Distributed architecture for resource description and discovery in the IoT

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Abstract—Nowadays, the Internet of Things (IoT) creates a vast ecosystem of intelligent objects interconnected via the Internet, allowing them to exchange information and to interact. This paradigm has been extended to a new concept, called the Web of Things (WoT), considering that every physical object can be accessed and controlled using Web-based languages and protocols, such as: the CoAP protocol which is becoming the most accepted and suitable protocol in this context. Moreover, the architectures currently proposed for the creation of IoT environments lack efficient and standard support for the discovery, selection and composition of IoT services and their integration in a scalable and interoperable way. To overcome this, in this work, we propose a hybrid and distributed CoAP-based architecture, considering all these aspects by combining the Fog Computing paradigm and structured P2P overlay networks. Furthermore, we describe the different components of our architecture and explain the interaction between them.

Index Terms—IoT, CoAP, Service, Smart Object, Distributed Architecture, Semantic Web Technologies, Service Discovery, Peer-to-peer, IoT gateway, Fog Computing.

I. INTRODUCTION

The IoT is a revolutionary technology that is gaining popularity by leaps and bounds. It represents the connection and cooperation of the physical and the virtual worlds through the constitution of a network of objects connected to the Internet capable of collecting and exchanging data and sending them over the Internet, through the use of low-cost computer processing, the Cloud, Big Data, network connectivity, analytics and mobile technologies [1]. These objects can be simple devices, as well as highly complex industrial equipment, such as: sensors, smartphones, home appliances, cars, thermostats, baby monitors, etc. With more than 10 billions IoT devices connected today, experts expect this number to rise to 22 billions by 2025. In this hyper-connected world, digital systems can record, monitor and adjust every interaction between connected objects. These physical entities provide IoT with services that can be used to accomplish many different tasks. However, they are limited in terms of resources such as: storage capacity, processing and computation, battery power, etc. To ease the interactions in the IoT domain, the concept of IoT gateways has been introduced as an intermediary entity between users of IoT applications and constrained devices, enabling the registration, the discovery and the access to IoT resources. Such a gateway can be viewed as a broker that exposes different resources and handles application requests while taking into account the possibility that IoT objects may not be available. Many approaches for the deployment of these gateways have been proposed in the literature [2], which consist mainly in placing the gateways in the Cloud to ease the deployment and to ensure scalability, flexibility, availability of resources (e.g. storage, CPU, etc.) for data analysis and low-cost management [3]. However, as the physical distance between data centres and users increases, so does the transmission latency and hence the response time [3]. Therefore, the Fog Computing paradigm has emerged to extend the traditional Cloud Computing and cover its limitations. This concept aims at bringing intelligence, processing and data storage closer to the edge of the network in order to provide IT services faster and closer to the interconnected smart objects that are part of the IoT. Such an architecture offers several benefits, including: reduced latency and network bandwidth by improving quality of delivery and enhancing operational efficiency as well as faster real-time processing while providing better support for mobile communications. The placement of IoT gateways in Fog Computing near to IoT devices is already being explored and recognized as a major application scenario for this paradigm [3].

Furthermore, IoT objects are often incompatible with standard Internet protocols, such as HTTP, which require resources-rich equipment. Among the proposed solutions to address this issue, the Constrained Application Protocol (CoAP), which is emerging as a widespread standard. However, the major limitation of CoAP is that it allows only simplistic static registration and syntactic queries and provides only keyword-based string matching (exact matches), which is not common in the real world scenarios, and appears to be highly inadequate to provide automatic and intelligent resource discovery in IoT. The integration of semantic aspects within CoAP can overcome this limitation. Several works have been proposed in this sense by exploiting the use of reference ontologies to enrich the attributes of the CoRE Link Format by annotating objects, and services. However, the majority of these solutions focus only on sensors using the SSN ontology and neglect other types of objects [16] [17]. Also, the proposed semantic models do not present all aspects related to objects and their services, such as: QoS, context attributes, location, etc. Furthermore, the process of mapping concepts from the semantic model to CoAP is not clearly defined and is at a
preliminary stage.

Moreover, implementing an efficient discovery system needs first to design its architecture, by describing the structure and the behavior of each of its modules in order to meet all the technical and operational requirements of the system. This architecture shows how a system is decomposed, how the processes interact, or the different ways in which system components are distributed across the network.

In this work, we are interested in CoAP-based architectures. Within this context, all the existing solutions defined in the literature focus only on the resource discovery and access process, besides the lack of several modules, including: composition, selection, indexing, etc. To this aim, we propose a hybrid distributed CoAP based architecture for the discovery, the selection and the composition of IoT services using web technologies in a constrained IoT environment. In the proposed solution, we combine the Fog Computing paradigm and structured P2P overlay networks to provide a judicious placement for the Fog nodes (IoT gateways). We describe each component of this architecture and explain the interaction between them.

The remainder of this article is organized as follows. Relevant articles are presented and discussed in Section 2. Section 3 is devoted to present our proposed architecture and explain its components in detail. The last section concludes this paper and highlights the future research directions.

II. RELATED WORKS

The IoT environment is composed of a large number of objects connected to each other, providing a variety of heterogeneous services. For this purpose, many techniques have been defined to describe and discover these objects and their services, while several protocols (e.g.: DNS-SD, MQTT, CoAP, REST, etc.), have been designed to meet the requirements of resource-constrained devices and allow them to communicate with each other and to automatically discover services without human intervention. Among the solutions based on these protocols, we can cite: the work presented in [8], where authors introduced a DNS-SD/mDNS-based SD technique which operates on Contiki OS embedded devices and is initiated by sending a record containing the searched service name. In the same regard, Stolikj et al. have extended the mDNS/DNS-SD protocol with a context-based model for describing and discovering services [9].

Moreover, Pareira et al. developed a distributed MQTT-based resource discovery architecture for M2M communications, providing plug and play capabilities for network devices to enable zero-configuration networking [10]. Similarly, Venanzi et al. proposed an MQTT-based node discovery protocol, considering MQTT brokers as fog nodes to trigger turning on/off the BLE interfaces of the surrounding objects (battery-powered IoT nodes) [11].

The choice of the protocol to consider depends strongly on the application goal. In the context of the WoT, every physical object can be accessed and controlled using Web-based protocols, including: the CoAP protocol which is emerging as a widely used standard for many reasons. One of the main advantages of this protocol is that it is REST-based and therefore allows interoperability with HTTP and the RESTful Web Services through simple proxies [2]. Thus, it can easily be integrated within the web. It shares the same methods as HTTP (e.g., GET, POST, PUT, DELETE, etc.) and uses URLs to invoke services. In addition, this protocol is designed for constrained environments and has a very light and simple packet structure with binary data representation. It thereby enjoys a lower overhead as well as a reduced bandwidth requirements and parsing complexity. Moreover, CoAP supports both request/response and resource/observe models and allows the definition of context and QoS attributes as key-value pairs.

In this work, we are mainly interested in architectures based on this protocol. Among the CoAP-based solutions proposed in the literature, we can cite the work presented by Ferdousi et al. in [12], where they proposed a Cloud-based middleware, called LOAMY, following a hybrid model which combines two forms of the CoAP protocol (centralized and distributed) for service discovery. The client request is sent to the Refinery Node to analyze its type. If the directory node address is known, the request is forwarded to the Border Router in the distributed form, otherwise it will be transferred to the Client Request Handler (CRH) in the centralized form. The CRH of the context responds to the request either with an acknowledgement, if the service providers or services are not available, or with a payload containing the requested service, if available.

In another work, Cirani et al. introduced a P2P-based architecture for self-configurable and scalable SD at local and global scales. This architecture relies on the use of IoT gateways which interact with other IoT nodes through CoAP and may act as both CoAP client and CoAP server. These gateways are used to store and retrieve information about IoT nodes and their provided services. They can be federated in a P2P overlay to provide a distributed and global discovery. In this solution, authors consider two P2P overlays: the Distributed Location Service to retrieve all the information needed to access a resource identified by a URI, and the Distributed Geographic Table to retrieve a list of resources matching the geographic criteria [13]. In the same regard, Tanganelli et al. designed an edge-centric distributed architecture to federate different IoT gateways deployed in fog nodes in order to discover and access IoT services [4]. The proposed architecture is based on a structured P2P overlay and thus on DHT (Distributed Hash Table), where information about the IoT resources is stored for global lookup across multiple domains. All the IoT devices in the same domain are managed by the same gateway. The latter is responsible for the registration, discovery and access to IoT resources using the CoRE Resource Directory and CoAP protocol. Moreover, for the implementation of the DHT, the eXtensible Metadata Hash Table (XMHT) has been adopted to exploit its extensible interface that resembles the CoRE Link Format.

Moreover, various research works have been proposed re-
cently to improve interoperability between heterogeneous IoT devices using semantic web technologies and CoAP protocol, we can quote the work presented in [14], where a CoAP-based framework is proposed. The latter is divided on four layers. The first one is the Sensor Abstraction Layer which represents the real-world physical objects exposed through the use of standard interfaces. Secondly, the Data Access Layer which comprises three modules: repository, triple store and reasoner. In this layer, the resource descriptions are stored in the repository, while the triple store is used to store RDF. The role of the reasoner is to match the desired requirement with the most suitable and available services by inferring logical consequences from a set of axioms based on QoS, location and application entity. The third one is Resource Registration and Discovery Layer where the CoAP CoRE Link Format is enriched with semantic tags provided by the semantic matchmaker module and the request is resolved by fetching from the repository using SPARQL. Finally, the Social-ambient Overlay layer to perform semantic-based group composition by the cluster head. Each resource semantic must have an attribute called Social Relation Type which represents the relationship between the different resources. In addition, Djamaa et al. have proposed a CoAP-based framework structured around five main components namely: Resource Directory, Device, Border Router, User Interface, and Reference Ontologies Server [15].

Moreover, Gramegna et al. [16] proposed a Semantic Sensor Network (SSN)-based framework that implements a backward-compatible extension of CoAP to support a logic-based matchmaking of semantic-enriched sensors as well as to detect and annotate high-level events from raw data collected from sensing devices using a simple data mining component. Similarly, in [17], the authors proposed a semantic Web of things framework, enabling the collaborative discovery of sensors and actuators in pervasive contexts. It is based on a backward-compatible extension of CoAP, supporting advanced semantic matchmaking via non-standard inference services and event annotations using a simple data mining method.

Finally, Jin et al. designed and implemented a Semantically Enhanced CoAP Gateway (SECoG), located between Low-Power Lossy Networks and the Internet, which supports the simple and complex CoAP service mashups via a single HTTP request [18]. Also, two HTTP request templates (one for simple mashups and the other one for complex mashups) were presented to allow users to specify the description of a desired service mashup. In this solution, a group generating method was proposed to group services which are similar to the required ones and a semantic similarity calculation method was designed to provide partial correspondence results in case where there are no exactly matching servers.

III. THE PROPOSED ARCHITECTURE

In this section, we describe the proposed architecture for the discovery, selection and composition of services, as well as its components and the interactions between them. A roadmap of the creation of this solution is presented in Fig. 1. First of all, the IoT objects and the network infrastructure must be installed and the gateways, representing the Fog nodes, must be placed and organized as a structured P2P overlay. Then, CoAP-HTTP and HTTP-CoAP proxies have to be set up at each gateway. Besides, a semantic model needs to be defined by considering appropriate basic ontologies to be used. The latter can be enriched, if necessary, to annotate and improve the description of the IoT objects/services that are stored in their respective repositories. For the local discovery process, an indexing structure is defined and a selection process is implemented in order to choose the best services from the discovered ones.

We have opted for a distributed and modular architecture to bring more flexibility and resilience into IoT environments and to distribute the workload on a number of interconnected cooperating nodes. This type of architecture has several benefits, such as: resource sharing, fault-tolerant, scalability, flexibility and robustness, etc [2]. As depicted in Fig 2 our architecture is mainly composed of three layers, which are:

A. IoT Layer

This layer includes physical IoT devices equipped with sensors, actuators, RFID tags, etc. and capable to communicate. These objects publish and share their data and services in the nearest Fog nodes where they will be processed. They can be programmed to send their descriptions and those of their services, once connected to the gateway to which they are linked, via the POST method of the CoAP protocol.

B. Fog Layer

The Fog layer consists of multiple nodes (IoT gateways), deployed over a wide geographical area close to users to bring intelligence, processing and data storage closer to the edge of the network in order to deliver services faster and closer to the interconnected intelligent objects that are part of the IoT. IoT gateways manage these objects and their services, control their availability and enable the local discovery. Also, they have the right to process data and make decisions and this makes the process faster. In addition, to address latency-sensitive applications by minimizing delays and the number of network hops, a judicious placement of Fog nodes is required.
solution, we have opted for the use of a structured P2P network based on DHT to link the different IoT gateways together. This choice is motivated by several advantages, including: the support of scalability, reliability and mobility, robustness and efficiency, high availability, no central control and so on. In this model, Fog nodes are considered as peers identified by specific known logical identifiers. They do not have particular roles. Therefore, they can be both service requesters and providers, so they are equal with no primary administration device at the center of the network. In this layer, at each IoT gateway, a framework is implemented. As shown in Fig. 2 the architecture of this framework is modular, which greatly facilitates its maintenance in case of failure. In the following, we describe each module of this architecture.

- **Local Thing Directory (LTD):** It is a directory containing the description of IoT devices and their metadata, following the JSON-LD format. It offers an API to create (POST_THING), read (GET_THING), update (PUT_THING) or delete (DELETE_THING) these objects.

- **Local Service Registry (LSR):** It is a directory of registrations describing resources hosted on IoT devices, offering several simple services in JSON-LD format. It implements a set of methods, allowing devices to register their services (POST_SERVICE), maintain them (PUT_SERVICE and DELETE_SERVICE) and retrieve them (GET_SERVICE). An SR can be logically segmented into sectors (clusters) to facilitate the search for the appropriate service.

- **Ontology server:** It is a web server containing all the reference ontologies used in our work and allows access to them (lightweight version). The information of these ontologies can be retrieved or updated via the SPARQL language.

- **HTTP-CoAP proxy:** It allows HTTP clients to access resources on CoAP-based servers via an intermediary.

- **CoAP-HTTP proxy:** It enables the translation and the mapping of CoAP requests into HTTP ones.

- **Registration module:** It is responsible for registering objects and their services in the two directories via dedicated APIs. As aforementioned, an object can send its description and those of its services to the selected gateway. Similarly, a user can do this following the following steps:
  - First, we distinguish two kinds of users: CoAP users and HTTP users.
  - If an HTTP user sends a registration request (HTTP POST method), he must pass through the HTTP-CoAP proxy which then forwards it to the Registration Module. Otherwise, if it's a CoAP user, the communication is direct and no translation is required.
  - Then, this module extracts the object description from the registration request to invoke the POST_THING method to register the description into the LTD. Once the object is saved, its ID is returned to the sender (i.e. Registration module).
  - Once the object ID is retrieved, this module invokes the POST_SERVICE method to register one by one the services offered by this object in the LSR (it also saves the object ID in the service description).

- **Discovery module:** It is responsible for the search and the discovery of objects/services according to the functional capabilities matching the properties which are specified by the user in his discovery request.

- **Request formulation:** This component extracts the necessary information from the CoAP request sent by the user and formulates a SPARQL query that will be executed by invoking the methods offered by the LTD and the LSR.

- **Semantic-based matchmaking:** This component calculates the semantic correspondence (semantic similarity) between the information provided by the user and the descriptions of the objects/services existing in the local directories.

A list of descriptions, meeting the user’s requirements, is retrieved and subsequently sent to the Selection and ranking module. When a service is not found on a given gateway, it is forwarded to the Request forwarder module.

- **Indexing module:** This component is used by the Discovery Module to accelerate and optimize the query processing.

- **Selection and ranking module:** This module receives the list of the candidate services and selects the most appropriate service(s) based on the non-functional properties, which are known as the QoS parameters, e.g. price, security, reliability, delay, etc.

- **Request forwarder:** This component is responsible for routing the user request to another node (IoT gateway), if no matching service is available locally, via the Routing table.

Each peer has a local Routing table which stores a list of routing rules and is used by the forwarding algorithm to redirect the query to other nodes of the overlay. It is initialized when a gateway joins the overlay, using a defined procedure. The peers periodically exchange updates of their routing tables as part of the maintenance of the overlay. Also, the join and leave of the IoT gateways are dynamically managed by the P2P overlay without requiring any configuration on a central server.

Moreover, there are different protocols that build structured P2P networks: Content Addressable Network (CAN), Tapestry, Chord, Pastry, Kademia, etc., but in this work, we do not specify any type of these protocols since they only use the lookup function that is provided by any type of DHT.

**C. Cloud Layer**

The service composition process is complex and involves several techniques, such as: discovery, selection, classification, etc. In our architecture, this process is performed at the Cloud
Layer level for many reasons, including: the availability of unlimited computation and storage resources, the flexibility and scalability, as well as the adoption of the pay-as-you-go model which can dispense users from maintaining high-end hardware resources. In the proposed solution, if a service is not found at the fog layer, the node forwards the request to the Discovery module at the Cloud layer. First, this module searches in the Composite Service directory to find a combination that can answer this request if it has already been processed, otherwise the composition process is triggered, by following next steps:

- The Discovery module selects the gateways to which it will forward the request (simultaneously) via Gateway indexing module, containing all the gateways’ information as well as their locations, and then it forwards it for processing.

- After performing a local search, each gateway returns a list of its available services, matching exactly or partially (i.e., only part of it) this request, to the Discovery module. The latter aggregates the several returned results from each gateway and sends the list of candidate services to the Service Classifier component.

- This module then divides these services into several clusters according to their functional properties.

- The selection and ranking process is triggered afterwards (Selection and Ranking Module), by considering and evaluating the non-functional properties, i.e. the QoS parameters, (QoS & Cost Evaluator) to choose the most adequate and performing services within each class of services matching the functional parameters.

- The list of selected services is sent to the Service Composer module to orchestrate the composition, but before that, the QoS of this combination is evaluated (QoS & Cost Evaluator) and an optimal execution plan is established based on the set of selected services and the optimization techniques provided by the Optimizer Module.

- Finally, the composite service will be saved in the Composite Service directory to avoid reprocessing it each time. This directory is maintained by the Service composite monitoring module, which can replace a simple service by another if it’s no longer available.

Furthermore, we take into account external user requests received at the Cloud layer by the Request Handler component which will trigger the discovery and selection process as previously described. Besides, at this level the ontology server contains complete and enriched ontologies used for more complex query processing, when required.

IV. Conclusion

In this work, we have designed a hybrid and distributed architecture for the discovery, the selection and the composition of services offered by IoT objects using web technologies (e.g. CoAP, HTTP, etc.) in a constrained (IoT) environment. This architecture is modular and is divided into three layers: IoT layer, Fog layer and Cloud layer. We described the functionalities of each component of this solution and explained the interaction between them. Future work will lead us to implement the different components to evaluate its performances.

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Fig. 2. The proposed distributed architecture for IoT Resource discovery, selection and composition.