Major challenges of Smart Cities based on the Internet of Things paradigm : A Survey

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ABSTRACT

The Internet of Things (IoT) is predicted to become the biggest technological revolution in history, even surpassing the expansion of computers in terms of number of devices. It is therefore a predictable consequence that such domain has a significant amount of attention amongst academic researchers and industrials. Modern cities need to be able to provide automatic urban services, that are no longer achievable by humans due to overly dense population. IoT systems are capable of integrating a great amount of heterogeneous devices and providing relevant data to any application. Therefore, the idea of IoT-based Smart City is being rapidly and thoroughly studied to provide better urban services. This paper will focus on highlighting the similarities and differences between several of the most popular visions of the IoT Smart City environments. Predominant factors such as integration of heterogeneous devices, and implementation of efficient middleware are common challenges faced by all IoT Smart Cities. The paper will therefore present a comprehensive overview of those challenges, and discuss existing approaches to overcome them.

KEYWORDS

Smart Cities, Internet of Things, WSN, Urban Management

1 INTRODUCTION

In an era where most of the world population is predicted to live in urban areas, the services that are required to sustain those municipalities and their inhabitants become intrinsically more complex every day. As early as in 2030, urban citizens will represent 60% of the planet's occupants [4]. In this context, the concept of Smart City arises as one of the most viable long term infrastructures for urban services. In fact, a city that could monitor and manage most of the redundant work by itself would allow to dedicate human effort to it solely when it is absolutely inevitable. The rest of the time, a Smart City could function autonomously with minimal human intervention.

Such city will probably rely on the Internet of Things paradigm, that currently appears to be a catalyst for connected devices offering services to humans. The constant effort put into developing more scalable and efficient IoT networks that can provide increasingly larger amount of services, and on broader geographical areas have made it possible to conceive systems that can be disseminated over a whole town.

The work presented in this survey aims to provide a generic description of IoT Smart Cities and pinpoint the most common denominators among the difficulties that IoT-based Smart Cities will be facing. The rest of this document is organized as follows.

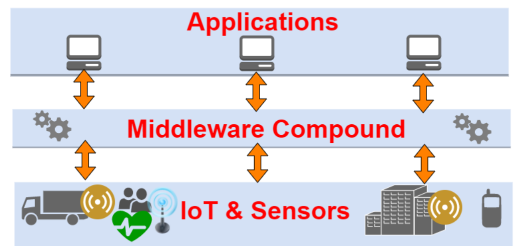

Figure 1: A generic IoT Smart City Architecture.

Section 2 provides a brief description of the Internet of Things paradigm. Then, Section 3 defines the notion of *Smart City*, and breaks it down into 3 main components. Further, Section 4 describes some of the criteria on which Smart Cities can be compared to each other. Finally, the remainder of the paper presents diverse recent efforts towards conceiving optimal Smart Cities with respect to the criteria stated in Section 4.

2 INTERNET OF THINGS

The Internet of Things paradigm is a recent trend that designates infrastructures of objects of the everyday life that are interconnected over the Internet. Equipped with micro-controllers and transceivers for digital communication, these devices gather a large spectrum of data from their respective environments in accordance to their inherent role and send this data to an upper layer in the IoT network. The latter is responsible for processing and storing the bits of information. These devices are of particular interest to humans as they can help addressing a number of key challenges in urban environments effectively and efficiently. They are considered "smart" in the sense that they provide useful information on a large scale and can react accurately upon sensing changes in their environment. In this regard, cities, which will inhabit up to 70% of the world's population by 2050 [6] are major fields of interest for companies of the public and private sector.

3 IOT SMART CITIES

Smart Cities relying on the Internet of Things paradigm can be succinctly defined as urban areas utilizing IoT devices in order to collect data, *sense* their environment and perform actions that improve the quality of urban applications [16]. This definition bestows 3 crucial concepts that constitute the notion of an IoT Smart City as depicted in Figure 1.

3.1 Urban milieu sensing

The sensing layer is a fundamental constituent of any IoT Smart City infrastructure. Regardless of the exact implementation of a Smart

City and its specificities, the peripheral stratum is necessarily a network of IoT devices and their users [8, 10]. This similarity yields one identical precondition that all adaptations of the IoT paradigm to a Smart City must fulfill : **integrating heterogeneous objects**. In pursuance of the highest possible sensing coverage of the city area, the Smart City has to incorporate a broad spectrum of sensing devices embodied in a Wireless Sensor Network.

3.2 Middleware

To address the previously mentioned heterogeneousness issue, each Smart City must implement a middleware that encompasses and interconnects a large number of non-interoperable real world objects i.e. IoT devices and sensors [6, 8]. In contrast to the sensing layer that is scarcely variable between implementations by nature, there is currently no standardized design pattern for the Smart City middleware.

Nonetheless, the integration frameworks all share the same goal, that is : collect data from the IoT network and transmit it in form of relevant interpretations to the upper layer. The differentiation between approaches comes from the exact method implemented in order to achieve relevant and scalable ability to provide correct data when requested by urban applications.

3.3 Applications and Urban Services

The upmost component of the Smart City is the application layer. A concrete deployment of a Smart City is viable and will be adopted by municipalities only if it satisfies the dual requirement of simultaneously increasing urban service quality and reducing operational costs [2].

The profitability part of the objective is to be addressed by the 2 lower layers, since only an efficient use of resources can generate a positive return on investment. Servicewise, the possibilities to satisfy the prerequisite are unlimited, considering that there is no upper bound on the amount of different urban service applications that can rely on a well-functioning Smart City framework. Some of the most commonly suggested applications include :

- Air quality
- Traffic congestion
- City energy consumption
- Smart parking
- Smart lighting

4 COMPARISON CRITERIA

It can easily be established that nearly all of the emerging techniques designed to construct Smart Cities based on the IoT paradigm rely on the architecture depicted in Figure 1. This makes it possible to provide a comparative overview on common characteristics of different approaches. There are 3 major elements that can be used to establish a qualitative measurement of a Smart City :

(1) **Tackling heterogeneity** : this is a direct consequence of the nature of the lower layer. As mentioned in Section 3.1, effective integration of non-interoperable devices in a single system is a *sine qua non* of any Smart City.
(2) **Middleware performance** : the scalability of an IoT Smart City greatly depends on it's ability to handle and process the immense amount of data that comes with the IoT urban sensing, and is an essential criteria since the number of devices is predicted to grow exponentially.
(3) **Ease of deployment** : urban administrations are prone to pick one Smart City approach over another based on the *operational cost to service ratio*, that can be improved by developing the most simply deployable and maintainble system.

5 TREATING HETEROGENEITY

Smart cities environments are, by nature, composed of different heterogeneous systems, applications and non-interoperable real-world objects. These systems must be able to communicate with each other to exchange information and thus need to have a common language. To tackle this problem, Neslon et al., in their effort to delineate Guiding Principles for creating replicable and standardised-based IoT architecture for Smart cities [1], have suggested some foundational interaction patterns to help organizing hardware, software and systems. Nelson et al. [1] discuss the purpose of Bridging functions which are used to tie heterogeneous systems together. Bridging functions are described as:

> A bridging function is an application program or service that knows how to interface to the APIs of each system being integrated.

In this sense, a bridging function is a middleware that has a one-to-many relationship with other systems.

6 IMPLEMENTING EFFICIENT MIDDLEWARE

In the context of a Smart City, an *efficient middleware* can be defined as :

> A solution that fully integrates heterogeneous and non-interoperable real-world objects [6] while avoiding any waste of resources.

A middleware fully integrates objects if it is capable of self-managing the entire network, providing relevant data from sensors to applications and correctly executing requests from applications on actuators and sensors. It is noteworthy that efficiency greatly differs from effectiveness when characterizing a middleware. A middleware is effective if it fulfills it's purpose by enabling full integration of objects, it is a boolean property that is either held or not. On the contrary, efficiency is a **measurable** characteristic of a system that can be used to determine which one is optimal. In the case of Smart Cities efficiency is fundamental since it increases scalability, which is crucial in very large IoT networks.

6.1 Cognition

Cognition can be briefly defined as the procedure of acquiring knowledge and understanding. Since only adequate information available at the right moment can lead to actual *understanding*, Vlacheas et al. propose a **Cognitive Management Framework (CMF)** [11] to supply Smart City applications only with relevant data from IoT objects. The CMF is a middleware solution intended to addresses the issues of heterogeneity, unreliability and quantity of IoT devices in Smart Cities. In this framework, the building blocks of cognitive reasoning are **Virtual Objects (VO)** that represent real-world objects. These VOs are enriched with semantic metadata

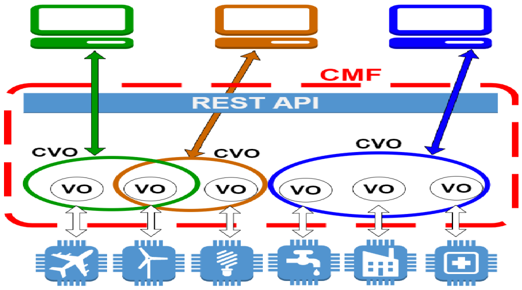

Figure 2: The Cognitive Management Framework.

following a specific model [14]. This renders any object information *understandable* by the framework, that can proccess it automatically without any human interaction.

VOs can be associated to form a **Composite Virtual Object (CVO)**. Each CVO is aggregation of VOs that matches the requirements of specific application request. The CMF relies on cognition to determine the exact set of VOs and CVOs that should be combined. The cognitive process consists of 3 major parts :

- Monitoring VOs to perceive data from real-world objects
- Analysis of contextual information and knowledge accumulated via learning techniques from previous requests. Combining the latter two allows the framework to decide what objects are useful or not for a specific application.
- Pattern recognition techniques that detect semantic similarities between requests and already existing CVOs that could be immediately reused

Figure 2 depicts a simplified view of the CMF, where each bidirectional flow between an urban application and the relevant IoT devices and sensors have been established through cognition. Vlacheas et al. introduce encouraging scalability results for a cognitive middleware. In fact, it is stated that a cognitive solution could preserve linear service execution time in function of number of objects [11].

6.2 Ontology

Ontologies are formal rules that describe and categorize precisely any kind of information or relation in a certain domain. They are of particular interest for Smart Cities as they can enable automatic processing of urban data. There are several existing ontologies that can already be used to describe sensor data such as the Semantic Sensor Network Ontology [7] or the Web Ontology Language [15].

Imran Khan et al. present a **Data Annotation Architecture for Semantic Applications in virtualized Wireless Sensor Networks** [9] that allows Wireless Sensor Networks to provide urban services thanks to ontologies. Since WSNs produce only raw sensor data, WSN applications tend to be limited to monitoring. The proposed architecture aims to enhance WSNs and infer knowledge about their context and situation.

The architecture consists of two layers : a Virtual Sensor Layer and a Virtual Sensor **Access** Layer. Fig 3 is a simplified display of the architecture. The virtual sensor layer contains virtual representations of the actual sensors. Depending on the nature of the calling application, a sensor is virtualized either as a semantic or non-semantic virtual sensor. This is to ensure that the additional effort for semantic applications is only made when necessary.

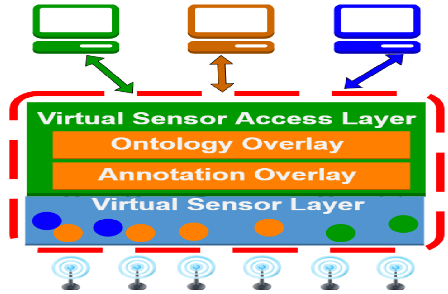

Figure 3: The WSN Data Annotation Architecture.

The Virtual Sensor Access Layer is made of 2 overlays. The ontology overlay is composed of agents that are responsible for disseminating the ontology through the network. The annotation overlay contains agents that annotate raw data from the virtual sensor layer and forward it towards applications. Upon receiving sensor data, each agent checks if it has the adequate ontology to annotate it. If it does not, it queries the ontology overlay to fetch it and proceeds to annotation. Otherwise, the agent can directly annotate and send the enriched data upstream.

Imran Khan et al. present their results after conducting a typical use case experiment within a heterogeneous sensor network composed of a little less than 10 nodes. It is shown that on average, the elapsed time between a virtual sensor sending raw data and the reception of the application's success code is around 4 seconds.

Supporting the ontological approach, A. Kazmi et al. introduce the **Virtualized programmable InTerfAces for innovative cost-effective IoT depLoyments in smart cities (VITAL)** [3] project. VITAL is described as a *system of systems*. A. Kazmi et al. state that VITAL introduces an integrated virtualized paradigm for development, deployment and operation of Smart Cities. And that this paradigm is specifically designed for gathering and processing of data streams from heterogeneous sensors and IoT devices in urban environments. Both VITAL and the WSN Data Annotation Architecture use the Semantic Sensor Network Ontology [7] as a basis to model sensors and their measurements. Therefore it appears that both converge towards an identical standardized sensor data model, that will enable interoperability between middlewares, and thus between Smart Cities.

Moreover, the Cognitive Management Framework [11] uses the W3C Resource Description Framework [14] to add metadata to virtual objects. This language defines a basic data model that is also part of the standards used by VITAL. Hence, all three previously described architectures rely on annotating data from virtualized devices and reasoning automatically using ontologies. Furthermore, Theodoridis et al. state that virtualization and semantic annotations contribute to the possibility of creating a middleware capable of processing IoT data in a way that increases efficiency [6]. Therefore it appears that a common middleware pattern emerges out of these multiple research efforts.

6.3 Proximity

Proximity denotes the establishment of a level of relatedness between any IoT application and the relevant objects that may be used to deliver this application's services [11].

$$\Delta(c,p) = \sqrt{\sum_{i=1}^{n=parameters}(req_i^{current} - req_i^{previous})^2}$$

where c and p are respectively the current and previous requests' coordinates.

Figure 4: The Euclidian distance between application requests.

It is worth remarking how the theory of proximity can be combined to cognition in the Cognitive Management Framework[11]. Once a request has been stated and translated into request and situation parameters, the Request and Situation Matching (RSM) checks for previous results for those arguments and **their satisfaction-rate-similarity metric**.

It is a reflection of the **Euclidian distance** between the current and previous requests, where each parameter can be viewed as a coordinate in its own dimension. This computation yields the previously mentioned score of **relatedness** and allows the framework to reuse existing virtual objects if deemed satisfactory enough and therefore *answer new questions with previously acquired knowledge*.

Figure 4 shows a basic metric of relatedness. It is calculated in the same way that the Euclidian distance between two points based on their coordinates, except that each parameter is a coordinate. The results indicate that implementing the use of proximity in the Cognitive Management Framework preserves near constant service execution time as the number of objects grows.

6.4 Cloud Computing

Jiong Jin et al. propose a framework that encompasses **Cloud-Centric IoT** for the realization of IoT Smart Cities [10]. The middleware of such architecture is composed of multiple distinct providers that offer their services for urban applications. These services can include computational resources, sensor data or analytics. Smart City applications would be able to benefit from *pay-as-you-go* pricing plans from Cloud providers. This can lead to a more efficient middleware as the business model does not compel to pay resources when they are not necessary.

This approach is supported by Petrolo et al., that introduces the **Cloud of Things** [13] paradigm. The underlying principle is to connect the IoT to the Internet of People through the Internet of Services. It is stated that CoT is suitable to be combined with the VITAL platform [3]. The authors argue that the latter two are a perfect match, as VITAL would allow building vertical platforms from sensors to applications via semantics and cognition, and the Cloud of Things could support horizontal scaling of such platforms. Also, **Sensing as a Service** [5] is presented by Petrolo et al. as a model that can enable the CoT paradigm. SaaS is a model of cloud middleware in which publishers make sensors available in the cloud, and providers select the ones that match the user application requirements.

7 EASE OF DEPLOYMENT

Ease of deployment for IoT Smart Cities is inherently difficult due to the arduousness of integrating heterogeneous environments but also because of the high level of fragmentation of technologies as explained by Petrolo et al. [13]. Further, it is to note that each Smart City projects have different needs and a wide variety of parameters have to be taken into account. Sokwoo Rhee [12] discusses the common problems and challenges that cities have when deploying their projects. Nelson et al. [1] propose general Guiding Principles as a set of rules that urban administrations should follow in order to create flexible and reusable smart cities architectures.

8 CONCLUSIONS

In this paper we have reviewed several approaches towards a more efficient and standardized implementation of IoT Smart Cities. It has been reported that the heterogeneity and non-interoperability of IoT devices was a major difficulty for an automated urban system. This has lead to a very broad spectrum of independent deployments and technologies that tend to be specific to their respective set of applications. Therefore the development of Smart Cities was slowed down by the lack of common efforts.

We have shown that multiple recent efforts have all addressed that issue. It has been found that the researchers concurred with the idea of a standardized model of a fully interoperable Smart City. Through virtualization of heterogeneous devices, cognitive reasoning, semantic metadata annotations following common ontologies and unified data models, Smart Cities are able to integrate, process and exchange on a planetary scale.

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