A Review on IoT Frameworks Supporting Multi-Level Interoperability – The Semantic Social Network of Things Framework

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Abstract— The Internet of Things (IoT) paradigm advocates the massive use of sensing and communication technologies embedded in the physical world, which provides the potential to collect huge volumes of data and connect them to intelligent systems. As the number of IoT devices is increasing with geometric progress, ensuring interoperability and handling of the big heterogeneous data they generate is of major importance for the development of smart applications and services. In this context, a systematic review of contemporary IoT frameworks based on a multi-level interoperability consideration is performed and findings are critically discussed. Challenges and open issues that emerge in this research area are pointed out, and research opportunities and insights are suggested. Motivated by the shortcomings of the current solutions to support open, interoperable, intelligent and collaborative IoT environments, the concept of Semantic Social Network of Things (SSNT) is introduced. SSNT specifies the integration of device-to-device collaborative services which semantically enable heterogeneous objects to (socially) interact and participate in communities of smart objects. By establishing social relationships and taking collaborative actions, such communities can support users to achieve their goals. A middleware-based framework architecture is presented to enact the SSNT abstraction, and a proof-of-concept application in the smart agriculture domain is outlined to demonstrate important features of this approach.

Keywords- Review; Internet of Things; Interoperability; IoT frameworks; Ontologies; Semantic Social Network of Things

I. INTRODUCTION

The Internet of Things (IoT) is the up-and-coming big step in the field of technology. The IoT concept, initially utilized as an umbrella term for a range of various emerging technologies such as “embedded internet” and “pervasive computing”, is currently paving its way for being the key driver for digital transformation in several application domains among which manufacturing, automotive, health, smart cities and smart farming.

IoT growth is explosive and there are already billions of connected smart objects, embedded systems, sensors and microcontrollers that have penetrated our world connecting home users, businesses, public facilities and enterprise systems. New technologies are being developed to meet the continuous incremental requirements of a new digital world where heterogeneous devices have been connected, forming a part of the IoT ecosystem. Since the density of IoT systems and technologies is becoming increasingly high, ensuring interoperability and handling of large-scale heterogeneous data is turning into a vital key factor in the development of successful smart applications [1].

Undoubtedly, there are still many challenges to overcome in order to fully realize the IoT vision [2][3]. The vast number of interconnected devices gives rise to scalability, heterogeneity and several interoperability issues [4]. One of the crucial issues is that IoT landscape is made up of proprietary devices and platforms that were created to provide a single service and act as "vertical silos" [5]. These silos require the creation of cross-domain, cross-platform and cross-organizational services due to their lack of interoperability and openness. Thus, there is an important need to revise the philosophy of IoT platforms and focus on trying to build synergies between different IoT platforms. This will lay the foundation for interconnecting IoT devices and services that collaborate together to achieve a common goal defined implicitly or explicitly by people.

In this paper, a review of contemporary IoT frameworks is performed to analyze and evaluate relevant contributions related to the establishment of open, interoperable, intelligent and collaborative IoT environments. Accordingly, a classification scheme is proposed to effectively represent the results of the related literature review analysis. The classification is based on the four interoperability levels, i.e., technical, syntactic, semantic and organizational, explored in our previous work [1], extended by the broader scope of the systematic literature review performed. The comparative analysis of the explored IoT frameworks allows us to identify important limitations, challenges and open issues that future research needs to address. Our investigation on the topic can be framed by the following research questions:

RQ1: Do the current IoT frameworks provide solutions supporting multi-level interoperability?

RQ2: What is missing from current IoT frameworks in order to fully support open environments/spaces of heterogeneous but collaborative smart objects?
RQ3: What are the open issues that future researchers should focus on in terms of smart objects interoperability?
RQ4: How collaboration and social interaction mechanisms can at a conceptual level address multi-level interoperability issues in open IoT environments?

The literature review follows a systematic approach consisting of three phases as suggested by [6]:

1) Review planning: specification of research questions and classification scheme; and development of the review protocol which includes the research strategy (literature databases, research keywords) and the definition of inclusion/exclusion criteria.
2) Review running gathering of scientific publications according to the research strategy; and selection of relevant work by applying the selection criteria.
3) Review reporting: overview of the selected work; and comparative analysis of the explored solutions based on the specified classification scheme.

Regarding the review protocol, several academic bibliography sources were used such as Web of Science, Google Scholar, IEEE Xplore Digital Library, Elsevier Scopus, ACM digital library, Citeseer library, Science Direct, and arXiv.org in order to search for relevant scientific contributions of the last 10 years. Search keywords were limited to the following terms: Internet of things, Web of Things, Interoperability, Ontologies, Semantics, and Social IoT. In addition, the following search expressions were used: IoT Frameworks addressing interoperability OR Interoperability OR Internet of Things OR Semantic Web of Things AND Semantic Web Technologies OR Interoperability OR ontology.

Besides the chronological filtering, other selection criteria for the bibliography collection included the publication language (studies had to be written in English) and the pertinence to the research agenda of the review. Selected studies had to present initiatives related to interoperability in the IoT domain, as well as current IoT frameworks that provide solutions improving interoperability, covering at least one of the research questions stated. Both conference and journal papers were eligible but not short studies.

Motivated by the identified shortcomings of the reviewed solutions to support open, interoperable, intelligent and collaborative IoT environments the concept of Semantic Social Network of Things (SSNT) is introduced. SSNT specifies the integration of device-to-device collaborative services which semantically enable heterogeneous objects to (socially) interact and participate in communities of smart objects. By establishing social relationships and taking collaborative actions, such communities can support users to achieve their common goals. In a sense, the interoperable societies of things, services and people are forming an SSNT structure that allows scalable object/service discovery as in the case of social networks of humans.

Towards realizing the SSNT concept, a framework is proposed for the establishment and exploitation of social relationships among heterogeneous but interoperable smart things. A high-level architecture is presented specifying the main components that enable things/objects to be identified as potentially able to participate in communities of smart things/objects, creating groups of common interest and working collaboratively towards achieving common goals. Furthermore, a proof-of-concept application in the smart agriculture domain is outlined to demonstrate important features of this approach. In this example scenario, summaries of sensor data are translated to the RDF modeling language based on the Semantic Sensor Network (SSN) ontology. When the sensor data streams are semantically annotated, semantic techniques (e.g., SPARQL queries and reasoning) can be used for efficient processing. Then, social groups of objects (generating and consuming the annotated data) are created that aim to achieve common goals, and new knowledge is produced from their interaction.

The contributions of this paper can be summarized as follows:

- We provide an extensive review of the up-to-date research progress on contemporary solutions regarding interoperability in the IoT domain.
- We propose a classification which contributes to representing a deep analysis of a comprehensive literature review, as well as comparing IoT frameworks with a view to providing solutions supporting multi-level interoperability.
- We identify a number of limitations, challenges and open issues that future studies in this research area of IoT need to focus on.
- We introduce the concept of Semantic Social Network of Things (SSNT) to describe a network of things that 'speak', 'behave', 'collaborate' and 'co-exist' just like a 'social network' of people, establishing social relationships and taking collaborative actions to support users to achieve their common goals.
- We propose an architectural design for the SSNT framework that specifies the main software components to seamlessly confront the problem of multi-level interoperability tackling also the constraints of devices with limited resources. An evaluation scenario of the SSNT framework in the agricultural domain, representing an instantiation of the SSNT framework, is also provided.

The structure of the paper is as follows. Section II presents background knowledge and motivation. In Section III state of the art approaches confronting interoperability in the IoT domain are reviewed and reported. Section IV outlines essential design requirements to develop a novel interoperable IoT framework and highlights open research challenges, as it also discusses the architecture and main modules of the proposed SSNT framework, with an aim to enhance interoperability and collaboration in IoT environments. Finally, Section V concludes the paper.

II. Background and Motivation

This section outlines the evolution of existing approaches in the direction of establishing interoperable and cooperative IoT environments. In addition, the multi-level interoperability taxonomy that is used in the systematic review of IoT frameworks is presented.

A. *From the Internet of Things to the Semantic Social Network of Things*

The IoT 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 [7]. Presently, one of the biggest problems which the IoT is facing, concerns the lack of interoperability, arising from the heterogeneity of devices, systems, protocols and platforms. Consequently, it is necessary to focus on an interoperable and collaborative IoT. A first step in this direction is provided by *Web of Things* (*WoT*) [8]. WoT provides an Application Layer that simplifies the development of IoT applications composed of multiple devices across different platforms and application domains. WoT develops IoT with a common stack based on web services. Unlike IoT that focuses on the Network Layer, WoT assumes that connectivity between devices is achieved and focuses on how to build IoT applications. But even if the problem of interconnection with the help of web protocols such as HTTP (Hypertext Transfer Protocol Secure) and CoAP (Constrained Application Protocol) has been resolved, the problem of perception and context awareness in IoT ecosystems remains.

For this reason, the *Semantic Web of Things* (*SWoT*) is proposed [9]. SWoT is a current exploration area targeting to assimilate Semantic Web-based technologies with the IoT. It can also be considered as a transformation of the WoT by incorporating semantics. SWoT targets the ability to exchange and use information among data and ontologies. However, the challenges to move from the IoT and WoT towards the SWoT are numerous; some of these are to define a common description that allows data, and device description to be universally understandable, create extensible annotations, i.e., from minimal semantic descriptions towards more elaborate ones.

Currently, there are significant ongoing efforts for the definition of common semantics to collaborate on different data modelling approaches. Cross-domain interoperability is expected to be one of the main drivers for the realization of the next state of IoT computing paradigm which is already getting shape under the term of *Internet of Everything* (*IoE*). The IoE "*is bringing together people, processes, data, and things to make network connections more relevant and valuable than ever before-turning information into actions that create new capabilities, richer experiences, and unprecedented economic opportunity for businesses, individuals, and countries*" [10]. Figure 1 depicts the IoE data management model.

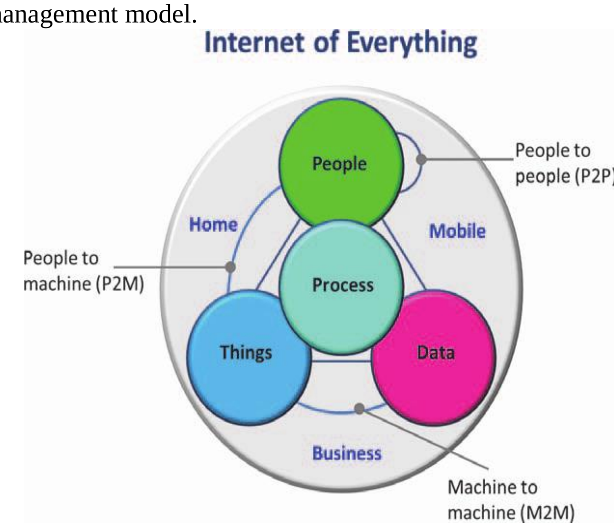

Figure 1. Data Management Model for the Internet of Everything [10].

Another approach towards a collaborative and interoperable IoT is the *Social Internet of Things* (*SIoT*). In social IoT, different devices work together to create social relationships with each other (such as social relationships on social network of people) [11][12]. The basic idea is to utilize human social networks (e.g., Twitter) as service discovery and provisioning infrastructure. However, the proposed notion does not align with the fundamental concept of IoT in which the ubiquitous connectivity of objects is envisioned to provide services to humans. Another attempt is made in a related work where authors discussed the integration of IoT with social networks [13]. An important step in laying down the vision of SIoT is taken in [14][15]. Therein, the various policies to determine the establishment and management of relationships among IoT objects are discussed. Different perspectives between human and IoT social networks are outlined in Figure 2.

SIoT defines several forms of socialization between objects. Firstly, the parent-object relationship is defined between objects manufactured by the same company. In addition, between objects there are relationships of people who share experiences, for example in a discussion or in their work or in any interaction. Another type of relationship is defined for objects owned by the same user such as smartphones, computers, smart TVs, etc. This relationship is called the object-ownership relationship. Finally, social-object relationship is defined when devices come in contact with their owners, such as smartphones belonging to friends. To manage the resulting network and relationships, a foreseen SIoT architecture is made of four major components [15] among others. Relationship management enables SIoT to begin updating and terminating relationships between objects. The service discovery identifies which items can provide the required service in the same way that people search for friendships and information. The composition of services allows for interaction between objects. Reliability management aims at understanding how information is processed by other members.

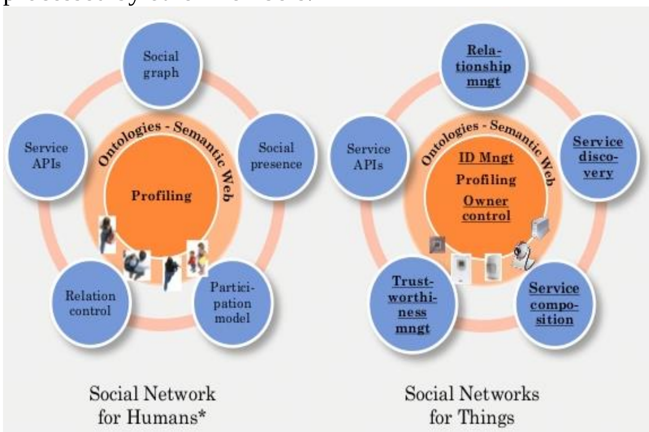

Figure 2. Comparison between Social Network of Humans and SIoT [14].

In this paper an approach that seeks to provide mechanisms to create interoperable, collaborative and open IoT environments is proposed and captured in the concept of *Semantic Social Network of Things* (*SSNT*). SSNT entails a network of things that 'speak', 'behave', 'collaborate' and 'co-exist' just like a 'social network' of people. For example, different intelligent objects that are able to interconnect and make decisions in an interoperable way, without human intervention, constitute an SSNT. This should not be misinterpreted as smart objects in a social network. Even a more elaborated case is that these devices may not only inform each other but negotiate a result. For example, smart home sensors working together to adjust the power consumption to suit the user preferences and concurrently optimize cost based on electricity provider charging policies.

An everyday life application scenario is described next to make the SSNT more understandable. Let us consider a businesswoman named Rafaela, who lives in Athens and employs an SSNT network and an SSNT recommendation system. Rafaela plans to invite her colleagues, who are based in other countries, to Athens for a critical meeting next week. She wants to make an appointment that should be accessible to all of her partners based on their availability. For this purpose, she initiates an appointment using her system which is based on an SSNT network containing all the information available to Rafaela and her associates. It is important to note that by the time Rafaela uses the SSNT network, IoT devices have already maintained social relationships with other IoT devices using the SSNT perception layer. The system coordinates with the affiliate scheduling systems and proposes an appointment time for her and other affiliates based on their availability, and the availability of airline flights. This is done by overcoming problems of lack of data interoperability as her colleagues are located in countries where the date and time system is different (e.g., USA, China).

In addition, Rafaela has some health problems, the most important of which is asthma, so there is information on her health in a system based on an SSNT network via wearables and sensors mounted in indoor and outdoor environments. In this way, an SSNT network can recommend that at the meeting location the air quality is acceptable or not. Again, data interoperability problems are overcome as city/building sensors measure their parameters, for example, in different units of measurement. Based on these recommendations from the SSNT networks, the proper recommendations of the meeting place and time can be provided. When all users confirm this appointment, the system sets it and sends an invitation to everyone.

Table I summarizes the evolution route from IoT to the proposed SSNT. It shows the key features and objectives of the approaches discussed such as WoT, SWoT, IoE, SIoT up to the SSNT. As shown in Table I, WoT attempts to reuse and adapt existing web technologies to build new applications and services [9]. SWoT focuses on machine-understandable data and in the description of data with common vocabularies, concentrating on the reuse of domain knowledge. SIoT targets to utilize human social networks as service discovery and provisioning infrastructure [11][12]. Finally, the proposed SSNT framework focuses on a network where different intelligent objects are able to interconnect and make decisions without human intervention leveraging on semantically annotated information.

B. *IoT Interoperability Levels*

There are numerous definitions in the literature for interoperability. The IEEE defines interoperability as "*the ability of two or more systems or components to exchange information and use the information exchanged*" [16]. Moreover, interoperability can be defined as a measure of the degree to which diverse systems, organizations, and/or individuals are able to work together to achieve a common goal [17]. IoT interoperability is a multifaceted issue and the solutions to be addressed must be in line with many factors that are also referred to in the literature as interoperability levels. A taxonomy of interoperability for IoT is based on four levels: technical, syntactic, semantic and organizational interoperability [18][19]. In the following each level is analyzed explicitly.

1) *Technical Interoperability*

Technical Interoperability includes three sublevels of classification, namely, the interoperability of devices, the interoperability of networks and the interoperability of platforms.

a) *Device Interoperability*

Typically, an IoT system or IoT Sensor Network communication is designed using one of the popular low-level standard technologies like Zigbee, Bluetooth Mesh, Z-wave, WiFi, etc. for devices to collaborate with each other. One of the current IoT challenges is to add a new device in an existing network that is having a different communication protocol to collaborate compared to the existing device network.

TABLE I. FROM SOCIAL NETWORK AND IOT TO SSNT.

	Source	Nodes	Connection	Enabling Technologies/Services	Target
World Wide Web	[2]	Web pages	Hyperlinks	HTML, XML	Share resources
Social Network	[11][12]	Persons	Social Relations	Network analysis, Community detection	Analysis relation principles and evolution
IoT	[2][3][4][7]	Devices/ Objects/ Things	Wireless signals	RFID, LoRaWan, Bluetooth, GPS, IPv6, …	Remote detection and control
WoT	[7][8]	Web-enabled objects	Web, Smart Gateways	REST, HTTP, CoAP, JSON, Web sockets	WoT attempts to reuse and adapt existing web technologies to build new applications and services
SWoT	[7][8][9]	Machine-Understandable Objects	Semantic Web, Smart Gateways	JSON-LD, linked data, Ontologies, Linked Open Vocabularies, Reasoners	Machine-understandable data - Describe data with common vocabularies - Reuse domain knowledge - Link to other data - Ease the reasoning
IoE	[10][11]	People, Things, Data	Internet, TCP/IP	IPv6 extensions (MIPv6, GLoWBAL IPv6)	Intelligent connection. Machines will become more intelligent and cognitive by having more access to data and expanded network opportunities.
SIoT	[12][13][14][15]	Objects, Humans, Data	Social Relations of Things' owners	Relationship management, Service discovery, Service composition, Trust management	Utilize human social networks (e.g. Twitter) as service discovery and provisioning infrastructure
SSNT	this work	Objects, Humans, Data	Social Relations and semantic links of Things, Platforms, Networks	SSNT Architecture Layers and Framework Modules	A social network where heterogeneous intelligent objects are able to interconnect and make decisions without human intervention

Interoperability of the IoT devices is hence becoming more and more important to build a scalable, adaptable and a seamless IoT device network [20]. The IoT ecosystem needs interoperability to create seamless programmability or configurability of the various products or devices or sensors to connect and collaborate. There is a need for a consolidated common standard that makes devices communicable, operable, and programmable, regardless of make, model, manufacturer, or industry. For example, consider a smart home scenario where the light bulbs and thermostats use ZigBee, speakers communicate with Bluetooth, and switches communicate through WiFi. Interoperability in this example enables different devices to understand and translate between these disparate communications technologies. An ideal IoT platform would offer a pool of standardized communication protocols where the device manufacturers may select the appropriate protocols [20] (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). For example, the Apple HomeKit, If-This-Then-That (IFTTT) Eclipse Ponte and Light-Weight M2M (LWM2M) are some of the gateway solutions in the literature [21].

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 [22]. 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 and NB-IoT [23]. This level of interoperability refers to the difficulty of communication of the IoT devices using different communication protocols.

At this level of interoperability, mechanisms are used that allow the continuous exchange of messages between systems across different heterogeneous networks. These include issues such as addressing, routing, resource optimization, security, QoS and mobility support.

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 appear 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 [24]. Each of the above platforms 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.

Today, the IoT environment comprises vertically oriented platforms for things. Developers who want to use them need to negotiate access individually and adapt to the platform-specific API and information models. Having to perform these actions for each platform often outweighs the possible gains from adapting applications to multiple platforms. This fragmentation of the IoT and the missing interoperability result in high entry barriers for developers and prevent the emergence of broadly accepted IoT ecosystems.

Today, we are dealing with various vertically oriented and mostly closed systems. Architectures for IoT are built on heterogeneous standards [25][26][27] (e.g., IETF CoAP, OASIS MQTT, OMA LWM2M, OGC SWE, or OneM2M) or even proprietary interfaces. As a result, most existing and emerging IoT platforms offer heterogeneous ways of accessing things and their data. This causes interoperability problems when overarching, cross-platform, and cross-domain applications are to be built, and eventually prevents the emergence of vibrant IoT ecosystems

For example, the Apple HomeKit supports its own open source language Swift, Google Brillo uses Weave, and Amazon AWS IoT offers SDKs for embedded C and NodeJS [24]. This non-uniformity causes hindrance for application developers to develop cross-platform and cross-domain IoT applications. Developers need to obtain extensive knowledge of the platform specific APIs and information models of each different platform to be able to adapt their applications from one platform to another. A cross-platform IoT application can access different IoT platforms and integrate data from various platforms. After cross-platform interoperability is enabled, cross-domain interoperability can be achieved in which different platforms within heterogeneous domains are federated to build horizontal IoT applications. For example, a smart home platform can provide domain-specific enablers such as air temperature and lighting conditions. These enablers can then be exploited by other IoT platforms, such as smart healthcare, to provide more innovative applications and scenarios.

2) 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 (Extensible Markup Language), JSON (JavaScript Object Notation) and RDF (Resource Description Framework) [28]. 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.

Syntactic interoperability, provided, for instance, by XML or the SQL (Structured Query Language) standards [29], is a prerequisite to semantic definitions. It involves a common data format and common protocol to structure any data so that the manner of information processing will be interpretable from the structure. It also allows detection of syntactic errors, thus allowing receiving systems to request resending of any message that appears to be garbled or incomplete. No semantic communication is possible if the syntax is garbled or unable to represent the data. However, the information represented in one syntax may in some cases be accurately translated into a different syntax. Where accurate translation of syntaxes is possible, systems using different syntaxes may also be interpreted accurately. In some cases, the ability to accurately translate information among systems using different syntaxes may be limited to one direction, when the formalisms used have different levels of expressivity (ability to express information).

3) 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 [30][31]. 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 [32]. 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 [33].

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 IoT. The most important Semantic Web technologies have been standardized by the World Wide Web Consortium and are: Resource Description Framework RDF - a lightweight data metadata model for describing ontology properties, SPARQL, and the RDF Query Language.

Existing solutions [35][36] 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 pose many challenges as each consolidated ontology proposes its autonomous classification. It is therefore imperative to improve ontology matching and ontology alignment [37] to discover the most appropriate strategies that can overcome the heterogeneity problem in the IoT and bridge the semantic gap between IoT entities at the level of Information / Applications.

4) *Organizational Interoperability*

Organizational interoperability refers to the successful organization of a system to communicate effectively and to transmit the information in a harmonious manner [37]. To do this, the other three levels of interoperability, i.e., 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 [38].

Organizational interoperability is concerned with the coordination and alignment of business processes and information architectures that span both intra- and inter-organizational boundaries. Coordination of business processes across organizational boundaries is essential if a single, aggregated view of a service from the customers' perspective is to be achieved. It is suggested that administrations could develop an exemplar scheme that would define standard approaches to each of the main requirements of any public service and use this exemplar to benchmark all other services; that common functionality could be provided on a shared basis through a broker service to reduce development, deployment and operational costs to the public administration and to each service fulfilment agency. Furthermore, it ensures consistency of experience for users of services across all agencies in the public sector through the use of agreed standards across all services; that expenditure reviews could be undertaken to ensure that financial priority is given to those schemes that comply with the structured customer support services set out above and with interoperability standards; and that each administration could develop a central programmed of organization development assistance and funding to bring this change about.

Table II provides a summary of the aforementioned interoperability levels analysis.

TABLE II. SUMMARY OF THE ANALYSIS OF THE INTEROPERABILITY LEVELS.

Interoperability Level	Source	Aim	Objects	Solutions	State of Knowledge
Technical	[20][21][22][23][24] [25][26][27]	Technically secure data transfer	Signals	Protocols of data transfer	Almost developed
Syntactic	[28][29]	Processing of received data	Data	Standardized data exchange formats, e.g. XML	Almost developed
Semantic	[30][31][32][33] [34][35][36][37]	Processing and interpretation of received data	Information/ Knowledge	Common directories, data keys, ontologies	Theoretically developed, but practical implementation problems
Organizational	[37][38]	Automatic linkage of processes among different systems	Processes (workflow)	Architectural models, standardized process elements	Conceptual clarity still lacking, vague concepts with large scope of interpretation

III. REVIEW OF IOT FRAMEWORKS ADDRESSING INTEROPERABILITY

This section presents our comprehensive review on existing IoT frameworks. The research was launched at a previous conference paper and is enriched with more information. The section concludes with a discussion on the technologies described and summarized their limitations and challenges.

A. Examined Solutions

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

1) BIG-IoT

BiG-IoT [38][39] focuses 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 middleware. 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 [40]:

- 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).
- 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.

2) 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 [41].

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

- Methods 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.

Three main types of interoperability (i.e., technical, syntactic and semantic) are enabled by INTER-IoT [24][42]. Universal syntactic and semantic interoperability among any platform with different data formats and ontologies is possible through the INTER-IoT DS2DS (Data & Semantics-to-Data & Semantics) solution. Moreover, other INTER-IoT layers like D2D (Device-to-Device) and N2N (Networking-to-Networking), can provide organizational interoperability among smart elements, enabling connectivity to the network.

3) VICINITY

The VICINITY project aims at interfacing cloud-based platforms from various application domains by providing "interoperability as a service" for the IoT [43]. 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 WiFi and ZigBee are mainly used. Main goal of the VICINITY project 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, extending the SAREF reference ontology [44] interoperability.

The VICINITY ontology network is composed of cross-domain ontologies, addressing the modelling of general concepts like time, space, Web of 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.

4) AGILE

The AGILE project builds a modular open-source interoperable Gateway solution (hardware and software gateway) for the IoT focusing on the physical, network communication, processing, storage, and application layers [24][45]. The AGILE software modules are addressing functions, such as device management, communication networks like area and sensor networks and solutions for distributed storage. Moreover, the AGILE approach includes security features that allow users to share data in a trusted way.

The AGILE project focuses on technical interoperability both at hardware and software levels. 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. The architecture comprises four layered domains.

5) Open-IoT

Open-IoT focuses on increasing semantic interoperability [46][47]. 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 sensor networks (SSN) 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 solutions. 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.

6) 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 innovative 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 [48][49]:

- Perception layer, which consists of physical IoT devices, such as sensors, actuators and RFID tags.
- Data acquisition layer, which focuses on collecting raw data from IoT devices/sensors and converting them in a unified way, such as RDF/XML compliant with the M3 ontology.
- Persistence layer, which takes over to store M3 in a database to store semantic sensor data which is called the triple store.
- 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) [49].
- Knowledge query layer executes SPARQL (an SQL-like 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.

7) FIESTA IoT

The FIESTA-IoT project is a Research and Innovation Action under the European Horizon 2020 Programme addressing the topic 'Future Internet Research and Experimentation'. The project focuses on large-scale experiments in the IoT domain that will utilize data and resources from heterogeneous IoT platforms [50]. These experiments provide a variety of tools and good practices to increase the interoperability of IoT heterogeneous platforms. FIESTA project promotes researchers and experimenters to share and reuse data from diverse IoT testbeds using semantic technologies seamlessly and flexibly.

The FIESTA-IoT architecture is a set of functional blocks allowing [51]:

- Testbed data streams and resources to be plugged into FIESTA-IoT; be discoverable using FIESTA-IoT and be accessible via FIESTA-IoT services.
- Semantic querying of both linked data sets (of collected testbed data) and IoT service APIs.
- Secure access to testbed resources by authenticated and authorized experimenters.

8) SymbIoTe

The SymbIoTe project (symbiosis of smart objects across IoT environments) focuses on the implementation of a flexible and secure interoperability middleware across IoT platforms. The main goal of the project is to create IoT applications on IoT platforms as well as dynamic and adaptive smart spaces that they can collaborate [51][52]. This is accomplished by:

- A semantic IoT search engine for connected (virtualized) smart objects (i.e., IoT resources) registered by platform providers;
- An abstraction layer for unified and secure usage of those resources across platforms;
- High-level, domain-specific APIs ("Enablers") for rapid cross-platform application development;
- IoT platform federations, i.e., associations between two platforms facilitating their secure interaction, collaboration and bartering of resources;
- Dynamic and self-configurable smart spaces offering interoperability for collocated devices and gateways;
- A secure interworking protocol between the IoT platforms, gateways and smart devices.

The SymbIoTe is built around the concept of virtual IoT environments provisioned over various cloud based IoT platforms. Virtual IoT environments are an abstraction composed of virtual representations of actual sensors and actuators being exposed by their host platforms to third parties. The symbIoTe framework is built around a hierarchical IoT stack and spans over different IoT platforms. Smart objects are expected to be connected to IoT gateways within the smart spaces which also host various computing and storage resources. The local infrastructure shares the available local resources (connectivity, computing and storage) and is connected to platform services running in the cloud. The architecture comprises four layered domains.

B. Discussion

The existing solutions are dealing with the heterogeneity of devices, data and services. Some of them integrate semantic web technologies to enhance interoperability [41][42][46][47][48][49]. The absence of standardized activities, life cycles and methodologies as well as a set of techniques and tools hinder an interoperable IoT. To all existing solutions interoperability challenges remain still present. For instance, they neither use the same model to structure the data produced by objects/things nor the same reasoning approach to deduce new knowledge from data produced by objects/things. To assess the degree of interoperability maturity and answer research question RQ1, Table III summarizes the results of the state-of-art IoT frameworks that were analyzed in this review.

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. The 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, the M3 Framework project addresses the semantic interoperability by the use of innovative semantic tools, such as M3 ontology tools, reasoning engines and M3 rules extracted from S-LOR. In addition, FIESTA-IoT project provides a blueprint of experimental infrastructure, software tools, semantic techniques, certification processes and best practices enabling IoT testbeds/platforms to interconnect their facility resources in an interoperable semantic way. Finally, symbIoTe, support fair and trustworthy interactions between platforms without a centralized mediator, so that IoT platform owners can engage in direct partnering relationships by use of symbIoTe platform federations.

At organizational level, BiG-IoT creates a common and generic API (Application Programming Interface) 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 of interoperability as a service for "IoT 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. Moreover, 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. Furthermore, FIESTA-IoT enables execution of experiments across multiple IoT testbeds, based on a single API for submitting the experiment and a single set of credentials for the researcher and the portability of IoT experiments. The focus is on resource sharing in the form of mutual registration, resource announcement, and subscriptions to information about resources offered by different platforms. However, features for the management of platform federations and collaboration mechanisms for fair and social interactions are not defined in most of the projects. Only VICINITY, and SymbIote have moved clearly in the philosophy of collaborative and open IoT Environments. Thus, by adopting this approach, organizational interoperability is increased, which, as we have argued, is not largely addressed by existing solutions. However, the tools that they proposed are still at an early stage and need to be evaluated in the future.

TABLE III. INTEROPERABILITY LEVELS COVERAGE BY THE EXAMINED IOT FRAMEWORKS.

	SOURCE	Technical level	Syntactic level	Semantic level	Organizational level
AGILE	[24][45]	Yes (Makers Gateway)	Yes (Makers Gateway)	No	No
Open-IoT	[46][47]	No	No	(Extend SSN ontology, Linked Data)	(Extend SSN ontology, Linked Data)
VICINITY	[43]	Yes (Generic Gateway supports common networks: Wifi, ZigBee)	Yes (OWL Language)	Yes (VICINI-TY Ontologies)	Yes (Interoperability as a service)
BiG-IoT	[38][39][40]	No	No	Yes (Expand the standards of WoT, vocabulary management for handling semantics)	Yes (BiG-IoT API)
INTER-IoT	[24][41][42]	Yes (DS2DS)	Yes (DS2DS)	Yes (DS2DS)	Yes (INTER-API)
Machine to Machine (M3) Framework	[48][49]	No	Yes (Data acquisition layer)	Yes (Knowledge management layer, Reasoning layer)	Yes (Application layer)
FIESTA IoT Project	[51]	Yes (Increase interoperability among platforms)	No	Yes (Reasoning and Linking technics)	Yes (FIESTA API, Middleware-Application layer)
SymbIoTe	[51][52]	Yes (Interworking protocol between the IoT platforms, gateways and smart devices)	Yes (Interoperable language)	Yes (A semantic IoT search engine)	Yes (IoT platform federation)

To resolve research question RQ2, we summarize in Table IV the shortcomings of the examined IoT Frameworks, by classifying them based on the interoperability level. At the technical interoperability level, a typical drawback of many frameworks, is the lack of focus on common communication standards between devices and systems. Furthermore, in several architectures it is imperative to implement interoperable IoT gateways, where raw data will be collected from different heterogeneous sensors supporting open source, and messaging systems. Moreover, at the level of syntactic interoperability, a common gap identified between these frameworks, is the lack of syntactic translation tools that convert the heterogeneous data in a unified way, such as RDF, XML and JSON.

At the semantic level, the ontologies that are created in most of the IoT frameworks are complicated and are not interoperable with each other and focus mainly on the interoperability regarding specific fields rather than on a general solution. Besides that, tools for ontology alignment and ontology merging have not been particularly emphasized on solutions that can radically improve interoperability levels. Certain future research should focus on this direction so that future ontology engineers are given powerful and “lightweight” tools, such as ontology alignment tools for low-power devices, tools to implement “lightweight” ontologies for cross-domains, and semantic reasoning tools.

At the organizational interoperability level, there is a lack of IoT platform federations, i.e., associations between more than two platforms facilitating their secure interaction, collaboration and bartering of resources. Moreover, collaboration and social interaction mechanisms that provide open and cooperative IoT systems have not been particularly emphasized. It is considered necessary to create tools that will manage the collaborations between IoT devices and systems, as well as manage the social relationships between IoT devices, with the aid of semantic techniques. Consequently, supporting collaboration and social interaction mechanisms between IoT systems will improve the organizational interoperability (research question RQ4).

TABLE IV. SHORTCOMINGS OF THE EXAMINED IOT FRAMEWORKS.

Technical level	Syntactic level	Semantic level	Organizational level
• Incompatibility of different versions. • Different communication protocols or formats (IEEE 802.11, IEEE 802.15, LoRaWan, SigFox). • Lack of a common standard of communication between devices and systems. • Lack of interoperable IoT Gateways.	• Not well-defined syntactic metadata schema and their mapping mechanisms. • Lack of syntactic translation tools that convert the heterogeneous data in a unified way, such as RDF, XML and JSON. • Solutions include the messaging protocols CoAP, XMPP, AMQP, MQTT offer cross-domain compatibility. • Lack of a common syntactic format identification, registration and management mechanisms.	• Semantically incompatible information models (incompatible general ontologies) • Lack of common standards • Lack of 'lightweight' semantic tools. (Ontology alignment, ontology matching, reasoning), and lightweight interoperable ontologies. • Incompatible reasoning approaches to deduce new knowledge from data produced by objects/things.	• Lack of Collaboration Mechanisms. • Lack of collaboration management methods. • IoT platform federations, i.e., associations between more than two platforms facilitating their secure interaction, collaboration and bartering of resources.

IV. Towards an Interoperable and Collaborative IoT Framework

In this section, we report design requirements and open research challenges that our review of the existing frameworks has highlighted. Moreover, we present a high-level design description of the proposed IoT framework (the SSNT framework). Although the evaluation of this framework is not covered in this paper, a proof-of-concept implementation scenario is provided.

A. Requirements and Open Research challenges

Existing IoT Frameworks have the potential to provide numerous solutions for improving multi-level interoperability, but many challenges have not yet been fully addressed and require collaboration from standardization committees, hardware manufacturers, software developers and IoT stakeholders. This section discusses several challenges related to multilevel interoperability in the context of IoT. Moreover, our review on the existing frameworks answers research questions RQ2, and RQ3, and suggests that a novel IoT framework needs to support specific functional features, as the ones outlined in the following paragraphs.

1) IoT Resource Management

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 multiple sources is a key challenge for IoT development and for the 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 [53].

2) Lightweight Semantic Tools

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 [54][55] 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 [56]. Future work in this area should provide lightweight semantic tools that are easily adapted to environments with limited and distributed resources.

3) Standardization

In the new world of IoT, standards will be more important due to the greater interoperability demands. As more systems, devices, systems and platforms are connected we will see that this is only possible if all agree on common standards [29][40][57].

Firstly, one standard has no direct control over other standards, which means that changes for one standard will not automatically be propagated to other standards. Secondly, in order to support interoperability among several standards, a large number of adapters have to be developed, which is clearly inefficient. There are distinct missing standardization activities related to data models, ontologies, and data formats to be used in IoT applications for service-level interfaces and protocols. Machine-to-Machine Measurement (M3) framework [48][49] is offered to supplement existing semantic standards by adding common format, nomenclature and methods for data interpretation. A semantic approach is aimed at resolving the issue of lack of standardization by introducing common ontologies, data models, and vocabularies; however, currently the application methods are non-unified, complicated, and require further improvement. So, a novel IoT framework should be based on common standards only and refrain from developing its own proprietary solutions.

4) Scalability

The exponential growth of connected objects to the Internet produces a massive quantity of data called" Big data". According to [58][59][60], the big data generated by IoT has different characteristics like large-scale data, heterogeneity, strong time and space correlation. Therefore, the main challenges encountered during the development of IoT applications/systems are the semantic IoT event processing, real-time processing of data streams and reasoning in a complex and dynamic context (spatiotemporal reasoning) in a scalable and secure way, etc. Consequently, these new requirements drive the need for the deployment of a scalable IoT system. Thereby, applying Semantic Web technologies (SPIN rules, SWRL, SPARQL, DL safe rules, RIF, etc.) to the IoT domain faces a new challenge on how to manage and interpret such heterogeneous data during a limited period in a scalable way.

5) Collaboration Mechanisms

Providing collaborative smart objects with interpretation and analytics methods to process and evaluate events in their surroundings is important for building new IoT-based applications [61]. Semantic descriptions serve the purpose of transforming large amounts of observed and perceived data created by users and things/objects into high-level concepts that are meaningful for establishing automated decision-making processes. However, the non-human perception contributes to existing pool of challenges in IoT. Similar to problems faced by the artificial intelligence research community, in IoT the challenges are data integration and amalgamation from different sources, rules of data aggregation, defining borders and thresholds, as well as describing events, actors and objects. Solutions are needed to integrate data from various environments, and patterns for further fusion of new knowledge based on learnt rules. So, a novel IoT Framework must have innovative mechanisms of cooperation between IoT devices and systems, not only to connect and interact, but also to socialize and collaborate with each other to achieve some specific task(s). In this way the organizational interoperability will be increased, an element that is missing from the IoT framework so far. This kind of social interaction requires cooperation among IoT devices.

B. SSNT Framework

To address the multifaceted problem of interoperability, and partially answer the research question RQ4, 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 confront the interoperability problem targeting all levels, and also provide solutions that are available for devices with constrained resources. In this vision, an indispensable, interoperable, global IoT ecosystem can be created in the form of an SSNT. Taking under consideration the open issues and shortcomings of the state-of-art frameworks, as discussed previously, an SSNT framework is proposed that consists of modules and tools to overcome interoperability issues.

Firstly, at the level of technical interoperability, new data collection and raw data filtering tools should be added to the system, so that data transferred 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). Following, at the level of syntactic and semantic interoperability, the SSNT architecture should include new tools creating interoperable ontologies that will extend the existing solutions. Initially, it is necessary to create an interoperable middleware framework with new semantic modules, through which heterogeneous devices will be interconnected. Moreover, with the successful implementation and development of the SSNT framework through which heterogeneous 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. For example, platforms can be enabled to perform collaborative sensing/actuation tasks to complement each other's infrastructure, and to interact directly in a decentralized way without exposing their business relationship to a centralized authority. Reasons for such a collaboration can vary e.g., similar IoT platforms that operate in different locations can federate to offer seamlessly to their clients IoT services in other locations, or collocated platforms can benefit from each other by forming partnerships to offer cross-domain solutions.

The SSNT architecture, as shown in Figure 3, is structured on four layers: Perception, Transmission, Middleware and Application.

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* includes the following modules:

1. ***SSNT Data Acquisition***, which gets data from different types of sensor devices.

This module is responsible for the collection and filtering of raw IoT data from various heterogeneous IoT devices with IoT Gateways. It consists of two components:

- *Data Collection*: Obtains raw data from various heterogeneous sensors using interoperable architectures that support distributed, open-source and messaging systems (Apache Kafka, ThingsSpeak etc.). This section supports different data sources and executes multiple processes at the same time.
- *Data Filtering*: Verifies the field of data collected from the previous section. Filtering requires a database search and applies filtering rules. With this function, the "bad" values are discarded minimizing storage costs and ensuring fast data transmission.

2. ***SSNT Data Integration,*** which converts the heterogeneous data in a unified way, such as RDF, XML and JSON. It consists of four components:

- *Metadata Creation*: Some important metadata objects are obtained, like data type, measuring units, time stamp, and geolocation. This module also describes the specific industrial environment, data, and applications.
- *Communication Interface*: Communication between each module of the data collection component is organized. Various types of data are translated into a single format so that the system can understand. For example, the data coming from various devices with different formats are translated into JSON message structure first and then sent to the next phase for data aggregation.
- *Data Aggregation*: The pre-processed data is transmitted to the aggregation component for further summarization. The aggregated data is more significant than the raw data collected by factory devices. The data stream coming from the physical layer is separated into data summarization modules as described below.
- *Data Summarization*: The datasets of various devices are represented into groups according to time-period. It reduces computational and storage cost and improves consultation performance by minimizing the volume of data. So, the event table generated by the data collection.

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

1. ***Data Storage***, which contains a) tools for storing semantic IoT data to a cloud database and to NoSQL databases such as GraphDB, Cassandra; b) functionalities for querying and searching in a different kind of databases.
2. ***Lightweight Ontology Creator/Annotator***, which contains:

- Tools for designing interoperable “lightweight” ontologies and semantic structures, according to standard ontologies that can be interpreted, shared and reused by other ontologies
- Methods to change an isolated ontology to a reusable and interoperable ontology (such as IoT-Lite, SSN ontology)
- Methods to enrich 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.

3. ***Connector***, which provides 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 an SSNT.
4. ***Reasoner***, which includes tools and components for the automated data configuration filtering, fusion and reasoning mechanisms, which obtain higher-level actionable knowledge from low-level sensor data
5. ***Ontology Alignment for Resource-Constrained Devices***, which includes tools for ontology merging, matching, and alignment related to the dynamics and complexity of the IoT systems.
6. ***Social Collaboration Generator / Manager***

This component is responsible for building and managing social relationships between various heterogeneous IoT devices. The social relations that will be created at each level will improve the various issues of interoperability as mandated by the research question RQ4. It consists of tools for automatically building relationships between things, and methods to manage SSNT relationships. These tools integrate information into IoT devices so that they can make “friends”, start a relationship, update a situation, and terminate a relationship. It is our proposed approach in the context of the answer to the 4 questions. The social relations that will be created at each level will improve the various issues of interoperability.

These relationships between IoT devices are classified according to the level of interoperability that they are addressed as follows:

i. ***Relationships between things in the level of device interoperability.***
These relationships take place for example between IoT devices that are on a different IoT network but are close together and can work together to achieve a common goal.

ii. ***Relationships between things in semantic and syntactic interoperability levels.***
These relationships are made at the level of semantic or syntactic interoperability and relate to IoT devices that represent data with common

vocabularies, ontologies (shared ontologies) or in a different way (different ontologies).

iii. ***Relationships between things in the organizational interoperability level.***
These relationships are made at the level of organizational interoperability between IoT devices belonging to different IoT platforms of organizations. Relationships between platforms can be enabled to perform collaborative sensing/actuation tasks.

Finally, the *Application Layer* leverages on the solutions provided by the underlined layers to accomplish disparate applications of IoT devices. The Application Layer is a user-centric layer which executes various tasks for the users. It represents innovative smart applications in various fields, such as smart homes, smart cities, smart healthcare, smart agriculture, smart buildings, etc. The provision of end user tools that enable people to engage in the formation of such applications by affording high level metaphors are also important [62].

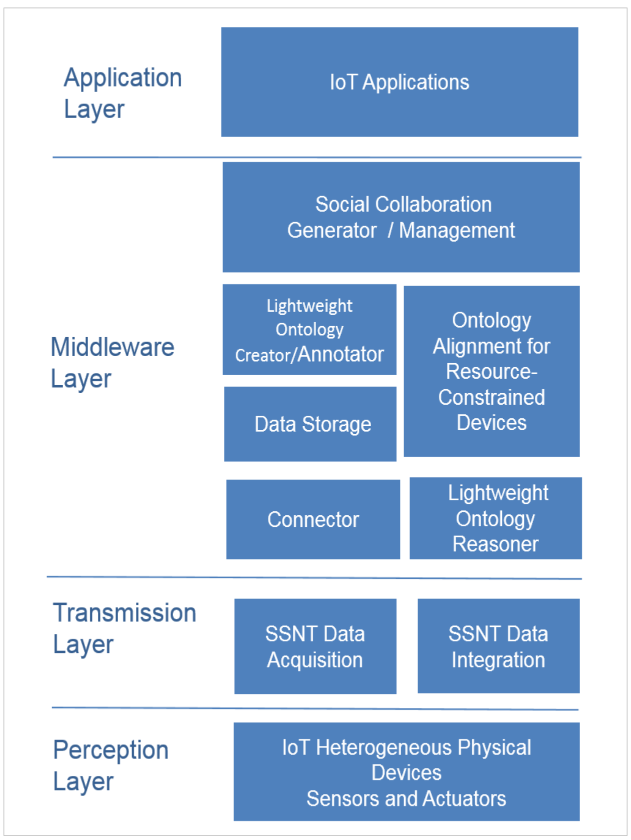

Figure 3. SSNT architecture overview.

A simple application scenario is given to illustrate part of the SSNT framework functionality. A smart lightweight application is designed as a result of the collaboration of different smart objects. In this case the SSNT consists of a smart desk, a smart chair, a smart book and a smart lamp. The application logic is that when the chair is occupied and is nearby the desk and the book is open above the desk the application infers that a study activity takes place and as service the application regulates the light depending on the brightness sensed on the book. Each smart object is described by properties in the form of an ontology (Figure 4, Figure 5, Figure 6, and Figure 7). Such ontologies may be independently developed and thus can be heterogeneous. The semantic interoperability support of the SNNT framework through ontology alignment may be required in this case to deduce the use of similar terms or structures between the ontologies.

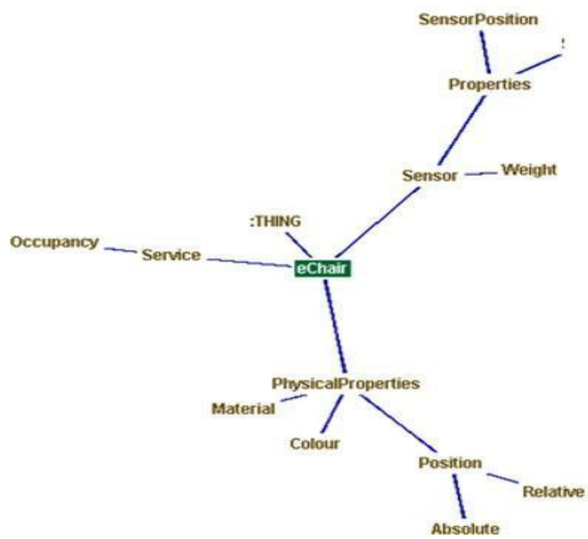

Figure 4. eChair Ontology.

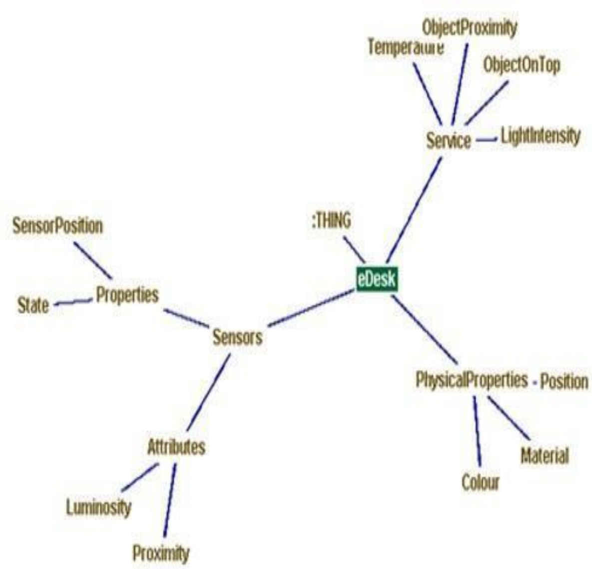

Figure 5. eDesk Ontology.

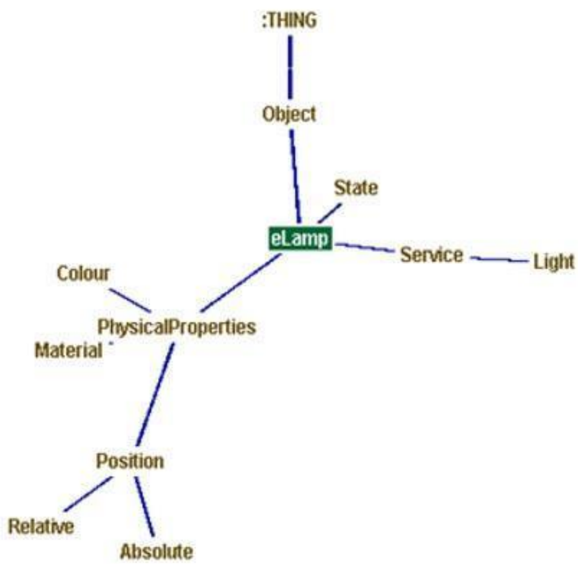

Figure 6. eLamp Ontology.

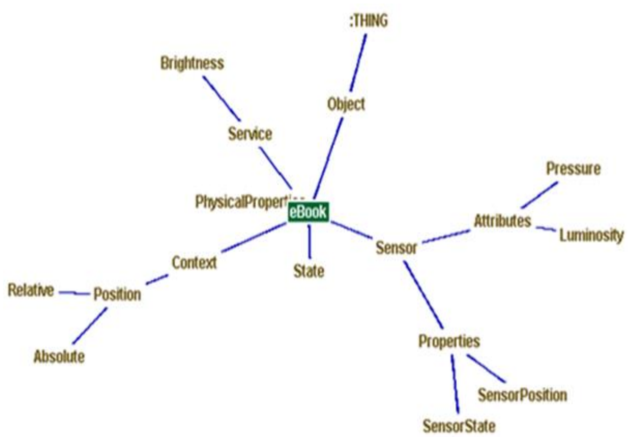

Figure 7. eBook Ontology.

In this context, an automatic ontology alignment module may apply linguistic and graph matching techniques [29]. Figure 8 shows an example of a linguistic similarity between two given ontologies based on descriptive information, like the property names. These similarities form the linking basis between smart object ontologies and provide the support mechanism to answer service discovery requests for a specific functionality that is required to instantiate an application. Similar questions may involve, for example, looking up a device that provides a light service or whether an IoT entity is of type desk. Such questions can be answered via the ontologies detailing semantically the smart objects and their alignments.

	Ontology 1	Ontology2	Similarity	Relation
0	SensorPosition	Position	0.715341	"="
1	hasProperties	hasPhysicalProperties	0.737579	"="

Figure 8. Example of similarities between two smart objects ontologies.

More rich knowledge can be acquired when individual ontologies are merged. Figure 9 illustrates the result of the merged ontology acquired using the ontologies of the smart objects involved in the smart light application. This merged ontology reflects the interconnected entities and can be used to infer knowledge regarding the collective behavior which can appear from the collaboration of the smart object services. Consequently, composite questions can be answered like whether a specific IoT environment is suitable for fulfilling the requirements of the smart light application.

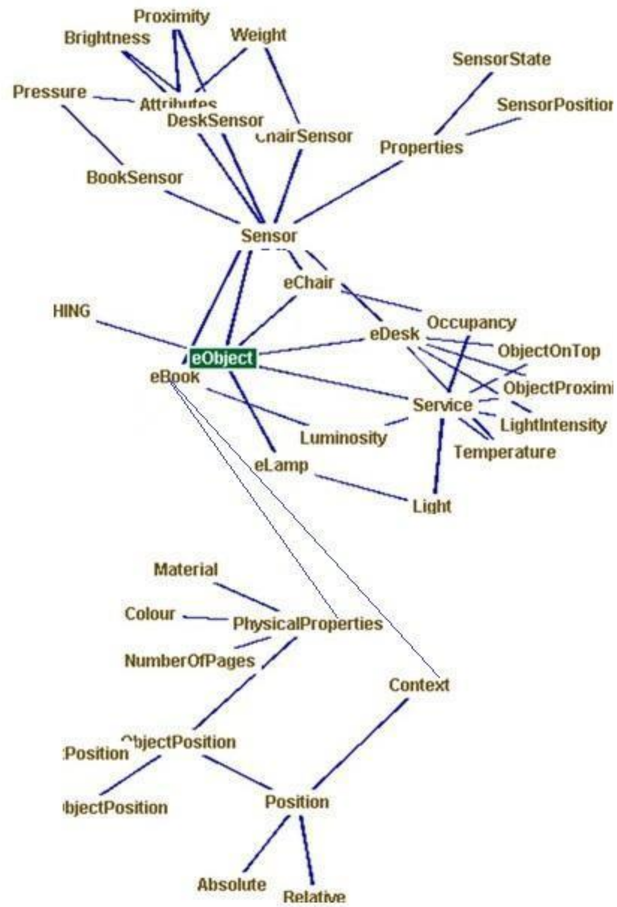

Figure 9. Merged ontology for the smart light application.

Figure 10 shows our future proof-of-concept implementation of SSNT in the domain of smart agriculture. The raw data streams will be collected by IoT sensors as they will be enriched with semantic annotation and will be modeled in ontologies with SSNT framework tools. Then, with semantic reasoning rules, social semantic groups will be created between the semantic data that aim to achieve a common goal, such as Greenhouse automation, crop management, and Monitoring of climate conditions. Finally, with SSNT semantic tools such as SPARQL queries, ontology alignment module etc., and new knowledge will be produced, and new services and applications will be created.

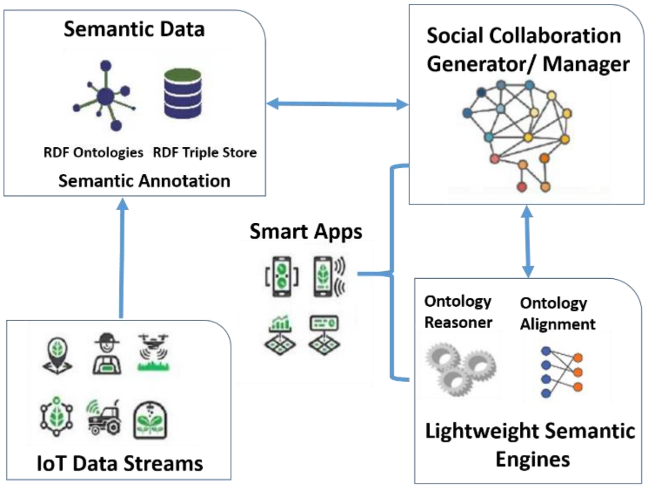

Figure 10. SSNT Framework in Smart Agriculture.

The SSNT framework has the capabilities of combining and analyzing data streams helping the farmers or agronomists in more informed decision-making in near real-time and fast reaction to changes and unpredictable events. For example, by automatically integrating sensory data about soil humidity with web services for weather forecasting, better decisions could be made about more precise irrigation and fertilization of the crops.

A basic application scenario of a smart crop management system is given to illustrate part of the SSNT framework functionality. We assume that an SSNT is deployed in a rural area. The system consists of various sensors (temperature, humidity, and thermal cameras), web services for weather forecasting, and actuators that help in the smart management of crops. Initially, heterogeneous IoT data streams are collected via the SSNT Data Acquisition module. Then, with the SSNT Data Integration module, the heterogeneous data are converted in RDF format. In this way, the raw IoT data modelled in interoperable ontologies that will be created with the Lightweight Ontology Creator/Annotator module. Furthermore, Data Storage module, storing semantic IoT data to a cloud database such as GraphDB, which is an enterprise-ready Semantic Graph Database, compliant with W3C standards.

Furthermore, with the application of semantic techniques using the appropriate tools of the SSNT framework, it is possible to create social groups of common interest which will be responsible for achieving a specific user goal. For the needs of the scenario, let us assume that two of the goals of the crop management system are: to increase fertility and to predict crop disease. After the goals are set by the user, through the Social Collaboration Generator / Manager Module, two social smart objects groups of interest will be created. In these groups, social relationships between things are created at the level of device interoperability, as well as relationships between things at semantic and syntactic interoperability levels. The first group will consist of soil humidity sensors, temperature sensors, data from web services for weather forecasting, and actuators such as solenoid valves. This group of smart objects will aim to collaboratively increase soil fertility. Through semantic functionality (SPARQL queries, reasoning rules), the semantically annotated data will feed special agricultural applications that will achieve the goal of increasing crops fertility. The second group of smart objects will consist of a thermal camera, and leaf wetness sensor. In the same way, the goal of disease control of cultivated plants will be pursued.

V. Conclusion

In contrast to other surveys of IoT research, this review study focuses on interoperability achieved by approaches in a multilevel perspective. Contemporary IoT frameworks have been systematically researched and their capability to achieve multi-layer interoperability between applications, services, and software platforms has been reported. Different solutions addressing interoperability issues at discrete levels have been studied, analyzed and compared to identify their limitations, such as lack of semantic lightweight tools, poor scalability and lack of collaboration mechanisms, while open issues and challenges were also identified. These limitations provide research opportunities and have motivated the Semantic Social Network of Things (SSNT) framework design. In this context, the concept of SSNT has been introduced for specifying device-to-device collaborative services based on the social interaction between smart objects while supporting interoperability at different levels and taking into account the limitations of IoT systems. Furthermore, a proof-of-concept application in the smart agriculture domain has been discussed to demonstrate important features of the presented approach.

Future activities will focus on implementing, deploying and evaluating the modules of the SSNT framework in real IoT environments. For instance, Generator / Manager social collaboration software will be evaluated in the agricultural domain where many heterogeneous IoT devices can be found. Software libraries and APIs related to the semantic data management (e.g., Jena, http:// https://jena.apache.org/), and open source IoT frameworks (e.g., openIoT framework, http://www.openiot.eu/), will be used to implement the proof-of-concept system of SSNT. Our future work aims also to address limitations of existing solutions such as the lack of lightweight semantic tools and the lack of tools for evaluating collaboration and social interaction mechanisms in order to assess how effectively such mechanisms can address multi-level interoperability issues in open IoT environments.

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