



# **A social Internet of Things application architecture : applying semantic web technologies for achieving interoperability and automation between the cyber, physical and social worlds**

Dina Hussein Ali

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**DOCTORAT EN CO-ACCREDITATION**  
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**Dina Hussein Ali**

**A Social Internet of Things Application Architecture -  
Applying Semantic Web Technologies for Achieving Interoperability and  
Automation between the Cyber, Physical and Social Worlds**

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To the memory of  
my grandmother  
whose scent held delight  
and unfettered serenity

To  
my brother  
who led me away from the lion

And  
to those who inspired it  
but will not read it

Midway on our life's journey, I found myself  
In dark woods, the right road lost. To tell  
About those woods is hard--so tangled and rough

And savage that thinking of it now, I feel  
The old fear stirring: death is hardly more bitter.

*Inferno* (Dante)



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My friends, for their humor, sometimes picnics and support. My colleagues for their ideas and their inspiring discussions. I am really grateful to each one of you.

My parents, who managed to send me homemade love and other delicious food.

My Shahinda who sent refugee from 3, 200 miles away.

....and to the only M. Tarik Alkawa who believes in miracles and hangs on to Camel songs in times of despair.

Dina Hussein  
Paris, France, July 2015

# A Social Internet of Things Application Architecture - Applying Semantic Web Technologies for Achieving Interoperability and Automation between the Cyber, Physical and Social Worlds

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## Abstract

Recently, the integration between computing and networking environments has been widely promoted for providing intelligent services to end users as well as effective resource usage. This convergence paved the way towards the emergence of the Internet of Things (IoT). The paradigm of IoT relies mainly on making objects, called things, disappear and weave themselves into the fabric of our daily life for supporting us in carrying out activities. Scalability and heterogeneity are among the major challenges which hinder the wide-scale realization of IoT services in users' daily lives. In order to address IoT challenges, a new research stream has come forward in the literature as a paradigmatic class of the Cyber-Physical Social Systems (CPSS), which is known as the Social Internet of Things (SIoT). The SIoT builds on the notion underlined by small-world phenomenon where social structure allowing trust-based social relationship among people and objects, in a manner resembling traditional Social Network Services (SNS) is suggested to address IoT challenges. This social structure can improve objects navigability and discovery by narrowing down its scope to a manageable social network of everything. However, since SIoT inherits characteristics from different computing and networking environments (i.e., IoT and SNS) this, actually, increases the quantity and the variety of contextual data that must be handled for adaptive service provisioning in SIoT, which acts as the major challenge addressed in this thesis. That is, in this thesis we propose the concept of cognitive context; where within certain spatio-temporal situation, reasoning about the objective aspects of context, which represents the physical environment, along with the subjective context, which represents behavioural and social aspects, is considered for improving SIoT services intelligence and adaptability to users' situational needs. We envisage Semantic Web technologies to deploy our proposed cognitive context in two application domains; context-aware recommendation of quotidian tasks in smart homes and situation-dependent social structure of things in smart spaces. A proof-of-concept prototype has been developed for each application domain, with the goal of demonstrating the smooth integration of objects to the Web for carrying out application tasks. Our empirical results show an improved level of service adaptability and run time complexity when applying our suggested cognitive context.

**Keywords:** *Social Internet of Things (SIoT); Social Network Services (SNS); Context-awareness; Semantic Web Services; Internet of Things(IoT); Service Adaptability; Application Architecture*

# A Social Internet of Things Application Architecture - L'application des technologies du Web sémantique pour réaliser l'interopérabilité et de l'automatisation entre les mondes physiques, cyber et sociaux

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## Résumé Français

Récemment, l'intégration entre les environnements informatiques et de réseautage a été largement promu pour fournir des services intelligents à des utilisateurs finaux ainsi que l'utilisation efficace des ressources. Cette convergence a ouvert la voie à l'émergence de l'internet des objets (IdO). Le paradigme de l'IdO repose principalement sur fabrication d'objets, appelés les choses, disparaître et se tissent dans le tissu de notre vie de tous les jours pour nous soutenir dans l'accomplissement des activités quotidiennes. Évolutivité et l'hétérogénéité sont parmi les principaux défis qui entravent la réalisation à grande échelle de services de l'IdO dans la vie quotidienne des utilisateurs. Afin de relever les défis de l'IdO, un nouveau volet de recherche est venu en avant dans la littérature comme une classe paradigmatique des Cyber-physiques systèmes sociaux (CSPR), qui est connu comme l'Internet social des choses (Siot). Le SIOT se fonde sur la notion soulignée par phénomène petite-monde où la structure sociale permettant relation sociale fondée sur la confiance entre les personnes et les objets, d'une manière qui ressemble à des services de réseaux sociaux traditionnels (SNS) est suggéré de relever les défis de l'IdO. Cependant, depuis SIOT hérite des caractéristiques de différents informatiques et de réseautage environnements (par exemple, l'IdO et SNS) cela, en fait, augmente la quantité et la variété des données contextuelles qui doit être manipulé pour Adaptive fourniture de services dans Siot, qui agit comme le principal défi adressé dans cette thèse. Autrement dit, dans cette thèse, nous proposons la notion de contexte cognitif; Lorsque, dans certaine situation spatio-temporelle, le raisonnement sur les aspects objectifs du cadre, ce qui représente l'environnement physique, avec le contexte subjective, qui représente les aspects comportementaux et sociaux, est considéré comme l'amélioration des services SIOT intelligence et la capacité d'adaptation aux besoins conjoncturels des utilisateurs. Nous envisageons technologies du Web sémantique pour déployer notre contexte cognitif proposé dans deux domaines d'application; sensible au contexte recommandation des tâches quotidiennes dans les maisons intelligentes et structure sociale dépendant de la situation des choses. Un prototype de preuve de concept a été développé pour chaque domaine d'application, dans le but de démontrer l'intégration harmonieuse des objets sur le Web pour la réalisation de certaines applications. Nos résultats empiriques montrent un niveau de service amélioré l'adaptabilité et la complexité en temps de fonctionner lors de l'application de notre contexte cognitif suggéré.

# LIST OF PUBLICATIONS

This thesis is based on the following original articles, which are referred to in the text by their Roman numerals (i–v) in addition to a list of already submitted articles:

## **Published Articles:**

- i. (2015) Hussein, D., Park, S., Han, S., & Crespi, N. Social Cloud-based Cognitive Reasoning for Task-oriented Recommendation in the Social Internet of Things. , *IEEE Cloud Computing Magazine*, accepted for publication.
- ii. (2015) Hussein, D., Park, S., Han, S., & Crespi, N. Dynamic Social Structure of Things: A Contextual Approach in CPSS. , *IEEE Internet Computing Magazine*, vol. 19, no. 3, pp. 12-20, May. 2015
- iii. (2015) Hussein, D., Soochang, P., & Crespi, N. (2015, January). A Cognitive Context-aware Approach for Adaptive Services Provisioning in Social Internet of Things. In *IEEE ICCE Conference Proceeding*.
- iv. (2014) Ortiz, A. M., Hussein, D., Park, S., Han, S. N., & Crespi, N. (2014). The cluster between internet of things and social networks: Review and research challenges. *Internet of Things Journal, IEEE, 1*(3), 206-215.
- v. (2014) Beltran, V., Ortiz, A. M., Hussein, D., & Crespi, N. (2014, March). A semantic service creation platform for Social IoT. In *Internet of Things (WF-IoT), 2014 IEEE World Forum on* (pp. 283-286). IEEE.
- vi. (2013) Hussein, D., Han, S. N., Han, X., Lee, G. M., & Crespi, N. (2013, May). A framework for social device networking. In *Distributed Computing in Sensor Systems (DCOSS), 2013 IEEE International Conference on* (pp. 356-360). IEEE.

**Submitted Articles:**

- i. (2015) Hussein, D., Han, S. N., Lee, G. M., & Crespi, N. The Social Internet of Things - A Cognitive Reasoning-based Framework for Adaptive Service Provisioning in Smart Spaces. In *IEEE Transaction on Consumer Electronics*.
- ii. (2015) Jose J. García Aranda, Dina Hussein. Coreset Sizing Using K-clustering Algorithms for Big and High Dimensional Datasets in the Social Internet of Things (SIoT). In *IET Communications Journal*.

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# Chapter 1: Introduction

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## 1.1. Background

The Internet of Things (IoT) is a novel paradigm that aims at completely changing the shape of modern wireless communications by making it possible for a broad array of devices around us, such as sensors, actuators, ID-tags, smart phones, tablets, etc., which are referred to as smart objects, to interact and cooperate to achieve common objectives and improve users' everyday life [DSL10]. On another hand, Social Network Services (SNS) services are being promoted in literature as a large network of people where the relationships among those in a certain community are modeled and described. SNS are composed of nodes of people, and the edges between these nodes represent their relationships.

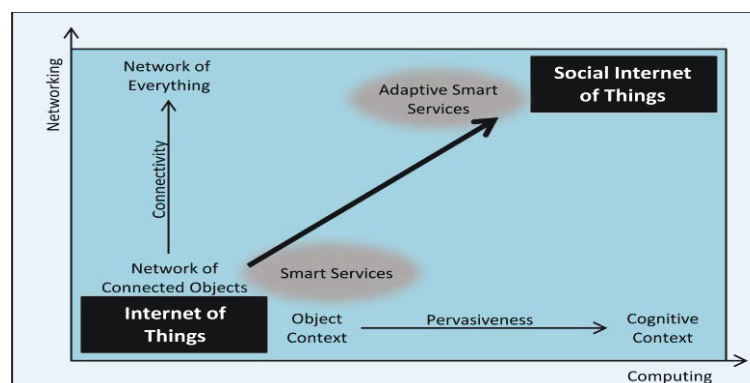
The overlap between IoT and SNS has been recently brought up in the literature to enable the connection of people to the ubiquitous computing universe. Within this framework, the information coming from IoT and that coming from SNS acts as the glue to allow human-to-device interactions [AIM14]. In this sense the worlds of the IoT and SNS can be integrated for the goal of bringing the physical and social worlds into the cyber one. The resulting paradigm, called the Social Internet of Things (SIoT), has the potential to support novel applications and networking services for the IoT in a more effective and efficient way [AIMN12], but it is necessary to find solutions for improving service intelligence, efficient resource visibility, service discovery, object reputation assessment, crowd-sourcing and service composition [AIM14], [AIMN12].

The Semantic Web technologies are an interesting approach which has the capability of managing SIoT services, since they provide interoperability and automation that can be used by different stakeholders to unambiguously access and interpret data. Despite the great interest in Semantic Web services over the last decade, the potential of these services have not yet been fully realized in the current Web. This is due to a large extent to the complexity of Semantic Web technologies, which are used to formally describe these services, and the absence of attractive uses cases. It is clear that if service providers do not envisage the use of their services by an automated application, they will not take up the effort to semantically mark-up their services. Moreover, it is necessary to develop user-friendly and intuitive tools that will motivate people without technical skills to use semantic services. Through context-

aware and proactive platforms that enable users to create their own services, it will be the users themselves who will bring out with new applications and use cases.

Since the ultimate goal of SIoT is to enrich human life by seamlessly integrating their devices into their quotidian routine, in this thesis we contribute to SIoT by proposing the convergence among the cyber, physical and social worlds based on situation-awareness of the users short-term goals and long-term objectives. That is, first, a cognitive reasoning approach is proposed which combines objective as well as subjective aspects of SIoT context which exists in smart spaces and environments surrounding the user for the goal of achieving situational intelligence. Secondly, Semantic Web Technologies are utilized for modeling context in SIoT for the goal of achieving interoperability and automation in services interaction. Lastly, we deploy the proposed cognitive reasoning approach in two different application domains to demonstrate the improvements in services adaptability which can be achieved by considering objective and subjective SIoT context in the process of decision making. That is, architectural solution along with a proof-of-concept prototype and an experiment to evaluate the service adaptability achieved by the cognitive reasoning approach in each application domain is proposed.

Figure 1 highlights the evolution of SIoT applications. In which, the increase of connectivity in one hand; which is introduced by the interactions of individuals and communities within the IoT service loop, along with the increase in pervasiveness on another hand; which is introduced by cognitive context (i.e., the integration between objective and subjective context), can derive the evolution from IoT to SIoT. That is, the SIoT could be characterized by the improved adaptability and matching to users' preferences and needs compared to the more generic smart services proposed by IoT.



**Figure 1.1** Evolution of SIoT

## 1.2. Motivations and Research Question

Considering the heterogeneous nature of SIoT and the huge volume of data made available within its paradigm, available data, services, and applications need to be easily reachable. The use of intelligence, reasoning, searching and discovery mechanisms is mandatory when working with such a data size. Existing discovery approaches for web services such as Universal Description, Discovery and Integration (UDDI), devices profile for web services (DPWS), or RESTful-based can be adapted to deal with the requirements of SIoT related to data, services and applications lookup, and discovery. Nowadays, there are a number of approaches to discover and perform service composition in the framework of the IoT. The SIoT demands new capabilities in this area, and intelligent reasoning approaches that provide advanced functionality seem to be the best-performance option. Afterwards, standards proposed by the W3C4 such as Resource Description Framework (RDF), DARPA Agent Markup Language (DAML), or Ontology Working Language (OWL) will help providing with meaning to the data coming from users and devices. Of course, advanced data analysis (such as those proposed for Big Data [R11]) and intelligent approaches will provide utility to the SIoT, so serving users and devices with meaningful and valuable information.

The main contribution in this thesis focuses on the intelligence and reasoning mechanisms for improving decision making. The ultimate goal is to achieve an efficient integration among the cyber, physical and social worlds existing around the user for adaptive services provisioning. We aim to realize situation-awareness as a knowledge reasoning mechanism to reach intelligence about users' spatio-temporal situations. The ability to correctly manage the current context based on users' situational needs will ultimately not only improve the performance of the system, but it will also make it more usable, by providing unambiguously access and data interpretation. Semantic approaches oriented to RDF and OWL is also extended to include descriptors for SIoT users and devices characteristics, therefore facilitating the interoperability among all the components.

The general research question in this thesis is “How to achieve a situational integration among the cyber, physical and social worlds?” and “How to bring end-users closer to smart services in smart locations?” Thus, to answer these questions a longer list of questions must be addressed first:

- How to represent users' situations, including aspects from the cyber, physical and social worlds?
- What kind of application domains and user cases can benefit from the situation – awareness and intelligence in SIoT?
- What is the significance, in terms of improving the services adaptability, of applying situation awareness in smart services compared to the more traditionally utilized location-awareness?

### 1.3. Thesis Rationale

In order to solve the problems presented in Section 1.2, the following we followed a certain rationale to achieve the research goals of this thesis:

First, Although there have been studies in social-driven IoT, however there's still a gap in terms of putting a uniform definition of the SIoT architectural elements as well as differentiate it from the more traditional paradigm of IoT. Therefore, we began our research and investigation in the domain of SIoT by studying its evolutionary history from Wireless Sensor Networks (WSNs), IoT until SIoT. Additionally we studied the basic SIoT architectural elements as deduced from the literature in order to form a concrete definition of what SIoT is.

Secondly, achieving the convergence among the cyber, physical worlds for adaptive services provisioning is recently being addressed in the literature as a major challenge, where handling heterogeneity of context which arises in such smart environments is a major obstacle in very early stages of research and investigation. Additionally, adding the social aspects coming from the users and communities would only help in increasing this challenge. In this thesis we opted for achieving situational intelligence in order to reach a situational convergence among the cyber physical and social worlds. That is, achieving situational-awareness would not only contribute to characterizing users' situations and goals for adaptive service provisioning; but it would also scale down the amount of contextual data that must be dealt with prior to decision making. In this sense, the visibility scope of objects' and smart services' which could meet the users' goals will be narrowed down to the limits of specific spatio-temporal situations.

Thirdly, providing interoperability among objects is one of the most fundamental requirements to support object interaction, monitoring and discovery as well as information representation, storage, and sharing. Additionally, within SIoT automation is a requirement to seamlessly integrate objects and services into quotidian tasks in users daily live. For this goal, we utilized the Semantic Web technologies as a means to develop automated, value-added applications for SIoT. Despite the great interest in Semantic Web technologies within the more traditional paradigm of IoT, it has not yet been fully realized to achieve its anticipated great potential. This gap is to a large extent caused by the absence of attractive use case scenarios and user-centric applications.

Finally, it's noticed the lack of user-centric applications and deployment scenarios within the domain of IoT. Particularly, there's a gap concerning achieving the required adaptability in IoT services which would enable the realization of various applications and use cases within users quotidian tasks. For this purpose we aimed at realizing cognitive reasoning in two two application domains – smart recommendation and situation-dependent social structure of things. In which in the former application domain, cognitive reasoning is utilized in order to reason about users' situations in smart spaces and thus provide timely recommendation of smart services and quotidian tasks that would meet users' goals. Whereas, in the latter application domain, cognitive reasoning is utilized to reason about the available objects and services in a certain smart space which is semantically matching with the user short-term goals for the purpose of creating spatio-temporal social structure between the user and the situational relevant things in smart spaces for direct interaction and service provisioning.

## 1.4. Contributions of the Thesis

In this section, the contributions of the thesis, which is mainly presented in the original publications, are detailed. These main contributions consist of three parts:

1. A survey of the novel domain of the SIoT which takes into consideration illustrating SIoT evolution along with core definition, classification and architectural elements. To our best knowledge this is the only survey, so far, which aims at discovering the domain of SIoT.



2. A novel reasoning approach, namely cognitive reasoning, which acts as the core intelligence engine for providing adaptive and context-aware services in the SIoT. In which, to actualize the proposed cognitive reasoning approach, Semantic Web technologies has been utilized for modeling objective, i.e., spation-temporal context, as well as subjective, i.e., social-based, context in SIoT.
3. Two different applications, prototype implementation and evaluation are provided to demonstrate the functioning of the cognitive reasoning approach in real life.
  - a. The architectural design, implementation, prototype and evaluation of an intelligent, context-ware recommendation engine for task-oriented quotidian tasks in the SIoT.
  - b. The architectural design, implementation, prototype and evaluation of a rule-based temporal dynamic social structure among people, services and objects in the SIoT.
4. Two empirical evaluation studies to analyze the performance of the second and third contributions are provided, with the goal to evaluate the level of services adaptability resulting from the utilization of cognitive reasoning approach in decision making. The results achieved shows a greatly improved Precision and Recall values when compared to location-based reasoning that's widely tackled in literature. These results demonstrate that our proposed cognitive reasoning approach can enhance the level of IoT services adaptability and matching to users' needs according to situational context.

The above mentioned contributions are published in research papers. The survey provided in contribution 1 is presented in the publication number (iv). Whereas contribution 2 is published in paper number (v) and (vi). Contribution 3 is accepted for publication in paper (i). Contribution 4 is published in paper (ii) and (iii).

## 1.5. Organization of the Thesis

The organization of the thesis is as follows:

In this chapter, the background of the research topics, motivation and research problems, thesis rationale, as well as a brief overview of the contributions of this thesis are discussed.

Chapter 2 presents a literature overview of the related research topics to this thesis, including a survey of the SIoT (definition, classification, and architectural elements), context-awareness in the SIoT and related work on Semantic Web Services.

Chapter 3 summarizes the scope and methodology of the thesis. Where the motives for utilizing Semantic Web Technologies are justified as well as an analysis of context-awareness concepts which are utilized in order to achieve situation-based intelligence in SIoT is presented. Finally, a Semantic approach which is oriented to RDF and OWL which is extended to include descriptors for SIoT users and devices characteristics, so facilitating the interoperability among all the components is presented as a core methodology to achieve intelligence in SIoT.

Chapter 4 presents the main contribution of the thesis which is composed of two components: 1- Task-driven Recommendation of Quotidian Tasks in the SIoT, 2- Dynamic Social Structure of Things (DSSoT). Both components are application domains where the proposed Semantic Web technologies are deployed in order to achieve intelligent decision making in SIoT.

Chapter 5 describes a conclusion of the thesis, its limitations and presents the further work.

## Chapter 2 : Literature Review

### Contents

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## 2.1. Introduction

We are standing on the brink of a new era with real ubiquitous computing and communication where many gadgets, such as sensors, RFID tags, and smart electronic/electromechanical devices, surrounding us are being connected to the network [U05], [GBMP13]. The gadgets is currently disappearing and weaving into the fabric of our everyday life to work in concert to support us in carrying out daily life activities, tasks and rituals in an easy, natural way using information and intelligence, hidden in the network connecting the gadgets. This pervasive paradigm known as Internet of Things (IoT) might increase the value of information generated by the number of interconnection between people and gadgets, denoted by things, this in addition to machine-to-machine communication and transformation of the processed information into knowledge for the benefit of mankind and society [VFGG+11]. IoT ushers a wide range of smart services and applications to cope with many of the challenges that individuals and organizations face in their everyday lives by allowing humans and things to be connected with either anyone or anything, in any place, at any time [U05], [ZSBM11].

The IoT envisions billions of things that are able to interact with the environment around us and receive information on its status that was previously not available by simply looking at a set of things [WGLB10]. In other words, while previous Intranet of Things [WGLB10] , [UHM11], which is a local network of a set of things such as Wireless Sensor Networks (WSNs), Machine-to-Machine (M2M), and smart homes, can only extract regional information containing specific content from the things, IoT can provide large scale, comprehensive, and historical information by collaborating between different intranet of things even if they have heterogeneity regarding devices, local communication technologies, and deployment goals. Furthermore, IoT enables the creation and composition of new services and applications, offering to individual users a new ecosystem where different intranet of things can collaborate.

Humans usually interact with others in a wide variety of relationships during their everyday life. Also, they would utilize many smart services and applications from IoT to improve their life quality. Hence, quality of experience (QoE) of those services and applications depends on how to satisfy the needs driven from the relations among humans. In addition, a high degree of correctness of each need is practically derived by the collaboration with humans in the

relationship related to a service. In IoT, as mentioned above, an individual user connects to the other(s) via legacy networks; on the other hand, sets of things collaborate with each other via the Internet for offering information to smart services and applications, while each user uses them. Thus the IoT follows two interaction paradigms: human-to-human and thing-to-thing, and then humans merely utilize data from things as an old-fashioned client-server interaction model [HKHB+10], [WTJH+11]. It means that IoT so far does not adopt a true connection between humans and things, i.e., human-to-thing, for real ubiquitous computing [UHM11].

In order to practically integrate the ubiquitous computing in our future daily life with the ultimate goal of providing improved QoE, we need to improve the connectivity of all the relationships between users and things, and to enhance the availability of computational power via sets of things surrounding us. Therefore, we take into consideration Social Networks (SN) of all entities (i.e., humans and things) for ubiquitous computing as an evolution beyond the IoT. In other words, things should be socialized for allowing humans to establish relationships with them in an easy way. It does not only mean physical connections between humans and things, but also logical configurations of social communities involving humans as well as things. This logical configuration can be realized through exhibiting features from people's SN and adopts them for the suggested universal SN of all entities. The feature set can include the interactivity scheme, profiling system, recommendation, and mashup of services. This SN assists in the emerging of new communities driven by increasing sociality, inherited from traditional SNs, could give the chance to understand user requirements, and thus they also improve the availability based on trust in each community. In fact, increasing the availability of processing power would be accompanied by decreasing the visibility [U05], [W91].

This novel pervasive vision with improved sociality is denoted by Social Internet of Things (SIoT). Consequently, new ecosystems coming out when clustering social networks and IoT allow the enrichment of/from both paradigms since IoT provides the connection to the physical world by sensing and actuating while SNs contribute towards many of the daily aspects of the human world. This contribution explores the evolutionary history of what has been called SIoT, analyzes the gaps in social-driven IoT studies in early stage, with an eye on future ubiquitous computing (i.e., SIoT), and comes up with a novel architecture design that

integrates different components from previous proposals, and with newly driven requirements and research challenges for SIoT.

## 2.2. The Social Internet of Things (SIoT)

In this section, we address three questions to help in understanding the concept of SIoT and its main contributions to the current technology. Next, we discuss each question trying to raise concerns and seek solutions to them.

### **A. Why Are We Considering SN Principles to be Integrated With Real Ubiquitous Computing?**

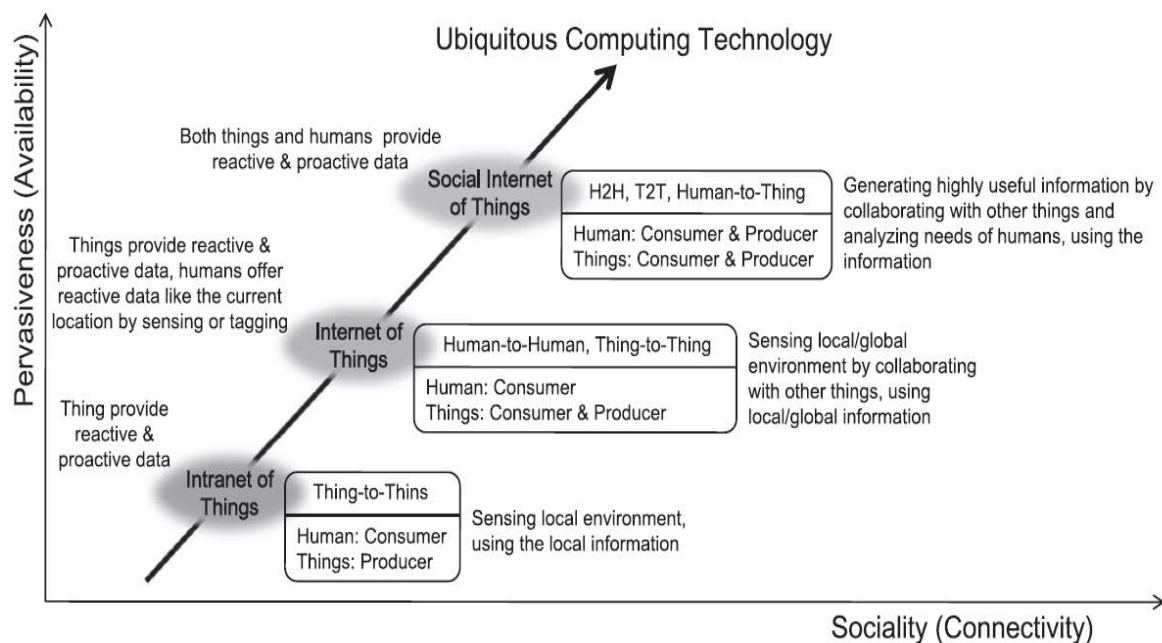
The term community of interest (COI) generally refers to a set of communicating entities [U05], [C06]; it may also be further extended to refer to a set of communicating entities engaged in wanted communication, namely “good COI” [GBMP13]. Individuals in such COI share various resources in online and offline settings. They share social relationships, interests, and contextual and multimedia resources. Also, in some scenarios they share physical devices and objects, i.e., office/home appliances. While social relationships and contextual data shared within an online community are considered as productive resources that would facilitate cooperation for mutual benefits [VFGG+11], SIoT suggests extending this principle to integrate physical elements and their contextual data from the real world into the social capital to reach a better understanding and modeling of the users’ real needs and objectives. In ubiquitous computing environments, realizing a vision of ambient intelligence [BSLB10] where many different devices, called things, will gather and process information from many different sources to control both physical processes and interactions with users, we can find diverse interaction models among devices and humans: human-to-human, thing-to-thing, and human-to-thing. They aim at supporting a wide variety of services and applications for individuals and social communities. In fact, when various scenarios of thing-to-thing interaction provide local/ global information to services, users trust and utilization of these services are considered as the core value in ubiquitous computing environments. Consequently, close interaction of human-to-thing forms the next wave of SIoT. Therefore, it eventually achieves optimization of the best services to be offered to users with improved QoE. Brought by the notion of trust in social communities, this shift from thing-to-thing

pairing toward human- to-thing implies that users are no longer only consumers of services but they also participate in creating services. This transit brings up new challenges in terms of context and communications as well as benefits. In this thesis, we mainly focus on two benefits: 1) improving services adaptability and 2) enhancing the collaboration within communities involving humans and things. On the other hand, achieving collaboration is one of the major goals of SNs. With the wealth of social and contextual data shared and stored, online presence of individuals and communities is no longer passive. They collaborate by publishing data and content aiming to meet their needs in everyday life. In SIoT vision, users and mostly devices are the core contributors to create services as well as consumers of services. The wheel starts turning from individuals and communities, it gathers social data and communicates with devices shared on the physical world to eventually offer a set of services and an enhanced collaboration back to communities and individuals. As the paradigm for ubiquitous computing [W91] implies making the computational power available anytime/anywhere and exploits it toward the benefit of mankind and societies [ZSBM11], this paradigm will not be completed without understanding society needs and challenges. Weaving the social/contextual data and relationships available within online SNs with physical thing worlds will ultimately reach this goal.

## **B. Why SIoT is the Next Step?**

Future ubiquitous computing will usher in a wide range of smart services and applications to cope with many challenges that individuals and organizations face in their everyday lives via allowing humans and things to be connected with either anyone or anything, in any place, at any time. While IoT studies [U05], [YZYN08] have typically mentioned communication to physical world by sensing or actuating through many of different devices to be the biggest novelty, SIoT paradigm, however, raises important concerns about why and how to utilize these services and applications. For this objective, there are two considerations as shown in Figure 2.1: 1) increasing social interactions (or connectivity) and 2) improving pervasiveness (or availability). In order to settle on all the properties of real ubiquitous computing in our future daily life with high QoE, we need to improve the connectivity of all the relationships between humans and things. As mentioned above, in human society, a person typically functions both as a consumer and as a producer to communicate with the others; moreover, in either physical or online world, SNs could provide long-term (or proactive) and on-demand (or reactive) information, e.g., needs, interests, locations, demographic properties, relationship

characteristics, etc., of individuals or communities through collaboration with each other. Storing, processing, and utilizing these social aspects could eventually help to improve QoE. In pervasive environments, users tend to access services anytime and anywhere using any kind of devices through any kind of communication networks. When overseen through the SIoT vision, pervasiveness will imply the weaving of actual, virtual, and physical things into SIoT. In SIoT, users themselves can unintentionally participate in the process of improving QoE through things they use and share on a daily basis which represent their interests and needs. Moreover, things will collaborate with other diverse things to satisfy their objectives which are driven from the humans. In this sense, humans and things are no longer seen as separate nodes inside a network, and their objectives and needs will weave together forming what we call SIoT. That is, such close link formation between humans and things would cause increasing availability of both elements (i.e., humans and things) as well as assuring their transparency. The two previously mentioned notions of transparency and availability will eventually drive us to the highly pervasive world, as promoted by future-driven ubiquitous computing systems.



**Figure 2.1.** Evolutionary history of ubiquitous computing technology.

### C. What Are the Key Perspectives for Future-Driven SIoT?



In order to achieve an actual implementation of the seamless integration between social and IoT worlds and to gain the benefits promoted by the SIoT vision discussed above, certain perspectives need to be considered. Figure 2.1 illustrates these perspectives together with the evolution history of ubiquitous computing technology.

**1) Interactivity Perspective:** The pairing between humans and things in IoT can take place in two forms: 1) human-to-human or 2) thing-to-thing interaction, and it can be achieved using the normal physical interaction in case of humans or various computer networks in case of things. In the current state of the art, most of the contributions focus on a single form of communication at a time whereas in this thesis, we claim that implementing human-to-thing interactions is essential to achieve the completed vision of SIoT. Such kind of communication opens the door to another level of pervasiveness in IoT environments and in fact opens the door to many other networking and communication issues that must be tackled.

**2) Collaboration Perspective:** This perspective appears to be the most important one in order to realize a complete convergence of both the social and IoT worlds because it endorses human-to-thing interactions. We explore the roles of humans and things. Considering social values, SIoT ultimately allows humans and things to act as producers or consumers, and this leads to increasing collaboration among all the entities as well as eventually enhancing QoE.

**3) Handled-Data Perspective:** It is also very important to consider the kind of data acquisition and handling techniques needed to be considered in pervasive environments. We categorize data acquisition techniques into two categories: 1) proactive data acquisition that is commonly uses crawling techniques, learning algorithms, or various data analysis algorithms and 2) reactive data acquisition which usually operate in a real-time manner using various data mining and query techniques. In SIoT, both kinds of data acquisition can be used depending on the given scenarios. For instance, location information of a user could indicate either the current location for an on-demand query or the historical trajectory by learning and analyzing. Also, this property could cause the same situation for temperature monitoring by things.

### 2.2.1. The Evolutionary Perspective: From Wireless Sensor Networks (WSN) to SIoT

WSNs appeared by the end of the last century, gaining wide attention from the research community and from a number of companies that developed commercial products using this technology. WSNs, composed of resource-constrained (i.e., battery, processing, storage, etc.) devices opened a research topic, where many studies started to propose new protocols, architectures, developments, and applications with the aim of extracting all the potential of this new paradigm [YMG08].

Many proposals were oriented to raise new ideas, while others were focused on the adaptation of existing developments to the requirements of this new technology. WSNs have typically no infrastructure. They consist of a variable number of low-power nodes (from few tens to thousands) that can communicate with each other, covering a region and working together to monitor different variables of the environment that are measured by sensors included in the nodes. Commonly, there exists a base station, central node, gateway, or sink, that gathers the data coming from network nodes to enable further data analysis. Applications for WSNs include environmental monitoring (e.g., flood detection, precision agriculture, forest fire detection and tracking, etc.), military target tracking and surveillance, health (e.g., tele-monitoring of human physiological data, patient tracking, drug administration, etc.), home and building monitoring and automation, security and surveillance, vehicular applications, warehouse management, etc. [ASSE02].

Moreover, WSNs are an important part of other technologies such as body area networks [LBMB11], vehicular networks [HL08], home automation and domotic [GP10], and smart cities [SKPT+11]. One of the main issues of WSNs is the availability of data (i.e., who and how data can be accessed). Generally, WSNs are proprietary deployments and data are private, and the use of no-standard communication approaches is very common. In that way, WSNs are isolated, and both users and devices cannot take advantage of other deployments, so increasing costs and reducing the functionality. From this point comes the idea of IoT, a network where anything, anywhere, anyone, at anytime is connected, providing communication among different networks through the use of Internet. IoT has been defined as

a world-wide network of interconnected objects uniquely addressable, based on standard communication protocols [BH08].

However, the main challenge of this technology is to find the appropriate approach to integrate generic objects (i.e., devices) into a common framework. When integrating such as number of devices with the communication capabilities expected from IoT, the application scope automatically grows, including new applications such as aerospace and aviation, automotive, telecommunications, healthcare, independent living, pharmaceutical industry, retail, logistics and supply chain management, smart cities, manufacturing, advanced environment monitoring, agriculture and breeding, media and entertainment industry, insurance, recycling, etc. [BJ11], [MSPC12]. As the interest of the community grows for the IoT paradigm, so does the need for sharing IoT data, services and applications, and the integration of ubiquitous computing in the everyday life also has to comply with social interactions. At this point is where social networking principles are progressively being integrated in the IoT, so bringing on the paradigm known as Social IoT. Section IV reviews the current technological developments that are oriented to include social skills in the loop, from the pioneer approaches that propose to publish sensor data in microblogging networks to the well-established architectures for SIoT, detailing the basics of this new paradigm, new application domains and industrial developments that are based on this technology.

### 2.2.2. From Smart Objects to Social Objects

Although the notion underlying the integration of social aspects with IoT as promoted by SIoT is still new and in an early stage of investigation, some research contributions already paved the way by offering solutions for engaging people, through Social Network Services (SNS), along with distributed sensors and embedded devices as a way to enhance services and applications. In [KRM10], for instance, the IoT paradigm is proposed to be enriched with Twitter communication capabilities to post updates and information about the status of some on-going tasks and activities. Similarly in [BK09], an approach based on WSN is presented making also use of Twitter to publish and share sensory data and resources. In [NW11], the IoT architecture is considered as a social organization framework to federate ubiquitous IoT architecture. Other approaches propose to extend the IoT through the use of SNs application

programming interfaces (APIs), for instance, [B10] suggests a platform that enables people to share their WorldWide Web-enabled devices so that others can use them.

### **A. SIoT Paradigm**

The SIoT paradigm represents an ecosystem that allows people and smart devices to interact within a social framework. On top of this framework, applications and services can be offered relying on Web technologies. To realize this framework, some major building blocks should be provided. In this section, we sum up these key aspects that constitute the basis of SIoT: the social role, intelligence, socialized devices, and everything as a service.

1) Social Role: In [AIM11], [ACI14], [AIMN12], the social role initiates from users' SN, where the argument to bring it into IoT world is to guarantee the network navigability, and an efficient service discovery. Similarly in [G11], the social role is promoted by the use of popular online SNs and their APIs to maintain a social structure and relationships with smart objects. Also, this suggested social structure allows sharing smart objects relying on the trust provided by the community. In [PCA12], users' SN accounts can help in service operation for SIoT, for instance, to utilize geo-location data or publish devices' status and updates. The social role appears in [ZCJ12] in terms of utilizing SNs as an interface to control smart objects.

2) Intelligence: In [AIMN12], the concept of intelligence is mentioned as an essential component of the SIoT paradigm which is responsible for starting, updating, and terminating the objects' relationships in SIoT. This is not only the scope of intelligence, in [G11], the notion of intelligence is to allow dynamic thing-to-thing service discovery where smart objects can understand each others' services in an automated way. The work presented in [CABC+13] envisions that intelligence is implemented as a middleware combining many technologies such as ontologies, techniques for processing user generated content, and recommendation techniques. In short, intelligence in literature appears to be limited to autonomous control systems which drive the use of services.

3) Socialized Devices: The concept of socialized devices as brought in by very early contributions in SIoT such as [AIM11], [AIM14], [AIMN12] may be the most essential

architectural component because it implies the mechanism which various smart objects and embedded devices will use to communicate with people through the Internet. Vazquez *et al.* [VL08] introduced the idea of collaboration between SNs and smart objects, an analysis of the features of social devices is also presented in this thesis, focusing on the vision of enabling smart devices to “talk” with other objects, to share experience about certain situations and to seek help. In [G11], social devices rely on Web protocols to communicate with users through an SN environment.

4) Everything as a Service: The notion of turning objects and SNs functionalities into services and enable them to be easily discovered and integrated with various other services has been presented in the literature to utilize the convergence between the social and devices roles as promoted by SIoT. Thus, people can share the services offered by smart objects with friends or objects [GFT10]. This kind of sharing implies the use of the social role to discover and promote services. However, the concept of turning “everything” to a service is presented in [AIMN12] as a wider vision, by associating smart objects with the services they deliver. The discovery of new services to be utilized or mashed-up with other services can take place endorsed by the social role, where a user can discover trustworthy services within her/his social community.

## B. SIoT Architecture

**Table 2.1**  
SIoT Architecture Design

Research Contribution	Social Role	Intelligence	Social Device	Everything as a Service
Atzori <i>et al.</i> [AIM11], [AIMN12], [AIM211], [AIMN14]			✓	✓
Atzori <i>et al.</i> [ACI14]	✓			✓
Zhang <i>et al.</i> [ZCJ12]		✓		
Pintus <i>et al.</i> [PCA12]		✓		
Ciortea <i>et al.</i> [CBZF13]	✓			
Guinard <i>et al.</i> [G11]		✓	✓	✓

In the literature, the Web of Things (WoT) is presented as an evolutionary step following the IoT paradigm [G11] where in the former, smart objects and people rely on Web standards and

protocols to interact as peers in an integrated ecosystem. The convergence between the social aspects in WoT and IoT paradigms formed the focus of many research papers; however, the two terms themselves are being alternatively used in the literature to refer to almost the same paradigm. In this thesis, we use the term SIoT; however, we consider contributions in the field of SWoT as well. Table 2.1 summarizes the research papers with their presented architectural components.

### C. SIoT Research Trends and Applications Domains

**Table 2.2**  
SIoT Research Trends

Research Contribution	Semantic Web Service	Social Cognition	Location-Based Awareness	Social Graph Analysis	Trust Management
Atzori <i>et al.</i> [AIMN12]	✓				
Pintus <i>et al.</i> [PCA12]	✓				
Guinard <i>et al.</i> [G11]	✓				
Misra <i>et al.</i> [MBO12]				✓	
BlackStock <i>et al.</i> [BLF11]				✓	
Guinard <i>et al.</i> [GFT10]	✓				✓
Lequerica <i>et al.</i> [LLR10]		✓	✓		
Mäkitalo <i>et al.</i> [MPRM+12]		✓	✓		
AN Jian <i>et al.</i> [AGZJ+13]		✓	✓		
Michelle Nitti <i>et al.</i> [NGAI+12]					✓
Fenye Bao <i>et al.</i> [BCG13]					✓

The potentials offered by SIoT make possible the development of a huge number of applications; however, due to the relatively novelty of the concept, it has not been fully exploited in many applications. We split contributions into two categories: 1) research trends utilizing the social aspects in an IoT environment to offer a higher quality of service and 2) some partially or fully implemented prototypes that propose the idea of integrating the SNs with IoT to improve aspects our daily life.

Various research trends exist in the literature, although they are not originally presented under the SIoT umbrella, they can still fit into it by combining the social role with IoT. We sum up those in Table 2.2. The research trends include semantic web service environments to enable devices and social service discovery and mash-up. Other trends focus on realizing some social aspects from online SNs or peer-to-peer SNs to offer social aware services. Location based awareness is another research trend where location data are collected and processed to offer customized services. The analysis of the SN graph has been also considered to gain understanding of the social relationships. Finally, trust management is offered to orchestrate the process of service discovery. Table 2.3 shows some of prototype examples in the field of SIoT.

#### D. SIoT- oriented Commercial Products

**Table 2.3**  
SIoT Prototype Domains

Research Contribution	Gastronomy	Smart Shopping	Smart City	Smart Home
Console <i>et al.</i> [CABC+13]	✓			
Ceipidor <i>et al.</i> [CMVM+11]		✓		
Stavroulaki <i>et al.</i> [SKFP+13]			✓	
Hussein <i>et al.</i> [HHHL+13]				✓

Many companies in different industrial sectors have already approached this new trend by using cutting-edge technologies to develop new products and services that will drive the next wave of innovation in SIoT. These social devices ranging from lowcost sensors to powerful embedded systems can gather data and communicate these data over the Internet to SNs of

people and devices who can respond to a problem, deliver a service, or sell a solution [S13]. Table 2.4 summarizes a number of off-the-shelf commercial social devices. These are very appealing products that bring the new experience of SIoT to the customers. Although, except products from that provide open APIs for third-party providers to interact with their devices, most of the products available on the market are still not capable of interacting with other third-party devices and application, this is a challenge for the future interoperability of SIoT products.

### E. Standardization Activities for SIoT

**Table 2.4**  
SIoT Commercial Products

Product	Manufacturer	Industry	Social Features	Communication	Open API
Social Vending System ( <a href="http://goo.gl/ZH7DX9">http://goo.gl/ZH7DX9</a> )	PepsiCo	Beverages	Social network of vending machine Gift/share a beverage to a friend with video messages	Wired	No
Nike+ FuelBand ( <a href="https://goo.gl/NoPquU">https://goo.gl/NoPquU</a> )	Nike	Apparel, Accessories	Fitness-tracking wristband social network. FuelBand users share their fitness data	Wireless	Yes
Nuvant MCT ( <a href="http://goo.gl/0bJmJL">http://goo.gl/0bJmJL</a> )	Corventis	Healthcare	Noninvasive, ambulatory arrhythmia monitoring Physicians, patients, and families coordinate	Wireless	No
Good Night Lamp ( <a href="http://goo.gl/Ad38Ko">http://goo.gl/Ad38Ko</a> )	Good Night Lamp	Appliances	Share your presence and availability in an ambient way	Wired	No

In order to standardize the diverse aspects of SIoT, several standardization bodies accept contributions related to the consideration of SN properties into the IoT, and also the inclusion of IoT devices into the SNs structure.



ITU-T<sup>1</sup> for instance, is focused on information and communication technologies, and proposals such as the one presented in [LRC13], that combines SNs and IoT, are part of the new era on standardization activities; oneM2M<sup>2</sup>, initiated in 2012, aims at creating a common M2M service layer to ensure that M2M communications can effectively operate in a worldwide manner. Considering the importance of SNs in the framework of IoT and thus in M2M, it is expected that a number of contributions to oneM2M are oriented to SIoT.

### 2.2.3. SIoT Architectural Elements

As stated in many research works, Social IoT appears to be the next step in the evolution of ubiquitous computing. However, there are still a number of challenges and open issues that should be faced by the research community in order to mature this technology.

After having illustrated the evolution from WSN to SIoT, described the main stages of this transformation, reviewed the literature and the commercial approaches associated to Social IoT, this section exposes the main research directions that will help to create this technology. First, we provide a general purpose architecture for SIoT that integrates the main architectural components proposed in the literature. Later, we analyze technological developments, both hardware and software that will make possible the successful operation of the paradigm. Finally, we focus on nonfunctional requirements that constitute an essential part of the SIoT ecosystem.

#### **A. Architecture—General Design**

To summarize our vision toward a future-driven SIoT, we consider the following elements to be part of the architecture: 1) actors (i.e., smart things and users); 2) an intelligent system to manage and orchestrate actors' interactions; 3) an interface for actors to enable interactions; and 4) the Internet to provide open access among all the involved entities. Next, we discuss about each element in the architecture in detail (see Figure 2.2).

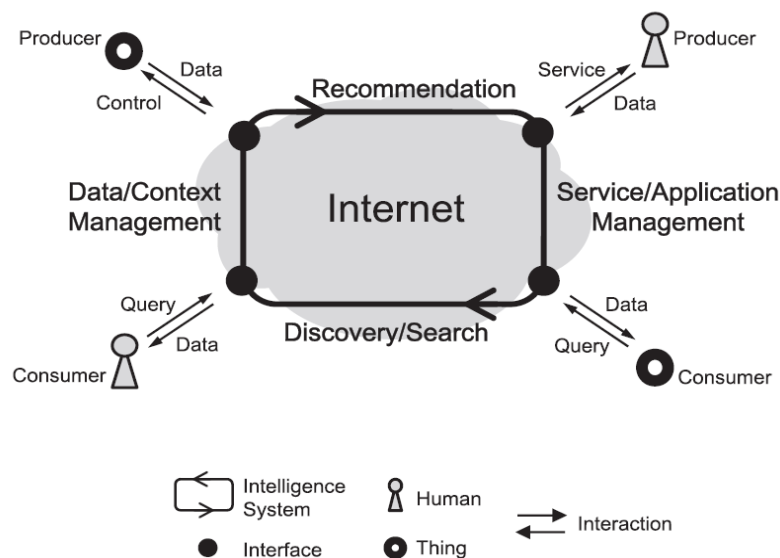
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<sup>1</sup> [Online]. Available: <http://www.itu.int/>

<sup>2</sup> [Online]. Available: <http://www.onem2m.org/>

1) Actors—the SIoT paradigm suggests a democratic environment, where both humans and things can participate equally by publishing data and receiving control commands for managing data being produced. These data can be represented as profiling data or simply responses to queries sent by users and/or devices. Queries in this sense can be sent to find the closest node, the most reliable node or service, or to simply receive updates about weather or a certain device status. In return, humans and things can receive services, or recommendations for services to consume that fulfill current situations and long term objectives, i.e., power efficiency plan for a smart grid in a smart home.

2) Intelligent system—is responsible for managing and orchestrating the whole interactions undertaken by the actors, we actually sum up the main sub systems to be part of the intelligent system such as service and applications management, recommendation, service discovery and search, and data and context management. 3) Interface—all the interactions with the system take place through an interface that enables the input of data and queries, as well as it provides the requested output (i.e., control commands or services). 4) Finally, the Internet acts as a communication medium to bring smart devices with their services to the users and also to allow them to interact with their devices and services.



**Figure 2.2.** Future SIIoT architecture.

## **B. Enabling Technologies**

In order to have a functional platform that successfully implements the requirements and achieves the objectives of SIoT, some advances in the technological field must be reached. With the objective of making any entity in the network (i.e., users and devices) identifiable and retrievable, it is necessary to map a unique identifier to each component [BS11]. Apart from the public names or nicks that will be used by the final users, the system needs an addressing scheme that enables different management tasks such as identity administration and authentication to ensure that the heterogeneity of individuals in the network can be identified.

Regarding the hardware developments, there is nowadays a vast variety of devices that can be adapted to be part of the SIoT. Sensor and actuator devices from WSN, M2M, domotic, etc., are good candidates to take part in this new paradigm. However, these devices usually cannot directly connect to the Internet, and need the use of gateways to transfer their readings and receive commands. Since many of the capabilities of SIoT are going to be accessed through web services, the use of web-enabled devices will facilitate the deployment and further use of this paradigm. Moreover, new deployments should address the energy-efficiency as a primary design goal, as well as adaptive and re-configurable interfaces and multiprotocol capabilities.

How this heterogeneous and huge network formed by billions of devices and users will communicate is also an important issue that has to be faced from the beginning. Developments oriented to enable interoperability among devices and users will be a critical pillar in the SIoT design. Again, the energy efficiency plays an essential role; operating systems, communication protocols, and algorithms that cooperate in the overall energy saving will be determinant in the establishment of SIoT. Lightweight and open middleware platforms as well as self-adaptive software will also favor the expansion of this technology. Next, we analyze some of the most relevant research and development challenges that will help to mature this technology and lead the way to the future massive deployment and everyday use of the SIoT ecosystem.

## 2.3. Context-awareness in SIoT

The convergence between computing and networking environments within smart service frameworks smart services rely on context and context-awareness [HSK09], [MSS13]. In order to provide adequate intelligent services for users, services should be aware of information surrounding users and their present status, and automatically adapt to users dynamic situations [MSS13]. Since SIoT inherits characteristics from different computing and networking environments (i.e., IoT and social networks) which has highly complex and broad properties, the nature of CA itself within the paradigm of SIoT is different than other domains. Context refers to information which characterizes situations of entities such as people, devices, organizations, and interactions between them, while CA is a methodology how to utilize context for providing relevant services that fulfill users tasks and goals [ADBD+99]. Hence, considering context-awareness in ubiquitous and pervasive computing facilitates efficient interactions and makes users situations understandable.

We analyze efforts related to CA in the SIoT in two categories; person-related context and object-related context. The novelty of this analysis comes from the importance of combining networking and computational intelligence in order to actually realize smart services with improved networking navigability, enhance scalability against large scale contextual data, reduce complexity resulting from heterogeneity of entities and improve the level of Quality of Experience (QoE). Although this analysis might appear to be common sense, current research efforts in the domain of CA in more traditional paradigms like IoT usually tackled either person or object-related context separately.

### 2.3.1. Person-related CA

Person-related CA is typically related to the social and human-related aspects which concern bringing individuals and communities everyday life activities, characteristics, preferences, relationships, surrounding environment etc. into a framework of social cognition in order to understand about users needs and behavior or to reason about the users surrounding environment.

- **Social Profiles-based Context:** Many research efforts aimed at building CA based on acquiring and reasoning about user behavior against data which are reactively provided in user profiles that spread across various SNSs. This kind of context-awareness utilizes social data about people, their relationships and reason about trust that's hidden in their communities to help provide better services. In research studies like [AIMN12], [AIM11], [ACI14], [PCA12], [CBZF13], intelligence based on SNS social profiles is proposed where the goal is to enhance connectivity between physical and online worlds and utilize this intelligence to provide better services to meet preferences.
- **Location-based Context:** Some research contributions offer a vision which is in-line with sensing and reasoning about environmental parameters surrounding users for the goal of reaching CA to improve the level of services provided. In [YLM14], for instance, consciousness about the physical environments and situations of users help in providing a more intelligent and proactive services. To reach this goal, inference of human behavior based on the analysis of acquired sensory data is proposed in literature. Similarly in [HLNL+14], a context-awareness model is proposed to orchestrate the contextual data gathered from various resources and models where the aim is to improve the level of crowd-sensing based services.
- **Body Signal Sensing and Behavior-based Context:** Gathering environmental contextual data for the goal of understanding collective behavior of people is provided generously in literature. In [CFAM+09], for instance, deals with a wireless pervasive communication system to support advanced healthcare applications. The proposed system is based on an ad-hoc interaction of mobile body sensor networks with independent WSNs already deployed within the environments in order to allow a continuous and context-aware health monitoring for patients along their daily life scenarios with an unprecedented precision and flexibility of sensing. That is, the paper relies on CA related to patient's physical location in typical daily life environments for increasing quality of healthcare application base body sensors. Similarly, in [WSVS+08], Anthony D. Wood *et al.* presents AlarmNet, an assisted living and residential monitoring network for pervasive adaptive healthcare in assisted living communities with residents or patients with diverse needs. In which, novel context-aware protocols using two-way network information flow: environmental, system, and

resident data flow into the back-end, and circadian activity rhythm (CAR) analysis feeds back into the system to enable smart power management and dynamic alert-driven privacy tailored to an individual's activity patterns.

- **Social-awareness:** In [LLR10], a solution, called DriveShare, is provided offering social services on the vehicle, where location-based CA is maintained to optimize providing such services. Authors, N. Maitalo et al, of the study [MPRM+12] suggest providing co-located social interactions where people, context sensing mobile devices are active participants and can initiate interaction among the devices and people. In [JXWJ11], on the other hand, A. X. Jian *et al.* suggest that the cognition of social relationships between mobile nodes is the basis of final mobile-aware services. In which, a framework involving decision factors, such as time, space and activity patterns and using social network theory, a new cognitive model for social relations of mobile nodes in IoT is proposed.

### 2.3.2. Object-related CA

Here, we provide literature review of up-to-dates studies on object-related CA in diverse scenarios of interconnections in legacy networks as well as infrastructure-less networks. To the best of our knowledge, CA in the more traditional domain of IoT [PZCG14] mostly focuses on person-related CA with improved sensing and monitoring methods by smart devices such as more correct location information by a tag, accurate real-time temperature surrounding a user, and so on instead of device-related data like device's condition, connecting quality, storage status, etc. Thus, we explore object-related CA in the legacy networks such as the Internet and cellular networks; however, the legacy networks are also core components of SIoT so that this review can be considered as one important part of object-related CA of SIoT.

- **CA with Cross Layering:** In the study of J. Sachs *et al.* [SKM06], context is used to reduce the delay of handover as well as to minimize the data loss during handover. That is, context transfer is used when the transmission path of a data session changes and session-related states is re-located from network nodes on the old transmission path to network nodes on the new transmission path. For Reduction of handover latency and improving throughput, the article [HNH06] designs a novel cross-layer

architecture that provides CA, smart handoff and mobility control in heterogeneous wireless IP networks based on context that is network conditions, available bandwidth, and network performance as well as interference or potentially unstable network connections. The article [TL11] takes into consideration the information required to transfer the current state of a routing-related service and contextual information from mobile devices and other sensors for improving quality of context and thus network throughput.

- **Layer-specific CA:** C. Y. Cho *et al.* [CHS04] proposed a novel reduction mechanism of packet sizes based on the TCP header as context. For this, context replication is used. Context replication is a new context initialization technique for header compression proposed by the Internet Engineering Task Force (IETF). It increases header compression gains by reducing the size of bulky initialization packets. Authors of [GMSB+09] present the design and performance of a new approach to packet switching with increased data delivery ratio and reduced latency in mobile ad hoc networks (MANETs), which we call a context-aware protocol engine (CAPE). As mentioned in [ABP11], K. Abrougui's protocols offer a scalable framework, which can increase data delivery ratio and system usage ratio, for the discovery of time-sensitive and location-based services in vehicular networks.

In consequence, through this review, we can understand the necessity of focusing on novel studies on object-related context for CA in the future, which should involve not only device information provided on top of heterogeneous environments of SIoT but also interacting data between highly diverse devices and different network technologies. Furthermore, the object-related context has to be composed and combined well with person-related context since SIoT is the social-technical network inheriting properties of both IoT and social networks. In other words, the integration of different networks brings big advantages as new intelligence to provide better smart services, but it also causes new challenges to make this new system manageable.

## 2.4. Semantic Web Services

The concept of Web Services emerged to enable the access of information distributed on the Web. With the aim of providing interoperability, SOAP and WSDL are examples of Web

services description languages which are proposed to standardize Web service access and metadata. Nevertheless, overly complex and verbose WSDL files, as well as their tedious maintenance are just two of the reasons why these technologies present a significant learning curve for developers. Although SOAP and WSDL provide interoperability, it is not enough for the automation of Web services. It is necessary to model the meaning of Web services in a way that machines can fully understand the services themselves as well as their inputs and outputs. In this sense, the Semantic Web technologies are capable of providing automatic Web service discovery, invocation and composition.

The Web has evolved on its own; the architectural REST style [FT02] has proven its success thanks to its alignment with the nature of the Internet. RESTful services basically model Web applications as a set of resources manipulated by HTTP methods (i.e., GET, POST, PUT, DELETE). RESTful services are increasingly made available over the Web; major websites such as Google, Facebook, Flickr, Salesforce and Amazon offer access to their functionality and data through RESTful APIs. By September 2013, 63% of the Web services registered in the programmableWeb were RESTfulbased, and only 20% were SOAP-based.

While SOAP-based Web services' composition has not yet been broadly successful, mashups of Web services have rapidly attracted great interest and popularity [YBCD08]. The programmableWeb contained 7190 mashups by September 2013. However, Web service communication in such mashups remains hard-coded. Since Web services are not annotated with their semantics, they cannot automatically interoperate. Recently, RESTful services have gained attention for being described by the semantics. Proposals emerged to semantically annotate RESTful services, such as hRESTS [KGV08] and SA-REST [SGL07]. The main criticism leveled at hRESTS and SA-REST is their adherence to the RPC-like interaction model, thereby disregarding the architectural properties of RESTful services. Instead of representing RESTful services as resources that can be created, updated, retrieved and deleted, these methods describe input-operation-output information as traditional RPC-based services.

SEREDASj [LG12] uses JSON to describe RESTful services as a set of resources that are semantically annotated by references to ontologies. This solution requires handling the description layer (i.e., a JSON document) and the data separately, which causes duplication of data and complicates the Web services maintenance. These reasons led the authors to propose



Hydra [LC13], which is a vocabulary that merges Web service documentation and operations following the principles of the Linked Data. The authors also proposed JSON-LD [SKL13] as the serialization format for Hydra. RESTdesc [VSDD+13] describes other work that shares the same motivation but it expresses the operation of RESTful services in Notation3. The authors of [JR12] propose a set of microformats for HTML service descriptions in a resource-oriented style. They also provide attributes to link resources with the aim of facilitating service discovery and composition.

## 2.5. Summary

The Social Internet of Things (SIoT) is a recently adopted term to refer to the integration of people and devices into the social network paradigm. The ultimate goal of SIoT is to enrich human life by seamlessly integrating their devices into their quotidian routine. We contribute to SIoT with a proposal that converge the Web, ‘things’ and users under a semantic approach. In this chapter we have reviewed the recently emerged domain of the SIoT. That is, we review the juncture of IoT with SN that defines the paradigm of SIoT. This union emerges from inheriting social networking features and values of interactivity, recommendation and filtering and services composition and suggesting a universal framework to combine users, devices and services and the interactions among them. This seamless integration allows the creation of novel user-centric services and applications which is the core goal of this study. In our state-of-the-art analysis we noticed a limitation in terms of handling context in SIoT. That is, intelligence in SIoT is usually limited to the autonomous control and service composition. However, the context of such autonomous behavior is not yet considered in literature. On the other hand, the notion of social objects is merely limited to enabling devices to comprehend, at a semantic level, the basic control operation. Thus, studying context in SIoT would contribute to enhancing the level of service adaptability and intelligence. Also, more effort should be made in order to allow social objects to comprehend users’ situations based on explicit semantic descriptions.

# Chapter 3: Research Rationale and Approach

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### 3.1. Introduction

In this chapter, we present our methodology and research approach which we utilized to realize the core contribution of this thesis which is achieving intelligence in the SIoT. While some early research efforts in the domain of SIoT suggested methods for bridging the gap between the social and physical worlds of users and communities by introducing social networks within the intelligence cycle. In this thesis we aim at achieving an efficient integration among the cyber, physical and social, worlds based on the knowledge about situations of the users and their short/long-term goals. This situation-based integration of the three worlds would contribute to:

- 1- Enhancing the personalization and the level of services' adaptability, by meeting users' situational demands.
- 2- Handling heterogeneity in terms of reducing the amount of contextual complexity which exists in SIoT as a result of the diversity of entities interacting within its paradigm.

In order to achieve this situational integration, intelligence is required. That is, understanding about the objective aspects forming a situation is required (e.g. physical location, states, environmental conditions, etc.), in addition to the understating about the subjective aspects in situations (e.g. demands, habits, situational preferences, etc.). While research efforts mainly tackles context in separation among the objective and subjective aspects, where either kinds of context are being usually considered, in this thesis we aim at combining knowledge about these two main aspects in order to gain the required situational intelligence.

We introduce the knowledge representation methodology which is utilized in order to reach situational intelligence. The deployment and evaluation of this methodology against our research goals are provided in the context of two relevant applications domains and their implementations. The contributions presented in this chapter and the following chapter is mainly presented in the original publications (except those presented in the survey Paper III).

## 3.2. *Using Semantics for Representing & Sharing SIoT Data*

### 3.2.1. Semantic Web technologies in IoT: Toward Achieving Interoperability

Evans [E11] provided an estimation indicating that there will be around 25 billion devices connected to the Internet by 2015 and about 50 billion by 2020. This huge number of highly heterogeneous and diverse objects being connected to the internet needs to communicate autonomously in various domain and applications. This implies that providing interoperability among “*things*” in IoT is one of the most fundamental requirements to support object interaction, monitoring and discovery as well as information representation, storage, and sharing. In SIoT the interoperability requirement becomes even more necessary based on the SIoT infrastructure which allows objects to communicate with Web services in order to activate a certain function. For instance, a coffee machine in an office prepares coffee every morning based on the user calendar, represented as a Web service, which indicates whether he/she are coming to the office on the regular daily time or another event will take place.

For this the technologies developed in the Semantic Web, such as ontologies, semantic annotation, Linked Data and Semantic Web Services can be used as principal solutions for the purpose of realizing the IoT. Barnaghi *et al.* [BWHT12] provided the following features to demonstrate the importance of semantics to the research and development of IoT. We find that these features are still relevant in the domain of SIoT:

- **Interoperability:** Semantic interoperability denotes the capability of various parties to access and interpret data and knowledge in a certain domain. In this sense, “Things” in the IoT need to exchange data among each others as well as among users and services on the Internet. Providing meaningful data descriptions in a way that can be processed and interpreted by things and services is a key enabler for achieving interoperability in IoT. Semantic annotation of the data (for example, with domain knowledge) can provide object-interpretable descriptions on what the data represents, where it originates from,

how it can be related to its surroundings, who is providing it, and what are the quality, technical, and non-technical attributes.

- **Data integration:** IoT data usually originates from a device or a human, and refers to attributes of a phenomenon or an entity in the physical world. The data can be combined with other data to create different abstractions of the environment, or it can be integrated to the data processing chain in an existing application to support context and situation awareness. In all these cases, it is important that heterogeneous data can be seamlessly integrated or one type of data can be combined with other cyber, social, or physical world data [HTS11]. Semantic descriptions can support this integration by enabling interoperability between different sources; however, analysis and mapping between different semantic description models is still required to facilitate the IoT data integration with other existing domain knowledge.
- **Data abstraction and access:** Data abstraction in IoT is concerned with the ways that the physical world data is represented and managed. The current research has mainly focused on representing the observation and measurement data from sensor networks according to the OGC2 (the Open Geographical Consortium) model. More recently, ontologies such as the W3C's SSN ontology [CBBC+11] have been developed, which provide a number of constructs to formally describe not only the sensor resources but also the sensor observation and measurement data. With the semantic descriptions, the sensor data, or more generally, IoT data, can also be characterized on different abstraction levels. Data access in IoT can be implemented at low-levels (e.g., device or network levels) by the use of low-level programming languages and operating systems [CC10]. Obviously, heterogeneity of the devices and (sensor) networks makes data access across the networks a difficult task. Service oriented principles, which allow complex software systems to be decomposed into smaller sub-systems or services have been used to integrate the IoT data with enterprise services [SKGS+09]. The idea of "sensing as a service" represents a scalable way to access the sensor data through standard service technologies and has received consensus from the community.

- **Resource/service search and discovery:** a resource is referred to as a device or entity that can provide data or perform actuation (e.g., a sensor or an actuator), and a service is a software entity that exposes the functionality of its corresponding resource [BBL11]. The search and discovery mechanisms allow locating resources or services that provide data related to an entity of interest in the physical world. Search and discovery are among the most important functionalities that are required in IoT. Semantic annotation of the IoT resources and services, and processing and analyzing the semantically annotated data are essential elements to support the search and discovery methods for resources, services, and real physical world entities with different attributes and functionalities. With the dynamicity of IoT and the resource-constrained nature of the many IoT resources, energy efficiency considerations for discovery (e.g., sending requests to the resource itself only when it is needed) or compensation mechanisms (e.g. when a resources becomes unavailable because of running out of power or network loss) are often needed.
- **Semantic reasoning and interpretation:** The knowledge representation formalism used by the technologies of the semantic Web allows logical reasoning that is able to infer new information or knowledge from existing assertions and rules. Semantic reasoning is an important instrument in the domain of IoT for various purposes such as resource discovery, data abstraction, and knowledge extraction. The actual inference algorithms are usually implemented within available reasoners (e.g., FACT++3 and Jena4) so IoT developers do not need to be concerned with the complexities of the reasoning process itself. Several query languages like DL Query and SPARQL can be used to construct queries to explore the semantic descriptions.

### 3.2.2. Emerging Requirements for Adopting the Semantic Web Technologies in SIoT: From Interoperability to Automation

The SIoT is aimed at integrating devices into users' daily life by taking advantage of the interconnectivity and user-friendliness of SNS. That is, SNS are proposed to as a service creation environment where users can create event-based actions involving their devices, friends, and Semantic Web services, as well as several Web APIs currently available on the Web (e.g.,

Google or Facebook APIs). In this thesis, we envisage Semantic Web technologies as a means to develop automated, value-added applications and use cases for SIoT. Despite the great interest in Semantic Web technologies within the more traditional paradigm of IoT, it has not yet been fully realized to achieve its anticipated great potential. This gap is to a large extent caused by the absence of attractive use case scenarios and user-centric applications. As we reviewed in the precious Chapter, State-of-the-Art, we notice that the service providers do not envisage the use of application scenarios where automatic Web service discovery, invocation and composition are involved. Moreover, there's another noticed gap in the domain of IoT, which is the lack of efforts for developing user-friendly and intuitive applications and context-aware use cases that would motivate users without technical skills to adopt Semantic services. The previous gap which exists in various research which we have reviewed previously hinders the realization of Semantic Web technologies in IoT fully. Thus, to overcome these gaps and to the success of Semantic Web technologies within the SIoT, we need to provide new attractive services that engage people to socialize their devices. Automation is a requirement to seamlessly integrate such services into user daily live. In this thesis, we aim to promote SIoT and dissolve the perception of the Semantic Web as a utopian promise by bringing practical applications into a familiar and easy-to-use platform.

Next we provide some features which demonstrate the emerging needs and challenges in the SIoT which requires the utilization of Semantic Web technologies:

- **Profile Portability:** This feature is used to describe the ability to reuse one's own profile across various social networking sites. Fitzpatrick *et al.* spoke from a developer's point of view about forming a decentralized social graph" [FR07]. The Semantic Web provides representation mechanisms: it links people, services and objects to record and represent the heterogeneous ties that bind us to each other. In this sense, SNS can interoperate by appealing to common semantics. SIoT-based platforms and service providers can benefit from the data portability feature facilitated by the Semantic Web technologies in a sense that it allows an augmented method in which services can be created, reused and linked to various other SNS. Ultimately, SIoT platforms would serve as a rich data sources for Semantic Web applications enabling a dynamically augmented service composition.

- **Identity and Social Network Management across SNS:** In order to augment identity and social network across many applications each service provider has to rely on some specific APIs, which means writing ad-hoc tools for each service provider. The Semantic Web technologies envision a solution to this challenge. That is, representing profile data and relationships in a shared and machine-readable way using ontologies and RDF formats is possible. The SIoT should rely a lot on this feature where user can automatically invoke and create event-based actions involving their devices, friends, and Semantic Web services which requires the shared access to identity, profile including relationships, service rating, preferences and trust.
- **Automation:** The vision which we envisage in this Thesis relies on enabling users to create timely Condition- Action (CA) rules that invoke an action on an object or a Web service (i.e., the action part of a semantic rule) when an event of interest occurs (i.e., the condition part of a semantic rule). Semantic rule events represent changes in the context, including the context of user, the social object context and the context of Web Service. Rule actions can be customized according to the nature of rule events. Thus, Semantic Web technologies with its underlying rules mechanism provides a simple mechanism for automatic service composition relying on an underlying Semantic data model, which within the context of this Thesis is modeled in ontology and RDF triples.
- **Intelligent Personalization of User Experience:** Intelligent personalization of user experience usually focuses on suggesting novel items and services based on predicting what users may find relevant. This approach doesn't take into consideration situations where users are unsure of exactly what they are looking for. In which, personalizing the relevance in information seeking activities, including recommendation and localization tasks is required. Literature has viewed relevance as a measure of the suitability of a result to the information need of the user as it is expressed in a query issued to the system [ES88]. The Semantic Web technologies provide an opportunity for richer personalization features to be developed. The availability of structured data adhering to common ontologies enables the integration of user-relevant content from more diverse sources. More importantly however, by allowing users to describe aspects of their context (such as



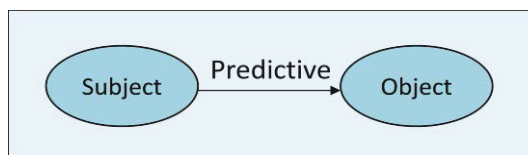
the social networks they are part of) in a standardized way, Semantic Web technologies enable new forms of personalization.

### 3.2.3. The Semantic Web as a Knowledge Representation Framework

Knowledge Representation is characterized as the combination of ontology, logic, and computation. In this section we provide a description for RDF, RDFS, and OWL to show how these techniques offer an increasingly sophisticated Knowledge Representation Framework.

#### a. Using OWL for Enriching Ontology

Ontologies are one way to describe semantic Web services and their data, the Semantic Web relies on ontologies described by RDF and OWL. OWL stands for Web Ontology Language (not WOL for esthetic reasons) and is represented in XML and built on top of Resource Description Framework (RDF) and RDF Schema (RDFS). The use of XML to represent OWL ontologies allows the interchange of ontologies between different systems and platforms. Also, RDF establishes the basis for semantic expressions using triples composed by a subject, a predicate, and an object. In Figure 3.1, the predicate or property represents the relationship that exists between things, which are represented by the subject and object.



**Figure 3.1:** An RDF Triple.

Even when OWL was designed for semantic web applications, its utilization has been spread to any area where ontologies are used. OWL is intended to allow applications to process information instead of only present it to the user. OWL comes in three sublanguage versions:

OWL lite, OWL DL, and OWL full. The difference between them is the level of expression they can reach [MVH04].

- OWL lite: it is the simplest sublanguage version of OWL. It provides a minimal subset of language features. OWL Lite provides the basics for subclass hierarchy construction: subclasses and property restrictions; but properties can be made optional or required. Implementations that support only OWL Lite are not able to perform reasoning tasks.
- OWL Description Logics (DL): it supports those users who want the maximum expressiveness while retaining computational completeness done in finite time. OWL DL includes all OWL language constructs, but they can be used only under certain restrictions, e.g. a class cannot be an instance of another class. OWL DL has a correspondence with description logics, a field of research that has studied the logics that forms the formal foundation of OWL.
- OWL Full: it is meant for users who need maximum expressiveness and the syntactic of RDF with no computational guarantees. For example, in OWL Full a class can be treated simultaneously as a collection of individuals and as an individual in its own right. OWL Full allows an ontology to augment the meaning of the pre-defined (RDF or OWL) vocabulary. It is unlikely that any reasoning software will be able to support complete reasoning for every feature of OWL Full.

In order to represent complex situations involving users, objects and Web services within the SIoT paradigm, within the scope of this Thesis we utilize OWL Full to take benefits from its expressiveness over complex situation representation. That is, the OWL Full allows an ontology to be freely mixed and augmented with the meaning of a pre-defined OWL vocabulary. It also allows full integration with RDF language (which is introduced in the following point). Other sublanguages of OWL like OWL Light is unlikely to support complete reasoning for every feature of OWL Full

## b. RDF Reasoning

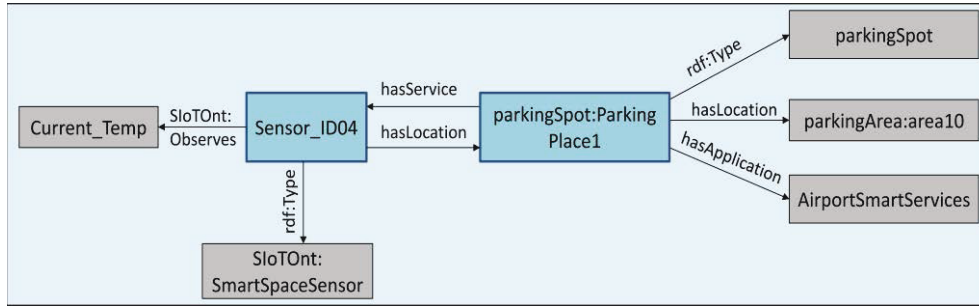
The Resource Description Framework (RDF) is a standard representation specified by the World Wide Web Consortium (W3C) for describing documents and other resources on the Internet, creating an interconnected Semantic Web [AH04]. Using a graph as its data model and using XML syntax to describe information, RDF allows data to be mixed, exported, and shared across different applications. Since Semantic Network Analysis has a graph-like data model, it makes sense to base a standard on an existing graph representation like RDF. This enables us to utilize existing tools and language bindings, making it easier to develop specialized tools since the elementary operations such as parsing the file format are performed for us. Using an existing standard also offers a potential to easily combine Content Analysis data with other Semantic Web data encoded in RDF, such as WordNet or the CIA Factbook.

As an example, Figure 3.2 presents part of an RDF description of current temperature (Current\_temp) detection sensor located in a parking spot. The triples state that a particular object is a sensor (Line 1) measuring current temperature (Line 2) located in a particular parking spot (Line 3). The parking spot (Line 5) belongs to an airport for instance (Line 6) and is located in a given area (Line 7) and the Sensor that has been the previously described sensor (Sensor\_ID04) is attached (Line 10). RDF format of the example illustrated in Figure 3.2 is shown in Listing 1.

```
1      Sensor_ID04 rdf:type SIoTOnT:SmartSpaceSensor .
2      Sensor_ID04 SIoTOnT:observes Current_Temp .
3      Sensor_ID04 hasLocation parkingSpot : ParkingPlace1 .
4
5      parkingSpot : ParkingPlace1 rdf:type ex: parkingSpot .
6      parkingSpot : ParkingPlace1 hasApplication AirportSmartServices .
7      parkingSpot : ParkingPlace1 hasLocation parkingArea :area10 .
8      parkingSpot : ParkingPlace1 SIoTOnT: attachedSystem Sensor_ID04 .
```

**Listing 1.** Example of RDF description of a parking spot occupancy detection sensor

The resulting RDF graph is shown in Figure 3.2. This shows how a sensor could provide an unambiguous machine-understandable self-description.



**Figure. 3.2.** Smart space service mapped to a smart space sensor

### c. Semantic Rules and Queries

Despite the fact that OWL is more expressive than RDF or RDFS, OWL has its limits and there are users that need more expression capabilities particularly for OWL properties. We are using technologies from the Semantic Web community such as SPARQL [HS12]. SPARQL is the standardized query language for RDF with a similar syntax as SQL. It can be used to express queries across diverse data sources, whether the data is stored natively as RDF or viewed as RDF via middleware. SPARQL contains capabilities for querying required and optional graph patterns along with their conjunctions and disjunctions. SPARQL also supports aggregation, subqueries, negation, creating values by expressions, extensible value testing, and constraining queries by source RDF graph. The results of SPARQL queries can be result sets or RDF graphs.

An example query is shown in Listing 2: This query asks for all temperature sensors with a current value between 15 °C and 25 °C. The first two lines contain namespace prefix declarations to allow using abbreviation in the query for better readability. The result set includes every resource that matches the variable ‘?s’ (Line 3). Lines 4–6 specify atomic triple patterns where known URIs and literals of triples are specified and unknown ones are marked as variables (prefixed by ‘?’). The results of the query must match with the RDF graph (in this case the type must be SloTOnt:Sensor, it must observe the property temperature, and have a value of ‘?value’). Line 7 removes results that are not in a given range (a so-called range query). In addition to these conjunctions, also disjunctive queries can be expressed using the UNION keyword.

```

1    PREFIX xsd:
2    PREFIX SIoTOnt:
3    SELECT ?s WHERE {
4        ?s SIoTOnt:Sensor .
5        ?s SIoTOnt:observes " Current_temp " .
6        ?s SIoTOnt:hasValue ?value .
7        FILTER (?value > "15"^^ xsd:integer AND ?value < "25"^^ xsd:integer )
8    }

```

**Listing 2.** Example of SPARQL query.

#### d. Semantic Services Filtering

**Table 3.1.** Service filtering relevance categories

Rule	Service Filtering Relevance
[Rule 1] Exact	If service $S$ and request $R$ are equivalent, then the match is Exact. ( $R = S$ )
[Rule 2] PlugIn	If request $R$ is super-concept of service $S$ , then the match is PlugIn. ( $R \supset S$ )
[Rule 3] Subsume	If request $R$ is sub-concept of service $S$ , then the match is Subsume. ( $R \subset S$ )
[Rule 4] Intersection	If the intersection of service $S$ and request $R$ is satisfactory, then the match is Intersection ( $R \cap S$ )
[Rule 5] Fail	If service $S$ and request $R$ are not equivalent concepts, then the match is Fail ( $R \neq S$ )

This component is responsible for applying services filtering algorithms in order to match available services in service repository with context queries. The result is a set of services, which semantically match contextual queries. To give an example about the operation of the service filtering algorithms consider a contextual request  $R$  and a service  $S$ . To validate the degree of relevance between  $S$  and  $R$ , service properties (i.e., type, input, output and contextual parameters) are matched with facts in  $R$ . Five different categories (see Table 2) can classify the match between  $S$  and  $R$  [R82]. However within the context of this thesis, a more generic service matching classification is utilized, that is:

- a.** Perfect match: It includes the Exact and Plug-in match. Where, the services resulting from the filtering process are capable of providing the requested functionality or more.
- b.** Partial match: It includes both the Subsume and Intersection match. In which resulting services are capable of partially meeting the requested functionality.
- c.** Not relevant: It includes the Disjoint match. Where services are not capable of providing the requested functionality and will not be returned to the user.

As defined above, Knowledge Representation is characterized as the combination of ontology, logic, and computation:

- **Ontology:** is the description of the things that are, i.e. the vocabulary. The semantic web does not assume or provide a certain definition of vocabulary. RDFS and OWL do provide mechanisms to define vocabulary, for example using the type, subclass, and sub-property descriptions mentioned above.
- **Logic:** The logical foundation of RDF is a very simple conjunctive-existential logic with only binary predicates. It is possible to link resources in statements and create anonymous resources (blank nodes), but it is impossible to define disjunction or general statements using universal quantifiers. RDFS adds to this a fixed set of axioms with universal quantification, for example for the transitivity of subclass definitions and the type inference for domain and range. OWL has a more expressive logical foundation in Description Logics, allowing for the expression of transitivity, disjointness, cardinality, etc. as discussed above.
- **Computation:** RDF does not have an inference mechanism, but RDF query languages such as SeRQL or SPARQL do allow for the definition of patterns that can be matched to an RDF graph, essentially a form of model checking. RDFS specifies a fixed number of inference rules; the closure of these rules is often computed at the moment the data is loaded. Since RDFS contains neither negation nor disjunction, RDFS graphs and their closure grow monotonically as more data is added, and computed inferences always remain valid. OWL has more sophisticated reasoning capacities, and a number of OWL

reasoners exist. Such reasoners can determine things such as whether an ontology expressed in OWL is consistent and whether any description, such as a conjunction of two classes, is satisfiable. OWL reasoning is not monotonic, so it is not possible to compute all inference in advance. Moreover, OWL reasoning is generally more computationally intensive than computing the RDFS closure and RDF(S) querying.

### 3.2.4. Utilizing Social Networks as a Service Creation Environment

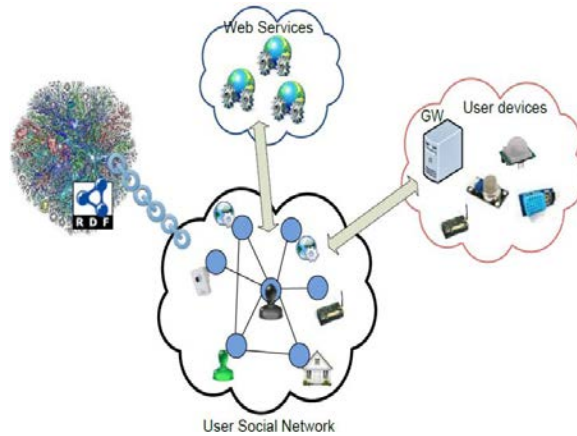
#### A. Concept

In this thesis we envisage an SNS to converge a user's world; not only their friends but also their appliances and Web services. All of these, as a whole, become context-aware, user-centric, and semantic. Devices and Web services become social since they are integrated in the SNS. Thus, each thing has a profile into the SNS, which determines the thing's graphical interfaces (i.e., walls) to users. We use the term social thing to refer to both a social Web service and a social device. The proposed SNS allows users to be continuously connected to and updated about their social things. Figure 3.3 outlines our proposal. In addition to 'friends', Web services and devices are part of the users' social network. Even logical groups of devices such as those at home or in an office can be seen as a single entity taking part in the user's social network.

Some studies such as [RMS13] and [MFSY12] have proposed service composition frameworks based on social networks. However, all of them extract information from social networks that, in some cases, is used to feed some external service creation environment. Our approach stands apart from the existing related work; we propose the social network itself as a service creation environment.

Through the proposed SNS, users can browse their social things' walls to check their status or send commands through intuitive graphical interfaces. Users can also create Condition- Action (CA) rules that invoke an action on a device or Web service (i.e., the action part of a rule) when

an event of interest occurs (i.e., the condition part of a rule). Rule events represent changes in the context of some social thing. Rule actions can be customized according to the nature of rule events. The proposed SNS therefore offers users a simple mechanism for service composition, which can be automated by relying on the underlying data model's semantics. The SNS maintains a set of interconnected OWL ontologies that describe information about people, social things, and their context. As an ontological model, it enables all the intelligence of the SNS, as well as the communication with semantic RESTful services. Moreover, the SNS works closely with a gateway that exposes semantic RESTful interfaces and is responsible for communicating with the user's devices. Through this gateway, the SNS can discover, get information from, and send commands to the user's devices. The gateway keeps the semantic description of devices and is responsible for performing the appropriate translations between the ontological model and the underlying data structures that devices understand.



**Figure 3.3.** Semantic SN for people, Web services and devices.

## B. Functionality

The SNS is the graphical interface that allows users to interact with their things and to create their own personalized automatic services. Therefore, we need to provide users with user-friendly and easy-to-use tools to navigate social things (i.e., devices that can interact in an SNS), communicate with such things, and create services. To achieve this goal, social thing profiles will contain graphical features that make it easy to understand the meaning of a thing, its functionality and



how a user can interact with it. A profile will facilitate the easy creation of simple commands and automatic actions. The proposed SNS makes it possible for people to communicate with their devices and Web services of interest by providing the following functionalities:

- **Browse social things:** The user can browse her/his social things' profiles that show information and updates (e.g., provider, location, etc.) from the "thing". The nature of such updates depends on the type of thing. For example a temperature sensor will post temperature updates on its wall and a calendar Web service will post calendar updates on its wall.
- **Receive the latest updates from a social thing:** The user can type a textual command on a social thing's wall to obtain the latest value of some information provided by the social thing. For example, a user may type on her/his home's wall give me the current temperature and the value will be posted on the home's wall.
- **Change the status of a thing:** Users will be able to type textual commands on the wall of social things whose status can be modified. This kind of interaction provides a usable manner of communicating with actuators in the physical world. As an example, a user may type turn air conditioner on her/his home's wall.
- **Create automatic actions interconnecting people and social things:** A user can set up event-triggered actions in the form of IF (condition) THEN (action) rules. For simplicity, rules contain a single action that is executed when the rule condition turns true. The condition part of a rule is a simple Boolean condition exhibited on one of the user's friends or social things such as temperature >20 or Anne's status is not busy. A social thing's profile will show icons that indicate other social things to which a thing can be connected by means of an automatic action. By clicking on one of these icons, a graphical window to assist the user in creating the rule will appear. This window will present a form with condition and action parts, which will be adapted to the characteristics of the social things to be connected. To enable this rule creation assistant, the system automatically

analyzes the ontology of social things so as to infer the possible combinations of conditions and actions that may be used by the user.

### 3.3. Towards Situation-aware Intelligence in the SIoT

Classically, intelligence within the more traditional IoT environments is being handled in a reactive way, where contextual changes are being tracked and notified to services, which in turn react accordingly. Examples of this are event-driven notifications and reminders at smart homes, best route recommendation for vehicular systems, location-aware recommendation systems, etc. However, in SIoT environments, where pro-activity and the autonomy of contextual handling are key challenges, the ability of decision-making systems and intelligence engines to anticipate changes in contextual data before it happens becomes necessary. For instance, the train comes late; accordingly, the user will arrive late for a scheduled meeting at the office. In this sense, during a spatio-temporal situation, and with some actions happening, i.e., taking a late train, certain changes on related contextual data should be anticipated and alternative solutions should be computed and sent to the services to act accordingly. Thus, understanding about the hidden goals and logic linking daily situations should be realized where in this sense contextual reasoning should act beyond filtering from a repository of smart services; it should be rather equipped with intelligent techniques in order to actively monitor and model situations and activities and provide solution-based services to meet daily needs.

#### 3.3.1. A Cognitive Reasoning Framework in the SIoT

The seamless integration between the principles of networking, or communication, along with that of computing, or intelligence, contributes toward realizing the emergence of the SIoT paradigm and services based on the evolution of pervasive and ubiquitous computing. In which:

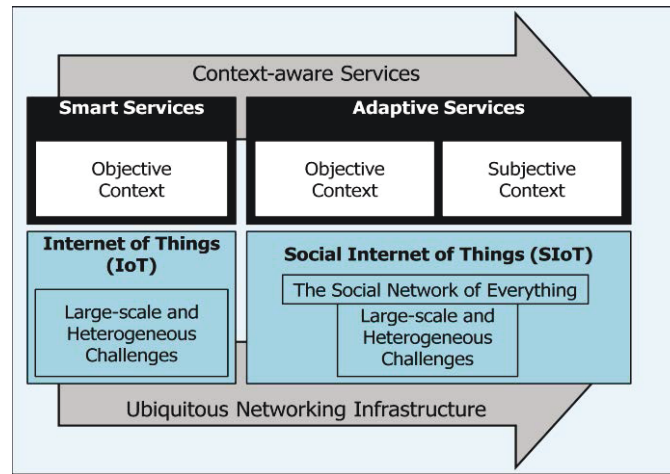
- From a networking perspective, the pattern of human-to-object communication in the traditional IoT paradigm exhibits large-scale and heterogeneous challenges due to the hundreds of smart devices and objects varying in resources and capabilities which are being connected to the Internet. On the evolutionary stream, the SIoT as a paradigm

extended from IoT, inherits the same challenges and overall it encompasses more complexity given the proposed nature of the social interactions among the social, cyber, and the physical worlds. With the main goal of handling heterogeneity in IoT and narrowing down its large-scale nature, the SIoT suggests the utilization of SNS to handle the inherited networking challenges; in which objects navigability, search and discovery is limited to those objects exposed on a social network resembling structure. In this sense, every object will acquire a certain identifier, profile and will have some relationships which allow it to act like a social entity. While this could resolve the issue of heterogeneity and object identification in the SIoT, however the adaptation of social networks properties and the utilization of the social interactions between people, objects and services add up a new challenge concerning maintaining trust and social relationships which in the SIoT.

- Whereas from a computational perspective, handling the variety of contextual data which exists in SIoT for intelligent decision making is another big challenge which is still in very early stages of research. Two kinds of context-awareness typically exist in smart environments: *objective* and *subjective* [HSK09]. The objective context describes existing states of entities, for example, certain location, states of a device, user identification, etc. The subjective context presents the cognitive states such as user's goal, preferences, mood, etc. Achieving intelligence which is driven by extracting and processing the objective aspects of context is necessary for providing smart services which could meet a broad range of users' requirements. However, in order to provide adaptive services to meet users' specific situational needs, considering the subjective aspects of context becomes a must [HSK09]. In other words, objective context refers to the settings within which a course of action emerges or the objective state of an activity, e.g., who, what, when, and where, which can be automatically sensed with a certain level of accuracy; while subjective context refers to a set of beliefs belonging to an individual or a community, e.g., purposes and preferences, which answers "why" a piece of information should be considered as "context" and "how" it affects the result.

Figure 3.4 shows the evolution of smart services along with the evolution of ubiquitous networks. With the large-scale and heterogeneous infrastructure challenges which appear within the

network of connected objects i.e., IoT, handling these challenges through intelligence generation, represented in context-awareness, based on considering its objective aspects of context, as widely addressed in the literature, helps in producing smart services which meets a broad range of users' requirements. Whereas, within SIoT which inherits the same challenges from IoT in addition to the challenges of handling a network of various social relationship between social, physical and cyber entities, i.e. The Social Network of Things, handling the objective and subjective aspects of context can help produce smart services that would adapt to users' specific situational requirements and needs.



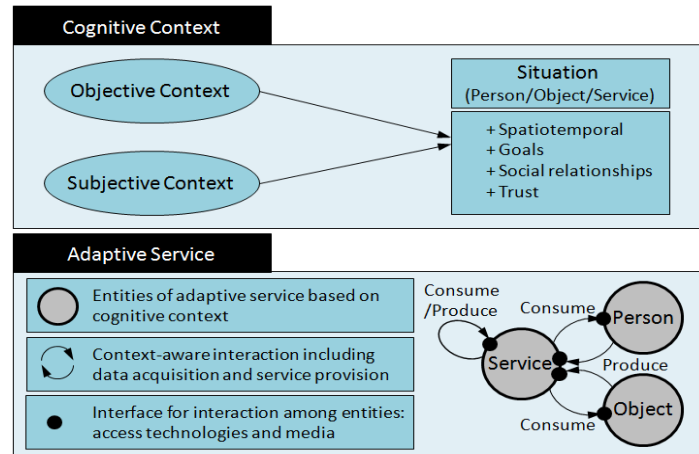
**Figure 3.4** The evolution of ubiquitous networks and context-aware Services which is led by the SIoT

The term *Cognitive context* has been introduced in the literature to refer to a model which represents the mental reasoning behind context [PZCG14]. Theories from sociology and philosophy, especially Ethnomethodology and Phenomenology, suggest that user experience, such as subjective perception of system features and past experience of similar contexts, may influence current activity [D04]. Ignoring human cognition in context analysis is therefore likely to frustrate and disorient users.

Within the scope of this thesis we represent cognitive states by combining both the objective and subjective aspects of context. While the objective context is directly utilized for external intelligence of services, the subjective context is more directed towards improving services adaptability to specific spatio-temporal situations. Both kinds of context contribute to the characterization of dynamic situations, and thus reasoning about personal preferences, social

relationships, and trust among entities to meet short and long term demands. As illustrated in Figure 3.5, three main components are essential for providing adaptive services: entities, context-aware interactions, and interfaces, represented in access technologies and media.

Context-aware interactions among entities, i.e., people, object, service, in the SIoT are based on providing and consuming services and/or data. In this sense, services itself can consumed data produced by other services to form a mashup of services etc. The interface acts as an enabler for entities' interactions. It could be considered as network interfaces including various network access or any other web-based interfaces to enable interactions taking place via the Web.



**Figure 3.5** Cognitive context in SIoT

### 3.3.2. Contributions vs. Related Work

To our best knowledge considering the modeling of cognitive states via subjective and objective context for leveraging the level of smart services adaptability in smart spaces has not been tackled in the literature. We additionally propose an ontology-based approach in order to provide information-based interoperability across the physical, cyber and social worlds. While it's very difficult to compare our work with other related work giving the highly diverse nature of the domain of SIoT, in addition to the fact that context and context-awareness are widely exploited topics in the literature within many domains and applications. In this section we try to define the comparison criteria in which we compare our work to related works in terms of two features: situational behavior analysis and social cognition. Table 3.2 summarizes the differences between our proposed contribution and relevant work in the literature.

**Table 3.2.** The contributions of the cognitive context proposed here compared to other platforms or middleware.

Research Contribution	Differences
[CFAM+09] [WSVS+08]	<ul style="list-style-type: none"> <li>➤ Doesn't support situation characterization based on social as well as physical aspects of context.</li> <li>➤ Does not have ontology support for providing information-based interoperability.</li> </ul>
[LLR10]	<ul style="list-style-type: none"> <li>➤ Does not support modeling of human social aspects of context.</li> </ul>
[MPRM+12]	<ul style="list-style-type: none"> <li>➤ Location-based context is utilized for initiating co-located interactions between users and devices; however this approach does not support modeling of human social aspects of context.</li> <li>➤ Does not have ontology support for providing information-based interoperability.</li> </ul>
[JXWJ11]	<ul style="list-style-type: none"> <li>➤ Location-based context awareness is utilized for situation characterization; however, it does not support modeling of human social aspects of context.</li> </ul>
[RKLK+12]	<ul style="list-style-type: none"> <li>➤ Similar approach in terms of considering a cognitive cycle.</li> <li>➤ It does not take into consideration context in the physical environment surrounding the user.</li> </ul>

- **Situational Behavior Analysis:** Chiti *et al.* [CFAM+09] deals with a wireless pervasive communication system to support advanced healthcare applications. The proposed system is based on monitoring ad-hoc interactions of mobile body sensors along with independent WSNs already deployed within the environments in order to allow a continuous and context-aware health monitoring for patients along their daily life. This contribution however relies solely on modeling contextual aspects which exists within patient's physical location in typical daily life environments for increasing quality of healthcare application base body sensors. Similarly, Wood *et al.* [WSVS+08] presents AlarmNet, which is an assisted living and residential monitoring network for pervasive adaptive healthcare in assisted living communities with residents or patients with diverse needs. Novel context-aware protocols using two-way network information flow: environmental, system, and resident data flow into the back-end, and circadian activity rhythm (CAR) analysis feeds back into the system to enable smart power management and dynamic alert-driven privacy tailored to an individual's activity patterns.

- **Social Cognition:** Lequerica *et al.* [LLR10], a solution, called DriveShare, is provided offering social services on the vehicle, where location-based contextual aspects are maintained to optimize providing such services. Maitalo *et al.* [MPRM+12] in their study suggest providing co-located social interactions where people, context sensing mobile devices are active participants and can initiate interaction among the devices and people. Jian *et al.* [JXWJ11], on the other hand suggest that the cognition of social relationships between mobile nodes is the basis of final mobile-aware services. They offer a framework involving decision factors, such as time, space and activity patterns and using social network theory, a new cognitive model for social relations of mobile nodes in IoT is proposed. Roussaki *et al.* [RKLK+12] proposes a context management architecture that is suitable for social networking systems enhanced with pervasive features and explored various research challenges in the area of community context management and exploitation.

### 3.3.3. SIoT Ontology-based Model

Semantic modeling for the SIoT and its more traditional ancestor the IoT has become essential in order to address the challenges of interoperability given the distributed and heterogeneous nature of "Things". However, most of the current research has primarily focused on modeling devices and physical resources while paying less attention on access, utilization and reusability of the information generated by physical objects in addition to the social information, spanning people and services, which are coming from the Web. The idea which the SIoT promotes is that things are able to expose standard service interfaces and thus it can be treated in a similar manner to standard Web services coincides with the service oriented computing and more importantly exposes a scalable means for various social services and applications which need context awareness and intelligence in order to access and consume data available in the physical world. Finally, it's an essential step in order to turn smart things into social things by allowing them to gain intelligence about their surrounding environment.

Already, we have seen many applications using semantic Web technologies in IoT research, in particular the SSN ontology [CBBC+11] for annotating sensors and sensor networks; Linked Data. However the ontological modeling provided in this section aims at representing physical

things in addition to information and social knowledge about users and smart services interacting with the things in order to bridge the gap between the cyber, physical and social worlds.

The SIoT Ontology extends some of SSN ontology vocabulary. It is a part of a project undertaken by the thesis writer which aims at modeling contextual aspects in smart spaces. The project is publicly available at this link [<http://goo.gl/oNKQst>]

### a. Context Description

In our work, we target the adaptation of different contextual aspects, describing objective and subjective context of entities which typically interact within the paradigm of SIoT; people, smart services and objects. Keeping in mind the challenge of resources limitation in most of the objects which exist in pervasive and ubiquitous environments, including limited CPU speeds and processing capabilities, a two-layer hierarchical approach for designing the ontology mode is adopted in this work: 1- general upper ontology representing general concepts and ontological classes in most pervasive environments and 2- a domain-specific ontology which represents details existing in specific domains and sub-domains i.e., home automation and smart spaces.

The upper ontology contains general context for all SIoT-based environments while the domain specific ontology is composed of details and properties which exists in a specific domain i.e., smart buildings, home automation, etc. In this subsection the description of upper ontology is presented, see Figure 3.6, whereas two domain specific ontology are described each to fit a use case and application domain in the next two sections. The detailed illustration of the upper level ontology which is independent of the application and the activity types and is presented in Figure 3.7. Whereas, the lower level ontology that populates the upper one by specific terms to an application scenario and is detailed per each application presented in the contributions which are presented in the next chapter.

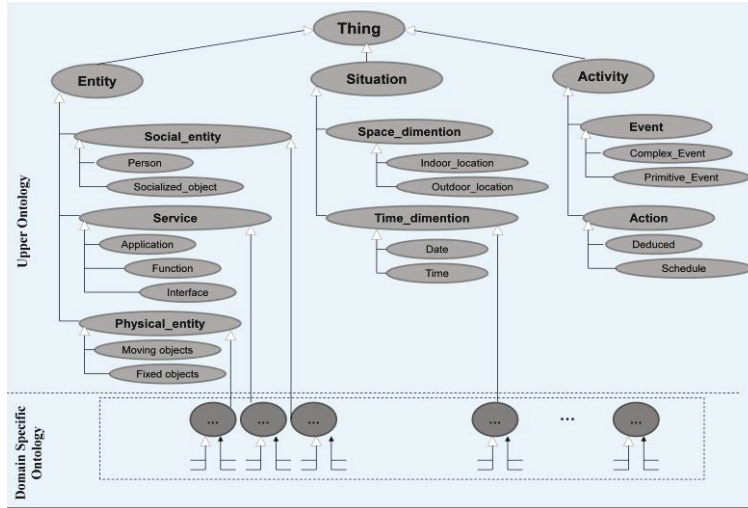
The generic level contains a concept **Event** that specifies a basic activity and/or function that is taking place in a certain physical location and is responsible for triggering the reasoning engine. The concept **Situation** represents spatio-temporal properties in which Event takes place in. The concept User describes a participant or user in a certain Event. The concept **Physical\_entity**



describes devices and objects available in a certain Situation and is participants in an Event. The concept **Service** describes the software or applications which requires either sensing a Situation, actuating a certain action or a Web service. The concept **Action** specifies a certain function to take place, via services or physical entities, in order to meet the Event goals. The concept **Time\_dimension** along with the concept **Space\_dimension** represents the current time and location value in which the Event is taking place at. The concept **Location** describes the physical space and spatial relations of involved devices and users in the system. Locations can be specified by physical representations (GPS coordinates) and symbolic high level representations (like smart places or areas identified by their names). The concept **Device** describes the hardware equipments with limited resources (like various smart space sensors). The concept **Object** describes hardware equipment that has sufficient resources to enable it to actuate a certain action (like mobile device, smart TV, robot cleaner). Finally, The Concept **Profile** specifies basic information and the status of entities which participates in an Event.

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extends the SSN ontology extends and builds on the SSN ontology. Where in addition to modeling physical devices and things, the SIoT context ontology represents users, social knowledge about users, relationships with the physical objects in a smart environment (e.g. smart home, smart airport) to bridge the gap between the cyber, physical and social worlds.



**Figure 3.6** An abstract view of the upper-level SIoT context ontology

### 3.4. Summary

In this section we provided our research rationale and approach along with the core enabling technologies and tools which we utilized in order to achieve our research goals, which is achieving situational intelligence in the SIoT. Additionally we reviewed the core contribution of this thesis compared to some relevant research effort to highlight the novelty of our research rationale. In order to evaluate the proposed research methodology we chose to deploy it first within two relevant applications domains in order to highlight its importance and evaluate the significance within real-life examples. The reason for providing two different deployment application domains is to highlight the role of the paradigm of SIoT in improving users' daily lives. Each application domain in the next chapter is presented along with a use case scenario and a prototype as a proof of concept.

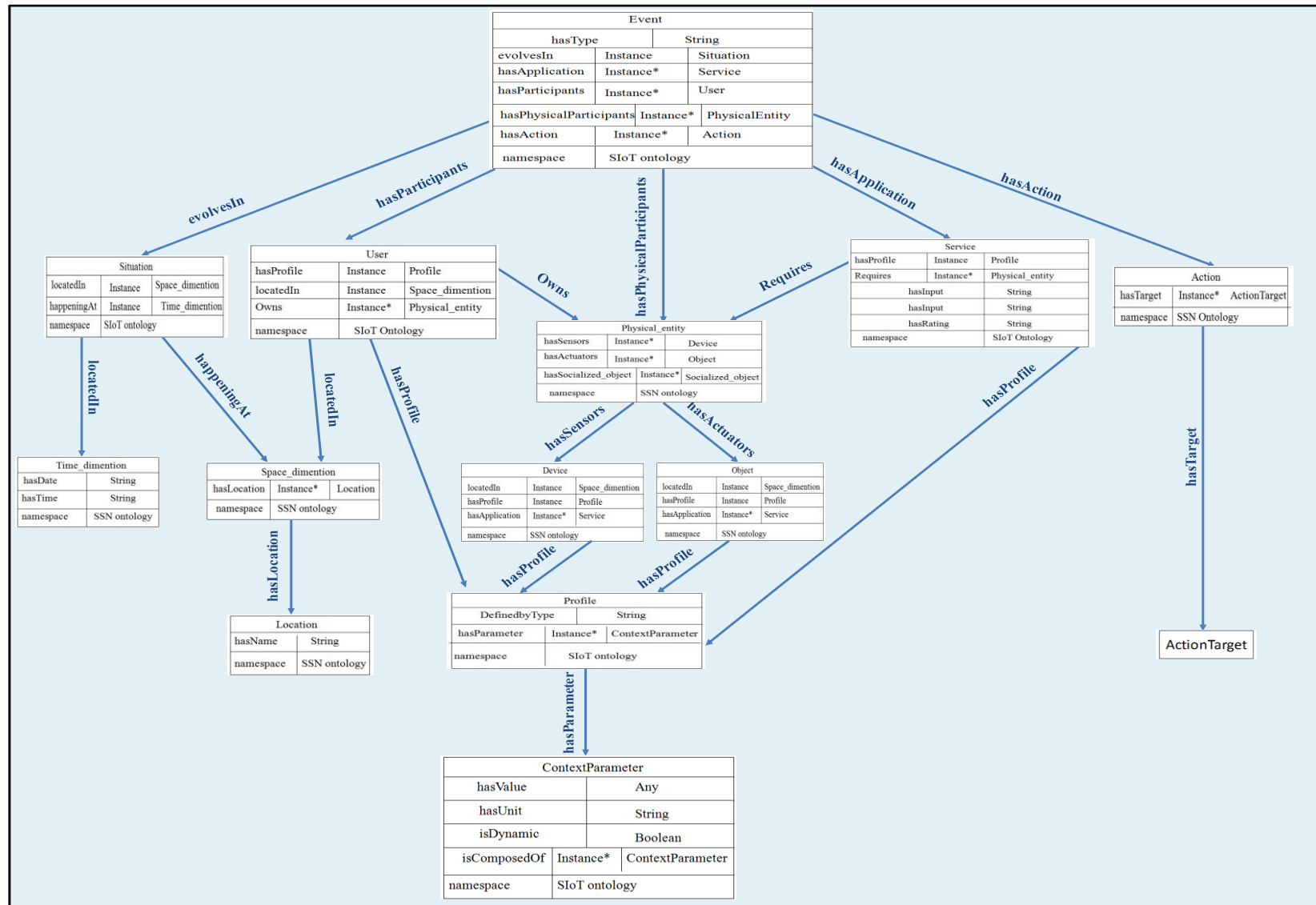


Figure 3.7 General structure of Slot context ontology.

# Chapter 4: Intelligent Decision Making in SIoT: Deployment and Applications

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## 4.1. A Cognitive Reasoning Approach for Task-oriented Recommendation in the Social Internet of Things

### 4.1.1. Introduction

Nowadays an increasingly growing number of smart objects and devices are being connected to the Internet. To benefit from the connectivity and the precious data generated by these objects smart spaces and building automation solutions and services are increasingly proliferating. However, there's still a huge need in improving the intelligence mechanisms which are required to make such solutions and smart services more adaptive to users' needs and conditions specially to aid senior people and those who need a specific medical care like people dealing with dementia.

Thus, in this contribution, we propose a novel reasoning mechanism - namely, cognitive reasoning which focuses on combining objective as well as subjective aspects of context for characterizing users' situations. This reasoning mechanism is applied within a task-oriented intelligent recommendation system, namely InRe, which recommends quotidian tasks based on users' situation in a smart home. InRe is fitted to users' situational goals, which we detect by means of schedules, preferences, daily habits as well as the devices and smart home conditions. From an architectural viewpoint, InRe is proposed as a service which could be built on top of the Social Cloud (SoC) to benefit from the contextual data extraction, reasoning and storage capabilities which is provided by SoC. From a technological viewpoint, we adopt Web Services at the device level to ensure network navigability and direct human-to-object interactions. Thus, an application named ThingsChat is provided to illustrate the operation of InRe in a smart home. We consider the light-weight version of W3C Web Service, Device Profile for Web Service (DPWS) which does not require devices with powerful capabilities to fit into the system. Our initial experiments show in adaptability of recommendation results to users' situations. Finally, within the context of this contribution we alternatively use the terms tasks, services and smart services to refer to quotidian tasks in smart home.

The content of this contribution is accepted for publication in paper (i) (see publications list in page viii).

### 4.1.2. Related Work

Collaborative filtering-based recommendation systems tend to use a rather simplistic user models. For instance, user-based collaborative filtering recommendation considers user as a vector of item ratings. As more information about users' profiles, including their preferences, location, status etc. the user models could be extended. Hence, a full utilization of user preferences and other information, which exist in user profile along with location, and time information could be used to generate recommendations and predictions [AT11]. This notion while it proved efficiency in terms of providing recommendation of smart services that matches users' preferences in a certain location and time as provided in the literature [MRMK10], it ignores the concept of *situated actions* [S87]. In which, users tend to interact with a given environment or a system within a particular context; hence users' preferences, trust, and other subjective contextual aspects within one context may vary in another context. For instance, a user may be interested in restaurant recommendation which has very good to excellent rating if he/she is going for a vacation, but they prefer moderate rating when on business trip.

In her PhD dissertation Rasch [R13] proposes the idea of smart assistant in smart homes including a recommender system that suggests useful services (i.e. actions carried out by smart devices and sensors at home). The suggested recommender system is fitted to users' current situation, habits and preferences, which are stored in some repositories prior to being utilized for generating recommendation. However, one issue was not considered by Rasch [R13] which is context-awareness. That is, contextual data like users' short term and long term goals and preferences, geographical information, calendar events extracted from social networks can be exploited for the purpose of detecting current context of users and thus provide relevant intelligent recommendation. This issue is suggested among other issues as a future work for the extensive study provided.

In the light of context-based recommendation system, the concept and applications of *Context* and *context-awareness* are interesting topics which are currently open for extensive research and investigations within various research domains including computing, networking and many other disciplines. Bazire and Brezillon [BB05] studies about 150 different definitions of context from different fields and conclude that the versatile nature of context makes it hard for researchers and people who are interested in that domain to find a unify definition for: "Is

context a frame for a given object? Is it the set of elements that have any influence on the object? Is it possible to define context a priori or just state the effects a posteriori? Is it something static or dynamic? Some approaches emerge now in artificial intelligence. In psychology, we generally study a person doing a task in a given situation. Which context is relevant for our study? The context of the person? The context of the task? The context of the interaction? The context of the situation? When does a context begin and where does it stop? What are the real relationships between context and cognition?” Although Bazire and Brezillon [BB05] do not provide a specific definition to what context is, the questions they raise does concern the domains in which context-awareness is essential or required, including recommendation systems.

Regarding achieving intelligence within the ancestor paradigm of IoT via context-awareness, a thorough analysis is presented by Perera *et al.* [PZCG14] that surveys a variety of contextual-based intelligence approaches in IoT. Where among the many challenges and future research directions they provided is the challenge of selecting sensors in sensing-as-a-service model. In which, within the highly heterogeneous environment of IoT that encompasses hundreds of connected sensors, there could be many alternative sensors to use in order to fulfill the same tasks: “let us consider a situation where an environmental scientist wants to measure environmental pollution in New York city. There are two main problems: (1) what sensors provide information about pollution? (2) when there are multiple sensors that can measure the same parameter (e.g. pH concentration in a lake), what sensor should be used?” To answer these questions Perera *et al.* [PZCG14] urged that, domain knowledge combined with IoT platforms should be achieved to answer question (1) whereas in order to answer question (2) quality frameworks for ranking sensors based on factors like accuracy, user feedback, cost, reliability are needed to be defined and employed.

Coming from the latter challenge and suggested solutions, we might rephrase similar research questions in SIoT relevant terms. That is, objects and services discovery in everything-as-a-service model might become the next logical challenge that particularly concerns the SIoT. In other words and in order to phrase some SIoT relevant research questions it would be as follows: “let us consider a situation where a conference attendee is interested in discovering available printers available in the same conference location. Two main problems arises (1) which printers provide printing services specifically for conference attendees and guests? (2) in case there are many printing services available in the conference location, which one

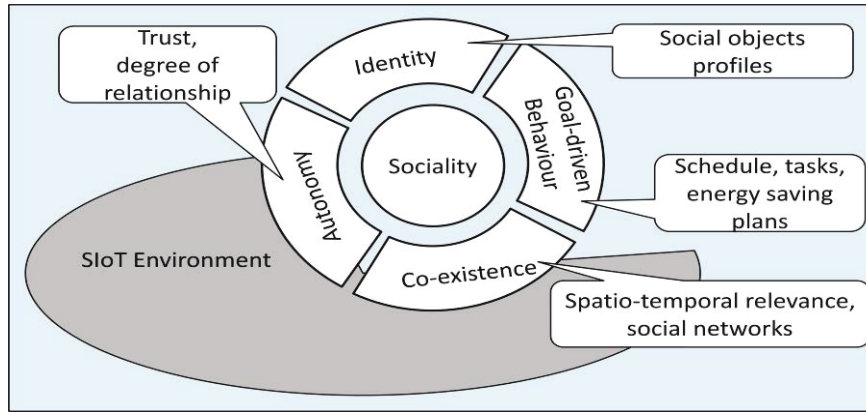
matches the attendee preference (colored or b&w printing, the page size), and/or registration package?” Addressing such questions would not only concern recommendations systems operating under the SIoT but it would also concern intelligence and context-awareness in smart spaces in general.

Along the line of the research question raised by Bazire and Brezillon [BB05] on the relationships between context and cognition, some research efforts targeted capturing and utilizing cognitive and human-centric factors of context like Mei and S. Easterbrook [ME09]. However, a quite noticeable issue arises here which is the tendency to link cognitive aspects to solely social or human-centric information. This vision could be relevant in SNS-related applications and technologies. Whereas, as the SIoT promotes the notion of turning smart objects into socially-aware entities, cognition would not be limited to human-centric aspects but additionally aspects related to the physical social objects surrounding the user. Figure 3.8 illustrates the cognitive features of social-objects, as deducted from literature, which are necessarily for turning objects from smart to socially aware ones. In addition, these features would be part of the notion of cognition that in case of the SIoT spans aspects of human as well as the surrounding social objects.

First, personality is the main cognitive feature of social entities that act in social communities. **Identity** allows social entities to carry out social role within the SIoT [AIMN12], [NW11], i.e., interacting with users within a social network of everything based on social relationship/ownership. Additionally this social role allows the entity to share, grant or revoke access to it based on relationships (ownership, friendship, etc.) and thus maintain trust with other entity on the social platform. **Goal-driven behavior** can be achieved through schedules, tasks and plans involving social objects [CBZF13]. In this sense, social objects have goals to meet which could be scheduled, inferred or directly requested by owners, e.g., a party at home involving a list of devices, energy saving plan for the summer, etc. **Co-existence** feature allows social objects to follow the small-world phenomenon, which is the notion that we are all linked through a short chain of acquaintances [K00]. In which, social objects with spatio-temporal relevance to users’ and/or exposed as social nodes on a social networking platform can facilitate their discovery, search and navigability [NW11]. Finally, **Autonomy** which is based mainly on trust that could be embedded from the social objects’ profiles represented in the degree of relationship etc.



Our goal in this contribution is not about the exploration of context-awareness in SIoT in general, and it's not about a yet new recommendation system. In this contribution we rather proposes a cognitive reasoning mechanism which combines objective as well as subjective contextual elements 1- for characterizing users' situations, 2- for inference about situational goals and thus tasks that would fit such goals. This reasoning approach is applied by a task-oriented intelligent recommendation system, namely InRe, which generates a list of quotidian tasks that are relevant to users' situations in smart homes.



**Figure 4.1.1** Cognitive aspects of social-objects in the SIoT

### 4.1.3. Approach

In order to achieve intelligence in SIoT, which entails situation characterization and proactive decision making, a detailed contextual model of users', social objects and their surroundings environment is needed. Utilizing Semantic Web Technologies would provide a scalable means for context-aware applications and services to access and reuse contextual data available in SIoT. While knowledge reuse is one important advantage of ontology, in this contribution we build on domain ontology such as friend-of-a-friend<sup>1</sup> and Semantic Sensor Network<sup>2</sup>. These domain ontology provide generic vocabularies that suit context modeling requirements. However, we extended these ontologies by adding new vocabularies aiming to utilize the context model for generating task-oriented recommendation of smart services in smart homes. In our SIoT context model we suggest two kinds of relationships between people and objects: Ownership, and authorization to use. Owners of devices or building managers can authorize users to establish social relationships with objects surrounding them (see Figure 4.1.2 (a)).

<sup>1</sup> FOAF, <http://xmlns.com/foaf/0.1>

<sup>2</sup> SSN, <http://www.w3.org/2005/Incubator/ssn/ssnx/ssn>

### a. SIoT Context Representations

The term ontology refers to the formal description of concepts which are often conceived as a set of entities, properties, instances, functions, and axioms. The Web ontology language (OWL) in this sense defines and instantiates ontologies in a manner that let Web agents interpret and exchange information based on a common sense vocabulary. Smart spaces typically cover a range of environment types like homes, offices, etc. Additionally, considering the resources limitation issue in most of smart spaces, including limited CPU speeds and processing capabilities, a two-layer hierarchical ontology model is adopted in this contribution: 1- general upper ontology (see Figure 4.1.2 (a)) representing general concepts and ontological classes in smart spaces and 2- domain-specific ontology (see Figure 4.1.2 (b)) which represents details existing in smart homes.

The contextual model shown in Figure 4.1.2 (a) - (b) represents context as ontology instances with their associated properties in which this combination is referred to as context markups. The upper ontology fragment shown in Figure 4.1.2 (a) represents context markups with relatively low changing rates. For instance, user preferences, relationships with devices, and devices associated services which are a kind of data that does not change quite often. Whereas the lower ontology fragment shown on Figure 4.1.2 (b) shows resources which provide dynamic contextual data like location, time, person status, etc. In this sense the automation of context markups is required by the applications running the ontology model. For instance, consider a mobile-device application which detects user location whenever the user presence at a certain spot exceeds 5 minutes. Thus, the mobile application composes the following OWL markup to announce user Nadia presence at the supermarket:

```
<Person rdf:about="#Nadia"> <hasLocation  
rdf:about="#Supermarket01"/> </Person>
```

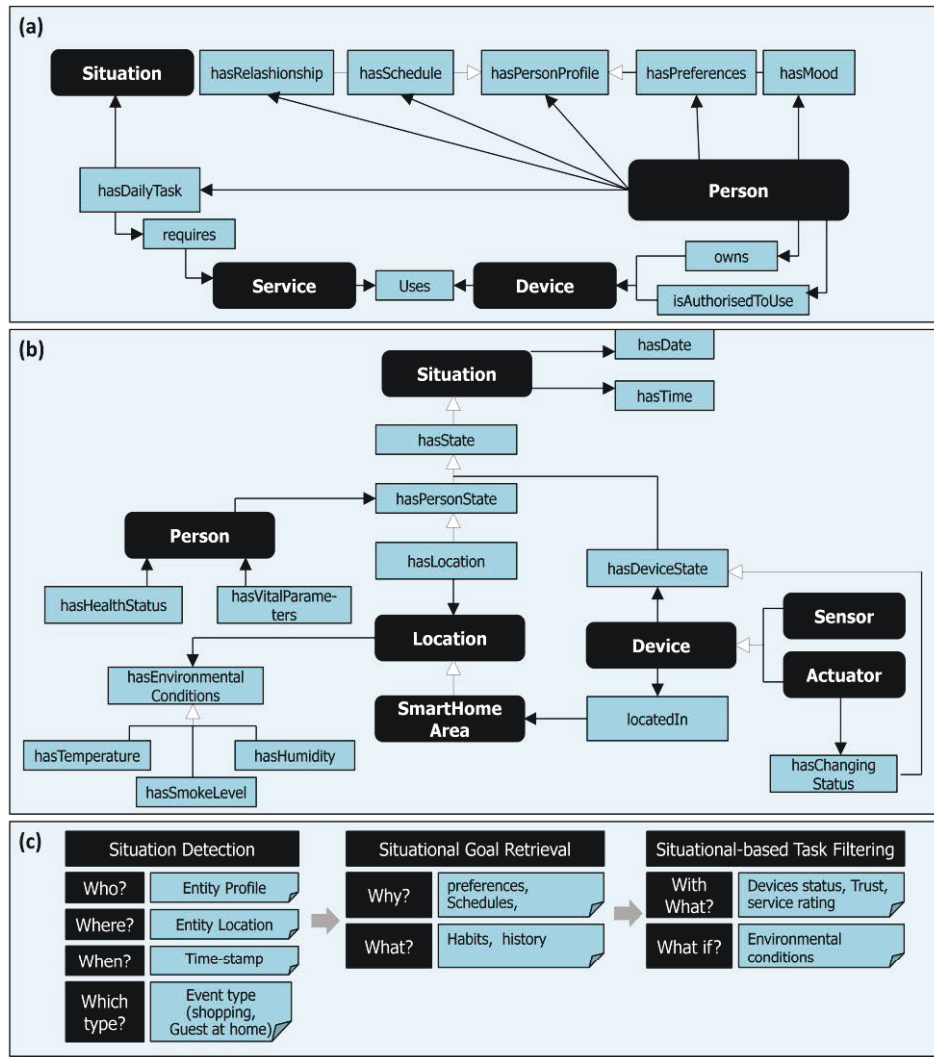
Each OWL instance, like the one shown above, has a unique URI. Thus context markups can link to other definitions using these URIs. For instance, the URI:

(<http://www.telecom-sudparis.eu/SIoTData#Nadia>) refers to a certain user and accordingly another URI refers to the supermarket which is defined somewhere else in our system.

### b. Three phases Situational Reasoning in SIoT

The SIoT context infrastructure, described above, lets applications running on top of it retrieve context using queries and it supports the inference of higher-level contexts from basic contexts. The notion of cognitive reasoning is proposed in this contribution to refer to combining the objective and subjective aspects of context in order to produce situational fitted recommendation list. The three phase situation reasoning model represents facts along seven dimensions corresponding to the so-called Seven WH-questions - what, where, when, who, with what, how, and why [14] (see Figure 4.1.2 (c)):

- **1<sup>st</sup> phase – Situation detection:** In this phase basic contextual data are exploited to identify the main entities involved in a certain situation. Thus, spatio-temporal data to detect where and when an event is taking place are fetched. Then the relevant event type is matched once based on the user location. For instance, if user Nadia's location is detected at a certain time in the supermarket, then the event is defined as "shopping". Similarly when a foreign member is detected at smart home the event is defined as "Guest at home". Finally, the whole combination of user, location, time, and event type context markups forms a situation.
- **2<sup>st</sup> phase – Situational goal retrieval:** This phase takes into consideration inferring high-level context from the basic context data fetched in the previous step. It represents contextual markups about user habits and history in similar previous situations in addition to user preferences, schedules. For instance, if user Nadia's habits are to do shopping on a Saturday while her schedule says she will be on trip on Saturday, so when she's close to the supermarket a reminder for her to do shopping would be considered as a situational goal.
- **3<sup>rd</sup> phase – Situation-based Task Filtering:** In this phase and based on the situational goals retrieved in the previous phase, a list of relevant tasks is generated. These tasks are then matched with smart services available in smart home. That is, the contextual aspects including service rating, environmental conditions, etc. are exploited for the elimination of irrelevant services.



**Figure 4.1.2.** Context representation and use in SIoT. (a) SIoT upper-ontology fragment. (b) SIoT lower-ontology fragment. (c) Three phase situational reasoning in SIoT following the 7 WH basic reasoning questions.

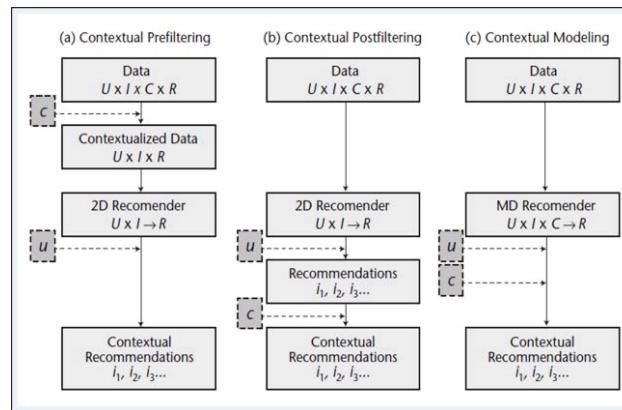
### c. Context-based recommendation paradigms

The input data for general recommendation systems typically takes the following form:  $\langle user, item, rating \rangle$ . That is, pre-stored knowledge about user preferences is mapped to a set of items:  $i_1, i_2, i_3$ , etc. This kind of recommendation is referred to as *two-dimensional recommendation* (2D) by Adomavicius, and Tuzhilin [ASST05] since they consider only user and item dimensions as input for the recommendation process. However, within context-aware recommender systems the knowledge of user preferences are inferred, as additional contextual dimension, from various contextual sources. In this sense, the input data takes the form of:  $\langle user, item, context, rating \rangle$ . Where the degree of a certain items' matching to user preferences does not only rely on how much the user likes an item but also in which context.

For instance, how much the user like the restaurant recommended to him/her within the context of a holiday, thus  $\text{context}=\text{holiday}$ . This kind of recommendation is referred to as *multi-dimensional recommendation (MD)* which uses contextual information directly as an explicit predictor of users' rating for an item [ASST05].

Context can be used in various stages of recommendation process, Adomavicius, and Tuzhilin [AT11] defined three paradigms for incorporating context in recommendations systems (see figure 4.1.3):

- **Contextual prefiltering:** Where within this paradigm context  $c$  serves as a filter for selecting a set of relevant data at the beginning of the recommendation process. For instance, if a user wants to allocate printing services available 'here' when attending a conference, if  $c$  is the conference hall then only printing services which exist in the conference hall will be returned in the recommendation list.
- **Contextual postfiltering:** Where  $c$  is used to adjust the generated recommendation list for each user. In which, the adjustments on the recommendation can be made via 1) filtering out recommendations which are irrelevant in a given context or 2) adjusting the ranking or the order of recommendations in the generated recommendation list. For example, if a user is prefers colored printing a document and needs colored printing the system will filter out b&w printers.
- **Contextual modeling:** Where  $c$  is used as a direct contextual input for predicting users' rating of an item.



**Figure 4.1.3** Paradigms for incorporating context in recommendation systems (taken from [AT11]).

$U$  = user,  $I$  = item,  $R$  = rating and  $C$  = context

Within our proposed recommendation system we consider the utilization of contextual prefiltering (see Figure 4.1.3 (a)). However, this recommendation model might be problematic due to its narrow scope. That is, relying on the exact context as a query to generate recommendation. For instance, consider the example of a user looking for a printing service ‘here’ while attending a conference, in this case  $c$  is going to be: (*user ID, printing service, user current location*) using this exact context as input for recommendation generation might either be overly specified in a sense that the recommender system would assume that the user is only interested in printing services which are tagged by the same location as the user or it could not be enough for accurate prediction of recommendation. To overcome this, we adopt the technique of *generalized* pre-filtering as proposed by Adomavicius, and Tuzhilin [AT11]. in which too specific  $c$  is mapped to generic  $c'$ . For instance (*here*  $\rightarrow$  *exact AND nearby location*).

#### d. A framework for context-aware recommendation in SIoT

There are six systems in the framework architecture: Devices, Services, People, Socialization, Intelligence and Recommendation (see Figure 4.1.4). Two lower systems of Devices and Services are used to bring Devices to upper Socialization system in a similar way that users in People system connect to it. Intelligence system consists of Semantic Rules and Semantic Reasoner to generate Inferred Data. It also has Natural Language Processor module for processing natural language and Social Search. Recommendation Decision Maker has two main components named New Event Detector and Decision Maker.

The Recommendation Engine has two main components: New Event Detector and Decision Maker (DM). The **New Event Detector** works as a driver and periodically launches new event detection command. Distributed sensors are deployed to explore changes in devices, in people’s activities or track the conversation between a user and his authorized devices. **Decision Maker** combines historical information with personal preferences for smart services recommendation. After performing the detection process, the New Event Detector sends the latest information to the Decision Maker, applying Collaborating Filter (CF) to find a set of items. As data gathered from the profiles include features description, content-based recommendation approach is expedited. The system mixes the results generated from the Mixer and the Splitter separates items into two kinds of recommendation results: Device list

and Service list. The recommendation results are finally ordered by the Ranker based on their recommendation scores.

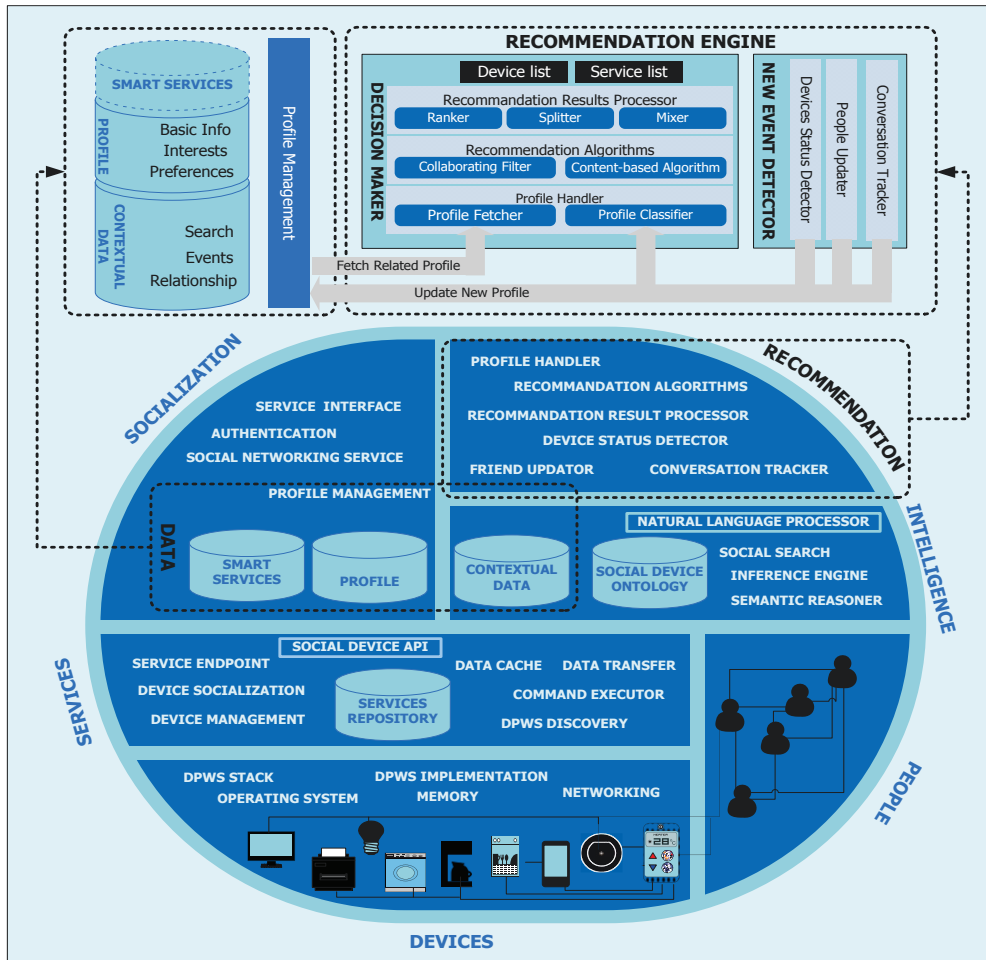


Figure 4.1.4. InRe architecture.

#### 4.1.4. InRe Framework: Towards Situation-aware Recommendation of Quotidian Tasks

As shown in Figure 4.1.5 depicts the overall recommendation system architecture which relies on the context infrastructure and the cognitive reasoning mechanism described before. The SoC is proposed from an architectural view point to store contextual data and all the reasoning and inference tasks. The framework consists of three main modules: the context management, the situation reasoning engine and the task navigator.

The user situation is first identified upon the triggering of system or user initiated events. In order to characterize users' situations and thus infer situational goals, additional contextual data are collected by the context enhancer component. Accordingly, the rule-based reasoning

component sends queries to gather information about the situation relevant goals which comprise user preferences in relevant situations, schedules as well as devices status and environmental conditions. These contextual data are then semantically matched against SIoT situation Ontology. This ontology represents common sense knowledge about typical daily tasks which corresponds to situations, i.e., turning on the robot cleaner before having guests, preparing an up-to-date shopping list when user is shopping, doing laundry before a scheduled trip, etc. Thus, a list of tasks will be sent to the situation-based services filtering module. The services filtering module semantically matches tasks with corresponding smart services using SIoT quotidian-tasks ontology. Thus is generates a recommendation list containing smart services which corresponds the user situation. Actuation of the user selected services then takes place.

### ➤ **Context management**

This module provides persistent context storage. It stores contextual markups which are gathered from context wrappers. The context wrappers are responsible for obtaining objective and subjective context from various sources such as physical objects, SNS profiles, etc. and transform them into context markups. These markups are described as OWL representations in order to make it accessed and reused by other components. This module also acts as an abstract interface for the situation reasoning engine module to extract desired context from the context enricher via queries. This lets the reasoning engine access context at the context management module.

### ➤ **Situation reasoning engine**

This module is responsible for context processing and ontology parsing based on logic reasoning. In which, developers can create their own rules based on predefined format. Once pre-defined rules are triggered, facts about the situation can be extracted and thus certain related tasks can be recommended to the user. Table 4.1 shows an example of rule-based recommendation.

- When the user is shopping, the reasoning engine checks the status of appliances at home, it detects some devices which are low on supplements (e.g., coffee machine needs a new filter, printer needs ink, dishwashing machine needs salt). It sends a list of devices needing supplements.



```

type(?user, User),locatedIn(?user, ShoppingMall),
TimerHasValueGreaterThan(currentTime(), 07:00:00),
TimerHasValuelessThan(currentTime(), 08:30:00)
→ situation(?user,AtShopping)
type(?event,AtShopping),type(?SmartHomeApplianceHasStatus,ApplianceStatus),
CoffeeMachineHasStatus (?ApplianceStatus,ChangeFilter),
WashingMachineHasStatus(?ApplianceStatus,Fine),
DishwashingMachineHasStatus(?ApplianceStatus,ChangeSalt),
PrinterHasStatus(?ApplianceStatus,ChangeInk),
TVHasStatus(?ApplianceStatus,Fine)
→ recommendation(?SmartHomeApplianceHasStatus,SupplimentsNeeded)

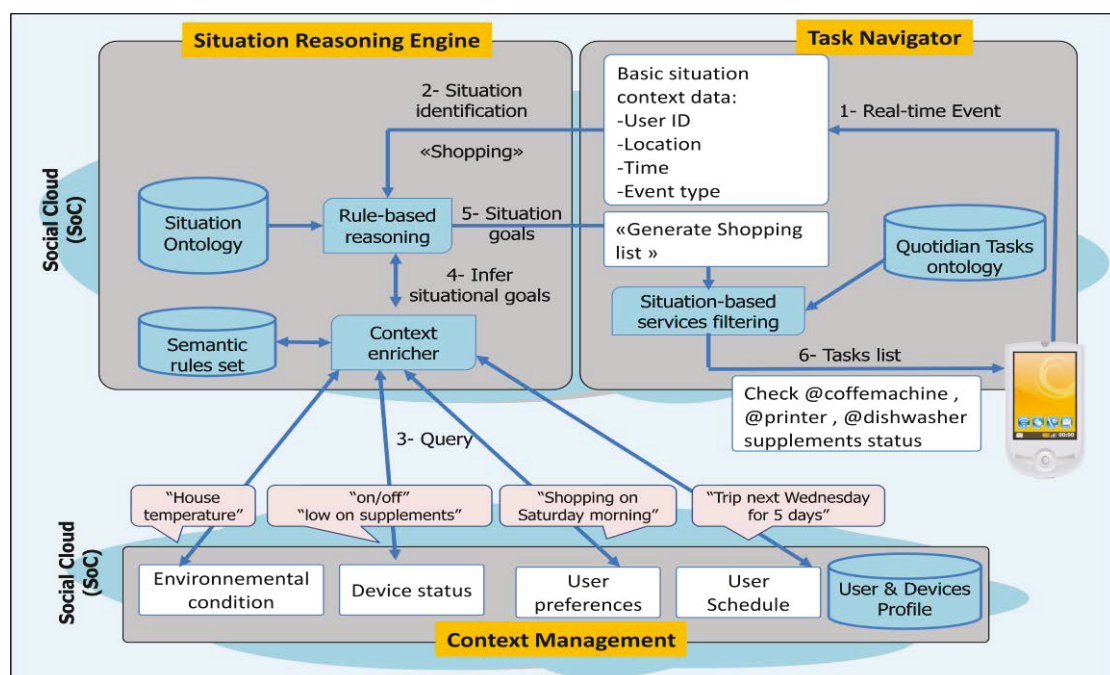
```

**Table 4.1** Sample rules to infer users' situation based on context, location and the surrounding objects

### ➤ Task navigator

This module acts as an interface for gathering basic context data, which can latter help infer more complex context, as well as display the situation relevant tasks. This module is also responsible for running situation based services filtering algorithm. In which this algorithm semantically matches situational goals against quotidian task ontology to determine which tasks the situation goals match to and which smart services can fulfill these tasks.

The architecture provided in Figure 4.1.5 has been partially implemented to reflect the functionalities of ThingsChat in a certain application scenario. The application scenarios as well as the implemented modules are presented in the following section.



**Figure 4.1.5.** The InRe framework

### 4.1.5. Application: ThingsChat

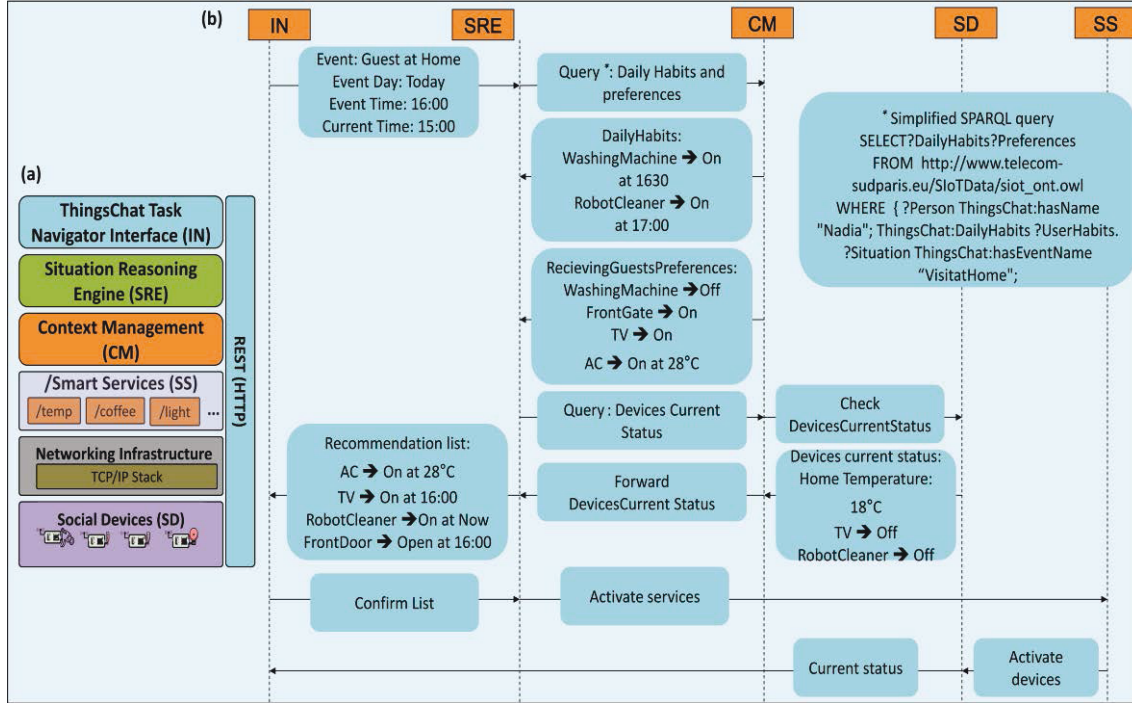
#### a. Application Scenario

In this contribution we build on SNS to converge users world, including social relationships, objects and standard Web services. That is, we build an SNS-based platform, ThingsChat, as a service creation environment enabling users to perform the following functions: create relationship with social objects, browse social objects, receive objects' status, control objects and finally receive tasks and smart home recommendations. Thus, the following application scenario highlights the main functions of ThingsChat. In addition some of the components which is discussed in the previous section are implemented within ThingsChat (see Figure 4.1.6 (a)). The detailed service procedure based on the following scenario is also provided (see Figure 4.1.6 (b)).

“Nadia is in her office and she received a text from her mother Leila who was near Nadia's house and asking if she can visit. Nadia, while unsure what tasks are needed to be done in the house, sends a message to her smart home virtual group, in ThingsChat, informing about the visit and asking to recommend a list of actions needed to make sure the house is ready to receive her mother. The InRe module inside ThingsChat will first checks for Nadia's preferences and habits when receiving a guest at home, then the condition of the house and status of devices are checked before reasoning about a list of tasks required for intelligent recommendation. After Nadia approves the recommendation list, device actions will be activated at home to prepare for the visit. While the services are running (i.e., house cleaning, dishes washing, putting the heater on, etc.), Nadia can directly interact with her coffee machine asking to prepare her mothers' favorite coffee when she arrives. The house is now ready to receive Leila.”

The architectural modules showed in Figure 4.1.6 (a) has been implemented to realize two functionalities: 1- ThingsChat as an interface allowing the direct interaction with social objects (in a simulated environment) and an extended social network that maintains profiles of users and objects. 2- The reasoning engine with a Natural Language Processing (NLP) module. The developed NLP detects and process user real-time events or queries to ThingsChat initiating certain events. For instance a user sending a message to his social objects at home informing about a guest who's planning to visit home. Then the reasoning

engine sends queries to the context knowledge base and match the query results using semantic rules to detect situational goals and thus generate tasks recommendation (see Figure 4.1.6 (b)).



**Figure 4.1.6.** InRe Application scenario. **(a)** Modules for actuating recommendation services. **(b)** InRe Service Procedure.

### a. ThingsChat: Your Things are Chatting

ThingsChat includes two modules: DPWSim and ThingsGate, which perform the communication with the underlying DPWS standards. DPWSim, introduced in [HLC14] is a Java-based simulation environment for DPWS devices with graphical interface to animate the operation of the devices. It uses WS4D JMEDS stack to handle DPWS protocols and is compatible with the DPWS Specification [HLC14]. ThingsGate is a gateway which acts as a “wrapper” to present DPWS device functionalities in RESTful style, *i.e.*, in HTTP methods (GET, PUT, POST, and DELETE), to allow applications in the Web to seamlessly interact with DPWS devices, and also to perform social networking applications. ThingsGate also provides a Social Device API to meet the requirements of designing an SNS.

We develop ThingsChat as SIoT platform for interacting with people and social objects for services provisioning. It is based on the open source phpBB Social Network with

Linux/Apache/MySQL/PHP stacks in the background. The original user profile in phpBB database is extended to store information about the gateway IP address. This information is unique for each device and used for the communication between ThingsChat and social objects (through Social Device API in ThingsGate). Figure 4.1.7 shows snapshots of ThingsChat. Listing 2 is an example of a user in ThingsChat asking his coffee maker to switch on by simply mentioning the device in his status update.

```

1      POST /mention.tsp HTTP/1.1
2      Host: http://157.159.103.10:8080
3      device_name=CoffeeMaker&post_id=135&text=switch%20on

```

**Listing 2.** POST message sent to device to switch it on when user mention the device on status share.

InRe is deployed in a separate server running Apache Tomcat, using Jena library for semantic data manipulation and the integrated reasoner for inference functionalities. The InRe collects information about Profile from the Jena reasoner and the inference engine and matches them with reasoning rules. This also provides RESTful API for the access from other ThingsChat.



**Figure 4.1.7.** ThingsChat. ThingsGate is accessed by using smartphone via the mobile Web interface to discover and manage devices at virtual home of DPWS devices created in DPWSim. Below are different ways for the communication between people and devices. (i) There is a user Nadia sending Home Appliances group on ThingsChat to ask for receiving her mother Leila who is coming home while Nadia is still at the office. (ii) InRe accesses Nadia and Leila profile to recommend a list of services to be done at home, i.e., cleaning, opening the external gate, etc. (iii) Nadia accepts then most of the recommended tasks except the TV to be switched on. She also can directly chat with the coffee maker to prepare a coffee when her mother arrives.

We also develop a small module of NLP inside the InRe module, to detect and process conversation-based events i.e., chatting. This NLP is based on the profile of each device at the setting-up phase to get the keywords of the device's functions. It also includes a set of rules for obtaining the meaning in English context. Output from NLP is then converted into semantic format and processed by the InRe, to match with the list of events stored in the context knowledgebase and to generate a recommended list of tasks. Listing 3 delineates the event called Visit at Home.

```
1    @prefix : <http://www.telecom-sudparis.eu/siot_data#> .
2    @prefix siot: <http://www.telecom-sudparis.eu/siot_ont#> .
3    :Visiting
4        a siot:ReceptionEvent ;
5        siot:hasVisitor "Leila" ;
6        siot:locatedAt :NadiaHome ;
7        siot:time "15:30" .
```

**Listing 3:** Data of Leila's visit from NLP is stored in N3 format. They are processed by Inferred Profile to get a specific list of recommended tasks at Nadia's home to serve Leila based on the predefined Visiting event.

#### 4.1.6. Performance Evaluation

Context can be incorporated in various stages of the recommendation process. In SIoT giving the richness of contextual data coming from Cyber, physical and social worlds, narrow down the amount of contextual data needed to be processed prior to decision making. We develop InRe based on Pre-filtering context paradigm [ASST05]. In which, based on a certain context, the semantic rules for recommendation generation are going to be performed against only the services with matching properties, i.e., input and output.

The effectiveness of information retrieval is mostly measured in literature by means of precision and recall. In which, precision ( $p$ ) is the proportion of retrieved results which are relevant and recall ( $r$ ) is the proportion of relevant results retrieved [R79]. Here, we measure the quality of recommendation results retrieved in terms to its relevance to users' situations in smart home by means of  $p$  and  $r$ . That is, Precision ( $p$ ) is the ratio of the number of situational relevant quotidian tasks to the total number of recommended tasks, whereas, recall ( $r$ ) is the ratio of the number of recommended situational relevant services to the total number of

relevant services existed. The F-measure is the measure of the testing accuracy with consideration to both the values of  $p$  and  $r$  (see equations 1 - 3).

$$Precision(p) = \frac{Recommended\ Services \cap Relevant\ Services}{Recommended\ Services} \quad (1)$$

$$Recall(r) = \frac{Recommended\ Services \cap Relevant\ Services}{Relevant\ Services} \quad (2)$$

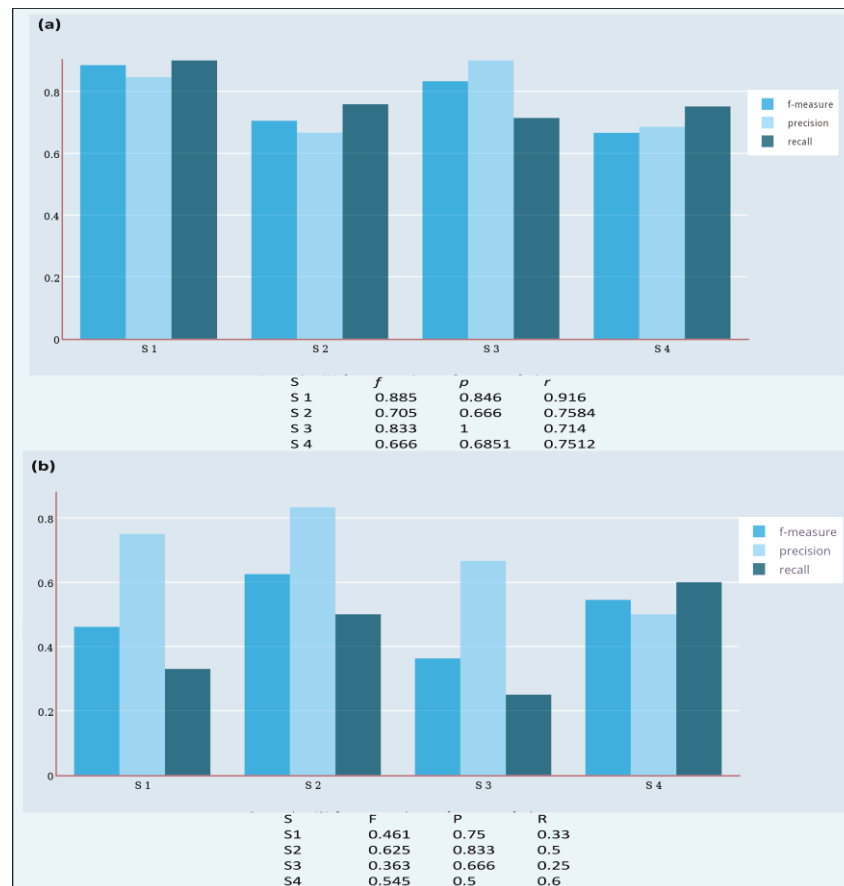
$$F - measure = 2 \cdot \frac{p \cdot r}{p + r} \quad (3)$$

We ran our experiment using a synthetic test set composed of 3,057 triples (or 600 OWL classes and instances). This dataset is created synthetically with unique classes and instances to contextually model family members in a smart home as well as model quotidian situations in smart home. In order to highlight the significance of including subjective context along with objective context in the process of recommendation pre-filtering, we calculated  $p$ ,  $r$  and  $f$  values in 4 different scenarios for smart home events: 1- Having a visit at home, 2- Shopping, 3- High temperature in kitchen and 4- Having a conference call at Home. The matched recommendation result of each scenario is evaluated by comparing two context pre-filtering methods: (a) where user's daily habits, preferences, and environmental conditions are used for generating recommendation. (b) where time, location and environmental conditions are used. The results are illustrated in Figure 4.1.8 showing an improved performance of recommendation based on method (a) versus method (b). The  $p$  and  $r$  values achieved by method (a) vary depending the relevant results achieved from the recommender but they prove to achieve a better performance than the results of method (b).

Additionally, we tested the performance of ThingsChat platform to measure its response time utilizing the following experiment setup: i) Virtual home simulated by DPWSim consisting of several DPWS devices including robot cleaners, TV, coffee maker, and floor lamps, ii) ThingsGate gateway, iii) the social network ThingsChat, and iv) The Intelligent Recommendation system (InRe). The ThingsChat and InRe are implemented on application servers on a computer with Intel(R) Core(TM) i5-2540M CPU @2.60GHz, 6GB RAM. DPWSim runs on a Windows 7 computer, and ThingsGate is implemented on a virtual machine on the same computer with one CPU, execution cap of 50%, and 512MB RAM. All servers are deployed in the same local network. We performed 25 tests focusing on the scenario of a user sending various messages to device via ThingsChat and asking it to accomplish a task. For each message, sent users' text is analyzed, matched with semantic

rules to convert it into a set of commands to be executed on the device. We achieved encouraging results with a response time stable at 2-3 second for each message sent. Figure 4.1.9) shows the processing time of the gateway for a single request from Web application ThingsChat to the underlying DPWS device. With an average of 7 ms, the gateway is considered transparent to the whole system. Due to the wording limitation and in order not to distract readers from the core scope of the contribution we did not add this performance evaluation result to our revised manuscript.

Achieving these stable results on a rather limited test-bed draws attention towards the great capabilities which could be achieved when incorporating SoC as an infrastructure for running the required reasoning processes as well as storing and managing the huge amount of contextual data.

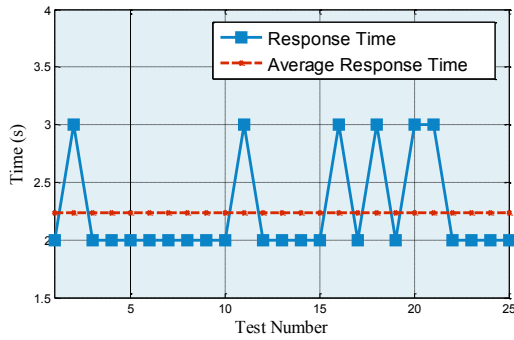


**Figure 4.1.8.** Precision and Recall Results for applying recommendation pre-filtering methods (a) and (b) on event-based recommendation scenarios 1- 4

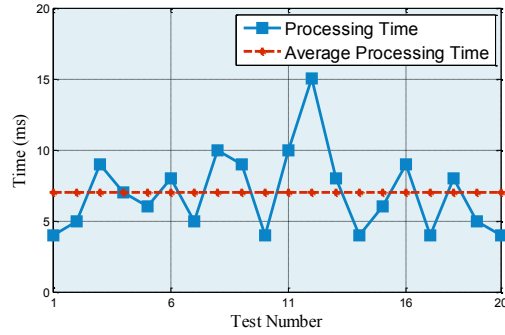
Finally, a key factor to successfully manage and evaluate the network scalability represented in the growth of the network complexity is to measure the rate of that growth by quantifying



the complexity level at any given moment in time. In this sense a demonstration of the proposed framework to show that decision making and reasoning can be performed in polynomial time is needed. That is, the network complexity does not increase as the number of users enhances. In this contribution we propose ThingsChat as a home automation platform that run a recommendation module on top of it. Thus, the scale of growth is somehow, by nature, limited to residents in a smart home and maybe some other guests. ThingsChat growth scale is hence limited. However, in the future we intend to implement ThingsChat within an elderly care house scenario where the network growth becomes a very crucial factor to maintain and measure.



(a) ThingsChat response time



(b) ThingsGate gateway processing time

**Figure 4.1.9.** Gateway Processing Time

#### 4.1.7. Summary

In this contribution we propose a cognitive reasoning mechanism for generating task-oriented recommendations for supporting users in finding appropriate smart services which correspond to quotidian tasks in smart homes. The recommendation results are fitted to users' situational goals. This reasoning approach aims at achieving intelligence in smart spaces, particularly smart homes, which would allow SIoT services to operate in an intelligent way to aid users in their daily lives. Our initial experiments which show stable results draw attention towards the great capabilities which could be achieved when incorporating SoC as an infrastructure for running the required reasoning processes as well as storing and managing the huge amount of contextual data. In the future, we plan to investigate and incorporate dynamic ranking of recommendation results in order to produce an adaptive ranked list of recommendation on-the-fly according to daily situations in various smart spaces. We also plan to investigate the utilization of trustworthiness in terms of security, privacy and usability as contextual aspects in the recommendation process with the integration between the SIoT and the SoC



## 4.2. Dynamic Social Structure of Things (DSSoT)

### 4.2.1. Introduction

This contribution proposes a novel service framework, wherein based on a cognitive reasoning approach, a temporal and goal-driven social structure combining users, objects and services can be established, namely the Dynamic Social Structure of Things (DSSoT). The proposed cognitive reasoning approach derives users' short term situational goals, and accordingly creates a filtered list of available objects and smart services which could meet such goals. This reasoning approach acts as the intelligence core for adaptive service provisioning in the SIoT and smart spaces. To realize the cognitive reasoning approach, a semantic service matching algorithm is provided. In which, contextual data are first represented ontologically to unify and share access to them. Then users' situations are being characterized according to a suggested criterion in two stages: 1- Situation Identification, 2- Situational Goal Detection. Matching the situational goals with available smart services that could meet these goals is finally accomplished before listing goal-driven services in a social structure. An empirical study analyzing the performance of the suggested reasoning approach in terms of run time complexity and the amount of contextual data needed to be processed and stored prior to decision making is additionally provided.

From a theoretical perspective, DSSoT aims at situational-relevant services localization which is location-independent. That is, unlike location-based filtering of services, reasoning about services which would meet users' situational goals would help in 1- enhancing services' adaptability by matching them to users' needs. 2- narrow-down the amount of contextual data processing where service allocation is not going to be processed each time user change his/her location, which is suitable especially in smart spaces where users' are expected to move dynamically from one location to another, e.g. airports.

From a technical perspective, this contribution attempts to explore advances of consumer-based applications in smart spaces beyond the typical applications of building and home automation. Thus, implementation of DSSoT is provided at the airport as an example of smart spaces with the goal of enabling users to easily interact with available consumer products and smart services. Additionally, in order to offer an effortless deployment of DSSoT without the

need for protocol translation gateway or intermediary server to cope with the heterogeneity of devices in smart spaces an application is provided, namely Airport Dynamic Social, to benefit from Internet Protocol version 6 (IPv6) in a smart space represented in an airport.

The content of this contribution is accepted for publication in paper (ii) (see publications list in page viii).

### 4.2.2. Related Work

#### a. Service frameworks in smart spaces

The concept of *smart spaces* refers to physical places where smart services can be provided to users via consumer electronics (CE) devices and objects which vary in capabilities and are heterogeneous in terms of their interface and the data they provide. Smart spaces are characterized by being heterogeneous, resource constrained and dynamic in terms of the context dependency behavior of nodes which can typically join or leave the smart place arbitrary [BOLU12]. Many research efforts aim at providing a smart space platform or service frameworks [BW11]. These frameworks are characterized by being highly abstract to enable easy application development. However, these frameworks are designed to fit smart spaces which are composed of rather capable devices, e.g. mobile devices, various gadgets and appliances. However, since resource constrained nodes can't run powerful application stacks, such nodes are usually enabled in smart spaces via translation gateways or intermediary servers. This leads to an increased latency to the smart services and applications and make it more difficult to install and manage [OLBU10]. A typical wireless sensor node, as shown in Figure 4.2.1 is a good example of the low-capacity nodes, which smart spaces can be composed of. Thus, facilitating heterogeneous and resource constrained node interaction in smart spaces is one of the challenges addressed in this contribution.

#### b. Problem statement

Handling the variety of contextual data which exists within smart spaces for intelligent decision making is a major challenge that is typically dealt with in the literature with a distinction between social and physical aspects of context. That is, research efforts targeting achieving context-awareness in smart spaces mainly focus on handling the objective aspects

of context which are mainly extracted from the sensors existing in the physical world. The objective aspects of context are essential for decision making, however, in order to provide personalized services that match users' preferences, emotional states, etc. extracting and reasoning about the subjective aspects of context are essential [HSK09]. In which, situational decision making is the core of what is referred to in this contribution as cognitive reasoning. To the authors' best knowledge, reasoning about cognitive elements hidden in social behavior of people and combining this knowledge with that which exists in the smart spaces for intelligent decision making in the SIoT paradigm is a challenge not yet addressed in the literature.



**Figure. 4.2.1.** Example of a resource constrained node used in smart spaces

### c. Background

The SIoT paradigm proposes enhancing the network navigability in the traditional IoT and enabling the composition of services by utilizing SNS as a service creation platform [OHPH+14], [PCA12]. However, dealing with the contextual complexity of the SIoT is another challenge which is in very early stages of research. Various research contributions have addressed the issue of contextual-based reasoning in smart spaces, many of which are listed by Bettini *et al.* [BBHI10]. However, this contextual approach among various others which are additionally presented by Perera *et al.* [PZCG14] typically deals with context with separation between its objective and the subjective aspects.

Providing context-aware services based on the interaction with sensors in smart spaces is proposed by Byun *et al.* [BP12]. In which, reasoning about energy saving services that matches user situations, at home or buildings, takes place through interaction between the sensors and a gateway. Avoiding going through an intermediary gateway for service interaction is a challenge which we are trying to address in this contribution. A rule-based framework for heterogeneous subsystem management in smart homes is proposed by Leong *et al.* [LRP09]. However, allowing the interoperability with semantic Web services (e.g.,

weather, calendar) and user profiles within this framework to allow for service composition is not considered.

Finally, while the applications of home automation, smart homes and buildings form the majority of technical implementations in the domain of smart spaces; this contribution, however, attempts to provide software advances in a next-generation CE applications domain, which in this case is the airport. According to Kaur [K13], location-based personalized services within airports, are an example of next-generation applications aiming at blurring cyber and physical space for the goal of engaging CE users [K13].

### d. Contributions

Although both semantic networks and context-awareness has been used in literature a lot to improve the scalability of *things* discovery and search in IoT [MGRP13] and other related fields, there are major important differences which we try to provide in this contribution:

First, we utilize the semantic networks to model the ad-hoc relationships between *things* and people in smart spaces, while most existing work focuses on modeling devices and physical resources while paying less attention to access, utilization and reusability of the information generated by physical objects in addition to the social information, spanning people and services, which are coming from the Web.

Second, this contribution combines semantic network with context-awareness. Using semantic networks alone would improve the recall of retrieving knowledge, however it might not improve the precision of knowledge retrieval because not all retrieved knowledge will be considered relevant to the user. This contribution, particularly, focuses on utilizing the subjective and objective aspects of context to filter-out irrelevant *things*. This approach would lead to achieving better precision and recall.

Third, there has been little work on the discovery of situational available *things* that would meet users' short term goals. This has become increasingly important in the SIoT – specially considering the large amount of physical objects and services which are becoming increasingly exposed in smart spaces. To the best of our knowledge, we are not aware of any study that

uses both semantic networks and context for discovering ad-hoc relationships between *things* and people in smart spaces. Specifically our contributions are as follows:

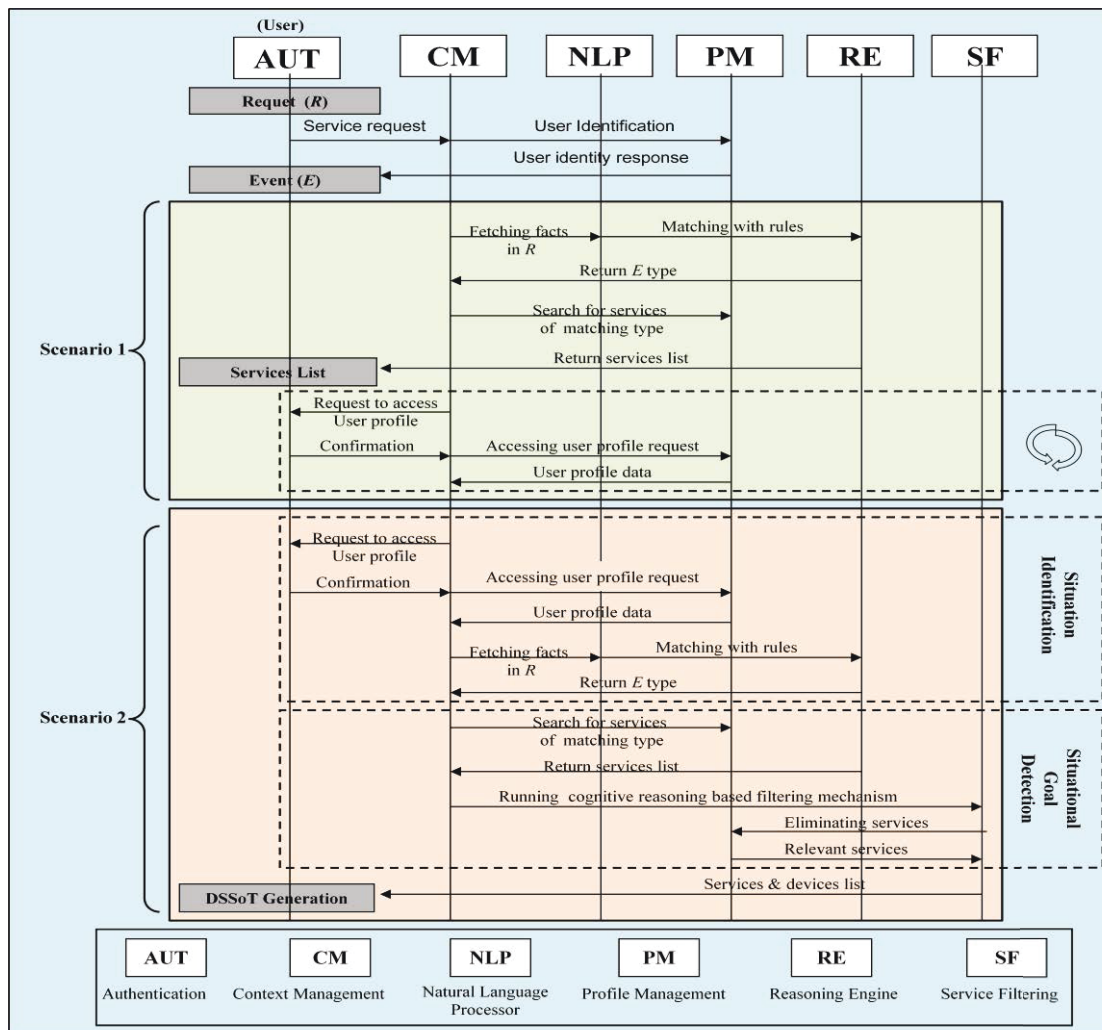
- 1- Upon the triggering of a certain event, we automatically construct a semantic network of event-relevant *things*, namely Dynamic Social Structure of Things (DSSoT) and their associated characterizing attributes.
- 2- We apply some pre-developed semantic rules in order to characterize a certain spatio-temporal situation of the users' including their short term goals.
- 3- We use the objective and subjective contextual aspects of user habits, preferences, trust, environmental conditions and device status to filter-out the list of irrelevant *things*.
- 4- We provide a prototype as a proof-of-concept to highlight DSSoT operation in a smart space, i.e., airport.

### e. Motivating Service scenarios

In order to realize the difference between the traditional services interaction scenario that is offered in the literature based on the objective reasoning (scenario 1) against the proposed novel service interaction based on objective as well as subjective, or cognitive, reasoning (scenario 2), the following two service scenarios are presented:

1- Nadia is in a foreign airport, in order to discover surrounding smart services and social objects she sends a search request. This request will be matched with services in exact or close location. For each service she selects (e.g., interacting with a coffee machine, finding the closest ATM machine, allocating the baggage claim, etc.) her authorization to use this service will be matched against the service profile. While Nadia's selected services will maintain her profile, even if she is not actually using these services after the situation ends, she will have to revoke access to individual services later when needed. Additionally, in case of any changes or updates in a certain service status (e.g., flight delay), destinations existing in the profiles of all the people registered for flight updates service, for instance, will have to be matched to each person with that of the delayed flight; and so on for any other update (Scenario 1 in Figure 4.2.2).

2- When Nadia make a search request to find services nearby, her preferences, schedules, service rating will be matched once with the services profiles in an exact or close location. Social objects and smart services which match Nadia's goals and destination while she has authorization to access will be listed. Finally, a temporal, spontaneous, social structure can be established between Nadia and these objects/services, for direct service interaction, which will expire by the end of the situation, where access to Nadia's profile will be automatically revoked for privacy and security considerations. If there is a change in flight status, or in case of any updates, while the destination of Nadia was processed *a priori*, no further matching is required for sending a particular flight status update (Scenario 2 in Figure 4.2.2).



**Figure. 4.2.2.** Objective vs. cognitive-based services scenarios in the SIoT. In Scenario 1, users' profiles and/or level of authorization are matched for each service selected. In Scenario 2 users profiles as well as authorization level and goals are detected once to allow interaction with all relevant services.

As demonstrated in the previous two scenarios, two main motivations for establishing DSSoT arise: 1- With the heterogeneity and the large scale of contextual complexity needed to be

handled, dealing with the integration among cyber, physical and social knowledge should be limited to the scope of situations, thus reasoning about the cognitive elements within these situations is the key to reach efficiency in smart spaces. 2- dynamicity is one of the main features characterizing smart spaces, additionally in order to maintain privacy and security in handling social profile data; social relationships and interactions among people, services and objects in the SIoT should be established and maintained in a temporal manner where outside certain spatio-temporal situations such relationships should automatically vanish.

### 4.2.3. DSSoT Conceptual Framework

Based on the SIoT context ontology model provided in Chapter 3 which aims at providing a semantic infrastructure for context-aware services in SIoT and for intelligent decision making, here we present the DSSoT conceptual framework, including the architecture and problem definition. The core functionality of DSSoT architecture is to acquire context from a diversity of resources, and transfer it into semantic knowledge which can be easily shared and accessed by context-aware services. Then by applying semantic rules and services matching, selection algorithms a semantic network of situational-relevant services can be initiated.

#### a. DSSoT: A novel service framework

As shown in Figure 4.2.3 the DSSoT approach can be realized through a service management framework allowing goal-driven interactions among a diversity of entities for providing and consuming services in CPSS environments. The intelligence generation initiates when an event is triggered which could be via 1) real-time requests for services or event initiation, where facts are extracted from the requests using a Natural Language Processor (NLP); or 2) sensing the users' condition, users' surrounding environment, device status update etc. where the Context Management conducts the acquisition and storage of contextual data; or 3) an event stored in user profiles i.e., schedules where facts about an event is extracted and handled by Profile Management. To perform situational reasoning, semantic rule-based matching (see Figure 3.c) is carried out by the Semantic Service Relevance assessment Rules Engine (SSRRE), which can eventually scale down the scope of services and objects discovery. Based on the filtered list of matching objects and services extracted from SSRRE, DSSoT can be generated and managed by the Service Controller. When the service itself is provided, an NLP model is required at this level to allow direct interactions between users and

objects. Finally, the feedback acts as an essential contextual data for the adaptive service learning conducted by the CPSS Service Management. A detailed service procedure to be built on top of this framework is presented in the following section.

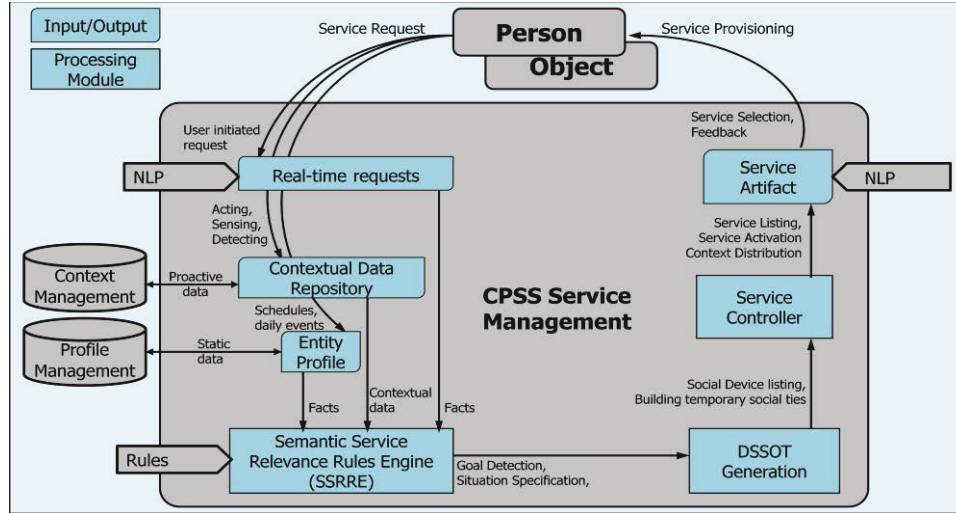


Figure 4.2.3 DSSoT Service Framework. NLP: Natural Language Processor

## b. DSSoT architectural components

The DSSoT architecture consists of several collaborating components: context providers, context reasoner and context-aware services (see Figure 4.2.4).

- **Context provider:** Within this component contextual data coming from heterogeneous resources are stored and managed. It could be proactive, real-time, data stored in contextual data repository or static data stored in profiles including user, services and objects profiles. Contextual data are then converted into Web Ontology Language (OWL) representations so that it can be shared and reused by other components.
- **Context reasoner:** This component is responsible for context processing, including natural language processing (NLP) and ontology parsing based on logic reasoning. Running context queries across contextual data stored in the context repository is among the tasks executed by this component. Also, the context reasoner could act as a context provider where processing about deduced context takes place. In this sense, developers can easily create their own rules based on predefined format. In this sense, reasoning about situational goals initiates either via 1- real-time requests for services,



where facts are extracted from the requests using NLP; or 2- an event stored in the user profile, i.e., schedules were in case predefined rules are triggered, some facts about the event can be extracted and handled by Context Management (CM).

- **Context-aware services:** In order to construct context-aware services, a set of rules are needed to be defined where these rules specify situations that will be triggered whenever there is a change in the current context. In this sense DSSoT service developers can write a pre-defined set of rules which specify some methods to be invoked when certain conditions become true. Such pre-defined rules will be stored in external file sources and it can pre-loaded into the cognitive reasoner before running or it can be loaded during runtime.

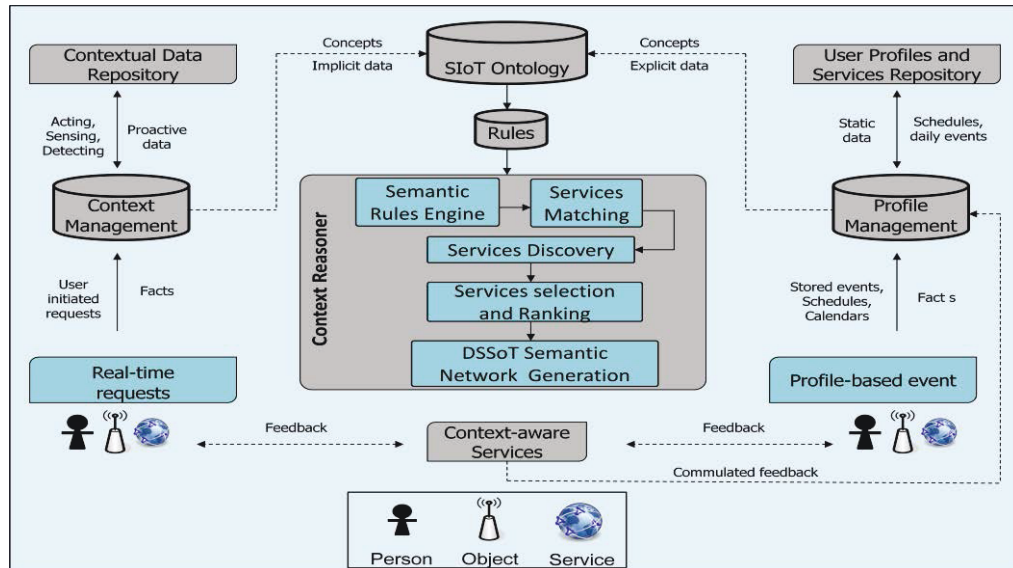


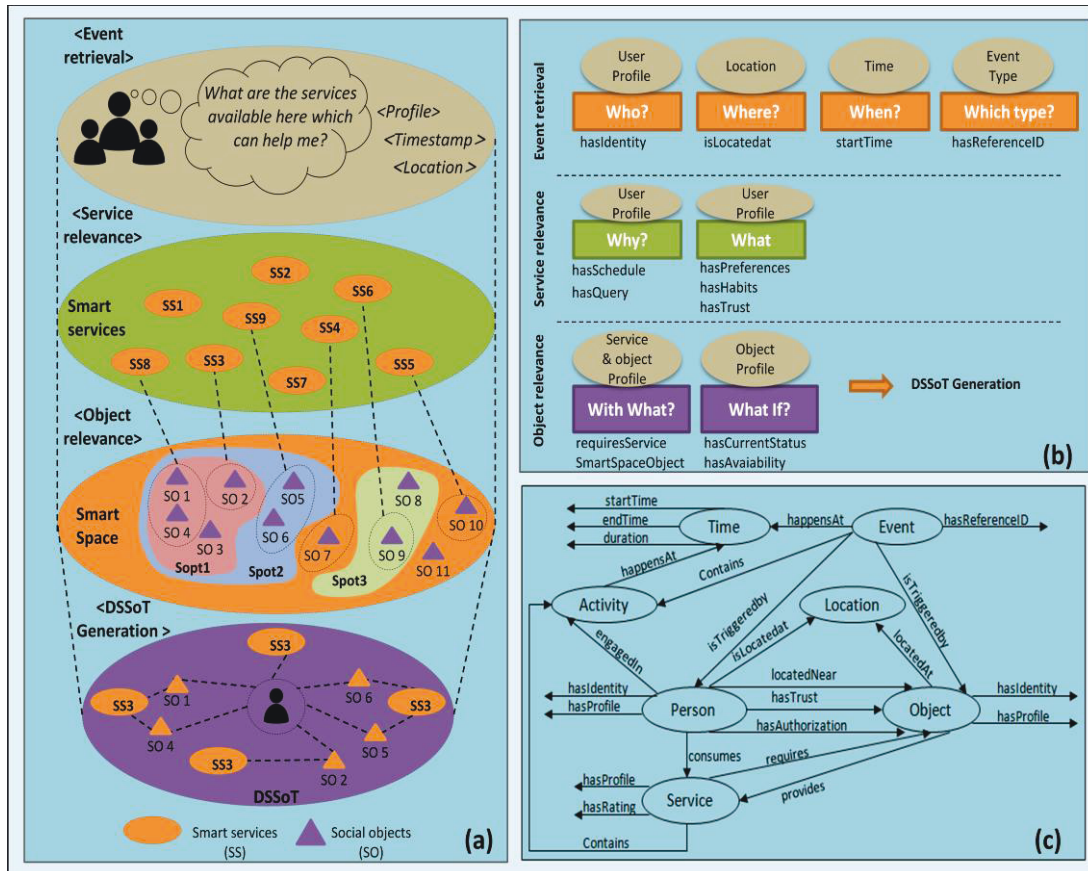
Figure. 4.2.4. DSSoT Architecture

### c. Dynamic Social Structure of Things (DSSoT)

Reasoning about spatio-temporal situations takes place upon an event triggered by the user or stored in profiles i.e., schedule. Accordingly reasoning about relevant smart services and social objects is undertaken. In this sense, some smart services (SS) are mapped to certain social object (SO) i.e., a self check-in machine in an airport is annotated with the service it provides which is self checking-in. While some other SSs are mapped to multiple SOs i.e., detecting a spot suitable for reading might include detecting and comparing the light condition outside and inside a building. Additionally, some services could be web applications which are not mapped to SO i.e., information and maps services. Social structures can then be

established based on services and objects relevance (see Figure 4.2.5 (a)). Figure 4.2.5 (c), shows the data model in which the main entities interact for DSSoT generation including their relationship properties. DSSoT is based on three types of contextual reasoning (see Figure 4.2.5 (b)):

- **Event retrieval**—it reasons about the user's spatio-temporal physical setting.
- **Service relevance**—it reasons about users' requirements, preferences, history of interactions, trusted services, authorization restrictions and services rating.
- **Object relevance**—it reasons about available objects to meet goals.



**Figure. 4.2.5.** DSSoT Generation Model. (a) Goal-based Services Restriction in DSSoT (b) Context Reasoning Model for DSSoT Generation (c) DSSoT Data Model.

Event retrieval restricts the discovery scope of the social structure generation to object entities, i.e. things, which are matched with the generated event. The service relevance refines the discovery scope of social structure to create a personalized network of services which matches users' individual requirements, trust, ratings, etc. And finally, the object relevance provides a list of objects which are capable of undertaking the required services and tasks to finally meet the goals.

#### 4.2.4. Approach

DSSoT utilizes a service matching, selection and ranking approach to enable the establishment of a location-independent social structure of things in a smart place. DSSoT determines place-independent social structures through three semantic-matching algorithms (see Figure 4.2.6):

- The first matching algorithm (Situation Identification) operates on user, smart space and event profiles to identify first the situation of the user. Once the triggering of an event, the user identity, location and time are selected. Then the activities in the event are matched with the activities of the services available within the location and time discovery area. Only those services with relevant activities that match activities in the triggered event will be selected as eligible services. The algorithm returns the semantically relevant services which are matching with the event type.
- The second matching algorithm (Services relevance) operates on user and services profiles to identify a set of relevant services within a place's discovery scope. It first semantically match the user schedule/ calendar and preferences with that in the services input then it compares service rating and access authorization with the user profile. The algorithm returns the semantically relevant services which can meet users' situations.
- The third matching algorithm (Objects relevance) selects only those devices which can provide the set of eligible services identified in the previous step. These objects' attributes semantically match that of the relevant services. In particular, the algorithm iteratively analyzes all objects profile parts to determine whether the objects can provide the services selected by the previous algorithm. Additionally, it selects only those objects with available status. By applying the matching algorithm to all eligible services and objects which are relevant to the triggered event, DSSoT is generated as a semantic social network of situational relevant entities.

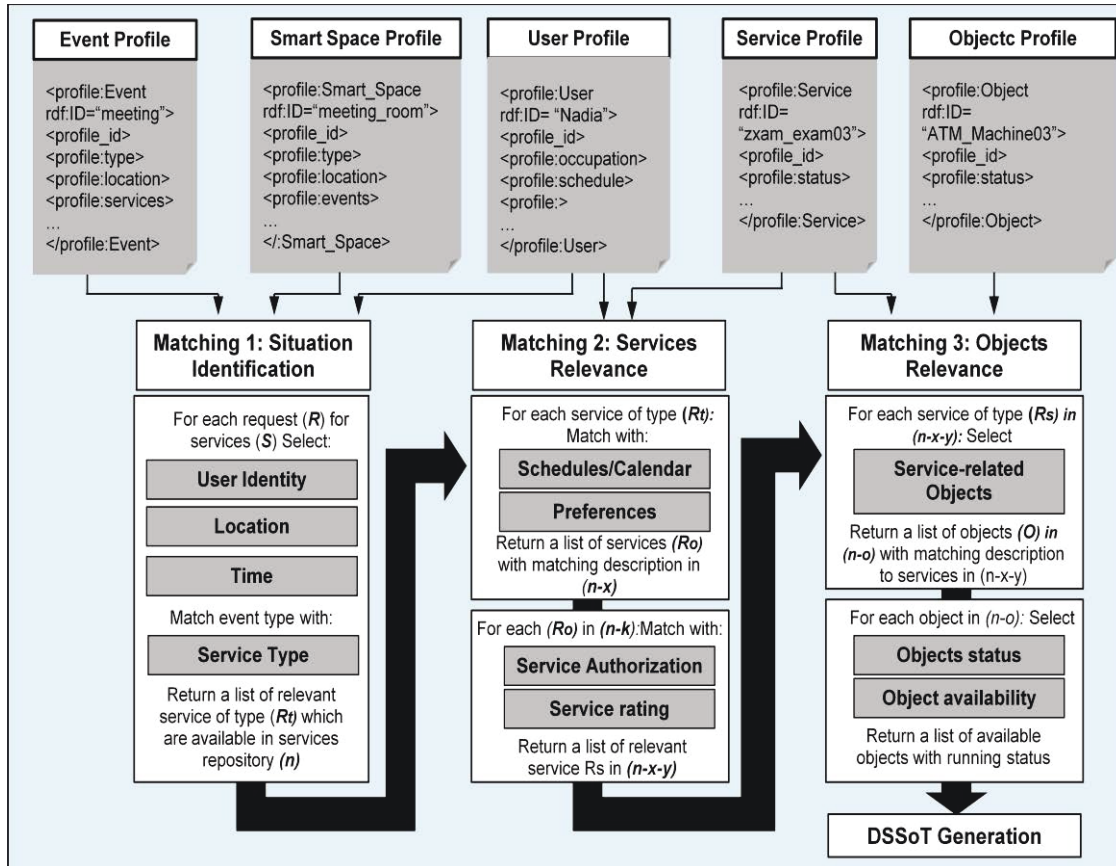
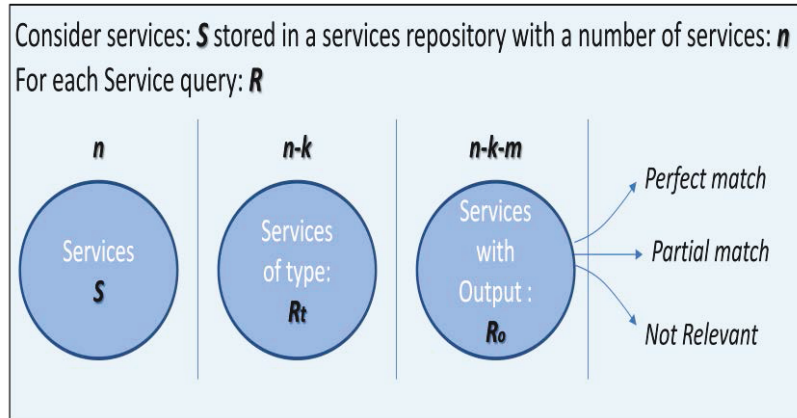


Figure. 4.2.6. Proposed Services filtering mechanism for DSSoT generation

### a. The DSSoT Service Relevance Matching

Within the scope of this contribution we implemented and evaluated the Service Relevance Matching algorithm, where in this section we detail its functionality. The proposed matching algorithm aims at returning services which fit into these categories based on user or event-based requests in spatio-temporal situations. As shown in Figure 4.2.7, the algorithm starts by matching against a set of all available services ( $S$ ) which exist in a service repository ( $n$ ). The first step is responsible for filtering out services that are not of the event type based on request  $R$ . In which, events and their semantically matched services are stored in advance in the event profile. This step results in a smaller set of services ( $n-x$ ) where services returned are of type  $R_t$ . The second step is responsible for filtering out services whose output properties, which is available in the service profile, doesn't match  $R$ . This again results in a smaller set of services ( $n-x-y$ ) where services returned are of type  $R_o$ . The services inputs ( $si$ ) in ( $n-x-y$ ) are queried. If  $si$  is already provided as a contextual concept with  $R$  (e.g., user identity, time, location) or

can be provided via user profile (e.g., user preferences) the matching result is classified as a Perfect match. Else the match is classified as Partial match.



**Figure. 4.2.7.** Services filtering mechanism

The service filtering mechanism shown in Figure 4.2.7 is formulated into the algorithm shown in Listing 1 which describes the process of filtering the relevant services into Perfect, Partial and Not Relevant categories.

```

1 Matching(R, S) {
2     S1 = query_Service_Registry(Rt, s)
3     S2 = query_Service_List(Ro, S2)
4     for all s in S2 {
5         si = query_service_inputs(s)
6         if provided(si, Ri) then {
7             Perfect.append(s)
8         }
9         else {
10            if query_Profile(user_profile,
11                missing_Inputs(si, Ri)) then
12                {
13                    Perfect.append(s)
14                }
15            else {
16                Partial.append(s)
17            }
18        }
19    }
20    P = order_with_ContextualAttributes(Perfect)
21    A = order_with_ContextualAttributes(Partial)
22    return relevance_result(P, A)
23 }
  
```

**Listing 1.** Service relevance matching algorithm

## b. Service selection and ranking

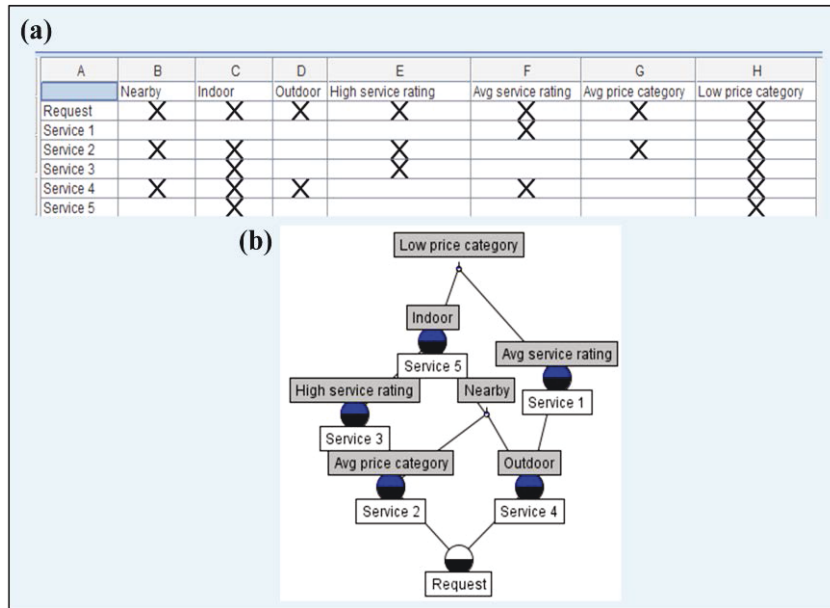
The services list resulting from the service matching algorithm presented in the previous subsection can then be ordered according to user preferences about certain service properties. For instance, users could prefer services which are nearby, or services with a high rating, or certain price category, etc. These user defined preferences are called *contextual attributes*. The contextual attributes are defined in the following rule: Attribute-definition-> Statement. Statement defines the meaning of the attribute. (E.g., nearby –definition-> distance (userposition, SmartObjectPosition) < maxdistance). These contextual attributes are used to order the list of returned services, prior to service matching, according to their match with the preferences.

In this contribution a clustering mechanism is utilized to order services based on the user preferences reflected in service's properties. For this purpose, *concept lattices* [F82] is used which represents a mechanism used in formal concept analysis. It can be utilized to study how services can be ordered, hierarchically, according to their attributes or properties which are common with user preferences [GSW05]. The context attribute consists of a triple (G, M, I). G is a set of objects, they represent services, M is a set of attributes or service properties, and I is a binary relationship between G and M in which:  $I \subseteq G \times M$ .

The request R along with the service descriptions, extracted from service profiles, which is retrieved upon sending R are added to the table shown in Figure 4.2.8 (a) as objects within the rows. Whereas users' preferences, which are to be evaluated for ordering the retrieved services according to their relevance to users' preferences are added as attributes within the columns.

From the table presented in Figure 4.2.8 (a) a lattice line diagram can be calculated and produced as shown in Figure 4.2.8 (b). Reading Figure 4.2.8 (b) vertically from top to bottom, a parent attribute inherits its attributes to child nodes (e.g., Service 2, Service 4 and Request all have attributes Nearby, High service rating, Low price category). Thus, by comparing the position of services to the position of Request, the services can be ordered. In which, the higher the service is positioned the less relevant it is to the user preferences (e.g Service 5) and vice versa.





**Figure 4.2.8.** DSSoT Contextual Attributes Model. (a) Lattice cross table. (b) Lattice line diagram.

#### 4.2.5. Application: *Airport Dynamic Social*

In order to realize the DSSoT in a real life setting an application prototype namely *Airport Dynamic Social*, is proposed to benefit from IP-based protocols. The test-bed setting of Airport Dynamic Social is built utilizing Internet Protocol version 6 (IPv6) which is being promoted as an IoT technology aiming to accommodate the increasingly growing number of smart objects and consumer electronics that are being connected to the Internet.

Various standardization bodies, including Internet Engineering Task Force (IETF), are making an effort for the goal of reducing the footprint of IPv6 for resource constrained hardware nodes. Among these efforts is adding wireless sensor connectivity to the IPv6 protocol to allow its use in Low-power and Lossy Networks (LLNs), such as those based on IEEE 802.15.4. Additionally, the Routing Protocol for LLNs (RPL) and the Constrained Application Protocol (CoAP) in the application layer which are key IP networking protocols that seamlessly integrate resource-constrained objects into the Internet.

Airport Dynamic Social is designed to utilize and benefit from these advances in order to offer an effortless deployment of such systems without the need for protocol translation gateway or intermediary server to cope with the heterogeneity of devices typically exist in smart spaces.

a. Technical Configuration

The application Airport Dynamic Social is built using low-power sensor nodes, a router, and a smart phone application for Android operating systems using IPv6 and related networking stacks for smart objects to demonstrate the creation and operation of the DSSoT in a real life which in this case is an airport. A “Zolertia Z1 WSN mote” device is used for temperature sensing inside the airplane, CM5000 TelosB for sensing the lighting level at the airport boarding gate is also used, in addition to another “CM5000” device to track the boarding by using its button sensor.

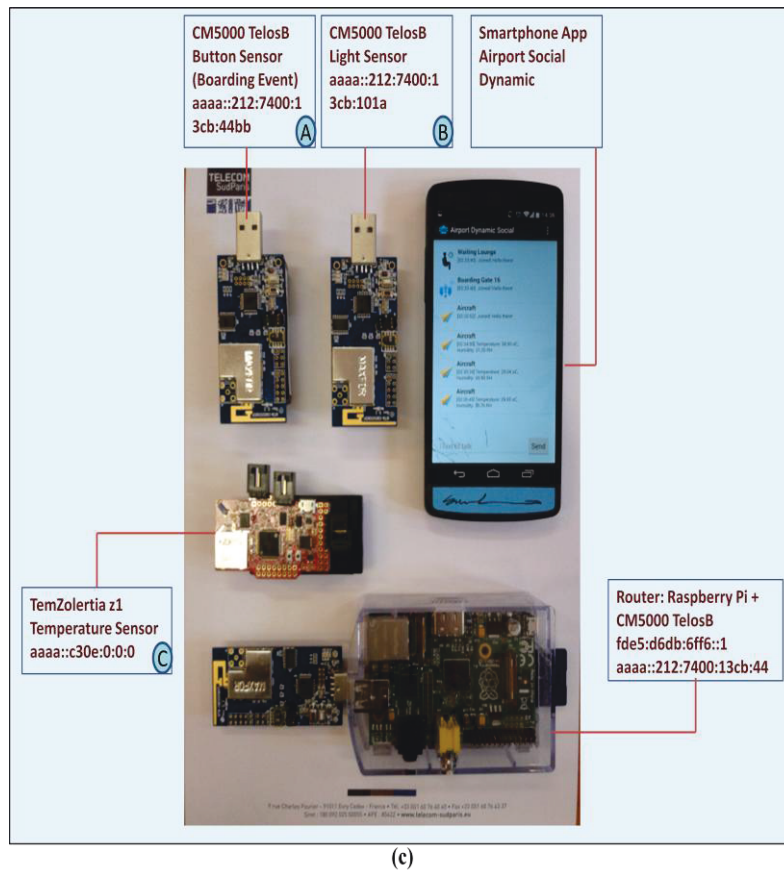
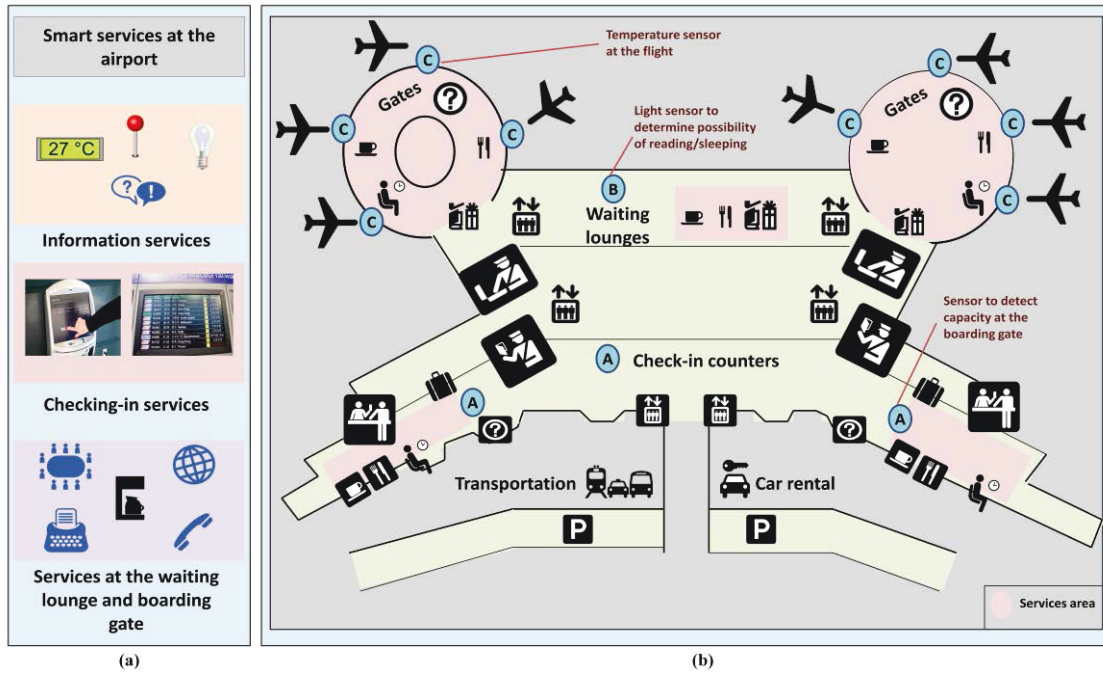
\* **The main processor:** composed of a microprocessor and system memory. A 32-bit microprocessor acts as the main CPU. It's responsible for handling reasoning tasks and processing about events, running the service framework, and managing the service interactions.

\* **The network interface:** consists of a network device called Border Router was developed with a Raspberry Pi computer board combined with a CM5000 TelosB as an IEEE 802.15.4 radio device which acts as a router between the IPv6 IEEE 802.15.4 network and the users' IPv6 Wi-Fi phone network.

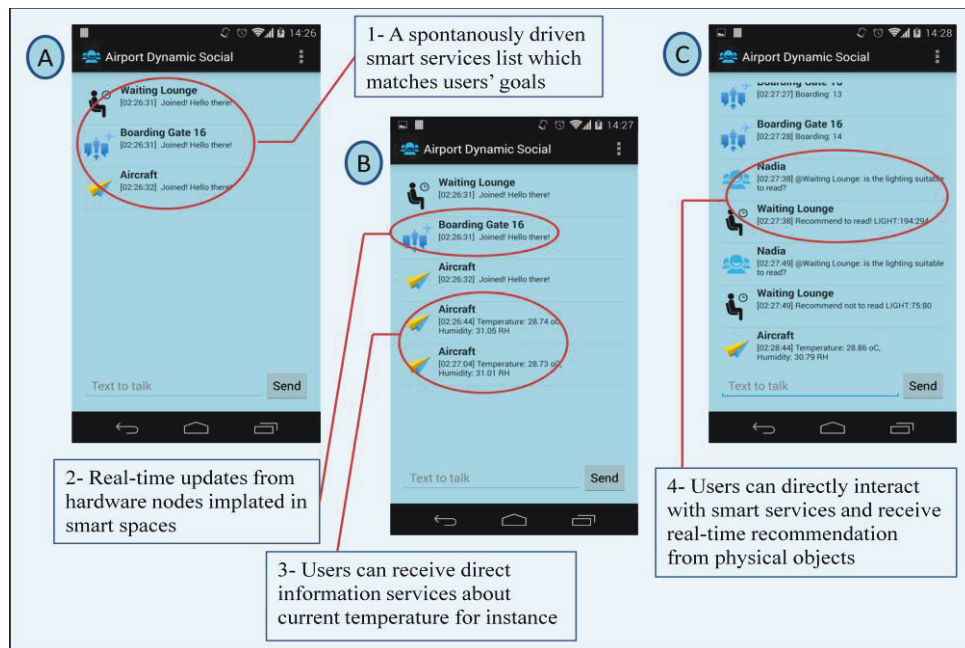
\* **The application:** composed of Android phone connected to AP by means of DHCP.

Examples of smart services available at the airport are shown in Figure 4.2.9 (a). Whereas, 4.2.9 (b) shows the environment for Airport Dynamic Social where some hardware nodes, also utilized within the application, could be installed in order to turn such environment into a smart space. In 4.2.9 (c) the equipments used within Airport Dynamic Social are represented. Each sensor provides its service by means of a CoAP endpoint which users can subscribe to via smart phone application in order to receive updates such as temperature inside the airplane or the number of passengers currently boarding the airplane. Users can also request information such as if the lighting condition at the boarding gate is good enough for reading. The sensors utilized are labeled with characters which corresponds the area in the airport where this node could be installed.





**Figure 4.2.9.** Airport Dynamic Social application environment and used equipments. (a) Example of smart services at the airport, (b) Airport Dynamic Social environment, (c) Airport Dynamic Social used equipments



**Figure 4.2.10.** Airport Dynamic Social service examples

### b. Service examples

Some service examples using Airport Dynamic Social are presented in Figure 4.2.10. These service examples are implemented by interacting with the application and a smart phone.

- Once a passenger log-into Airport Dynamic Social app from any portable device, a situation event will be initiated and the list of relevant services, which would meet the passenger's situational goals, will be computed. Accordingly, devices which could provide the required services will be sent to the passenger awaiting approval before listing relevant services and objects, allowing direct access and interaction with them (Figure 4.2.10 (a)).
- A social structure (DSSoT) connecting passengers with the services and devices which would meet their situational goals will be created. Accordingly, the services and devices on the passenger's social structure will push notifications about status updates, for instance the airplane, will send updates about current temperature and the boarding gate will send notifications about the number of passengers currently boarding so the passenger can target a less crowded boarding time (Figure 4.2.10 (b)).
- Finally, passengers can interact directly with the boarding gate asking, for instance, if the lighting condition over there is suitable for reading, for this inquiry an embedded

NLP fetches the request, and transfers it to the corresponding sensors at the boarding gate, after checking the light condition the status is sent from the boarding gate to the user, which within the context of the provided service example recommends the passenger not to read there (Figure 4.2.10 (c)).

Listing 2 & 3 provide an excerpt of a smart service in an airport definition. The example showed in Listing 2 is for query parser location service which returns list of matched location names and their coordinates (latitude/longitude), also a map with the matched locations. Listing 3

```

1    <service:Service rdf:ID="QUERY_PARSER_LOCATION_SERVICE">
2    <service:presents rdf:resource="#QUERY_PARSER_LOCATION_PROFILE"/>
3    <service:describedBy rdf:resource="#QUERY_PARSER_LOCATION_PROCESS"/>
4    <service:supports rdf:resource="#QUERY_PARSER_LOCATION_GROUNDING"/>
5    </service:Service>
6
7    <profile:Profile rdf:ID="QUERY_PARSER_LOCATION_PROFILE">
8    <service:isPresentedBy rdf:resource="#QUERY_PARSER_LOCATION_SERVICE"/>
9    <profile:serviceName xml:lang="en">
10   Query Parser location finder service.
11 </profile:serviceName>
12 <profile:textDescription xml:lang="en">
13   This service allows the user to enter a string like 'Services around me' or 'Services here' and get a
14   result that splits the location query apart from the textual query. It returns list of matched
15   location names and their coordinates (latitude/longitude), also a map with the matched locations.
16 </profile:textDescription>
17 <profile:hasInput rdf:resource="#_LOCATION-QUERY"/>
18 <profile:hasOutput rdf:resource="#_MATCHED-LOCATION"/>
19 <profile:hasOutput rdf:resource="#_LATITUDE"/>
20 <profile:hasOutput rdf:resource="#_LONGITUDE"/>
21 <profile:hasOutput rdf:resource="#_MAP"/>

```

**Listing 2.** Excerpt of query parser location service

```

1    service:Service rdf:ID="GATE038_TEMPERATURE_SERVICE">
2    <service:presents rdf:resource="#GATE038_TEMPERATURE_PROFILE"/>
3    <service:describedBy rdf:resource="#GATE038_TEMPERATURE_PROCESS"/>
4    <service:supports rdf:resource="#GATE038_TEMPERATURE_GROUNDING"/>
5    </service:Service>

```

```

6
7   <profile:Profile rdf:ID="GATE038_TEMPERATURE_PROFILE">
8   <service:isPresentedBy rdf:resource="#GATE038_TEMPERATURE_SERVICE"/>
9   <profile:serviceName xml:lang="en">
10  City WeatherSystem Service
11  </profile:serviceName>
12  <profile:textDescription xml:lang="en">
13  This service returns temperature condition in airport gate number 38.
14  </profile:textDescription>
15  <profile:hasInput rdf:resource="#_AIRPORT"/>
16  <profile:hasOutput rdf:resource="#_TEMPERATURE"/>
17
18  <profile:has_process rdf:resource="GATE038_TEMPERATURE_PROCESS" />
19  </profile:Profile>
20  <!--<process:ProcessModel rdf:ID="GATE038_TEMPERATURE_PROCESS_MODEL">
21  <service:describes rdf:resource="#GATE038_TEMPERATURE_SERVICE"/>
22  <process:hasProcess rdf:resource="#GATE038_TEMPERATURE_PROCESS"/>
23  </process:ProcessModel>-->

```

**Listing 3.** Excerpt of temperature service

## 4.2.6. Empirical Evaluation

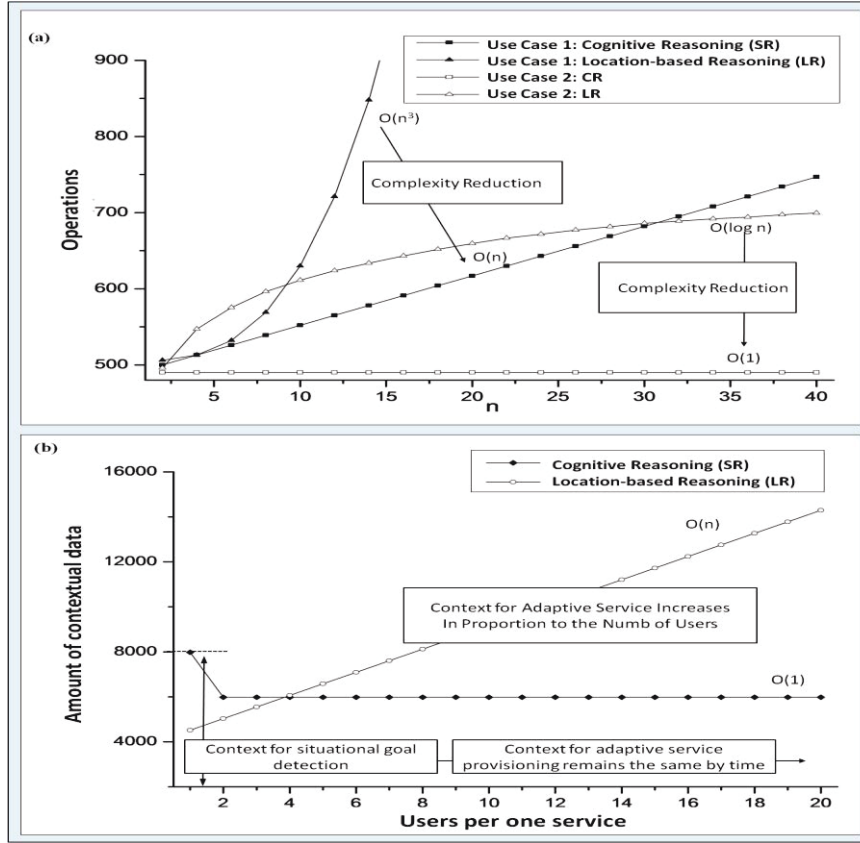
### a. Empirical Analysis

The reasoning approaches which consider processing about objective context, represented in spatio-temporal elements, i.e., Location, as input for reasoning and service matching based on explicit search request are suggested in the literature. This reasoning mechanism is referred to as Location-based Reasoning (LR) in this section. This contribution proposes extracting objective and subjective elements about users' situations either from proactive contextual data or from static profiles. Thus, reasoning about situational goals can take place. This approach is referred to as Cognitive Reasoning (CR). An empirical analysis of CR performance, specifically in terms of run-time complexity and contextual data growth rate needed for decision making is provided in this section, following the principles provided by Papadimitriou *et al.* [P03].

\* **Run-time complexity:** In an airport, consider that passengers have various service access permission levels, according to their status, i.e., frequent traveler, normal traveler, airport employee, random visitor, and the corresponding air carriers in case they are travelers.

- Use Case 1: Consider a passenger sending request (R) to access smart services available at the boarding gate. In case of LR, after matching the passenger's identity with his corresponding profile, his air carrier and finally his access permission level will be identified. Thus the number of operations (n) undertaken by LR to process each R is by an order of  $O(n^3)$ . Whereas, in case of CR, upon the passenger's first R, his profile will be retrieved, and so his corresponding air carrier and access permission level. For each R after the first one, no further identification or verification will be needed. Thus, (n) operations will be required to meet each R. In this sense, the time complexity to process every R in CR, after the first one, is by an order of  $O(n)$  (see Figure 4.2.11 (a)).
- Use Case 2: Consider an update on the boarding time sent directly as an information service to registered passengers who are waiting at the boarding gate, as a result of this update a certain announcement is needed to be sent to passengers who are having a connecting flight. Giving the LR algorithm, for each announcement the destinations of passengers are needed to be processed before it can be sent. This makes the time complexity of (n) operations needed by LR to become with an order of  $O(\log n)$ . Whereas, giving the SR algorithm, while destinations are processed in advance, certain announcements will be sent to corresponding passengers directly, in this sense the time complexity of CR becomes by an order of  $O(1)$  (see Figure. Figure 4.2.11 (a)).

\* **Contextual data growth rate:** Within the previously mentioned Use Case 1 and as shown in Figure. 4.2.11 (b), the contextual data growth represented in the amount of contextual data needed to run operations (n) is proportioned with the number of services' consumers. Considering the LR algorithm the amount of contextual data increases with an order of  $O(n)$  giving the amount of data which are needed to be fetched and stored to complete the operations run by LR, examples of these operations are shown in Use Case 1 & 2. Whereas, the amount of data needed to run the operations held by CR is fetched and stored in advance for all users to run all the operations, then the increase remains with an order of  $O(1)$  for all users after fetching the initial required context.



**Figure. 4.2.11.** Empirical Runtime Complexity Analysis. (a) Run-time complexity graph, (b) Contextual data growth rate graph.

## b. Precision and Recall Evaluation

This section evaluates the DSSoT Situation-based reasoning approach by calculating precision and recall rates. Consider a set of relevant services ( $R$ ) within a big set of advertised services ( $A$ ) ( $R \subseteq A$ ). We define:

- **Recall:** The number of relevant services retrieved, divided by the total number of relevant services in the services repository. The highest value of recall is achieved when all relevant items are retrieved.
- **Precision:** The number of relevant services retrieved, divided by the total number of services retrieved. The highest value of precision is achieved when only relevant items are retrieved.

The results are categorized in three categories: A, B and C. Where A = number of relevant services retrieved. B = number of relevant subclasses not retrieved. C = number of irrelevant

subclasses retrieved. For this evaluation, we used a context synthetic dataset with 3,057 triples (or 600 OWL classes and instances) and we created a registry with thirty advertised smart services which exist in the airport. We queried this registry with requests using the services relevance approach identified above (based on situation matching). With the result, we calculated the recall and precision rates. We compared these calculations with queries using current location to identify services relevance.

In fact it's important to mention here that we held an initial experiment to compute the precision and recall based on two queries: 1- Find all Services in the Airport that can facilitate my "travel" and 2- Find all Services in the Airport "lounge". The precision and recall values we received from CR were trivial (100% average precision in each location). The reason behind these unrealistic results is justified by Kanthavel *et al.* [KMP13]. In which Semantic Web matching techniques have some limitations due to matching with semantically tagged descriptions that in this case requires some knowledge of terms related to the services from the service requestor. Hence, in the initial two queries we assumed that the service requestor have some knowledge about the terms "travel" and "lounge". Thus, the results we obtained seemed unrealistic to us. Therefore we used very generic queries in a second round of experiments that would not assume any previous knowledge of services related terms. The results are shown below:

**Query 1: "what kind of available services can help me today?"**

**Table 4.2**  
DSSoT Query 1 Precision and Recall results

		Location 1 – Airport terminal (around check-in counters)	Location 2 – Airport gateways and lounges	Location 3 – Boarding gate
Location-aware Reasoning (LR)	Matching result (services)	A = 5, B = 4, C = 2	A = 4, B = 2, C = 3	A = 4, B = 3, C = 5
	Precision (%)	50%	60%	50%
	Recall (%)	60%	50%	40%
Cognitive Reasoning (CR)	Matching result (services)	A = 5, B = 1, C = 2	A = 3, B = 2, C = 1	A = 8, B = 2, C = 1
	Precision (%)	80%	60%	80%
	Recall (%)	70%	70%	90%

This query is targeted to return all services which are currently available. The LR approach would reallocate the user each time the user location changes. The CR approach will query user profile, schedules to compute all relevant services which would meet users' goals in all locations within a certain situation i.e., travelling, receiving a friend, etc.

In the set of advertised services, there are 19 available services. The LR approach retrieves only the services that exist round the user in each location. Since no specification in the query to the required types of services, the LR approach retrieves all the services available in each location. Whereas the CR approach selects services which match the user preferences and schedule. Thus, a user who's schedule states that he/she has a trip and the preferences states a certain favorite restaurants, cafes etc. then only these services matching this criteria will be selected. The results of the query 1 are shown in Table 4.2. As we can notice the precision and recall values of CR is improved than LR since it returns services with matching preferences to the user.

**Query 2: "What are the services available here?"**

**Table 4.3**  
DSSoT Query 2 Precision and Recall results

		Location (Lounge)
Location-aware Reasoning (LR)	Matching result (services)	A = 5, B = 2, C = 6
	Precision (%)	70%
	Recall (%)	40%
Cognitive Reasoning (CR)	Matching result (services)	A = 6, B = 1, C = 2
	Precision (%)	80%
	Recall (%)	70%

Assuming that the user moved to a certain lounge area, this query is targeted to return all services types in location "lounge".

While the LR approach returns all available services which are located in the Lounge the CR approach returns only relevant services which match with user preferences and are available in the lounge. Thus the CR approach can achieve much improved precision and recall compared to LR.



#### 4.2.7. Summary

Cognitive reasoning about users' situational goals and the surrounding objects/services to meet these goals is proposed in this contribution. To benefit from this reasoning approach, the Dynamic Social Structure of Things (DSSoT) has been provided and implemented as a novel service framework in the SIoT. The significance of the proposed service framework and reasoning approach lies in the importance of achieving scalability when dealing with the heterogeneity and contextual complexity in the SIoT that is inherited from the paradigm of IoT; as well as the importance of elevating the adaptability of services to the users' situational needs to improve users experience in smart spaces. We provided an empirical analysis of DSSoT service framework and we demonstrated that within the proposed cognitive reasoning in DSSoT decision making is resolved in a polynomial time complexity as well as a polynomial data growth. We evaluated the efficiency of decision making via Precision and Recall factors and our cognitive reasoning approach achieved a much improved results compared to the location-based reasoning which is widely tackled in the literature. The application Airport Dynamic Social demonstrates the implementation of the DSSoT. Currently, several directions are being studied, primarily focused on integrating the DSSoT with security supports to address privacy issues, a crucial obstacle to leveraging DSSoT's adoption in various other SIoT environment.

## Chapter 5: Conclusion and Future Work

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## 5.1. Summary

The IoT or the connected revolution as mentioned sometimes by the media, is gradually penetrating our daily life, with hundreds of appealing products on the way to fill up the shelves. These smart devices and products are now built with inexpensive sensors, low-power wireless communication protocols to sense and transmit from the physical world to the Internet. Several new exciting applications are being developed, creating a connected ecosystem. The goal is not only to interact with one single device at a time but also using mashup and composition between devices, services and a plethora of existing Web applications, to generate a new experience. Thus, the Web of Things (WoT) paradigm comes to the spotlight as an extension of the IoT in terms of network connectivity, which focuses on the application layer. WoT enables bringing embedded devices to the Web by adopting Web standards and developing ubiquitous applications for these connected devices.

In the mean time, SNS has emerged as an inter-connectivity forum, encouraging people to establish and expand their network of friends and acquaintances for interacting and sharing ideas, as well as various resources, in textual or multimedia formats. Information about users' interests, preferences, group of friends and activities on the SNS are accumulated to form user profiles. SNS relies mainly on such rich data provided by the user profiles to realize a system for recommendation & filtering. The applications of content mashup for instance encourages users' customization of their own profile by adding news feeds or services. These characteristics of SNS help to change social interaction over the Internet, from enhancing the way we reach information to the way we reach for each other, and with IoT, to the way we reach our things.

Thus, the cluster between Internet of Things (IoT) and social networks (SNs) enables the interaction of people to the ubiquitous computing universe. Within this framework, the information coming from the environment is provided by the IoT, and the SNS brings the glue to allow human-to-device interactions. Research studies in the domain of SIoT already paved the way through enhancing the networking aspects, by introducing and promoting the concept of social objects, however in this thesis, we are trying to move a step forward, where from a computational aspect we consider improving the intelligence and adaptability of SIoT services to users' situational needs.

The scope of this thesis builds on taking both ubiquity and sociality (or intelligence and autonomy), to bring a key point of technical issues to realize the SIoT vision on computing and networking: context-awareness. That is, the situational integration among the computing and networking environments for the goal of smart services provisioning relies on context information (or context) and context-awareness architecture. Thus, in order to provide adequate intelligent services for users, services should be aware of information surrounding users and their present status, and automatically adapt to users' dynamic situations. Since SIoT that inherits characteristics from different computing and networking environments (i.e., IoT and social network of people) has highly unique and broad properties, context and context-awareness architecture should be newly designed as part of this thesis contribution.

In order to practically reach a framework combining sociality, autonomy and the novel intelligence introduced within the paradigm of SIoT an approach based on cognitive context is suggested within the scope of this thesis, in which locality appears as the key to narrow down the scope of interactions and services discovery. This suggested cognitive approach relies on creating scenarios combining a diversity of entities i.e. objects, users and services where the goals of such entities are being predicated prior to building a social structure among all the interacting entities and finally such locally created, goal-driven social structure is the core for providing, discovering and consuming smart services.

To achieve interoperability and automation for the goal of realizing the seamless integration among objects and services in users' daily life, Semantic Web Technologies are utilized in this thesis. In which, within two application domains, i.e. context-aware recommendation of quotidian tasks in smart homes and situation-dependent social structure of things in smart spaces the Semantic Technologies are deployed on top of a social network as a service creation environment. From a technical viewpoint, we adopt Web Services at the device level to ensure network navigability and direct human-to-object interactions within the proof of concept prototypes applied for each application scenario. We consider the light-weight version of W3C Web Service, Device Profile for Web Service (DPWS) which does not require devices with powerful capabilities to fit into the system. Again, the goal is to demonstrate the effortless integration of physical objects within the Web to apply certain applications tasks.

The main impact resulting from the work provided in this thesis would be a social impact in IoT domain generally and in the SIoT. Where the challenges of improving service discovery and enhancing network navigability in SIoT is already addressed in the literature, in this work we rather investigate how to improve the level of service adaptability to users' needs.

### 5.2. Limitations

We have identified some limitations of the two proposed applications domains:

- The cognitive context model provided is not suitable for expressing relationships existing between people in real life, such as: expecting a visit from a friend, a colleague or a family member should reflect different kinds of recommendation in smart homes. This limitation is considered as a main future research direction as described in the next section.
- The dataset which we used for evaluating the efficiency of the proposed cognitive reasoning mechanism is not based on a real dataset instead it's composed of a synthetic data created with unique OWL classes and instances for the purpose of experiment.
- The two provided application domains can only be used in single-person context because intelligence is personalized to one context, habits, and preferences.
- Whereas the application scale of the two provided proof-of-concept prototypes is somehow limited to a few sensors and devices we hoped by providing them to demonstrate the effortless integration of physical objects and devices into the Web as well as to demonstrate an improved usability and user-friendliness of SIoT services by applying Semantic Web technologies. This particular limitation hinders us from modeling and evaluating dynamically updated proactive data in SIoT as well as evaluating uncertainty of context data in smart spaces.

### 5.3. Future Work

With the aim of making real the SIoT paradigm, there are still numerous challenges that must be faced prior to the worldwide deployment of this technology.

1) Energy Management: Devices taking part in the SIoT are typically moving around, and not connected to an unlimited power supply. So do users, carrying hand-held devices that usually operate with batteries. Hence, the energy conservation is a conditioning factor in the design and operation of SIoT, and efficient energy management should be implemented at all levels; from M2M device communications to interface design. All stages in the design of SIoT technologies have to be oriented to low-energy consumption. While energy harvesting technologies do not yet provide enough resources, this is a broad research topic where some approaches proposed for WSNs and other low-power technologies can be adapted to deal with the requirements of the SIoT (e.g., scalability, availability, and heterogeneity).

2) Security, Privacy, and Trust: These might be the most sensitive requirements for the success of SIoT; without a secure technology that ensures user privacy, safe communications, and trustworthy interactions, the SIoT paradigm will not reach enough popularity to be considered a well-established technology, and all its potential will be lost. Methods to guarantee data confidentiality and user privacy that are also required for other platforms can likely be reused in the SIoT context, always considering the special requisites of this paradigm. Lightweight mechanisms for data confidentiality and integrity, as well as effective ID management and privacy enhancing technologies represent the basis that will make users trust the SIoT ecosystem.

3) Self-Operation, Management, and Organization: As it has been commented before, the SIoT expects to be a worldwide technology composed of billions of devices and people. When imaging how the global management of such a huge platform should be, one easily realizes that automatic operation is needed at most levels. Mechanisms including self-organization, self-management, self-operation, self-healing, and self-protection capabilities will definitely be a decisive part of the SIoT. Not only automatic network management will be relevant but also autonomic data analysis, and service discovery and composition will contribute to enhance the user experience. Again, the adaptation of approaches proposed for other technologies can be a starting point to automatize the operation of the SIoT ecosystem.

4) Heterogeneity: Sensors, actuators, ID-tags, smart phones, tablets, computers, etc., will be part of the SIoT, different brands and technologies will have to work together to achieve a common goal: provide users with advanced services and applications. For this, SIoT developments have to be able to integrate many types of devices, technologies, and services.

Interoperability at device level ensures that different technologies are able to communicate among them; the system should ideally be open to support a huge variety of different applications, whose characteristics and requirements may be extremely diverse, in terms of bandwidth, latency, reliability, availability, etc. The necessity of dealing with heterogeneous devices will probably degrade the overall system performance compared to a highly optimized vertical design, but the extended functionality offered by the SIIoT ecosystem will compensate this drawback. New designs that efficiently deal with heterogeneous technologies will be of great importance for the successful deployment of SIIoT.

5) Interactions and Interfaces: The SIIoT infrastructure will be focused on providing users with an advanced experience able to consume and produce data and services coming from devices and other users. Thus, the human-centric interface should provide a user-friendly medium to interact with devices and users. How users and devices interact with each other is still an open challenge. In which, a global set of interactions needs to be defined, as well as methods to manage these interactions, e.g., users can get data from their own devices, but how to get data from other users' devices is not completely clear, and it is very aligned with the privacy issues commented before; should I give completely free access to my devices? What about sensitive data such as my current location? Can I provide/ get anonymized data?

6) Application Development: All the functionality offered by SIIoT is meaningless without applications that make use of them. The application development process will vary depending on each situation; what devices and services are involved and which set of users the application is oriented to are determinant in this process. The use of open APIs will be helpful, and the implication of the users will bring new use cases that contribute to make the SIIoT more accessible and functional.

7) New Business Models and Stakeholders: How to get benefits from the SIIoT technology is a decisive point in the establishment of this new paradigm. When designing an advantageous platform, where both developers, stakeholders and users feel comfortable, and bearing in mind the collaborative nature of the SIIoT,<sup>5</sup> it is essential to take into account several considerations: 1) offer attractive and useful services and applications that encourage people to use them; 2) look for non-conflicting business models that boost collaboration; 3) recognize the customer experience by inviting the customers to participate; and 4) target the adequate customer segment. Once users find attractive the use of SIIoT-based applications, capitalizing

plans can be studied and launched, including marketing and sales, research and development, advertising, application fees, device commercialization, etc.

8) Fault Tolerance: In such a dynamic and mobile world, with context changing rapidly and with the heterogeneity that characterizes the SIoT, the reliable operation of the different components should be guaranteed. Efficient adaptation to challenging situations will make the difference for a trusty platform, as well as a correct architectural organization that supports redundancy at several levels to ensure that it offers reliable information to the final users.

9) Community Engagement within SIoT Service Provisioning Loop: while engaging the user, his preferences, habits and service rating, etc .within the loop for providing smart services is considered among the most important goals of this thesis. Engaging the relationships between people and/or social communities within SIoT loop is considered as a major future direction for us. In which, social relationships can derive intelligence and context-awareness in SIoT which could improve service adaptability and overall enhance the level of Quality of Experience (QoE).



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