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Semantic enablers for dynamic digital–physical object associations in a federated node architecture for the Internet of Things

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ABSTRACT

The Internet of Things (IoT) paradigm aims to realize heterogeneous physical world objects interacting with each other and with the surrounding environment. In this prospect, the automatic provisioning of the varied possible interactions and bridging them with the digital world is a key pertinent issue for enabling novel IoT applications. The introduction of description logic-based semantics to provide homogeneous descriptions of object capabilities enables lowering the heterogeneity and a limited set of interactions (such as those with stationary objects with fixed availability) to be deduced using classical reasoning systems. However, the inability of such semantics to capture the dynamics of an IoT system as well as the scalability issues that reasoning systems encounter if too many descriptions have to be processed, necessitate that such approaches should be used in conjunction with others. Towards this aim, this paper proposes an automated rule-based association mechanism for integrating the digital IoT components with physical entities along temporal–spatial–thematic axes. To address the scalability issue, this mechanism is distributed over a federated network of nodes, each embodying a set of objects located in the same geographical area. Nodes covering nearby geographical areas can share their object descriptions while all nodes are capable of deducing interactions between the descriptions that they are aware of.

1. Introduction

The Internet of Things (IoT) concept envisions a future where numerous physical world objects interacting with each other are engrained in the fabric of our environment [1]. Inspired by the RFID and Wireless Sensor Networks (WSNs) research areas, this concept that was initially considering RFID tags, readers and sensors as ‘things’, has evolved over the years to now encompass all types of devices supporting interactions between the physical and the virtual world [2]. Facilitating such interactions requires provisioning of mechanisms that enable virtualization of such objects to allow interaction with them, ultimately leading to a realization of the vision of “technology rich human surroundings that often initiate interactions” [3]. Finding sensors, actuators and other digital world objects that are relevant for interactions with any particular physical world object is a key precursor to achieving this IoT vision, which requires lowering the heterogeneity implied by the plethora of possible devices and their resulting data.

The applicability of Semantic Web technologies to create homogeneous, standardized and machine-processable representations has already been identified in the literature [1,4] as an enabler of object interoperability. Existing

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research works in sensor networks [5–7] have focused on sensor (and actuator) middleware frameworks that offer sensor measurement data services on the Web and/or at the application level. Finally, standardization activities such as the Semantic Sensor Network Incubator Group (SSN-XG) [8] have resulted in the Semantic Sensor Network (SSN) ontology [9] that represents a high-level schema model to describe sensor devices, their capabilities, observation and measurement data and the platform aspects. However, using Semantic Web technologies brings at least two strong limitations that prevent building efficient and accurate provisioning systems in an IoT context. First, due to the impossibility of describing and reasoning over the dynamics of a system, the use of the Semantic Web precludes representing that objects in the IoT can evolve over time (e.g. having their access policy, availability, geo-location, etc. changing over time). Secondly, almost all the works on Semantic Web reasoning still assume a centralized approach where the complete terminology has to be present on a single centralized system and all inference steps are carried out on this system. While this assumption is acceptable when considering a small set of described entities, the highly dynamic nature of envisioned IoT systems – composed of a very large number of smart objects producing and consuming information – requires adopting a different approach to avoid scalability issues. Moreover, this requirement is strengthened by the fact that disregarding IoT systems dynamics may lead to the computation of meaningless interactions (e.g. an association being asserted between two objects based only on their functionalities without considering their respective geo-locations).

We believe that the use of Semantic Web in the context of the IoT must be coupled with additional processes addressing these two limitations. More precisely, temporal and spatial reasoning must be added on top of classical semantic reasoning in order to accurately reflect the behaviour of the considered IoT systems. This overall reasoning process must also be distributed to cope with computation spikes without having to maintain and administer the computing, network and storage resources each time a reasoning step is performed.

Towards this aim, this paper presents a federated distributed framework of nodes for an IoT architecture. Within this framework, the contributions proposed are focussed on two aspects: inferring automated associations that integrate the IoT digital components with physical entities and a notification algorithm to share knowledge between a determined set of nearby nodes. Each node of the framework refers to a managed geographic location that encompasses reasoning capabilities enabling associations (applicable to the objects contained in the location managed by the node) to be derived. Determining these associations is achieved by a novel rule-based mechanism along temporal–spatial–thematic axes. This mechanism builds upon our earlier work [10] on semantic models that capture the components of the IoT domain and provide a formal representation to the interactions. In line with the identification by Miorandi et al. [1] that architectures may make use of proximity communications whenever possible, each node of our framework is capable of selecting a set of geographically nearby nodes to share the knowledge about the IoT digital components that it manages. As a consequence, each node always uses a well delineated set of IoT digital components – i.e. those attached to or nearby the geographic location managed by the node – to derive associations. The consequent reduced size of the set enables reducing the computation cost implied by the reasoning process while elements composing the set still allow almost all associations to be derived. Though the proposed approaches are focussed towards IoT systems in indoor environments, the contributions can be applied to other conceivable IoT deployments as well.

We evaluate the proposed mechanisms by testing the applicability of the implemented association mechanisms for indirect inference in an entity mobility scenario and show the feasibility of the approach by quantitatively evaluating the scalability of the proposed framework.

The rest of this paper is organized as follows. The federated architecture concept and the embodiment of semantically-enabled nodes are presented in Section 2. Section 3 presents the description of the semantic models supporting both the association mechanism detailed in Section 4 and the knowledge sharing algorithm explained in Section 5. An implementation of the framework is detailed in Section 6, with a scenario validation and evaluation results discussed in Section 7. Related state of the art is presented in Sections 8 and 9 concludes the paper and discusses future work.

2. Federated architecture of nodes

In the literature, federated network systems refer to shared resources among multiple loosely coupled nodes [11] in order to optimize the use of those resources, improve the quality of network-based services, and/or reduce costs. Widely used in scenarios involving information sharing between different tiers [12], such distributed systems can cope with storage and computation limitations and offer efficient – i.e. fast – search processes using optimization techniques [13]. Due to these advantages, federated systems are particularly suited to interconnecting heterogeneous physical world objects with the surrounding environment, which relies on the capability to store, retrieve and process a high number of semantic descriptions of IoT digital components.

Supporting the aforementioned IoT paradigm through a federated system is achieved by considering each loosely coupled node as the digital representation of a place hosting physical world objects. In this paper, we define a place as an indoor premise (e.g. a building, a room, etc.) and propose a model allowing such places to be described. However, nothing precludes adapting our architecture to address other kinds of places such as outdoor areas (e.g. a crossroad, a district, etc.). An example of a node (say N) presented in this paper may represent a meeting room equipped with a webcam, a presence sensor and other equipment. Embedding storage and computing capabilities, each node manages a pool of semantically described IoT digital components and can determine all possible associations between such components and the surrounding