

Ubiquitous Knowledge Bases for the Semantic Web of Things

Michele Ruta¹, Floriano Scioscia¹, Eugenio Di Sciascio¹, Domenico Rotondi²

¹Politecnico di Bari

²TXT e-solutions S.p.A.

E-mail: {m.ruta, f.scioscia, disciascio}@poliba.it, domenico.rotondi@txtgroup.com

1. INTRODUCTION

The *Semantic Web of Things* (SWoT) is an emerging vision in Information and Communication Technology, joining the Semantic Web and the Internet of Things. The *Semantic Web* initiative (Berners-Lee, Hendler & Lassila, 2001) aims to allow software agents to share, reuse and combine information available in the World Wide Web. The *Internet of Things* vision (International Telecommunication Union, 2005) promotes on a global scale the *pervasive computing* paradigm, which aims to embed intelligence into ordinary objects and physical locations by means of a large number of heterogeneous micro-devices, each conveying a small amount of information. Consequently, the goal of the Semantic Web of Things is to embed semantically rich and easily accessible information into the physical world, by enabling storage and retrieval of annotations from such tiny smart objects.

The SWoT vision has significant impact also on human-computer interaction models, with the goal of reducing the amount of user effort and attention required in order to benefit from computing systems. This applies also to computer-computer interaction: traditional Internet-based applications (email, Web browsing, VoIP) adopt a *node-centric* conversational model, allowing a host to address another one and establish a connection. In contrast, in pervasive computing user agents –running on personal mobile computing devices– should be able to interact simultaneously with many embedded micro-devices and other network nodes, extracting data from objects deployed into the environment. Such data should be automatically processed in a context-aware way, in order to better support the current activity of a user and satisfy her needs in an automated and unobtrusive fashion, with the user even not necessarily aware of specific device interactions.

Consequently, the SWoT calls for pervasive knowledge-based systems that achieve high degrees of autonomic capability for information storage, management and discovery, also providing transparent access to information sources in a given area. This implies necessarily an *information-centric* (a.k.a. data-centric, content-centric) network infrastructure (Jacobson et al., 2009a), where information resources, not hosts, are at the core of protocol design. While research in sensor networks has already shown (Intanagonwiwat, Govindan, & Estrin, 2000) that a content-centric approach is more effective than a node-

centric one for information exchange in resource-constrained and volatile contexts, this is becoming true even for the Internet itself. Moreover trends in Internet and Web usage show that *what* is being exchanged is becoming more important than *who* are exchanging information (Trossen, Särelä, & Sollins, 2010). In information-centric networks, and particularly in mobile and dynamic environments such as the SWoT ones, resource discovery becomes a pivotal feature. Nevertheless, current mobile and information-centric discovery paradigms employ elementary “string matching” of encoded resource attributes, which results largely unsuitable for advanced applications. Ideas and technologies borrowed from the Semantic Web vision may allow to overcome these limitations, since the formal Knowledge Representation (KR) foundations and the Linked Data guidelines for information sharing (Bizer, Heath & Berners-Lee, 2009) provide common vocabularies to describe resources and express requests. In this paper the *ubiquitous Knowledge Base (u-KB)* is proposed, a semantic content-centric framework enabling to build cooperative environments where autonomous objects can be discovered, queried and inventoried in a peer-to-peer, collaborative framework, without requiring a central control and coordination. The proposed framework includes a general architectural model bridging Mobile Ad-hoc Networks (MANETs) for pervasive computing to the Internet, as well as a peer-to-peer distributed application-layer protocol for dissemination and discovery of knowledge. Information is gathered through different identification and sensing technologies to be exploited by inference engines and semantic-aware applications, in either pervasive or Web contexts, through a uniform set of operations. RDF (Resource Description Framework, W3C Recommendation 10 February 2004, <http://www.w3.org/TR/rdf-primer/>) is adopted as language for resource annotation w.r.t. RDFS (RDF Schema, W3C Recommendation 10 February 2004, <http://www.w3.org/TR/rdf-schema/>) vocabularies, so allowing semantic-based applications to leverage querying, reasoning and matchmaking tools, based on formal logics, originally conceived for the Semantic Web effort. These design choices provide flexibility in architecture adaptation to specific application requirements.

In the next section motivation for the work and possible application scenarios are provided. Architectural aspects of the approach are detailed in Section 3, as

well as the data propagation and resource retrieval protocol. In Section 4 relevant related work is discussed, outlining the main technological issues that the design decisions for the proposed framework seek to address. Conclusion closes the paper.

2. MOTIVATION

Each resource in the semantic-enabled Web –not only documents, but any entity of interest such as people, institutions, common knowledge topics, etc.– can be annotated, using semantic web languages, with respect to a reference vocabulary. Both languages and vocabularies are based on Knowledge Representation models and formalisms. In the majority of current applications –see Section 1.5 of (Baader, Calvanese, Mc Guinness, Nardi & Patel-Schneider, 2002) for a survey– Knowledge Representation Systems (KRSs) are used as single fixed entities which are immediately available for information queries and updates, either in local storage 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 needed to adapt KR tools and technologies to functional and non-functional requirements of mobile and pervasive computing applications. They are characterized by severe resource limitations, user and device mobility and dependency on context. This means that applications must adapt the way they support user tasks according to availability of nearby resources –which are volatile due to mobility– and of information characterizing both the environment and the user. As a consequence, knowledge-based systems conceived for wired networks are hardly adaptable to wireless ones, due to architectural differences and performance issues. In fact the integration of a pervasive knowledge-based system with emerging monitoring and sensing technologies is a challenging issue. Several emerging technologies are suitable to bridge the gap between physical and digital world. *Radio Frequency IDentification* (RFID) is the most widespread technology for product/object identification and tracking. *Wireless sensor networks* (WSNs) allow to monitor environmental parameters, supporting both queries and automatic alerts triggered by application-defined events. Both technologies are characterized by the dissemination of unobtrusive, inexpensive and disposable micro-devices in a given environment. Each mobile host in the area can access information only on micro-devices in its communication range. Consequently, approaches based on centralized control and information storage are utterly impractical in such scenarios. Pervasive computing calls for a decentralized and collaborative coordination between autonomous mobile hosts.

In order to realize the SWoT vision, information compression is a relevant technical challenge. because XML-based formats adopted in the Semantic Web are too verbose to allow efficient data storage and management in mobility. Benefits of compression apply

to the whole ubiquitous computing environment decreasing data size means shorter communication delays, efficient usage of bandwidth and reduced energy consumption for handhelds (Di Noia et al., 2008). A noteworthy feature of the proposed approach is that backward compatibility is preserved with respect to the above-mentioned standard identification and sensing technologies, thus allowing legacy applications to co-exist with new advanced services. Analogously, the information dissemination and discovery protocol is designed at the application level on top of IP (Internet Protocol) and UDP (User Datagram Protocol), in order to preserve compatibility with standard protocols and equipments for end-to-end routing in the Internet. This is a key requirement for the practical adoption of novel information-centric networking approaches (Jacobson et al., 2009a).

The overall goal of the proposed framework is to allow objects, places, events and phenomena to be easily and thoroughly described by means of semantically annotated data stored within an associated tag or sensor. That can provide tangible benefits e.g. to the management of supply chains and of the life cycle of industrial products. Benefits include an accurate descriptions of raw materials, components and processes; improved item tracking; introduction of *u-commerce* (ubiquitous commerce) capabilities (Venkataramani & Iyer, 2008) without expensive investments in infrastructure; integration of knowledge discovery and reasoning capabilities into home and office appliances (Ruta, Di Noia, Di Sciascio, Scioscia & Piscitelli, 2007) for smart post-sale services. In healthcare applications, equipment, drugs and patients can be thoroughly and formally described and tracked, not only to ensure that appropriate treatments are given, but also to provide decision support in therapy management improving the quality of service with respect to infrastructures lacking support for formal semantics, such as (Pallapa & Das, 2007). Finally, Wireless Semantic Sensor Networks (Ni et al., 2009) involving sensor and actor nodes with different roles and capabilities (Akyildiz & Kasimoglu, 2004) are an emerging and challenging paradigm. Advanced solutions can be built for environmental monitoring, precision agriculture and disaster recovery, by means of semantic sensory data dissemination and resource discovery features that are provided by the framework.

3. FRAMEWORK

Figure 1 shows the conceptualization of the proposed knowledge dissemination and discovery framework. The *u-KB* layer grants common access to information provided by semantic-enhanced embedded devices and sensors populating a smart environment. Internet Protocol (IP) is leveraged for basic addressing and routing in local (typically wireless and ad-hoc) networks and internetworking between autonomous networks (including wide area networks and the Internet).

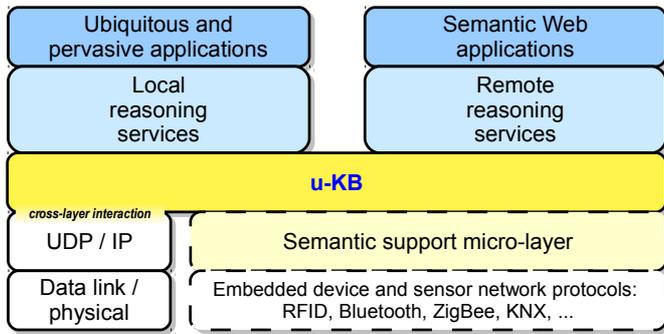


Figure 1. Ubiquitous Knowledge Base framework .

In order to allow the extraction of information resources from the environment, the framework provides interoperability with available protocols for mobile ad-hoc networks of embedded devices and sensors. In order to support both semantically annotated information exchange and backward compatibility toward standard interactions and current applications, each mobile identification and sensing technology requires a *semantic support micro-layer* for adapting into the framework. Previous research work introduced semantic support into widespread technologies such as Bluetooth (Ruta, Di Noia, Di Sciascio & Donini, 2006), EPCglobal RFID (Di Noia et al., 2008), ZigBee (Ruta, Scioscia, Di Noia & Di Sciascio, 2010) and KNX protocol for home and building automation (Ruta, Scioscia, Di Sciascio & Loseto, 2011, in press), assessing benefits and issues of the approach. Further embedded device domains could be integrated into the framework in a similar fashion. Applications use the information-centric network to discover knowledge resources, upon which they can execute logic-based queries and reasoning services. In MANET environments, mobile hosts with embedded reasoning capabilities adapted to resource-constrained mobile devices (Ruta, Scioscia & Di Sciascio, 2010) enable ubiquitous and pervasive semantic-aware applications. Furthermore, by means of the same protocol primitives, a gateway node can expose semantically annotated resources towards remote hosts and forward remote requests inside the local network, so enabling the integration of pervasive information with the Semantic Web and Linked Data (Bizer, Heath & Berners-Lee, 2009).

3.1 Architecture

In KR approaches adopted by the Semantic Web, two kinds of knowledge are modeled: *conceptual* knowledge, or general knowledge about the problem domain, and *factual* knowledge, which is specific to a particular problem. Conceptual knowledge is represented in the form of an *ontology*, describing general properties of concepts and relationships among them. Factual knowledge is specific to the individuals of the domain of discourse. An ontology and a set of asserted facts form a Knowledge Base (KB) from which further entailed knowledge can be derived. In the proposed approach, the KB becomes *ubiquitous*: ontology files can be managed by one or more hosts,

while individual resources are scattered within a smart environment, because they are physically tied to micro devices deployed in the field. For example, in RFID-based scenarios, each individual resource is a semantically annotated object/product description, stored within its RFID tag. Since several object classes, described w.r.t. different ontologies, can co-exist within a physical environment, they share the system infrastructure. Nevertheless, each individual resource annotation refers to one ontology providing the conceptual knowledge for the particular domain. Ontology Universally Unique Identifier (OUUID) codes (Ruta, Di Noia, Di Sciascio & Donini, 2006) are adopted to mark ontologies unambiguously and to associate each individual to the ontology w.r.t. which it is described. OUUIDs are preferred to URIs and URLs, suggested in Linked Data best practices, because URIs are generally much longer than OUUIDs introducing overhead in bandwidth-constrained mobile ad-hoc networks targeted by our framework. Moreover OUUID is easily mapped to data types for resource class identifiers adopted by most standard mobile discovery protocols. However ontology access is still granted by means of OUUID-to-URL mapping mechanisms (Di Noia et al., 2008). In detail, each resource is characterized by: (i) 96-bit ID, globally unique item identifier (e.g. the 96-bit EPC code for an RFID tag or the 64-bit MAC address for a ZigBee sensor); (ii) 64-bit OUUID; (iii) a set of data-oriented attributes, which allow to integrate and extend logic-based reasoning services with application-specific and context-aware information processing; (iv) semantic annotation, stored as a compressed RDF document fragment. For the compression of RDF annotations, a *homomorphic* encoding scheme for XML-based documents introduced in (Scioscia & Ruta, 2009) is adopted enabling query processing directly on encoded annotations, without requiring preliminary decompression. In the proposed framework, the overall network can be imagined as a two-level infrastructure, as depicted in Figure 2.



Figure 2. Field and Discovery layers in the proposed framework architecture.

Pervasive identification and sensing technologies are exploited at the *field layer* (interconnecting embedded micro-devices dipped in the environment and hosts able to receive the transmitted data) whereas the *discovery layer* is related to the inter-host communication. Each network host acts as a cluster head for field devices in its direct range, using available communication interfaces (e.g. RFID, ZigBee). It is worth noting that the proposed approach is fully decentralized. In short, the information-centric framework 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 (to make nearby nodes fully aware of the “network content”);
3. resource discovery based on a peer-to-peer collaborative protocol;
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.

3.2 Information dissemination

An efficient dissemination protocol is fundamental to balance network resource usage and ease of resource retrieval. Address and main characteristics of each resource/object are autonomously advertised by the related cluster head, using small-sized messages throughout the network. To this aim, resource providers periodically send *Advertisement* messages to detect one or more micro-devices in its direct range, also specifying the maximum number of hops that the advertisement must travel. During such lifetime, advertisements are forwarded in broadcasts and can be stored in the cache memories of intermediate nodes. For example, embedded micro-devices consist in EPCglobal RFID tags storing semantically annotated object descriptions, while network nodes are PDA (personal digital assistants) equipped with RFID reader and IEEE 802.11 transceiver. A network node, which has detected a device in its direct range, broadcasts an advertisement every predefined period. When a node receives an advertisement, it extracts information about the resources and, in case of “new” resources, it adds cache entries; otherwise, before updating stored data, the node verifies if the received information is more recent or has ran across a shorter path than the existing one. If the cache is updated and the maximum advertisement range has not been reached, then the advertisement is forwarded; otherwise the whole frame is silently discarded. This simple mechanism ensures that each node in the network sends the same advertisement at most once.

3.3 Resource discovery

The discovery procedure occurs in two steps to avoid an uncontrolled flooding, largely inefficient in terms of bandwidth usage and power consumption. The first one is syntax-based and aims to select resource descriptions

potentially interesting for the request via the OUID matching and the contextual parameters evaluation. When starting a resource retrieval process, a node generally attempts to cover the request by using resource descriptions stored within its own cache memory. If some semantically annotated description is missing, it can be retrieved in unicast using specific *Request* messages. On the contrary, if a requester has no resource descriptions in its cache or if managed resources are considered insufficient to satisfy the request, the node can send a *Solicit* message with a specified maximum travel diameter in order to get new resource locators. When receiving a solicit, a node replies (in unicast) providing cache table entries matching parameters contained within the solicit frame. If it does not manage any information satisfying the solicit, it will reply with a “no matches” message. During their travel, replies to the demand and solicit packets are used to update the cache memory of forwarding nodes. Basically, the soliciting mechanism is analogous to the advertising one, exploiting controlled broadcast of request in an *expanding ring* fashion.

The second discovery step is semantic-based and aims to select the best available resources. The requester downloads in unicast semantic annotations of resources directly from the provider, so preparing the further reasoning and semantic query processing. This hybrid, on-demand approach has been chosen considering that semantic descriptions are needed only in the last discovery phase, whereas a preliminary ontology-based selection procedure is mandatory. In this way, a significant reduction of the induced traffic can be obtained.

3.4 Preliminary experiments

The proposed u-KB approach has been implemented and tested using *ns-2* network simulator (available at <http://www.isi.edu/nsnam/ns/>) in a simulation campaign of the full protocol stack for semantic-enhanced information-centric networking in complex MANET environments. As performance metrics, *network load*, *hit ratio* (i.e. percentage of successful resource retrieval, where a hit has to be intended as the delivery of at least three complete resource descriptions referred to the same ontology) and *service time* (i.e., duration of a successful resource discovery session) were considered. Several scenarios were created for simulation, with nodes moving in a plain 1000 m x 1000 m area. Scenarios were set up with 3, 5 and 7 nodes detecting annotated resources in their direct range (providers) while 15 and 30 nodes acted as requesters.

Preliminary results (full analysis not reported) showed that:

- Overall network load is acceptable (an average of about 0.4 kB/s per node in performed tests).
- Network traffic has higher correlation with the number of providers rather than requesters. This happens because advertisements are

regularly sent in a proactive way by providers, even if there are no requests. Furthermore, the data dissemination protocol adapts well to increasing node mobility, when radio links are lost more often.

- The hit ratio is very high in general, with values above 90% in all tests and above 95% in more than half the tests.
- Service time decreases as the number of clients increase. This is due to the fact that intermediate nodes cache the resource records, so reducing latency of later requests. Overall values are between 1.5 and 2.5 s, still slightly high with respect to the requirements of pervasive computing scenarios.

Results indicate the relevance of the proposed approach.

4. RELATED WORK

Building the SWoT requires decentralized and collaborative middleware suitable for pervasive and ubiquitous computing. Several proposals infrastructures can be found in literature. Unfortunately, most solutions rely on centralized brokers for management and discovery of information (Chakraborty, Joshi, Yesha & Finin, 2006; Pallapa & Das, 2007; Toninelli, Corradi & Montanari, 2008). Vazquez & Lopez-de Ipiña (2007) presented an infrastructure for ubiquitous semantic-based resource discovery. It is closely related with our proposal for the decentralized collaborative paradigm, but it is based on a direct reuse of traditional Semantic Web technologies not optimized for pervasive computing environments. The present work shares core ideas with other information-centric approaches for general-purpose computer networks. In their position paper, Trossen, Särelä & Sollins (2010) discuss current challenges of node-centric networks: at present, issues are addressed by applications on a case-by-case basis, although they could be solved in a more effective and efficient way by holistic information-centric network models. Moreover, Lee, Rimac & Hilt (2010) analyze benefits of content-centric frameworks from the energy efficiency standpoint, which is important for mobile networks. Most information-centric paradigms use *route-by-name* for resource discovery and for routing required by content delivery (Gritter & Cheriton, 2001; Koponen et al., 2007). Among them, CCN (Content-Centric Networking) (Jacobson et al., 2009a) stands out for its elegant, practical approach at deep integration within current IP routers for progressive transition of the Internet toward the CCN model. Further notable features are end-to-end security and the exploitation of the broadcast property of wireless channels, which makes the protocol suitable to MANETs. Nevertheless some open issues remain. Primarily, the unique name of each CCN packet is a binary string with hierarchical structure, so that resource discovery based on meaningful properties related to actual resource content is not possible. Furthermore, the construction of such

structured names relies on application-defined shared policies, which appears as a limitation to broad interoperability, and experimental results in (Jacobson et al., 2009a) and in subsequent work (Jacobson et al., 2009b) concern only networks with 2 nodes: scalability issues due to the flooding of packets are not investigated. Efficient peer-to-peer data dissemination is, in fact, a key technological issue to make information-centric paradigms successful. In latest years, *epidemic protocols*, a.k.a. gossip protocols (Eugster, Guerraoui, Kermarrec & Massoulié, 2005), have been receiving significant interest, as they require no network configuration and provide a good trade-off between algorithmic complexity and performance guarantees.

5. CONCLUSION

An information-centric networking approach for the Semantic Web of Things named u-KB was presented. A peer-to-peer, collaborative and dynamic framework supports semantic information dissemination and resource discovery in pervasive environments. Information gathered in the field through different identification and sensing technologies can be exploited at discovery layer. A uniform set of primitives is available to semantic-aware applications both in mobile ubiquitous contexts and in the Web.

A complete implementation is ongoing in a testbed with real computing devices linked via IEEE 802.11. This will allow to provide a more significant assessment of real-world performance w.r.t. the outcomes of infrastructure simulations.

REFERENCES

- Akyildiz, I., Kasimoglu, I. (2004). Wireless sensor and actor networks: research challenges. *Ad hoc networks*, 2(4), 351–367.
- Baader, F., Calvanese, D., Mc Guinness, D., Nardi, D., Patel-Schneider, P. (2002). *The Description Logic Handbook*. Cambridge, UK: Cambridge University Press.
- Berners-Lee, T., Hendler, J., & Lassila, O. (2001). The semantic Web. *Scientific American* 284(5), 28–37.
- Bizer, C., Heath, T., Berners-Lee, T. (2009). Linked data-the story so far. *Int. J. Semantic Web Inf. Syst.*, 5(3), 1–22.
- Chakraborty, D., Joshi, A., Yesha, Y., Finin, T. (2006). Toward distributed service discovery in pervasive computing environments. *IEEE Transactions on Mobile computing* 5(2), 97–112.
- Di Noia, T., Di Sciascio, E., Donini, F.M., Ruta, M., Scioscia, F., Tinelli, E. (2008). Semantic-based Bluetooth-RFID interaction for advanced resource discovery in pervasive contexts. *International Journal on Semantic Web and Information Systems*, 4(1), 50–74.
- Eugster, P., Guerraoui, R., Kermarrec, A., Massoulié, L. (2005): Epidemic information dissemination in distributed systems. *Computer*, 37(5), 60–67.
- Gritter, M., Cheriton, D. (2001): An architecture for content routing support in the internet. In: *Proceedings of the 3rd conference on USENIX Symposium on Internet Technologies*

- and Systems-Volume 3 (p. 4). Berkeley, CA, USA: USENIX Association.
- Intanagonwiwat, C., Govindan, R., Estrin, D. (2000). Directed diffusion: A scalable and robust communication paradigm for sensor networks. In Pichholtz, R., Das, S.K., Caceres, R., Garcia-Luna-Aceves, J.J. (Eds.): *Proceedings of the 6th annual international conference on Mobile computing and networking* (pp. 56–67). New York, USA: ACM.
- International Telecommunication Union (2005). *Internet Reports 2005: The Internet of Things*. Geneva, Switzerland: ITU.
- Jacobson, V., Smetters, D., Thornton, J., Plass, M., Briggs, N., Braynard, R. (2009a). Networking named content. In Liebeherr, J., Ventre, G., Biersack, E., Keshav, S. (Eds.): *Proceedings of the 5th international conference on Emerging networking experiments and technologies* (pp. 1–12). New York, USA: ACM.
- Jacobson, V., Smetters, D. K., Briggs, N., Plass, M. F., Stewart, P., Thornton, J. D., Braynard, R. (2009b). VoCCN: voice over content-centric networks. In: *Proceedings of the 2009 Workshop on Re-architecting the Internet* (pp. 1-6). New York, USA: ACM.
- Koponen, T., Chawla, M., Chun, B., Ermolinskiy, A., Kim, K., Shenker, S., Stoica, I. (2007). A data-oriented (and beyond) network architecture. *ACM SIGCOMM Computer Communication Review*, 37(4), 181–192.
- Lee, U., Rimal, I., Hilt, V. (2010). Greening the internet with content-centric networking. In Katz, R., Hutchison D. (Eds.): *Proceedings of the 1st International Conference on Energy-Efficient Computing and Networking* (pp. 179–182). New York, USA: ACM.
- Ni, L., Zhu, Y., Ma, J., Luo, Q., Liu, Y., Cheung, S., Yang, Q., Li, M., Wu, M. (2009). Semantic Sensor Net: an extensible framework. *International Journal of Ad Hoc and Ubiquitous Computing*, 4(3), 157–167.
- Pallapa, G., Das, S.: Resource Discovery in Ubiquitous Health Care (2007). In Barolli, L., Thulasiram, R.K., Durresi, A. (Eds.): *Proceedings of the 21st International Conference on Advanced Information Networking and Applications Workshops, Volume 02*. Washington, DC, USA: IEEE Computer Society.
- Ruta, M., Di Noia, T., Di Sciascio, E., Donini, F.M. (2006). Semantic-Enhanced Bluetooth Discovery Protocol for M-Commerce Applications. *International Journal of Web and Grid Services*, 2(4), 424–452.
- Ruta, M., Di Noia, T., Di Sciascio, E., Scioscia, F., Piscitelli, G. (2007). If objects could talk: A novel resource discovery approach for pervasive environments. *International Journal of Internet Protocol Technology*, 2(3/4), 199–217.
- Ruta, M., Scioscia, F., Di Noia, T., Di Sciascio, E. (2010). A hybrid ZigBee/Bluetooth approach to mobile semantic grids. *International Journal of Computer Systems Science and Engineering* 25(3), 235–249.
- Ruta, M., Scioscia, F., Di Sciascio, E. (2010): Mobile Semantic-based Matchmaking: a fuzzy DL approach. In Aroyo, L., Antoniou, G., Hyvönen, E., ten Teije, A., Stuckenschmidt, H., Cabral, L., Tudorache, T. (Eds.): *The Semantic Web: Research and Applications. Proceedings of 7th Extended Semantic Web Conference (ESWC 2010)*, Lecture Notes in Computer Science, vol. 6088 (pp. 16–30). Berlin/Heidelberg, Germany: Springer.
- Ruta, M., Scioscia, F., Di Sciascio, E., Loseto G. (2011, in press). Semantic-based Enhancement of ISO/IEC 14543-3 EIB/KNX Standard for Building Automation. *IEEE Transactions on Industrial Informatics*, 7(4).
- Scioscia, F., Ruta, M. (2009): Building a Semantic Web of Things: issues and perspectives in information compression. In: Proceedings of Semantic Web Information Management, in the 3rd IEEE International Conference on Semantic Computing (pp. 589–594). Washington, DC, USA: IEEE Computer Society.
- Toninelli, A., Corradi, A., Montanari, R. (2008). Semantic-based discovery to support mobile context-aware service access. *Computer Communications*, 31(5), 935–949.
- Trossen, D., Särelä, M., Sollins, K. (2010): Arguments for an information-centric internetworking architecture. *ACM SIGCOMM Computer Communication Review*, 40(2), 26–33.
- Vazquez, J., Lopez-de Ipiña, D. (2007). mRDP: An HTTP-based lightweight semantic discovery protocol. *Computer Networks*, 51(16), 4529–4542.
- Venkataramani, G., Iyer, P. (2008). Semantics Aware RFID Middleware for Personalized Web Services to Retail Consumers. *Relation* 10(1.94), 7530.