Standardizing Generic Cross-Domain Applications in Internet of Things

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***Abstract*—Domain-specific Internet of Things (IoT) applications are becoming more and more popular. Each of these applications uses their own technologies and terms to describe sensors and their measurements. This is a difficult task to help users build generic IoT applications to combine several domains. To explicitly describe sensor measurements in uniform way, we propose to enrich them with semantic web technologies. Domain knowledge is already defined in more than 200 ontology and sensor-based projects that we could reuse to build cross-domain IoT applications. There is a huge gap to reason on sensor measurements without a common nomenclature and best practices to ease the automation of generic IoT applications. We present our Machine-to-Machine Measurement (M3) framework and share lessons learned to improve existing standards such as oneM2M, ETSI M2M, W3C Web of Things and W3C Semantic Sensor Network.**

Keywords*—*Linked Open Data; Linked Open Rules; Linked Open Vocabularies; Internet of Things; Machine-to-machine; Semantic Sensor Networks; Semantic Web of Things.

I. INTRODUCTION

Recently there has been an increasing interest in extending the Internet with connected devices containing sensors, actuators and RFID tags (also called things). These things can be used to develop new applications for home automation, health & fitness monitoring, smarter transport management, intelligent waste disposal and more. This results in an ecosystem known as Internet of Things (IoT) where the things are interconnected using Machine-to-machine (M2M) communications. The current initiatives in IoT demand creation of applications and services by exploiting the physical things. In order to develop applications based on the M2M data, they must be processed. Simple sensor data processing would limit the functionalities of the resulting application. Thus, additional information (unit and context) is necessary to derive any conclusion. Therefore a primary goal of the IoT is to create context awareness enabling the things, applications and services to respond dynamically to their surrounding environment. Another aspect of the M2M data processing is that the data collected by the physical things are multimodal and represent different domains with diverse nature. This poses numerous challenges to efficiently interpret the data. It is predicted that 30 billion of things will be connected to the internet by 2020[1]. Therefore the challenges will magnify exponentially without a standardized way of processing and interpreting the huge volume of M2M data. Also additional requirements would be necessary to support these devices with proper naming and addressing schemes, interoperability and providing service discovery. The semantic web technologies (ontologies, linked data, linked rules, etc.) can be used to develop and deploy effective solutions for the mentioned issues. The M2M data transformation using semantic can be explained through the "knowledge hierarchy" portrayed in Figure 1 [2].

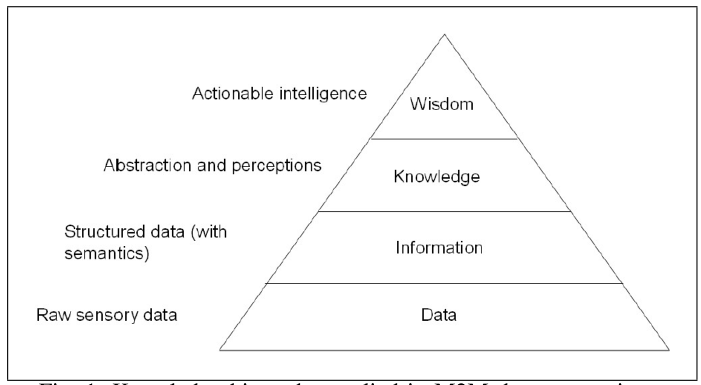

Fig. 1: Knowledge hierarchy applied in M2M data processing

The physical things generate raw measurements at the lowest layer. The layer above adds additional information to create a structured metadata. In this case, Sensor Markup Language (SenML) [13] has been chosen which provides a structured, lightweight and uniform format to describe sensors. The metadata contains information about the unit, sensor name, unique identification, sensor type, timestamp etc. The metadata is implemented using JSON to preserve interoperability and provide a uniform way to exchange metadata among several connected devices. Capabilities of SenML have been extended to use same uniform way to interact with actuators also [6] [7]. This is the first step of enriching the M2M data using semantic processing. The next step is to create abstractions and perceptions that give detailed insights to the M2M data by further reasoning using rules and knowledge of different domains. These results into actionable intelligence and can be used to make high level decisions and control something using actuators. The next big challenge is to develop generic cross-domain IoT applications. To combine several domains, there is a real need to explicitly describe the meaning of the sensor measurements. For example, a temperature has different meaning in healthcare, in smart home or in the weather domain. To explicitly describe sensor measurements and reason on the generated M2M data, we use the semantic

[1] http://www.gartner.com/newsroom/id/2621015

web technologies, more precisely, ontologies to describe sensor concepts and their properties. Ontologies ease the reasoning by integrating semantic rules and inference engine to reason about sensor data. But there are several challenges:

- Domain experts constantly redefine new domain knowledge (ontology and rules) without considering the existing ones.
- Domain experts are not aware of the semantic web best practices or semantic web tools.
- Existing mapping tools are not tailored to link our domain knowledge. Synonyms for instance are not recognized even with the use of dictionaries since they are not specialized for our domain knowledge.

To build generic IoT applications we could reuse more than 200 ontology and sensor-based applications that have been already designed, among them more than 60 projects share their ontologies or rules online. Since ontologies and rules are designed according to the W3C recommendations such as Resource Description Framework[2] (RDF), RDF Schema[3] (RDFS), Ontology Web Language (OWL) and SPARQL Protocol and RDF Query Language[4] (SPARQL), we expected that it would be easy to reuse existing works and interlink them to build cross-domain applications. Our gap analysis shows that existing applications use their own terms to describe sensor measurements and related rules [12]. Indeed, ontology mapping tools tested do not detect synonyms employed to represent the same measurements and rules (e.g., precipitation and rain). Therefore, to develop generic cross-domain applications and services in IoT, several aspects of semantic web have to be standardized. Contributions of this paper in standardizing the generic cross-domain IoT applications are explained below.

Firstly, a Machine-to-Machine Measurement (M3) framework to build generic cross-domain applications is described. It includes the M3 nomenclature and the M3 ontology which define uniform terms to describe sensors, their measurements and units. Secondly, the usability and applicability of the M3 framework is demonstrated through a cross-domain IoT application use case. Thirdly, we describe our vision to improve the related standards including W3C Web of things, W3C Semantic Sensor Network (SSN) ontology [5], oneM2M and ETSI M2M [3]. Then ETSI M2M architecture is proposed to enrich M2M data based on semantic web technologies. The architecture incorporates M3 ontology, M3 domain knowledge and M3 rules to describe the sensors, measurements, units and domains in a uniform way and reason on them [8] [10]. This lays the foundation for IoT domain interoperability for developing cross-domain applications. Finally, the paper concludes by summarizing the overall work.

II. Machine-to-Machine Measurement Framework

The M3 framework assists the developers in semantically annotate M2M data and in building novel applications by reasoning on M2M data originating from heterogeneous IoT domains. The M3 framework is displayed in Figure 2 and is composed of several layers as following:

- **Perception layer** is composed of physical devices such as sensors, actuators and RFID tags.
- **Data acquisition layer** retrieves sensor data (SenML) from M2M devices and convert them in a unified way (RDF/XML) compliant with the M3 ontology, an extension of the W3C SSN [5] Observation Value concept to provide a basis for reasoning.
- **Persistence layer** stores M3 domain ontologies, datasets and semantic sensor data in a triple store. A triple store is a database to store semantic sensor data. We also stored SPARQL queries and rules.
- **Knowledge management layer** is responsible for finding, indexing, designing, reusing and combining domain-specific knowledge (e.g., smart home, intelligent transportation systems, etc.) such as ontologies and datasets to update M3 domain ontologies, datasets and rules. Linked Open Vocabularies for IoT (LOV4IoT)[5] is a huge knowledge based composed of domain ontologies, datasets and rules based on semantic web technologies which could be reused for cross-domain applications.
- **Reasoning layer** infers new knowledge using reasoning engines and M3 rules extracted from Sensor-based Linked Open Rules (S-LOR) [11]. M3 rules are a set of rules compliant with the M3 ontology to infer new knowledge on sensor data. For instance with a luminosity equal to 50000 lux, M3 rules indicate that is highly sunny outside.
- **Knowledge query layer** executes SPARQL (a SQL-like language) queries on inferred sensor data.
- **Application layer** employs an application (running on smart devices) which parses and displays the results to end users. For instance, the M3 framework suggests safety devices to switch on in your smart car according to the weather forecasting (e.g., sun visor when it is sunny).

A. Uniform descriptions of sensors, units, measurements and domains with the M3 ontology

The uniform descriptions of above are fundamental necessity to develop cross-domain applications and services. A common nomenclature is described here after and the lists are not exhaustive. Such recommendations are relevant for standardization bodies like oneM2M, ETSI M2M, W3C Web of Things and W3C SSN.

The second column of the Table I is the recommended uniform sensor and measurement name, various other names are listed in the third column and units in the fourth column. Table I presents such a common nomenclature for the sensors used in weather domain. The entire M3 nomenclature is available here[6]. Similar study has been performed for sensors

[2] http://www.w3.org/TR/2014/REC-rdf11-concepts-20140225/Overview.html

[3] http://www.w3.org/TR/rdf-schema/

[4] http://www.w3.org/TR/rdf-sparql-query/

[5] http://www.sensormeasurement.appspot.com/?p=ontologies

[6] http://www.sensormeasurement.appspot.com/documentation/NomenclatureSensorData.pdf

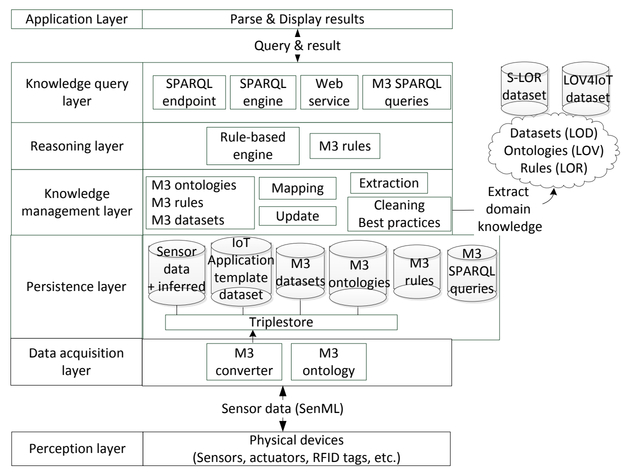

Fig. 2: Architecture of the M3 framework

M3 or SenML domain	M3 or SenML sensor/ measurement name	Description, other names (synonyms)	M3 or SenML Unit
Weather	HumiditySensor/ Humidity	Hygrometer, humidity sensor, moisture sensor, soil moisture probes	Percent
Weather	WindDirectionSensor/ WindDirection	Wind direction	DegreeAngle
Weather	SunPositionDirectionSensor/ SunPosition	sun position direction to detect east, west, south, north	DegreeAngle
Weather	AtmosphericPressureSensor/ AtmosphericPressure	Atmospheric pressure sensor, Barometer, barometric pressure sensor	Pascal
Weather	CloudCoverSensor/ CloudCover	Cloud cover sensor	Okta
Weather	SunPositionElevationSensor/ SunElevation	sun position elevation to detect (twilight, day, night, etc.)	DegreeAngle
Weather	SolarRadiationSensor/ SolarRadiation	Solar radiation sensor, par (photo synthetically active radiation) sensor, sun light, solar sensors, sun's radiation intensity	WattPerMeterSquare
Weather	VisibilitySensor/ Visibility	Visibility sensor to detect fog	Miles, Meter
Weather	Thermometer, AirThermometer/ Temperature	Thermometer, temperature sensor, thermistor	DegreeCelsius
Weather	LightSensor/ Luminosity	Light, luminosity, illuminance, lighting	Lux
Weather	PrecipitationSensor/ Precipitation	Precipitation sensor, rainfall sensor, rain fall, pluviometer, rain, rainfall gauge	MilimeterPerHour
Weather	WindSpeedSensor/ WindSpeed	Wind speed sensor, wind velocity sensor, anemometer	MeterPerSecond

TABLE I: Uniform description for sensors in weather domain

used in health care, smart home, transportation, agriculture, air quality measuring and with actuators. Table II proposes uniform domain names. The uniform descriptions have already been communicated to oneM2M WG-5 (MAS)[7] [9].

III. Cross-domain IoT application use case implementation

This section describes development of a cross-domain IoT application by utilizing the M3 framework. Consider a scenario where an end user chooses a sensor (e.g., light sensor) and the domain (e.g., weather). The choices are communicated to the M3 framework which finds IoT application templates using the sensor and combined it with other domains as depicted in Figure 3. The proof-of-concept is available here[8]. For the given example, the M3 framework can propose four cross-domain templates such as:

- Weather, transport and safety devices

M3 or SenML Domain name	Description, other names (synonyms)
BuildingAutomation	Smart home, building automation, or building or room (kitchen, bathroom, living room, dining room)
Health	healthcare
Weather	Weather forecasting, meteorology
Agriculture	Agriculture, smart farm, garden
Environment	Environment (earthquake, flooding, forest fire, pollution)
Emotion	Affective science, emotion, mood, emotional state; brain wave
Transport	Intelligent transportation systems (ITS), smart car/vehicle, transportation
Tourism	Tourism
Location	Location, place, GPS coordinates
City	Smart city, city automation, public lighting
RFID	Tracking RIFD goods
Generic	Others

TABLE II: Uniform Description for IoT Domain Names

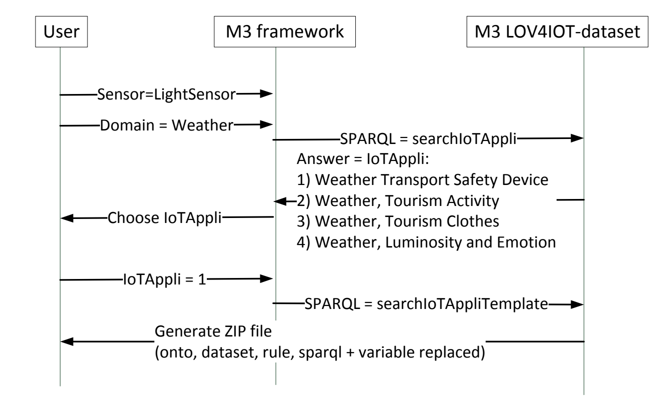

Fig. 3: Sequence diagram to generate IoT applications

- Weather, tourism and activities
- Weather, tourism and clothes
- Weather, luminosity and emotion

The user chooses one of these templates and the M3 framework will automatically generates the M3 domain ontologies, M3 datasets, M3 rules and M3 SPARQL queries in a ZIP file as displayed in Figure 4 that we will use to build the application. Then, the light user data (from end user) is sent to the M3 framework, which annotates them with semantics and applies the M3 reasoning engine with the rules provided in the ZIP file. Finally, M3 returns high-level cross-domain information (the results of the SPARQL query) to the user. Such scenarios have already been developed and available at[9]. Here a cross-domain application use case is mentioned that takes advantage of the ontologies for weather and transportation.

The M3 framework reused works designed by Staroch [15] for the weather domain and Ruta et al. [14] for transportation and design Semantic Web Rule Language (SWRL)[10] rules that could be reused in other intelligent transportation systems. For example, switch on the fog lamp when it is foggy. Some of the design rules are:

- Rule: IF Precipitation > 20 AND < 50 mm/h THEN HeavyPrecipitation [15]

[7]http://onem2m.org/MAShome.cfm
[8]http://www.sensormeasurement.appspot.com/?p=m3api
[9]http://www.sensormeasurement.appspot.com/
[10]http://www.w3.org/Submission/SWRL/

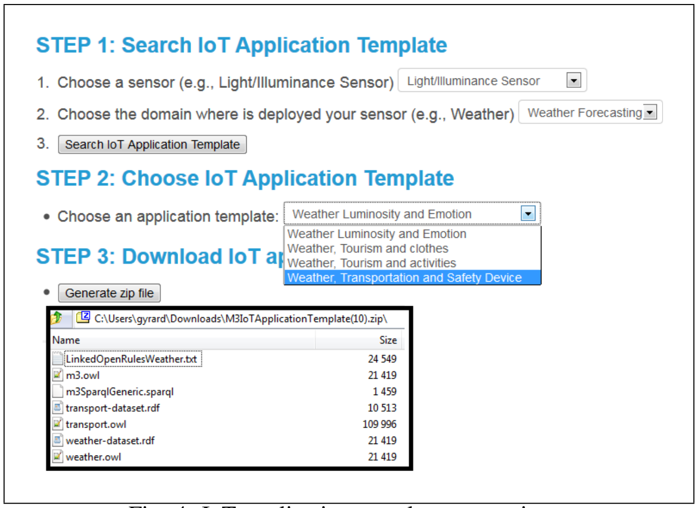

Fig. 4: IoT application template generation

- Rule: IF Rainy THEN hasSensorSpeed = LowSpeed AND hasSafetyDevice = (ABS, ESP) [14]
- Rule: IF Snowy THEN hasSensorSpeed = LowSpeed AND hasSafetyDevice = (SnowChains, ABS, ESP) [14]

Note that ABS is Anti-lock braking system and ESP is Electronic Stability Program. Using the M3 system and the mentioned architecture the occurrences of these rules and related events can be easily located and accordingly necessary services can be proposed.

IV. Improving Standardizations

Improving the current standards will contribute to interoperability among IoT domains and cross-domain applications We analyze the current limitations in standardizations such as W3C Web of Things, ETSI M2M, oneM2M and W3C SSN and demonstrate that the M3 approach solves the interoperability issues.

A. State of the Art

The W3C Web of Things[11] aims to: (1) interpret sensor data, (2) use semantics to ensure interoperability, and (3) encourage to employ common vocabularies but do not propose any methods to achieve these goals. No standardizations have been proposed yet.

ETSI M2M [1] explains the necessity to: (1) semantically annotate M2M data to build M2M applications, (2) combine domains, (3) reuse data across different applications, and (4) interpret M2M data. They do not provide any nomenclature to describe sensor data in an unified way to easily combine domains and do not recommend any common domain vocabularies in the context of IoT.

oneM2M [16] plans to integrate semantics in their architecture. They do not explain the limitations of the W3C SSN ontology.

The W3C Semantic Sensor Network (SSN) XG Final Report[12] explained they "do not provide a basis for reasoning that can ease the development of advanced applications". They explicitly describe to standardize the domain ontologies to bridge the Internet of Things as a future work. The W3C working group has designed the "Review of sensor and observation ontologies"[13] web page to reference sensor ontologies, the ontology URL and related papers to later design the W3C SSN ontology to combine, merge and standardize in a unify way all existing ontologies. It has been done for sensor ontologies but not for domain ontologies relevant for IoT.

B. Standardization limitations

We highlight that existing standards such as W3C Web of Things, ETSI M2M, oneM2M and W3C SSN ontology [5] should pay attention to interoperability issues, they lack:

- A common format or syntax to describe sensors, measurements, units and domains.
- A nomenclature defining common terms to describe sensors, measurements, units and domains.
- Interoperable and standardized domain knowledge (ontologies, datasets and rules):
    - To easily combine domains.
    - They should recommend a semantic language to describe rules among SWRL[14], SPIN[15], SPARQL CONSTRUCT[16], etc.
    - Domain ontologies, datasets and rules are generated by ontology and rule editor tools which are not interoperable. They should recommend and advice semantic web tools to automatically generate ontologies, datasets and rules interoperable with each other from a syntax point of view to easily combine domain knowledge.
    - Domain knowledge has not been designed in the same manner, since it has been done by various domain experts, even in the same domain.
- A basis to ease the reasoning and interpret high-level abstraction from M2M data.
- Methods to interpret M2M data.
- Semantic web and linked data best practices are not known and not followed by domain experts.
- Semantics components are not explicitly describe in ETSI M2M and oneM2M architectures.

The proof of concept of the M3 framework shows that our approach is feasible and could be standardized to overcome these limitations.

C. Standardizing the M3 approach

A list of recommendations to the standard bodies are provided below.

[11] http://www.w3.org/2014/02/wot/
[12] http://www.w3.org/2005/Incubator/ssn/XGR-ssn-20110628/
[13] http://www.w3.org/2005/Incubator/ssn/wiki/Review_of_Sensor_and_Observations_Ontologies
[14] http://www.w3.org/Submission/SWRL/
[15] http://spinrdf.org/
[16] http://www.w3.org/TR/rdfsparqlquery/#construct

1) Describing sensor measurements in a unified way: Concerning the syntax and format, our proposal is to use SenML to exchange sensor measurements between devices. SenML is a lightweight format compared to OGC Sensor Web Enablement (SWE) [4]. Concerning the lack of common terms, the M3 nomenclature is proposed to describe sensors, measurements, units and domains in an unified way as described in section II-A.

2) Standardize common domain ontologies for sensor networks/IoT domains: Interoperability issues to easily combine domain knowledge are addressed by designing the M3 domain knowledge (ontology, dataset and rules) for various domains such as weather, transportation, building automation, healthcare, etc. The M3 domain knowledge has been designed and inspired by existing 200 domain-specific applications relevant for sensor/IoT domains that we referenced in the LOV4IoT web page[17]. The sensor-based domain ontologies have been classified by domains, date and ontology status. For instance, in the health domain, we redesigned the health ontology, dataset and rules in a interoperable way, inspired by 40 existing health ontologies.

3) M3 ontology as an extension of the W3C SSN ontology: We provide an extension of the W3C SSN ontology [5] (ssn:ObservationValue concept) as M3 ontology to allow the interpretation of high-level concepts from M2M data. The M3 ontology has been designed and developed to describe sensors, measurements, units and domains in uniform way and to reason on them [8] [10] [11]. The M3 ontology is a synthesis of sensor measurements found in more than 200 ontology-based and sensor-based applications. It describes more than 40 sensors, 22 actuators and 8 RFID tags embedded on products by taking into account their synonyms and classify them by domains (e.g., smart home, healthcare, transportation, weather, etc.). The M3 ontology is being updated and improved continuously.

4) Interpreting M2M data: We have proposed a Sensor-based Linked Open Rules (S-LOR), more precisely, the M3 rules to easily share, combine and reuse interoperable rules which are interoperable with the M3 ontology, M3 domain ontologies and datasets. We preconize the SWRL language to design these rules, frequently, rules are designed as owl:Restriction in ontologies. Our proposed M3 rules are compliant with the Jena[18] framework and reasoning engine. To design M3 rules, there is a need of a common nomenclature to reason on sensor data. Such standardizations enable efficient sensor-based domain knowledge interoperability to combine rules, ontologies and datasets, since existing ontology mapping tools are not enough mature to automatically align sensor-based domain ontologies.

5) Encouraging best practices and semantic web tools: We synthesize, popularize and encourage semantic web and linked data best practices to design ontologies and rules by adhering to the following:

- We recommend Protege and OWL API tools to design ontologies, datasets or rules. Rules in this case are defined as owl:Restriction.

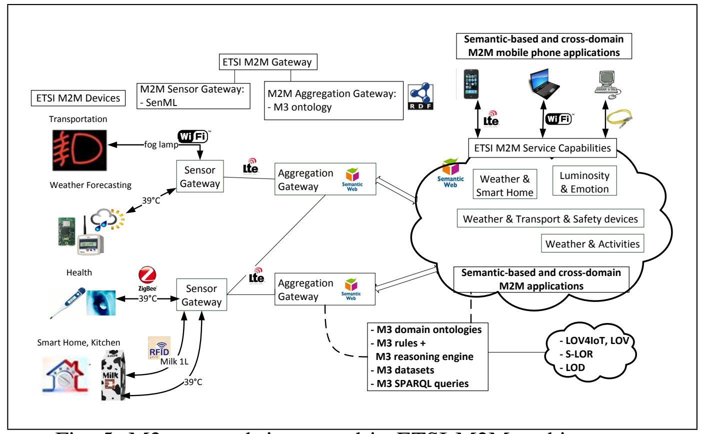

Fig. 5: M3 approach integrated in ETSI M2M architecture

- Sharing ontologies, datsets and rules online (open source approach)
- Proper URI to access the ontology code
- Proper labeling and comments useful for ontology mapping tools to detect etymology, synonyms, etc.
- Submitting the ontology to the Linked Open Vocabularies[19] (LOV) project which references more than 400 well-designed ontologies and check ontology metadata such as authors, title, and creation date.

The set of best practices are described in oneM2M semantic web best practices [9].

All of these points are packages in our M3 framework which is integrated in a semantic-based ETSI M2M architecture.

V. Semantic based ETSI M2M architecture

An ETSI M2M architecture is developed for cross-domain IoT applications and services development[20] [8] [10] to show the feasibility of the proposed M3 approach. The M3 approach could be compatible with other standardized architectures as well. The architecture is generic and can be adapted to suit the need of different use cases. Figure 5 displays the various domains and components of the architecture. The different M2M domains are explained as follows:

A. M2M device domain

The M2M device domain contains the physical things called M2M devices. In order to develop cross-domain applications, things belonging to different domains are incorporated. The different sensors generate the raw measurements which are communicated to the resource gateway. The gateway converts the sensor data into sensor metadata by adding additional information. The resulting metadata is described using SenML format. The metadata in-turn is converted to XML to provide interoperable measurement. The gateway forwards the XML formatted metadata to resource server. The M2M device domain server semantically annotates XML M2M measurements. It is achieved by employing the M3 ontology.

[17] http://www.sensormeasurement.appspot.com/?p=ontologies
[18] http://jena.apache.org/
[19] http://lov.okfn.org/dataset/lov/
[20] http://goo.gl/7ThaEy

B. M2M application domain

The M2M application domain houses the semantic-based IoT applications. These are accessible as RESTful web services in the cloud. Computers or mobile clients can query these web services to use the services. The framework and web services are also available for the 3rd party users who can get XML or JSON results, parse and display it as they intent to without learning semantic web technologies. A SPARQL endpoint can also be used to query the web services to receive the semantically enriched M2M data. For non semantic web experts, the M3 framework generates the relevant M3 domain ontologies, datasets, rules and SPARQL queries to automatically build cross-domain applications. Currently we are integrating the M3 framework in mobile devices. A light version of the Jena framework such as AndroJena[21] has been integrated in constrained devices such as smartphones.

VI. CONCLUSION

Based on the experience with the M3 approach, we provided a set of recommendations that could be used in standardization bodies. It summarizes the motivation behind such standardization efforts as semantic web technologies are seen as enablers for such IoT application development. Although researchers and industry experts are attempting to outline the standardizations requirements in M2M and IoT [17], several aspects still remain unaddressed. This paper attempts to address the issues related to semantic web technologies in building generic cross-domain IoT application development. Our gap analysis has shown that several aspects of such technologies are not uniform. Uniform nomenclature for sensors, units, measurements and IoT domains are proposed as the fundamental stepping stone towards standardizing such development. Our vision to improve the current standards is also presented. The M3 framework is incorporated into the ETSI M2M architecture to highlight the feasibility of the approach. It is generic in nature and can be adapted as per the need of different application use cases and for different standard architectures like oneM2M. The M3 framework is being continuously upgraded and are being communicated to relevant bodies to be included into future standardization efforts.

The M3 approach could be integrated in future initiatives of the standardization bodies (ETSI, oneM2M, W3C Web of Things, W3C SSN ontology). Since oneM2M brings together the standardization initiatives of ETSI, ARIB, ATIS, CCSA, TIA, TTA, TTC, oneM2M could lead such efforts.

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[21] http://code.google.com/p/androjena/

[22] http://www.pole-scs.org/

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