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Enabling the Semantic Web of Things: framework and architecture

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***Abstract*—The *Semantic Web of Things* is a novel paradigm combining the Semantic Web and the Internet of Things, aiming to associate semantic annotations to real-world objects, locations and events. This paper presents a general framework for the Semantic Web of Things, based on an evolution of classic Knowledge Base models, also providing architectural solutions for information storage, communication and processing.**

I. Semantic Web of Things

The *Semantic Web of Things* (SWoT) [1] is an emerging vision in Information and Communication Technology, joining together the Semantic Web and the Internet of Things. Its goal is to associate semantically rich and easily accessible information to real-world objects, locations and events, by means of inexpensive, disposable and unobtrusive micro-devices, such as *Radio Frequency IDentification* (RFID) tags and wireless sensors. This can enable new classes of smart applications and services in several business areas as well as for personal lifestyle. In order to enable this vision, technologies and frameworks must cope with typical pervasive computing issues: platform heterogeneity; resource, user and device volatility; dependence on context; severe computing limits. Hence, the SWoT vision requires pervasive knowledge-based systems with high degrees of autonomic capability in information storage, management and discovery, also providing transparent access to information sources in a given area.

In such volatile and dynamic environments, resource discovery becomes a pivotal feature. Nevertheless, most solutions inherit design from common stable networked infrastructures, relying on centralized brokers for management and discovery of information [2], [3]. More optimized alternatives have been recently gaining acceptance, such as 6LoWPAN [4] and the Constrained Application Protocol (CoAP) [5]. In parallel efforts, ontologies for device and data annotation were proposed, such as OntoSensor [6] and the SSN-XG ontology of the World Wide Web Consortium for semantic sensor networks [7]. Recent projects, such as UBIWARE [8], Sense2Web [9] and SPITFIRE [10], combine networking and semantic technologies to build complete frameworks for a semantic-enabled Internet of Things.

In this paper we outline a novel general framework for the Semantic Web of Things, based on an evolution of the classical Knowledge Base model, named *ubiquitous Knowledge Base* (u-KB). It is sketched in Figure 1. A u-KB is defined as a distributed knowledge base whose individuals

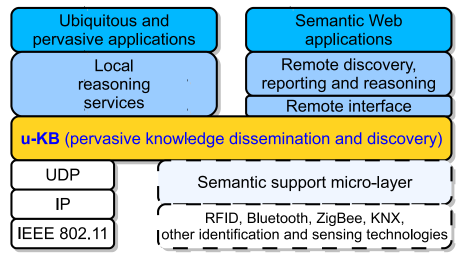

Fig. 1. Proposed Semantic Web of Things framework

(assertional knowledge) are physically tied to micro-devices on the objects disseminated in an environment, without centralized coordination. Each annotation refers to an ontology providing the conceptual model for the particular domain. With respect to the above-mentioned related work, the approach presented here is more focused on allowing semantic-based dynamic resource dissemination and discovery in mobile ad-hoc contexts, without necessarily linking to the Internet to provide useful services (even though it can be exploited when available), so being more inclined to really ubiquitous and pervasive computing.

The remainder of the paper is as in what follows. Section II explains the u-KB framework, while Section III discusses the related architecture and the integration of pervasive computing technologies. Conclusion and future work close the paper.

II. Ubiquitous Knowledge Bases

In the Semantic Web, two kinds of knowledge can be expressed: *conceptual* knowledge about the problem domain; *factual* knowledge, referred to specific instances. The domain conceptualization is an *ontology*, describing general properties of concepts and relationships among them. Factual knowledge is specific to the individuals in the modeled excerpt of the observed reality. An ontology along with a set of asserted facts build a Knowledge Base from which further knowledge can be inferred. In the proposed approach, the KB –usually intended as a fixed and centralized component– evolves toward a pervasive entity: ontology files can be managed by one or more hosts in a Mobile Ad-hoc NETwork (MANET), while individual resources are scattered within the environment, because they are physically tied to micro devices deployed in the field. Since several object classes, described w.r.t.

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different ontologies, can co-exist in a physical environment, they share the system infrastructure. Resources belonging to the same domain will likely be described by means of the same ontology, while objects of different categories may refer to different ontologies. Nevertheless, each individual resource annotation refers to a single conceptualization. Ontology Universally Unique Identifier (OUUID) codes [11] are adopted to mark ontologies unambiguously and to associate each individual to the ontology w.r.t. which it is described. URIs are most commonly used to identify ontologies and, according to Linked Data best practices, they should also be used as URLs (Uniform Resource Locators) linking to the actual ontology document via HTTP. Nevertheless, in our SWoT framework OUUIDs are preferred as they have fixed length, generally much shorter than URLs, and are easily mapped to data types for resource class identifiers adopted by most standard mobile discovery protocols. Furthermore, in many pervasive contexts mobile devices cannot connect to the Internet due to technical or environmental constraints, so URIs cannot be exploited to locate ontologies. Whenever Internet connection is available, ontology access is granted by means of OUUID-to-URL mapping mechanisms such as the ONS (Object Naming Service) facility of EPCglobal technological stack for RFID [12] or similar mechanisms based on DNS or HTTP redirection.

In detail, in the proposed framework each resource is characterized by: (a) 96-bit ***ID***, globally unique item identifier (*e.g.*, the 96-bit EPC code for an RFID tag or the 64-bit MAC address –padded to fit the space and to allow different MAC protocols to be distinguished– for a ZigBee sensor); (b) 64-bit ***OUUID***; (c) a set of ***data-oriented attributes***, which allow to integrate and extend logic-based inferences with application-specific and context-aware information processing; (d) ***semantic annotation***, stored as a compressed RDF/OWL document fragment. A homomorphic encoding scheme for XML-based documents [1] is adopted to compress annotations. Homomorphism preserves XML document structure during compression, so enabling query processing directly on encoded annotations, without requiring preliminary decompression. Moving from KBs to u-KBs, the classic functional *Tell/Ask* paradigm is inherited, but it is implemented in a novel fashion. Tell/Un-Tell operations are now hidden to users, *i.e.*, no explicit knowledge declaration/retraction is needed. Knowledge fragments are carried by individual micro devices that populate a smart environment, hence the presence/lack of some of them automatically reveals what is added/retracted to/from the u-KB. An autonomic and adaptive protocol is adopted for knowledge base maintenance and information alignment among network hosts, needing no centralized supervision. Ask operations require a preliminary resource selection. The requester specifies the ontology identifier and range values for attributes it is interested in, so as to reconstruct a local subset of the whole KB, containing only the ontology and individuals which are actually needed. Finally, it is able to submit any Ask-type request to a local or remote reasoning engine.

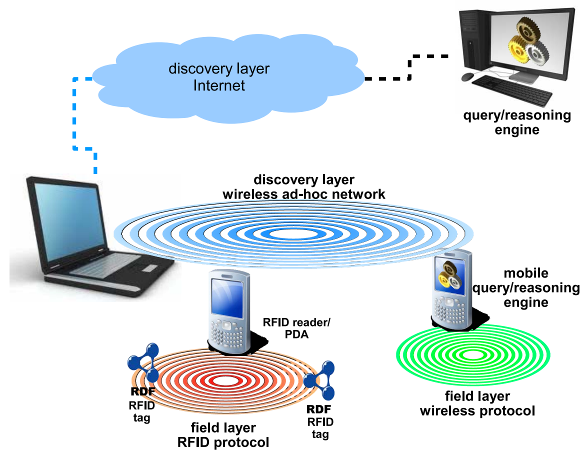

Fig. 2. Proposed SWoT framework architecture

III. Architecture

The proposed framework is featured by a two-level infrastructure as depicted in Figure 2. Pervasive sensing and identification technologies are exploited at the *field layer*, interconnecting embedded micro-devices dipped in the environment with hosts able to extract their data. The *discovery layer* is related to the inter-host communication for knowledge dissemination and retrieval. Each network host acts as a cluster head for field devices in its communication range, using available interfaces (*e.g.*, RFID, ZigBee). Resources acquired at field layer through different protocols are exposed at the discovery layer in a uniform fashion, according to the structure described above. Interaction among hosts is performed by means of a cooperative IP-based protocol for *information dissemination and resource retrieval*. If two nodes are in wireless range or share the same wired transmission medium, the interaction between them can happen directly, otherwise it is necessary to adopt a multi-hop routing by exploiting other nodes as intermediate links. However, a node does not depend on some other ones to advertise/register object descriptions. Resources are autonomously acquired from the field layer and exposed. At the same time, nodes are able to discover them thanks to the preliminary propagation of data each cluster head has seen in its range. In short, the protocol is based on four interaction stages: (1) extraction of resource parameters (for carrying object characteristics from field layer to discovery one); (2) resource information dissemination (diffusion of resource parameters at the discovery level); (3) peer-to-peer collaborative resource discovery; (4) extraction of selected resource annotations (for carrying semantic-based descriptions from field level to the discovery one) to allow semantic-based queries and reasoning. The framework provides common access to information embedded into semantic-enhanced micro-devices populating a smart pervasive environment, while information processing and reasoning tasks can be performed either by local hosts (so enabling semantic-enhanced ubiquitous applications) or by a remote entity through a gateway exposing

Technology	Application scenarios / case studies	Performance evaluation highlights
Bluetooth	Mobile commerce [11]. Peer-to-peer resource discovery [13].	Compression of semantically annotated object descriptions produces a significant speedup on Bluetooth communication performance [12].
EPCglobal RFID	Real-time analysis of product flows [14] and massive semantic stream analytics [15] within the supply chain. Ubiquitous commerce [16] and post-sale customer services [17]. Decision support in healthcare [18].	On-tag semantic annotations do not impair performance of RFID equipment in the field [12].
ZigBee	Mobile semantic computing grids for smart infomobility services [19].	Adequate performance of data dissemination and discovery for small- and medium-sized mobile ad-hoc networks [19].
EIB/KNX	Service discovery and decision support in Home and Building Automation, supporting dynamic home self-configuration [20].	Careful design of system architecture allowed satisfactory response times [20].

TABLE I
MAIN RESULTS IN INTEGRATING PERVASIVE COMPUTING TECHNOLOGIES IN THE PROPOSED SWOT FRAMEWORK

a high-level interface (so integrating the local environment with the Web).

In order to support both semantic annotation exchange and discovery, each communication, identification and sensing technology requires a *semantic micro-layer* for adapting into the framework. Bluetooth, EPCglobal RFID, ZigBee and EIB/KNX (European Installation Bus/Konnex) ISO/IEC standard for Home and Building Automation were enhanced in order to manage semantic object/resource/service annotations referred to a given ontology instead of trivial identifiers. Main results are summarized in Table I. Protocol modifications maintained a backward compatibility in all cases. The integration of semantics at the application level enabled novel resource discovery and decision support features. Smart objects/appliances can self-describe w.r.t. any mobile ad-hoc network they join that supports the proposed framework, advertising managed services/resources via the u-KB model.

IV. CONCLUSION

The paper proposed a theoretical framework for enabling the Semantic Web of Things. Models for knowledge storage and processing are recalled along with infrastructural protocols for information management. Future work will be devoted to validate the approach through widespread case studies. In addition, more sophisticated data management schemes are under investigation to enhance platform-independence and interoperability.

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