Internet of Things

IoT Semantic Interoperability: Research Challenges, Best Practices, Recommendations and Next Steps

European Research Cluster on the Internet of Things

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"If I have seen further it is only by standing on the shoulders of the Giants"

Sir Isaac Newton

European Commission
Information Society and Media

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Revision History

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Executive Summary

The European Research Cluster on the Internet of Things[1] (IERC) has created a number of activity chains to initiate close cooperation between the projects addressing the IoT related topics and to form an arena for exchanging ideas, to have an open dialog on important research challenges and to disseminate the ideas and best practices in the areas around the IoT to other communities. The activity chains are defined as work streams that group together partners or specific participants from partners around well-defined technical activities that work on addressing the IERC objectives.

As result of the organization of activity chains within the IERC and the continued collaboration and active participation between all the projects participation the ProbeIT, OpenIoT, IoT.est and GAMBAS projects, the managers of those projects, were nominated as coordinators of the IERC Activity Chain 4 (AC4) on Service Openness and Interoperability.

The design of the Internet and The Information and Communication Technology development relies on the convergence of Software Engineering and Technology (infrastructure). A common practice is required to think/design cross solutions between software and infrastructure in order to provide integrated solutions for some of the complex problems in the current and future Internet systems. In Information Technology and Communication (ITC) systems this convergence is evident, and the continuous evolution generates more and more smart devices (Internet connected objects - ICOs) that are embedded with sensors and their respective associated services.

"Internet of Things" (IoT) is the network or associations between those Internet connected objects (smart Devices) that are able to exchange information by using an agreed method and data schema. The recent progress on Internet of Things deployments have give a strong push to the IoT to be today's considered as one of the most promising emerging technologies. However the conceptual realization of Internet of Things is far from achieving a full deployment of converged IoT services and technology. Current ITC research is focused on providing integrated solutions and primarily on the feature that enable convergence or what is called as "Interoperability". Interoperability can be generalized as the feature for providing seamless exchange of information to, for example, personalize services automatically or simply exchanging information in a way that other systems can use it for improving performance, enable and create services, control operations and information processing. This type of scenarios requires increased interoperability in service management operations.

This document is an outcome of the activity Chan 04 in the Internet of Things Cluster. In this document we review the recent trends and challenges on interoperability in IoT domain, discuss physical versus virtual sensors and while addressing technology interoperability challenges in parallel, discuss how, with the growing importance of data understanding and processing, semantic web technologies, frameworks and information models can support interoperability in the design of services in the Future Internet. The objective of this position paper is to identify relevant issues and challenges that need to be taken into account in the coming and future projects and H2020 and to identify synergies across the participating FP7 projects. This can be used to define an overall framework to address the interoperability challenges.

[1] http://www.internet-of-things-research.eu

IoT Research and Innovation Challenges

The Information and Communication Technology development generates more and more things/objects that are becoming embedded with sensors and having the ability to communicate with other objects. This is transforming the physical world into a source of information and knowledge.

Internet of Things (IoT) enables the things/objects in our environment to be active participants, i.e., they share information with other objects and/or communicate over the networks (wired/wireless) often using the Internet Protocol (IP). Processing the IoT data enables to recognize events and changes in the surrounding environments and “things” can act and react autonomously. However, all these require heterogeneous objects to exchange information in an interoperable way to make their data and services accessible and interpretable by other objects and services.

Objectives

In the area of IoT, Europe is addressing the competitiveness in the context of globalisation. The technological specialisations built up over decades are transforming rapidly. In the area of IoT, IERC is focusing on increasing the link of projects, companies, organizations, people and knowledge at European level as a way of making projects more innovative and competitive.

This new approach is visible across a number of different policy fields implemented by the IoT Cluster. One of them is the creation of common activity chains (ACs) to enable close cooperation between the IoT Cluster projects and to form an arena for exchanging ideas and initiating open dialog on important research challenges.

The activity chains are defined as work streams that group together partners or specific participants from partners around well-defined technical activities that will result into at least one output or deliverable that to address the IERC objectives.

Evolutions in the global environment and evolutions in national policy, science and technology policy and industrial/enterprise policy are converging to support this type of collaboration at the national level. One of the vehicles proposed by the IoT Cluster in order to achieve a pan European coordination and cooperation is to support the national cluster liaison with “national value creation networks/clusters, innovation/research incubators” (concentrations of projects and supporting actors financed by the national public authorities) in every European country.

Internet of Things Research and Innovation on Semantic Interoperability

Introduction

Internet of Things (IoT) is an emerging area that not only requires development of infrastructure but also deployment of new services capable of supporting multiple, scalable (cloud-based) and interoperable (multi-domain) applications. In the race of designing IoT as part of the Future Internet architecture, academia and Information and Communication Technology (ICT) industry communities have realized that a common IoT problem to be tackled is the interoperability of the information and services. In this report we review the recent trends and challenges on interoperability, and discuss how semantic technologies, open service frameworks and information models can support data interoperability in the design of the Future Internet, taking the IoT and Cloud Computing as reference examples of application domains.

IoT refers to objects ("things") and the virtual representations of these objects on the Internet. It defines how the things will be connected through the Internet and how those things "talk" amongst other things and communicate with other systems in order to expose their capabilities and functionalities "services".

IoT is not only linking connected devices by using the Internet; it is also web-enabled data exchange in order to enable systems with more capacities to become "smart". In other words, IoT aims to integrate the physical world with the virtual world by using the Internet as the medium to communicate and exchange information.

IoT is mainly supported by continuous progress in wireless sensor and actuator networks and by manufacturing low cost and energy efficient hardware for sensor and device communications. However, heterogeneity of underlying devices and communication technologies and interoperability in different layers, from communication and seamless integration of devices to interoperability of data generated by the IoT resources, is a challenge for expanding generic IoT solutions to a global scale.

In this report we present various parallel and inter-related interoperability challenges ensuring that technologies deliver information in a seamless manner while this information is understood whatever the context and can be efficiently processed to deliver the potential of innovative services that IoT is aiming for.

To provide seamless communication and interaction between and with the real world objects, at anytime and anywhere in future, we need to solve today's complex interoperability issues.

Dimensions for Interoperability

The main objective of this report is not to produce a new definition on interoperability but to explore the different roles and functionality that interoperability plays in IoT. There are many definitions of interoperability; we try to provide a common definition that can be extracted from many of those definitions (bringing from the 3rd Generation Partnership Project, 3GPP). Interoperability is:

"the ability of two or more systems or components to exchange data and use information"

This definition provides many challenges on how to:

- Get the information,
- Exchange data, and
- Use the information in understanding it and being able to process it.

A simple representation of interoperability can be seen as follow:

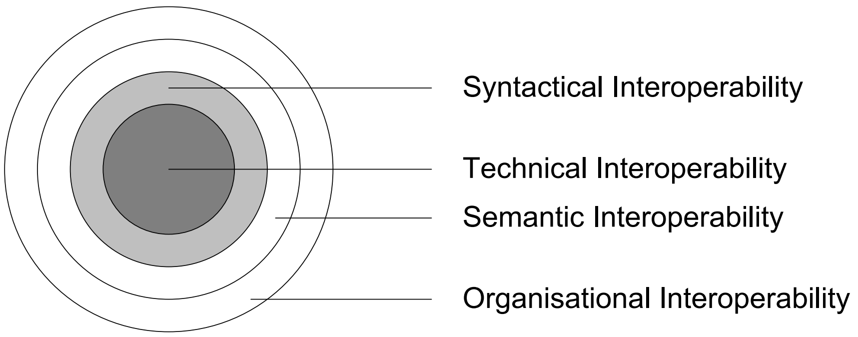

Figure 1 The Dimensions of Interoperability

In a white paper on interoperability [47] it is discussed that:

Technical Interoperability is usually associated with hardware/software components, systems and platforms that enable machine-to-machine communication to take place. This kind of interoperability is often centred on (communication) protocols and the infrastructure needed for those protocols to operate.

Syntactical Interoperability is usually associated with data formats. Certainly, the messages transferred by communication protocols need to have a well-defined syntax and encoding, even if it is only in the form of bit-tables. However, many protocols carry data or content, and this can be represented using high-level syntaxes such as HTML or XML

Semantic Interoperability is usually associated with the meaning of content and concerns the human rather than machine interpretation of the content. Thus, interoperability on this level means that there is a common understanding between people of the meaning of the content (information) being exchanged.

Organizational Interoperability, as the name implies, is the ability of organizations to effectively communicate and transfer (meaningful) data (information) even though they may be using a variety of different information systems over widely different infrastructures, possibly across different geographic regions and cultures. Organizational interoperability depends on successful technical, syntactical and semantic interoperability.
Following the definitions and the trends on ICT sector about sensors and sensor data we can add two other dimensions: **Static** and **dynamic interoperability**

Dynamic interoperability: Two products cannot interoperate if they do not implement the same set of options ("services"). Therefore when specifications are including a broad range of options, this aspect could lead to serious interoperability problem. Solutions to overcome these aspects consist of definition clearly in a clear document the full list options with all conditions (e.g. defined as PICS in [49]) as well as to define set of profiles. In the latter case, defining profile would help to truly check interoperability between two products in the same family or from different family if the feature checked belongs to the two groups. We could consider this aspect as:

Static interoperability using approach of the well-known OSI overall test methodology ISO 9646 [49], where there is definition of static conformance review. Conformance testing consists of checking whether an Implementation Under Test (ITU) satisfies all static and dynamic conformance requirements. For the static conformance requirements this means a reviewing process of the options (PICS) delivered with the IUT. This is referred to as the static conformance review. This aspect could appear easy but that represent serious challenge in the IoT field due the broad range of applications.

The solutions that use non-interoperable solutions lead to increase of complexity in communicating and interpreting their data and services. One interesting research is to accept differences and potential non-interoperability for instance between two different protocols but to adapt on the fly. We see also such features in intelligent gateways and middleware. This can be called **dynamic interoperability** and should be a continuous important research area in particular with the growing complexity and heterogeneity of IoT environments.

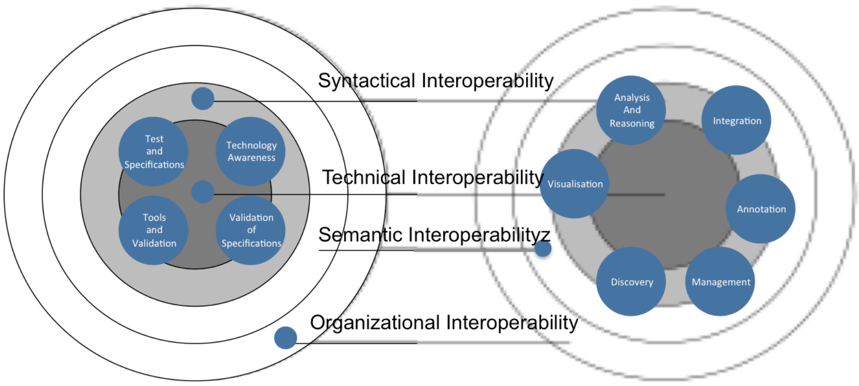

Figure 2 The Dimensions of Interoperability and their associated General Challenges

Interoperability: Challenges and Requirements

The overall challenges in interoperability is first to stabilize the foundation of the real world data/services, ensuring technical interoperability from technologies to deliver mass of information and then complementary challenges are for the information to be understood and processed. Before entering into details present a summary of the challenges for technical and semantic interoperability in *Table 1*.

Table 1 IoT Technical Interoperability Challenges/Requirements

Requirement(s)	Rationale & Remarks
Technology Awareness • Spreading effort in addressing interoperability for worldwide protocols	• Coordinate worldwide interoperability initiatives on market support specifications or protocols • Develop market acceptance roadmap • Use clear specifications development and testing methodologies leading to improve quality while reducing time and costs in a full chain optimized development cycle • Define if needed profiles to improve interoperability
Validation of specifications • Reduce ambiguities in specifications and development time	• Specifications development time could be too long • Ambiguities in specifications could lead to major non interoperability issues • Quality, time and cost factors lead to the needs of models and automation
Tests and Specifications • Provide market accepted test and when existing/possible specifications ensuring minimum accepted level of interoperability	• No test specifications lead inevitably to different specifications implementation and interoperability issues • Development test specifications is often too expensive for limited set of stake holders and effort should be collectively shared • Tools processing and automation are only way to reduce time and market (e.g. use of MBT)
Tools and validation programmes • Develop market accepted and affordable test tools used in market accepted validation programs	• Development of test tools are expensive • Available test tools developed spontaneously by market forces can have test scopes overlapping and even not answering to all tests needs. • Full chain of specifications to tool development not considered • Providing final confidence to end users with consistent tests not always considered

Table 2 summarizes the main requirements associated with the development of the IoT service(s) / application(s) in reference to semantic interoperability requirements. It also provides the main rationale that has led to these requirements.

Table 2 IoT Semantic Interoperability Challenges/Requirements

Requirement(s)	Rationale & Remarks
Integration • Support multiple ICOs (sensors, actuators) and relevant types of data sources (independently of vendor and ICO location).	• Enable scalable sharing and integration of distributed data sources. • All IoT applications involve multiple heterogeneous devices. Orchestrate ICOs in order to automatically formulate composite workflows as required by end-user applications.
Annotation • Enable the (automated) linking of relevant data sources.	• Linking of data sources facilitates application integration and reuse of data. • Enable interactions between ICOs and between IoT services. • Built on the standards (i.e. W3C SSN standard ontology) for description of sensors and ICOs.
Management • Enable the creation and management of virtual sensors and virtual ICOs based on the composition and fusion of streams stemming from multiple (ICO) data sources.	• Application development and integration involves multiple distributed and heterogeneous data sources to be processed in parallel. • The definition and management of virtual sensors eases applications integration.
Discovery • Provide the means for discovering and selecting ICOs and data sources pertaining to application requests (according to their capabilities).	• End users need a high-level interface to be accessed. • Provide the means for describing/formulating IoT services and applications according to high-level descriptions. • Provide (configurable) visualisation capabilities of multiple integrated data sources (in a mash-up fashion).
Analysis and Reasoning • Provide analytical and reasoning tools on top of semantic level capabilities.	• IoT addresses large-scale environments with numerous ICOs featuring different functionalities and capabilities. • End-user applications involve the monitoring of virtual and/or Physical sensors
Visualisation • Optimise usage of resources (storage, computing cycle, sensor utilisation) across multiple users sharing these resources.	• Several applications involve object-to-object (e.g. M2M) interactions or interactions between services; such interactions could be either defined explicitly (i.e. by end users) or derive implicitly (based on the application context).

The *Figure 3* summarizes the main requirements associated with the development of the IoT service(s) / application(s) in reference to semantic interoperability requirements. It also provides the main rationale that has led to relate general requirements with research and innovation objectives via links between the objectives and the active projects working on those topics.

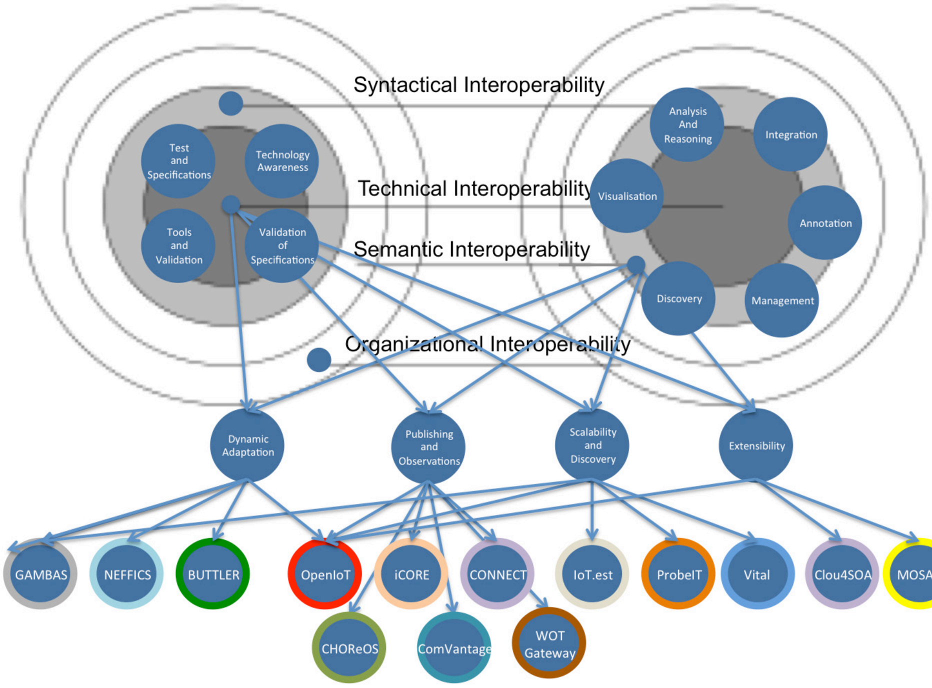

Figure 3 The Dimensions of Interoperability mapping to challenges

The Figure 4 represents the relation between the two main areas for interoperability, including technical and semantic interoperability, with the general challenges defined in the scientific research and innovation agenda and the activities where the active projects are related.

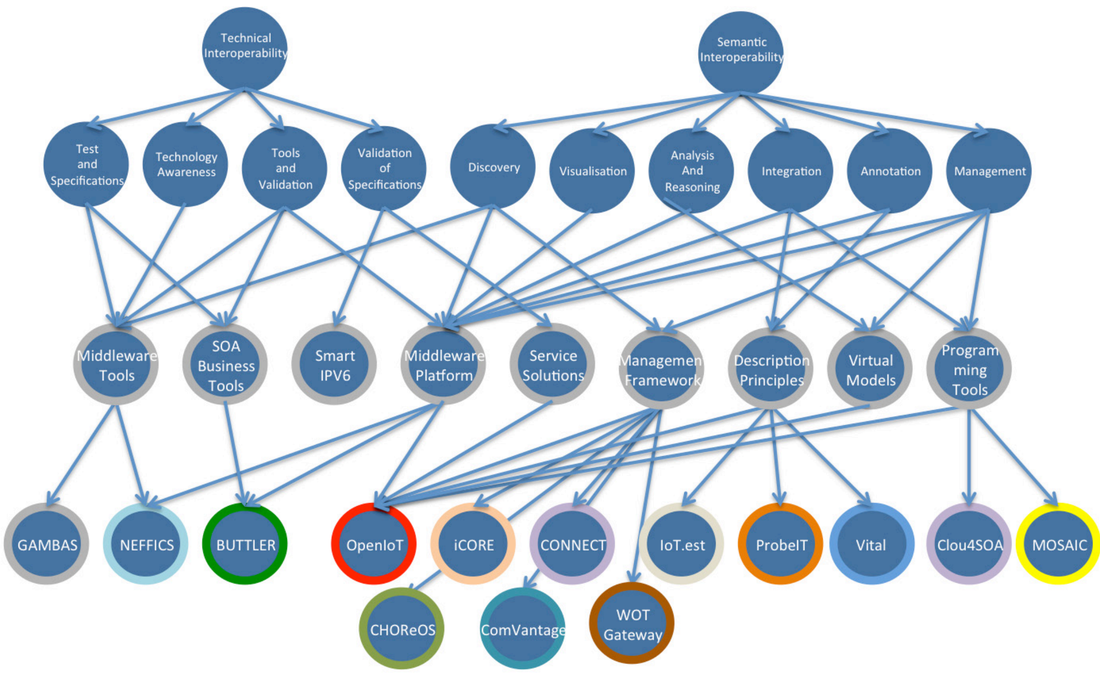

Figure 4 The Dimensions of Interoperability and their associated General Challenges

Semantic Interoperability Research Challenges

Main high-level challenges in Interoperability

Convergence in Technology

IoT environments for Internet-connected objects facilitate the deployment and delivery of applications in different domains and will enable businesses and citizens to select appropriate data and service providers rather than having to deploy physical devices. At the same time, they will provide capabilities such as on-demand large scale sensing beyond what is nowadays possible. It is important to highlight the origins of IoT are found in the area of Radio Frequency IDentification (RFID) domain where RFID tags are extensively used for data collection. The static information a group of RFID tags can generate motivated the quick development of RFID middleware frameworks to the extent that nowadays FID frameworks provides functionality for RFID data collection, filtering, event generation, as well as translation of tag streams into business semantics.

Several initiatives have produced several open-source RFID frameworks, such as Mobitec [50], AspireRFID [51] as well as the fosstrak project [52] which provide royalty-free implementations of RFID middleware stacks. The evolution has continued and the generators of data are now generally named "sensors" by their capacity to produce data and their flexibility to create cells or groups of them by using embedded wireless technology. In this sense several middleware platforms have also been devised in the area of Wireless Sensor Networks (WSN). Specifically, there are platforms addressing only the level of the sensor network, whereas other deal also with devices and networks connected to WSNs. Some middleware platforms are characterized as sensor databases, other as virtual machines, whereas there are also publish-subscribe approaches. Systems such as Moteview [53] and ScatterViewer [54] are examples of WSN development and monitoring systems, which however provide limited extensibility (tightly coupled approach). Other environments such as Hourglass [55], SenseWeb [56], jWebDust [57] and GSN [58] provide more complete development and/or programming environments for WSN applications.

Beyond the limits of physical devices (e.g. sensors) there is also a notion of "Virtual Sensor" that refers to virtualization of an element of the IoT platforms representing new data sources created from live data. These virtual sensors can filter, aggregate or transform the data. From an end-user perspective, both virtual and physical sensors are very closely related concepts since they both, simply speaking, measured data. The Semantic Sensor Network (SSN) ontology, providing the most important core vocabulary for sensing data, defines the notion of sensor and physical devices in general, therefore formally the concept of a virtual sensor as a subclass of the sensor concept as defined in the SSN ontology. Due to the rising popularity of IoT technologies and applications the emergence of a wide range of platforms that enable users to build and/or use IoT applications is unavoidable. In general there is a clear trend towards the convergence of physical worlds and virtual solutions by using IoT technologies.

In all cases either Physical or Virtual sensors, a middleware framework is the core element to be used for providing baseline sensor functionalities associated with registering and looking up internet-connected objects, exchanging messages between objects, as well as fusing and reasoning data from multiple-objects. Some features of these implementations are:

1. Integrate ontologies and semantic structures, in order to enable semantic interactions and interoperability between the various objects, which will be a significant advancement over the existing syntactic interactions.
2. Provide Open Linked Data interfaces (e.g. SPARQL (SPARQL Protocol and RDF Query Language) over ontologies for internet-connected objects within the physical world middleware to interact with virtual world).
3. Define techniques for the automated data configuration of filtering, fusion and reasoning mechanisms, according to the problems/tasks at hand.

Taking a broader view of state-of-the-art and current developments in interoperability and in converging communications, many of the problems present in current Internet will remain in the Internet of Things systems and mainly generated by interoperability problems, thus there are three persistent problems:

1. Users are offered relatively small numbers of Internet services, which they cannot personalise to meet their evolving needs; communities of users cannot tailor services to help create, improve and sustain their social interactions;
2. The Internet services that are offered are typically technology-driven and static, designed to maximise usage of capabilities of underlying network technologies and not to satisfy user requirements per se, and thus cannot be readily adapted to their changing operational context;
3. Network operators cannot configure their networks to operate effectively in the face of changing service usage patterns and rapid networking technology deployment; networks can only be optimised, on an individual basis, to meet specific low-level objectives, often resulting in sub-optimal operation in comparison to the more important business and service user objectives.

As the move towards Internet of Things, the convergence of communications and a more extended service-oriented architecture (SOA) design gains momentum, worldwide there is an increasingly focussing on how to evolve communications technologies to enable the “Internet of Things”. The aim is directed mainly by pervasive deployment of Internet protocol suites and VoIP is a clear example of this. We believe that addressing evolution of networking technologies in isolation is not enough; instead, it is necessary to take a multi-domain adaptable holistic view of the evolution of communications services, their societal drivers and the requirements they will place on the heterogeneous communications infrastructure over which they are delivered as depicted in Figure 5 Internet of things is an interconnection of collaborative domains (Diagram adapted from L. Atzori et al., 2010,).

By addressing information interoperability challenge issues, Internet of Things systems need to exchange information and customize their services. The Future Internet can reflect changing individual and societal preferences in network and services and can be effectively managed to ensure delivery of critical services in a services-aware design view with general infrastructure challenges.

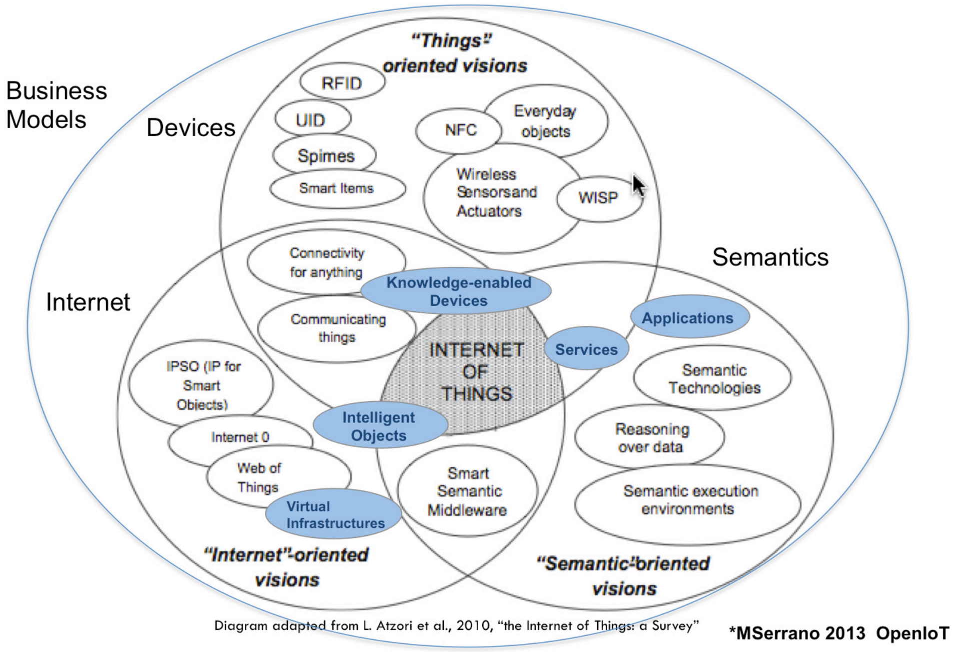

Figure 5 Internet of Things Multidomain Holistic View [59]

Integration of multiple data-sources

In a dynamic environment like the Internet of Things, where technology evolves rapidly and thus data sources change formats at all the time, there is an strong requirement to integrate multiple information sets. This describes the necessity to be interoperable at the data/event level so that it becomes easier to combine/aggregate data/event coming from heterogeneous data sources. This raises also the challenge of being able to look up/discover data source and relevant data.

Unified Data Map / Ontology as point of reference

In the Internet of Things it is normal to think in multiple devices (smart or not, this is not a constraint to get them connected), devices that are able to "talk" in the form of exchanging information or simply data. Semantic interoperability means having a unique point of reference at the data level (data grapch / data representation / ontology level). Semantic Interoperability can be solved by third party responsible for translating between different schemes or via a directly generated ontology merging/mapping the terms and concepts involved. Likewise when implementing the ontology there could be also protocols for agreeing upon a specific ontology.

Mobility and Crowdsensing

The evolution of sensors networks towards personal networks relies on smart devices capacities. Connectivity and processing has reached the level that today's is not considered anymore a limitation to process and exchange data in a local environment. This describes the necessity to support mobility of the device and transport of data beyond boundaries. Crowdsensing is a common area where Interoperability can not be ignored, first because there is technloogical at lower-levels and data implications at a higher-level.

P2P Communication

This describes the necessity for applications to communicate at a higher-level through exchange of "business" knowledge. Interoperability can be ignored at lower-levels and can be implemented at a higher-level.

Main challenges in Semantic Interoperability and foreseen needed research

Data Modeling and Data Exchange

The nature of the information is the most important feature to consider when data is being handled, IoT systems needs data to process instructions and generate outcomes; if IoT applications can fully exploit the richness of the data, services around data management will be dramatically improved [12].

Other important challenges in the Internet of Things in relation to data include: (1) how to represent the data and standardize the data specifications, (2) if the data is correctly collected (trust and validity) and represented, and (3) if the information can be translated to a standard format (information model), then different applications can all use the information. Finally, some types of data also depend on user interfaces (which can make retrieving data much easier), or the type of technologies used to generate the information.

Modelling data is one of the major challenges in the Internet of Things services deployment, without having a clear and at same time flexible information model, applications will not be able to use such information in an efficient way. The information model needs to be expressive and flexible enough to accommodate not only the current facets of information, but also future ones [24]. It has to be based on standards as much as possible and moreover, the model should scale well with respect to the associated technology and the applications. This introduces a great challenge for managing this information in a consistent and coherent manner. Storage and retrieval of this information are also important.

Another important aspect to consider in the information model is the continuous evolution in technology and mobility issues in IoT. The IoT systems require the development of extensible context models that enable the efficient representation for handling and distribution of the information in the information systems.

The model in IoT for exchanging data is based on simple concepts and its relationships, as syntactical descriptions, between those concepts; for example an object or entity is composed of a set of intrinsic characteristics or attributes that define the entity itself, plus a set of relationships with other entities that partially describe how it interacts with those entities. The objects/entities can represent anything that is relevant to the management domain (in this case IoT). Moreover, the relations that can exist between the different model entities can represent many different types of influence, dependence, links, etc. depending mainly on the type of entities that these relationships connect. The model's objective is to describe the entity and its interaction with other entities by describing the data and relationships that are used in as much detail as is required. This abstraction enables the model to be made more comprehensible by different applications. Since the abstractions can be represented in machine-readable forms, the information can be processed by applications much easier than a free-form textual description.

Ontology merging / Ontology matching & alignment

In IoT the knowledge modelling depends on the point of view of the application definition and scope. The information model is a first approximation on how to structure, express and organize the information [24] [25] the knowledge representation is the information associated to the service. The information model is based on the concepts of entity and relationship and derived from the definition of entity the knowledge model is derived from the service or application.
The concept of the local context of an entity can be defined as the information that characterizes the status of the entity. This status is made up of its attributes and its relationships. Moreover, the relationships that can exist between the different entities inside the model, as well as the entities themselves, can represent many different types of influences, dependencies, and so on, depending on the type of entities that these relationships connect.
With this type of model, one can construct a net of entities and relationships representing the world surrounding the activity of a context-aware service and thus the models can influence the development of the activity or service. This enables a scenario made up of many different types of information, and the influences or nexus that links one with the others. The local context enables the service to select and use context information from this scenario that is considered relevant in order to perform its task and deploy its service.

Data/Event Semantic Annotation (and dedicated ontologies)

In Semantic Web Ontologies are used to share and reuse knowledge [29] and recently, applications have concentrated on using ontologies to solve the interoperability problems (e.g., the inability to exchange and reuse data) when different systems that use different knowledge representations and languages interact with each other. Ontologies provide enrichment to the information model and provide semantic expressiveness to the information [29]. Ontologies can also support the information exchange between applications and between different levels of abstraction, which is an important goal for IoT.

Typically Ontologies are used to provide semantic augmentation, addressing the cited weaknesses of data models [36] and beyond with ontologies the integration of information and interoperability is achieved, resulting in improved IoT system control and management. The relationships are shown in Figure 6, where the ontologies are used for making ontological commitments in form of cognitive relationships (i.e., an ontological commitment is an agreement to use a vocabulary in a way that is consistent to different domains of application).

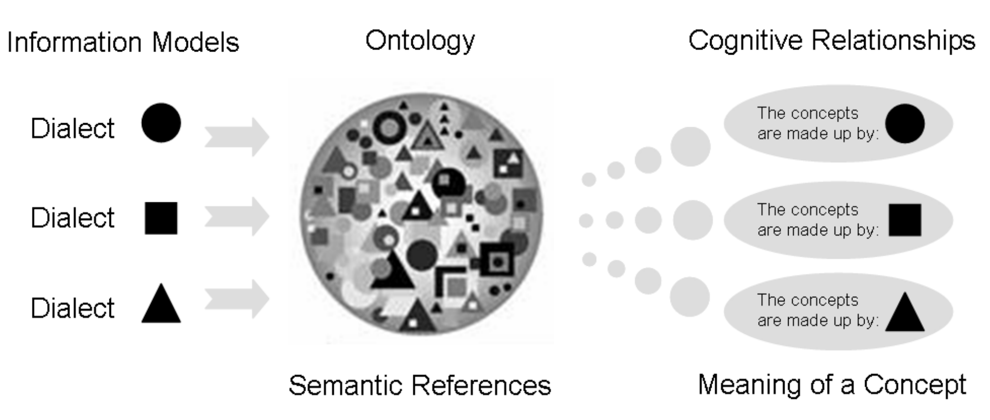

Figure 6 Information Models – Ontology Engineering.

Knowledge Representation and related ontologies

In IoT an important aspect is the identification of the data to collect, gather and store accordingly to a defined information model. The format to contain the information is work of the model to be followed. The information model can be used not just to model information in services, but also to manage the services provided. The information model must be rich in semantic expressiveness and flexible enough to consider the variations of current status of the object being managed [38]. The model should scale well with the IoT technology and accordingly with the application which it is implemented.

If the information models are expressive enough, different systems can use that information to provide better management service operations. In order to formalize the information contained in the information model, ontologies appear to be a suitable alternative. However, this does not mean that other approaches are unsuitable for different applications. In the Internet of things ontologies, appears as a suitable alternative to exchange knowledge as per the result of providing the required semantics to augment the data contained in the information model in order to support service management operations.

Knowledge Sharing

The tools that could be used to represent and implement data model, and the way to integrate this information model inside the general IoT system architecture, need to be identified and tested, as they are potential tools for representing the context information. The Resource Data framework Definition (RDF) is a flexible and platform-independent description framework that can be used in different stages of the information representation, which makes implementation consistent and much easier. The use of RDF is increasing but it is by definition generic. Therefore, new languages that are based on RDF have been developed that add application-specific features as part of the language definition. For example, to customize services, languages must have concepts that are related to the operational mechanisms of that service.

It is in this context that we propose the RDF/XML Language to represent the context information models. XML has the following advantages:
XML is a mark-up language for documents containing structured information.
The use of RDF facilitates the validation of the documents created, even in a more basic but in some way also functional the use of Document Type Definition (DTDs) is also an alternative for validation. This validation can be implemented in a JAVA program, which can be the same used for creating and maintaining these RDF/XML Schemas and/or documents.

The use of XQuery, as a powerful search engine, to find specific context information inside the XML documents that contain all the information related to a specific entity. These queries can select whole documents or sub-trees that match conditions defined on document content and structure. Once the data is expressed in RDF, the use of SPARQL, as query processor engine, to find specific knowledge information is extensible effective. These queries can go from simple to more complex and select whole documents or sub-trees that match conditions defined on document content and structure.

Knowledge Revision & Consistency

The linked-data principles have been applied to the IoT domain to support creation of more interoperable and machine process-able data and resource descriptions (e.g. for sensors and sensor networks). Including domain knowledge and linking IoT resources to external data (e.g. the linked open data cloud) that describe different thematic, spatial and temporal concepts is also another key aspect in supporting effective interpretation and utilisation of the IoT data. The same principles should be applied in a broader range (not only for sensors) to create a truly interconnected network of Things.

Most of the challenges and future research issues are closely related to the dynamicity and pervasiveness of the domain. While there are many efforts in creating common models for describing and representing the IoT data and resource descriptions, the community still lacks on common and widely accepted models for wide-scale interoperability.

Semantic Discovery of Data Sources, Data and Services

The IoT community requires coordinated efforts to define common vocabularies and description framework to represent data, resources and interfaces in the IoT domain. These vocabularies and ontology models, preferably lightweight and easy to use, need to be reused and broadly adopted to create an interoperable way of data/service exchange across different domains and applications. Furthermore, providing automated or semi-automated methods and tools or built in procedures for devices to annotate, publish and access the semantic descriptions play essential roles in using semantic technologies to enhance the interoperability of the data and resource descriptions in the IoT domain [8].

Semantic Publish/subscribe & Semantic Routing

Observation or measurement data collected from the real world can be semantically described to facilitate automated processing and integration of the data in relation to domain knowledge and other existing resources in the cyber world; resources and components in IoT (e.g. sensors, actuators, platform and network resources) can be described using semantic annotations to enable effective discovery and management of them; on a higher-level, the IoT services and their interfaces can be semantically described to enable discovery and composition of the IoT data/services.

There is sometimes this perception that by using ontologies and semantic descriptions the IoT data will be interoperable across different domain and various applications. Having a number of ontologies, however, will cause an interoperability issue between different models and ontologies.

Data access in IoT can be implemented at lower-levels (e.g. device or network levels) by the use of low-level programming languages and operating system level access [21]. The heterogeneity of the devices and (sensor) networks in IoT makes data publishing and access across the networks a difficult task. Service oriented principles, which allow complex software systems to be represented as sub-systems or services, have been used to integrate the IoT data with enterprise services [46]. The idea of "sensing as a service" represents a scalable way to publish and access the sensor data through standard service technologies and has received consensus from the community.

The middleware components and services can also act as intermediaries to allow publishing the IoT data and presenting it to the consumer applications and users. The data can be published directly as raw data or it can be associated with the metadata and semantic descriptions. However, often there is no direct association to the domain knowledge in the core models that describe the IoT data [8]. Different resources, including observation and measurement data, also need to be associated with each other to add meaning to the IoT data.

Effective reasoning and processing mechanisms for the IoT data, and making it interoperable through different domains, requires accessing domain knowledge and relating semantically enriched descriptions to other entities and/or existing data (on the Web). An effective approach for publishing and consuming the IoT data can be using Linked-data model. Linked-data is an approach to relate different resources and is currently adopted on the Web. The four principles, or best practices, of publishing data as linked data include [9]:

1. Using URI's as names for things; everything is addressed using unique URI's.
2. Using HTTP URI's to enable people to look up those names; all the URI's are accessible via HTTP interfaces.
3. Providing useful RDF information related to URI's that are looked up by machine or people;
4. Linking the URI's to other URI's.

Publication of data as described above can be performed by submitting/publishing data as linked data or it can include other semantically described forms or it can be only submitting raw observation and measurement data. In any case, common interfaces and/or service models are required to enable publishing the data and integrating it into the existing data or enabling consumers to access the data.

Analysis & Reasoning

In IoT, binary data and syntactic data models offer limited interoperability at data and resource description levels. Using semantic annotations and adding metadata descriptions to different parts of the IoT systems ensures that data originated from different resources and with heterogeneous forms can become accessible and process-able across different domains and users.

Achieving Semantic Interoperability: Solutions and Best Practices

Internet of Things Stack

The first step to solve semantic interoperability and particularly in the Internet of Things particularly is situating the problem in the IoT value chain for services and applications. This section introduces the stack for service delivery models and interoperability for the Internet of Things. The main characteristics and functional layers of the IoT Stack are described. The applicability of the IoT stack is described based on particular use cases and deployed pilots and demonstrated in terms of interoperability as examples.

The deployment of the Internet of things (IoT) systems rely on the correct definition of principles for configuration, discovery and control of devices (things) by means of particular service delivery models [96], [62] having in consideration its applicability at the business level and under user-centric design principles [90],][89].

In practical terms an IoT deployment involves technology with certain level of autonomy and self-organising capacity in order to satisfy the service demands form overlay service and application levels. In certain scenarios or use cases where technology interconnection is not a restriction the barrier for service deployment is the business model and mainly the application not having a service delivery model defined. A service delivery model in the IoT is commonly named vertical and it is characterized by providing a specific solution following a defined technology and data model [92]. While the service control loop for IoT systems has already been proposed (autonomics) [72], the dynamic deployment of their different modules is still due. Interoperability between different verticals is still an issue [61], [69].

This section introduces methods and describes functionality about interoperability by means of enabling semantic annotation, identification, registry and discovery in the framework of the OpenIoT project2. The main

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

characteristics and building blocks of the OpenIoT middleware enabling IoT interoperability, along with methods and standards that boosted realistic implementation about edge intelligence are described in this paper. Generally speaking, an edge intelligent component acts as gateway between two different applications or sources of information [98], [62], [42], [63].

Particularly in the framework of the OpenIoT project the OpenIoT platform acts as the gateway for the Extended Global Sensor Networks (X-GSN) middleware (based on the GSN3) that is responsible for providing an interface for the raw and heterogeneous sensor data; and the Linked Sensor Middleware (LSM-Light) [42], responsible for organizing the X-GSN data to become Linked Data and to annotate the data to enable sophisticated sensor discovery and service orchestration. Both X-GSN and LSM-Light provide various means for filtering, aggregating and managing the data before being handed over to overlying applications. The implementation of OpenIoT as edge intelligence enables service providers to deploy cloud/utility-based infrastructures by means of information that can support the delivery of IoT services through responding to appropriate end-user requests [63], [88], [87] [86].

The stack for service delivery models and interoperability for the Internet of Things (IoT) is shown at the *Figure 7*. The main characteristics and functional layers of this IoT Stack are described as follow.

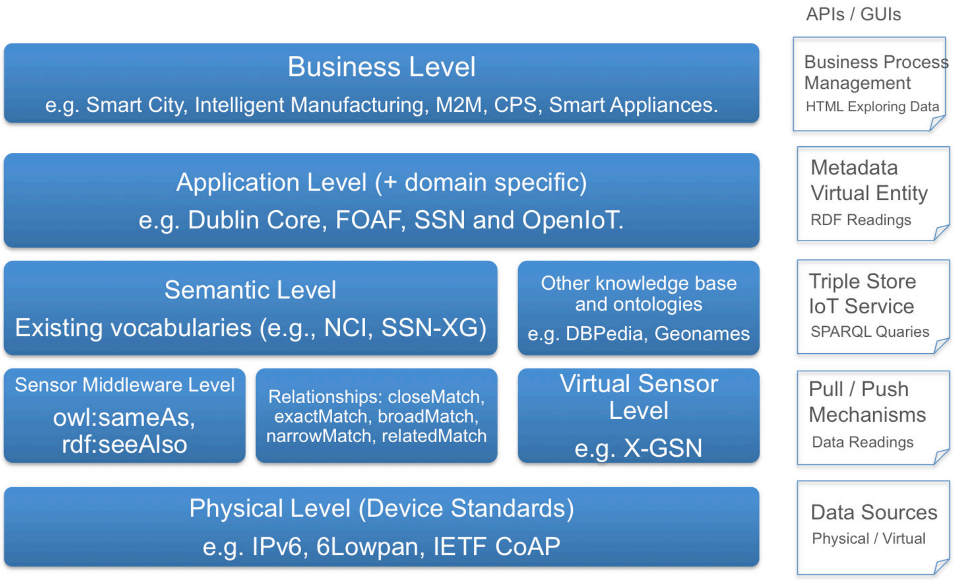

Figure 7 IoT Stack for Service Delivery Model and Interoperability

Physical Device Level – Raw Data

At this level the collection, identification and handling of data relevant to a particular technology is performed. The technology that is connected to the IoT platform is responsible for sensor network protocols and the data transfer models can be proprietary to each manufacturer.

[3] http://github.com/LSIR/gsn

Sensor Middleware Level – Data Transformation

Transformation is performed on moving windows (expressed by time durations) to define useful data, It can be described at the level of wrappers or combination of them with aggregation functionalities, the rationale of performing aggregation as early as possible is to alleviate the sensor middleware and annotations.

Virtual Sensor Level – Data Aggregation

Aggregation occurs on digital data to identify, mark and classify useful data, Information that is useful for control and provisioning applications and services deployments is usually added at this level. As consequence of this aggregation parts of a vocabulary must be used and universally used. The links or associations are called relationships and can be generated as much as possible to better describe the nature of the data that is being annotated.

Semantic Level – Data Management and Control

Data management layers to provide data management tools to query information and offer intermediate access from Application to data by means of linked data. At this level knowledge database or repositories for data and annotations reside and other vocabularies and ontologies too.

Application Level – Data Representation

Reducing the burden of performing common aggregation, thereby boosting specific representations and reducing ambiguity in a trade-off manner with complexity. At this level all the data can be offered by means of standard open software interfaces or tailored for specific domains.

Business Level – User Data Visualisation

Provisioning and visualizations for end users are offered as service. In this level domain specific representation has non-technological dependency and majorly data is driven in the form of aggregated services.

IoT Stack – Information Service Lifecycle

Internet of Things systems demand a level of awareness about the applications and behaviour of the technology supporting the services. A service-agnostic design for data management in IoT systems is not an efficient way to achieve interactive solutions enabling service composition and supporting information sharing capabilities between heterogeneous (public and private) IoT infrastructures. The *Figure 8* depicts the information lifecycle, from an IoT Information management perspective in the form of services range from sensing as a service to actuation as a service. Information exchange (interoperability) between data and service levels is a key challenge. Linked Data is seen as an opportunity to face up with data interoperability requirements in cloud computing systems. In order to understand the data cycle is necessary to explain the *Figure 8*.

Data sources are located in intra-domains and offer their data as services individually (i.e. sensors) or as a results for a sum of number of operations (i.e.

sensors networks offering only a operational value),. The enabled monitoring services orchestrate and promote the data into a expose interfaces for announcements of the data exposition that the service is capable to offer. The data exposed is taken for data transformations. The data transformation is the process adding descriptions as result of semantic annotations in conjunction with privacy methods to guarantee a) the integrity of the data, and the validation of the source and b) protect the data from possible intrusions. The data has been annotated and thus now is part of an information domain where query processing can take such descriptions into consideration offering a more efficient re-collection of data.

The storage of information is typically a matter of extra storage services, traditionally any distributed geo-spatial database can perform this activity. Recently cloud-based systems are making more cost-effective this process reducing he burden of running complicated process in large computing centres. At this stage the information is ready to be used to execute more complex information management operations like stream processing and reasoning. As result of those complex process or simply as response of a query the outcomes are re-defined for the application and with corresponding privacy mechanisms and credentials executed the information suffer a step down for transforming the outcome collected information into readable data for the consumer data service (i.e a script line instruction or actuation in a device).

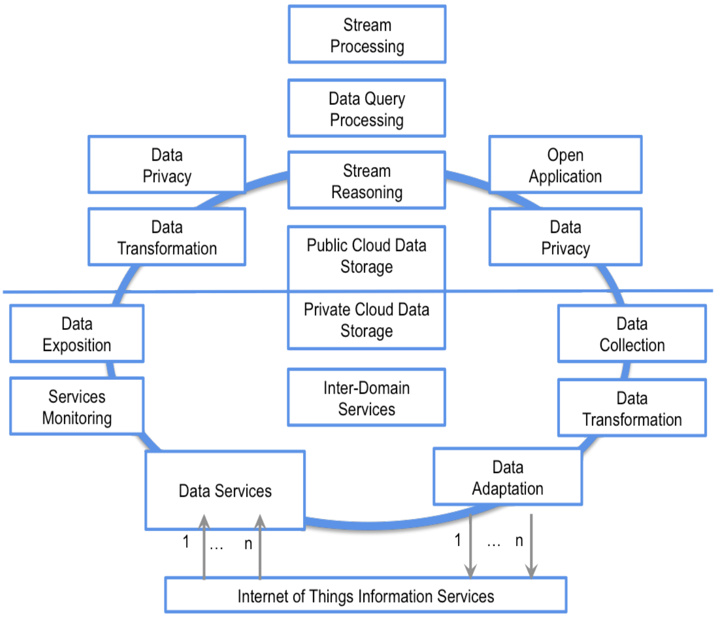

Figure 8 IoT Information Lifecycle for the IoT of services

Current Internet architecture as a design conception is not service-oriented nor user-friendly and does not Include service openness neither free information Exchange (inter-operability) between data and service levels; these facts rises a challenge for academic and industry for designing cloud systems where Information interoperability is a key challenge [84]. Use Service Control Loop and Linked-Data Lifecycle design principles for controlling infrastructure and services in cloud [91]. Enable Linked-Data Layer; an extensible, reusable, common and manageable information layer following cloud and end user service principles. Use high-level data Infrastructures and data representations to enable the management of resources when they are not required to support or deploy services.

IERC AC4 position and envisioned solution(s)

The current report and investigating the existing solutions has shown that:

- Often there is no general agreement on annotating the IoT data
- There are several models, each having their own semantics and their own schema
- In addition to the schema, it is also important to decide how the annotation will be done (according to the chosen schema)
- The models are often complex and express-ability vs. usability can be an issue in using complex and very detailed models (especially in large-scale deployments)
- Using different representation formats can also cause interoperability issues at the serialisation level

The following summarises a set of recommendations to enhance the interoperability and to provide common solutions for semantic interoperability among various providers and users in the IoT domain. Some of the technical solutions that can be proposed to address the above issues are:

- Providing alignment between different and using ontology Mapping/Ontology Matching solutions
- Using coordinated efforts to designing common specifications and core schema/reference models
- Providing metrics, tools and interfaces for annotations, test and validation and integration

Using linked-data can be also an effective solutions to link descriptions from different domain and models, to link resource descriptions to external metadata, and to use common vocabularies and taxonomies to describe different attributes of the data; e.g. Location (e.g. GeoNames), theme (e.g. DBpedia)

At the community level, setting up special taskforce among the projects can be considered to design a common (and minimum set) specifications that can be used for semantic descriptions of IoT data (i.e. observation and measurement data), resource descriptions (i.e. devices, network resources), command and interactions (i.e. actuation commands, publish, subscription, discovery and other similar messages), services (i.e. interfaces, application and higher-level services). The result of such an effort will be a set of basic models that can be used (and accepted) across different projects, tools for publishing and validating the descriptions according to the designed model and a set of best practices to annotate the legacy data according to these models.
Table 3 summarizes the best practices and trends in relation to the interoperability in IoT.

Table 3 IoT Interoperability Areas within the IERC Summary

Challenges	Current Solutions	Topics / Application Areas
Technical interoperability Provide confidence on IoT products to market with market-accepted level of free information exchange	• MOBITEC technology • AspireRFID platform • FOSSTRAK tools • BULLSEYE platform • SCATTERVIEWER tools • HOURGLASS platform • SENSEWEB Platform • JWEBDUST tools • GSN Framework	• RFID and sensors networks • Manufacturing and automation • Agri-Food and machinery standards • Architectural principles and design guidelines. • Design and implementation guidelines • Experiential platform and user experience. • industrial automation
Semantic Interoperability Linking of data sources for facilitating application integration and reuse of IoT source data.	• OpenIoT Middleware Platform • LSM Linked Sensor Middleware • SSC Super Stream Collider Middleware • COIN platform • CONNECT solutions • ComVantage Management framework • IoT.est middleware tools • COMUS project - Korea	• Linking heterogeneous data formats. • Exchange of Information. • Querying and analysing of Data • Reasoning functionalities • Hybrid data-bases • Ontology Editor • Web application server and file server. • Data analytics and reasoning operations. • Security and Privacy resilience in IoT • Sensor Networks

	• ProbeIT Interoperability Principles	(description of sensors and ICOs.) • Semantically-Interlinked Online Communities • Integration of online community information. • Ontology Associations • Event/Data Modelling • Ontology Alignment
	• ProbeIT Interoperability Sensor Middleware and Ontology Tools	
	• GAMBAS Middleware tools	
	• SPIFIRE Interoperability principles	
	• VITAL Distributed Virtual principles and tools	

IERC AC4 position and Recommendations

Best practices and recommended Tools

Table 4 IoT Interoperability Best practices and Recommendations

Challenges	Best Practices / Recommendations
Technical interoperability Provide confidence on IoT products to market with market-accepted level of free information exchange	• RFID Standards and associated technologies (KNX, BACnet DyNet, SMAP, 6LoWPAN, CORE, COAP, Contiki, ZigBee, etc.) • Factory automation Standards Description formats (EDDL, FDT/DTM, GSD/GSDML, OPC UA Data Model). • Agri-Food GS1 and ISOBUS machinery standards • IoT-A top-down architectural principles and design guidelines. • IoT6 design and implementation guidelines • ELLIOT experiential platform where users/citizens are directly involved in co-creating, exploring and experimenting technological artefacts. • IoT@Work, IoT-based plug-and-work concept focused on industrial automation
	• Linked Data W3C RDF (Reference Data Framework) for

Semantic Interoperability Linking of data sources for facilitating application integration and reuse of IoT source data.	linking heterogeneous data formats. • SPARQL language as standard data base language for RDF data. Best known as SPARQL end points of triple data store. • Sesame Framework for querying and analysing RDF data • Jena JAVA libraries for basic reasoning functionalities on RDF • OWL Pellet, HermIT and other reasoners. • Virtuoso middleware and database engine hybrid combining traditional RDBMS, ORDBMS, virtual database and RDF, XML, free-text, web application server and file server functionalities. • Ontology Web Language (OWL) for extensive usage on data analytics and reasoning operations. • Protégé Ontology Editor as a complete data editor framework. • W3C SSN-XG Semantic Sensor Networks Ontology (description of sensors and ICOs.) • SIOC initiative (Semantically-Interlinked Online Communities) for enabling integration of online community information. • FOAF (Friend of a Friend Ontology) for describing characteristics of people and social groups that are independent of time and technology • AO (Association Ontology) provides features from the social/community context, to associate any kind of comment, rate or feedback from each community member, with any other kind of things. • Event Model-F ontology is robust and easily extendible because of both being made of design-patterns and being based on the upper level ontology Dolce+DnS Ultralite • SPITFIRE ontology (SPT) aligns the SSN, Event, FOAF, SIOC and AO ontologies according to a well-defined Linked Sensor Data model.

Possible solutions

- The semantic Web has faced this problem earlier.
  - Proposed solution: using machine-readable and machine-interpretable meta-data (e.g. Resource Data Framework –RDF)
  - Important note: RDF represetnations are machine-interpretable but not directly machine-understandable!
  - Well defined standards and description frameworks from semantic web can be adopted. e.g. RDF, OWL, SPARQL
  - Variety of open-source, commercial tools for creating/managing/querying and accessing semantic data
  - Tools and APIs such as Jena, Sesame, Protégé.
- Ontologies that defines conceptualisation of a domain.

- Terms and concepts
- A common vocabulary
- Relationships between the concepts

- There are several existing and emerging ontologies in the IoT domain.
    - IOT-A information model and ontologies
    - SENSEI information model
    - W3C SSN ontology
    - OpenIoT
    - and several other models and ontologies

In IoT there are various common use libraries, platforms and development tools that are applicable. By using them it will be easier for the advanced users and developers to get involved and to move from one IoT module system to another system without having to develop new skills to get involved. Some of the more widely use open source libraries, platform and development tools can be found in the IERC AC4 Manifesto available at: http://www.probe-it.eu/?p=1820

IERC AC4 Position and Recommended Tools

In the continuous evolution of the IoT domain, in particular for technical and semantic interoperability, successful research initiatives and products have emerged and also solutions from the industry will continue to be introduced to the market. A set of current solutions contained in this report are listed in Table 5 which can be considered as an initial analysis for facing up the early requirements included previously in this document and as part of the evolution of IoT realizations. Similar to the best practices, the most recognized practices and trends associated with IoT applications and services are also included in Table 5.

Table 5 IoT Interoperability Best Practices and Recommended Tools Summary

Challenges	Best Practices and Recommended Tools
Dynamicity Focused on Mobile Application(s) / Service(s)	• C-SPARQL Libraries. • CQELS Tools • XML/HTTP • RESTful HTTP • Internet protocol IPV4, IPV6
Publishing Data and Observations Dynamic establishment and reservation of services	• Eclipse IDE platform • Apache Tools, Maven project management tools; Apache CXF services framework for front end APIs services programming • JAX-WS and JAX-RS APIs for building multiple of services interfaces. • Java Server Faces (JSF) as technology standard for building server-side user interfaces. • PrimeFaces development tools for consulting and training activities of IoT services

	• Jena Java framework for building Semantic Web applications • CORBA Platform work over a variety of transports such as HTTP, JMS or JBI
Scalability & Discovery Discovery should be enabled based on multiple criteria	• JavaServer Pages (JSP) technology for a fast way to create dynamic web content. • SOAP protocol enables rapid development of data transmission server- and platform-independent • Eclipse Rich Client Platform (RCP) designed to serve as an open tools platform • JavaManagement Extensions (JMX) tools for building distributed, Web-based, modular and dynamic solutions for managing and monitoring devices, applications, and service-driven networks.
Extensibility Computational and storage resources based on Cloud infrastructures	• JBoss Application Platform for an enabling cloud-based services-driven components and is running OSGi and the Java EE application server side by side. • PROV Ontology for enabling providers making their sensor deployment easily accessible for others over the Cloud. • ITSO ontology allows to express IT service lifecycles concepts on the Cloud • OpenIoT Ontology enabling IoT cloud data being accessed by applications for service and device discovering

Other Related Semantic Interoperability Challenges

IoT data issues

- Internet-connected objects (ICOs) data models which lack of providing machine-interpretable meanings to the data.
- Syntactic representation or in some cases XML-based data
- Often no general agreement on annotating the data
- Requirement for a pre-agreement between different parties to be able to process and interpret the data
- Limited reasoning based on the content and context data
- Limited interoperability in data and resource/device description level
- Data integration and fusion issues

IoT Data Requirements

- Structured representation of concepts
- Machine-interpretable descriptions
- Reasoning mechanisms
- Accessible mechanisms to heterogeneous resource descriptions with diverse capabilities

- Automated interactions and horizontal integration with existing applications

IoT Data Challenges

- The models provide the basic description frameworks, but alignment between different models and frameworks are required.
- Semantics are the starting point, reasoning and interpretation of data is required for automated processes.
- Real interoperability happens when data/services from different frameworks and providers can be interchanged and used with minimised intervention.

Summary of Envisioned Solutions

Practical Steps

- Linked-data approach is a promising way of integrating data from different sources and interlinking semantic descriptions.
- Alignment between different description models for Services/Resources/Entities;
- Proposing reference and abstract models for semantic descriptions in IoT e.g. similar to W3C Semantic Sensor networks Approach (SSN Ontology approach).

How to cluster the solutions?

- By using domain knowledge and instances
  - Common terms and vocabularies
  - Location, unit of measurement, type, theme, etc.
- Link it to other resource(s)
  - Linked-data
  - URIs and naming

How to adapt the solutions?

- Creating ontologies and defining data models are not enough
  - tools to create and annotate data
  - data handling components
- Complex models and ontologies look good, but
  - design lightweight versions for constrained environments
  - think of practical issues
  - make it as much as possible compatible and/or link it to the other existing ontologies

Summary of Interoperability Challenges and Approaches

Project Approach / High-level challenge	IoT-A	Probe-IT	OpenIoT	GAMBAS	IoT-est	IoT-I	ebbits	Smart AgriFood	IoT6	iCore	BUTLER	IoT@Work
Technology Awareness		*					*	*	*			*
Validation of Specifications	*		*			*					*	*
Test and Specifications			*	*	*		*	*	*	*		*
Tools and Validation Programmes			*	*	*	*		*	*	*	*	
Project Approach /Semantic Interoperability	IoT-A	Probe-IT	OpenIoT	GAMBAS	IoT-est	IoT-I	ebbits	Smart Agrifood	IoT6	iCore	BUTLER	IoT@Work
Integration	*	*	*	*	*	*	*	*	*	*	*	*
Annotation	*	*	*	*	*	*	*	*	*	*	*	*
Management	*	*	*	*	*		*	*	*	*	*	*
Discovery		*	*		*				*		*	*
Analysis and Reasoning			*					*				
Visualisation		*	*	*	*			*		*	*	*

*s indicated it is addressed as part of the project objective(s)

Semantic Interoperability

- Structured representation of identified IoT concepts
- Machine-interpretable descriptions
- Reasoning mechanisms
- Homogeneous access mechanism to heterogeneous objects with diverse capabilities
- Automated interactions and horizontal integration with existing applications

Modelling Things and IoT Resources

- Resource model
    - Gateway, sensors, processing resources
- Entity model
    - Physical world objects
    - Features of interest for each entity
- Service model
    - IoT services and interfaces

What are the challenges?

- The models provide the basic description frameworks, but alignment between different models and frameworks are required.
- Semantics are the starting point, reasoning and interpretation of data is required for automated processes.
- Real interoperability happens when data/services from different frameworks and providers can be interchanged and used with minimised intervention.

What are the practical steps?

- Linked data approach is a promising way of integrating data from different sources and interlinking semantic descriptions.
- Alignment between different description models for IoT Services/Resources/Entities;
- Proposing reference and abstract models for semantic descriptions in IoT (e.g. similar to W3C SSN approach).

Internet of Things - Next Steps

Summary of IERC Project activities Vs. Semantic Interoperability Tools and Solutions

In this section the popular tools and solutions related to interoperability are summarized. As described in previous sections the widely used open source libraries, platform and development tools can be found in the IERC AC4 Manifesto available at: http://www.probe-it.eu/?p=1820

Semantic Interoperability Tool and Solution/ IERC Project	IoT-A	Probe-IT	OpenIoT	GAMBAS	IoT-est	IoT-I	ebbits	Smart AgriFood	IoT6	iCore
Development IDE			*		*			*	*	*
Web Tool				*			*	*		*
User Interfaces	*	*	*	*	*		*	*	*	*
Management Platform	*	*	*	*	*		*	*	*	*
Enterprise Application Platform	*	*	*			*	*	*		*
Knowledge - base			*	*	*	*				
Data Graph Representation		*	*	*	*		*	*	*	*

*s indicated it is developed within the project as a tool

What is expected in service/application level?

- Unified access to data
  - unified descriptions and at the same time an open frameworks
- Deriving additional knowledge (data mining)
- Reasoning support and association to other entities and resources
- Self-descriptive data an re-usable knowledge
- In general: Large-scale platforms to support discovery and access to the resources, to enable autonomous interactions with the resources, to provide self-descriptive data and association mechanisms to reason the emerging data and to integrate it into the existing applications and services.

Possible solutions?

- The semantic Web has faced this problem earlier.
  - using machine-readable and machine-interpretable metadata
- Important note: machine-interpretable does not mean that the data is directly machine-understandable!
- Well defined standards and description frameworks: RDF, OWL, SPARQL
- Variety of open-source, commercial tools for creating/managing/querying and accessing semantic data
  - Jena, Sesame, Protégé, ...
- Using Ontologies to define conceptualisation of domains.
  - Terms and concepts
  - Proposing a common vocabulary
  - Defining relationships between the concepts

- There are several existing and emerging ontologies in the IoT domain.
  - IOT-A information model and ontologies
  - SENSEI information model
  - W3C SSN ontology
  - And several other common models

Summary of needed research

Challenges	Research topics
Discovery of objects and Clustering	• Algorithms for data selection and classification • Efficient clustering mechanisms • IoT service management systems
Privacy and Security at Technical and Semantic level	• Access control algorithms and tools • Rules-based systems • IoT systems federation
Quality of Data	• Data filtering and data selection • Data mining • Control and assurance
Reasoning and Analysis	• Taxonomy, modelling, • Probabilistic modelling • Inference, Abstraction and Abduction
Data Management	• Data fusion • Mash-ups processing • Stream processing

What are the main research requirements?

- The current IoT data communications often rely on binary or syntactic data models which lack of providing machine interpretable meanings to the data.
  - Syntactic representation or in some cases XML-based data
  - Often no general agreement on annotating the data
  - Data requires a pre-agreement between different parties to be able to process and interpret the data
  - Limited reasoning based on the content and context data
  - Limited interoperability in data level
  - Data integration and fusion issues

- Creating ontologies and defining data models are not enough
  - tools to create and annotate data
  - data handling components

- Complex models and ontologies look good, but
  - design lightweight versions for constrained environments
  - think of practical issues
  - make it as much as possible compatible and/or link it to the other existing ontologies

- Domain knowledge and instances
  - Common terms and vocabularies
  - Location, unit of measurement, type, theme, etc.

- Link it to other resource
    - Linked-data and mash-up techniques
    - URIs and naming

Practical issues

- There is sometimes an assumption that if we create an Ontology our data is interoperable
    - Reality: there are/could be a number of ontologies for a domain
        - Ontology mapping
        - Reference ontologies
        - Standardisation efforts

- There could be an assumption that semantic data will make the data machine-understandable and the system will be automatically intelligent.
    - Reality: it is still met-data, machine don't understand it but can interpret it. It still does need intelligent processing, reasoning mechanism to process and interpret the data.

- There is sometimes an argument against using semantics in constrained environments. Some could argue that ontologies and semantic data are too much overhead; we deal with tiny devices in IoT.
    - Reality: Ontologies are a way to share and agree on a common vocabulary and knowledge; at the same time there are machine-interpretable and represented in interoperable and re-usable forms;
    - You do not necessarily need to add semantic metadata in the source- it could be added to the data at a later stage (e.g. in a gateway);
    - Legacy applications can ignore it or to be extended to work with it.

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Annex II: Relevant organizations and forums working with/on Semantic Interoperability issues

Project Acronym	Name of Project	Coordinator
PROBE-IT	Pursuing ROadmaps and BEnchmarks for the Internet of Things	Frank Le Gall and Philippe Cousin INNO AG, France
OpenIoT	Open Source Solution for the Internet of Things into the Cloud	Manfred Hauswirth and Martin Serrano National University of Ireland, Galway, Ireland
GAMBAS	Generic Adaptive Middleware for Behavior-driven Autonomous Services	Sandra Kramm, Universitaet Duisburg-Essen, Germany
IoT.est	Internet of Things Environment for Service Creation and Testing	Klaus Moessner and Payam Barnaghi University of Surrey, UK
IoT-I	Internet Of Things Initiative	Rahim Tafazolli and F. Carrez, University Of Surrey, UK
IoT-A	Internet of Things Architecture	Sebastian LANGE, VDI/VDE-IT
ebbits	Enabling the Business-Based Internet of Things and Services	Markus Eisenhauer, Fraunhofer FIT, Germany
SmartAgriFood	Smart Food and Agribusiness	Sjaak Wolfert, Stichting Dienst Landbouwkundig Onderzoek, The Netherlands
iCore	Internet Connected Objects for Reconfigurable Ecosystems	Raffaele Giaffreda, CREATE-NET, Italy
IoT@Work	Internet of Things at Work	Amine M. Houyou, Siemens AG, Germany
BUTLER	Secure and Context Awareness in the IoT	Frank Le Gall, INNO AG, France
IoT6	Universal Integration of the Internet of Things through an IPv6-based Service Oriented Architecture enabling heterogeneous components interoperability	Sébastien Ziegler, Mandat International, Switzerland
Initiative Acronym	**Name of the Initiative**	**Representative**
IoT Council	The Internet of Things Council	Rob van Kranenburg
WoT China	The Web of Things	Cheng Sheng and Ji Yang
IoT Korea	Common Open seMantic USN Service Platform	Marie Kim
IoT Japan		
IoT USA	Open Source Internet of Things	Michael J. Koster

Annex III: Abbreviations

6LoWPAN	IPv6 over Low power Wireless Personal Area Networks
ARM	Architecture Reference Model
BPM	Business process modelling
BPMN	Business Process Model and Notation
BPWME	Business Process Workflow Management Editor
CoAP	Constrained Application Protocol
CRUD	CReate, Updated, Delete
DOLCE	Descriptive Ontology for Linguistic and Cognitive Engineering
DoW	Description-of-Work
DSO	Decision Support Ontology
EPC	Electronic Product Code
EPC-ALE	Electronic Product Code Application Level Events
EPC-IS	Electronic Product Code Information Sharing
ERP	Enterprise Resource Planning
GPL	General Public Licence
GSN	Global Sensor Networks
GTIN	Global Trade Item Number
HTML	HyperText Markup Language
HTTP	Hypertext Transfer Protocol
ICO	Internet-Connected Objects
ICT	Information and Communication Technologies
IEEE	Institute of Electrical and Electronics Engineers
IERC	Research Cluster for the Internet of Things
IETF	Internet Engineering Task Force
IoT	Internet of Things
JSF	Java Server Faces
LGPL	Lesser General Public License
MRP	Manufacturing Resource Planning
OGC	Open Geospatial Consortium
OMG	Object Management Group
ONS	Object Naming Service
PDA	Personal Digital Assistant
PET	Privacy Enhancing Technologies
QR-Code	Quick Response Code
RDF	Resource Description Format
REST	Representational State Transfer
RFID	Radio Frequency Identification
SGTIN	Serialized Global Identification Number
SLA	Service Level Agreement
SOA	Service Oriented Approach
SOS	Sensor Observation Service
SPS	Sensor Planning Service
SSN	Semantic Sensor Networks
UML	Unified Modelling Language
WSN	Wireless Sensor Networks
XML	eXtensible Markup Language

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