A semantic-enabled mobile directory service for RFID-based logistics applications

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***Abstract*—We propose a mobile directory service explicitly devised for pervasive RFID contexts. The registry adopts an OWL-S 1.1 Profile instance annotation of mobile services and resources. Ontology-based metadata are exploited in order to perform a semantic-based service discovery w.r.t. a given request. A case study to support logistics RFID environments is presented along with experimental results on a prototype implementation.**

I. INTRODUCTION

Pervasive computing paradigms aim at increasing the integration of information technology into ordinary human activities in a transparent way for users, reducing the effort and attention required to benefit from computing systems. In classical Human-Computer Interaction (HCI) paradigms, a user perform a task by explicitly operating a single computing device, which then possibly mediates the interaction with other computing systems for information processing and communication. In pervasive computing, on the other hand, the user will receive support by interacting –simultaneously and often implicitly– with many different computing devices in her surroundings. To enable this novel HCI model, computational capabilities are deeply "embedded" into the environment (*i.e.*, into everyday objects and places) for information storage, processing and discovery. For instance, by embedding "knowledge" into semantic-enhanced RFID tags populating a smart environment, discovery and reasoning tasks can be performed to derive implied relationships starting from explicit resource annotations. Such knowledge is then available to both hosts in the local Mobile Ad-hoc NETwork (MANET) and remote entities, through a gateway exposing a high-level interface (*e.g.*, Web Sevices of RPC[1] or REST[2] type. A semantic-based pervasive infrastructure, which is both lightweight and flexible, can enable more agile business solutions to be built and adapted to the ever-evolving needs of modern organizations. Moreover, a general framework for service description and discovery can foster interoperability at the boundary between industry partners.

In [1] we devised a framework and protocol for the integration of semantic-enhanced EPCglobal[3] RFID into Bluetooth-based MANETs. The proposed solution, however, relied on a central component for reasoning over a Knowledge Base (KB). The computational resource requirements of reasoning engine were too large for mobiles device, hence it was deployed on a fixed server and became a single point of failure for the system. That approach nevertheless enabled objects equipped with RFID tags to accurately describe themselves w.r.t. "rest of the world" in a self-contained fashion. While we achieved a strong decentralization of factual knowledge by storing individual annotations in RFID tag memory banks, reasoning services were provided only by fixed Bluetooth hotspots. In this contribution we show how the pervasiveness of the system can be enhanced if a more decentralized and distributed approach is followed.

In previous contributions [2], the basic discovery features of *UDDI* were extended with semantic-based capabilities. In this work we optimize and adapt the approach to pervasive RFID contexts, proposing a mobile directory service developed by extending the open source *jUDDI*[4] implementation. The proposed solution adapts Knowledge Representation (KR) techniques to volatile and resource–constrained pervasive computing scenarios. The system adopts an OWL-S 1.1 Profile instance [5] annotation of mobile services and resources. Ontology-based metadata are used to perform a semantic-based discovery of advanced services w.r.t. a given request. In particular, advanced matchmaking can be carried out exploiting metadata stored in RFID tags, without any central and fixed reasoning engine. RFID readers are used as semantic-based *field data collectors* w.r.t. tags in their radio range and they are able to automatically perform a service discovery without wired intermediaries. The mobile directory service exploits an m-DBMS (Oracle 10g Lite [3]) for efficient retrieval and processing of service descriptions. Due to the complexity of OWL DL[6], a simplification of ontologies and class descriptions was devised: (1) a subset of OWL DL was selected as reference logic formalism; (2) allowed ontology structure was constrained according to well–studied theoretic results in KR. The chosen approach allows standard reasoning tasks (*i.e.*, subsumption and consistency check) to be reduced to set comparison, so downscaling the

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[1] Remote Procedure Call
[2] REpresentational State Transfer
[3] EPCglobal consortium, http://www.epcglobalinc.org
[4] Apache Software Foundation, *jUDDI*, http://ws.apache.org/juddi/
[5] OWL-S: Semantic Markup for Web Services, http://www.daml.org/services/owl-s/1.1/overview/
[6] OWL Web Ontology Language, W3C Recommendation 10 February 2004, http://www.w3.org/TR/owl-features/

computational demand of inference algorithms to meet current capabilities of handheld computing devices.

The proposed approach has been implemented and evaluated within an RFID-based logistics application scenario. Adopted design choices provide flexibility in architecture adaptation to application–specific requirements. Moreover, reuse of Semantic Web standards can simplify the integration of the proposed framework in larger information infrastructures. In what follows both implementation details and experimental results are presented.

The remaining of the paper is structured as follows. Section II introduces the state of the art in the area of service discovery in pervasive environments, then Section III elaborates on motivation of the proposed approach. Section IV describes the proposed architecture and algorithms, as well as their integration in the OWL-S 1.1 framework. Section V reports a case study illustrating the approach and the rationale behind it, whereas Section VI outlines system implementation and obtained experimental results. Conclusion closes the paper.

II. STATE OF THE ART

Radio-Frequency IDentification (RFID) technology is attracting growing attention in industry and commerce as a pivotal element to interface objects in the physical world with organizational information infrastructures [4]. Basically, RFID solutions are based on: **(i)** transponders to store data (*tags*), which are attached to objects to be identified; **(ii)** interrogators (*readers*) that scan tags in the environment and access their contents. Supply chain management and asset tracking are currently prevalent applications [5]. In recent years, worldwide standardization efforts for RFID technology have been seeking to promote interoperability among business partners.

Low-cost tags can be attached to objects unobtrusively, preserving their normal appearance and functions. They usually contain a unique item identification code, which can be read by readers. Reader devices are usually integrated in handheld devices or in passages such as doors and gates. The ID code is then used as a key to retrieve relevant information about the tagged item from an information server through a fixed network infrastructure. Hence, RFID technology is currently used as a link between physical objects and their so-called "virtual counterpart" [6], *i.e.*, their representation in computing systems.

This approach suffers from two major shortcomings if applied to mobile and pervasive computing environments, which are characterized by heterogeneity and volatility. RFID-based applications depend on a support infrastructure with stable network links and centralized information servers. In pervasive contexts, on the contrary, the location of nodes could change frequently and unpredictably, so that services/resources may become unavailable without prior notice. Furthermore, RFID standards allow only string matching for item identification. Syntactic match of encoded attributes is a common approach in traditional service discovery protocols, such as *SLP* (Service Location Protocol), *Jini*, *UPnP* (Universal Plug aNd Play), *UDDI* (Universal Description Discovery and Integration) and Bluetooth *SDP* (Service Discovery Protocol). They typically involve *requesters*, a *directory service* (or lookup registry) and resource *providers*. They work in a fundamentally similar way, providing primitives for resource registration and lookup, together with a matching mechanism. A requester issues a query to the registry (or directly to a resource provider). The query may contain a resource identifier and/or one or more attributes to be searched for. The service registry (resp. the resource provider) checks the query pattern against stored services descriptions and it replies with identification and location of matching services.

The main advantage of string matching is simplicity, which has made it suitable to resource-constrained mobile environments. Nevertheless, purely syntactic match mechanisms cannot support more advanced wireless applications, since they provide only boolean "yes/no" outcomes. It is desirable to manage requests and service descriptions with richer and unambiguous meaning [7], by adopting formalisms with well-grounded semantics. An agreement on shared vocabularies to describe services is also important for context-aware pervasive computing scenarios involving several independent partners.

Wireless communication technologies and mobile computing systems are approaching sufficient maturity to overcome the above limitations. In particular, an advanced mobile directory service should be able to support non-exact matches [8] and to provide a ranked list of discovered resources or services. This allows satisfaction of a user request "to the best possible extent" whenever fully matching resources/services are not available. A decentralized approach is also important for applications aiming to be really pervasive. In RFID-based environments, a major issue is seen in the high cost of transponders equipped with sufficient memory to store accurate item descriptions. Nevertheless, the growing demand of RFID equipment and the progress in microelectronics allow to expect that tags with larger memory amounts will be available at competitive costs in few years [9].

Our approach borrows and adapts ideas and technologies from the Semantic Web effort in order to support flexibility in dynamic and decentralized service discovery protocols. In a previous work [1], a fully backward-compatible extension of the EPCglobal standard for UHF tags and protocol was proposed with semantic-based capabilities. An RFID tag could then store a rich description, expressed in ontological languages based on Description Logics (DL) [10]. Integration at the application layer with a semantic-enhanced version of Bluetooth discovery protocol, so tagged objects dipped into Bluetooth mobile ad-hoc networks could be dynamically discovered based on the degree of correspondence between their characteristics and a user request. As part of the solution, a compression algorithm was introduced for semantically annotated object descriptions, in order to cope with the limited storage and transmission capabilities of RFID systems.

A. Related research work

Many research efforts have exploited in novel ways the identification and monitoring capabilities of RFID [6], [11],

[12]. Nevertheless, they are based on the “virtual counterpart” approach, which greatly limits mobility and pervasiveness. To the best of our knowledge, our proposal represents the only framework devised specifically for pervasive RFID applications where item identification is not enough. In [13] a ubiquitous architecture is presented for tracking products in real-time to support logistic processes and B2B transaction management. A global and persistent IT infrastructure is required in order to interface RFID systems of partner organizations through the Internet. This makes the approach unsuitable to MANET environments. As a further limitation, adopted discovery protocols only support exact matches through code-based formats, with no explicit semantics of object characteristics.

The computational resources required by advanced matchmaking algorithms still remains an open issue in fully mobile and decentralized scenarios. In our system prototype for ubiquitous commerce [1], resource matchmaking was executed by a fixed Bluetooth hotspot running a DL inference engine, because inference procedures are inherently resource-intensive for expressive logical languages. The mobile directory service proposed in this paper aims at a trade-off between matching complexity and expressive possibilities of the language. To the best of our knowledge, Pocket KRHyper [14] is currently the only available DL-based reasoning engine for mobile devices. It provides consistency and subsumption inference services, exploited by authors in a matchmaking facility between user profiles and descriptions of resources/services [15]. The proposed approach allows comparable expressiveness of service descriptions w.r.t. ours, but the former does not support non–exact matches and result ranking.

III. MOTIVATION

Motivation for this work comes from previous efforts at exploiting languages with formal semantics in really pervasive environments [16]. By annotating objects directly through RFID tags which store metadata along with subsidiary product information, each object can self–expose its relevant characteristics to nearby computing devices, and advanced semantic–based services can be provided on–demand through dynamic wireless MANET infrastructures. In traditional applications of Knowledge Representation Systems (KRS), however, automated inference procedures are typically executed on a fixed server in order to extract implicit knowledge from the one stated in a centralized KB. Hence a reasoner is viewed as a software entity which is immediately available, either locally or via a high-throughput network link. This approach is effective only as long as large computing resources and a stable network infrastructure are granted. A different approach is required to adapt KR tools and technologies to mobile computing applications and pervasive business infrastructures. They are characterized by user (and device) mobility, dependency on context, severe resource limitations. Knowledge-based systems designed for wired networks are hardly adaptable, due to architectural differences and performance issues. Our goal is therefore to build a key element of such envisioned architecture, namely a mobile directory service providing suitable services to perform a discovery directly starting from the data collected at the field level via RFID, only considering objects disseminated within the environment. In this manner reasoning tasks can be performed by wireless nodes endowed with reduced computational capabilities and the requirement of a dependable support infrastructure for inference can be removed.

Several application areas of RFID technology [5] can be enhanced by introducing a semantically rich object description as well as a discovery layer, able to provide advanced services in a wireless context. In particular, asset management can be greatly improved in those scenarios where retrieval should be based on relevant object properties and purposes, rather than mere identification codes. Let us consider the lifecycle of industrial products. Manufacturing and quality control can exploit accurate descriptions of raw materials, components and processes. Supply chain management benefits from improved item tracking and the verification of multi-factor service level agreements between commercial partners can be automated. Sale depots benefit from easier inventory management and can introduce u-commerce (ubiquitous commerce) capabilities [1] without expensive investments in infrastructure. Finally, smart post-sale services can be provided to purchasers, by integrating knowledge discovery and reasoning capabilities in various appliances [17].

IV. FRAMEWORK

The proposed framework is based on a two-level architecture. RFID is used at the **field layer** (interconnecting readers and tags dipped in the environment), whereas **discovery layer** enables communications between a reader and another mobile host in the wireless context, playing the role of a mobile directory service. Figure 1 shows the structure of the proposed discovery architecture in comparison with traditional approaches (initially devised for the Web and progressively refined for pervasive applications). Both the communication between the tag field and the related reader and the one between reader and other mobile devices are based on a radio channel, but the first one exploits the semantic-enhanced EPCglobal RFID protocol data exchange [17], whereas the mobile directory service can be queried via a semantic-enhanced Bluetooth Service Discovery Protocol [18].

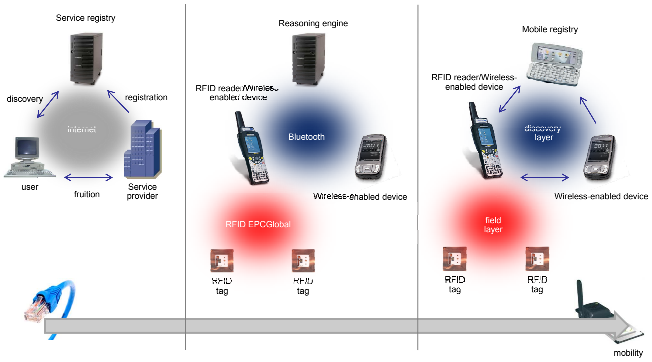

Fig. 1. Evolution of service discovery architectures

By means of the proposed discovery framework, the requester can start her service discovery moving from object properties and features (so directly taking into account item annotations) to retrieve appropriate services and/or resources. Actually service discovery proceeds from the object level (field layer) to the user one. This approach allows to extract the knowledge "embedded" in the environment to perform the discovery from the tagged objects without fixed coordination or manipulation, so permitting truly pervasive applications.

Mobile hosts that run the directory service maintain a registry containing the managed services and resources; they are involved in the discovery process as lookup services. RFID readers retrieve semantic metadata from tagged objects and exploit them to address requests toward nearby mobile directories to discover further services [7]. In the proposed approach, there is no need for wired reasoning centres. RFID readers play a fundamental role in the whole service oriented architecture as they (i) collect descriptions and contextual parameters referred to tags in their radio range (at the field layer) and (ii) forward composed requests via Bluetooth (at the discovery layer) to a directory node in their proximity, waiting for a reply.

In what follows the discovery layer is described in greater depth, showing the structure and functionality of the mobile registry-based directory service. For the sake of brevity, the reader is referred to the semantic-enhanced RFID protocol proposed in [17] for features and details of the field layer.

A. Background

In this subsection, preliminary notions are introduced about the adopted language and reasoning tasks.

Language. In order to reduce computational cost due to the full expressiveness of OWL DL, a subset of OWL DL was selected to represent mobile service descriptions and requests in the OWL-S framework, where ***class descriptions*** consist of:

- class identifier (a URI reference);
- `owl:complementOf` class identifier;
- datatype property restriction;
- the intersection of two or more class descriptions.

Furthermore, ontologies are bound to adhere to the *simple-TBox* conditions defined in Description Logics literature [19]: (i) all the axioms in ontologies are bound to contain a class identifier only in their left hand side; (ii) only one `rdfs:subClassOf` or `owl:equivalentClass` axiom is allowed for each class identifier; (iii) for `owl:disjointWith` axioms, both left hand side and right hand side are class identifiers such that they do not appear as left hand side of any `owl:equivalentClass` axiom. Possible axioms are then in the form:

- *class identifier* `rdfs:subClassOf` *class description*
- *class identifier* `owl:equivalentClass` *class description*
- *class identifier* `owl:disjointWith` *class identifier*

With these positions, standard ontology reasoning tasks such as subsumption and consistency check can be reduced to set comparison, with drastically lower computational costs. Given two class descriptions –*e.g.*, a mobile service description MSD and a query Q– and an ontology $\mathcal{T}$(for Terminology), proceed as follows:

```
For each class identifier $C$ in $MSD$ and $Q$:
    if the axiom $C$ rdfs:subClassOf $D$ is in $\mathcal{T}$
        then recursively rewrite $C$ as
        owl:intersectionOf $\{C, D\}$;
    if the axiom $C$ owl:equivalentClass $D$ is in $\mathcal{T}$
        then recursively replace $C$ with $D$;
    if the axiom $C$ owl:disjointWith $D$ is in $\mathcal{T}$
        then recursively rewrite $C$ as
        owl:intersectionOf $\{C,$ owl:complementOf $D\}$;
```

After this preprocessing step, known as *unfolding* [10], both MSD and Q are rewritten as a conjunction of class identifiers, negated class identifiers and datatype property restrictions.

Subsumption. In order to verify whether MSD is **subsumed by** (is more specific than) Q, just check if for each conjunct C_i in Q, C_i is also a conjunct of MSD.

Disjointness. If one wants to check whether Q and MSD are **disjoint with each other**, it suffices to check if there exists a class identifier C_i in Q such that `owl:complementOf` C_i is a conjunct of MSD (or vice versa).

In other words we consider the conjunction of elements in Q and MSD and, in general, in every class expression allowed by the language we chose, as sets of elements.

Concept Abduction. With this set-based formalization, also solutions to a **concept abduction problem** (CAP) [20] can be easily computed. Basically, a CAP can be described as: given two class descriptions MSD and Q, such that MSD is not subsumed by Q –*i.e.*, the mobile service description does not completely satisfy the query– hypothesize a class expression H representing what is underspecified in MSD in order to be more specific than (subsumed by) Q. From an operational point of view, for each conjunct C_i in Q, check if C_i is also a conjunct of MSD. If not, hypothesize C_i and add it to H. We write $H = solveCAP(MSD, Q)$ to indicate that H is what has to be hypothesized and added to MSD in order to completely satisfy the request Q.

Actually, minimality criteria on the size of H have to be defined and adopted in order to avoid trivial and redundant solutions. In particular, for class expression represented as a conjunction of elements in [20] *irreducible solutions* are defined as solutions that are minimal w.r.t. the number of conjuncts (taking into account also the axioms in the ontology $\mathcal{T}$). *Rank potential* is then defined as a measure for abduction-based ranking of several services w.r.t. a given Q. In the subset of OWL DL adopted here, it is easily computed as the number of conjuncts in H, *i.e.*, $R_{pot}(MSD, Q) = |H|$ being $H = solveCAP(MSD, Q)$ [21].

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[7] Notice that a reader can itself play the role of directory service w.r.t. resources/services simply running an instance of the application.

B. Architecture details

The mobile directory service copes with OWL-S based annotation of mobile services/resources. Each service/resource specification is modeled as an OWL-S 1.1 Profile instance.

System implementation allowed to validate the approach, test algorithms behavior and carry out experiments. The main component of the system is the **Service Selector** module. It performs the discovery of services via an m-RDBMS and computes a ranked list taking into account incomplete or missing information. Functionalities of a reasoner (as in [16]) are substituted –to some extent– with structured queries over a database. Recall that the relational model –due to its intrinsic structure– allows to establish well-known relationships among generic entities. Hence it can be correctly exploited to extract new information from a simple-TBox, starting from the one stated within a specific resource instance. The proposed E-R model consists of the following tables.

- **`Parents_0`** table is built after an analysis of the OWL ontology. It contains all the first degree "parent/child" relationships, also expressed by means of possible properties.
- **`Parents_i`** table (i=1..N) are built expanding all the relationships of order higher than one among concepts. `Parents_i` is derived joining `Parents_i-1` and `Parents_0`.
- **`Ancestors`** table is built by joining all the `Parent_i` (i=0..N) and resumes all the subsumption relationships among concepts in the ontology.
- **`Resources`** table collects service/resource descriptions. Each tuple will contain a component concept with a possible role.
- **`Normalized`** table is obtained joining **`Resources`** and **`Ancestors`** tables. It will contain all the relationships among service/resource instances and related parents.

Due to the sublanguage we use to model ontologies, service descriptions and queries, the proposed model is able to cope with a discovery procedure which is the basic feature of *Service Selector*. The information stored within the database is used to compute on the fly the "unfolded" version of Q and of mobile service descriptions. These unfolded class descriptions are then used to solve corresponding concept abduction problems as described in Subsection IV-A. The adopted algorithm is outlined hereafter. Discovery procedure receives in input the set of conjuncts in Q. They are considered individually and for each of them all the parents within the `Ancestors` table are extracted. The corresponding query is:

```
SELECT parent
FROM Ancestors
WHERE child = <component concept>
```

This collection of parents will be then used for selecting from `Normalized` table services that contain, in their semantic annotation, at least a class among them within the just created set. The corresponding query is:

```
SELECT service
FROM Normalized
WHERE class IN (<parent list>)
```

V. CASE STUDY

Characteristics and benefits of the proposed framework are discussed in an advanced logistics scenario, namely the *operational control system* for a warehouse. It performs low-level decision processes such as the destination of each incoming container. The main goals are efficient space usage and assignment of the area that best fits storage requirements for the particular product or material in each container.

Exploiting our approach, semantic-enabled RFID tags can be attached to products at different packaging levels: item, case and pallet. Item-level tags may contain detailed product descriptions, which are mostly useful in manufacturing and sale stages [17], while pallet-level tags may contain other types of assertions (possibly expressed w.r.t. a different ontology) specifically related to transportation and storage. This kind of knowledge can be then used to control logistic operations. Our semantic-enhanced RFID protocol allows to select only semantic-enabled tags, while preserving standard capabilities for filtering tags based on logistic unit type through EPC code fields. The two functions can be combined, so that readers in a warehouse can preselect semantic-enabled pallet tags only. This greatly reduces the number of tags to be inventoried, so enabling to meet real-time processing requirements of logistic applications.

A simplified domain ontology was developed for this case study. It models product macrocategories and storage conditions, which may be required by products and provided by warehouse areas. Figure 2 reports a portion of its axioms to help understand the following example (classic logic-based formalism is adopted for better readability).

The considered scenario is summarized hereafter: *A seaport warehouse comprises several departments, both indoor and outdoor. Each department is further divided into storage areas. Vans deliver cargos from the hinterland for overseas shipments. The warehouse supports semantic-enhanced RFID technology, with a gate reader at each entry point. Annotated RFID tags are attached to product containers and pallets, describing primary product category and required storage conditions.*

A van is delivering a cargo of insulin for clinical use. It is a pharmaceutical product requiring freezing, low humidity and indirect lighting for proper preservation. A conveyor belt and shelving are also requested for stocking, as well as an access control system for security purposes. This can be expressed w.r.t. our reference ontology as:

R: $Pharmaceutical \sqcap Freezing \sqcap Low\_Humidity \sqcap Indirect\_Lighting \sqcap Conveyor\_Belt \sqcap Shelving \sqcap Access\_Control$

Such description is stored in encoded form onto the container's RFID tag. Upon entry, the gate interrogator reads the tag and matches its description with those of the warehouse departments, in order to route the van to a compatible one.

Descriptions of warehouse departments are stored in the interrogator's mobile registry, so it can work as a semantic-based directory. The first inference stage is a simple sub-

Chemical_Product ⊑ Product
Manufactured_Product ⊑ Product
Edible_Product ⊑ Product
Edible_Product ⊑ ¬Chemical_Product
Edible_Product ⊑ ¬Manufactured_Product
Chemical_Product ⊑ ¬Manufactured_Product
Pharmaceutical ⊑ Chemical_Product
Equipment ⊑ Storage_Requirement
Transport_Equipment ⊑ Equipment
Crane ⊑ Transport_Equipment
Conveyor_Belt ⊑ Transport_Equipment
Stocking_Equipment ⊑ Equipment
Pallet_Rack ⊑ Stocking_Equipment
ISO_Pallet_Rack ⊑ Pallet_Rack
Shelving ⊑ Stocking_Equipment
Metal_Shelving ⊑ Shelving
Plastic_Shelving ⊑ Shelving
Location ⊑ Storage_Requirement
Indoor ⊑ Location
Outdoor ⊑ Location
Outdoor ⊑ ¬Indoor
Lighting_Source ⊑ Storage_Requirement
Indirect_Lighting ⊑ Lighting_Source
Direct_Lighting ⊑ Lighting_Source
Direct_Lighting ⊑ ¬Indirect_Lighting
Lighting_Type ⊑ Storage_Requirement
Fluorescent_Light ⊑ Lighting_Type
Incandescent_Light ⊑ Lighting_Type
Fluorescent_Light ⊑ ¬Incandescent_Light
Temperature ⊑ Storage_Requirement
Room_Temperature ⊑ Temperature
Refrigeration ⊑ Temperature
Cold_Temperature ⊑ Refrigeration
Freezing ⊑ Refrigeration
Room_Temperature ⊑ ¬Refrigeration
Humidity ⊑ Storage_Requirement
Natural_Humidity ⊑ Humidity
Controlled_Humidity ⊑ Humidity
Controlled_Humidity ⊑ ¬Natural_Humidity
Low_Humidity ⊑ Controlled_Humidity
Very_Low_Humidity ⊑ Low_Humidity
Security_Measure ⊑ Storage_Requirement
Video_Surveillance ⊑ Security_Measure
Access_Control ⊑ Security_Measure
Biometric_Identification ⊑ Access_Control
Unlocking_Device ⊑ Access_Control
RFID_Badge ⊑ Unlocking_Device
Magnetic_Badge ⊑ Unlocking_Device

Fig. 2. Axioms in the example warehousing ontology used in the case study

Supply	Compatibile (Y/N)
Dep. A	N
Dep. B	N
Dep. C	Y

TABLE I
RESULTS OF THE FIRST INFERENCE STAGE

Supply	Residual volume (m^3)	Match outcome	Rank potential	Overall rank
Area C1	-1.0	Discarded	N.A.	N.A.
Area C2	0.7	Hypothesis: $H = \top$;	0	1^{st}
Area C3	0.5	Hypothesis: $H = Shelving$ $\sqcap Conveyor\_Belt$	2	3^{rd}
Area C4	2.5	Hypothesis: $H = \top$;	0	2^{nd}

TABLE II
RESULTS OF THE SECOND INFERENCE STAGE

sumption test between product requirements and department facilities. Outcomes are sent to the mobile computing device within the van via Bluetooth. Let us suppose that the following departments exist in the warehouse:

A: indoor department for edible products, with refrigeration and low humidity:

$Edible\_Product \sqcap Indoor \sqcap Low\_Humidity \sqcap Refrigeration$

B: outdoor department for manufactured products, with natural humidity and temperature:

$Manufactured\_Product \sqcap Outdoor \sqcap Room\_Temperature \sqcap Natural\_Humidity$

C: indoor department for chemical products, with very low humidity and freezing facility:

$Chemical\_Product \sqcap Indoor \sqcap Very\_Low\_Humidity \sqcap Freezing$

Notice that department descriptions contain only the main features. This level of detail is sufficient for early decision making, while the Open World Assumption allows further information to be specified later for individual storage areas.

Result of the first matchmaking step is reported in Table I. Only department C is compatible with the cargo, according to the domain ontology.

The van is routed to department C. Upon arrival, the insulin pallet is unloaded. Warehouseman picks up the pallet with his forklift, which is endowed with a portable RFID reader. It scans the pallet tag and reads the semantically annotated description. Reader collects descriptions for each storage area from the first available Bluetooth hotspot in the department. Then it executes matchmaking locally, to select the best storage area having sufficient available space.

Let us suppose that total pallet volume is 2.5 m^3 and also that department C contains the following storage areas:

C1: indoor storage area (available volume is 1.5 m^3) equipped with ISO-compliant pallet rack and conveyor belt for stocking, storing items at refrigerated cold temperature and low humidity, with indirect fluorescent light source:

$Indoor \sqcap ISO\_Pallet\_Rack \sqcap Conveyor\_Belt \sqcap Cold\_Temperature \sqcap Low\_Humidity \sqcap Indirect\_Lighting \sqcap Fluorescent\_Light$

C2: indoor storage area (available volume is 3.2 m^3) equipped with biometric identification for security, metal shelving and conveyor belt for stocking, storing items at freezing temperature and very low humidity, with indirect fluorescent light source:

$Indoor \sqcap Biometric\_Identification \sqcap Metal\_Shelving \sqcap Conveyor\_Belt \sqcap Freezing \sqcap Very\_Low\_Humidity \sqcap Indirect\_Lighting \sqcap Fluorescent\_Light$

C3: indoor storage area (available volume is 3.0 m^3) equipped with RFID badge readers for access control, a crane for stocking items, freezing temperature and low humidity, with indirect incandescent light source:

– $Indoor \sqcap RFID\_Badge \sqcap Crane \sqcap Incandescent\_Light \sqcap Indirect\_Lighting \sqcap Freezing \sqcap Low\_Humidity$

C4: indoor storage area (available volume is 5.0 m^3) equipped with RFID badge readers for access control, with a plastic shelving and conveyor belt for stocking, storing items at freezing temperature and low humidity, with indirect fluorescent light source:

$Indoor \sqcap RFID\_Badge \sqcap Plastic\_Shelving \sqcap Conveyor\_Belt \sqcap Freezing \sqcap Low\_Humidity \sqcap Indirect\_Lighting \sqcap Fluorescent\_Light$

Areas with insufficient free volume are discarded before matchmaking to avoid unnecessary processing. Remaining ones are ranked based on (i) increasing rank potential score and (ii) increasing residual volume. Since rank potential is a measure of semantic distance, the lower the better. Residual volume is computed as the difference between available volume in an area and volume of the pallet to be stored. Favoring areas with lower residual free space is an allocation policy that aims at minimizing wasted space (classically proposed also for the memory allocation problem in operating systems theory).

Table II reports matchmaking results for our example. Area C1 is discarded before semantic-based matchmaking, since it has insufficient free volume. Both C2 and C4 fully satisfy product storage requirements; C2 is ranked first as it has smaller residual volume. C3 is ranked last, since it does not explicitly satisfy the requirements of shelving and conveyor

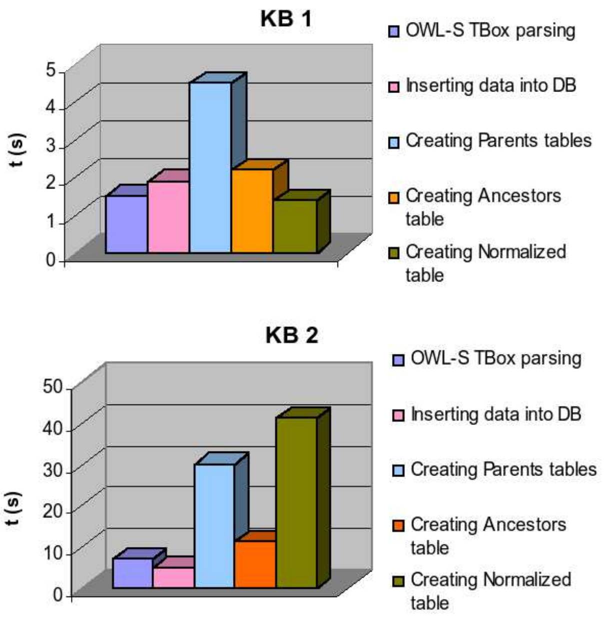

Fig. 3. Time consumption of bootstrap phase

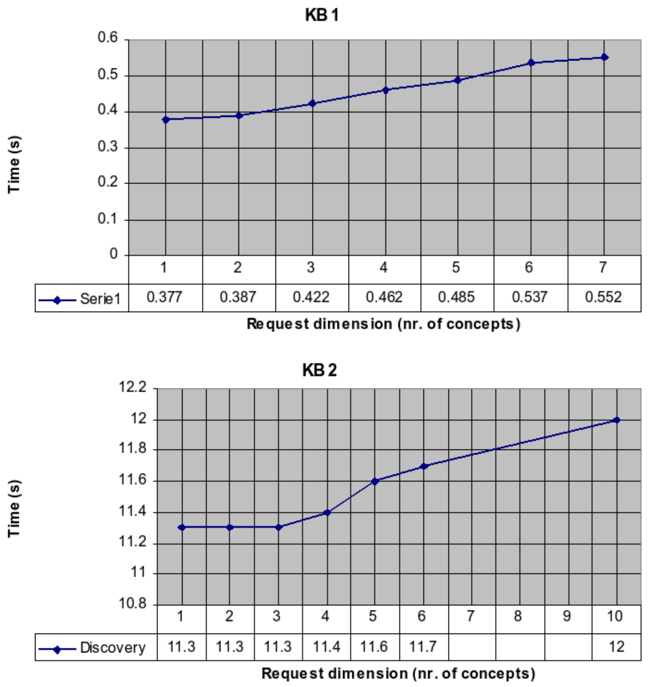

Fig. 4. Time progression of discovery process w.r.t. request size

belt.

The warehouseman's mobile device shows area C2 as the best storage area for the insulin pallet.

The example shows that the proposed mobile directory service can correctly support non–trivial tasks of practical interest, even though it allows limited language expressivity. Our decentralized matchmaking framework can be easily applied to other logistic problems, such as directing garaging and maintenance operations in vehicle or aircraft depots.

Finally, it is useful to remark that our prototype adopts Bluetooth connectivity for communications, but the framework is general and hence applicable also to wireless networks based on other technologies, such as IEEE 802.11.

VI. SYSTEM IMPLEMENTATION AND EXPERIMENTS

The proposed approach has been implemented and tested on an HP iPAQ 2210h PDA[8]. Tests have been conducted with the aim of assessing the order of magnitude of time consumption of the implemented system. This evaluation can give only partial view of real-world application behavior, but it provides an insight into the feasibility of the proposal.

Two different ontologies (not reported for brevity) have been used for tests. The first one (labeled as *Onto1*) contains approximately 50 among classes and properties. The second one (labeled as *Onto2*) contains approximately 100 among classes and properties. The number of service instances is 6 for *KB1* referred to *Onto1* and 33 for *KB2* referred to *Onto2*. Figure 3 reports time consumption for the *bootstrap phase* (comprising the mapping of both the ontology and the individuals into database tables). Then an average time progression of discovery procedure w.r.t. size of request (in terms of conjuncts number) is reported in Figure 4.

A general comparison of bootstrap phase duration against the discovery one (computed in the worst case, *i.e.*, attempting a discovery given a 10 concepts request exploiting *Onto2*) points out that the former prevails, as depicted in Figure 5. Time consumption for mapping the Knowledge Base into the DB is relevant and in particular the creation of `Parents_i` and `Normalized` tables takes up most of bootstrap time. Due to this important limitation, mapping operations are performed only after ontology agreement and only if necessary. That is the KB mapping is a preprocessing stage preliminary w.r.t. the further service discovery. Hence, it happens only the first time a mobile directory has to exploit a specified KB. As long as the registry is the same application context, it will preserve the previously mapped KB and new discovery sessions will be performed only mapping the given request.

The application shows an overall good response in terms of delay in the interactions between requester and mobile directory. For a thorough analysis, a complete comparison w.r.t. a fixed reasoner should be provided. In our previous implementations *MAMAS-tng*[9] matchmaker was adopted, but it is surely an uncorrect term of comparison because of its deep diversity deriving from the allowed expressiveness of the managed formalism. More correctly, analogies are identifiable in jUDDI directory servers on the web. With respect to them, the proposed application shows a better quality of the provided service discovery feature and furthermore a concrete

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[8] All tests have been performed using a fully charged battery for the PDA

[9] http://sisinfab.poliba.it/MAMAS-tng/

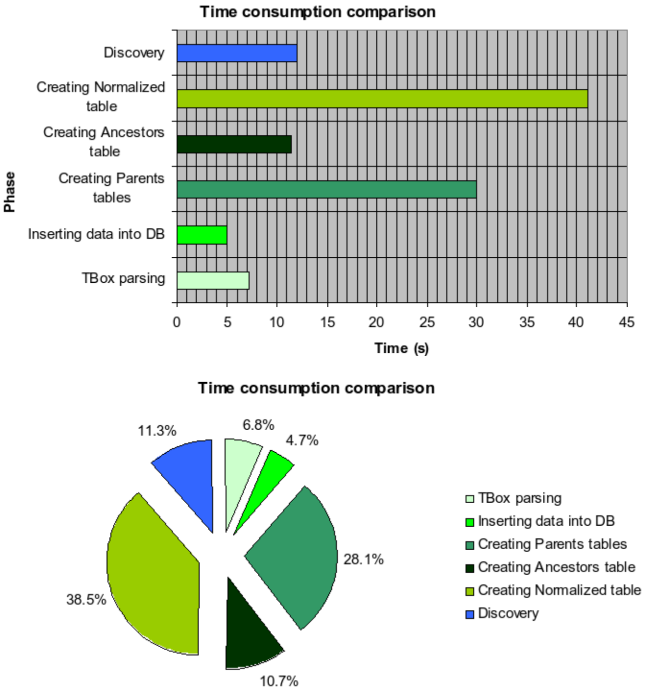

Fig. 5. Time consumption general comparison

applicability to mobile volatile scenarios.

VII. CONCLUSION

Building on our previous work, we have presented a cross-protocol approach to carry out advanced service discovery exploiting semantic metadata stored in RFID tags without wired and computationally heavy reasoners. A mobile directory service based on an m-DBMS as Oracle 10g Lite is adopted to surrogate the presence of a centralized engine. The registry adopts an OWL-S 1.1 Profile instance annotation of mobile services and resources. RFID readers are considered as field data collectors. They are able to retrieve semantic annotations coming from tags in their radio range and automatically address a service discovery request without wired intermediaries. The feasibility of the proposed framework has been tested by means of a prototype for a logistics case study where functionality tests have been carried out. Future work is aimed at extending the approach with composition and substitutability features as well as to a thorough comparison of performances w.r.t. the ones obtainable by means of traditional approaches, and to adoption of other recent service description frameworks.

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