Mechanisms for distributed data fusion and reasoning in wireless sensor networks

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Abstract: Decision making in decentralized and dynamic environments is challenging due to the continuous changes in the network topology and the absence of specific nodes that are responsible to take decisions. These challenges are increased in case of sensor networks deployments. In this paper, a novel approach is presented for realizing distributed data fusion and reasoning in wireless sensor networks. The approach is based on the storage and retrieval of data in stable overlay networks that abstract the physical network topology and the design of proper mechanisms for the semantic annotation of the available information in order to be used in the decision making process.

Keywords: distributed reasoning, data fusion, p2p networks, overlay networks

1 Introduction

Sensor Networks (SN) have attracted enormous research effort and triggered a great deal of technological developments during the last decade. Despite the impressive progress, several shortcomings and bottlenecks still exist which prevent SN from being fully deployed and exploited in everyday life applications, such as resource limitations, heterogeneity of infrastructure and the requirements for vast amounts of data collections. Most of all, however, what is really missing in the field is a concrete methodology and a well-defined business model of how to build an integrated information system on top of existing SN infrastructures, capable of coping with the entire chain of operations and orchestrating the various parts together in a flexible, efficient and economic way without the need of centralized components in the network that act as single points of failure. This information system has to be capable to proceed to proper reasoning and decision making over the collected information in a distributed manner. Towards this direction, two basic prerequisites are posed: (i) the existence of a framework for reliable and decentralized storage and retrieval of data and (ii) the use of an suitable ontology. The first prerequisite is fulfilled through the use of an already proposed framework in our previous work for the creation and maintenance of stable overlay networks, over which p2p techniques may be applied reliably and efficiently for storage and retrieval of data [1]. Regarding the second prerequisite, we are going to use an already proposed context model that describes entities and interactions in ad-hoc networks [2] in combination with complementary context models or ontologies for the description of sensor networks parameters and services [3][4][5].

2 Proposed approach for distributed reasoning

In distributed systems, such as WSNs, the application of semantic web techniques cannot be realized in a scalable way if all reasoning is expected to take place in a central node that collects all the semantically annotated data from the SN participating nodes. Furthermore, the existence of a central Knowledge Base (KB) is opposed to in-network processing that is usually required in order to reduce overall power-consumption of the network.

The available approaches for distributed reasoning can be classified in two main categories based on the underlying peer-to-peer network and the ability to control its overlay structure: the artificial intelligence area [6] and the database systems area [7,8]. Our approach leverages mechanisms from both areas and follows a hybrid solution similar to the one proposed in [8].

According to the proposed approach, every peer in the overlay can either distribute an RDF triple in the overlay or otherwise store it in its Local Knowledge Base (LKB) and distribute links to its used terms, what we will call *semantic links*. Every peer in the overlay is also required to maintain a Global Knowledge Base (GKB) where key-value pairs from the established p2p network (based on Distributed Hash Tables - DHT) will be stored. These key-value pairs will be, as sketched previously, either semantic links or actual RDF triples. For instance, a peer with the RDF statement <s,p,o>, where s is the subject, p is the predicate and o is the object, can either store in the overlay the pairs (hash(s),<s,p,o>), (hash(p),<s,p,o>) and (hash(o),<s,p,o>) or otherwise use its LKB and store in the overlay (the GKBs) the semantic links (hash(s),IP), (hash(p),IP) and (hash(o),IP), where IP is the IP address of the corresponding node. This is essential for large in scale or resource constrained networks where every peer is not necessarily willing to disseminate its entire KB. Imagine for example a WSN application in which there is a need to include an external source such as DBpedia. A KB containing statements, <s_1,p,o>,...,<s_n,p,o>, would require to store *3n* key-value pairs if fully distributed, while a semantic links approach would require *n+2* key-value pairs.

Our approach differentiates from the approach proposed in [8] in the use of both LKBs and GKBs, semantic links and distributed statements. Semantic links pose an extra step (forwarding the query to the IP address of the corresponding node) in the reasoning process, so well known ontologies can be fully distributed to avoid this extra step and to avoid also the redundant semantic links (these statements are expected to appear in many nodes). Another significant difference is that of query rewriting. To enable inferred results, we propose the distribution of rules (either ontological axioms or policy/application rules). The distribution is the same as in statements, using again semantic links for the (rare) policy/application rules and fully distributing the common ontological axioms (e.g. RDFS rules). An extra choice to make is the use of backward or forward chaining. Backward chaining would involve the distribution of the headers only, whereas forward chaining would involve the distribution of the bodies of the rules.

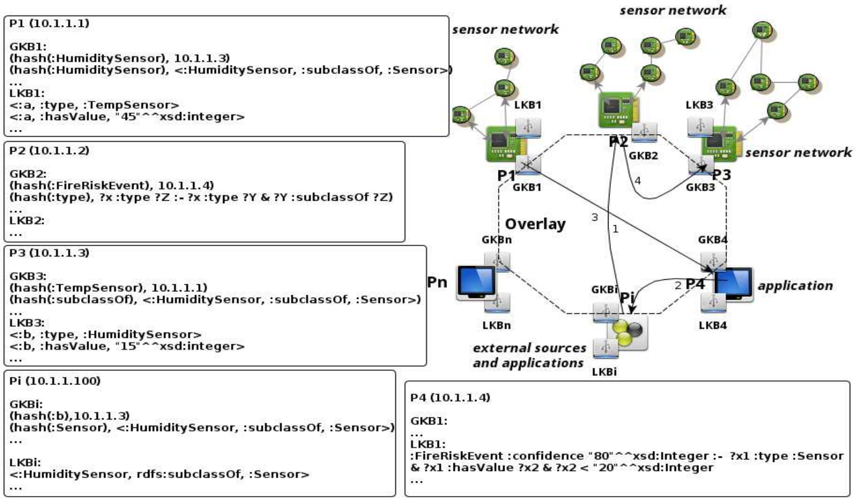

Fig. 1. Backward chaining over a DHT overlay for querying whether there is a fire risk event with 80% confidence. The presented LKB and GKB contents are indicative.

Table 1. Query path example and description.

No	Path	Forwarding term	Remaining query
1	P1-P2-P4	:FireRiskEvent	?x1 :type :Sensor & ?x1 :hasValue ?x2 & ?x2 <"20"^^xsd:Integer
2	P4-Pi	:Sensor	?x1 :type :Sensor & ?x1 :hasValue ?x2 & ?x2<"20"^^xsd:Integer
3	Pi-P2	:type	?x1 :type ?Y & ?Y :subclassOf :Sensor & ?x1 :hasValue ?x2 & ?x2 <"20"^^xsd:Integer
4	P2-P3	:subclassOf	?x1 :type :HumiditySensor & :HumiditySensor :subclassOf :Sensor & ?x1 :hasValue ?x2 & ?x2 <"20"^^xsd:Integer

In Figure 1, a backward chaining example is presented. Peer P1 makes a query whether there is a fire risk event with 80% confidence. The method for evaluating conjunctive triple pattern queries in the DHT overlay is based in the one proposed in [7] with the difference that now each node in the overlay maintains two KBs. Using the overlay to find statements about a FireRiskEvent the query is forwarded to P4 through the semantic link in P2. The remaining query after the application of the rule in P4 is shown in the first row of the Table 1. After that, P4 sends the remaining query in Pi, using as forwarding term the term :Sensor – the sequence for selecting a forwarding term from a clause is, as in [7,8], first the subject, then the object, and finally the predicate, for non-variable terms. In Pi the evaluation is not successful and the next forwarding term of the clause (:type) is selected, which routes the remaining query to P2. In P2 the RDFS subsumption rule is applied and the produced query is forwarded through the term :subclassOf to P3, where the query is successfully evaluated (against both GKB and LKB) and the result is returned to P1.

3 Conclusions and Future Work

In this paper, existing mechanisms for the design of decentralized decision making techniques in wireless sensor networks are analyzed, taking into account the existing representation schemes and models for the sensor networking world. Challenges that arise due to the dynamic and volatile nature of wireless sensor networks are reported and taken into account in our design. Based on these challenges, an approach is proposed for distributed reasoning in sensor networks.

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