Towards Common Vocabulary for IoT Ecosystems—preliminary Considerations

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Abstract. The INTER-IoT project aims at delivering a comprehensive solution to the problem of interoperability of Internet of Things platforms. Henceforth, semantic interoperability also has to be addressed. This should involve a hierarchy of ontologies, starting from an upper ontology, through core and domain ontologies. As a starting point, we have analyzed ontological models of the concepts of *thing*, *device*, *observation* and *deployment*, as occurring in the IoT domain. We have chosen five popular ontologies: SSN, SAREF, oneM2M Base Ontology, IoT-Lite, and OpenIoT, as candidates for a central INTER-IoT ontology.

Keywords: Internet of Things · Semantic interoperability · IoT ontology

1 Introduction

Lack of interoperability between Internet of Things (IoT) platforms/systems/applications is recognized as an important issue that prevents faster development of IoT ecosystems. Therefore, the European Commission has funded seven research projects, to find a comprehensive solution. Among them, the INTER-IoT project will use semantic technologies to deal with meta-level interoperability. Specifically, the semantic interoperability will be established through the use of a modular *central ontology*, ontology alignments, and semantic transformations. Therefore, one of key questions becomes: what should the central ontology be based on? Therefore, we took an initial look at the state-of-the-art IoT ontologies and analyzed how they conceptualize *thing*, *device*, *observation* and *deployment*.

In what follows, we report our findings. We start by briefly outlining the INTER-IoT approach to semantic interoperability. This allows us to discuss the

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proposed structure and role of the central ontology. Next, we describe key technical details of selected ontologies. Finally, we present a general analysis of the ontologies and their applicability in the INTER-IoT. Here, let us note that for the purpose of this contribution, we will use the term "IoT artifact" to denote any entity that can join an IoT ecosystem, e.g. platforms, systems, applications, etc.

2 Semantic Interoperability—the INTER-IoT Way

The goal of the INTER-IoT project [2] is to facilitate interoperability across the hardware-software stack. However, here, we are solely interested in semantic interoperability. In [10], we have outlined the state-of-the-art in ontologies of the Internet of Things (as well as these related to project's main use cases). As expected, we have found that there is no single, comprehensive, *all agreed* ontology of the IoT. Taking this into account, in [11], we have proposed the following approach to reaching semantic interoperability. Here, for simplicity, only the core assumptions and the basic flow of information is described.

1. We assume that multiple IoT artifacts are to be joined into an ecosystem (we try to avoid conceptual traps of a scenario where only 2 artifacts are considered). This process involves human developers, who will establish the necessary data flows. We assume that bringing about interoperability should force only minimal changes to the joining artifacts (ideally, none).
2. For each artifact, its semantics is lifted to an OWL-based representation (see, [13]). If the original semantics was not OWL-based, bi-directional converters (named *producer* and *consumer*) are created, to allow communication in "own language". Specifically, original semantics and data format is mapped onto the OWL ontology in the RDF format (and a similar mapping is created for communication "back").
3. A central modular ontology is instantiated. Its modules capture necessary aspects of the IoT, as well as domain specific concepts. Here, the key assumption is *modularity*. For instance, if in a given IoT ecosystem it is not necessary to provide geospatial information (e.g. when all sensing devices are placed in stationary locations), the geospatial module will not be included.
4. Ontologies representing each joining artifact are *aligned* with appropriate modules of the central ontology (see, [12]). The resulting alignments are persisted and form the basis for translation between communicating artifacts.
5. Communication, in addition to conversions performed by producers and consumers, involves semantic translations (using alignments) from semantics of a source artifact to the common semantics and then, to the semantics of the target artifact. Obviously, process is repeated "on the way back".

Clearly, construction of the central ontology, plays key role in the proposed approach to semantic interoperability, and thus, is the focus of this paper.

3 Comparing IoT-Related Ontologies

The space of ontologies is fragmented, regardless of the domain of interest. The richer an ontology is, the larger area it spans. Hence, uniqueness and intersections with other ontologies become more intricate and complex. Internet of Things spans enormous number of domains, and expands with the growing popularity of "smart devices". Use of ontologies in the IoT mimics this expansiveness. There are many ontologies that represent models relevant to the IoT, including, but not limited to, devices, units of measurement, data streams, data processing, geolocation, data provenance, computer hardware, methods of communication, etc. We assume that the centerpiece of the IoT is a smart device capable of communication. From this perspective, we have identified ontologies that capture the idea of a device, and are well established in the IoT space: SSN, SAREF, oneM2M Base Ontology, IoT-Lite, and OpenIoT. Each of them takes a different approach to modeling the IoT space but, despite the differences in conceptualization, they cover intersecting fragments of the IoT landscape. Below, we discuss divergence, contrariness and overlaps between these ontologies.

SSN, or "Semantic Sensor Network" [4,8] is an ontology centered around sensors and observations. It is a de-facto extension of the SensorML language. SSN focuses on measurements and observations, disregarding hardware information about the device. Specifically, it describes sensors in terms of capabilities, performance, usage conditions, observations, measurement processes, and deployments. It is highly modular and extendable. In fact, it depends on other ontologies in key areas (e.g. time, location, units) and, for all practical purposes, needs to be extended before actual implementation of an SSN-based IoT system. SSN, formulated on top of DUL[1], is an ontological basis for the IoT, as it tries to cover any application of sensors in the IoT.

SAREF [9], or "The Smart Appliances REFerence" ontology covers the area of smart devices in houses, offices, public places, etc. It does not focus on any industrial or scientific implementation. The devices are characterized predominantly by the function(s) they perform, commands they accept, and states they can be in. Those three categories serve as building blocks of the semantic description in SAREF. Elements from each can be combined to produce complex descriptions of multi-functional devices. The description is complemented by device services that offer functions. A noteworthy module of SAREF is the energy and power profile that received considerable attention, shortly after its inception[2]. SAREF uses WGS84 for geolocation and defines its own measurement units.

oneM2M Base Ontology (oneM2M BO; [3,6]) is a recently created ontology, with first non-draft release in August 2016. It is relatively small, prepared for the release 2.0 of oneM2M specifications, and designed with the intention of providing a shared ontological base, to which other ontologies would align. It is similar to the SSN, since any concrete system necessarily needs to extend it

1 http://www.ontologydesignpatterns.org/ont/dul/DUL.owl.
2 https://goo.gl/1OXTJb, https://goo.gl/ZaGjCJ.

before implementation. It describes devices in a very broad scope, enabling (in a very general sense) specification of device functionality, networking properties, operation and services. The philosophy behind this approach was to enable discovery of semantically demarcated resources using a minimal set of concepts. It is a base ontology, as it does not extend any other base models (such as DUL or Dublin Core). However, alignments to other ontologies are known [5].

IoT-Lite [7] is an "instantiation" of the SSN, i.e. a direct extension of some of its modules. It is a minimal ontology, to which most of the caveats of the SSN apply. Specifically: focus on sensors and observations, reliance on other ontologies (e.g. time or units ontologies), high modularity and extendability. The idea behind the IoT-Lite was to create a small/light semantic model that would be less taxing (than other, more verbose and broader models) on devices that process it. At the same time, it needed to cover enough concepts to be useful. The ontology describes devices, objects, systems and services. The main extension of the SSN, in the IoT-Lite, lies in addition of actuators (to complement sensors, as a device type) and a coverage property. It explicitly uses concepts from a geolocation ontology [1] to demarcate device coverage and deployment location.

OpenIoT [15,16] ontology was developed within the OpenIoT project. However, here, we use the term "OpenIoT" to refer to the ontology. It is a comparatively big model that (re)uses and combines other ontologies. Those include all modules of the SSN (the main basis for the OpenIoT), SPITFIRE (including sensor networks), Event Model-F, PROV-O, LinkedGeoData, WGS84, CloudDomain, SIOC, Association Ontology and others, including smaller ontologies developed at the DERI (currently, Insight Centre). It also makes use of ontologies that provide basis for those enumerated earlier, e.g. DUL. Other than concepts from the SSN, OpenIoT, uses a large number of SPITFIRE concepts, e.g. network and sensor network descriptions. While some mentioned ontologies are not imported by the OpenIoT explicitly, they appear in all examples, documentation, and project deliverables. Therefore, one can treat OpenIoT as a combination of parts of all of those. Similarly to the SSN, OpenIoT does not define its own location concepts and does not explicitly import geolocation ontologies. It relies on other ontologies for that but, in contrast to the SSN, it clearly indicates LinkedGeoData and WGS84 as sources of geolocation descriptions. It defines a limited set of units of measure (e.g. temperature, wind speed), but only when they were relevant to the OpenIoT project pilot implementation.

The rich suite of used ontologies means that OpenIoT provides very rich description of devices, their functionalities, capabilities, provenance, measurements, deployments and position, energy, relevant events, users and many others. Interestingly enough, it does not explicitly describe actuators or actuating properties/functions. It can be observed that the broad scope of the ontology makes it rather complicated. This is also because, it is not documented well-enough, i.e. the detail level and ease-of-access of the documentation do not match the range of coverage of concepts in the model. Moreover, it is not clearly and explicitly modularized, despite being an extension of the SSN.

Let us note that, while there are other IoT models of potential interest (such as OGC Sensor Things, UniversAAL ontologies, FAN FPAI, IoT Ontology[3], M3 Vocabulary), we will not consider them here. This is because of (a) space limitation, and (b) the fact that they have generated much less "general interest". Nevertheless, we plan to include these ontologies in subsequent work.

Let us now compare the selected ontologies side-by-side. To do this, we have selected key aspects, or categories, *directly pertaining to the IoT*; placed the first column of Table 1. However, because of intricacies and disparate philosophies behind compared ontologies (see, above), each category needs to be further investigated. In other words, proposed categorization is a tentative way of visualizing and analyzing similarities and differences between ontologies of choice. Here, we follow an approach proposed by Raúl García-Castro during June 2016 European Platform Initiative (IOT EPI[4]) meeting.

Before proceeding it should be noted that there are numerous approaches to ontology evaluation, e.g. [14,17]. We have, however, found that applying them would not help in the context of specific, project-related, problem. Specifically, we were more interested in capturing and comparing *details* of each area that the selected ontologies cover, rather than their *overall evaluation* by some standard.

Table 1. IoT ontologies comparison

Category (Subdomain)	SSN	SAREF	oneM2M BO	IoT-Lite†	OpenIoT†
Thing	X	X	X	X	X
Device	X	X	X	X	X
Device deployment	X^{α}	X	$X^{\oslash\alpha}$	X	X
Device properties & capabilities	X				X
Device energy	X	X^{ϵ}			X
Function & service		X	X	X^{S}	
Sensing & sensor properties	X	X^{β}		$X^{\oslash}$	X
Observation	X^{α}	X	X		X
Actuating & actuator properties		X^{β}		$X^{\oslash}$	
Conditionals	X				

† Extends modules of SSN
α No time or location
β Implicit, implied by device functions
ϵ Rich energy model
S Service only
$\oslash$ Only small or provisional description, or a stub

In what follows, we discuss selected categories from Table 1. While, due to space limitation, we had to pick only some categories, this discussion should be valuable to anyone interested in use of semantic technologies in the IoT.

[3] http://ai-group.ds.unipi.gr/kotis/ontologies/IoT-ontology.
[4] http://iot-epi.eu/.

Thing. This category describes the general approach and provision of properties to any class of an ontology. All considered ontologies are, understandably, generic in this regard. Each contains only a handful of relevant properties that pertain to the very generic concepts. SSN's Things can have FeatureOfInterest (an abstraction of a real world phenomena, such as person, event or, literally, anything) and display Properties (a specification of DUL Quality; needs to be observable and inseparable from the SSN thing). SAREF defines a, similarly general, Property (specifying anything that can be sensed, measured or controlled). IoT-Lite extends the SSN with an Object (any physical entity) and its Attribute (any property exhibited by the Object that can be exposed by a Service). OpenIoT does not provide independent extensions or departures from the approach taken by the SSN. Instead, it provides subclasses for the SSN Property, mostly to describe entities needed in pilots of the project (e.g. WindSpeed, AtmospherePressure).

OneM2M BO is unique in its description of things, because the entire ontology is very general. It defines its own Thing class that captures, quite literally, any entity identifiable in a oneM2M system. OneM2M BO does not extend any upper ontologies, and its Thing is a direct subclass of owl:Thing. Here, a Thing can have ThingProperty (which has a self-explanatory, all-encompassing definition). In this way, oneM2M BO displays characteristics of an upper ontology.

Device. Devices are at the core of the IoT. This is reflected in all ontologies. OneM2M BO proposes the simplest structure of a Device class that uses a written description, instead of rich ontological relations. Device has a single subclass of InterworkedDevice (one that does not directly implement oneM2M interfaces). A Device can consistOf a number of other Devices.

In the SSN, the central taxonomy subtree consists of Device, Sensor, and SensingDevice subsuming both previous classes. An SSN System can represent any part of an infrastructure of devices connected in some way. In particular, it can be any Device in the System. Any System is comprised of subsystems (also of class System). IoT-Lite expands this structure with the addition of an ActuatingDevice and a (passive) TagDevice. Strangely, there is no definition of an Actuator. OpenIoT does not expand the basic structure of the SSN.

SAREF borrows from both, oneM2M and SSN. SAREF Device consistsOf any number of Devices, and has a DeviceCategory that, in turn, has its own subclass structure (which starts with FunctionRelated, EnergyRelated and BuildingRelated categories). It is meant to represent a given perspective (point of view) on a device (e.g. of user, administrator, manufacturer, etc.). On top of that, the ontology defines a couple of subclasses of the Device class, which range from general, such as a Sensor, to quite specific, like a WashingMachine (with classes, such as Switch, in between). Interestingly, Sensor and Actuator are not "neighbors" (the first being a subclass of a Device, and the latter of a DeviceFunction).

Observation. The second crucial element of any IoT ontology is the way that observations are modeled. They are fundamental data items, and their description very strongly affects possible use of a model and functionality of a concrete systems. In oneM2M BO, observations revolve around three general classes:

Variable, Aspect and Metadata. Variable class encompasses input and output variables, as well as a ThingProperty, that pertains to any entity and can have additional Metadata. The latter class is a catch-all way of annotating observations (e.g. with units or precision), which lacks specification, i.e. any property structure is permissible under the BO Metadata. Aspects describe functionality as well as input or output Variables. This simplistic, high-level model of observations allows for great flexibility. On the other hand, there are no examples, and the intended use is very tersely explained. Lack of documentation, combined with elasticity of interpretation, may lead to systems being barely interoperable, despite using the same base ontology.

SSN proceeds differently, by extending the general model proposed by DUL. It introduces the Observation class. Each Observation results in a SensorOutput, a class with relations with other relevant information, such as ObservationValue, or the Sensor that made the Observation. Observations have FeatureOfInterest that describes their characteristics, e.g. precision, latency, range, response time, etc. In general, the SSN Observation is a record of an occurrence of measurement, along with structured meta-data about the observation value, its properties, as well as the process leading to the Observation. Since the SSN lacks explicit units or time definitions, it needs to be complemented with relevant ontologies.

IoT-Lite does not extend the SSN Observation related modules. Instead, it proposes a vast simplification by introducing a Metadata class, similarly to the oneM2M BO. It is a generic class, intended to model any entity that does not fit the Unit or QuantityKind classes (a separate ontology is needed to describe the actual quantities). Observed values are not stored in the structure of the IoT-Lite. Instead, sensors are described in terms of types/kinds of observations made by them. For instance, one can construct a full description of a temperature sensor with meta-data of precision, unit, etc. However, within IoT-Lite, a series of concrete observations cannot be described.

OpenIoT extends the SSN Observation model by providing a Context, however, because of lack of documentation, the intended usage of this class is not clear. Nevertheless, it preserves the SSN Observation structure.

Finally, SAREF observations are described in terms of device Functions (in particular, SensingFunction and MeteringFunction). While lacking an explicit observation class, Functions have a number of properties that pertain to concrete values of measurements. Every relevant Function has a time value (e.g. hasMeterReadingTime) and an "observation" value (e.g. hasMeterReadingValue). These values are described in terms of Properties, which have concrete values alongside the UnitsOfMeasure. SAREF proposes its own taxonomy of units of measurements (currency, power, temperature, etc.). Other than the values of concrete measurements, Functions have "reading types" (e.g. gas, pressure, energy, etc.), which are implied to be relatively constant, vis-a-vis, for instance, meter readings of time and value. Compared to the SSN, the observation model in SAREF is simpler, and more focused on devices and their functions. It does not treat observations as pieces of data with their own structure and place in the system, which enables advanced data processing, e.g. analysis of historical data (within the structure given by the ontology). Instead, the SAREF model presents observations as tentative "outputs" of a function.

Device Deployment. A deployment description is a very important information in any system with multiple distributed devices. OneM2M BO interprets this category as a basic information about a network environment (AreaNetwork), but only if the device is proxied (InterworkedDevice). There is no standard way to model deployment information for any oneM2M BO Device.

SSN describes device deployment in terms of Platform(s) a Device is on, and System(s) it is part of. Even though the SSN itself does not define time or location properties, it is strongly implied that Devices, Systems and Platforms should be annotated with such information (no specific ontology to fulfill that function is suggested). SSN also defines a Deployment, a process with subprocesses (DeploymentRelatedProcess) that lead to the device becoming deployed. IoT-Lite extends the deployment aspect of the SSN by explicit use of geolocation from the WGS84 model. OpenIoT, on the other hand, provides a very peculiar extension of the SSN, namely it adds an OperatingProperty of Device, named EaseOfDeployment. No further description or explanation of its usage is provided.

In SAREF, deployment is understood in terms of physical space, in which a device is deployed, i.e. BuildingSpace, annotated with geolocation data from the WGS84. This is an interesting design decision, as it restricts SAREF Devices to be deployed only in buildings. It seems to contradict the design-time assumption that SAREF devices, i.e. smart appliances, can be located also in public spaces.

4 Summary of Key Findings

Each of considered ontologies proposes a different approach to modeling the IoT space. The biggest differences are in the details. **(a)** OneM2M BO proposes a small base ontology, similar to upper ontologies that provides only a minimal set of highly abstract entities. This allows for a very broad set of domain ontologies to be easily aligned with it. It also means that the BO itself is not enough to model any concrete problem (or solution) in the IoT. Furthermore, it does not capture some aspects that are very common in other ontologies. **(b)** OpenIoT contrasts this philosophy by providing a detailed model for a specific problem (i.e. pilot implementations from the OpenIoT project) that can be also applied in a more general case, or in other solutions. Its heavy usage of external ontologies provides high semantic interoperability by design. **(c)** SSN is a developed model of the IoT in general, but with strong focus on sensors. It is based on DUL, and is clearly modularized, which makes it a good candidate for extensions into concrete systems and implementations. This is evidenced by the fact that other ontologies, evaluated here, make good use of it. When it comes to specificity, it places itself in the middle between oneM2M BO and OpenIoT. **(d)** IoT-Lite is an extension of selected SSN modules, mainly to include actuators. Rather than focusing on providing a detailed description of a delimited problem space within the IoT, it approaches the modeling problem from the perspective of an implementation device. It aims to deliver a small, but complete, model in order to simplify processing of semantic information. This is also its distinctive characteristics. **(e)** SAREF is a model with a strong focus on its own area—of smart appliances. Even though mappings to other standards exist, SAREF was developed from scratch to represent a specific area of application of the IoT. In this area, it delivers a strong and detailed base, that is also clear and easy to understand. At the same time, it is general enough to be used when extended to other domains, or solutions. Interestingly, all these ontologies almost completely disregard hardware specifications. It seems that the "place" of a device in an IoT system is much more important to ontology engineers than its hardware specification and resulting capabilities.

5 Concluding Remarks

The aim of this work was to compare how selected (most popular) ontologies capture and formally represent key aspects of "the world of IoT". The results of this investigation are important in the context of the INTER-IoT project, where the question: which ontology should be used (if any) to provide foundation of the central ontology, is of utmost importance. Moreover, the results of our comparison can be of use to the Semantic Interoperability Working Group of the IoT EPI initiative.

Results of our preliminary investigations show how different can be existing conceptualizations of the same domain, depending on the context of the approach, and the applied ontology engineering methodology. Separately, we conclude that, while each considered ontology has its uses and caveats, two of them stand out in the context of potential use in the INTER-IoT project. These are SSN and SAREF. The first presents a model focused on sensors, but still robust enough, and with strong ontological basis. Those features make it a good choice in terms of interoperability (which is the focus of the project). In addition, the SSN is modular, extendable, and has been actually implemented and extended in other systems and ontologies (e.g. IoT-Lite and OpenIoT). SAREF, on the other hand, is a thoroughly modern ontology with many recommendations and relatively large scope, despite targeting only smart appliances. It already has alignments with other models, thus improving its interoperability.

In the immediate future, we will complete work reported here, by including less popular ontologies and extending the list of concepts. This will allow us to choose the base device ontology for the INTER-IoT project. Next, we will extend it (or align with other ontologies) to create a modular core ontology for interoperability in the IoT.

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