Introducing Thing Descriptions and Interactions: An Ontology for the Web of Things

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Abstract. The Internet of Things (IoT) and the Web are closely related to each other. On the one hand, the Semantic Web has been including vocabularies and semantic models for the Internet of Things. On the other hand, the so-called Web of Things (WoT) advocates architectures relying on established Web technologies and RESTful interfaces for the IoT.

In this paper, we present a vocabulary for WoT that aims at defining IoT concepts using terms from the Web. Notably, it includes two concepts identified as the core WoT resources: Thing Description (TD) and Interaction, that have been first elaborated by the W3C interest group for WoT.

Our proposal is built upon the ontological pattern Identifier, Resource, Entity (IRE) that was originally designed for the Semantic Web. To better analyze the alignments our proposal allows, we reviewed existing IoT models as a vocabulary graph, complying with the approach of Linked Open Vocabularies (LOV).

Keywords: Web of Things, ontology, Semantic Web, Linked Open Vocabularies

1 Introduction

Since the beginning, semantics have been a constituent part of the Internet of Things (IoT). As it is envisioned that the number of devices and software agents on the Internet will grow exponentially, domain models and ontologies will likely play an important role to allow for more automation in controlling and maintaining them [2]. As a consequence, proposals have emerged to integrate concepts from the IoT into the Semantic Web and benefit from alignments with existing vocabularies [16, 3, 8, 12]. The most successful example is probably the Semantic Sensor Network (SSN) ontology [4].

In the mean time, the idea of a so-called Web of Things (WoT), that consists in using the Web as an interoperable platform for IoT data, has grown a large community and found adoption by the industry [7, 17]. The approach of the Web of Things is resource-centric. It advocates the use of RESTful interfaces to expose sensor data and controls. Although vocabularies and ontologies for the IoT often offer a means to semantically describe the Web services of an IoT device, none materializes the concept of resource. For a given URI, there is no way to distinguish WoT resources (that interact with the physical world) from more generic Web resources, such as personal Web pages or pages from e-commerce platforms (that are either static documents or interfaces to other digital systems). This limitation weakens interoperability and prevents truly automated Web agents from interacting with the Web of Things.

Since 2014, a W3C interest group dedicated to the Web of Things has been actively working on that topic[3]. Among others, it has developed the notions of *Thing Description* and *Interaction*, as the core WoT resources. As part of this interest group, we have got interested in formally defining these two concepts in the Semantic Web. With this work, we pursue two objectives: first, alignment with other IoT vocabularies and, to a lesser extent, the capture of a common understanding throughout the discussions within the group.

As alignment with existing IoT vocabularies is our main objective, we start our work by reviewing vocabularies for the IoT. More precisely, we seek to analyze the relations between them, i.e. the graph they form. This is presented in the next section. We then present our proposal for a WoT ontology in Section 3, including Thing Descriptions and Interactions. In section 4, although we do not detail strict alignments, we show how to integrate our ontology to the graph of IoT vocabularies. We then conclude.

2 Related Work

2.1 Ontologies for the Internet of Things

In order to be interoperable, IoT devices need to be able to share knowledge about their capabilities or their environment. To that end, Semantic Web technologies and more precisely RDFS and OWL appear to be good candidates to model such knowledge. In this paper, we focus on vocabularies and ontologies that rely on the Semantic Web and discard other IoT data models (such as Bluetooth Low Energy profiles or IPSO Smart Objects). We were able to find five projects in the literature where an IoT vocabulary was formalized with RDFS/OWL and used in concrete applications:

- IoT-lite[4] used in the European project FIESTA-IoT;
- the Smart Appliance REFerence ontology (SAREF)[5], standardized by ETSI under the name SmartM2M [1];
- OWL-IoT-S[6], as part of the reference architecture IoT-A [12];
- IoT-O[7] with connections to the standard oneM2M [15];

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[3] https://www.w3.org/WoT/IG/

[4] http://purl.oclc.org/NET/UNIS/fiware/iot-lite

[5] https://w3id.org/saref

[6] http://purl.oclc.org/net/unis/OWL-IoT-S.owl

[7] https://www.irit.fr/recherches/MELODI/ontologies/IoT-O

- SA[8] from another European project, CHOReOS.

All these vocabularies aim at reusability and modularity, both in the sense that they rely on upper ontologies but also that they are supposed to link domain models to applications. As such, they are sometimes refered to as horizontal vocabularies.

Our selection is included in the list of vocabularies the authors of IoT-O surveyed [16]. However, since horizontality was our main selection criterion, we discarded some of the vocabularies they considered that we believe to be either application models (such as oneM2M and SPITFIRE ontologies), or domain models (SSN, to some extent).

Each of these vocabularies imports other vocabularies, which in turn also import external vocabulary modules. As a result, all the vocabularies directly or indirectly involved in the specification of concepts of the IoT form a directed graph, part of the so-called Linked Open Vocabulary (LOV) cloud[9]. To facilitate our analysis of IoT vocabularies, we constructed the subgraph with the five vocabularies mentioned above as sources. We followed the LOV methodology [18], that defines different types of alignment between vocabularies: import as previously mentioned but also extension, specialization, generalization, equivalence and disjunction[10]. Such relations can be materialized by SPARQL construct queries. The result is shown in Figure 1 (top).

The resulting graph includes 51 vocabularies (vertices) and 120 alignments between them (edges). An interesting characteristic to show is the level of reuse of a given vocabularies (i.e. the in-degree of the graph vertices). Thus, in the figure, the size of the vertices is proportional to their in-degree, which brings two vocabularies out: Dolce+DnS Ultralite (DUL)[11] and, to a lesser extent, SSN[12]. SSN itself specializes DUL. A couple of other graph metrics can also be of interest: in average, a vocabulary is aligned with 5.0 other vocabularies (average vertice degree); the average indirect alignments with a given vocabulary is 3.7 (average path length); the maximum indirect alignments for a vocabulary equals 8 (graph diameter). At last, it is worth noting that the sizes of the vocabularies (i.e. the number of axioms they define) are extremely unbalanced, as shown on the figure. DogOnt, SWEET and QUDT account for most of the vocabulary set from that point of view.

This analysis of the LOV segment for the IoT could allow us to quantify the reusability and modularity of the above mentioned source vocabularies. However, our goal is less to compare them than to identify the parts they have in common. It turns out that all IoT vocabularies eventually align with DUL, partly through SSN. SAREF is the furthest vertice from DUL (shortest path of length 3).

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[8] http://sensormeasurement.appspot.com/ont/sensor/hachem_onto.owl

[9] http://lov.okfn.org/

[10] No subject vocabulary generalizes some object vocabulary without having the object vocabulary specializing the subject vocabulary. We therefore discard generalization in the figure.

[11] http://www.ontologydesignpatterns.org/ont/dul/DUL.owl

[12] http://purl.oclc.org/NET/ssnx/ssn

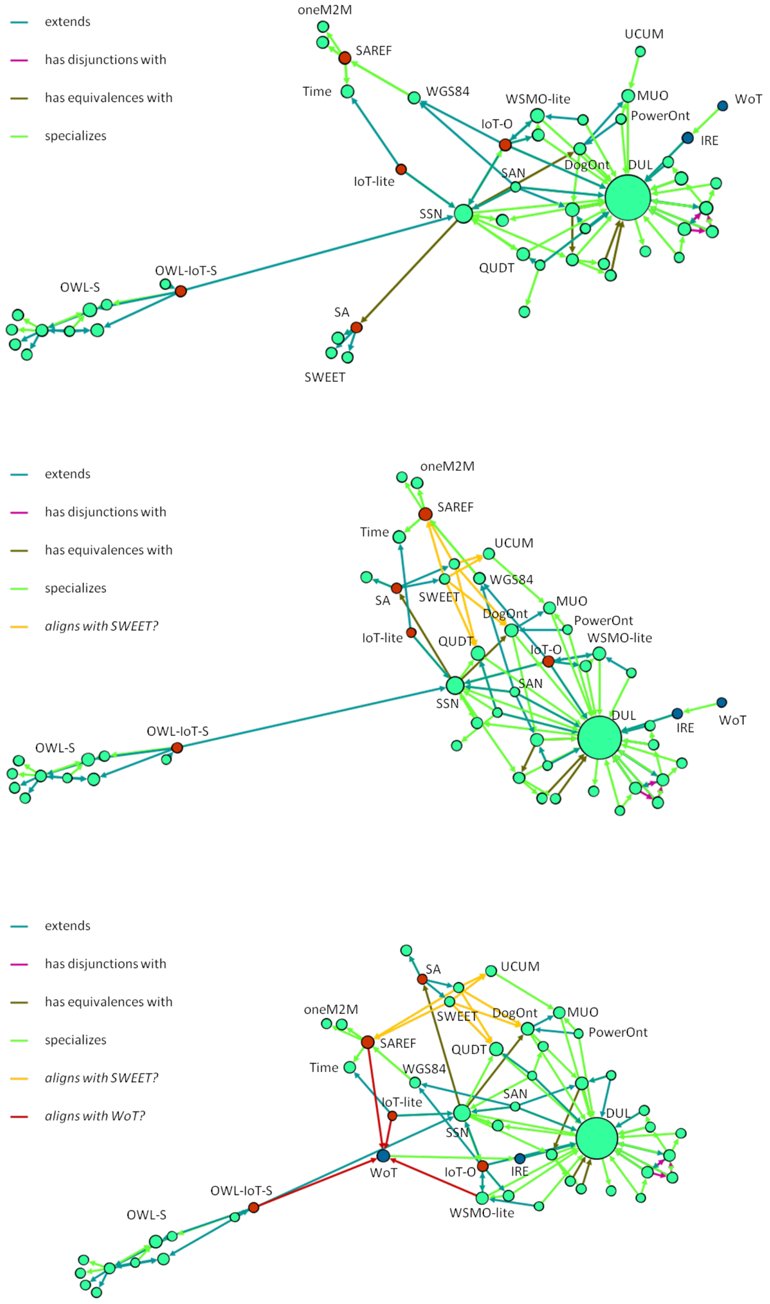

Fig. 1: IoT fragment of the LOV cloud (top) with hypothetical alignments between vocabularies for physical quantities (middle) and Web services (bottom). Source vocabularies are marked in red, and our contribution (including imports) in blue. The names of vocabularies not further mentioned in the paper have been omitted

On the other hand, the graph diameter is relatively high. 3 or 4 would have been a more adequate value. The redundancy of definitions in the domain of physics is in part responsible for spreading the graph. There are as many domain vocabularies for quantity kinds and units as source IoT vocabularies. QUDT, SWEET, UCUM are dedicated vocabularies that rely on standardized units and quantity kinds, while DogOnt and SAREF redefine them according to their own need. Figure 1 also shows what the IoT LOV fragment would be if all these vocabularies were aligned, with SWEET as reference (middle). Similarly, we observed redundant conceptualizations for Web services (either through OWL-S or WSMO). Finally, Figure 1 (bottom) represents the graph as envisioned by WoT, where vocabularies for Web services align with our ontology. More details towards possible alignments are presented in Section 4.

2.2 Ontologies for the Web

Most of the vocabularies we have reviewed so far include a way to describe how to serve IoT data, that usually turn out to be Web services with a specific endpoint URI. Yet, the Web is first a collection of interlinked resources (uniquely identified by a URI) and resources are the only artifacts agents can interact with. To be able to use a Web service, an autonomous agent has first to understand the interplay between the underlying Web resources.

As an illustration, IoT-A relies on OWL-S to semantically describe IoT Web services while IoT-O favors the Web Service Modeling Ontology (WSMO). It has been shown in the past that these two concurrent approaches are hardly interchangeable and unable to capture the semantics of RESTful Web services, that precisely exploit the centrality of resources on the Web [9]. As RESTful services play an important role in the Web of Things, it is possible to find a conceptualization for Web resources in the recently started ASAWoO project [11], combining definitions from the Hydra vocabulary [10] and schema.org[13].

As a matter of fact, the concepts behind Web resources and URIs have regularly been the subject of discussions since the creation of the World Wide Web. In the past, refinement in their definition was required to fit the idea of a Semantic Web, where any entity in the world could then be given a URI. This question of identity on the Web anticipated the idea of Web resources that would allow to interact with the physical world [14].

The pattern that emerged around (Semantic) Web resources involves three concepts: Identifier, Resource and Entity (therafter refered to as the IRE ontological pattern). It has been formalized both with predicate logic axioms [6] and OWL [13]. We develop the principle behind IRE in the next section, immediately followed by our proposal for a Web of Things ontology, that consists in an extension to IRE that includes WoT resources.

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[13] https://schema.org/

3 An Ontology for the Web of Things

3.1 Identifier, Resource, Entity

The IRE pattern is essentially based on the idea that Web resources can act as addressable proxies for real-world entities. They have a unique Web location associated to a resoure identifier (aka a URI) and involve a given resolution method to be accessed. Real-world entities do not have a URI themselves.

Several types of proxy relations are materialized in IRE. For instance, a resource is either an informal or a formal proxy, if it e.g. relies on OWL. A resource in DBpedia is formal while its Wikipedia counterpart is informal. Moreover, a resource is an exact proxy if it relates to a single entity.

In terms of OWL, IRE defines the following concepts: `WebResource`, `ProxyResource` and `SemanticResource`. It imports concepts from DUL, namely `Entity`, `InformationEntity` and `InformationRealization`. The following roles are also defined by IRE: `proxyFor`, `exactProxyFor`, `formalExactProxyFor` and `informalExactProxyFor`.

Definition 1 details IRE axioms in Description Logic (DL) notation, conform to the OWL DL profile. We separated role axioms (RBox) from terminological, concept axioms (TBox) as per DL theory. An updated version of the original OWL ontology is available at http://w3c.github.io/wot/w3c-wot-td-ire.owl. Besides namespace updates, we aligned `WebResource` with the concept `Resource` from Hydra, which is rather straightforward.

$$\mathtt{formalExactProxyFor} \sqsubseteq \mathtt{proxyFor},$$
$$\mathtt{informalExactProxyFor} \sqsubseteq \mathtt{exactProxyFor} \sqsubseteq \mathtt{proxyFor}$$

—

$$\mathtt{WebResource} \sqsubseteq \mathtt{InformationRealization} \sqsubseteq \mathtt{InformationEntity},$$
$$\mathtt{ProxyResource} \equiv \mathtt{WebResource} \sqcap \exists \mathtt{proxyFor}.\mathtt{Entity},$$
$$\mathtt{SemanticResource} \equiv \mathtt{ProxyResource} \sqcap \leq 1.\mathtt{formalExactProxyFor}.\mathtt{Entity} \sqcap \geq 1.\mathtt{formalExactProxyFor}.\mathtt{Entity}$$

Definition 1: RBox & TBox of the IRE ontological pattern

3.2 Thing Description, Interaction

The IRE ontological pattern helped define the Semantic Web, which is now supported by a large number of recommendations from the W3C. Today, as the W3C embraces the idea of extending the Web to the physical world, IRE might again prove relevant in the design of the Web of Things. We further detail WoT concepts in the following.

The discussions within the W3C WoT interest group —which the authors took part in— first focused on defining semantic models for "Things" and their capabilities. On the basis of these discussions, it appeared that only a few concepts were needed for WoT agents to start to communicate with each other. Alongside the implementation work done within the interest group, two main concepts have emerged. First, WoT Things should describe themselves and be able to exchange their description with other agents. We call such a description a Thing Description (TD). Second, WoT Things should expose to the Web a set of Interactions, which corresponds to their interface to the physical world. More details can be found on the working documents of the interest group[14].

TDs are the main vector for interoperability. It is clear that a semantic description of the real-world entities a Thing interacts with should be included in its TD. Yet, it has not been clear so far what kind of Web resources Interactions are and how they relate to real-world entities. We propose a textual definition of both TDs and Interactions, from which an OWL conceptualization naturally follows, building on IRE. Our OWL conceptualization should help map real-world entities to Web resources and eventually materialize such mappings by means of alignment between IoT vocabularies and the meta-model of WoT. We define TD and Interaction as follows:

Thing Description Semantic resource formally describing a unique WoT Thing that a software agent can interact with. Examples of WoT Things include building rooms, manufactured products, mechanical systems but also digital control devices, i.e. any real-world entity without a priori restriction.

Interaction Web resource of arbitrary content format acting as a digital proxy for any real-world entity that is not already digital information. Such entities can be physical quantities like temperature or pressure, natural phenomena like raise of temperature or object motion, arbitrary states like on/off, etc.

From the above definitions, we can state that `ThingDescription` subsumes `SemanticResource` and `Interaction` subsumes `ProxyResource`.

Even though we do not formulate a priori constraints on the entities related to Interactions, the implementation work of the interest group revealed recurrent interaction patterns that could further specialize our definition. These patterns are usually referred to as the concepts Property, Action and Event. We included these concepts in the ontology as proxifiable entities but left their definition empty, as different interpretations still coexist within the group.

The complete axioms are detailed in Definition 2. The OWL ontology is also available at http://w3c.github.io/wot/w3c-wot-td-ontology.owl.

3.3 An Example

Figure 2 gives a concrete example of TD, as per definition of the W3C interest group. It uses the JSON-LD format, a JSON serialization format for Linked Data. No prior knowledge of our ontology is needed to design a TD. In fact, we have got interested in semantically characterizing it while implementations of

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[14] http://w3c.github.io/wot/current-practices/wot-practices.html

$$\texttt{isThingDescriptionOf} \sqsubseteq \texttt{formalExactProxyFor},$$
$$\texttt{isInteractionOf} \sqsubseteq \texttt{informalExactProxyFor},$$
$$\texttt{hasThingDescription} := \texttt{isThingDescriptionOf}^{-},$$
$$\texttt{hasInteraction} := \texttt{isInteractionOf}^{-}$$

—

$$\texttt{Thing} \sqsubseteq \texttt{Entity},$$
$$\texttt{ThingDescription} \equiv \texttt{SemanticResource} \sqcap \leq 1.\texttt{formalExactProxyForThing} \sqcap \geq 1.\texttt{formalExactProxyForThing},$$
$$\texttt{Interaction} \equiv \texttt{ProxyResource} \sqcap \leq 1.\texttt{informalExactProxyFor}(\texttt{Entity} \sqcap \neg\texttt{InformationEntity}) \sqcap \geq 1.\texttt{informalExactProxyFor}(\texttt{Entity} \sqcap \neg\texttt{InformationEntity}),$$
$$\texttt{Property} \sqcup \texttt{Action} \sqcup \texttt{Event} \sqsubseteq \texttt{Entity},$$
$$\exists\texttt{forProperty}.\top \sqsubseteq \texttt{Action} \sqcup \texttt{Event},$$
$$\top \sqsubseteq \forall\texttt{forProperty}.\texttt{Property}$$

Definition 2: RBox & TBox of our ontology for WoT

WoT agents capable of generating and processing TD documents were already available. The only element needed is the context URI provided by the W3C, https://w3c.github.io/wot/w3c-wot-td-context.jsonld, where are defined mappings between keywords like `uris`, `hrefs` or `properties` and Semantic Web entities (here, `hasThingDescription`, `hasInteraction` and `hasProperty`, respectively). Based on these mappings, RDF serialization of this JSON document is possible. In addition, a standard-compliant OWL DL reasoner can infer implicit knowledge from the RDF data and our WoT ontology. The RDF representation of the example also presented in Figure 2 includes inferred data.

This example describes a Thing named "TD example". It is formally described by two TDs (one of them is the JSON sample itself) and it has relations to at least two entities. The first of these entities is a Property, which is proxyfied by the Interaction with the URI coap://thing.example.org/val and the second one is an Action, proxified by another Interaction that acts on the Property (`property` maps to `onProperty`).

Several aspects are of importance in this example. First, all real-world entities are blank nodes (i.e. they have no URI). Indeed, if they had a URI, they would then either be Interactions or semantic resources. They can have specific local identifiers, though (e.g. `"@id": "_:val"`).

Moreover, there is no one-to-one mapping between real-world entities and resources, which explains why `uris` and `hrefs` are arrays and can contain more than one URI. For instance, if the same Property can be accessed both with HTTP and CoAP, it will have two Interactions. Similarly, the same data can be represented in different formats like XML or EXI, potentially by two distinct Web resources, and still realize the same entity.

At last, anything can potentially be an Interaction as long as it has a URI. The IoT relies on a wide range of protocols, including BLE and MQTT, which do not officially support URIs. According to IRE and our WoT ontology, adopting

```
{
  "@context": [
    "http://...w3c-wot-td-context.jsonld",
    {"dogont": "http://.../dogont.owl#"}
  ],
  "name": "TD example",
  "@type": "dogont:Lamp",
  "uris": ["coap://thing.example.org/"],
  "properties": [
    {
      "@id": "_:val",
      "@type": "dogont:ColorStateRGB",
      "hrefs": ["val"],
      "valueType": "xsd:integer",
      "writable": true
   }
  ],
  "actions": [
    {
      "@type": "dogont:ToggleFunctionality",
      "hrefs": ["tg"],
      "property": "_:val",
      "outputData": {
       "@type": "dogont:OnOffState",
        "valueType": "xsd:float"
      },
      "inputData": {}
    }
  ],
  "events": []
}
```

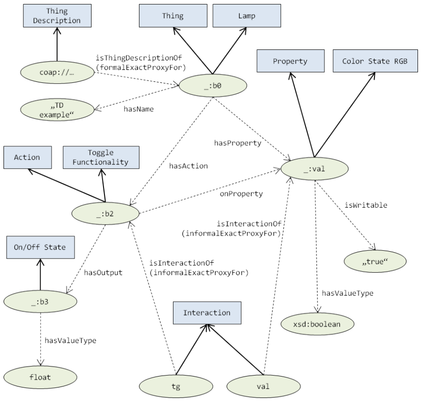

Fig. 2: Thing Description example in JSON-LD (left) and RDF (right)

a scheme officially endorsed by IANA is the only criterion for these protocols to be part of the Web of Things.

One can note as well that the TD is annotated with external types from DogOnt, that belong to the IoT LOV segment. Without these annotations, it would indeed be hard if not impossible to understand that the Thing we take as example is actually a LED lamp. We deal with this subject more in details in the next section.

4 Relationship to Other Ontologies

As pointed out by the TD example, semantic interoperability in WoT stems from annotating a Thing Description with external vocabularies. In our proposal, we defined the concepts `Thing`, `Property`, `Action` and `Event` but we intentionally left open some aspects of their definition. They are thought of as placeholders for alignments with existing IoT vocabularies. We have investigated different means towards alignment based on our ontology, which we present in the following. Yet, we assume that concrete alignment with WoT (i.e. the model the W3C will adopt eventually) should be carried out by the authors of the vocabularies we have reviewed in Section 2.1.

When TD elements declare types like `Lamp`, `ColorStateRGB` or `ToggleFunctionality`, implicit alignment between DogOnt and our WoT ontology is meant (e.g. through a specialization relation). This alignment at instantiation time might be assisted by automatic reasoning: confronting axioms from the imported ontology with those from our ontology, a computer program could check whether the TD is satisfiable or not. In practice, for such program to be relevant, the two vocabularies should be aligned with a common upper ontology. As highlighted by our analysis of IoT vocabularies, DUL appears to play that role. Here is an example: if, instead of `"@type": "dogont:ToggleFunctionality"`, the lamp TD had declared `"@type": "dogont:ToggleCommand"` for the `Action`, it would have led to unsatisfiability. Indeed, `Action` subsumes $\neg$`InformationEntity` while `ToggleCommand` is declared in IoT-O as a subclass of `InformationEntity`, meaning they are mutually disjoint.

We implemented a validation tool that follows this principle, available at: https://github.com/thingweb/thingweb-playground. Ontologies usually have various expressiveness levels, mostly RDFS, OWL Lite or OWL DL. We used the HermiT reasoner[15], that is capable of reasoning over OWL DL axioms. Such reasoners are known to have scalability issues but since the vocabularies we consider often have reasonable sizes, our tool is able to solve the satisfiability task within a few seconds. We hope this tool will also help evaluate our conceptualization of WoT by members of the W3C interest group: the higher the number of satisfiable TDs with annotations from the IoT LOV fragment, the more accurate our model.

Furthermore, besides exploiting logical axioms, one can also see vocabulary definitions as graphs and explore the connections between them at a syntactic level. Inspired by well-known structure-based ontology matching techniques [5], we searched for possible matches with the IRE pattern in the IoT LOV fragment. More precisely, we first identified matches for Entity and Identifier and then computed the shortest path between them. To match concepts with Entity, we used our definition of WoT proxifiable Entity, that is, `Entity`$\sqcap\neg$`InformationEntity`. On the other hand, matches for Identifier are usually not directly materialized in vocabularies. Instead, we looked for data type restrictions on the RDF data type `xsd:anyURI`. We found 26 data type properties from 7 distinct vocabularies and used them as sources. The algorithm runs until the node `Entity` (DUL) is found. The paths we found are shown in Table 1 (excluding loops).

Property path	Defined by
`^hasOutputType/hasAccessInterface/hasServiceEndpoint`	OWL-IoT-S
`isAssociatedWith/endpoint`	IoT-lite
`hasService/hasOperation/hasAddress`	WSMO-lite

Table 1: Possible paths between `Entity` and `Identifier` from the IoT LOV fragment (SPARQL property path syntax)

Hypothetical alignments between these vocabularies and WoT based on the matches we found do not significantly change the graph metrics of the IoT LOV fragment (average vertice degree, average path length, diameter). Yet, interestingly, all paths starting from Identifier eventually lead to the concept of Ser-

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[15] http://www.hermit-reasoner.com/

vice (with a maximum path length of 4). Four vocabularies have a definition for `Service`: SAREF, OWL-S, WSMO-lite and IoT-lite. As already mentioned, some of them are not compatible but they have that in common that they all rely on Identifiers, hence on the Web architecture. Since Resource is the atomic concept of the Web architecture, all modelings of services are theoretically compatible with our WoT model, what speaks in favor of using WoT as a basis for ontological alignment.

5 Conclusion

Our work concentrated on defining semantics for the Web of Things, based on the activity of the W3C. The recommendations that the group will publish will prove us right or wrong, with respect to the definitions we give for TDs and Interactions in this paper. However, in the mean time, we hope that our WoT model will be used as a framework by W3C members, as illustrated with our validation tool, and assist further development of the semantic models involved in WoT.

Another aspect of our work was the materialization of the LOV fragment for IoT. It revealed, among others, the dominant position of DUL. We therefore turned our work towards DUL as well, and chose a vocabulary (IRE) that provided alignment with DUL. This characteristic facilitates alignment of WoT with existing IoT vocabularies. Yet, the IoT LOV fragment is still broad and the need for light-weight semantics involving a limited set of concepts —some kind of "iot.schema.org"— has been clearly expressed by the industry. We believe that one way to achieve this is by progressively tightening the IoT LOV fragment by means of alignments. As it is expected that the number of resources on the Web that relate to real-world entities will rapidly increase, an early conceptualization of WoT resources was needed to achieve that goal.

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