologies, such as Bluetooth, ZigBee, Beacons, RFID belonging to the WBAN IEEE 802.15.6 family. While a new category created for sensor applications is that of long-range and Low-Power Wide-Area Networks (LPWAN). Some of them are the wireless technologies LoRaWan, SigFox, NB-IoT [8]. This level of interoperability refers to the difficulty of communication of the IoT devices using different communication protocols.

c) Platform Interoperability

The IoT platform is a comprehensive suite of services that facilitates services, such as development, maintenance, analysis, visualization and intelligent decision-making capabilities in an IoT application. Interoperability issues of IoT platforms are because many of these systems are tailored for specific IoT applications. Some of the most popular platforms are Google Cloud Platform, IBM Watson IoT, ThingWorx, oneM2M, Microsoft Azure Cloud, ThingSpeak [9]. Each of the above follows its data sharing policy, it has its operating system, and this has the effect of creating heterogeneous IoT systems and increasing the problem of interoperability.

B. Syntactic Interoperability

Syntactic interoperability refers to the interoperability of data formats and encodings used in any exchange of information or services between heterogeneous systems and IoT entities. Such forms of standardization are, for example, XML, JSON and RDF. The encoding and decoding of messages are done using editorial rules, defined by a grammar. The problem of syntactic interoperability arises due to the great variety of grammars that each architecture employs and consequently, the IoT devices could not communicate properly.

C. Semantic Interoperability

Semantic interoperability is characterized as the ability to transmit information, data and knowledge among agents, services and applications in a meaningful way, inside and outside the Semantic Web [10][11]. It is the description of smart devices according to their data, services, and capabilities in mechanically comprehensible form using a common vocabulary. Semantic interoperability is achieved when the exchange of data is made harmoniously independent of the structure of the original data giving a common meaning [12]. This can be done either by existing standards or agreements on the form and importance of data or can be done using a common vocabulary either in a schema and/or in an ontological approach [13].

The use of an ontology is the most common way of adding semantics to the IoT data. It is a way of modelling information that extends the concept of the Semantic Web into the Internet of Things. The most important Semantic Web technologies have been standardized by the World Wide Web Consortium and are Resource Description Format (RDF), a lightweight data metadata model for describing ontology properties, SPARQL, and the RDF Query Language [14].

Existing solutions [11][14] suggest the use of unified ontologies to address semantic interoperability issues and automation related to the heterogeneity of data. However, the multiple possible consolidations developed by field experts [2] pose many challenges as each consolidated ontology proposes its autonomous classification. It is therefore imperative to improve ontology matching and ontology alignment [15][16] to discover the most appropriate strategies that can overcome the heterogeneity problem in the Internet of Things and bridge the semantic gap between IoT entities at the level of Information / Applications.

D. Organizational Interoperability

Organizational interoperability refers to the successful organization of a system to communicate effectively and to transmit the information in a harmonious manner [10]. To do this, the other three levels of interoperability: technical, syntactic and semantic interoperability, must be ensured. High organizational interoperability means that information has been properly transmitted irrespective of the heterogeneity of devices, networks, types of compilation and modelling of information [17].

III. CHALLENGES

With the rapid expansion of various heterogeneous devices and systems, addressing the interoperability challenges is a major issue. The IoT devices must be compatible with their devices communicate with this and this is only possible if they follow common protocols and communication standards. Below we present the most important interoperability challenges in IoT.

A. Heterogeneous Connected Devices/Things

One of the most important challenges in IoT systems is the interoperability of connected devices. Some of the most important issues are:

- Heterogeneous equipment from different manufacturers: Devices not manufactured by the same manufacturer cannot communicate correctly [18].
- Incompatibility between different platforms. Some of them are Evrythng (www.evrythng.com), ThingWorx

(www.thingworx.com), Xively (www.xively.com), Google Cloud IoT, Yaler (yaler.net), Microsoft Azure IoT [9].

- Incompatibility of different versions: Newer devices do not take backward compatibility issues.
- Different communication protocols / formats (IEEE 802.11, IEEE 802.15, LoRaWan, SigFox).

B. Multimodal, High Heteogeinety Data

IoT Systems collect data from different distributed sensors. These data are multimodal, including heterogeneous data, such as video streams, images, audio, and simple text [2]. How to integrate these distributed data from multisource is a key challenge for IoT development and for implementation of new innovative smart applications.

Moreover, communication between heterogeneous devices generates a large volume of real-time, high-speed, and uninterrupted data streams. These data streams include structured, semi-structured and unstructured data. When heterogeneous and various sensor data are acquired, multisource data should be merged to create a comprehensive and meaningful view for further utility [19].

C. Syntactic interoperability between Things

As discussed previously, syntactic interoperability involves packet and data networking mechanisms. Thus, when the above challenges are overcome, there is still a need to ensure that the data flow is interoperable between different networks and between a combination of devices. Translation functions to networks or on some devices, gateways or in the form of intermediate software sitting on the edge of one network are most likely to be necessary [20].

Moreover, IoT frameworks prefer to use popular and tried-and-tested solutions to increase syntactic interoperability. These solutions include the messaging protocols CoAP, XMPP, AMQP, MQTT, DDS and Hy-LP, as well as the DPWS, UPnP, and OSGi [21]. However, these solutions only offer cross-domain compatibility and usually operate as closed silos with a close application focus, enforcing specific data formats and interfaces.

D. Semantically Incompatible Information Models

As mentioned in the previous section, ensuring semantic interoperability is very important to address the inability to exchange and reuse data. Unfortunately, even today, IoT systems consist of semantically incompatible information models, such as incompatible general ontologies that offer different descriptions or even understandings of resources and processes, and thus are a barrier to the development and adoption of the IoT.

Most of the existing semantic tools and techniques, such as Linked Data, ontology alignment and ontology matching [14][15] have been created primarily for Internet resources. Existing models provide the basic description frameworks, but alignment between different models and frameworks are required. In addition, the capacity of the natural environment and the resource constraints on IoT systems have not been taken into account [16]. Future work in this area should provide capability, security and scalability and provide solutions that are easily adapted to limited and distributed resource environments.

IV. EXISTING SOLUTIONS

A significant research effort has been devoted to providing solutions in the direction of increasing interoperability at all four levels presented in Section III. In this section, we examine solutions provided by six related projects (AGILE, BiG-IoT, VICINITY, Open-IoT, INTER-IoT, and Machine-to-Machine Measurement (M3) Framework). These six projects are developing interoperability solutions at different interoperability levels and for this purpose were chosen to be analyzed in this particular work.

A. BIG-IoT

BiG-IoT [22][23] focus on addressing the semantic and organizational levels of IoT interoperability issues by creating the BiG-IoT API. It is about a generic web platform that unifies multiple platforms and different middlewares.
The Web API and semantic information representation models are defined in cooperation with the Web of Things Interest Group at W3C, expanding the standards of this community. The project has chosen schema.org as a basic vocabulary of concepts.

Through the API, which has a defined architecture, it is easier to create applications and services for heterogeneous platforms. To increase the level of interoperability at semantic, but especially at the organizational level the IoT API is framed by the following functions [19][24]:

- Identity management for registering resources.
- Discover resources according to user-defined search criteria.
- Access metadata, and data (download data as well as publish / record feeds).
- Work with forwarding commands in Things.
- Vocabulary management for semantic descriptions of concepts.
- Security, including identity management, authorization and key management.
- Billing that allows you to make money through payment and billing mechanisms.

B. INTER-IoT

The INTER-IoT project aims to comprehensively address the lack of interoperability in the IoT realm by proposing a full-fledged approach facilitating "voluntary interoperability" at any level of IoT platforms and across any IoT application domain, thus guaranteeing a seamless integration of heterogeneous IoT technology [23][25].

INTER-IoT is based on the above main functionalities to address technical and syntactic interoperability:

- Techniques and tools for providing interoperability among and across each layer of IoT platforms.
- A global framework called INTER-FW for programming and managing interoperable IoT platforms, including INTER-API and several interoperability tools for every layer.
- Engineering Methodology based on the CASE tool for IoT platforms integration/interconnection.

Regarding the main types of interoperability (technical, syntactic, semantic), INTER-IoT enables all of them [18]. Universal syntactic and semantic interoperability among any platform with different data formats and ontologies is possible through the INTER-IoT DS2DS solution. Moreover, other INTER-IoT layers (D2D and N2N) can provide organizational interoperability among smart elements, enabling connectivity to the network.

C. VICINITY

The VICINITY project aims at interfacing cloud-based platforms from various application domains by providing "interoperability as a service" for the Internet of Things [26]. The proposed interoperable platform is presented as a virtual neighborhood, a "social network" where users can share access to their smart objects without losing control. The project team has thoroughly reviewed all existing standards and platforms, selecting those needed to build a service or increase interoperability.

The project is not so concerned with technical interoperability. For communication between devices, wireless networks like Wi-Fi and ZigBee are mainly used. VICINITY's main goal is to increase semantic interoperability. Using the standard W3C Web Language Ontology, specific ontologies are developed in a variety of areas, such as ontologies for energy and building, etc., extending the SAREF reference ontology [27] interoperability.

VICINITY ontology network is composed of cross-domain ontologies, addressing the modelling of general concepts like time, space, web Things. It will represent the information for exchanging IoT descriptor data between peers. Domain-oriented ontologies aim to cover vertical Domains, such as Health, Transport, Buildings, etc.

D. AGILE

The AGILE project builds a modular open-source interoperable Gateway solution (hardware and software gateway) for the IoT focusing on the physical layer, network communication layer, processing, storage, and application layers [22]. The AGILE software modules are addressing functions, such as device management, communication networks like area and sensor networks and solution for distributed storage. Moreover, AGILE approaches include security features that allow users to share data in a trusted way.

The AGILE project focuses on technical interoperability both at hardware and software level [23][25]. Within the project, various popular and low-cost technologies, such as Raspberry Pi are being developed and expanded. This creates the "Gateway Maker", a proposal to create interoperable gateways that will be used for multi-purpose and heterogeneous purposes. At the same time, the project provides open-source code and a web-based environment (Node-Red) for developers to develop new, innovative applications. The project does not address any approach to the semantic and organizational level of interoperability.

E. Open-IoT

Open-IoT focuses on increasing semantic interoperability [28]. In the framework of the project, a middleware platform was created that allows semantic integration of applications on the cloud. For information modelling, the ontology of W3C (SSN) sensor networks are used as a common standard for the semantic integration of various IoT systems. Appropriate infrastructures collect and semantically comment on the data of the different sensors. Also, another semantic technique called Linked Data is used to enrich the data and interface it.

Open-IoT innovates with other programs as it implements a platform with modules for collecting data and applications in cloud computing infrastructures, modules for creating semantically interoperable applications, and applications for mobile sensors. The implementation of semantic techniques in the cloud is something that adds value to the project and makes it stand out from other similar solution. These functionalities provide a basis for the development of novel applications in the areas of smart cities and mobile crowdsensing, while also enabling large scale IoT experimentation and increase the level of organizational interoperability. The project does not address any approach to the technical and syntactic level of interoperability.

F. Machine-to-Machine Measurement (M3) Framework

The M3 Framework project focuses on addressing the lack of semantic interoperability in IoT. The framework of the project assists the developers in semantically annotating M2M data and in building innovate applications by reasoning on M2M data originating from heterogeneous IoT systems and domains. To increase the level of interoperability at syntactic, but especially at the semantic level the M3 Framework is framed by the following layers [30]:

- Perception layer, which consists of physical IoT devices, such as sensors, actuators and RFID tags.
- Data acquisition layer, which focus on collecting raw data from IoT devices/sensors and converting them in a unified way, such as RDF/XML compliant with the M3 ontology. These formats are compliant with the M3 ontology, an extension of the W3C SSN Observation Value concept to provide a basis for reasoning.
- Persistence layer, which takes over to store M3 in a database to store semantic sensor data which called triple store.

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- Knowledge management layer, which is responsible for finding, indexing, designing, reusing and combining domain-specific knowledge, such as ontologies and datasets to update M3 domain ontologies, datasets and rules.
- Reasoning layer, which infers new knowledge using reasoning engines and M3 rules extracted from Sensor-based Linked Open Rules (S-LOR) [31].
- Knowledge query layer executes SPARQL (a SQLlike language) queries on inferred sensor data.
- Application layer, which employs an application (running on smart devices) to parse and display the results to end-users.

V. DISCUSSION

To conclude the degree of interoperability maturity, we summarize in Table I the tools of state-of-art platforms that were analyzed in section IV, which attempt to solve interoperability issues at the layers discussed in Section II.

At technical and syntactic level AGILE, VICINITY and INTER-IoT attempt to provide solutions by creating Generic Gateways and device to device modules that integrate several wireless and wired technologies. All of these need to be incorporated into supported technologies like families of Low Power and Wide Area wireless networks (LoRaWan, SigFox, etc.), as well as other short-range wireless indoor technologies, such as Beacons.

A recurring aspect is that most efforts are focused on addressing the semantic interoperability challenge. VICINITY platform uses the standard W3C Web Language Ontology and implements cross-domain ontologies, whereas Open-IoT extends SSN ontology, and uses semantic tools such as Linked Data. BiG-IoT expands the standards of WoT and uses vocabulary management for handling semantics tools. Moreover, INTER-IoT increases semantic interoperability compared to the rest of the platforms by introducing different data formats and ontologies through the INTER-IoT DS2DS solution. In addition, M3 Framework Project addressing the semantic interoperability by innovative semantic tools, such as M3 ontology tools, reasoning engines and M3 rules extracted from S-LOR.

The solutions developed in this direction are promising, but they are still at an early stage. The proposed frameworks do not take into account the limitations of IoT systems, i.e., low device resources, energy consumption, mobility, etc. Moreover, the ontologies that are created are complicated and not interoperable with each other and focus mainly on the interoperability of specific fields rather than on a general solution. Besides that, the tools for ontology alignment and ontology merging, solutions that can radically improve interoperability levels, have not been particularly emphasized. Certain future research should focus on this direction so that future ontology engineers are given powerful "light" tools, such as ontology alignment tools for low-power devices or tools to implement "light" ontologies for cross-domains.

In addition, as already mentioned, organizational interoperability will be realized provided that all other interoperability levels are properly addressed. In this context, BiG-IoT creates a common and generic Application Programming Interface (API) between the different IoT middleware platforms. Open-IoT implements a cloud-based middleware platform with innovative tools and functionalities. Also, VICINITY project creates a framework that follows the philosophy interoperability as a service for "Internet of Things Neighborhood" with many modules and tools. Moreover, the INTER-IoT platform increases the levels of organization interoperability with INTER-API, which includes several interoperability tools for every layer. Finally, M3 Framework project with innovative semantic engines and solutions at the Application layer, which parses and displays the results to end-users, increases the organizational interoperability level.

TABLE I. INTEROERABILITY LEVELS COVERAGE BY THE EXAMINED RESEARCH PLATFORMS.

Interopera-bility level / Project	**Technical level**	**Syntactic level**	**Semantic level**	**Organiza-tional level**
AGILE	Yes (Maker's Gateway)	Yes (Maker's Gateway)	No	No
Open-IoT	No	No	Yes (extend SSN ontology, Linked Data)	Yes (extend SSN ontology, Linked Data)
VICINITY	Yes (Generic Gateway supports common networks (Wifi, ZigBee,))	Yes (OWL Lang.)	Yes (VICINI-TY Onto-logies)	Yes (interopera-bility as a service)
BiG-IoT	No	No	Yes (expand the standards of WoT, vocabulary manage-ment for handling semantics)	Yes (BiG-IoT API)
INTER-IoT	Yes (DS2DS)	Yes (DS2DS)	Yes (DS2DS)	Yes (INTER-API)
Machine to Machine (M3) Frame-work	No	Yes (Data acquisi-tion layer)	Yes (Knowle-dge mana-gement layer, Reasoning layer)	Yes (Application layer)

To address the problem of interoperability, equal emphasis should be placed on all levels of interoperability as they have been presented in this work. It is necessary to create tools and software modules that will seamlessly solve the problem of interoperability at all levels in parallel, and also provide solutions that are available for devices with minimal resources. In this way, an indispensable, interoperable, global IoT ecosystem will be created in the form of a new "Social Network" of Things.

Taking under consideration, the open issues and shortcomings of the state-of-art frameworks, as presented in this survey, we aim to design/implement a framework/architecture called "Social Network" of Things framework that consists of modules, tools and functionalities that will increase interoperability at all levels.

Firstly, at the level of technical interoperability, it is proposed to extend the AGILE and VICINITY solutions as well as other solutions from similar platforms and to create an architecture that includes even more interoperable devices. Expansion of tools, such as Maker's Gateway by supporting technologies and new widespread technologies, such as Arduino, Wispmote, Beacons, Libelium products, etc., are promising to make device compatibility much easier. New data collection and raw data filtering tools should be added to the entire system, so data going to the cloud can be edited with edge computing techniques. Additionally, these new technologies should be also compatible with the new wireless technologies of the LPWAN family (LoRaWan, SigFox, NB-IoT).

Also, at the level of syntactic and semantic interoperability, the new architecture should include new tools creating interoperable ontologies that will extend the existing solutions that have been analyzed in this paper. Initially, it is necessary to create an interoperable middleware framework with new innovative semantic modules, through which heterogeneous devices will be interconnected. Moreover, with the successful implementation and development of the proposed framework and the creation of a "Social Network" of Things where all devices and systems can communicate seamlessly, many innovative applications could be spawned in various fields leveraging on the raw data collected. Consequently, the level of organizational interoperability will increase rapidly.

The new architecture, as shown in Figure 1, consists of Perception, Transmission, Middleware and Application layers. The Perception layer contains all the IoT heterogeneous physical devices, such as Beacon sensors, ZigBee sensors, LoraWan sensors, actuators, etc. from which all heterogeneous data are derived. The Transmission layer, comprises the following modules:

- *Data collection module*, to get data from different types of sensor devices
- *Data integration module* which converts the heterogeneous data in a unified way, such as RDF, XML and JSON.

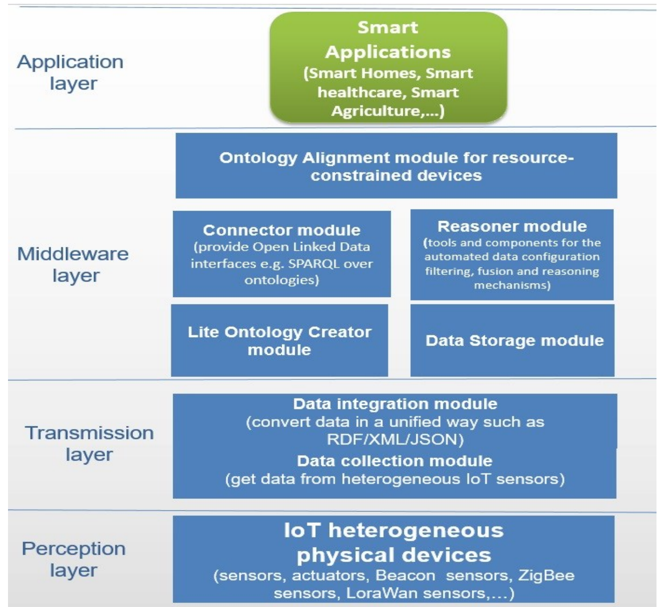

Figure 1. Overview of "Social Network" of Things Architecture.

The Middleware layer contains components and functionalities that can be divided into several functional modules as follows:

- *Data Storage module,* which contains tools to store semantic IoT Data to a cloud database.
- *"Lite" Ontology Creator module*, which includes tools for creating interoperable "light" ontologies and semantic structures, and methods to enrich with metadata and create reusable data, to enable semantic interaction and interoperability between the various heterogeneous "Things", offering a significant advantage compared to existing syntactic interactions.
- *Connector module*, to provide Open Linked Data interfaces e.g. SPARQL (SPARQL Protocol and RDF Query Language) over ontologies for internet-connected objects within the physical world abstracted by the middleware to interact with the "Social Network" of Things.
- *Reasoner module*, which includes tools and components for the automated data configuration filtering, fusion and reasoning mechanisms, according to the problems/tasks at hand.
- *Ontology alignment module for resource-constrained devices*, which includes tools for ontology merging, matching, and alignment related to the dynamics and complexity of the IoT systems.

The top layer is the Application layer. It implements and presents the results of the other three layers to accomplish disparate applications of IoT devices. The Application layer is a user-centric layer which executes various tasks for the users. It contains the innovative smart application of various fields, such as Smart homes, Smart cities, Smart healthcare, Smart agriculture, Smart buildings, etc.

VI. CONCLUSION

Addressing interoperability in IoT systems is a crucial key factor for IoT development. There is an urgent need to address the problem at all levels of IoT interoperability and to take into account the limitations of IoT systems.

In this context, we report the current developments on this issue, comparing the solutions of six major research platforms, and we discuss the main open issues and challenges. Finally, we propose to design and implement a framework/architecture that utilizes tools and methods that increase interoperability at all levels simultaneously and address the issue with low-cost devices and minimal computing resources, such as common IoT devices.

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