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Towards an Adaptive Ontology Based Model for Interoperability in Internet of Things (IoT)

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Abstract: Interoperability is key in any networked system. In the IoT environments, the need is further amplified by the presence of numerous heterogeneous devices. To address device and service disparity, the things will need proper addressing, registration and de-registration. This can be implemented through abstraction technologies and models such as ontologies for semantic expressiveness. The aim of this paper is to investigate some of the requirements for semantic interoperability and expose some of the current challenges in device and service discovery. We also explore current models for resource discovery highlighting their strengths and weaknesses and how they can contribute to an ontology based IoT device and service discovery model. Furthermore, the paper concludes by proposing a model for device and service discovery.

Keywords: Interoperability, IoT, Semantic, Discovery, Ontology.

1. Introduction

Manual device configuration and supervision has been employed in the large part of the existing Internet. However, the emergence and development of the Internet of Things (IoT) presents a larger and more dynamic context in which human assisted configuration may prove to be difficult, time consuming and inefficient. The IoT is a network of physical objects or things embedded with electronics, software, sensors, and network connectivity, which enables these objects to collect and exchange data [1]. The IoT vision therefore requires the development of platforms that will be able to constantly adapt to addition and removal of devices. Stationary and mobile devices with differing computing capabilities will be hosted in the IoT. These devices will originate from different manufacturers and vendors, bringing along with them varying platforms, capabilities and differing communication technologies. The development of the IoT then requires devices to be able to automatically join and integrate with existing infrastructure. Mobile devices pose an even bigger challenge as they do not have a fixed geographical location [2]. This means that gateway devices in IoT should be able to constantly add and remove devices as they enter and leave the network. Proprietary gateways are capable of automated device registration and deregistration, but the demands of the IoT require a platform which is able to handle heterogeneous devices [3].

Since the IoT is be made up of numerous highly distributed and heterogeneous devices that need to interconnect and communicate autonomously, there is need to facilitate interoperability among the things to support addressing, tracking and discovery as well as information representation, storage and exchange [4]. This can be done by means of models that support the seamless interoperability of things in IoT to facilitate convergence of services and devices from different vendors and suppliers.

The IoT introduces connectivity of entities in a global network. The entities, formally defined as things, represent physical and virtual objects that can be uniquely identified and addressed in the network. The extent and the nature of the IoT carries along some challenges such as device heterogeneity, differences in communication technologies and interoperability incompatibility in different layers, from communication and integration of devices to interoperability of data formats [5]. This is a challenge in developing a generic IoT solution for a global scale. Integration and interoperability in the IoT is more than a requirement, it is the backbone on which the whole network will stand on. Though interoperability will be required on different levels in the network, device discovery and communication proves to be a more primary requirement[4].

The objective of connecting devices and collecting contextual data from them is to create situation awareness thus enabling other applications, machines, and users to understand their surrounding environments [6]. Data collected by different devices is usually multi-modal and diverse in nature [7]. The disparity in data quality and nature adds to heterogeneity in IoT environments. Device and information diversity makes interoperability and data processing challenging. Since IoT data is generated by different devices, integration of data from these heterogeneous devices will require a common description and data representation framework that support machine-readable and interpretable data descriptions and annotations. Semantic technologies in IoT will therefore promote interoperability among devices and facilitate effective data access and utilization [8]. The IoT represents an ever-growing network of numerous heterogeneous devices. Heterogeneous devices in the IoT will need to communicate and in most cases, autonomously so as to provide services and functionality. Semantic web technologies such as ontologies can thus aid in addressing device heterogeneity in IoT [9].

In this work, we study and highlight the requirements for an ontology based model for device and service discovery. We explore the literature on semantic interoperability and device discovery in order to highlight challenges for future research trends in semantic interoperability and propose a model for semantic device and service discovery. Thus, the contributions of this survey paper can be summarized as follows:

- A comprehensive review of current device and service discovery associated technologies.
- A summary of open challenges in device and service discovery based on the literature study and analysis.
- Suggested ontology based device and service discovery, device information storage and management.

These requirements are crucial in facilitating interoperability of disparate devices in a heterogeneous IoT environment. The rest of the paper is organized as follows: Section 2 and 3 reviews the current state of art and related work. Section 4 will focus on the IoT challenges and requirements. Section 5 describes the proposed Device and Service Discovery Model (DSDM). Implications of the model will be discussed in Section 6. The paper concludes with a discussion and future work in section 7.

2. Integration and interoperability

As the IoT presents an ever-expanding network of heterogeneous devices, there is need for facilitating the automated addition of new devices to the network. Newly added devices must be able to register their services as well as read existing services on the home IoT network. Devices should be afforded the ability to interoperate regardless of discrepancies that may exist amongst the disparate devices. Interoperability can be generalized as the feature for providing seamless exchange of data and information between products from different vendors [10], [11]. The IoT requires integration of heterogeneous devices and things in order to provide interoperability. For instance, a device may customize its services automatically or simply exchange information that other systems can use for improving performance, enabling the creation of composite services, control operations and information processing [11]. These types of scenarios require increased interoperability in service management and orchestration operations. Service management can only be implemented when devices and systems are integrated.

In IoT things are controlled and monitored through service frameworks and applications [11]. These monitoring and control frameworks can be generic as well as custom. The introduction of new infrastructure components or objects should not alter the existing IoT configuration. Integration is formally defined as the process of linking together different computing systems and applications physically or functionally, to act as a coordinated whole [12]. In IoT environments resources expose their capabilities, thereby allowing coupling with other resources. Resources expose their capabilities through services. Exposure of resource capabilities via services allows for search and discovery mechanisms [13] enabling the location of resources or services in the physical world. Search and discovery therefore becomes one of the fundamental capabilities for integration in IoT.

Interoperability in IoT is largely based on semantics[8]. Semantic interoperability allows heterogeneous stakeholders to access and interpret data in IoT environments unambiguously. Unambiguous data description allows data to be interchanged and processed by devices and machines in IoT and also facilitates better understanding of information for human users [9]. Semantics therefore provide annotations to data that can facilitate interoperability in terms of data origins, meaning and representation[9]. Semantic annotation of IoT resources and the processing of the semantically annotated data provides essential elements for supporting search and discovery methods as well as assisting in maintaining the IoT environment configuration [14]. Semantic annotation of data and services in IoT can be implemented through the use of technologies such XML and OWL [3] [15].

One of the important aspects in the IoT environment is the identification of the data to collect, gather and store [16]. This can be done through the use of an information model which can be used to manage the services provided. The information model for IoT environments must be rich in semantic expressiveness and flexible enough to consider the variations of current status of the objects being managed [17]. A fully expressive information model allows pervasive systems to better use the data things to provide better management service operations [18]. Ontologies offer a means to formalize the information contained in the information model. However, this does not mean that other approaches are unsuitable for different applications. Ontologies in IoT offer a suitable way to exchange knowledge as they support the required semantics to augment the data in the information model, consequently supporting service orchestration.

Ontologies offer a practical way to express semantics. The purpose of ontologies is to share and reuse knowledge [19], [20]. Ontologies provide enrichment to the information model[6], they also allow the information exchange between applications and between different levels of abstraction, which is an important goal for the Internet of Things [3], [21]. Semantic augmentation gives ontologies greater capabilities over other data models [8]. Integration and interoperability is also achieved by the use of ontologies, resulting in improved IoT system control, management and service orchestration [22]. Ontologies provide a way to map cognitive relationships that can be used for making ontological commitments providing consistent use of vocabulary to different domains of applications [23]. Semantic models can be used to relate the physical world to the real world, providing access to information in the context of the real world in a consistent way.

3. Related Work

Devices on a network typically provide one or more services which can be made discoverable to other services on the network, thereby allowing for pairing and service consumption, through broadcast queries [3]. Following the initial discovery, more specific service queries can then be sent to a particular service provider [24]. The strengths of the implementation of this model is being able to find services of the right kind and finding more information about the services [24]. The model also allows for the discovery of service control information allowing interested and authorized parties to determine the state of the service. However, this model presents challenges such as collision between identifiers in cases where there is dynamic registration and de-registration of devices and services [25]. Due to the fact that this model also lacks persistence, matching and interoperability is difficult to implement due to poorly stored service and device information [25].

A model that can be implemented in IoT environments is proposed and introduced in[11]. The model described involves devices that use similar communication technologies and pair with them. This implementation is widely employed in Bluetooth and NFC based piconets. The model incorporates the effective discovery of devices and services that use low-power technologies making a more preferred choice for IoT. However, the model is functional over shorter ranges of proximity [26]. These limited range makes the model inappropriate for the highly mobile and dynamic IoT environment

Models proposed for Device and Service Discovery (DSD) in IoT lack semantic expressiveness. [27] describes semantic infrastructure as a bridge between human and machine communication. In IoT, human and machine communication is even more crucial. According to [27], semantic interoperability can be used to support high level and context sensitive information request over heterogeneous devices abstracting syntax and structural heterogeneity. This is a typically useful aspect of semantic infrastructure such as ontologies in heterogeneous IoT set-ups. However, other types of heterogeneity may exist such as social values as based on manufacturers' perspectives. [17] argues that, while ontologies can be successful in supporting interoperability, they do not provide comprehensive frameworks for representing all aspects of the IoT. Ontologies however offer a base for the development of an interoperable IoT.

4. IoT Challenges and Requirements

The IoT still faces a number of challenges related to dynamic device and service discovery. Though the challenges cannot be exhaustively stated, our emphasis in this work is to present those challenges aligned with device and service discovery. Amongst these challenges, Heterogeneity is the most outstanding challenge in IoT environments [5].

First, in heterogeneous IoT, there is a demand for semantic interoperability. Semantic interoperability enables devices to communicate meaningfully and utilize shared knowledge. Interoperability needs to be implemented independent of device and service manufactures and vendors. This will ensure efficient scalability of the IoT. There are many attempts that have emerged to answer these issues but most are theoretical and lack the practical implementation [9][25].

Second, information persistence is a big challenge in existing models. The IoT requires a more robust persistence mechanism. This will reduce the discovery time when devices reconnect to the IoT infrastructure.

Thirdly, syntactical issues around data formats pose a major challenge to interoperability. Messages transferred by communication protocol require well defined encoding. This can be abstracted by the use of mark-up languages such as XML, although more concise and less verbose languages might be more preferable.

Fourth, the dynamism in device and service registration and de-registration requires an adaptive model. Current models have challenges with constant device addition and removal as well as fluctuating service statuses as noted in the literature study. The heterogeneity and mobility of the devices adds to this complexity.

Finally, the IoT is not only machine based, discovery models should take into consideration the human users. This is done by addressing aspects such as security, privacy, and legal implications.

5. Proposed DSDM

The proposed conceptual model for DSDM is illustrated in Figure 1. It shows four components: the Knowledge Base (ontology), Device Discovery Module (DDM), Service discovery and Management module and the Communication component. Communication between the components is done by means of a query service. The query service is responsible for querying the components of the model and delivering information among components.

The knowledge base ontology is built for semantic interpretation and storing device and service information. The ontology is built on modularity thereby allowing reuse. It describes semantics for interoperability and device relationships. The ontology consists of a device repository and service repository. Device and service descriptions are stored and their relationships are mapped. Relationships in the ontology are described using Web Ontology Language (OWL). The knowledge base also manages device and service information.

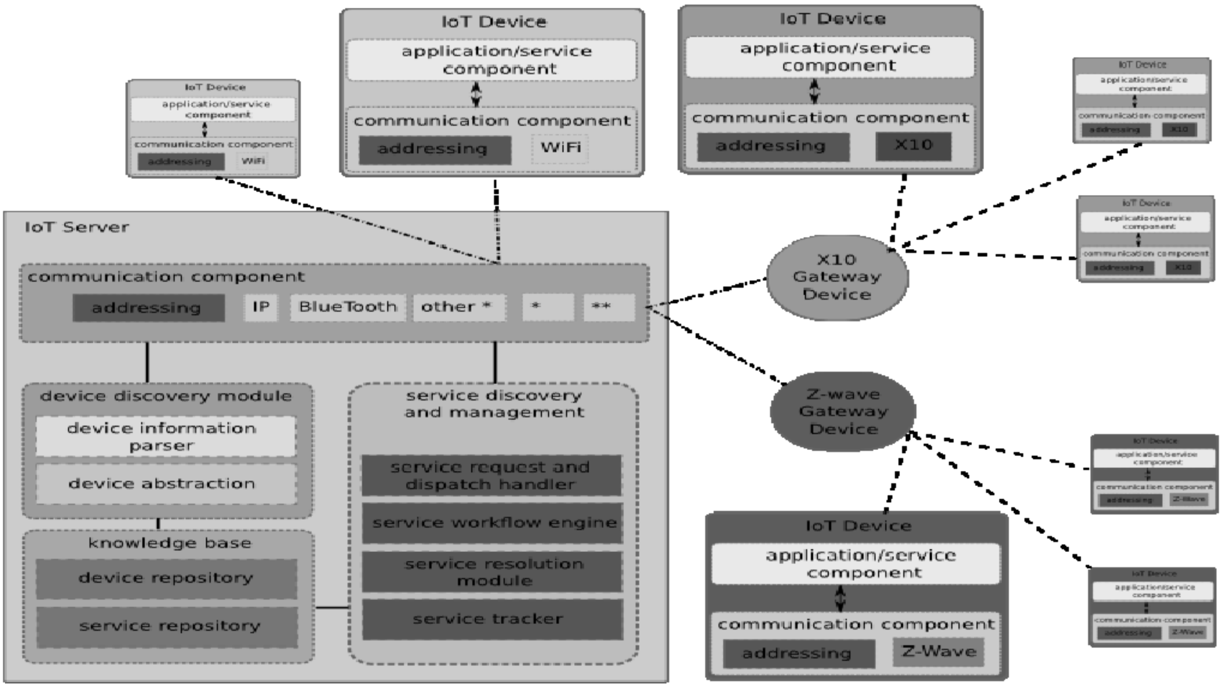

Figure 1. Proposed DSDM

The Device Discovery module is responsible for investigating device metadata and device communication protocols. It also allows for communication with different communication protocols. Device discovery can be carried out in two ways. The first one being initiated by the device requesting to join the network. The device sends a request to the DSDM by means of a broadcast. The DSDM responds to the call via a unicast. Alternatively, a device can be discovered when it responds to the DSDM broadcast. This means that devices that are in an off state remain invisible to the DSDM. Device discovery is implemented using UPnP discovery protocol's Simple Service Discovery Protocol

(SSDP). SSDP uses a communication protocol that supports the announcement of service state as they become available and unavailable. It also allows clients to query the network to ask what services are available.

Communication Component provides an interface for devices to communicate with the DSDM. This component abstracts devices for the DSDM. It facilitates for heterogeneous interaction with other devices by encompassing a variety of communication protocols. The communication component is also responsible for acquiring addressing information from a device requesting for the DSDM services. Addressing information is used to uniquely identify a device or a service. Once a device has been contacted and its addressing information has been acquired, the communication component sends the information to the device discovery module.

Service discovery and management module (SDMM) of the DSDM serves as a work flow centre for the DSDM. By making use of the information stored in the ontology, the SDMM is capable of composing services as per device request. It also works with the communication component in managing service request. Most importantly, the SDMM provides an accounting service for the DSDM keeping track of the services available and those requested. It also manages connected devices.

6. Implications of the model

Considering the requirements for both the devices and the human owners, we proposed an ontology-based DSDM that integrates a Service-Oriented Architecture (SOA) pattern in achieving effective communication amongst the devices. In addition to Device and Service Discovery (DSD), the model also includes service composition modules to generate composite services to address complex tasks. The model also supports system adaptation by constantly updating the repository thereby keeping the environment up-to-date

The DSDM has some apparent benefits, Firstly DSD are inseparable and complementing components of any network, allowing the two to be executed by a singular model allows for a faster and easily manageable integration and interoperability model. The Dynamically adaptive model ensures that the network has up-to-date device information by dynamically adding new service descriptions as new devices get added to the network.

The use of semantic data in device and services discovery provides machine readable information which can be used in constructing trust models in IoT and ultimately provide security in the IoT. The model therefore provides a way of collecting such semantic information about devices and storing it in a persistent manner that can allow other models to query and interact with the stored device and service information.

The use of the DSDM will benefit both the manufacturer and consumers. Automated DSD in IoT will ensure continued competition in device quality and subsequently map to improved consumer products. This is possible since devices and service interaction will be independent of the proprietary constraints. Furthermore, developers will be presented with an open environment for developing IoT applications that are not tied to a specific device manufacturer, thereby providing diversity for the consumers. Consumers will not require complex technical knowledge in setting up their custom environments since most of the processes will be automated.

7. Conclusion and future work

This paper highlighted the importance of developing DSDMs for the easy integration and interoperability of devices in IoT environments. We highlighted some of the challenges being faced in the development of the IoT. The paper conjures that currently there is no proper or widely accepted DSDM for the IoT heterogeneous environment. A suitable DSDM was proposed in this paper. The proposed DSDM facilitates for the automated discovery of devices and services in IoT. This will enable interoperability in the IoT environment. The proposed model also tackled scalability issues in order to prevent the model from becoming a ‘bottle neck’ as the network expands. The work presented in this paper is motivated by the need to create a gateway system for the IoT that will facilitate for the integration of disparate devices without having to alter device manufacturing processes. For future work we hope to implement and test a prototype of the proposed DSDM. We also hope to increase the content of the ontology to enrich its ability to be expressive in defining complex services and also the documentation of the ontology.

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