Semantics for Connectivity Management in IoT Sensing

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Abstract. There are a large number of Internet of Things (IoT) devices that transmit information over the Internet, each with a different data format to denote the same semantic concept. This often leads to data incompatibilities and makes it difficult to extract the knowledge underlying that data. The only way to close this gap is to establish a common vocabulary in order to achieve interoperability between different sources and semantic data integration. This is the main goal of our proposal: to specify a general semantics for IoT sensing that allows the management of data between gateways, nodes, and sensors in a homogeneous way. Our proposal builds upon the joint Semantic Sensor Network and Sensor-Observation-Sample-Actuator (SSN/SOSA) ontology.

Keywords: IoT · Interoperability · Sensors · Ontologies · Semantics

1 Introduction

Kevin Ashton coined the term Internet of Things (IoT) about twenty years ago when he spoke of Radio Frequency IDentification (RFID) [11]. A *Thing*, in this context, is a physical object that aims to connect and exchange information with other devices over the Internet. Currently, there are more than 8 billion IoT devices communicating data periodically, heterogeneously, and globally.

The IoT world has evolved drastically since then, due to the need for comprehensive monitoring of different devices to provide real-time information about the status of a given domain.

Today, all IoT devices have the ability to communicate, at least, with their own ecosystems. What happens, though, when you need to include different devices from different manufacturers in the same system? All devices have their own properties, data format, and communication technologies. This makes it difficult to share information with each other.

To be able to provide generic solutions that apply to different monitoring environments and domains, we need to abstract from the particular syntax and

data formats of the different devices and provide common semantics to all the data managed. We achieve it through the definition of an *ontology* for connectivity management in the IoT sensing domain. Ontologies provide several benefits: (1) share a common understanding of the structure of information among software agents; (2) enable the reuse of domain knowledge; (3) domain assumptions are made explicit; (4) domain and operational knowledge are kept separated [14].

In our understanding, an ontology is an abstract interpretation of the concepts and properties of the domain and of the data stored in the information base, in the same way as a data model is. Therefore, both ontology and data model can be understood as synonyms.

Our work is related to industrial research at Worldsensing⁵, a company focused on providing services through the monitoring of industrial environments from IoT devices. The development of a platform able to control and act on its own and third-party industrial IoT devices has become a critical goal for the success of the company, and the need to consider different types of devices can only be successfully addressed through this common vocabulary.

The ontology we propose aims to interact and manage a custom platform based on ThingsBoard⁶, an open source IoT platform for device management, data collection, processing and visualization. Our project will extend the management and interaction capabilities of ThingsBoard, not only to IoT devices but also to its network elements; sensors, nodes and gateways needed to communicate information over the Internet. Our ontology is specified as an instantiation of common sensing ontologies such as Semantic Sensor Network Ontology (SOSA/SSN) and the information gathered from their surrounding standards.

LoRa⁷ is the main technology used to communicate nodes and gateways. In [13], the authors compare three standards for transmitting low-power messages over a long distance; NB-IoT, Sigfox, and LoRa; and concludes that LoRa is currently the best option for smart monitoring applications. This technology makes it possible to operate low-cost devices with very long range, infrequent communication rates, and high battery longevity. However, it is beyond the scope of this paper to decide which technology will be used. Data packets have a maximum size of 243 bytes, sent over a configured schedule in a given installation. The advertised commercial maximum range is currently between 5 and 15 km [1].

Summarizing, we propose in this paper the *Connectivity Management Tool Semantics (CMTS)* ontology; an extension of the World Wide Web (W3C) and the Open Geospatial Consortium (OGC) joint Semantic Sensor Network and Sensor-Observation-Sample-Actuator (SSN/SOSA) ontology [10,12]. Our proposal makes use of two auxiliary ontologies for location (GeoSPARQL - Geographic Query Language for RDF Data) and temporal properties (OWL-Time Ontology). Our main contribution is to provide such a system, with the set of language elements needed to achieve semantics interoperability.

⁵ Worldsensing: <https://www.worldsensing.com>

⁶ ThingsBoard: <https://thingsboard.io>

⁷ Long Range - LoRa Alliance Standardisation Committee: <https://lora-alliance.org>

We build upon and extend our previous work in [15] where we proposed a prototype to monitor IoT devices to automatically react and notify through alarms when data surpasses a certain threshold.

2 Related Work

2.1 Semantic Web Background

The World Wide Web uses the term “Semantic Web” to refer to the representation of the world data and vocabularies, with the objective of making it readable for humans and machines. In the Semantic Web, the information is written in the form of Triples, three entities with which to refer to a concept.

Consider the example *geo:Barcelona geo:partOf geo:Catalonia*, which follows the subject-predicate-object format. In this example; *geo:partOf* means that the *geo*⁸ “Barcelona”, is a location which is part of “Catalonia”. Where the non-literal values are URIs⁹; like “Barcelona” or “Catalonia”.

As mentioned in [3]; “the Resource Description Framework (RDF) is the basis of the Semantic Web. Things in the world are referred to as *resources* and they can be anything that someone might want to talk about. *i.e.* ‘the value of X’ or ‘all the cows in Texas’”. RDF is intended to be used for representing information about those resources in a graphical form.

Fig. 1. Sample RDF in graphical notation

As shown in Figure 1; classes are rounded rectangles while literal values are represented in rectangles. The text linking classes refers to properties of an object, while the text linking classes and literal values refers to the property of the data to be displayed. The property *rdf:subClassOf* makes one class a subclass of another. Hence *Region* and *City* are both subclasses of *Land*. Whilst *xsd* stands for *XML Schema Definition* and indicates that the element linked is a String. So to say, “Catalonia” is an instance of *Region* but also of *Land*. At the same time, “Barcelona” is an instance of *City* but also of *Land*. And also that “Barcelona” is part of the “Catalonia” *Region*.

⁸ Namespace made-up but understood to refer to geography.

⁹ URI: Uniform Resource Identifier, a sequence of characters that identifies a resource.

Fig. 2. Simplification of The Semantic Layer Web

Figure 2 represents a simplified view of the technological elements used in the “Semantic Web Architecture”. Starting with the character set; UNICODE ensures that the language can be read by humans and computers using a standardized form. The resulting character string forms a URI. In the next layer, there is the Extensible Markup Language (XML), together with its Namespace and Schema, ensuring that the syntax used is common through the Semantic Web. Following this is the RDF we have just seen. Then, the RDF Schema (RDFS) provides guidelines on how to use or combine different RDFs and allows describing taxonomies of classes and properties to be used in lightweight ontologies. Going up, we find the OWL ontology; a language derived from logical descriptions that enable extending vocabulary over RDFS. At this point, RIF/SWL rules can be introduced in order to constrain the ontologies. Finally, the SPARQL -Simple Protocol and RDF Query Language- allow executing queries in RDF and SQL.

2.2 Ontologies and Semantics in the Internet of Things

The first ontology proposed for wireless sensor networks was defined in OWL-Lite¹⁰ and dates back to 2004. In 2007, Eid et al. [7] proposed a universal ontology to solve the data heterogeneity problem in sensor networks.

The Open Geospatial Consortium (OGC) then published a series of standards with the aim of improving the interoperability of sensor and actuator systems. Among those that stand out in the subject treated are: Observations and Measurements (O&M)¹¹, which defines standard XML Schema and models for observations and features involved in sensor measurements; Sensor Model Language (SensorML)¹², which provides robust and semantic means of defining characteristics and capabilities of sensors, actuators, and computational mechanisms; and Sensor Observation Service (SOS)¹³, which defines a web service for querying and manipulating observations and sensors.

¹⁰ OWL-Lite: <https://www.w3.org/TR/owl-features/>

¹¹ Observations and Measurements (O&M): <https://www.ogc.org/standards/om>

¹² Sensor Model Language (SensorML): <https://www.ogc.org/standards/sensorml>

¹³ Sensor Observation Service (SOS): <https://www.ogc.org/standards/sos>

In 2011, the Semantic Sensor Network Incubator Group (SSN-XG) developed an ontology to describe sensors and sensor network resources [17]. They also gave recommendations for using the ontology to semantically enable applications and to provide better support for abstraction, categorization, and reasoning. In 2017, the World Wide Web Consortium (W3C) recommended an updated version of the SSN/SOSA Ontology [16] to be used when Semantic Web and Linked Data technologies are needed.

Work is pursuing to steer the IoT ecosystem towards the homogenization of the data to be transmitted, and tools to facilitate the integration of IoT devices into systems are being developed [8]. A similar problem, interoperability of multiple sensors from different manufacturers, is addressed in [4] by using SOSA/SSN for the development of semantics to manipulate this data. In [9], the M3 ontology was proposed as an extension of the SSN ontology, which allows reasoning on cross-domain M2M sensor data using rules to infer contextual information. IoT-Lite [5] proposes a lightweight instantiation of the SSN ontology where the concepts *Object*, *Service*, *Coverage* are defined and where devices are divided into three groups *Sensing Devices*, *Actuating Devices* and *Tag Devices* but this is a different classification than the one we consider. In [2], a unified ontology (FIESTA-IoT) is presented with the aim of addressing interoperability issues, merging different IoT Ontologies (*SSN*, *IoT-Lite*, *M3*, among others).

If we consider domain-specific applications, we find that ontologies such as SAREF (Smart Appliance Reference) [6] that are close to ours. However, they do not manage a multi-level architecture and in this approach, devices are not related to each other.

Summarizing, we can observe that there is a need to develop new solutions to improve the interoperability of IoT devices. Generic solutions exist when there is a need to have a platform based on device observations but where the concern is simply to obtain sensor data, without having a more complex level of detail in the structure of the devices. When a higher granularity is introduced at the device level (by distinguishing, for instance, between gateways, nodes and sensors) no solutions have yet been found. This is the main objective of this work.

3 Knowledge-Engineering Methodology

We have been motivated by [14] to develop semantics that can be correct. As they suggest, there is no single way to develop semantics, and the modeling of a domain depends to some extent on several factors, including the purpose of the system it will support. The process of modeling an ontology is iterative. Below there is a summary of the steps to follow as proposed by [14]:

1. **Determine the domain and scope to be covered**

We have provided in the Introduction a description of the project domain and its intended use.

2. **Sketch a list of competency questions that should be answered**

We give in Section 3.1 the competency questions that the ontology should be able to answer.

3. Consider reuse of existing ontologies

In Section 2 there is an introduction to Semantic Web and ontologies related to the project domain. A detailed explanation is given in Section 5.

4. Enumerate important terms in the ontology

This is done in Section 4 when explaining our ontology.

5. Develop the ontology

The ontology we propose for connectivity management in IoT sensing is explained in Section 4.

6. Validate the list of competency questions:

Competency questions are formulated in Section 3.1 and answered in 4.

3.1 Competency Questions

One of the ways to determine the scope of an ontology is to make a list of questions, in order to obtain the baseline knowledge. These questions are called “Competency Questions”. The answers of which should define the scope of the ontology. If the ontology is able to provide an answer for each question, it will mean that the described ontology contains enough information to work.

- **Q1:** Which elements or features can be observed by a sensor?
- **Q2:** How can an observation be made?
- **Q3:** How can the embedded sensor of a gateway be observed?
- **Q4:** How can the embedded sensor of a node be observed?
- **Q5:** How can an external sensor connected to a node be observed?
- **Q6:** If there are a batch of devices, is there any way to group them?
- **Q7:** Where is a given sensor located?
- **Q8:** How can we know which is the gateway providing an observation?
- **Q9:** Are there any other devices than gateway, node and sensor?
- **Q10:** How can one know if the device is enabled in a site?

These competency questions arise from the current industrial needs of World-sensing and the IoT domain under consideration and are aimed at providing an abstract interpretation of the different implementations of the kind of IoT devices they handle, in order to be able to provide a uniform treatment of all this information. They are complete in the sense that they correspond to their actual needs, but this does not ensure that they will remain exactly as such forever.

4 CMTS Ontology

The Connectivity Management Tool Semantics (CMTS) Ontology is aimed at allowing tools for monitoring physical infrastructures through the use of three common types of IoT devices: gateways, nodes and sensors. The ontology builds from two key concepts: *Site*, i.e. a physical area being monitored, and the *Devices* installed in the *Site* to allow it. In our sites, three different types of devices co-exist: *Gateways*, *Nodes*, and *Sensors*. A *Sensor* may be either *Hardware* or

Software and the structure of *Gateways* and *Nodes* can also be specified through the ontology. Finally, *Observations* are registered as a means to monitor the *ObservableProperty* of each *Sensor*.

The proposed ontology is depicted in Figure 3 by means of a UML Class Diagram that states the concepts of the domain that have to be specified in order to provide the aimed connectivity management in IoT sensing across different devices and settings of the sites being monitored. “*cmts*” is the default namespace when none is provided. A more detailed explanation of the concepts in the ontology is given in Section 4.2.

Fig. 3. CMTS Ontology

We have also had to specify some integrity constraints (i.e. conditions that any instance of the ontology should satisfy) to properly model the domain:

- C1: Location must have at least one Feature or one Geometry.
- C2: Sensors of a Node must be at the same Site as the Node.

- C3: Sensors of a Gateway must be at the same Site as the Gateway.
- C4: Software Sensors must be at the same Location as the Gateway or Node they are connected to.

This ontology is complete in the sense that it incorporates all concepts and properties required by the IoT domain under consideration. Moreover, as it happens with all the approaches based on ontologies, it is easily extendable since new concepts and properties can be added to the ontology without having to modify the programs running on the current ontology.

4.1 Resource URIs

Using URIs increases the simplicity and manageability of systems. We show in Table 1 the main design of the URIs in our system. The first column represents the class name of the object, and the second represents the format of the URIs that have been generated. The `BASE_URI` refers to the URL entry point, located in a Worldsensing’s domain. The format of the URIs follow the pattern:
`{BASE_URI}:{CLASS_NAME}/{CLASS_ID}?{CLASS_PROPERTY_1}&{CLASS_PROPERTY_N}`

Class	URI Patterns
Site	<code>cmts:Site/{SiteName}?{LocationName}&{Devices}</code>
Gateway	<code>cmts:Device/{DeviceName}?{DeviceType}&{SoftwareSensors}&{LocationName}&{SiteName}</code>
Node	<code>cmts:Device/{DeviceName}?{DeviceType}&{SoftwareSensors}&{HardwareSensors}&{LocationName}&{SiteName}</code>
Hardware Sensor	<code>cmts:Device/{DeviceName}?{NodeName}&{DeviceType}&{ObservablePropertyName}&{LocationName}&{SiteName}</code>
Software Sensor	<code>cmts:Device/{DeviceName}?{NodeName GatewayName}&{DeviceType}&{ObservablePropertyName}&{LocationName}&{SiteName}</code>
ObservableProperty	<code>cmts:ObservableProperty/{ObservablePropertyName}</code>
Observation	<code>cmts:Observation/{ObservablePropertyName}?{ObservationName}&{Value}&{Time}&{SensorName}&{GatewayName}</code>
Location (Feature)	<code>cmts:Location/{LocationName}?{Feature}</code>
Location (Geometry)	<code>cmts:Location/{LocationName}?{Geometry}</code>
Time	<code>cmts:Time/{Date}T{Time}+{TimeZone}</code>

Table 1. Summary of the main URIs in CMTS

4.2 Component Description

Site A *Site* is a physical working area in the project. They are intended to group devices in the system by work areas so as to monitor these devices by granularity levels. It contains location information; the type of work being carried out; and, optionally, the start and end dates. This covers the competency question **Q6**.

Figure 4 provides a visual description of a *Site* having one *Gateway*, one *Node*, and one *Sensor*, whose *Location* is “LocationBCN”.

Fig. 4. Example of a Site description

Device *Devices* are the essential elements that carry out the monitoring of the infrastructures. A *Site* can contain multiple *Devices*. A *Device* is categorized by a *DeviceType*, such as the model name. This covers the competency question **Q9**. A *Device* is an element which can report to different *Sites*; the system can discern availability of a *Device* for each *Site*, whether it is active or not. This covers the competency question **Q10**. *Devices* have information about the infrastructure communication in terms of connection status and can handle *Location* information. *Devices* are classified in three types: *Gateways*, *Nodes*, and *Sensors*:

Gateway It is a physical element that acts as a router, gathering data from incoming wireless transmissions, grouping it and sending it to the data server, thus allowing to receive information sent wirelessly via the *Nodes*. *Gateways* are in charge of receiving the message via *LoRa* and send it to the Internet. *Gateways* contain *Sensors* that capture metrics related to the *Gateway* such as the internal temperature or processor usage. For each *Gateway* we know its location, the way it communicates with the *Sites*, as well as other operational aspects.

Figure 5 provides a visual description of a *Gateway* having “GW_EU” as *DeviceType*; contains a *Software Sensor* “SoftwareSen03” as *Sensor*; its *Location* is “LocationBCN”, and it is in the *Site* “Site A”.

Node It is a small physical element with limited processing capabilities, i.e. that of communicating directly to *Sensors* through a wired connection. They are responsible for collecting raw data measurements from the *Sensors*, building a well-formed message and sending it via *LoRa* to the *Gateways* in range, and reporting *Sensor* failures. They also have internal *Sensors* to be monitored. The visual description of *Node* is similar to the one of *Gateway* given in Figure 5.

Sensor They are the elements capable of making observations of a given feature. They can be either *Software* or *Hardware*. *Software Sensors* are used to monitor the infrastructure that supports the work, and we are only interested to know their sensor type, whether they work correctly and the values they report. They are the ones embedded into *Gateways* and *Nodes* and are used to

Fig. 5. Example of a Gateway description

monitor information like temperature, voltage, etc. This covers the competency questions **Q3** and **Q4**. For *Hardware Sensors* we need to know data related to the manufacturer, the model, and specifics on how are they working and how they communicate. In addition to emphasizing the calibration of the data they report. They are the ones that are directly connected to the *Nodes*. This covers the competency question **Q5**.

Figure 6 provides a visual description about a *Hardware Sensor*. It has “Tiltmeter” as *DeviceType*; the *Sensor* has been named “HardwareSen01”; is connected to the *Node* “Node01”; is measuring *ObservableProperty* “Accelerometer”; its *Location* is “LocationBCN”, and it is in the *Site* “Site A”.

Fig. 6. Example of a Hardware Sensor description

ObservableProperty Are the properties to be observed in *Sensors*; for a given characteristic, property or feature. For example, the temperature inside a *Gateway*; the temperature of a sensor in an environment or the inclination of a surface.

This covers the competency question **Q1**. Figure 3 explicitly distinguishes five possible *ObservableProperty*. However, other properties to be observed can be added when necessary as new subclasses of *Observation*.

Observation When a *Sensor* captures the value of an *ObservableProperty* at a given time it generates an *Observation*. In addition, it is possible to include a time interval to support those *Observations* that cannot obtain the value instantly. This covers the competency question **Q2**.

An *Observation* will always be generated from a *Sensor*. The *Node* is the device that sends it wirelessly as a radio signal. *Gateways* are the devices that will listen to this information, hence the “observedThrough” of an *Observation*, and will transmit it to the data server. This covers the competency question **Q8**.

Figure 7 and Figure 8 provide a visual description about an *Observation* made by a *Hardware Sensor* “HardwareSen01”; the communication of this *Observation* was made through the *Gateway* named “Gateway01”; is measuring *ObservableProperty* “Accelerometer”; its *Location* is “LocationBCN”; it is in the “Site A”; it also has the value measured “0_0_9.8m/2”, and the *Time* has a value of “2021-03-15 at 16:15”.

Fig. 7. Example of an Observation description - Part 1

Fig. 8. Example of an Observation description - Part 2

Due to the use of *LoRa* communication technology; active communication between a *Gateway* and a *Node* is not possible. The *Node* sends out radio waves with the information, and the *Gateways* independently listen to these transmissions. More than one *Gateway* can receive the information. The server will only consider one packet as valid, and duplicated messages will be discarded.

Location If desired, the user is given the possibility to indicate the location of the elements in the physical world. With this purpose, the system is provided with the ability of locating elements, as well as *Sites* and *Devices*, which comprise *Gateways*, *Nodes* and *Sensors*. This covers the competency question **Q7**.

5 Matching Existing Ontologies

The Semantic Sensor Network and Sensor Observation Sample Actuator (SSN/SOSA) ontology [16] is being used as the core ontology for the observation of measurements. Hence, a network of ontologies has been achieved, which is structured as follows (see Table 2 for the URLs):

- SSN/SOSA: Ontology to gather measurements from devices and sensors.
- GeoSPARQL: Ontology to describe geographical locations.
- OWL-Time: Ontology to describe temporal properties.

Prefix	Namespaces
SSN	http://www.w3.org/ns/ssn/
SOSA	http://www.w3.org/ns/sosa/
GeoSPARQL	http://www.opengis.net/ont/geosparql
OWL-Time	http://www.w3.org/2006/time

Table 2. Ontologies used in this project

In the following, we briefly explain how these ontologies have been used, along with the elements that have been newly added in order to define our solution.

5.1 SSN/SOSA Ontology

As said, SSN/SOSA is the ontology that comes closer to the ontology we propose here. This is why we use it as a baseline. As described in [16]: “SOSA provides a lightweight core for SSN and aims at broadening the target audience and application areas that can make use of Semantic Web ontologies. At the same time, SOSA acts as minimal interoperability fall-back level, i.e. it defines those common classes and properties for which data can be safely exchanged across all uses of SSN, its modules, and SOSA.”

The SOSA/SSN classes that have been (re)used in our solution are:

- *sosa:Platform*, to describe:
 - *Sites*, the physical working areas, which can contain multiple devices.
 - *Nodes*, the physical elements that gather information from *Sensors* and send it to *Gateways*.
- *sosa:Sensor*, to describe the low-level *Sensors* that are collecting information.
- *sosa:ObservableProperty*, to specify the elements to be observed by a *Sensor*.
- *sosa:Observation*, to provide the value of the measurements of the *ObservableProperty* collected by the *Sensors*.

This is also true for some of the properties in our ontology that allow us giving more clarity to the actions being carried out: *sosa:hostedBy*, *sosa:hosts*, *sosa:observedBy*, *sosa:observes*.

5.2 OGC GeoSPARQL

Several ontologies exist for the management of geospatial elements. However, we decided to use GeoSPARQL; an OGC Standard that has a small but powerful ontology that fits perfectly with the scope of this project. It enables describing data in *Geographic Markup Language* (GML) and also with *Well-Known Text representation of geometry* (WKT).

The GeoSPARQL classes that have been (re)used in our ontology are:

- *geo:Location*, to describe the location of *Sites* and *Devices*.
- *geo:Feature*, to specify points of interest from written language, in other words, as a *String*. For instance, “Barcelona”.
- *geo:Geometry*, to define points of interest as coordinates from geometries such as points, lines and polygons, etc.

Moreover, we have used the properties *geo:hasGeometry*, *geo:hasGML* and *geo:hasWKT* to complement the definition of geometries and spatial objects.

5.3 OWL-Time Ontology

The *OWL-Time* allows the Semantic Web to describe concepts and temporal properties. In our use case, this ontology is used to define when there has been an *Observation*, i.e. when a *Sensor* has taken a measurement. Using the properties *time:hasBeginning* and *time:hasEnd*. Also, through the class *time:Instant* we define the moment of time in which it has occurred.

6 Conclusions and Future Work

The interest in facilitating homogeneous information handling in IoT sensor networks has been acknowledged. Homogenization makes it simpler to enable compatibility between devices from different manufacturers. In this work, we proposed a semantics for the data management of gateways, nodes, and sensors, carrying out the theoretical and descriptive part of it. The ontology we used to specify such semantics builds upon recognized ontologies like SSN/SOSA or GeoSPARQL. We have used competency questions, stating what we expected from the semantics, to validate the appropriateness of our ontology.

As further work, we plan to incorporate additional features to our ontology to integrate IoT monitoring with the operational part of the company and we are also focused on the implementation of a system taking advantage of our ontology for IoT sensing of Worldsensing’ sites.

As far as further applications, we have in mind the possibility of adding rule inference to the ontology, thus first enabling to develop applications with a context-awareness system and then allowing to incorporate an automatic notification system when a certain declarative condition over the data is met.

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