Efficient algorithms, architectures and implementations in internet of things and smart environments

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Efficient Algorithms, Architectures and Implementations in Internet of Things and Smart Environments

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La Faculté des sciences, sur le préavis de Monsieur J. ROLIM, professeur ordinaire et directeur de thèse (Département d'informatique), Monsieur P. LEONE, docteur (Département d'informatique), Monsieur K. M. ANGELOPOULOS, docteur (Département d'informatique), et Monsieur S. NIKOLETSEAS, professeur (University of Patras, Computer Engineering and Informatics Department, Patras, Greece), autorise l'impression de la présente thèse, sans exprimer d'opinion sur les propositions qui y sont énoncées.

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Logic will get you from A to Z;
Imagination will get you everywhere.

— Albert Einstein

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Abstract

More than just a vision, ubiquitous computing is applied in many fields of Computer Science and it has well been established. However, there are aspects which still need to be optimized and necessitate a more in-depth research, to exploit even further the potential of ubiquitous computing. In this thesis we tackle problems and challenges of the ubiquitous computing arising from the use of wireless and mobile networks in the Internet of Things (IoT) and Smart Environments domains.

In Part II, chapter 2 we compare a traditional non-IP with a modern IPv6 enabled architectural approach for realizing Smart IT Building systems with the use of Wireless Sensor Networks (WSN). We find out, after a theoretical and practical analysis, that an IPv6-enabled approach is more suitable for the IoT era, since it provides energy efficiency, scalability, robustness and easy integration with WEB technologies. Having demonstrated which approach one should follow when designing Smart Buildings using WSNs, in chapter 3 we propose an efficient IT architectural framework with which Smart and Personalized IT Building Systems can be facilitated. The interoperability, robustness, efficiency and scalability of our proposed framework are one of the major contributions of this work.

Since the quality of the air that we breathe inside any kind of environment plays an important role in our health and our quality of life, we should not only reduce the emissions of pollution in the air but also at the same time monitor them to be aware of the potential dangers and to assess better the impact to our health. In chapter 4 we study the impact of the air pollution to the environment and to the people, and we propose a system with which we can efficiently monitor the ambient air pollution in 3-dimensional environments in a low-cost and automated way, making a step further from traditional, expensive and 2-dimensional monitoring systems.

Two of the relative new and important aspects in the Internet of Things era, in which we are walking in, are the Crowdsourcing and Crowdsensing methodologies. Since those domains are still in their infancy in relation to the IoT, there are quite many interesting IT challenges to tackle such as the ones we address in Part III and Part IV. Particularly, in chapter 5 we study the crowd motivators and we categorize the contemporary crowdsourcing initiatives and modes. We show here that there are major differences in the way people are incentivized to participate in Crowdsourcing but the common denominator is the interest of the crowd in gaining reputation and recognition, and its enjoyment in learning something new. In chapter 6 we propose an architectural design approach of an IoT and Crowd-enabled platform. This platform augments the existing testbeds by adding crowdsourced resources from the smart devices of the platform's users and it enables heterogeneous IoT resources to be homogeneously available and interoperable with each other. At the same time, the crowd can actively participate in the research or experiments defined in the platform by researchers or experimenters.

In chapter 7 we scale down Internet technologies to fit in the constrained devices of the IoT and combining them with the wisdom of the crowd. In particular we design a user-enabled architecture with Mobile Crowdsensing support for Smart and Green Buildings. The architecture among others incorporates Incentive Mechanisms for engaging people to contribute environmental sensing information to the system while the latter one tries to adapt itself in order to increase the benefits for the end-users. The main aim of the architecture is to provide back to the people efficient services and increased experienced comfort.

In chapter 8, as in physics and in life each atom is characterized by a set of functions that define the correlations and synergies with other atoms, we study the relations and the synergistic analytics of people, and by extracting information on their behaviour with other people and their relation with their surrounding environment, we present a privacy-preserving, location and context based platform. With the use of this platform, we can better capture the interactions between users and their context and thus provide them with benefits in terms of increased quality of life.

In Part V chapter 9 we study the Wireless Power Transfer which more than a speculative technology, it seems to challenge our most basic intuitions about how electric power is and can be transferred. Although Nikola Tesla performed experiments in wireless power transmission at the turn of the 20th century, only recent advances in computer science, electronics and material engineering have started to change the way in which for more than 100 years we used to transfer power. In particular we study the Wireless Power Transfer technique in Mobile Ad-hoc Networks in which we present traversal strategies for a Mobile Charger. We demonstrate here that our proposed realistic local-knowledge strategy achieves in heterogeneous network deployments a good performance-overhead tradeoff and outperforms simple or naive strategies.

This thesis tackles various challenges and proposes some efficient solutions in the domains of WSN, IoT and Smart Buildings, Crowsourcing and Crowdsensing and Wireless Power Transfer.

Keywords: Algorithms, Architectures, Wireless Sensor Networks, Internet of Things, Smart Environments, Crowdsourcing, Crowdsensing, Wireless Power Transfer

Résumé

Plus qu'une simple vision, ubiquitous computing est bien établi et appliqué dans de nombreux domaines de l'informatique. Malgré cela il reste de nombreux aspects qui doivent être optimisés et qui nécessitent une recherche plus approfondie afin d'exploiter encore plus le potentiel de l'ubiquitous computing. Dans cette thèse nous attaquons les problèmes et défis posés par l'ubiquitous computing dérivant de l'utilisation de réseaux mobiles et sans fil dans l'Internet of Things et Smart Environments.

Dans la Partie II lors du chapitre 2 nous comparons la traditionnelle architecture non-IP avec une moderne, basée IPv6 pour réaliser des Smart IT Buildings Systems en utilisant des réseaux de capteurs sans fil. Après une analyse théorique et pratique, nous remarquons qu'une approche par IPv6 est meilleure dans l'époque IoT, puisque cette dernière apporte une meilleure efficacité en terme d'énergie, de la scalabilité, de la robustesse et une intégration facile avec des technologies WEB. Après avoir montré quelle approche on devrait suivre lorsqu'on projette des Smart Buildings en utilisant des réseaux de capteurs sans fils, dans le 3 nous proposons un IT architectural framework efficace avec lequel on facilite les Smart and Personalized IT building Systems. L'interopérabilité, la robustesse, l'efficacité et la scalabilité de notre framework sont une des plus grandes contributions de ce travail.

Comme la qualité de l'air que nous respirons à l'intérieur de tout type d'environnement joue un rôle important dans notre santé et notre qualité de vie, nous devons réduire les émissions de pollution dans l'air et dans le même temps les surveiller d'être conscients des dangers et mieux évaluer l'impact sur notre santé. Dans le 4 nous étudions l'impact de la pollution atmosphèrique sur l'environnement et la population et nous proposons un système dans lequel nous pouvons, à bas couts et de manière automatisée, efficacement monitorer la pollution de l'air dans un espace tridimensionnel, en faisant un ultérieur pas en avant par rapport aux couteuses et traditionnelles méthodes à deux dimensions.

Deux des aspects relativement nouveaux et importants à l'époque de l'Internet of things dans laquelle nous entrons sont les Crowdsourcing et le Crowdsensing. Comme ces domaines sont encore relativement jeunes en ce qui concerne l'IoT, il y a beaucoup de défis à relever, comme ceux des Parties III et IV. En particulier, dans le chapitre 5 nous étudions les crowd motivators et au même temps le Crowdsourcing initiatives and modes. Nous voyons ici qu'il y a plusieurs différences majeures dans la façon dont les gens sont incités à participer au Crowdsourcing, mais le commun dénominateur c'est l'intérêt des gens à gagner de la réputation et de la reconnaissance ainsi que le plaisir à prendre part à quelque chose de nouveau. Dans le chapitre 6 nous proposons une approche de création d'une architecture pour une plateforme IoT et crowdsourced-enabled. Cette plateforme exploite des testbeds existants en ajoutant des Crowdsourced ressources à partir de smart devices de la plateforme utilisateurs et permet à des ressources IoT hétérogènes d'être disponibles de manière homogène et interopérables entre elles. Au même temps, les gens peuvent participer activement à la recherche ou aux expériences définies dans la plateforme par les chercheurs et expérimentateurs.

Dans le chapitre 7 nous concevons une architecture axée utilisateur avec Mobile Crowdsensing support pour des Smart and Green Buildings. Pour faire cela, nous redimensionnons les technologies d'Internet de manière à satisfaire les contraintes des appareils de l'IoT et les combiner avec la sagesse des gens, afin de donner à tous les utilisateurs des services efficaces et un confort accru. Cette architecture comprend parmi le reste un mécanisme de motivation pour engager les gens à contribuer avec des informations environnementales captées pour le système, pendant que ce dernier essaie de s'adapter de manière à augmenter les bénéfices pour les utilisateurs finaux.

Dans le chapitre 8, comme en physique et dans la vie, chaque atome est caractérisé par un ensemble de fonctions qui définissent ses corrélations et synergies avec les autres atomes, nous étudions les relations et le Synergistic Analytics des personnes et en extrayant l'information de leur comportement avec d'autres personnes et la

relation avec leur environnement, nous présentons une plateforme préservant la vie privée, basée sur le contexte et leur lieu. Grace à cette plateforme, nous pouvons mieux capturer les interactions entre utilisateurs et leur contextes et ensuite leur fournir des bénéfices sous forme d'une meilleure qualité de vie.
ans la Partie IV au chapitre 9 nous étudions le transfert d'énergie sans fil (Wireless Power Transfer) que plus qu'une simple technologie spéculative, elle semble défier nos plus basiques intuitions sur ce qu'est l'énergie électrique et comment la transférer. Bien que Nikola Tesla ait fait des expériences sur le transfert d'énergie sans fil à cheval du XXème siècle, seulement de récentes avancées en informatique, électronique et ingénieries en matériaux ont permis de changer la manière avec laquelle nous transférons l'énergie depuis plus de 100 ans. En particulier nous étudions la technique de transfert d'énergie sans fil dans les réseaux mobiles Ad-Hoc, où nous présentons des stratégies transversales pour un Mobile Charger. Nous prouvons ici que notre Realistic Local-knowledge Strategy atteint une bonne performance d'échange aériens dans des réseaux à déploiement hétérogène et battent en termes de performance les stratégies simples ou naïves.

Cette thèse présente diverses aspects et solutions compréhensibles dans les domaines des réseaux de capteurs sans fils, IoT, Smart Buildings, Crowdsensing et Crowdsourcing.

mots clés: Algorithmes, Architectures, Réseaux de Capteurs sans Fil, Internet des Objets, Environements Intelligents, Crowdsourcing, Crowdsensing, Transfert d'Energie sans Fil.

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Part I

Introduction

1 Introduction

When Mark Weiser coined the term "Ubiquitous Computing" back in 1988 he could apparently foresee that in the beginning of the 21st century the concept of ubiquitous computing would be so much integrated in our everyday lives. Billions of electronic devices are able nowadays to communicate with each other. The concept of Ubiquitous Computing in which software engineering and computer science are coupled to provide computing services to users from any location, any device and in any format, is becoming more and more apparent through the recent technological advancements. The underlying technologies that support ubiquitous computing include: the Internet, advanced middleware, sensors, microprocessors, I/O, user interfaces, networks and protocols. Mark Weiser dreamed a world in which the use of the computer systems would be so immersive where the everyday devices could have interactions within them and with people as users. They could in that way, handle and respond so well in our actions that the computing process would be invisible to us. Behind this vision, there lies the assumption that we should be able (with sensing devices) not only to sense our environment but also the data and parameters around us so as to create a unified embedded system where those devices would communicate and interact with each other with or without our intervention. The key to this vision is to introduce the appropriate computing systems and mechanisms into the physical world with high density, and invisibly deploy them so that the sensors, the actuators and the gateways will seamlessly and autonomously work together. It is of extreme importance for this technological and scientific community to make these dominant systems, prevailing for themselves. We need to re-use the "bricks" to help us escape from the dedicated organization of each specific environment and to turn to the construction of "buildings" using the technics and mechanisms of understanding, computing and handling of the physical world. Our physical world exhibits an amazingly rich set of inputs and forms such as: sound, movement, temperature, pressure, light, humidity, electromagnetic waves and so on. Traditionally, the perception and the handling of physical world, implies the development and deployment of highly technological devices that take specific inputs and report data through a specialized and connected protocol in an also specialized computational data collection center. The opportunity that lies ahead of us is to design and develop, feasible, efficient, flexible and interoperable wireless systems, so as those systems to be of general purpose and to be able to be organized and integrated into a wide range of applications.

Wireless Sensor Networks

Perhaps one of the most suitable systems that is able to implement and exploit a wide variety of applications related to ubiquitous computing are the Wireless Sensor Network (WSN) systems. Wireless Sensor Networks have been widely considered as one of the most important technologies for the twenty-first century [1]. With the recent advances in *micro electro-mechanical systems* (MEMS) technology, wireless communications, and digital electronics, the design and development of low-cost, low-power, multifunctional sensor nodes that are small in size and communicate untethered in short distances have become feasible [2]. The ever-increasing capabilities of these tiny sensor nodes, which include sensing, data processing, and communication, enable the realization of wireless sensor networks (WSNs) based on the collaborative effort of a large number of sensor nodes. WSNs have a wide range of applications, ranging from environmental monitoring to smart homes automation and earthquake detection systems. In order to realize and exploit the potential of the

WSNs applications, sophisticate and extremely efficient communication protocols are required. WSNs are composed of a large number of sensor nodes which are densely deployed either inside a physical phenomenon or very near to it. WSNs typically consist of four basic components: 1) an assembly of distributed or localized sensors; 2) an interconnecting wireless network; 3) a central point of data gathering and 4) a set of computing resources at the central point or beyond it for handling data correlation, event trending, status querying, data mining, and service provisioning. WSNs are composed of individual embedded systems that are capable of: (1) interacting with their environment through various sensors; (2) processing information locally and (3) communicating this information wirelessly with their neighbours. Inside a WSN, each single sensor node is typically composed of the following three components and can be either an individual board or embedded into a single system: 1) a wireless module or mote responsible for the communications and the programmable memory; (2) a sensor board which is able to sense environmental parameters, such as temperature or human presence; and (3) a gateway board which provides multiple interfaces such as USB or serial ports used either for programming the mote or collecting data from them. The intrinsic properties of individual sensor nodes pose additional challenges to the communication protocols in terms of energy consumption. The heterogeneity in the available sensor platforms results in compatibility issues for the realization of envisioned applications. Hence, standardization of certain aspects of communication is necessary. To this end, the IEEE 802.15.4 [3] standardization body was formed for the specification of low-data-rate wireless transceiver technology with long battery life and very low complexity. On top of the IEEE 802.15.4 standard, several standardization bodies such as the 6LoWPAN [4] have been formed to proliferate the development of low-power networks in various areas (see chapter 2). In chapters 2, 3, 4, 7 we tackle challenges related to WSNs.

Internet of Things

With billions of devices already connected to the Internet and many billion more to come in the next years, the idea behind the Internet of Things (IoT) is not any more just an idea but it is already here to stay. CISCO is estimating that by 2020 there will be 50 Billion electronic devices, while Intel sees this number much higher at 200 Billion devices [5]. The term Internet of Things was coined in 1999 by Kevin Ashton [6], where his vision was of a global network of physical objects or "things" embedded with electronics and sensors connected with each other via Internet able to communicate and exchange data. Each "thing" is uniquely identifiable through its embedded computing system but is able to interoperate within the existing Internet infrastructure. These "things" can be anything from industrial plants, planes, cars to any kind of goods or even human body sensors. However, low-cost tiny small electronic devices with embedded systems capable of connecting to the Internet via their microscopic antennas are bringing the Internet of Things to the next level. Wireless Sensor Networks play a key role in the development of IoT networks and they proliferate many applications and many industries. The small, rugged, inexpensive and low powered WSN sensors bring the IoT to even the smallest objects installed in any kind of environment, at reasonable costs. Integration of these objects into IoT constitutes a major evolution of WSNs. In chapters 2, 3, 7 and 9 we propose architectures and algorithms in the domain of Internet of Things.

Smart Environments

The opportunities offered by the IoT make possible the development of a huge number of applications, of which only a very small part is currently available to our society. Many are the domains and the environment in which new applications would likely improve the quality of our lives: at home, while travelling, when sick, at work, just to cite a few. These environments are now equipped with objects with only primitive intelligence, most of time without any communication capabilities. Giving these objects the possibility to communicate with each other and to elaborate the information perceived from the surroundings imply having different environments where a very wide range of applications can be deployed. These can be grouped into the following domains: (1) Transportation and logistics domain; (2) Healthcare domain; (3) Smart Environments (home, office, buildings, leisure) domain; (4) Personal and social domain [7]. Among the possible applications in this work we deal with the domains of Smart Environments in chapters 2, 3, 4 amd 7, and with the social domain in chapters 8 and 6. The Smart Environment term refers to environments ranging from homes and offices to buildings, planes and even cities which have been augmented with intelligence in order to increase the experienced comfort of the people that reside in them, and to make them efficient in terms of energy consumption, pollution and energy resource management. Typically, Smart Environments are deployed with the use of sensors and actuators. The intelligence that such sensors and actuators bring into a house or an office can make our life more comfortable in several aspects: rooms heating, ventilation or luminance levels can be adapted to our preferences and to the weather; domestic incidents can be avoided with appropriate monitoring and alarm systems; energy can be saved by automatically switching off the electrical equipments when not needed (see chapters: 3 and 7). As to smart leisure environments, the museum or the concert hall are two representative examples where the IoT technologies coupled with WSNs can help in exploiting their facilities at the best. In the museum, for instance, expositions in the building may evoke various historical periods (ancient Greek period or ice age) with widely diverging climate conditions. The building can adjust locally to these conditions, while taking into account the outdoors environmental conditions and the occupancy levels of the number of people. Figure 1.1 shows sensor network applications forming Smart Environments within the Internet of Things.

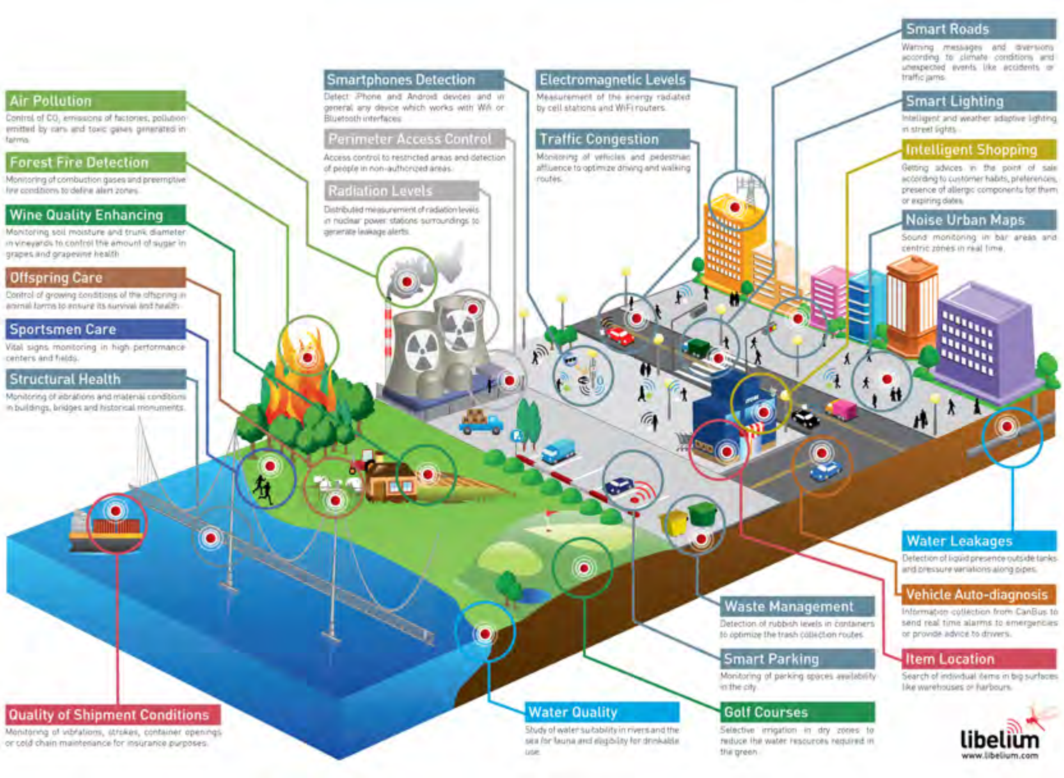


Figure 1.1: Sensor network applications forming Smart Environments in Internet of Things

Crowdsourcing and Crowdsensing

Over the past years there is a growing trend in the business society and in the research society as well where the process of accomplishing a task is carried out by soliciting contributions by a large group of people usually via online platforms such as smart phones, smart watches and webpages. This mode of "outsourcing" used to divide tedious work between people in the crowd already since the 18th Century. It has a history of success prior to the digital age when for example in 1714 the British government was trying to find a way to precisely measure a ship's longitude in the sea and they offered to the public a monetary prize namely as "Longitude Prize" to whomever would come up with the best solution. Nowadays crowdsourcing can be applied in a wide range of activities ranging from crowdsearching and crowdfunding to health care crowdsourcing. In the context of this thesis we study and we try to exploit the Mobile Crowdsourcing (MC) paradigm. The idea behind the Mobile Crowdsourcing is that the crowdsourcing activities take place in smart phones or mobile smart devices that usually are featured with geolocalization systems such as GPS and Internet connectivity. This allows for real-time and location-stamped data collection and provides projects and tasks an increased level of reach, accessibility and accomplishment. One of the most apparent MC examples in our days include Uber [8] and Waze [9]. In chapters 5 and 6 we tackle problems related to the conjunction of Internet of Things and Mobile Crowdsourcing.

Inside the context of Mobile Crowdsourcing a new paradigm of Mobile Crowdsensing is emerging due to the increased versatility of smart phones, tables and smart watches which embed sensors such as accelerometers, gyroscopes, light, temperature and pulse sensors. Mobile Crowdsensing takes advantage of the pervasive mobile smart devices which are able to sense, collect and analyze data in a context and scale that previously was not feasible. With a use of a Mobile Crowdsensing system, an experimenter or a "crowdsourcer" can engage people to participate in her experiment or task, in order to collect sensed information from their surrounding environment. Typically in the exchange of data and information from the end-users towards the experimenter, the latter provides incentives to them either in a monetary form or in bonuses and coupons. During the measuring process in the end-devices, feature extraction processes can take place in order to distil the raw data into meaningful ones, non-redundant, facilitating the better human interpretation. In the Internet of Things era, the Mobile Crowdsensing Systems (MCS) are gaining more and more attraction from the research and scientific community as their joint forces allow the exploitation of a great variety of smart application services such as the ones we discuss in chapters 7 and 8.

Wireless Power Transfer

An other very interesting and challenging research domain is the one of Wireless Power Transfer (WPT), which although its conception lies in the begging of the previous century, only recently the technological advancements have made such technologies more promising. Wireless Power Transfer refers to the transmission of electrical power from a power resource to an electronic device capable of receiving it without the use of solid wires. The advantages that technologies can bring utilizing WPT techniques are enormous since nowadays we are completely depended on wired electricity supply. WPT techniques are mainly separated into two categories: the radiative and the non-radiative. In near-field, non radiative techniques are utilizing inductive coupling between coils of wire or electric fields using capacitive coupling between electrodes to wirelessly transfer the power. Already existing applications of this type are mobile phones charging, RFID tags and implantable medical electronic devices. In chapter 9 we investigate mechanisms related to mobile charging of electronic devices using non-radiative techniques.

Scope and Structure

The scope of this PhD thesis was to come up, study, analyze, develop and implement novel ideas and visions from multidisciplinary domains of the Computer Science focusing on Wireless Sensor Networks (WSN), Internet of Things (IoT), Smart Environments (SE), Crowdsourcing and Crowdsensing, and Wireless Power Transfer (WPT). All these research fields although they can be examined and studied separately, in most parts of this work we demonstrate that they can be correlated and also strongly synergize with each other, providing added benefits to the technology advancements.

In *Part I* we study some aspects of Wireless Sensor Networks inside the vision of Internet of Things and focusing on Smart Environments. In chapter 2 we investigate two approaches that are related to Wireless Sensor Networks for Smart Buildings and in chapter 3 we utilize the results and outcomes of those approaches to develop a framework for creating personalized Smart Environments using WSNs. In chapter 4 we propose an Airborne WSN which is objective is to monitor the Ambient Air Pollution in 3D environments.

In *Part II* we investigate some Crowdsourcing aspects of the Internet of Things. In particular in chapter 5 we analyze the Crowdsourcing modes and the Related Crowd-motivators. In chapter 6 we propose an Crowdsourced-enabled Experimental Architecture for IoT.

In *Part III* we examine how we can better exploit the advantages of Mobile Crowdsensing focusing on the provisioning of smart services to end-users. In chapter 7 we design a testbed architecture with Mobile Crowdsensing Support for Smart and Green Buildings along with Incentive Mechanisms for its users. In chapter 8 we present a privacy-preserving, location- and context-based platform, based on Mobile Crowdsensing and Internet of Things for capturing more efficiently interactions between users and their context.

In *Part IV*, chapter 9 we investigate the problem of Wireless Power Transfer in Mobile ad-hoc networks and particularly proposing traversal strategies for a Mobile Charger which is able to charge electronic devices in its near-neighbourhood.

Lastly, in *Part V* we present the conclusions of this thesis followed by the annex and the bibliography.

Part II

WSN, IoT and Smart Environments

2 Evaluating Wireless Sensor Networks Design Approaches for Smart Building Systems

2.1 Introduction

With the rapid advancements in processor technologies and hardware platforms, embedded network systems have drawn a lot of attention in the IT research community. Wireless Sensor Networks (WSN), are one of the realizations of networked embedded systems. Subsequently, with the significant research effort both from academia and industry, the WSN combined with IP technologies are becoming the future of embedded internet. Millions of tiny devices connected to the internet are taking the pervasive computing to the next level. This line of research envisions a seamless integration of day to day commodities with the internet, namely the Internet of Things (IoT).

IoT technologies provide an infrastructure for wide range of applications such as industry automation, vehicular ad-hoc sensor networks and smart building systems. Among these, smart building systems are becoming more and more vital due to the improvement they provide to the quality of life. One of the key components of a smart building system is a WSN, which provides the necessary information to the smart building system allowing it to control and monitor the physical environment.

Frequently WSN operate in isolation but towards their collaboration in the IoT technologies, interconnectivity between two or more networks is a challenging task. This is mainly due to the fact that different protocols, systems and implementations do not always operate in harmony. An obvious move towards the de-isolation of the isolated WSN is to adapt multiple and diverse sensor networks to the existing protocols and make them work together seamlessly. Recent research and development have incorporated IP technologies with WSN, bridging the gap between heterogeneous networks. Without the use of IP protocols, "smart" gateways which are capable of interconnecting different protocols should be used to overcome the problem of isolation.

In this chapter we present an analysis and a comparison of two different approaches in the context of WSN in smart buildings; an IP-enabled approach and a non IP-enabled [10]. Specifically we present these two approaches both from a design and an implementation perspective. Moreover, we present the communication schemes of each approach and how the several components of the network communicate with each other. In the first approach of the IP-based architecture, a key factor is the IPv6 over Low power Wireless Personal Area Networks (6LoWPAN) protocol [11]. On top of that the Constrained Application Protocol (CoAP) [12] allows direct and simple interactions. In the second approach without the use of IP, the heart of the system is the mesh routing protocol RIME [13].To the best of our knowledge this is the first time such an analysis is being done.

The outline of the chapter is as follows; in the section 2.2 we briefly describe the background material. In section 2.3 we present a system's architecture for smart building applications, followed by the description of the two approaches where we analyse them in section 2.4. An evaluation of the schemes is presented in section 2.5 via an implementation based on a scenario in the WSN. In section 2.6 we present the evaluation of the approaches after a testbed implementation. Finally in section 2.7 we present our conclusions.

2.2 Related Work

As we are moving towards the IoT era we can clearly see the impact of WSN in the future. One of the main aspects of the IoT is the improvement of the Information Technologies and their applications which surrounds us and our environment. Important domain of the scientific efforts and research of the IT challenges is the smart building systems. As shown in [14], the challenges of the next-generation wireless sensor networks in the intelligent buildings could be overcame using state-of-the-art technologies. By exploiting them, we could reach a credible future in the development of smart buildings.

To be able to realize such systems that are auto organizing, easily accessible, efficient and energy aware, new protocols and standards have to be deployed. The state-of-the-art protocol suit 6LoWPAN [11, 15, 16] deployed by the 6LoWPAN working group of Internet Engineering Task Force (IETF) has defined the frame format for transmission of IPv6 packets to be sent and received over IEEE 802.15.4 networks. They have also designed the formation of IPv6 link-local addresses and statelessly autoconfigured addresses on top of IEEE 802.15.4 networks. The 6LoWPAN stack enables each device to be directly connected to the Web. Based on these IP packets, a RESTful API for sensor nodes has been developed. REST (REpresentational State Transfer) is a style of software architecture for distributed systems such as the World Wide Web [17]. REST-style architectures consist of clients and servers. Clients initiate requests to the servers, they process these requests and return appropriate responses. In REST, every resource has its own URI and by using these URIs it is possible to access these resources. The resources themselves are conceptually separated from the representations that are returned to the client.

An implementation of CoAP for the Contiki [18] operating system leverages the ContikiMAC low-power duty cycling mechanism to provide power efficiency [19]. The CoAP enables interoperability at the application layer through RESTful Web services [12]. The experimental evaluation in [19] of their low-power CoAP, demonstrates that an existing application layer protocol can be made power-efficient through a generic radio duty cycling mechanism. Furthermore it is shown that the use of ContikiMAC substantially reduces the motes energy consumption while keeping a reasonable end-to-end latency. The ContikiMAC is the MAC protocol that we are using in our implementation which is described in section 2.4.

Inside a smart building many sensors and actuators are interconnected to form a control system. Nowadays the deployment of a building's control system is complicated due to different communication standards. In [20] authors implemented an API to access services on sensor nodes following the architectural style of REST. An approach towards an integration of tiny wireless sensors or actuator nodes into an IPv6 6LoWPAN based network is presented. They propose the use of lightweight web services based on REST and the representation of data in the JSON format together with the stateless address auto-configuration mechanisms provided by the IPv6 protocol.

In the home automation design field a wireless sensor networks system using 6LoWPAN is proposed [21]. Besides, the JavaScript Object Notation (JSON) format is used to encode the data from the sensors which are deployed in the building. An IPv6 address is given to them allowing flexibility to the system. Data is sent over the network in a simple text format and none of the components of the system needs to know which are the capabilities of each individual node since they can be discerned easily from the data that is sent.

A vital part of an architecture design of WSN is a gateway. The gateway provides all the necessary interconnection schemes that makes WSN feasible to connect to other WSN and to the Web. The design and the construction of a wireless sensor and actuator network gateway based on 6LoWPAN are shown in [22]. A new gateway device which enables end-to-end connectivity between 6LoWPAN-based sensors and IP enabled devices is presented. The 6LoWPAN adaptation layer is the part of the gateway, which is responsible for the compression of packets addressed to the WSN and the decompression of packets targeted to the IPv6 network.

2.3 WSN System Architecture for Smart Buildings Applications

Wireless sensor networks are being used widely in smart building applications. Multiple sensors deployed around an area of interest such as an office building, can transfer diverse information of their resources to the system while other sensors can receive data to drive appliances connected to them. One of the key requirements for a smart building is that all sensors and actuators are accessible over the network from humans or other devices in an efficient and reliable way. With the current development efforts, IPv6 has become feasible in sensor networks and nodes are connected to the network using the IEEE 802.15.4 standard which is specifying the physical layer and the media access control for energy efficient communications with low data rates. On top is the IEEE standard, 6LoWPAN is used which allows IPv6 packets to be sent and received throughout the network. IPv4 and IPv6 are the work horses for data propagation. In our work, between the wireless sensor network and the broader network or the internet, a gateway is used to forward the packets from one subnetwork to the other and the WEB. The gateway is represented and implemented by a node connected to a serial port to a computer, which is connected to the Web or to other networks; either wired or wireless. The main architecture of our system is presented in Figure 2.1.

2.4 WSN Design Approaches; IPv6 vs non-IP

In this section we present two different approaches for the system architecture for smart building applications. The right choice of protocols when developing a wireless sensor network and the general system itself is very critical as the devices are tightly constrained in terms of energy, payload, communication bandwidth, memory and portability. Questions such as; which communication protocol is more energy efficient, which needs less overhead and which is more feasible, need to be answered. The two approaches that we present here are using different communication schemes. However the main aim of both approaches remains the same; to deploy a

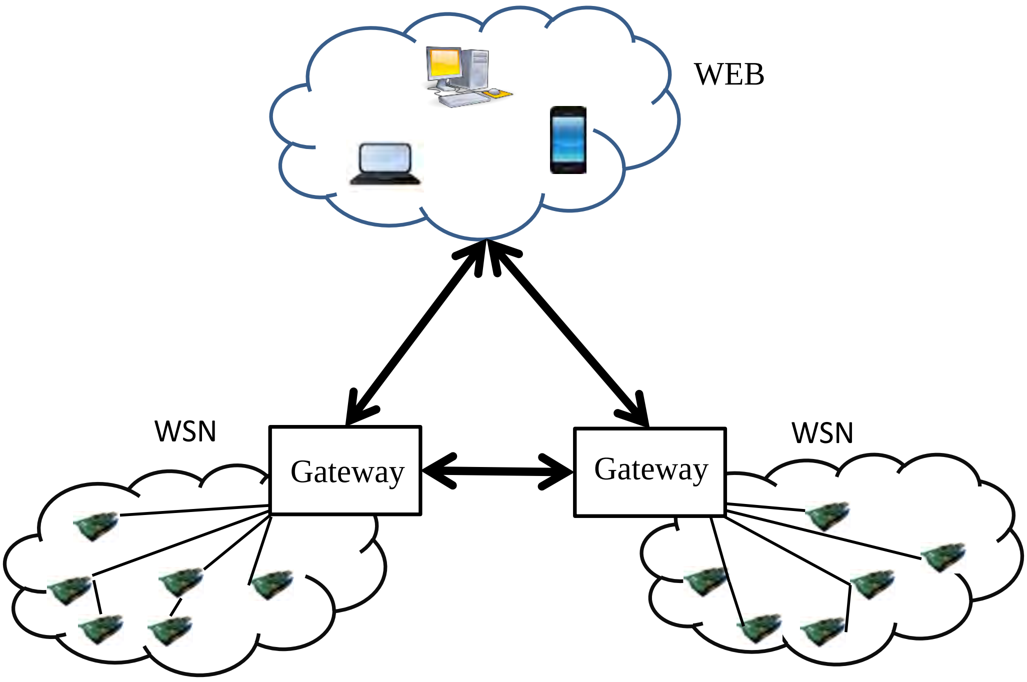


Figure 2.1: Interconnection of WSNs using gateways

wireless sensor network in a smart building and to develop an infrastructure for accessing the sensor network from the web or another network in a feasible and efficient way. The two systems differ in the communication patterns and the protocols they use, but also in the format of the packets that are being transmitted over the network. On the other hand they use the same 802.15.4 protocols for the Physical and Link layer. The main difference between these two approaches is that one is using IP-enabled protocols while the other one is not IP-enabled. The two approaches are presented below in detail, later their comparison follows as well.

2.4.1 WSN System designed with IPv6 over 6LoWPAN

2.4.1.1 IEEE 802.15.4

The 802.15.4 is a standard for wireless communication designed and issued by the IEEE. While IEEE has issued other standards for wireless communications such as the

802.11 (wireless LAN) or the 802.16 (Broadband Wireless Metropolitan Area Networks), their high bandwidth rates and high needs in energy consumption, do not fit well in the constrained energy resources and needs for low data rates in the Wireless Sensor Network field. The 802.15.4 standard specifies that communication can occur in the 868-868.8 MHz, the 902-928 MHz or the 2.400-2.4835 GHz Industrial Scientific and Medical (ISM) bands. While any of these bands can technically be used by 802.15.4 devices, the 2.4 GHz band is more popular as it is open in most of the countries worldwide. The 868 MHz band is specified primarily for European use, whereas the 902-928 MHz band can only be used in the United States, Canada and a few other countries and territories that accept the FCC regulations. The 802.15.4 standard specifies that communication should occur in 5 MHz channels ranging from 2.405 to 2.480 GHz. The 16 channels offered by the standard although they are defined to use a spectrum of 5MHz, only about 2MHz spectrum is consumed by each of them. Moreover, the standard is designed to support both star and peer-to-peer topologies, supporting the diversity of WSN where sensors form mesh networks and cluster trees. One of the most important characteristics of the 802.15.4 protocol is its low power consumption and support for low latency devices. Also it has dynamic device addressing and very low complexity. All of those characteristics confirm the suitability of the standard for low-rate wireless personal area networks. [3]

2.4.1.2 IPv6 over 6LoWPAN

Following the revolution of Ubiquitous Computing which started in 1990's, and the Internet of Things subsequently, the IETF 6LoWPAN group developed a standard and defined the mechanisms that allow IPv6 packets to be send to and received over Low-Power and Lossy Networks (LLNs) such as those based on IEEE 802.15.4 networks. 6LoWPAN is the efficient extension of IPv6 into the wireless embedded domain, thus enabling end-to-end IP networking and features for a wide range of embedded applications. Issues such as power and duty cycle, multicast communications, mesh topologies, bandwidth and frame size have been extensively addressed. The 6LoWPAN has defined efficient encapsulation and header compression mechanisms along with neighbour discovery. Communication between 6LoWPAN Nodes and IP nodes in other networks happens in an end-to-end manner, just as between any normal IP nodes. Each 6LoWPAN Node is identified by a unique IPv6 address and is capable of sending and receiving IPv6 packets. Typically, 6LoWPAN Nodes support ICMPv6 traffic such as "ping" and use the UDP protocol as a transport [16]. The interoperability that the 6LoWPAN offers in both eliminating the need of knowing the constrains of the physical links that carry the packets and the interoperability in communication with other wireless 802.15.4 devices as well as with devices on any other IP network link via a simple bridge device, is constituting it as the most appropriate protocol when choosing it as network layer in the IoT and WSN domain.

2.4.1.3 UDP

The UDP protocol is used in between of the 6LoWPAN and the CoAP protocol in the transportation layer. It uses a simple transmission model avoiding a big overhead and error correction mechanisms that are used in other layers to ensure correct delivery of packets. Since the 6LoWPAN networking has features that require special handling mechanisms on application protocol design such as the compression of UDP that provides, and simplicity which are really useful because a 6LoWPAN typically has a limited number of applications. Moreover, since most of the applications in the IoT do not require the establishment of a reliable connection before the actual transmission of data is started and there is no requirement for an ordered communication UDP suits better than TCP, although also the later is supported by 6LoWPAN. In our approach here, the type of messages that are exchanged are mostly of query/response type and so a simple mechanism for packet loss suffices.

2.4.1.4 CoAP

The CoAP application protocol designed by the Constrained RESTful Environments (CoRE) group of the IETF, is providing the the framework at the application layer for resource-oriented applications intended to run on constrained IP networks. CoAP which must run on top of UDP layer is designed to easily translate to HTTP for simple integration with the Web. Its main characteristics are constrained machine-to-machine web protocol, simple proxy and caching capabilities, low header overhead and parsing complexity, and reliable unicast and multicast support. It has also the ability to advertise resources or queries from a constrained device, including its name, services, characteristics, type and so on. Moreover, through CoAP, non-reliable multicast messages can be sent to a group of devices for accessing or manipulating a resource on all the devices in the group. Generally, its low overhead, multicast support, efficiency and simplicity are extremely important for the Internet of Things.

2.4.2 WSN System designed without IP

In this approach, we employ a much simpler network layer protocol for WSN connectivity in contrast to TCP/UDP and IP protocol suit. Furthermore we identify the absence of established transport/application layers in such configurations, and we propose simple alternatives as described below. In the link and physical layer the 802.15.4 protocol is used as in the previous approach because of its special design purpose to serve Low Power and Lossy Networks.

2.4.2.1 RIME

The RIME communication stack provides a set of lightweight communication primitives ranging from best-effort anonymous local area broadcast to reliable network flooding. RIME is Contiki's inbuilt network layer, which provides addressing and multi-hop networking addresses [13]. RIME is build inside the Chameleon architecture defined by the authors in [23]. The Chameleon architecture is an adaptive communication architecture for sensor networks. The purpose of the architecture is threefold. First, the architecture is designed to simplify the implementation of sensor network communication protocols. This is done through

Table 2.1: Comparison of the communication protocols used by the two different approaches as per the Wireless Networking Protocol Stack Model; with IPv6 and without IP

	IPv6 over 6LoWPAN	**non-IP**
Layer	**Protocol**	**Protocol**
Application	CoAP	JSON
Transportation	UDP	Custom
Network	IPv6 - 6LoWPAN	RIME
Link-Physical	IEEE 802.15.4	IEEE 802.15.4

the use of the RIME protocol stack. Second, the architecture allows for sensor network protocols that are implemented on top of the architecture to take advantage of the features of underlying MAC and link layer protocols. This is done by using packet attributes instead of packet headers. Third, the architecture allows for the packet headers of outgoing packets to be formed independently of the protocols or applications running within the architecture. Despite the fact that IP is more comprehensive, RIME carries relatively less overhead in terms of message headers and occupies a less amount of bytes in RAM. Therefore RIME-stack is a good choice as the network layer for local subnetworks of an architecture for WSN.

2.4.2.2 JSON

Compared to the TCP/IP stack RIME does not provide transport layer service, therefore a combined transport and application layer has to handle the application data accordingly. As a well-established messaging format, JSON is used to handle the application messages, which is developed and tested for constrained environments. Although originally derived from the JavaScript scripting language, JSON is a language-independent data interchange format [24]. JSON is promoted as a low-overhead alternative to XML and thus suits well in our design approach. We constraint our messages' size to fit RIME packets so that special transport control is not needed.

2.4.3 Comparison of the two approaches

Table 2.1 shows an overview of the layers of the communication protocols for the two approaches.

From the deployment and programming perspectives, both of these approaches have their own pros and cons. In the first approach, setting up the IP network is much simpler mainly due to the auto-configurable addressing, in contrast to the manually configurable RIME addresses. Furthermore, IP is more comprehensive in the context of internet, since it has inbuilt support for auxiliary services, such as DHCP and DNS. In addition, the transport layer supports the UDP and applications can easily adapt to the RESTful nature of World Wide Web along with application layer protocols such as CoAP.

On the non-IP approach we argue about the fact that WSN subnets can use much simpler communication stacks in local area. These sub-networks can be mediated by the gateway to communicate with the internet hosts. This can greatly reduce the memory burden on WSN nodes and communication overheads. Despite this advantage, RIME stack does not provide any transport layer support and applications need to take care of the transport layer level. In this approach, in the application layer we use the JSON format for communicating with the Web.

We summarize the comparison of the two approaches in the Table 2.2.

Table 2.2: Comparison of IPv6 vs non-IP scheme

	IPv6 over 6LoWPAN	**non-IP**
Address Configuration	Automatic	Manual
Service discovery	Simple	Complex
Integration with WEB	Straight-forward	Proprietary
Scalability	Easy	Difficult
Overhead	Large	Small
Complexity	High	Low

2.5 Implementation of Approaches

In order to evaluate our approaches, we implemented a scenario with the use of a wireless sensor network in the context of smart buildings. Our argument is to find out which of the two approaches is more appropriate to use for implementing this scenario. Is IPv6-6LoWPAN along with CoAP more efficient than simpler solutions such as RIME ? A comparison of these two approaches after we implemented them in the simulator and in our testbed is presented in the next section. Problems such as feasibility of technology, efficiency in the embedded systems, relation with the Internet of Things, schemes for interoperability and others have been tackled. We have chosen the scenario of profiling because it comprises of general communication patterns and components required by most of the smart building scenarios. The technology, the protocols and the systems we are evaluating behind this scenario could be applied to several other scenarios in the smart buildings systems.

2.5.1 Description of Case Study

We implemented the profiling scenario with the above described approaches (with IPv6 and without IP) to evaluate the feasibility, energy consumption, memory footprint and latency of each one of them. The scenario consists of a profiling system in a WSN which is able to identify people, take decisions according to their profile and make the resources of the WSN available to the Web. Upon the arrival of a person in the proximity of an agent-node, the agent-node identifies the person (user) and it is transmitting a message to the profiling server through the gateway. The purpose of the agent-node is solely the identification of the users of the system. The message that is sent contains the profile ID of the person and the profile service decides whether to allow the access of the person in the room or not. In addition, it provides the agents and the node-actuators customized information based on the user's profile. According to the profile and the needs of each person, several actions take place such

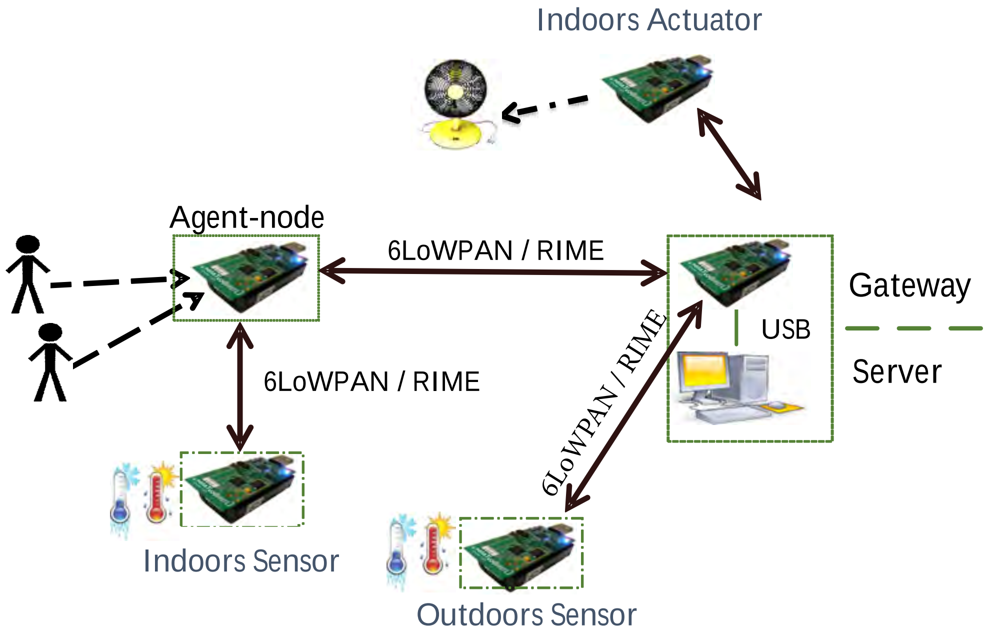


Figure 2.2: Interconnections and communication pattern in the profiling scenario.

as switching on/off a light and turning on/off a fan. The interconnections and the communication pattern of the nodes of the scenario are shown in Figure 2.2

In a centralized version of the profiling scenario the agent-node is acting as a forwarder without taking any decisions or actions. It is the responsibility of the profiling server connected to the gateway to run the necessary services and drive the node-actuators.

A larger scale figure of the proposed scenario is shown in the Figure 2.3 where multiple nodes are placed in each of the four rooms in the premises of our a building comprising a wireless sensor network connected to the Web. The actuator nodes are placed in the corner of each room, driving the lights and the blinds of the windows. Next to each door of the building an agent-node is placed which is connected to the node-actuators and the gateway as well. The main gateway is handling all the received information by the agent-nodes and the Web while at the same time is able to drive the node-actuators.

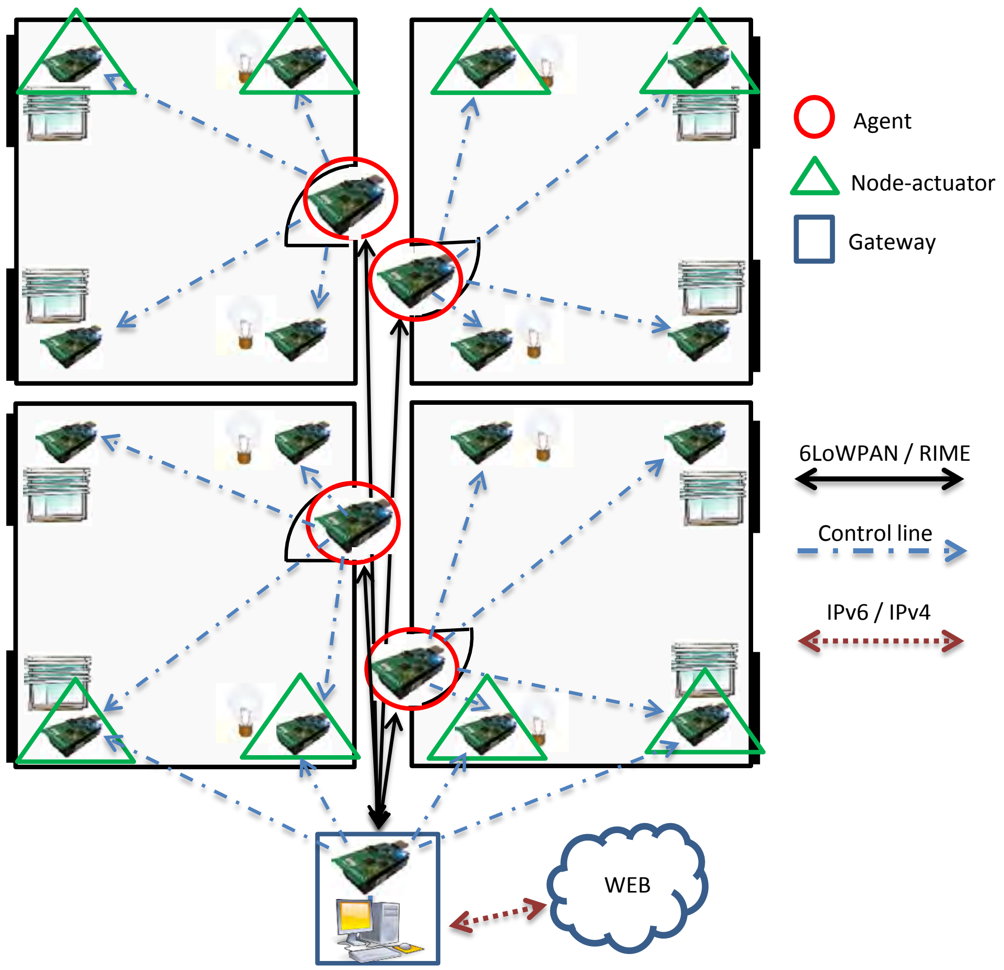


Figure 2.3: WSN deployment of the profiling scenario in a smart building.

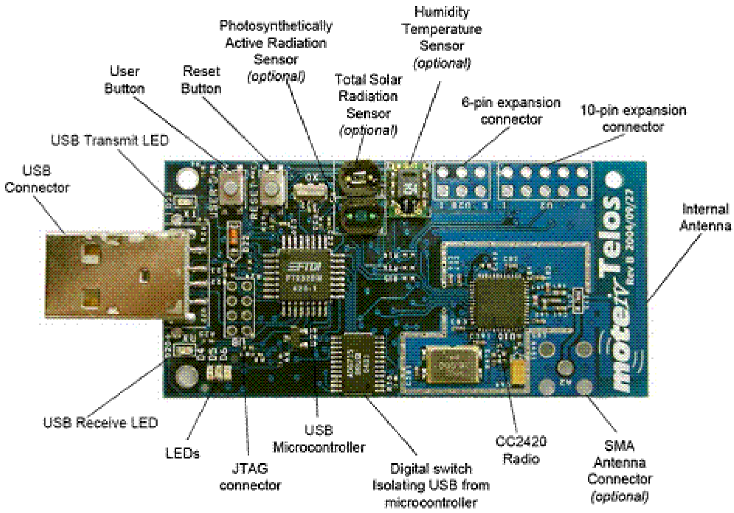
2.5.2 Experimental Setup

2.5.2.1 Hardware

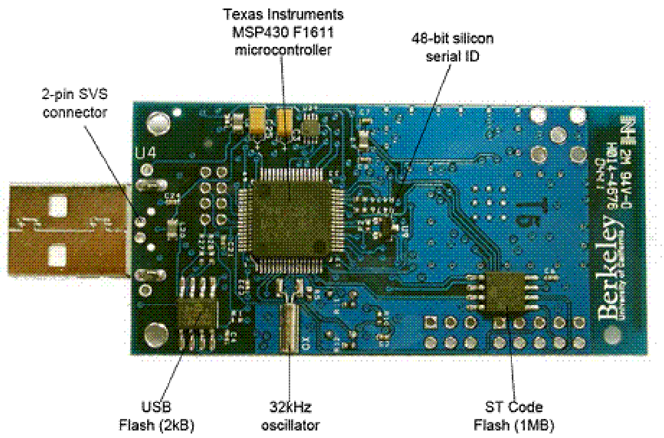
For our implementation we used motes [25]. The TelosB motes are an open source platform designed to enable cutting-edge experimentation. The TPR2400[12] mote from Crossbow industries which our lab has and which we used in this work, bundles all the essentials for our lab studies into a single platform including: USB programming capability, an IEEE 802.15.4 radio with integrated antenna, a low power MCU with extended memory and a build on sensor suite. The motes offer many features including: IEEE 802.15.4 / ZigBee compliant RF transceiver, 2.4 to 2.4835 GHz a globally compatible ISM band, 250kbps data rate, integrated onboard antenna, 8 MHz TI MSP430 microcontroller with 10kB RAM, Low current consumption, 1MB external flash for data logging, programming and data collection via USB, sensor suit including integrated light temperature and humidity sensor. It is powered by two AA batteries. If the mote is plugged into the USB port for programming or communication, power is provided from the host computer. If the mote is always attached to the USB port no battery pack is needed. The TPR2400 provides its users with the capability to interface with additional devices. The two expansion connectors and onboard jumpers may be configured to control analog sensors, digital peripherals and LCD displays. Figure 2.4 shows the TelosB platform. A TelosB apart from being either a sensor or an actuator, it offers the capability (with the appropriate software programming) to act as a gateway, i.e.acting as a border router between the web and the WSN or between two WSN (see Figure 2.1. In our work here, one TelosB was connected to a computer running an Ubuntu distribution of Linux. In the node-actuator, we used the General I/O pins of the TelosB motes to drive a table lamp and a fan. (More details on that are given in 3.4.

2.5.2.2 Software

To program our sensors we used the version 2.6 of Contiki OS. For the simulations, we used the Cooja simulator developed by the Contiki community. Cooja allows large and small networks of Contiki nodes to be simulated. Nodes can be simulated at the hardware level, which is slower but allows precise inspection of the system behaviour, or at a less detailed level, which is faster and allows simulation of larger networks. We used the Contiki's CoAP API to implement a CoAP client and server in the agent-node and node-actuators. We used JSON as the message format with the JSON support of Contiki in both approaches.



(a) TelosB front size layout



(b) TelosB back size layout

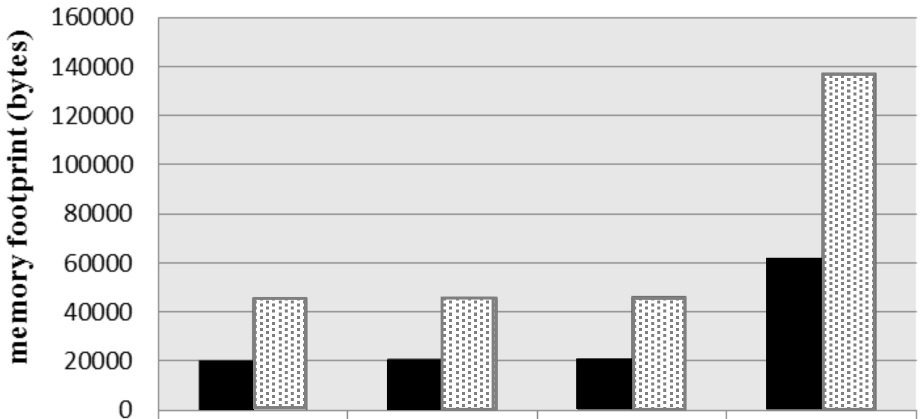
Figure 2.4: TelosB Mote components

2.6 Evaluation

In this section we evaluate the two implemented approaches, based on their ROM memory footprint, energy consumption and latency for a Round Trip Time (RTT) transaction. We implemented a use case of the profiling scenario interconnecting the three different components; agent-node, gateway and node-actuator according to Figure 2.2. The agent-node initiates a "transaction" requesting the profile from the server and transmitting the appropriate message to the node-actuator. We evaluated the above mentioned metrics performing 100 transactions for 200 times. The nodes were placed 3 meters away from each other in an office environment. The transmission power of the nodes was set to their maximum. The evaluation of the two approaches took place at the same place with the same conditions, allowing us to make accurate comparisons.

2.6.1 Memory Footprint

Figure 2.5 shows the memory footprint (in bytes) of the ROM occupied by the different components of the system. As shown in the table, the ROM memory footprint of the non-IP approach is significantly smaller than the IP-based implementation in all the three components. In total the non-IP approach requires less than half of the memory resources required by the IP approach. This is due to the complexity of the CoAP and 6LoWPAN implementations compared to the much simpler RIME stack.

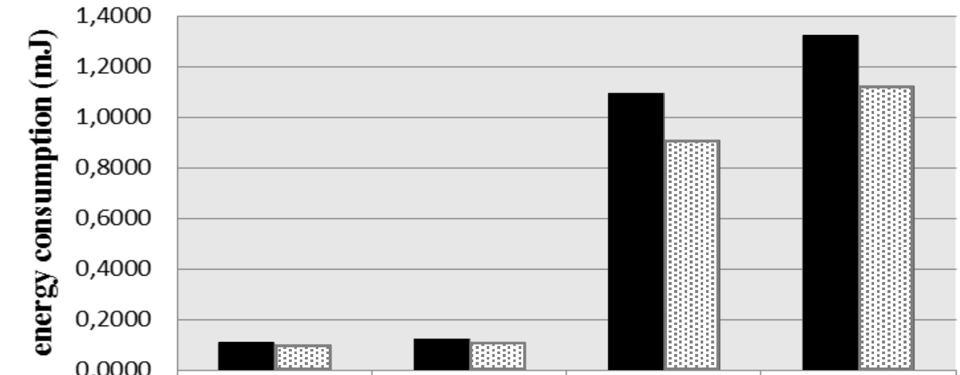


	node-actuator	gateway	agent	Total
Non – IP	20512	20546	20566	61624
Ipv6	45432	45424	46256	137112

Figure 2.5: ROM memory footprint of the non-IP and the IPv6 approach. The non-IP has more than half less memory footprint.

2.6.2 Energy Consumption

In order to extract metrics on the energy consumption of the three components of the system, we used the software-based online energy estimation mechanism proposed for Contiki [26] in order to calculate the energy consumptions of the three components. Figure 2.6 shows the total and the individual energy consumptions in micro-Joule (mJ). We observe that the IP-based approach consumes slightly less energy than the non-IP approach.



	node-actuator	gateway	agent	Total
Non – IP	0,1069	0,1209	1,0935	1,3213
Ipv6	0,1002	0,1101	0,9098	1,1201

Figure 2.6: Energy consumption of the non-IP and the IPv6 approach. The IPv6 approach is more energy efficient.

2.6.3 Latency

Figure 2.7 shows the latency in seconds of an RTT transaction in the two approaches. We calculate the latency based on the number of clock ticks spent for a RTT. We observe that the IP-based implementation performs faster.

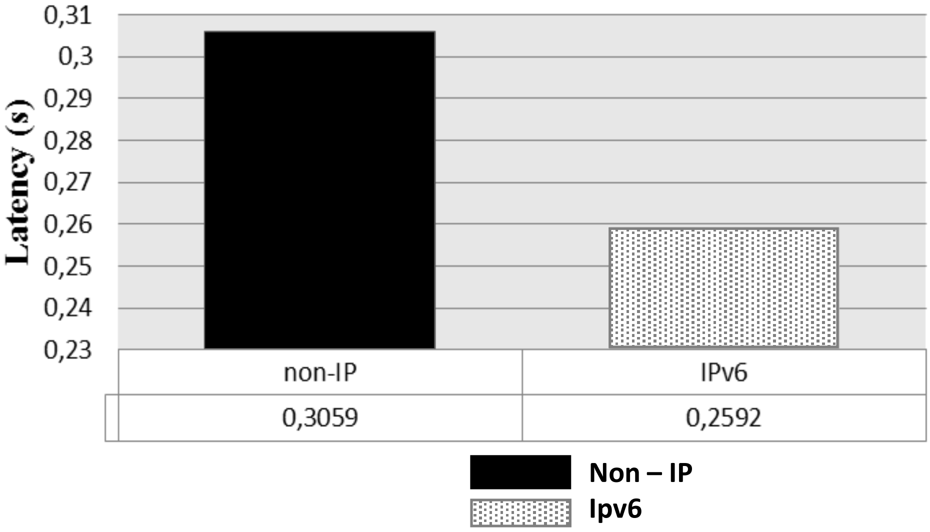


Figure 2.7: Latency for one RTT of the non-IP and the IPv6 approach. The IPv6 implementation clearly outperforms the non-IP.

2.7 Conclusions

In this work, we presented two different design approaches for smart building systems using WSN. One approach is based on IP and particular on IPv6 while the other one is based on a custom non-IP approach. After the system's architecture presentation we analysed the advantages and disadvantages of the approaches. We showed the differences of the two approaches from the theoretical and implementation perspective.

We conclude that IPv6 approach is more advantageous for large scale WSN systems. This is mainly due to the auto-configurable networking setup and the interoperability that the IPv6 technology provides with the standard protocols. Furthermore, the support in the transport layer with UDP, allows easy integration of Web applications via protocols such as CoAP.

Even though in the WSN the non-IP implementation is simpler, CoAP 6LoWPAN design provides more flexibility when connectivity with the internet is needed. This is due to the fact that in the non-IP approach, a "smart" custom gateway is needed to interconnect the simple RIME addresses of the WSN with the IP addresses of the Web. Additionally, without IP addresses in the WSN, the individual nodes are difficult to be accessed from outside the WSN. Moreover, when a large number of nodes need to be deployed in a WSN, by using the non-IP approach the set up of the network would require a significant amount of time in order to be deployed. For the fact that our lab does not possess hundreds of nodes to conduct large scale experiments, the investigation of the feasibility in the deployment of a large scale WSN can be considered as future work.

On the other hand, the non-IP design is good for small scale WSN because of its light complexity of the protocols and communication layers that are used. Furthermore, the small memory footprint of this design, suites well to the nature of the constrained embedded devices. In addition, not all the devices of the IoT need necessarily to be connected to the internet, favouring in those cases the non-IP implementation.

After our experimental evaluations of the profiling scenario we find out that the only drawback of the IP-based solution is the relatively large memory footprint requirements. However, with the advancements of hardware electronics, this discrepancy could be eliminated. Even though the design of 6LoWPAN is more advanced and its implementation is more complex, it performs better due to its well established and well defined protocols. This results in outperforming the non-IP approach in terms of latency and energy consumption.

Finally we can conclude that considering the IoT vision, inter-connecting a large number of embedded devices in WSN and connecting them as well with the Internet, IPv6 prevails as the most scalable and efficient mechanism.

3 *Syndesi*: A Framework for Creating Personalized Smart Environments using Wireless Sensor Networks

3.1 Introduction

Computer and communication technologies have greatly affected day to day lives of human society. Especially, mobile and wireless devices with increased computation and communication capabilities, provide easy access to various and ubiquitous information services. Wireless Sensor Networks (WSNs) technologies can be used to enhance the accessibility and availability of such ubiquitous services. With recent advancements in IP enabled WSN, these services are further enhanced. WSNs coupled with IP technologies become a viable candidate for various applications in many domains such as health care monitoring, environment monitoring and smart infrastructure.

Smart infrastructure is an important area of concern especially in the face of climate change and the foreseeable energy crisis. With the use of smart technologies, designers and architects expect sustainability and maintainability of infrastructures while optimizing the utilization of resources. In this context, wireless sensor networks play an important role due to the balance they offer between flexibility, feasibility and efficiency.

Even though there are available many WSN technologies and devices, combining these technologies remains a challenge. This is mainly due to the lack of developments in unified frameworks which can support combination of heterogeneous devices and services. Such a framework should provide support for discovery, maintainability, user-friendliness and combination of services. Furthermore, it should support various auxiliary services which can be used to develop and integrate other applications.

Our contribution in this work is a framework for unifying heterogeneous devices and services in the WSN domain, which can be used to develop more advanced and integrated applications for creating personalized smart environments [27]. Our framework consist of the hardware interfaces and software services to support combined WSN based application development, electrical and electronic integration and user identification. Furthermore we use the REpresentational State Transfer (REST-style) [17] web service abstraction based on Constrained Application Protocol (CoAP) [19]. To demonstrate our framework we implement it in the premises of our building where we transformed the old traditional infrastructure into a personalized smart environment, which is also interconnected to the Web and to electrical appliances through our developed electrical-electronic interface.

In the following sections we present our work as follows: in Section 3.2 we briefly describe the background material and what motivates the need of such a framework. In Section 3.3 we present the general design of *Syndesi* framework, in Section 3.4 its architecture and in Section 3.5 its layered overview. Section 3.6 shows the management of the framework and the User Interactions. The deployment of the framework follows in Section 3.7 where we implement two different real life scenarios in an office space. In Section 3.8 we present the augmented *Syndesi* framework with Mobile Crowdsensing support. In Section 3.9 we present the performance results of the framework and finally in Section 3.10 we present our conclusions.

3.2 Related Work

The advantages of distributed sensor networks including but not limited to reliability, scalability, dynamicity, efficiency have brought the WSN systems into the next generation. WSN systems play an inevitable role in our everyday life. A smart environment is a small world where all kinds of smart devices are continuously working to make inhabitants' lives more comfortable [28]. The use of WSN in this context has drawn a lot of attention due to the flexible nature of such networks. With the developments in IP technologies and web service standards in WSN further extends the capability to develop smart environment applications based on standard protocols. The challenges of next-generation WSN in the smart environments' domain can be overcome using state-of-the-art technologies. By exploiting them, we could reach a credible future in the development of smart buildings.

Smart environments should act based on the individual occupants and their preferences. Therefore it is important to identify and track the occupants in the environment as well as provide the necessary services to them so that they can control and monitor their environment. Besides, a smart environment should be able to take autonomous decisions in order to provide comfort and safety to the occupants as well as being energy efficient.

To be able to realize such systems that are auto organizing, easily accessible, efficient and energy aware, new protocols and standards have to be developed. The state-of-the-art protocol suit 6LoWPAN [11,15,16] deployed by the 6LoWPAN working group of Internet Engineering Task Force (IETF) has defined the frame format for transmission of IPv6 packets to be sent and received over IEEE 802.15.4 networks. In [10] we present an analysis of smart building systems design approaches and implementation with WSN to conclude that the IPv6/6LoWPAN prevails against the IPv4. The 6LoWPAN stack enables each device to be directly connected to the Web. Based on these IP packets, a RESTfull API for sensor nodes has been developed. REST is a style of software architecture for distributed systems such as the World Wide Web [17].

Inside a smart environment many sensors and actuators are interconnected to form a control system. The deployment of such a control system is complicated due to different communication standards. In [20] the authors implemented an API to access services on sensor nodes following the architectural style of REST. An approach towards the integration of tiny wireless sensors or actuator nodes into an IPv6 6LoWPAN based network is presented. They propose the use of lightweight Web services based on REST and the representation of data in the JSON format together with the stateless address auto-configuration mechanisms provided by the IPv6 protocol.

In the home automation design field a wireless sensor network system using 6LoWPAN has proposed [21]. A vital part of an WSN architecture design is gateways. The gateway provides all the necessary interconnection schemes that makes a WSN able to connect to other WSN and to the Web. The design and the construction of a wireless sensor and actuator network gateway based on 6LoWPAN are shown in [22].

An application framework for Web-based smart homes is presented in [29]. RESTful services over HTTP to connect sensors directly to the Web is used. We go further than the results of this work that are limited in an 6LoWPAN WSN inside a home environment, by creating a general framework for smart environments which includes heterogeneous WSNs, user identification and interconnection of electrical devices.

The authors in [30] are mentioning the capabilities of using NFC in smart home environments of the future IoT systems but their system is not yet connected with any WSN network for monitoring the environment and controlling appliances.

A framework to integrate sensors and actuators with IP networks based on the REST architecture is proposed in [20]. The authors propose a dynamic service discovery mechanism based on a REST API through which services provided by the WSN nodes can be discovered. Since both the architecture and the Web protocols are location transparent, we identify a need of a location based service discovery mechanism, especially in smart environment applications.

3.3 *Syndesi* Framework

The aim of the *Syndesi* framework [1] is to create personalized smart environments using WSNs. It combines networks of sensors, nodes and actuators with different communication technologies such as Near Field Communication (NFC), Bluetooth, ZigBee, and 6LoWPAN along with an electrical interface.

By using state of the art technologies and communication protocols in the domain of distributed computing, the *Syndesi* framework can transform an old traditional infrastructure into a smart environment. Through this framework practically any electrical device can be controlled via the Internet, a smart-phone or automatically by the framework itself. The WSN that is deployed at the heart of the framework has the ability to monitor the environment of an infrastructure and, if required, to control it as well. Furthermore, this framework provides an external interface so that each individual node or the whole system can be operated through Web-based applications. Apart from the general management of the system, taking into account the preferences of the occupants of a smart environment, the framework leads to personalized and optimized system performance. In order to provide personalized services to the occupants it is necessary to incorporate tools for their identification, tracking and localization. In this context we interconnect within the framework NFC tags, NFC enabled smart phones and Bluetooth enabled devices which provide a better user experience to the occupants. Moreover, this framework eases the management and the maintainability of such an environment.

General Design of the *Syndesi* Framework

The behaviour/design of the *Syndesi* framework is twofold. On one hand the framework acts as a *centralized system*, where the system relies on centralized information so as to provide specific services. This centralized behaviour of the

[1] all the source files of the code behind *Syndesi* are available online at GitHub in the following link: https://github.com/tcslab/Syndesi

framework is activated when the system requires, for example, the profile information of a user from the gateway in order to drive some actuators of the system. Specific examples include: when a user needs its personal heating to turned on when it is cold outside or when the management of a building requires information about the status of the sensors via the Web.

On the other hand, the framework has a *distributed behaviour*. The system reacts in a distributed manner when individual sensors perform autonomously. A descriptive scenario of such behaviour is the case of an emergency situation when a fire breaks out in a room. In that case an alarm can be triggered directly and automatically by the fire detection sensor.

This twofold behaviour of our framework allows for the realization of multiple and complex real life scenarios where a centralized and/or a distributed processing is needed.

3.4 Architecture of *Syndesi*

The overall architecture of the framework is illustrated in Figure 3.1, which presents the interconnections between the components of the framework. Following we describe each component of the framework in details.

3.4.1 WSN for Users' Identification

For the identification, simple tracking and localization of the occupants in our framework is dedicated a WSN which is deployed with the use of Waspmotes by Libelium[2]. The Waspmotes are sensor devices oriented for developers. They support ZigBee, WiFi, Bluetooth, NFC/RFID and GSM/GPRS communication interfaces, which makes them a good candidate for being used as gateway nodes between nodes that do not share a common communication interface. An inevitable part of a smart

[2]www.libelium.com

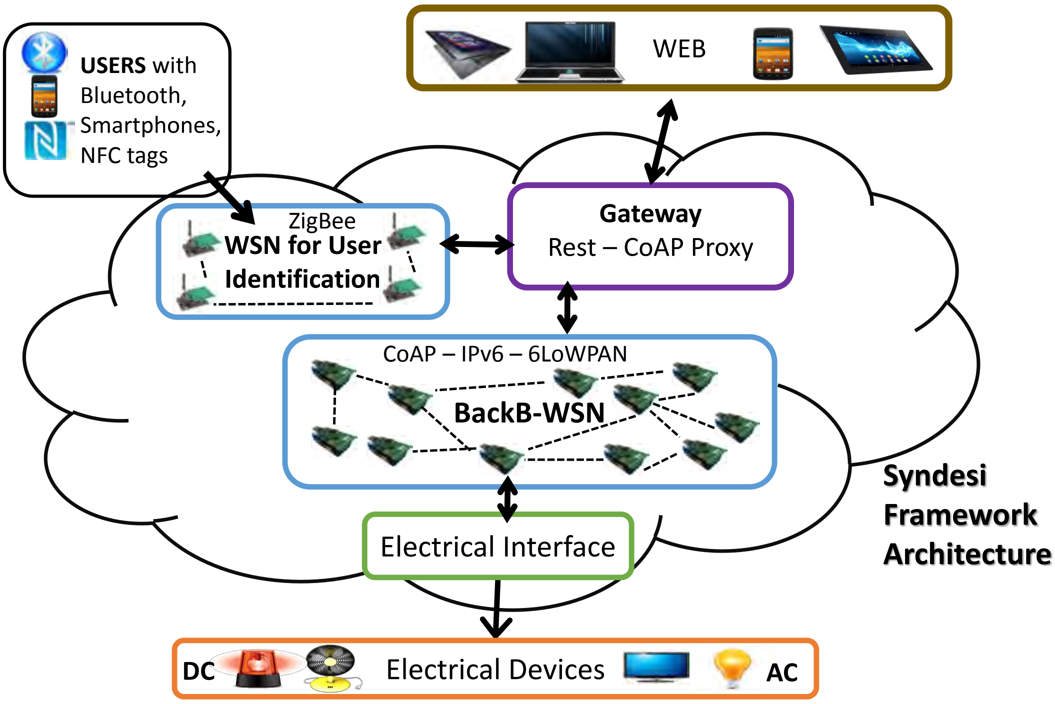


Figure 3.1: Architectural Overview of the *Syndesi* Framework

environment is its occupants, consequently it is crucial for the framework that controls this smart environment and provides smart services to its occupants to be capable of identifying and tracking them.

3.4.2 Gateway

The gateway of the *Syndesi* framework is interconnected with the *Backbone WSN*, the *WSN for Users' Identification* and the *Web*. It contains the two base-stations of the two different WSNs so as to provide connectivity with them. On the other side it provides a proxy server in order to make the whole framework accessible to the Web connecting both CoAP and HTTP enabled systems.

3.4.3 Backbone WSN

The *Backbone WSN* comprises the sensors which are responsible for the monitoring and control of the smart environment. These sensors are capable of communicating over the wireless medium. For the backbone WSN, TelosB sensor nodes are used. The TelosB node is an open source platform designed to enable cutting-edge experimentation. These nodes form a wireless sensor network based on the 6LoWPAN protocol implementation available in the Contiki operating system. Therefore, the network is IPv6 addressable with optimized IP services such as routing for low power wireless links. Some of the WSN's motes are used as actuators taking part also in the *Electrical-Electronic Interface* which is connected to electrical and electronic appliances.

3.4.4 Electrical-Electronic Interface

As one end of our framework consists of electrical and electronic appliances, we developed an interface with which we are able to control them. An electrical or an electronic device can be powered with one of the two following ways; Alternating Current (AC) and Direct Current (DC) supply. For manipulating these two different types of current and as result controlling the appliances powered by them, we need two different types of relays: one for switching AC circuits being driven by DC and the other one for switching DC circuits being also driven by DC. Thus, to be able to control any AC or DC electrical and electronic device we use DC-DC and DC-AC relays which are driven by the General I/O (GI/O) of the sensors. Figure 3.2 depicts the design of the electrical-electronic interface using the TelosB output, a DC to DC solid state relay and a DC circuit powering a LED. The same design applies for the AC circuits with only modification the replacement of the DC-DC relay with a DC-AC relay. We use solid state relays which have increased long-term reliability as a consequence of the in-existence of moving components. In this way, via the *Syndesi* framework, is feasible

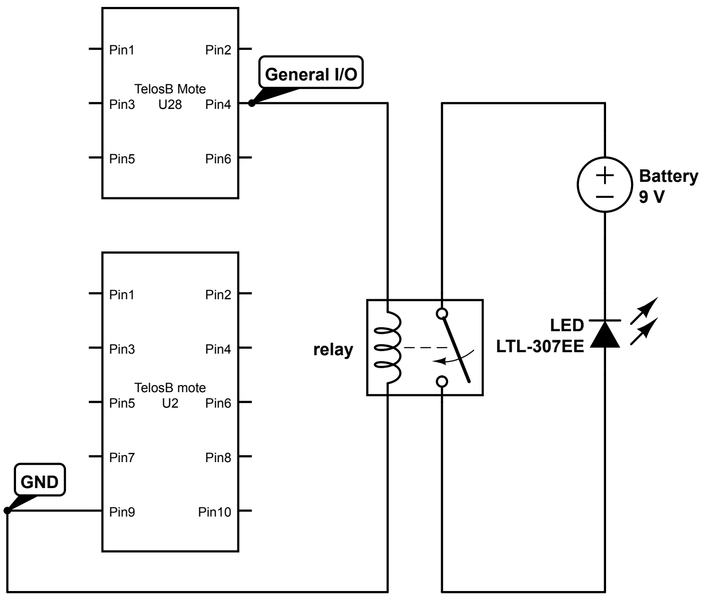


Figure 3.2: Electrical-electronic interface; connection of the GI/O of the TelosB mote with a relay. The relay acting as an electrically operated switch, controls a circuit which can be a DC or an AC

to control practically any electrical or electronic appliance, be it a light bulb, a fan, a LED array or a TV set.

3.5 Layered overview of *Syndesi*

Interconnection of heterogeneous networks has to be handled by standard messaging and communication protocols. As our framework comprises two different wireless networking technologies (ZigBee and 6LoWPAN), a service oriented architecture can be used to unify the different components. In other words, we define REST style services using CoAP in the embedded domain, and mediate them with HTTP services using the proxy service. This mediation takes place in the gateway, which eventually

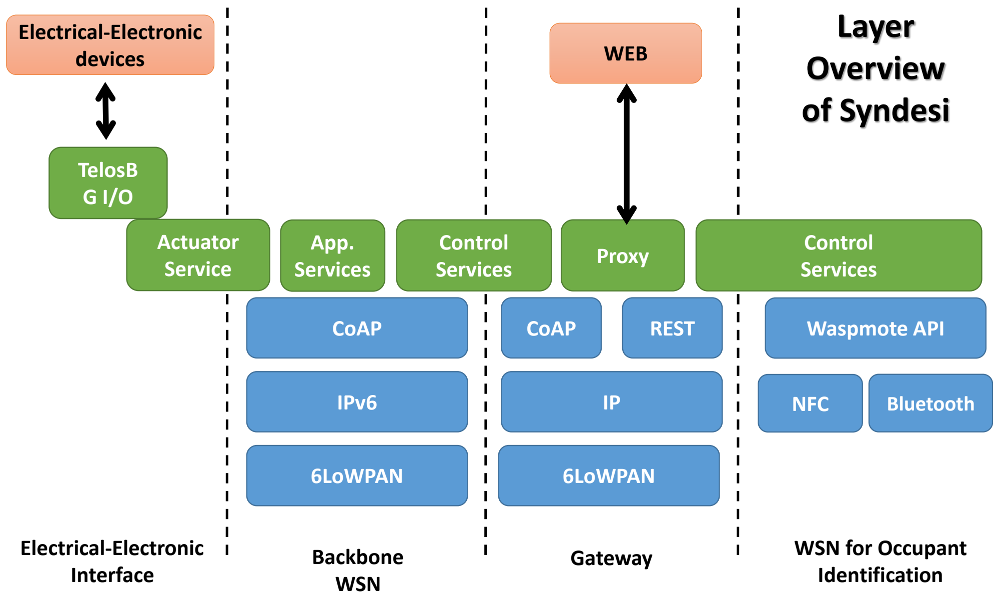


Figure 3.3: Layered Overview of *Syndesi* Framework

connects both WSN with the web. Therefore it leads to an easy application integration of the framework. We use the light weight JavaScript Object Notation (JSON) as the message format, since it is preferred over XML, especially for the embedded domain applications. Figure 3.3 illustrates the layered overview of our framework across its components. The set of gray boxes illustrates the main services provided by the framework, which are described below.

3.5.1 Actuator Service

Sensors and actuators available in the sensor platform act as an interface between the physical environment and the framework. Such sensors provide readings of the environment parameters via the system software available in the Contiki operating system. Similarly we implemented actuator drivers in Contiki. Services can use these actuator drivers to make them available to the framework.

3.5.2 Control services for the backbone WSN

Control services provide auxiliary services to facilitate the control and monitoring of the application services. For example, these can be services defined to ensure the quality of service requirements of the framework. We define these services in such a way that the overhead added by them is compensated with the quality of service they provide to the system.

Application Services

Application services are the services required by specific applications intended to be built upon the framework. In general, these application services expose sensors as services, which are inputs to the framework or expose actuators as services, which control objects of the system. These individual services are combined to perform useful application tasks.

Localized Service Mapping

Most of the algorithms performed in smart environment applications need to have a knowledge of the physical locations of the sensors and actuators (nodes of the WSN). Moreover, such algorithms need to be aware of the physical correspondence of the nodes within a context of the considered space. In a smart building scenario nodes have to be mapped with the floor plan of the building. By contrast, IP networks do not maintain any knowledge of the nodes in the network. Therefore, to compensate the fact that IP addressing is location independent, there should be a service discovery mechanism based on the location. This ideally should maintain a mapping between the physical location of a node with its IP address and the services provided.

Due to the lack of low cost and accurate localization protocols implemented in practical settings, we implemented a centralized location mapping service. In other words, we assume a sensor is bound to a specific location and identified by a unique location identifier. We label the nodes of the network with this location identifier

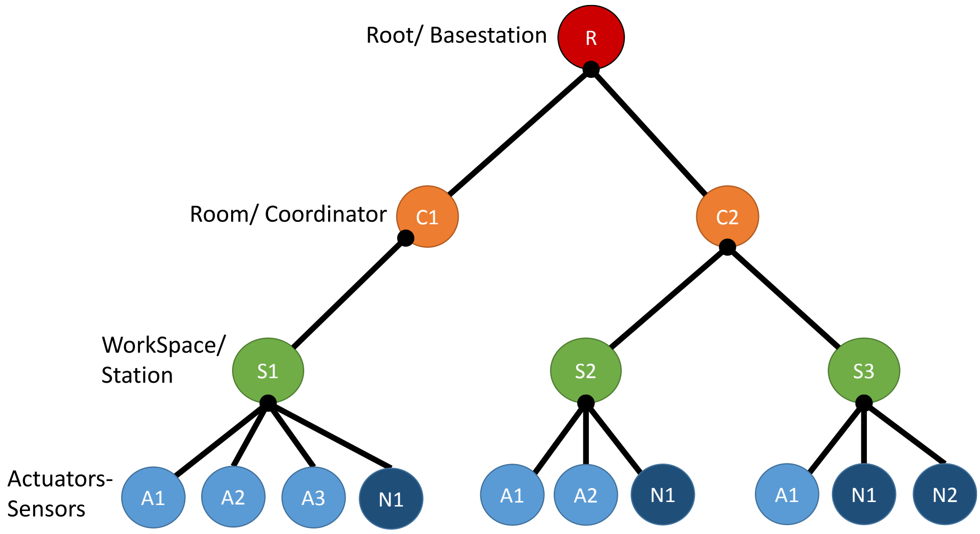


Figure 3.4: Location based service tree

when deploying the individual nodes. These labels form a logical tree structure which is rooted at the base station connected to the gateway. The framework maintains a centralized registry of these labels, essentially a tree structure of labels as illustrated in Figure 3.4. For example the actuator A1 that is located in room C1 at the workspace with ID: S1 will have the C1S1A1 which is also a unique identificator for this particular actuator. Although that the location identifier is one for each node, there is no limitation (apart from memory constrains) in the number of services or resources that each node can provide. In the following section we describe how these location identifiers are used to access resources and services.

During the initialization, nodes register their IP addresses in the centralized registry along with their location identifier. Once registered each node gets its position of the tree topology, essentially the location identifier and the IP address of its parent. Maintaining a tree topology is natural mainly since the objects needed to be considered in a smart infrastructure system can be modelled as a hierarchical structure. Especially in a scenario like a smart building system, whole system can be hierarchically modelled as a tree with the root being the central coordinator of the system.

Maintenance Services

As most of the smart environment systems are time and safety critical, there must be provisions to ensure such demands. Therefore, we designed additional services to ease the management and monitor the health of the system. We first define a periodic status update service which sends sensor readings and the status of a node to the central registry. In addition, each node exposes a service which can be invoked to check the presence of a node (namely, a "heartbeat" service). To track failures in the tree topology, each node invokes the heartbeat of its parent and detects its presence from time to time. In the case of failure, node notifies the failure to the central registry, which will be notified to the monitoring applications. As illustrated in the *Algorithm* 1, a node maintain a state of itself and changes the state accordingly.

3.5.3 Control services for the WSN for Users' Identification

As the scope of this work is not to deploy complex algorithms for user discovery, tracking and identification, we deploy a simple algorithm in the Waspmotes-WSN which is able to identify a user by the two following ways:

Bluetooth

The first way for the identification and simple tracking of a user is realized with the use of the sensing capabilities of a *Bluetooth radio for device discovery sensor* with which we are able to identify or track any Bluetooth enabled device a user carries in the transmission range of the sensor. The algorithm for this sensor is looking for users and is saving the MAC addresses of the users' devices once they are discovered. In this way we are able to make a one to one correlation of unique MAC addresses and specific users. The range of the sensor with a 5 dBi antenna allows us to scan devices in a range of few dozens meters around the sensor.

Proxy Service

Both application and framework services are CoAP services, which are not possible to invoke over standard Web protocols. Therefore, to expose these services to the Web, we implemented a proxy service, which supports RESTful interaction over HTTP with CoAP service. We define RESTful services interfaces to utilize both application and framework services, which can be used to develop required applications based on our framework. Due to its compliance with standard Web protocols, these applications are easily portable across all the platforms and devices.

Algorithm 1: Pseudocode for the control services

```
begin
    state=init,registered,processing
    parentID=null
    state=init
    while true do
        if state=init then
            parentID ← Register with the central registry
            if parentID ≠ null then
                state=registered
        if state=registered then
            Register with parentID
            if Successfully registered then
                state=processing
        if state=processing then
            Invoke heartbeat of parentID
            if parentID is not alive then
                Notify the central registry
end
```

NFC

The other way to identify and locate the position of a person is done via the Near Field Communications [31] sensor reader. This sensor is supporting read and write functionalities of the ISO 14443A/MIFARE/ FeliCaTM and NFCIP-1 protocols. Smartphones which support the NFCIP-1 protocol and NFC cards can interact with the sensor transmitting their unique ID and/or and any other necessary information to the Waspmotes-WSN. The maximum distance for a NFC chip to activate the

NFC-sensor-reader is 7 cm. A simple touch of an NFC card on the sensor is enough to interact with the reader transmitting data with a maximum speed of 424kbps. Due to the short range of transmissions (from a touch to a few centimetres) the NFC is inherently secure. This new emerging technology of the NFC communications creates a new and universal interface to existing devices through simple touch interaction.

With both of the above identification systems, the unique ID of a user is being transmitted from the identification sensors to the base-station of the Waspmotes-WSN and afterwards to the Gateway of the *Syndesi* framework. There are two ways by which we can transmit the data to the gateway: the first one is via a USB serial connection and the other one is via a ZigBee communication by which the data are wirelessly transmitted to the Gateway.

3.6 WEB APIs and User Interaction

In order to manage and access the resources of the system we have build Web service APIs that adhere to the REST architectural constraints, called as RESTful APIs. Every service or resource provided by the sensors or the actuators is represented by a RESTful architecture via a form of a URI such as the one in Figure 3.5. By using the GET or POST methods and the appropriate attributes under the "*fan?status=* " service which in the case of a fan controller can be *status=on* or *status=off,* one can get the current value (status) of the actuator (GET method) or change its value (POST method). In the URI the unique IPv6 address of the node is used and on the nodes' side we implemented CoAP handlers in order for the node to be able to receive such requests. Once a GET or a POST method has been invoked in the node, it sends back to the requester an acknowledgement of whether the request has been received and whether it was successfully executed. If there is no acknowledgement received it means that either the request packet or the ack packet was lost and a GET request should be invoked in order to control the status of the previous one.

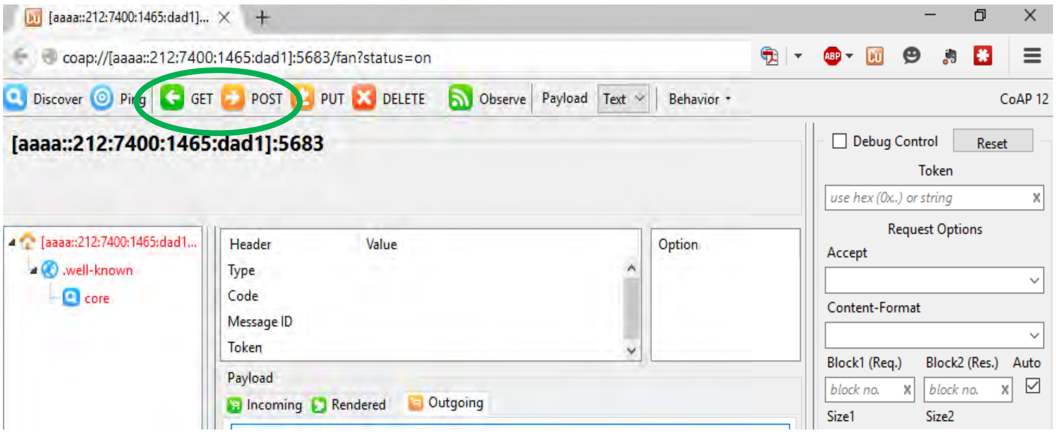


Figure 3.5: CoAP GET/POST request using the IPv6 address of the node. Changing the status of the fan to "ON".

Since our buildings's backbone networking infrastructure did not support global IPv6 addresses we could not use the unique IPv6 addresses of the nodes from Web locations outside the local area where the WSN was deployed. For this reason we implemented a proxy server named "ero2proxy" in the gateway, to support the translation from HTTP to CoAP requests and vice versa. An example of such a request is shown in Figure 3.6. Instead of using the unique IPv6 address of the node that we want to interact with, we use the IPv4 address of the *Syndesi's* gateway proxy and the unique location identifier e.g. C1S2A1. In this example we use the "Bulb" resource of this node and we set its status to "ON". After the request is made the node replies with an ack stating that the Bulb has been turned ON.

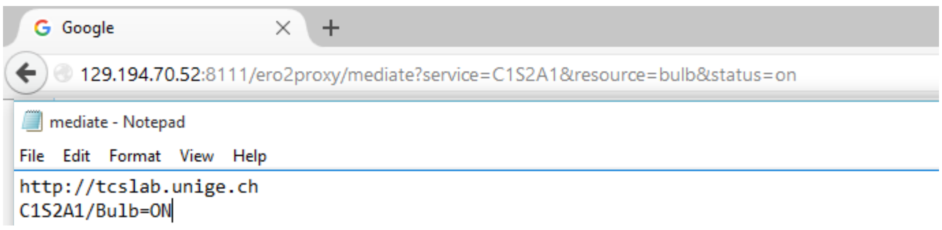


Figure 3.6: Mediate service for accessing a node's services from the WEB.

An other API that we have implemented in the *Syndesi* is a monitoring service in which a request can be made to a specific node using its location identifier in order to list all its available sensor resources together with their current values. An example is shown in Figure 3.7 where the node C1S7A2 has two sensor resources: one for temperature and one for luminosity. We note here that temperature is measured in °C and the luminosity in "lux" (where higher values of "lux" mean more light).

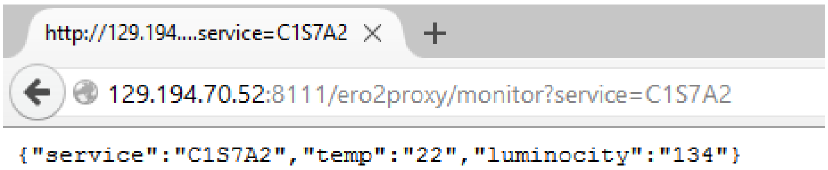


Figure 3.7: Monitor service for accessing the sensor resources of a node.

In the cases where an experiment or a user would need to monitor all the sensor resources from all the nodes that are connected to the *Syndesi*, we implemented the "SensorValues" service which lists all the latest active sensor resources and measurements. This list of sensor values is in JSON format and their values are collected by the period heartbeats of the nodes to the gateway. An example of this service is shown in Figure 3.8.

Since some of the nodes are acting as sensors, some as actuators and some as both, we needed to implement a service which would provide the specifications of each node i.e. access port, protocol, hardware type, host-name, available resources, its URI, its IPv4 IP address and the unique location identifier "node_id". Through this API one can get the full specifications of all the active nodes currently connected to the WSN. Figure 3.9 illustrates the service API.

Additionally to the "service" API we implemented an API which has similar function to the first one but the difference here is that the information provided for the testbed and its resources are following the XML RSpec format augmented and incorporated into the IPSO Application Framework. The Resource Specification (RSpec) is a schema standardized by the Global Environment for Network Innovations (GENI) [32] on XML

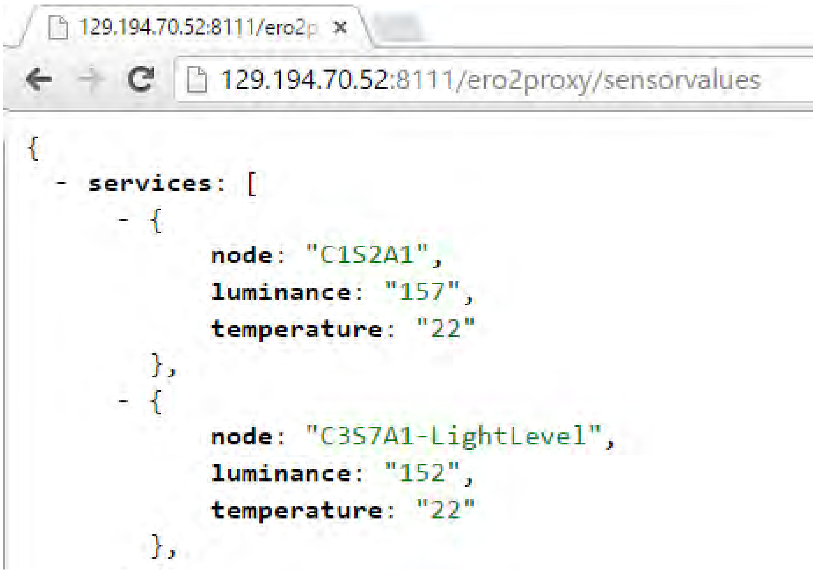


Figure 3.8: "SensorValues" service which lists all the active sensor resources of all the nodes connected to *Syndesi*.

Figure 3.9: Services and specifications of connected nodes to *Syndesi*.

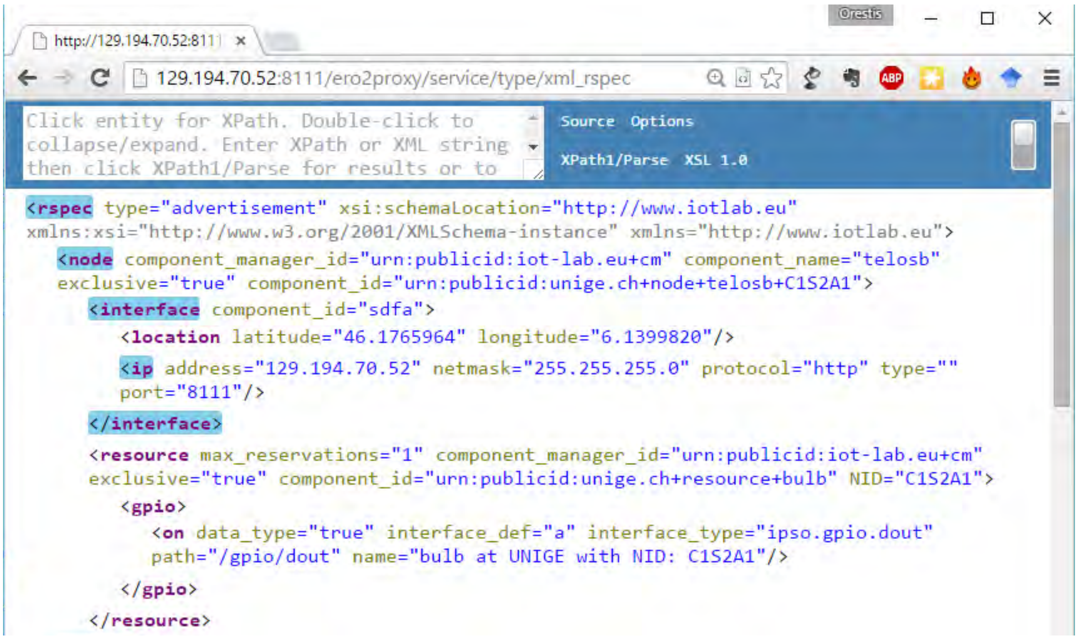


Figure 3.10: XMl RSpec description of the testbed resources integrated with the IPSO Application Framework.

documents, which describes resources, their requests and reservations, with aggregate or resource specific extensions. The IPSO Application Framework makes use of the IETF standards as building blocks for a simple and efficient RESTful design model for IP Smart Objects. This design defines sets of REST interfaces that may be used by a Smart Object to represent its available resources, interact with other Smart Objects and backend services. This framework is designed to be complementary to existing Web profiles and it does not constitute a standard. The XMl RSpec description of the testbed resources integrated with the IPSO Application Framework is shown in Figure 3.10.

3.7 Implementation of *Syndesi*

In this section we present the deployment of the *Syndesi* framework with which we implemented two real life scenarios in two rooms of our office. As our building is an old traditional infrastructure we use our framework, the WEB and some electrical devices to transform our office into a smart personalized environment. In both scenarios we focused on personalization, comfort, safety and energy efficiency.

3.7.1 Environment of deployment

The implementation took part in two rooms of our office where 8 people work. We connected to our framework the existing electrical and electronic devices which are used every day. As it is shown in the 3D representation of our office (Figure 3.11) the electrical and electronic devices connected to the framework are marked with a label and an "on - off" button. Following we present the devices connected to our framework in more detail. We connected the 4 personal desk lamps placed on each desk. There are six floor lamps that are placed in between of the desks which produce enough light to cover with sufficient working light the two desks next to it and sufficient ambient light for the area around them. We have placed a fan and a heater in each room to maintain comfortable room temperatures in the office as our infrastructure is old and it has insufficient HVAC system. On top of one of the windows we placed a roll-curtain which we connected to an electrical motor for raising and lowering it. On the inside part of the doors we installed electric locks while on the top of the doors we installed a siren alarm together with an emergency red light. Finally as our coffee machine is placed in the corridor outside of our office and everybody is able to access it, we connected it as well to our framework so that certain people could have access to it.

3.7.2 Scenarios Implementation

The implemented scenario involved all the 8 person who work in these two rooms. For each person was created a profile account in a database which contains basic personal information about him/her such as: Name, Age, Sex, Profession, Desk Location, preferable Temperature and Lighting condition. All this information is stored in a database in our framework. Consider now an ordinary day when "Bob" is arriving to

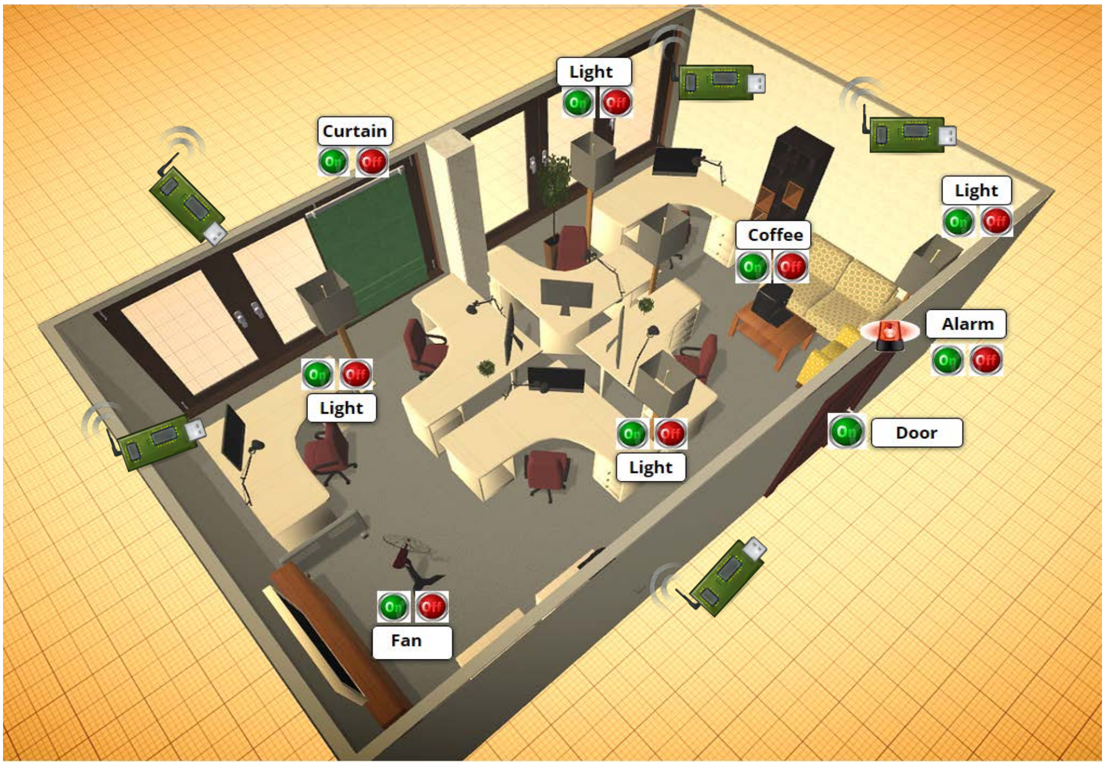


Figure 3.11: 3D Representation of office. Web UI

his office; he approaches with his personal and unique NFC-tag the sensor which is placed outside the door of his room (Figure 3.12) and then the system propagates the unique ID of his card to the *Gateway* where his ID is correlated to his profile in the database. Since the system identifies that Bob has the privileges to enter in the room, it disengages the electrical door lock (Figure 3.13) and then the door can be opened. At the same time, if the luminosity inside the room is below the default threshold then the system raises the curtains of the room if they were down. In the case when the outside light is still below the personal threshold of the light preferences of Bob, then his personal desk lamp will switch on (Figure 3.14). The same algorithms apply for the personalized temperature, heating and ventilation control. The above descriptive scenario represents an example of a centralized behaviour of the framework.

Figure 3.12: NFC sensor reader connected to the WSN for user identification

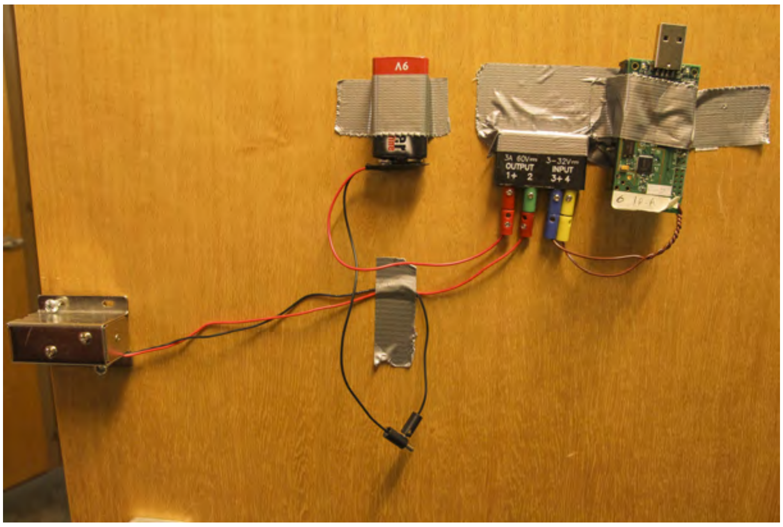


Figure 3.13: Electric door lock connected to the Electrical-Electronic Interface

On the other hand, the distributed behaviour of the framework is presented in the following scenario: people are working at the office when suddenly a fire breaks out in a floor lamp that was placed in a corner of a room. The system then recognizing the extreme high temperature due to the fire, automatically cuts off the power to this lamp and triggers immediately the siren alarm and the emergency light which are

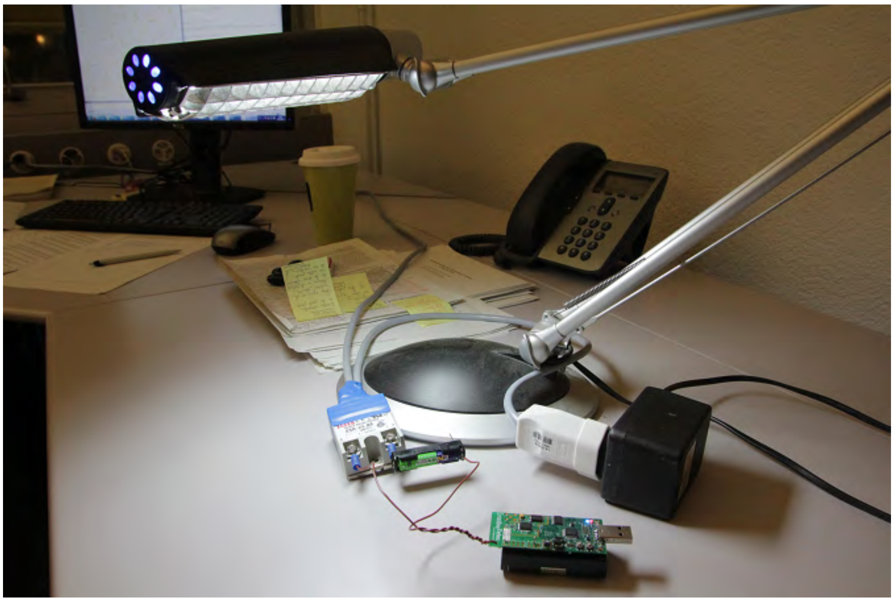


Figure 3.14: Lamp connected to the Electrical-Electronic Interface

Figure 3.15: Siren and Alarm light

placed on top of the exit door (Figure 3.15. In that case the messages generated by the sensor are transmitted directly to the actuators and afterwards the gateway will be updated concerning the status of the environment.

3.8 Enabling Mobile Crowdsensing

3.8.1 *Syndesi* 1.0 App

In order for the users of *Syndesi* to be able to access the actuator nodes that are registered to the backbone WSN, we implemented a simple Android application. The user interacts with the actuators connected to *Syndesi* by using the buttons: "Open Door", "Light On", "Light off" as shown in the Figure 3.16. This first version of the *Syndesi* smartphone application has been designed with aim to demonstrate the capabilities of the framework which allows interactions to be initiated from any Android based smartphone with Internet connectivity, either via GPRS or WiFi. This application had to be modified for each user in order to have the appropriate requests bound with her related physical actuators. Once a button is clicked an http request is transmitted via Internet to the gateway which then translates it into a CoAP request and forwards it to the appropriate actuator to execute the request.

Figure 3.16: First version of *Syndesi* Smartphone App

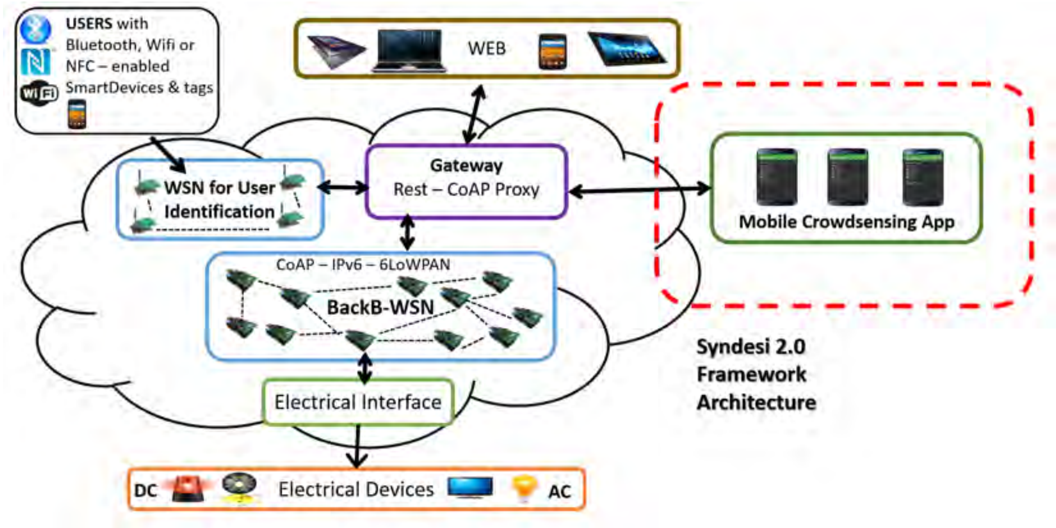


Figure 3.17: Augmented *Syndesi* framework architecture with Mobile Crowdsensing support

3.8.2 *Syndesi* 2.0 App

The latest update on the general architecture of *Syndesi* is a new component which enables the whole framework to become Mobile Crowdsensing enabled as shown also in Figure 3.17. In that end, people by downloading the new updated version of the smartphone application, *Syndesi 2.0*, [3] can actively participate in contributing sensory data from their smartphones to the system. Hence, they can augmented the sensory infrastructure of the facility by letting the embedded sensors of their smartphones to opportunistically sense their surrounding environment and send the raw data to the backend server.

Server side

In order to support the participatory sensing and contribution from the users of the *Syndesi 2.0* smartphone application, we implemented a new set of "crowdsensing" RESTful APIs on the server's side. This new set of APIs can be divided into two categories: one focusing on gathering the sensed information from the smartphones

[3]The always latest version of *Syndesi 2.0* application can be downloaded here : https://github.com/tcslab/Syndesi-2.0-Smartphone-App

and the other one on forwarding the list with the registered actuator-nodes of the server to the smartphones. In the first one, the smartphones are sending periodically information from their sensors (as it is explained later) and the *Syndesi* server is registering this information. By using the "../crowddata" service via a Web browser a user can see all the sensed measurements either those are reported by a **mobile** smartphone user or by **fixed** sensors and actuators. In addition, a timestamp is embedded in the data, and in the case of the mobile data, the unique *accountId* of the smartphone user is also reported. Figure 3.18 shows the result of the "crowddata" RESTful service.

Similarly, to the "crowddata" RESTful API, the "crowdusers" RESTful API is implemented in order to provide information related to the users of the *Syndesi 2.0* application. Every user receives a unique ID, and the available sensors from her smartphone are also propagated to the server. In addition, profile information of the user: "Name", "Surname", "Device Model", "Office Number", "Preferred Light Value", "Preferred Temperature Value", "IP address of the phone", and "Crowd Points" is listed as well. The result from the request on the *crowddata* is also represented in JSON format. Figure 3.19 shows the "crowdusers" service.

Smart Phone Application

The smart phone application *Syndesi 2.0* has been developed with the Android Studio SDK and it supports devices running the API 15 and up. The application is an easy to use interface to manage sensors, preferences and actuators. By using this application users are except of opportunistically sending data to the backend server, they are able to have a direct access to the actuators that are registered on the system. The first time a user boots up the application, an "Account Setup" screen is shown where the user is requested to insert the following basic personal information: "Name", "Surname", "Office Number", "Preferred Light Value" and "Preferred Temperature Value" as shown in Figure 3.20. After the user enters her information, the main menu of the application

Figure 3.18: *Crowddata* API for reporting Mobile Crowdsensed information as well as measurements from fixed wireless nodes

Figure 3.19: *Crowdusers* API for reporting Mobile Crowdsensing Users registered in *Syndesi*

appears. This menu is shown in Figure 3.21, in which the application at this time is not reporting anything because the user needs to access first the "settings" menu.

In the "settings menu" as shown in Figure 3.22, the user can "Modify her account", choose the "Sensing rate" between the values: Very slow (5 min.), Slow (2 min.), Medium (1 min.), Fast (30 sec.) and Very fast (10 sec.), insert the "Server IP address" and finally "enable the sensors", for start sensing and sending data. Every time a user modifies her personal data, an update package is send to the server in order to update also in the server's side the account information.

Once the adjustments have been made in the settings menu, in the main menu of the application there is shown information from the sensors, as in Figure 3.23. In the tested phone there are available sensors on proximity, temperature, pressure, light and humidity. The application is designed in a dynamic way in terms of incorporating the available sensors of the phone. Once the application starts, it scans the phone

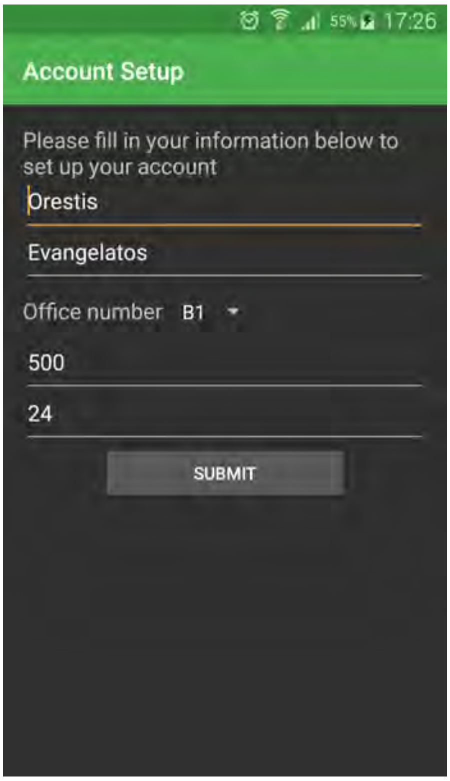


Figure 3.20: *Syndesi 2.0* App. - Account Setup

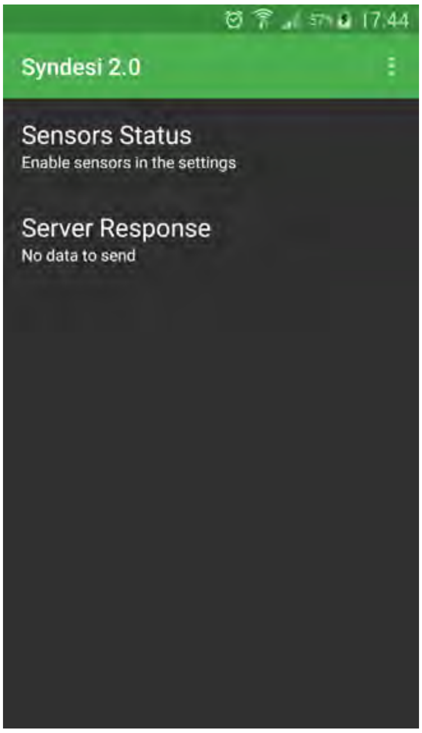


Figure 3.21: *Syndesi 2.0* App. - Main menu with Sensor Reporting disabled

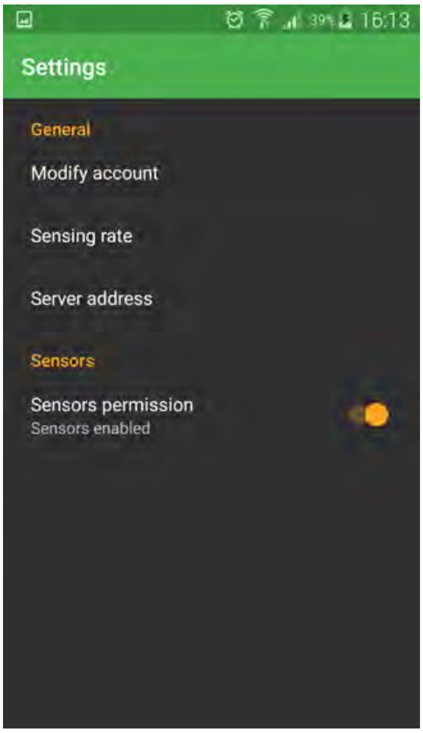


Figure 3.22: *Syndesi 2.0* App. - Settings menu

Figure 3.23: *Syndesi 2.0* App. - Main menu with Sensor Reporting enabled

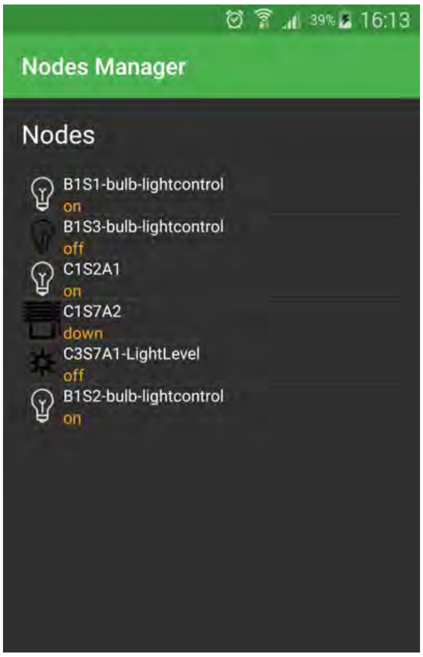


Figure 3.24: *Syndesi 2.0* App. - Nodes manager and actuator

for available sensors and when the users enables them, then they appear in the main screen. In Figure 3.24 is shown the "Nodes Manager" menu which is used to trigger commands to the actuators currently available by the *Syndesi* server. When a new actuator joins the *Backend WSN*, then it appears its ID, description and its current status (i.e. whether it is "ON", "OFF", "Up", "Down", etc.). The user by performing a simple click on the icon of the actuator can change its status. With this way, the user has the possibility to override the automatic control of the system.

Figure 3.25 shows the complete UML diagram of the *Syndesi 2.0* Android application. One of the aims while designing the architecture of the application was to keep each component as separated as possible from the others, following the SoC design principles. This separation gives to the application the necessary modularity and it is therefore straightforward to maintain and expand it. A developer, with minimal effort could port the application to smart watches, tablets, phablets or other smart electronic devices. The UML diagram is separated in 4 main components: a) the "User Interface" which is responsible for the for setting the activities on the screen, updating the relevant part of the main UI thread and adapting the data models to be displayed; b) the "Node" component, which is used to discover and actuate the devices connected to the server; c) the "Sensor" component, which handles the sensors of the phone, sets up the services and hosts the listener which reports and displays the data sampled from the sensors; and d) the "User" component, which contains all the classes related to the user, her preferences and the application settings she sets.

Incentivizing the Users

One of the key enhancements in the basic *Syndesi* framework from the Mobile Crowdsensing, is the implementation of an Incentivizing Mechanism which aims to attract the crowd to provide data and measurements from their smart phones. The users in order to participate in augmenting the "wisdom of the crowd" and consequently in improving the statistical smoothness of the data, need typically to receive a benefit, either this is monetary profit, satisfaction or achievement points.

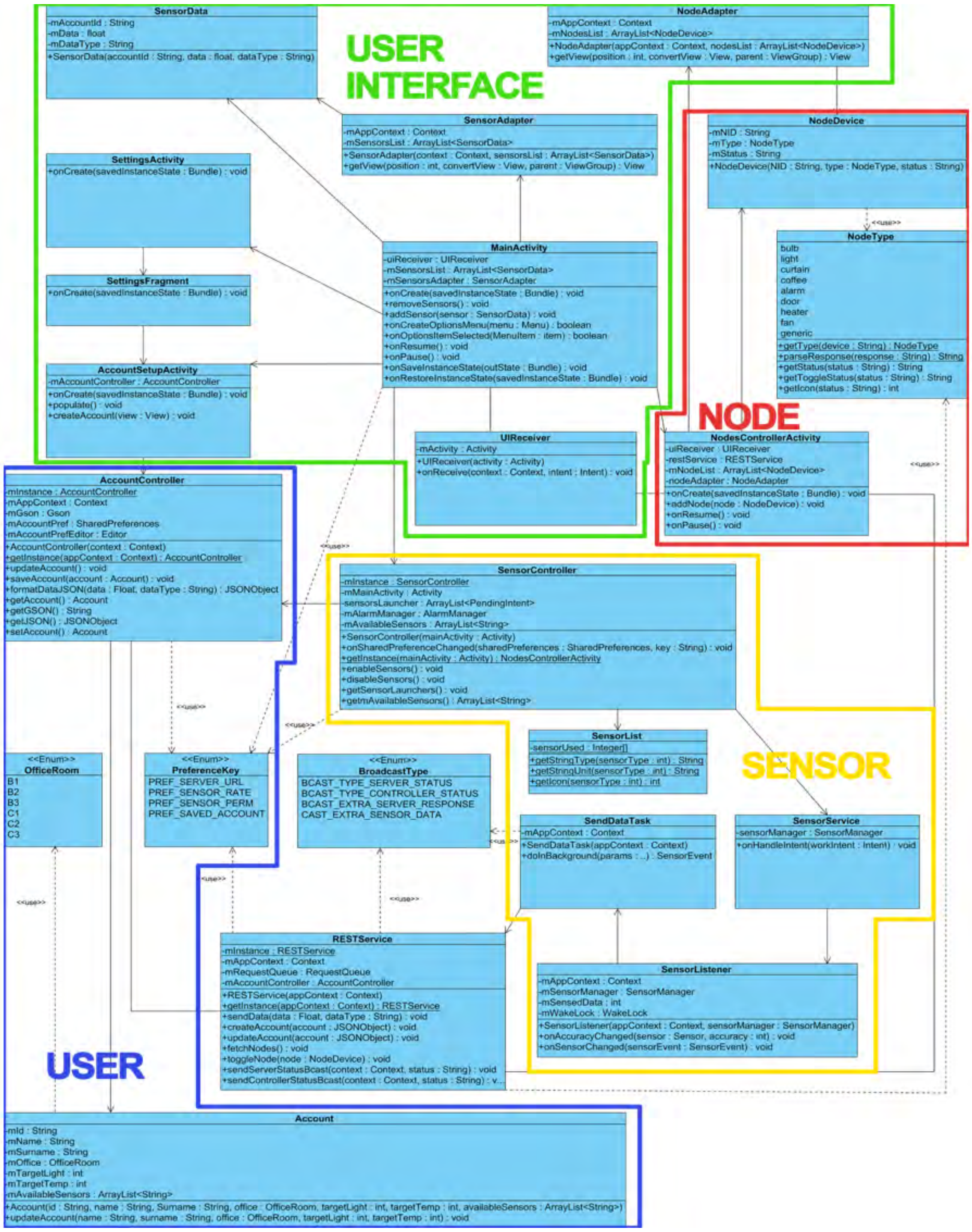


Figure 3.25: *Syndesi 2.0* App. - Account Setup

The Incentive Mechanism that we implement in the context of our work, awards users that participate in the provisioning of data with achievement points. The more sensors the user has and the faster she reports the data, the more points she gets.

Different approaches could be established in how many points a user can earn per minute or per sensor, however for avoiding to over-complex the system we use a naive simple approach. In chapter 7 we present several Incentive Mechanisms with which a system can motive users to take part in.

3.9 Performance

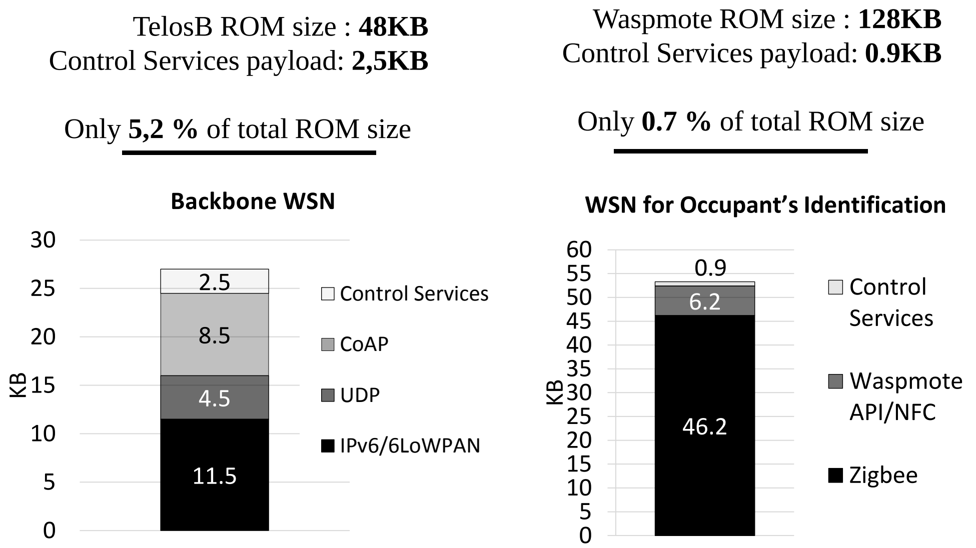


Figure 3.26: ROM memory footprint of system software components and added ROM values by the *Syndesi* framework

We evaluated the performance of our framework based on the distributed and centralized scenarios as described in section 3.7. We measured the response time in the two different scenarios and the ROM memory footprint of both WSN. In the first scenario, we define as response time the time between the moment that an NFC card is detected by the *WSN for users' identification* until the moment the door is unlocked by the *backbone WSN* and an acknowledgement has been sent to the *gateway*. We found out that the average response time is 2.3 seconds. In the second scenario, as response time we define the time between the detection of the high temperature of a sensor until the moment the lamp switches off and the alarm triggers. In that case, we found out that the average response time is 0.7 seconds.

Considering the control services of the *Syndesi* framework in both WSN, the ROM memory footprints are illustrated in Figure 3.26 along with the underlying system software components. As shown, our framework adds 2,5 KBytes and 0,9 KBytes to the system software of the *Backbone WSN* and *WSN for User's Identification* respectively

Regarding the performance of the *Syndesi 2.0* smartphone application we used a Samsung Galaxy Note 3 for evaluating it. We measured the application's memory footprint, which in average is using 25-30 MBytes when the sensors are enabled and the data is sending to the server. This footprint is considered as very low when taking into account the memory capacity of the today's market phone specifications. The CPU usage while the application is running is below 1% and only when packets are sent from the phone it momentarily increases to 15-20%. As shown in Figure 3.27 during an 8 hours open session, which corresponds to an average daily working period, with a polling rate set to "Medium" (i.e. extracting raw measuremtents from the sensors and sending them to the server once per minute), the CPU was used for less than 15 minutes, the application uploaded 8.2 KBytes and downloaded 5.6 KBytes. The total energy consumption accounted to our application for the period of 8 hours was only 3%. A significant low power consumption which highlights the efficiency of the application in respect to the constrained energy capacities of the smartphones.

3.10 Conclusions

In this paper we presented the *Syndesi* framework for creating personalized smart environments using diverse technologies, heterogeneous wireless sensor networks and state of the art communication protocols such as NFC and 6LoWPAN. We identify some of the shortcomings of existing frameworks based on WSN, and propose solutions for a comprehensive framework. We mainly identify the necessity of personalization in a smart environment and enable our framework with user identification capability. In order to control the electrical and electronic devices, we designed an electrical-electronic interface through which we make feasible the

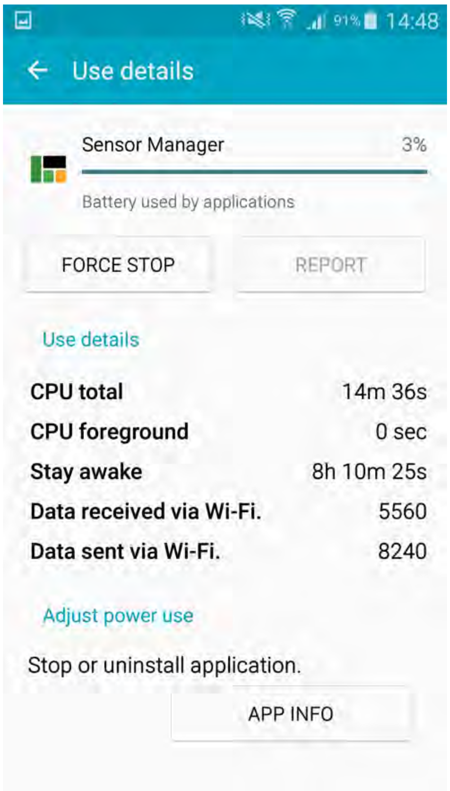


Figure 3.27: *Syndesi 2.0* App. - Performance Datasheet

connection of such devices to the smart environment. Furthermore, we propose a location based service discovery mechanism where, the web services exposed by the sensors are mapped with their physical location. Finally we conclude that our framework reacts relatively fast to the user interactions and to the changes of the environment while at the same time it adds a small overhead in the software memory requirements.

Syndesi is a framework which can be used in several types of infrastructures such as hospitals, schools, parking lots and houses. It is a scalable framework which can be easily expanded. The examples of the possible extended applications based on the *Syndesi* framework are numerous. Should someone need to connect more sensors/actuators and electrical appliances, the design of the framework allows for easy integration. Furthermore it provides energy efficiency, safety and convenience to the inhabitants, user-friendly interaction and accessibility over the WEB.

As a future work we envision the extension of the *Syndesi* framework in such a way that it will provide an optimized energy consumption in smart environments. Moreover we believe that this framework could be integrated with social networks and crowdsensing applications for a better incorporation of personal information and user experience.

Acknowledgements

We would like to thank here Blaise Carron for his valuable contribution in the implementation of the Mobile Crowdsensing *Syndesi 2.0* smartphone application.

4 AIRWISE: An Airborne Wireless Sensor Network for Ambient Air Pollution Monitoring

4.1 Introduction

The atmospheric composition has been continuously changing over the past thousands of years but it is just after the industrial revolution of the 18th century when the atmosphere started to be significantly affected. The huge growth of urbanization and the massive construction of polluting factories and industrial cities, coupled with the lack of legislation and standards for the atmospheric pollutants, led to a progressively increase of the concentrations of dangerous gases in the air. As the atmosphere is essential to support life on our planet, air pollution has long been recognized as a serious threat to human health and to the whole ecosystem. In that context, over the last few decades, governments and NGO's have set rules in the emissions of harmful substances in the atmosphere. Since the early 1970s the EU Air Quality Directive [33] and the U.S National Ambient Air Quality Standards (NAAQS) [34] have been working on improving the air quality by controlling those emissions and define maximum atmospheric concentrations.

Due to the hazardous effects of the air pollution to the people and to the environment, air quality evaluation is playing an important role in the assessment of the limits in the exposure of the population and the minimization of health impacts. Human exposure to air pollutants may have serious health effects depending on several factors such as: duration, magnitude and frequency of the exposure. People in their every day lives come in contact with various pollutants in the air both indoors and outdoors. As a matter of fact, air quality monitoring is crucial not only for assessing the exposure of the population to the air pollution but it can also be proven extremely useful for scientists in improving the pollution prediction models. In addition it can be used to provide emergency information in the cases of unpredictable disasters. Taking into account the importance of the air pollution monitoring, it is very challenging to monitor how the ambient pollutants are dispersed and diluted in the air both horizontally and vertically. In particular is at high interest a fine grained monitoring in various spatial and temporal distributions. Such a high-resolution ambient air monitoring and particularly in small scale atmospheric zones, where the pollutants' concentrations differ from their surrounding areas, is known as micro-climate monitoring.

In relation to the ambient air quality monitoring, several methods and techniques have been developed. Traditionally, the monitoring is done with the use of large monitoring stations placed in static locations such as on top of towers and buildings. However, due to their large size and cost of maintenance, these stations are deployed in relatively spatial areas and consequently they can not act as mobile stations. One of the main contributions of our work is the solution towards this problem; the development of a mobile monitoring system for the monitoring of the ambient air pollution.

In this work we contribute and we present a WSN system for automated ambient air quality monitoring [35]. Air quality sensors integrated with embedded devices enable the measurement of the air pollution in a very efficient and low-cost way. Our proposing system is able to measure with the use of unmanned aerial vehicles (UAVs) and WSNs and without the need of human intervention, the concentrations of several pollutant, gases and environmental parameters, in three-dimensional environments in near real-time. We name our system: *AIRWISE*.

In addition, the design of our system is allowing an easy and direct interconnection with other open testbeds such as: the WISEBED [36], HOBNET [37] or IOT-Lab [38]

Table 4.1: *AIRWISE* comparison to existing solutions

	Mobile	3D	Near-real time	Autonomous	Low-Cost	Highly Accurate
Large monitoring station	✗	✗	✓	✓	✗	✓
Mobile monitoring station	✓	✗	✓	✗	✗	✓
AIRWISE	✓	✓	✓	✓	✓	✓

testbeds. In that way, the *AIRWISE* system can become part of an open, broad and large-scale interconnected testbed, enabling other testbed users or researchers to use it or obtain data from it. Table 4.1 shows the comparison of *AIRWISE* to other existing solutions.We observe that our solution outperforms the traditional monitoring solutions in all the categories.

In the following sections we present firstly in Section 4.2 the related work and motivation. In Section 4.3 we show the theoretical schemes and algorithms and in Section 4.4 the general architecture and implementation of the *AIRWISE*. In Section 4.5 we present the system development together with our experimental results and their evaluation. Conclusions and future work are presented in Section 4.6.

4.2 Related Work

The significant advantages in distributed sensor network systems including but not limited to reliability, scalability, dynamics and efficiency, have brought the WSN systems into the next generation. WSN systems play an inevitable role in our everyday life and they have been widely adopted in sensing and monitoring applications. In [27] we have proposed a framework with which we can sense, monitor and control an environment by using WSNs. Apart from the use of WSNs in the area of smart environments, lately they have been used also in the context of air sensing and monitoring. Such a system for example, is described in [39], where sensors have been placed on top of cars forming a vehicular WSN dedicated to measure the pollutants' concentrations. In addition, the authors in [40] have developed a monitoring system for ground level air quality analysis in Qatar using a WSN. A system using WSN devoted to the monitoring of particular pollutants has been proposed in [41], where carbon monoxide (CO) sensors were used for the monitoring of the CO levels in the premises of a university campus area. Other similar systems that have been developed for air quality monitoring using WSN are proposed in [42] where the authors have designed a WSN node for remote monitoring of CO and in the [43] where it is proposed a simulation system for air pollution monitoring using WSNs.

Previous work regarding the air quality and the assessment of health impacts near the airports of UK [44] showed that high amounts of pollutants such as CO and NO_x are emitted in the air during the take off and the approach of a plane in an airport. Similar works such as the [45] and [46] are presenting models and estimations on the concentrations and behaviour of the pollutants in the air. In these regards we believe that those models and estimations could be verified and improved with the help of a WSN which would measure those pollutants in real environments. The authors in [47] are proposing a framework with which they can monitor in real time particulate matter evolution in construction sites in order to assess the air quality, but although such a system can provide a lot of important information on air quality, it is static and bound to the ground.

Due to the recent advancements in robotics, aviation and material sciences, the gap between airborne systems and WSNs has started to be closing. Over the last few years, engineers and researchers have impressively improved the designs of hover-capable UAVs leading to cost-efficient productions of drone aircrafts. Such drones are being used in a great variety of applications ranging from supporting search and rescue operations [48] to aerial robotic constructions [49]. Despite the fact that the drones are gaining ground in the research community, airborne wireless sensor networks are still in their infancy. The prior work of [50] has used a quadrocopter-drone for implementing a cropping monitoring system in the domain of precision agriculture using WSNs. In [51] the authors have developed a WSN composed of bird-sized micro aerial vehicles and ground nodes in which they have analysed networking performances, such as RSSI behaviour and packet loss rates. Experimental results on the integration of UAVs and WSNs have been presented in [52].

Systems and deployments that have been proposed so far are mainly investigating individually, or in the most relevant works two out of the three following domains: a) air quality monitoring, b) WSN and c) UAV. To the best of our knowledge there has not been yet proposed a system that combines WSNs, drones and air pollution monitoring mechanisms. Our work here presents a low-cost, automated pollution monitoring system which is comprised of a wireless network with sensors dedicated for measuring the concentration of air pollutants and a UAV for performing the measurements in different altitudes, latitudes and longitudes. Combining the fields of air pollution monitoring, unmanned aerial vehicles and wireless sensor networks we came up with two schemes and algorithms resulting in a system's application that can monitor in fine-grain resolution and in near-real time, the ambient air quality in real three-dimensional spaces using WSNs. The information acquired from the system regarding the pollutants' concentrations in the ambient air could be provided as profitable resource data to air quality scientists for improving their environmental models, to governments as prerequisite information for indexing the air quality of their districts and last but not least as influential dissemination information to the people in order to uphold their environmental awareness.

4.3 Algorithmic Design of Airwise

In this section we present the algorithmic design of the Airborne WSN system. In principle the measurement of the pollutants in the air is done by pollution sensors which are placed on top of unmanned aerial vehicles (drones). In order to be able to route the drone in an area of interest and hence measure the air pollution, we need to define a model which will help us facilitate the monitoring as well as the according algorithms. In the following subsections we present firstly the theoretical model and afterwards the schemes and the algorithms.

4.3.1 Theoretical Models, Schemes and Algorithms

In our work, in order to deal with the measurement of the three-dimensional air space environment, we propose the following general approach to facilitate exposition: we divide the three-dimensional area we want to investigate (denoted hereinafter as *D*) into "small" equally tessellated cubic-subareas (named as monitor-cubes). The three-dimensional area *D* with its monitor-cubes is depicted in Figure 4.1. By dividing the whole area of interest *D*, into these monitor-cubes, we are able to distributively monitor the concerned environment and extract individual pollution data for each of them separately. This allows us to create separate "3D-heat" pollution maps for each different physical subareas as well as for the whole area *D*. The size of each subarea (monitor-cube) can be defined by the user in accordance with the location and the circumstances of the monitoring area. At the same time, this tessellation gives us the possibility of conducting either fine-grained or macro-scaled measurements. We designate that the measurements in each monitor-cube regarding the pollutants, are taken from their center. Our approach, definitions, schemes and algorithms described below hold for both types of measurements; fine-grained and macro-scaled.

4.3.1.1 General Definitions

Prior to the description of our approach and models, we need make the following general definitions:

Monitor-Cubes (Subareas $S_{(x,y,z)}$): To facilitate the exposition of our schemes and algorithms, we assume without loss of generality, that the area *D* is cubic. As described above, the three-dimensional area *D* for monitoring, is tessellated into several "small"

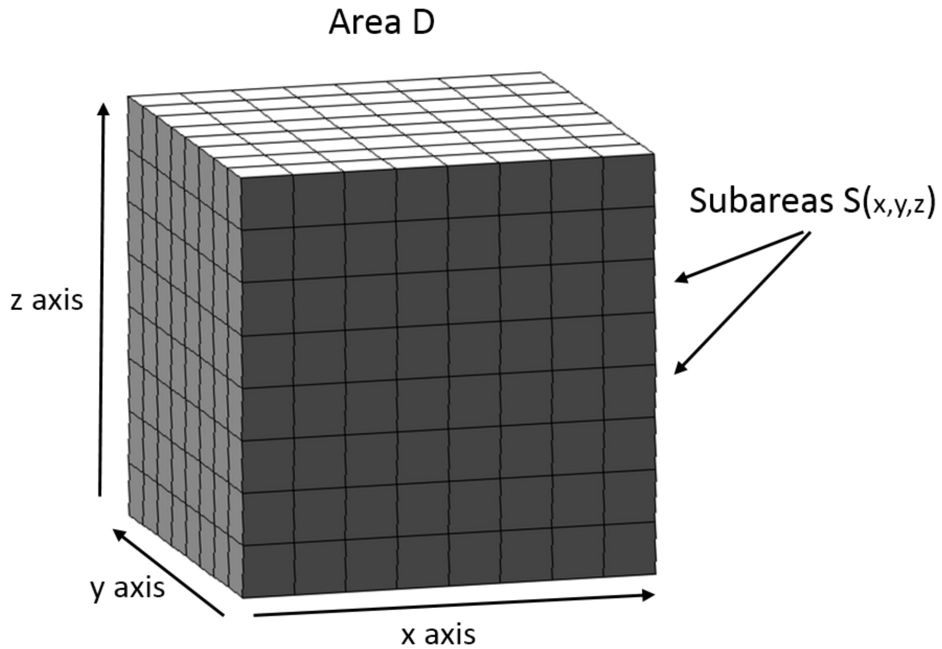


Figure 4.1: Tessellation of *Area D* for the air pollution monitoring.

cubic subareas *S*, which we denote as: $S_{(x,y,z)}$, where $x \mid x \in [0,k]$ (respectively $y \mid y \in [0,l]$ and $z \mid z \in [0,m]$) and *k+1* (respectively *y+1* and *z+1*) is the number of division of the first dimension (respectively of the 2nd and the 3rd) of *D*. The area *D* and its tessellation into the subareas *S* is depicted in Figure 4.1.

Concentration of Pollutant "*a*" ($\overrightarrow{CPa}$): There are several pollutants existing in the air such as: Nitrogen Oxides (NO_x), Carbon Oxides (CO_x), Ammonia (NH_4) etc, and their concentrations vary depending on a number of several parameters such as the: location, altitude, temperature etc. We define the vector: *Concentration of Pollutant "a" ($\overrightarrow{CPa}$)* which represents the measured concentration of a pollutant "*a*" in the air. The value of this parameter is obtained by the pollution sensor and its metric is usually in ppm (parts per million). Subsequently, the $\overrightarrow{CPa}$ values are also normalized between [0,1] in respect to the minimum and maximum concentration values the pollution sensor is able to measure.

Weight ($\overline{W}_{(x,y,z,i)}$): For each subarea $S_{(x,y,z)}$ we define a weight $\overline{W}_{(x,y,z,i)}$ where $i \in \mathbb{N}$. The weight $\overline{W}_{(x,y,z,i)}$ represents the arithmetic mean of the measured concentration of the pollutant $\overrightarrow{CPa}$ in a specific subarea $S_{(x,y,z)}$ of the *iteration (monitoring) cycle i*. The term *iteration cycle* represents one completed monitoring of the whole area D and its value i represents the i-th *cycle*.

Measuring Rate (MR): As *MR* we define the value which represents the measuring rate with which the pollution sensor is collecting pollution data from its nearby environment. The *MR* is defined as *MR = Samples / Second*.

Duration of Measurement (DM): As the pollutants in the air sometimes could be burdensome to measure, long time measurements might be required in order to collect trustworthy data. Therefore, we define the value: *Duration of Measurement (DM)*, to represent the duration of the measuring process. Depending on the environmental variables of the specific time and location, short time measurements might suffice to collect trustworthy data. However in situations such as toxic or harsh environments, long time measurements might be required to obtain more accurate results.

4.3.1.2 Schemes

In this section we present two different schemes with which we approach the problem of monitoring the ambient air pollution in 3-D spaces. For each of them we present also their respective algorithms.

Sequential Monitoring Scheme: In the *Sequential Monitoring Scheme*, the routing of the drone and subsequently the collection of the pollution data by the sensors it carries on, are done in a sequential manner. This means that the drone is routed in a deterministic and predefined trajectory whereas the sensors are collecting data systematically from the center of each subarea *S*. The sensing process and hence the routing pattern starts from the subarea $S_{(0,0,0)}$ and it covers progressively all the subareas until it will arrive to the subearea $S_{(x,y,z)}$. We consider one iteration cycle as completed every time the UAV returns to the subarea $S_{(0,0,0)}$ before it will start again an other monitoring cycle.

Sequential Monitoring Algorithm (SMA):

The pseudo-code of the *Sequential Monitoring Algorithm* (Algorithm 2) representing the *sequential monitoring scheme* is presented below. For each *iteration cycle* and for each subarea, the algorithm measures their concentration in absolute numbers and calculates their Weight $\overline{W}$.

Algorithm 2: Sequential Monitoring Algorithm (SMA)

Input: MR, DM, k,l,m
Output: The Weight $\overline{W}_{(x,y,z,i)}$, $\overrightarrow{CPa}$

$MR \leftarrow$ default Measuring Rate
$DM \leftarrow$ default Duration of Measurement
$k, l, m \leftarrow$ size of each axis of area D
$max\_i \leftarrow$ maximum iteration cycles
$x, y, z, i \leftarrow 0$

begin
  while $i < max\_i$ **do**
    for $z \leftarrow 0$ ***to*** $z = m$ **do**
      for $y \leftarrow 0$ ***to*** $y = l$ **do**
        for $x \leftarrow 0$ ***to*** $x = k$ **do**
          $\overrightarrow{CPa} \leftarrow$ Take $MR \cdot DM$ samples of pollutant a
          $\overline{W}_{(x,y,z,i)} \leftarrow$ Arithmetic mean of $\overrightarrow{CPa}$
          $x++$ %next subarea of x axis
        $y++$ %next subarea of y axis
      $z++$ %next subarea of z axis
    $i++$ %next iteration cycle
    $x, y, z \leftarrow 0$ %restart from $S_{(0,0,0)}$
    return $\overline{W}_{(x,y,z,i)}$, $\overrightarrow{CPa}$
end

Dynamic Monitoring Scheme:

In order to use more efficiently the limited and constrained resources of the airborne systems and the WSNs, we propose a more efficient monitoring scheme which acts in a dynamic way. In this scheme the subareas are given a potential of being monitored or not, depending on their previous weight values; for each monitoring subarea and for each monitoring cycle, we assign a weight $\overline{W}$ which represents the level of the pollutant's concentration. We consider a subarea as *stable* when its most recent weights $\overline{W}$ do not alter "much" during a specific time frame. In that case, we can avoid visiting and consecutively avoid monitoring a *stable subarea*. As a result we can use more efficiently the limited energy of both the drone and the sensors while increasing as well the duration of monitoring. Lower energy consumption could be exchanged to monitoring of larger areas and for longer periods of time. Moreover, in the dynamic monitoring scheme, the *measuring rate MR* and the *duration of measurement DM*, can vary depending on whether the monitored area D is considered as "highC." or "lowC.". By "highC" we refer to an area of substantial interest with relatively high concentrations of pollutants and/or relatively high deviations. The "lowC." term stands for areas where there exist almost no concentration of pollutants. The *DMS* gives us the advantage of visiting and monitoring subareas of "highC." environments in more detail, either this is executed by collecting more samples per second or for longer duration.

In order to be able to define the *dynamic monitoring scheme*, some further definitions in extension to the general ones (mentioned for the *sequential monitoring scheme*), are needed to be made;

Minimum Iteration Cycles (min_i): The parameter *min_i* is used to define the number of minimum iteration cycles (monitoring cycles) for which the algorithm will keep collecting data sequentially from all the subareas, before it will enter into the dynamic mode.

Threshold (Thr): The *Thr*, threshold parameter is an upper bound of the mean accumulated difference between subsequent weights over a specific number of consecutive iteration cycles. The *Thr* represents the sensitivity of the algorithm. With the term sensitivity we refer to the degree of the pollution variation each subarea is allowed to sustain in order to be considered as *stable*. It is an important parameter, as it allows the adjustment of the trade-off between the sensitivity of the monitoring process versus the time and the energy needed to complete an iteration cycle *i*.

Last iteration Cycles to Compare (LiC): The parameter *LiC* delineates the number of the most recent iteration cycles whose $\overline{W}$ will be used in the comparison with the threshold *Thr*.

Idle value ($Idle_{(x,y,z)}$): The $Idle_{(x,y,z)}$ is a parameter which represents the number of iterations for which a subarea remains in *stable mode* and thus is not being monitored.

Maximum Idle state (maxIdl): The *maxIdl* bounds the maximum *iteration cycles* for which a subarea is allowed to stay in *Idle*, i.e. considered as *stable subarea*. It is used to ensure the reliability of the algorithm in terms of avoiding the formation of "monitoring holes" and to guarantee the refreshness rate of each subarea. It assures that there will not exist any "ghost-subareas" i.e. areas which might remain unmonitored for a "long" period of time.

Dynamic Monitoring Algorithm (DMA):

In this subsection we present the *dynamic monitoring algorithm* which represents the *dynamic monitoring scheme*. In this algorithm, for each subarea and for each iteration cycle, the concentration and the weights of their pollutants are measured. The same conception holds for the *SMA* with the main difference that the *DMA* takes into consideration the property that a subarea might be monitored or not depending on its stability parameter. Initially the algorithm will monitor the area *D* for a minimum iteration cycles (*min_i*) before it will start taking into account the stability parameter of each subarea. The maximum iteration cycles for which the algorithm will be executed

---

Algorithm 3: Dynamic Monitoring Algorithm (DMA)

Input: MR, DM, k,l,m, min_i, Thr, LiC, maxIdl

Output: The Weight $\overline{W}_{(x,y,z,i)}$, $\overrightarrow{CPa}$

$MR \leftarrow$ default Measuring Rate
$DM \leftarrow$ default Duration of Measurement
$k, l, m \leftarrow$ size of each axis of area D
$min\_i \leftarrow$ minimum iteration cycles
$max\_i \leftarrow$ maximum iteration cycles
$Thr \leftarrow$ Threshold defining an subarea as "stable"
$LiC \leftarrow$ Last iteration Cycles to Compare
$maxIdl \leftarrow$ Maximum Idle-state value
$x, y, z, i \leftarrow 0$

begin
- **while** $i < max\_i$ **do**
  - **for** $z \leftarrow 0$ ***to*** $z = m$ **do**
    - **for** $y \leftarrow 0$ ***to*** $y = l$ **do**
      - **for** $x \leftarrow 0$ ***to*** $x = k$ **do**
        - **if** $i > min\_i$ **and** $\sum_{i-LiC}^{i} \frac{|\overline{W}_{(x,y,z,i-1)} - \overline{W}_{(x,y,z,i)}|}{LiC} < Thr$ **and** $Idle_{(x,y,z)} < maxIdl$ **then**
          - $\overline{W}_{(x,y,z,i)} \leftarrow \overline{W}_{(x,y,z,i-1)}$
          - $Idle_{(x,y,z)} ++$
        - **else**
          - $\overrightarrow{CPa} \leftarrow$ Take $MR \cdot DM$ samples of pollutant a
          - $\overline{W}_{(x,y,z,i)} \leftarrow$ Arithmetic mean of $\overrightarrow{CPa}$
          - $Idle_{(x,y,z)} \leftarrow 0$
        - $x++$ %next subarea of x axis
      - $y++$ %next subarea of y axis
    - $z++$ %next subarea of z axis
  - $i++$ %next iteration cycle
  - $x, y, z \leftarrow 0$ %restart from $S_{(0,0,0)}$
  - **return** $\overline{W}_{(x,y,z,i)}$, $\overrightarrow{CPa}$

end

---

is set by *max_i* and the maximum idle iteration cycles for which a subarea can remain at *stable* is set by $maxIdl$. The pseudo-code of the *Dynamic Monitoring Algorithm* (Algorithm 3) is presented below.

4.3.1.3 Complexity

In this section we present and compare the time complexity of our two proposed algorithms. In the first scheme (*SMA*), the visiting pattern of the subareas by the drone and hence their monitoring by the sensors, is done in a deterministic way, in which all the subareas are monitored in every monitoring cycle. To measure the time complexity of the two algorithms, we consider the number of measurements performed assuming the following: k=l=m=n-1 (in particular the x axis is tessellated in n equal parts and the same holds for the y and z axis); the *transportation time Ttr* needed to move from one subarea to a neighbouring one in comparison to the *monitoring time* needed to monitor a subarea (*Tm* = *MR*·*DM*) is negligible, i.e. $Ttr \ll Tm$. Therefore the time complexity of the *SMA* algorithm is: $n^3 \cdot MR \cdot DM$. In the second and dynamic scheme (*DMS*), the efficiency of the algorithm lies in the fact that some subareas might not be monitored which results in less power consumption of the whole system, or in extended monitor space. The time complexity of the *DMA* algorithm is $O(n^3 \cdot MR \cdot DM)$, but depending on the algorithm's input values and the environmental parameters at the time of monitoring, the *DMA* could perform much better than that.

4.4 Architecture and Implementation

As far as the architecture design and the implementation of the *AIRWISE* system is concern, we had to face the following challenges: a) the limited energy resources of the unmanned aerial vehicles and the sensor nodes; b) the assembly of a lightweight UAV which would be able to carry on the additional payload of the sensor node; c) the integration of a flying mechanism that could enable the UAV to fly also autonomously; and lastly d) the development a WSN system that would be able to support the mobility

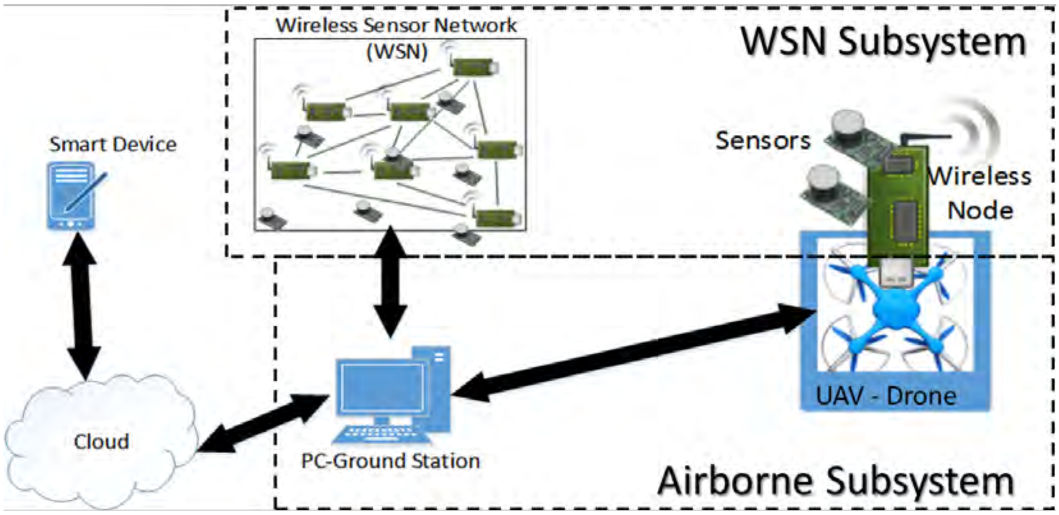


Figure 4.2: *AIRWISE* system's architecture

of the UAV in a three-dimensional environment and transmit its data in near-real time. The architecture and the implementation of our proposing solution towards those challenges is divided in two subsystems: the airborne-flying subsystem and the WSN subsystem as seen also in Figure 4.2 of the overall system's architecture.

4.4.1 Airborne Subsystem

Due to the nature of the problem of monitoring the ambient air quality, one of the key requirements that we had to meet was the implementation of a system that would be able to take measurements in the air in three-dimensional spaces. The solution that we propose towards this challenge is the use of unmanned aerial vehicles (UAVs) and in particular quadrocopters. Quadrocopters have the ability to take off and land horizontally, they are also able to spin around their vertical axis and most importantly hover in the air. Their ability of hovering allow us to maintain them at specific positions in the air for as long as it is needed. Alternative airborne systems that are using small planes are not able to hover and thus are not suitable for our design. The drone (the term is used interchangeably with the term quadrocopter) that we use in our system is shown in Figure 4.3 and we self assembled it from parts which are mainly produced

Figure 4.3: Assembled drone with embedded GPS and telemetry antenna, used for carrying the sensor mote.

by *3DRobotics*. It is a lightweight and powerful *APM Copter* with a load capacity of approximately 600gr. It benefits from mechanical simplicity and design flexibility and despite its small size it is capable of lifting small payloads. The four blades of the drone as well as its communications are controlled via the *ardupilot*, which is an open source UAV software platform able to autonomously control multicopters. We equipped the drone with a GPS antenna and with a telemetry set operating at 433Mhz. In our implementation we used the version of ArduPilotMega 2.6 which gives us a lot of advantages such as: autonomous flight; automatic stabilization; navigation using GPS; reception of telemetry information and control of the drone in real-time using the MAVLink protocol.

4.4.2 WSN Subsystem

To achieve the main goal of our work (i.e. to automatically monitor the ambient air and extract information regarding its quality) we use a wireless sensor network. As a

Figure 4.4: Sensor mote with Molecular Oxygen (O_2), Ammonia (NH_3), Methane (CH_4) and Carbon Dioxide (CO_2) sensors, its 3D printed cover box and the WSN Basestation antenna (left).

proof of concept we deploy a small network which comprise two nodes with gas sensing capabilities and one basestation for receiving the data from those nodes. One node was dedicated for the airborne measurements and the other one for ground measurements used for comparisons. Both of them were transmitting their collected data to the basestation. The wireless nodes are comprised of the following components: *a)* an electronic board for accommodating the gas sensors, *b)* the gas sensors, *c)* an external antenna for communicating with the basestation, *d)* a main board with the processor, *e)* a GPS module and *f)* a rechargeable battery. Due to the fact that the nodes and their components are very sensitive and fragile we designed and 3D-printed a cover box to enclose and protect them. The complete assembled sensor mote, its cover box and the basestation are shown in Figure 4.4.

Both the nodes and the basestation we used are manufactured by Libellium [53]. As far as the nodes are concerned, we used as their main board the Waspmote v1.2. The

Figure 4.5: *AIRWISE* system. The drone carries the sensor motes and the WSN basestation is connected with Laptop.

Waspmote node runs with the ATmega 1281 microcontroller at a frequency of 14.7456 MHz and with a memory of 128kB. Its high computing capabilities and its low energy consumption allows us to implement complex algorithms and programs. On top of the mainboard, a 2dBi XBee pro 802.15.4 antenna was integrated for communicating with the basestation. In addition, a sensor board with temperature, humidity, atmospheric pressure and gases sensors was integrated. In particular, the gases sensors that we installed were: Molecular Oxygen (O_2), Ammonia (NH_3), Methane (CH_4) and Carbon Dioxide (CO_2) manufactured by Figaro [54]. Moreover, we equipped the nodes with a GPS module so that we could time-stamp and position-stamp the measurements taken by the sensors. The energy supply of the nodes was provided by a Li-Ion rechargeable battery with a capacity of 6600mAh. The size of the box including all the components was 8x8x7 cm and it weighted in total 300gr. out of which the 200gr. was for the battery. On the other endpoint of our WSN subsystem, the basestation was equipped with a 5dBI XBee pro 802.15.4 antenna. It was connected via a USB to a laptop for receiving and propagating the information to

Figure 4.6: Area of experiments.

the *AIRWISE* backend program, which we developed in C#. This program was designed to be responsible for logging all the information that is receiving, analyse them in order to calculate the concentration of the pollutants $\overrightarrow{CPa}$ and their weights $\overline{W}_{(x,y,z,i)}$ and as well visualize them.

4.5 Experiments and Evaluation

4.5.1 Overall experimental set up

The overall experimental set up of the system can be seen in Figure 4.5. The weight of the drone itself was: 1.5kg and the additional weight of the sensor node was 0.3kg resulting in a total weight of 1.8kg. For our experiments we chose an area of 6.3 hectares in a heterogeneous environment in-between of a small forest area and residential buildings as shown in Figure 4.6. The experiments we conducted regarding the *AIRWISE* system were divided in the following three categories: a) WSN behaviour, b) Airborne system behaviour and c)integration of the WSN and airborne system.

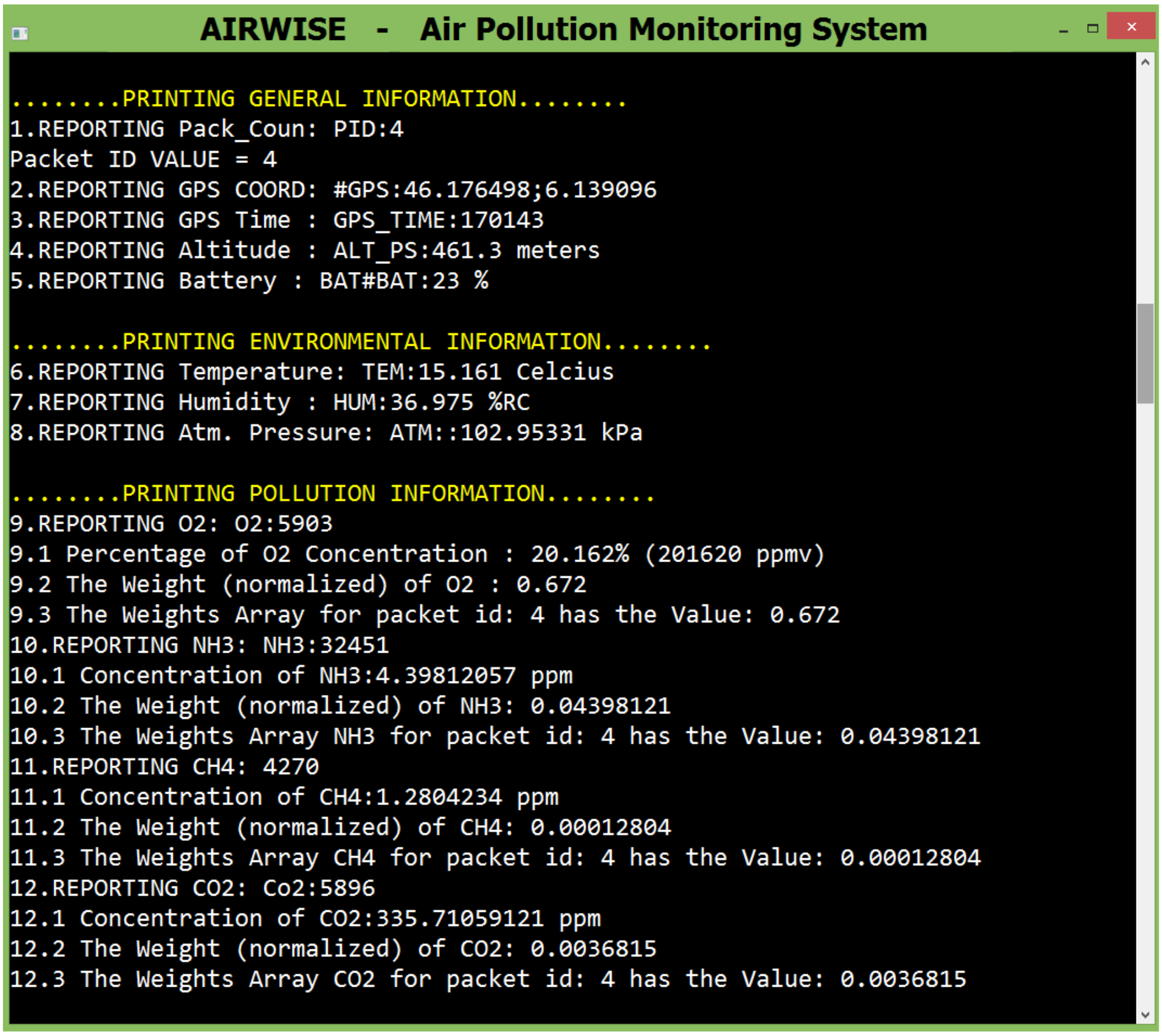


Figure 4.7: *AIRWISE* backend application while reporting in near-real time information regarding the air pollution collected by the sensors along with general information and environmental information.

4.5.1.1 WSN subsystem experiments

Firstly we run experiments on the WSN subsystem to analyse its behaviour. We note here that in order to achieve highly accurate calibration of the gas sensors, specific chemical gas tubes need to be used. However, as the measurements of the pollutants with high laboratory accuracy is out of the scope of this paper, the calibration of the gas sensors was done based on trial and error. Nonetheless, even if we could not achieve high accuracy we could obtain very accurately the variations in the concentration of the pollutants between different measurements.

In this first set of experiments we installed gas sensors for CO_2, CH_4, NH_3 and O_2, along with sensors for environmental parameters on temperature, humidity and atmospheric pressure. The raw data acquired from the gas sensors, the environmental sensors and the GPS, were sent to the basestation using the XBee antenna in four separate packets. Once the packets were received by the basestation, the *AIRWISE* backend application running on a laptop analysed the raw data and visualized them in a user friendly way. A screenshot of the program application while it was receiving data in near-real time from the wireless node is shown in Figure 4.7. From each subarea in the beginning of each report, general information was reported that contain: an incremental *Packet ID* number, along with the current GPS coordinates, the altitude, and battery status. Afterwards, information was sent on the environmental parameters of temperature, humidity and atmospheric pressure. In the end of each package was sent information on the percentage of the concentrations together with the weighted (normalized) values of each pollutant. In order to complete one data gathering cycle (from the sensors described above) in one location i.e. one subarea, it was required 1 minute and 15 seconds. This relatively big amount of time introduced some energy and time related problems that we will discuss below.

4.5.1.2 Airborne subsystem experiments

As far as the experiments of the airborne subsystem system are concerned, we are able to operate the quadrocopter described previously in two different flying modes: the automatic and the manual one. The automatic flying mode uses the APM 2.6, a GPS receiver, an accelerometer and the *mission planner* software installed on a laptop. Via this software we were able to set specific waypoints (representing the subareas) in an area and program the drone to fly towards them. Once we set up the waypoints on a graphical interface, we uploaded them to the APM of the drone using the MAVLINK protocol. The benefit of the automatic flying mode enables the drone to take off and land without our intervention. Moreover, we could send commands to the drone in real time, while it was flying in order to make it change its direction. This was proven especially useful when the pollution in some areas was higher than expected and the area had to be revisited. In the second flying mode of the drone i.e. the manual one, we used a Futaba 7-Channel Radio Transmitter. The auto-stabilization system of the APM stabilized the drone even in the presence of strong winds. In order to maintain the safety precautions, the drone was landing when its battery was dropping below 20%. Its maximum flying time with a fully charged 5000mAh 11.1V LiPo battery without any payload, was approximately 15 minutes.

4.5.1.3 WSN and airborne integration experiments

In the last set of experiments we combined and tested the integration of the WSN and the drone. For this category of experiments, we defined a fraction of our overall experimental area, a small cubic area *D*. The edges of this cubic area of interest were 39 meters long with a total volume of 59319m^3. This area was tessellated in 3x3x3 subcubes where the centres of each subcube (subarea *S*) were 13 meters apart from each other. Every time the measurements were gathered from each subarea, the collected data were sent to the basestation in near-real time, and simultaneously they were also saved locally. Due to the additional weight of the sensor node and its battery, the maximum flight time of the drone was reduced from 15 to 12 minutes. Initially we set up the sensor node to collect data from all of its sensors (i.e. pollutants, environmental parameters and GPS). In these initial experiments, the time needed to perform measurements from one subarea was 1 minute and 15 seconds and compared to the 12 minute of maximum flight time of the drone, we were able to gather measurements only from 9 subareas. Those 9 subareas correspond to only 0.33 *iteration cycles* and for covering the whole area *D* we needed at least 27 measurements (i.e. one *iteration cycle*). The travelling time from the endpoint of one layer to the starting point of an other one was in average 4 seconds.

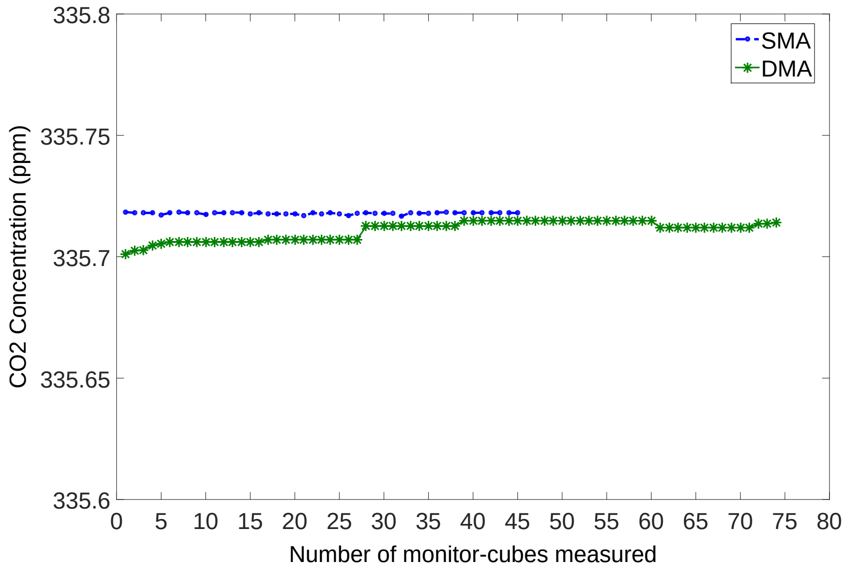


Figure 4.8: CO_2 concentrations reported by the SMA and DMA algorithms in the lifespan of the drone.

4.5.2 Evaluation

In order to evaluate better our algorithms in this real world development, we set the WSN subsystem to measure only the CO_2 in the air, including though GPS coordinates and environmental parameters. By isolating one pollution sensor we shortened significantly the subarea's data gathering cycle from 75 to 15 seconds. The fact here is that for the time being the batteries of the drones, despite being off the shelf, are not yet adequate to perform complex tasks. For this reason it is necessary to design and develop efficient mechanisms in all the levels of the system design in order to be able to overcome these energy constraints.

Figure 4.8 shows the results we obtained from measuring the CO_2 using the SMA and DMA during the 12 minute lifespan (flying time) of the drone. The *SMA* scheme reported in this lifespan, measurements from 45 subareas. These 45 subareas correspond to 1.67 *iteration cycles*. On the other hand, using the *DMA* scheme (with: *Threshold* at 0.5%, min_i and *LiC* at 5 and *maxId* at 10), for the same 12 minutes lifespan, a total of 74 measurements were reported. These 74 measurements correspond to 2.74 *iteration cycles*.

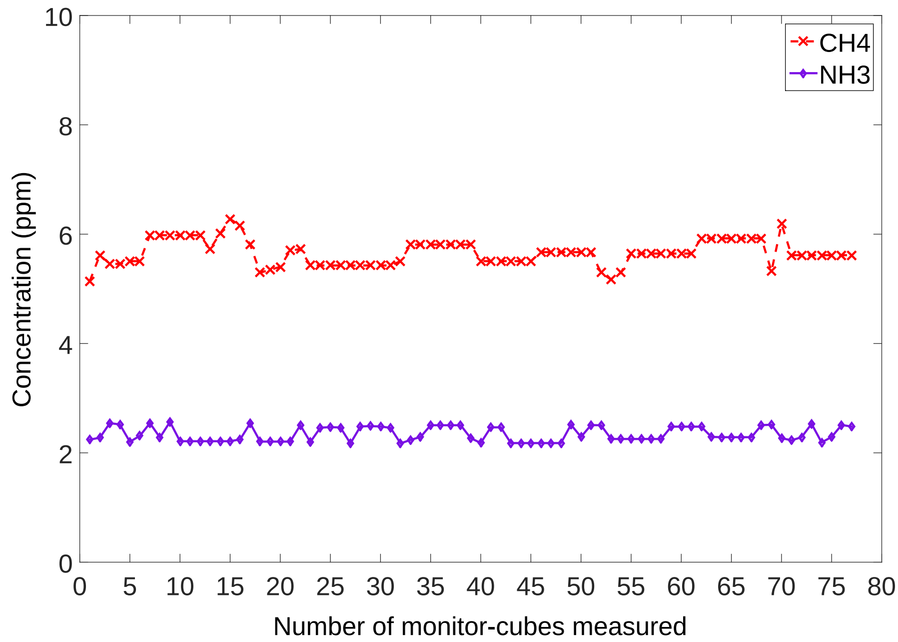


Figure 4.9: CH_4 and NH_3 concentrations reported by the DMA algorithm in the lifespan of the drone

Comparing the performance of the two algorithms, we observe that the *DMA* algorithm performs much better and in particular it reported 29 more measurements than the *SMA* with a 0.5% tolerance in the CO_2 concentration. In other words, the *DMA* is approximately 64% more energy efficient. In Figure 4.8 we observe also that the two algorithms report almost identical measurements. Given that the measuring range of the CO_2 sensor is between 300 and 10.000 ppm the maximum difference in the average reported values from the two algorithms is negligible since it is less than 0.002%. The only drawback using the *DMA* scheme is that more messages need to be sent and received to the basestation which impacts negatively in the energy consumption of the sensor node. Specifically, using the *DMA*, the battery of the sensor was reduced by 4% whereas using the *SMA* it was reduced by 2%. However, comparing the battery depletion rate of the sensor node to the one of the drone, the difference is almost negligible. Figure 4.9 shows the measured concentrations of CH_4 and NH_3 using the *DMA* algorithm.

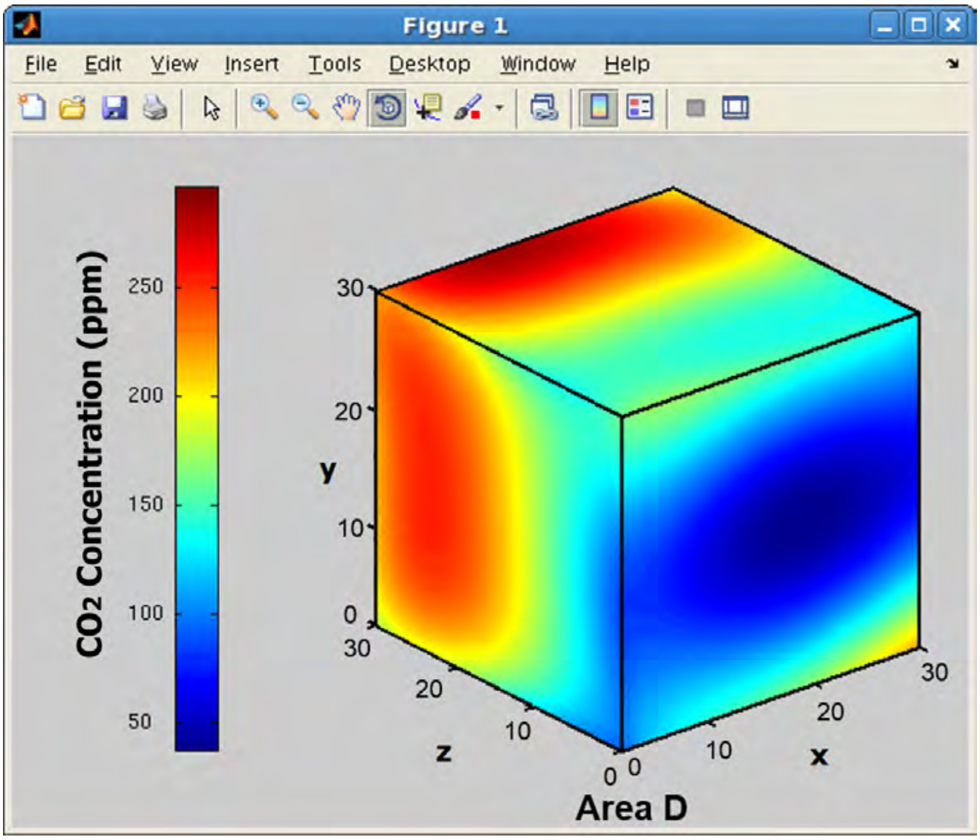


Figure 4.10: Illustration example of a monitored cube area *D* on CO_2 concentration.

Figure 4.10 depicts as an illustrative example the "3D-heat cube" of monitoring an area *D* for CO_2 concentration using the *AIRWISE*. Due to the design of the *DMA*, it is let on the freedom of the system operator to decide the tradeoff between the sensitivity of the measurements and their quantity. Meaning that: a bigger value in the *Threshold* would allow for more measurements while a smaller value would allow for more precise ones. The advantage of the near-real time monitoring of our system, is that a meteorologist for example in a scenario of a volcanic eruption, could change on-the-fly the trajectory of the drone towards another area of interest. In addition, in an emergency pollution situation for instance, by using the architecture of the AIRWISE system, more drones with more sensors could be dispatched for a more detailed monitoring. The *AIRWISE* backbone system which can be run on a laptop, makes the whole system easily portable and transferable.

4.6 Conclusions and Future Work

In this chapter we investigated the challenges of the air quality monitoring and we presented a system-solution using WSNs and UAVs. We proposed a system's architecture together with a theoretical framework and two schemes for monitoring the air pollution in 3D spaces. Furthermore, we showed the implementation of our approach with which the automatic monitoring of the ambient air can be facilitated. We have extended the capabilities of airborne systems by coupling them with WSNs. In particular, we implemented the *AIRWISE* system which is able to monitor pollutants in the air such as: NH_3, CH_4, CO_2, the O_2 percentage and environmental parameters such as temperature, humidity and atmospheric pressure. We developed the system, we run experiments with it and lastly we evaluated and compared our schemes and algorithms in a real deployment scenario.

Our future work plans include scaled up experiments with more drones and sensors acting in a collaborative way. In addition, we plan to investigate the direct interconnectivity between the wireless node and the autopilot system of the drone.

Part III

IoT and Crodwsourcing

5 Crowdsourcing, Modes and Related Crowd-motivators

5.1 Introduction

Over the past years, there is a growing trend of organizations tapping into the wisdom of the crowd to contribute to a specific topic, challenge or issue, namely crowdsourcing. This can be seen for instance, in the usage of the crowdsourcing platform Micro-mappers and Twitter after the devastating typhoon in the Philippines in December of 2014. In relation to this disaster, twitter posts and photos showing the damages and need for help, formed a crisis map of accumulated information from a crowd called “digital humanitarians” [55]. Based on this collected information, the rescue organizations obtained crucial information on the situation and the emergency response mechanisms could be managed more efficiently and deliver help to those needing at most. Even though this situation is acute and rare, the trend of engaging the crowd in different activities has grown and a lot of companies and governmental organizations are reaching out to the crowd for different reasons. These reasons can be, for example, to get new ideas, vote on an issue, carry out micro-tasks, develop solutions to a problem or simply provide information [56].

Crowdsourcing has also shown to be very efficient for activities such as for instance, developing marketing videos, translations, mapping information, interpreting photos or developing software development. However, the impact and full potential of crowdsourcing initiatives to a large extent remains to be seen since the understanding of crowdsourcing is in its infancy. Many organizations do not have sufficient insights regarding how the crowd can be constructed, how it can be developed and engaged, and how the results from the crowd can be used to support their cause [57]. A crowd usually does not pre-exist, but it needs to be engaged. Engaging a crowd is not an easy task to accomplish and requires knowledge about communication strategies to motivate the crowd to become engaged and contribute with their resources in terms of time, knowledge, information and insights.

At the time of writing this work, the landscape of crowdsourcing is very diverse, and due to that, it is important to understand the characteristics of the crowdsourcing as well as the role of the crowd so as to fully understand what motivates them to contribute to the initiative. The authors in [58] argue that such knowledge is very crucial and useful to obtain in order to exploit the capabilities of crowdsourcing. Hence, the purpose of this work is to categorize contemporary crowdsourcing initiatives and identify different motivational factors which can drive the crowd to contribute to their specific focus [59]. In this work we use a project; IoT Lab, to illustrate how crowd initiatives can explore what motivates the crowd to participate, since the motivation for participating in a business oriented crowdsourcing initiative might differ from what motivates the crowd to participate in citizen science projects. This project is focused on developing a platform for crowdsensing and crowd-driven research by means of mobile technologies and testbeds.

5.2 Dimensions of crowdsourcing and crowd motivations

The concept of crowdsourcing was first coined in 2006 by Jeffrey Howe who defined crowdsourcing as:

"Simply defined, crowdsourcing represents the act of a company or institution taking a function once performed by employees and outsourcing it to an undefined (and

generally large) network of people in the form of an open call. This can take the form of peer–production (when the job is performed collaboratively), but is also often undertaken by sole individuals. The crucial prerequisite is the use of the open call format and the large network of potential labourer's" [60].

Even though it was coined in 2006, the actions of engaging crowds have been ongoing for a long period of time. For instance, engaging citizens in research activities such as gathering weather data has been done for many years in the past. The main difference between these initiatives and the today's crowdsourcing trend is that today, the process can be facilitated by an ICT-based platform allowing also the involvement of people from different countries and irrespectively of their social status, preferences or age [57].

In the beginning of the development of crowdsourcing as a concept, many organizations largely engaged the crowd in micro-tasks as suggested by [61]. However, at the time being, the concept of crowdsourcing has been broadened and do not only refer to situations where an open call is being used, but also includes other types of situations where people join forces and create value. One such initiative is for instance Airbnb where people can rent out their homes to visitors. Another initiative is iStockphoto where people can upload and sell their photos to customers.

The basic idea behind the concept of crowdsourcing is that virtually everyone has a potential to contribute with valuable information [62]. The main aim of crowdsourcing is to mobilize the distributed and diverse competences and expertise that the crowd holds [58]. To support that process and in particular in a large-scale an ICT-based platform is needed. The items contributed by the crowd can either be created independently, e.g. in design contests or idea competitions, or collaboratively, e.g. as in Wikipedia or citizen science projects [58]. This movement is driven by meta-trends such as the rise of the entrepreneurial start-up culture, the growth of freelancers or independent employees, an expanded global marketplace, and the friction between transparency and monetization. A crowd can be engaged on many different ways and with different purposes each one answering to certain motivators for the crowd. Hence, in this work the goal is to shed light on some of the different modes of crowdsourcing that are known to us today and dig into the crowds motivators related to that mode. Due to the rapid growth in the area, it is nearly impossible to cover all aspects of crowdsourcing and that is not our purpose, but rather to show that crowdsourcing initiatives are triggering crowd motivations differently.

Starting with a system view on the crowd efforts, the systems involve three different categories of components; 1) the organisation benefiting from the crowd efforts, i.e. assigners of tasks (sometimes called seekers), 2) the individuals who carry out the tasks, i.e. providers (sometimes called solvers), 3) an intermediary-connective platform that link providers and assigners together [58]. Following a crowd approach also includes grappling with challenges such as effective incentive mechanisms, managing submissions, loosing control over the process, ensuring quality of ideas and creating trust among stakeholders.

The challenge to achieve the best possible outcome with crowdsourcing is to understand, choose and motivate the appropriate crowd [63]. One common approach when it comes to motivation is to make a distinction between intrinsic and extrinsic motivation [64]. Intrinsic motivation occurs when an individual engages in an activity, such as a hobby, that is initiated without obvious external incentives. This type of motivation refers to the desire of feeling competent and self-determined. Extrinsic motivation is activated by external incentives, such as direct or indirect monetary compensation, or recognition by others [65]. Both perspectives of motivations are of significant importance to the crowd's decision in order to take part in a crowdsourcing activity. For example, one might be motivated by the competitive factors in an new-idea's competition, while another might be externally motivated by the possibility to win a prize of monetary value, or being intrinsically motivated by the opportunity to have fun while competing [64].

In previous research on crowdsourcing and motivation (e.g. [63]) the focus has been on understanding what motivates people to share knowledge and what motivates them to contribute to a specific crowdsourcing initiative such as for instance iStockphoto and Threadless [66], [67], Wikipedia (e.g. [68], Amazon Mechanical Turk [69] or open innovation communities [70]. Based on this research, motivational factors such as enjoyment, career concerns, satisfying intellectual interest, supporting the community, feeling affiliated and create social contacts have been identified. In this work, we want to enrich this knowledge by clustering different crowdsourcing initiatives into modes and then explore the motivators related to the different modes. The authors in [57] have chosen to divide crowdsourcing initiatives into four modes; collaboration communities, contests, complementary and labour market . In this work, we have excluded complementary crowdsourcing initiatives (such as AppStore and Google Play where applications are developed by third party developers and offered as complements to the main product). We have also chosen to label one of the modes as compensation rather than as labour market since some of the initiatives do not mainly focus on labour but rather on getting compensated for the use of the crowd's resources as for instance in Airbnb [71]. Consequently, we have divided crowdsourcing into the three modes, collaboration (either in groups or individually contributing to a larger task), competition and compensation.

5.2.1 Collaboration mode

Collaborative crowdsourcing initiatives are driven by the idea that more people can collaboratively accomplish a better result [66], [72], [58]. This mode of crowdsourcing is more effective when people work together on projects that are relatively easy to coordinate [57]. To reach the best results from these initiatives it is important that the crowd can accumulate and recombine their ideas and share the information freely to solve a greater task. This can be accomplished in the form of individual micro-tasks where combined they contribute to a larger cause as for instance in Zooniverse [73] or Micromappers [74]. This, can be activities related to citizen science where the crowd, analyses pictures, gather data or take pictures of a specific event. Additionally the crowd can be working together in a joint project such as in Quirky [75] where innovations are created collaboratively, or as in Rappler where the crowd contributes with crisis information, which makes it possible for other crowds, such as standby task-forces, to respond in short time for providing support to humanitarian agencies in the disaster zones. Other collaborative crowdsourcing efforts are crowdfunding, or crowdlending, where the crowd join forces and fund a particular project that lies on their interest. Hence, the collaborative mode of crowdsourcing can by very different in nature, but they are all based on a collaborative mode.

Related to this type of crowd initiatives, the common motivators for the crowd are to contribute to a larger cause by adding their small part. This larger cause can be both societal and technological. This motivation can take different forms, as in open source projects the provider feel an obligation to contribute [65], in openideo they are motivated by collectiveness [76], while in other more societal crowds, such as rappler [77] or harrassmap [78], the crowd is motivated to contribute as a way to help others [79] or as in crowdfunding initiatives by sympathy [80]. Killing time by participating in meaningful activities is another motivator that is similar between most of these initiatives. This motivator can appear as being fun [81], entertaining, enjoyable or as learning [82], [68]. The crowd is engaged because it did not have anything better to do and thus, it might just as well contribute to a meaningful activity. Other motivators related to this mode are reputation building [81] or career building [83], rewards, recognition and curiosity. Reputation building, career building and recognition are all related to people's willingness to get visibility and thus being able to build a new career or learn new skills. In more innovation oriented crowd activities, such as idea generation, co-design and tests of innovation with an innovation intermediary organization such as for instance Living Labs, the main motivator for the crowd to participate is mainly to influence future innovations that are meaningful and have an impact on their personal life and consumption habits. Therefore, they are awarded with a token gift or mere formal recognition of their efforts in the project as a sufficient reward [84], [85]. Table 5.1 summarizes and categorizes the *Collaboration Crowdsourcing mode*.

Table 5.1: Collaboration Crowdsourcing mode

Example of Platforms	Action in Focus	Crowd Motivator	Crowd Role	Crowd labelling
Linux, SourceForge	Open source projects	Enjoyment based motivation, community/ obligation based motivation [65]. Reputation building, satisfy members needs and interest [83]	Developer	Crowd-labour
Quirky, OpenIdeo	Collective design	Monetary Rewards, Career, Recognition (supportiveness of the platform), Collectiveness, Appreciativeness/ Attention, Responsiveness, Trustworthiness [76]	Innovator	Crowd-creation
KickStarter, Petridish	Funding	Sympathy, Guilt, Happiness, Identity, Rewards, Support causes [80]. Fun, Altruism, Reciprocity, Identification, Personal Need [86]	Founder	Crowd-funding

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Table 5.1 – *Continued from previous page*

Example of Platforms	**Action in Focus**	**Crowd Motivator**	**Crowd Role**	**Crowd labelling**
Zooniverse, Kaggle, Foldit, SciStarter	Research Tasks	Fun, Enjoyable, Contributing to a larger cause, Reciprocity, Reputation Gains, Learning [81]. Desire to contribute to the society [87]	Investigator	Crowd-research
Wikipedia	Peer production	Ideology, Challenge, Career, Social, Fun, Recognition, Duty [82]	Creator	Crowd-production
HarrassMap, Urban Water Mappers	Influence Society, Community activism	Engaged in a cause, Rewards (to be used with caution) [79]	Expressionist	Crowd-engagement
Botnia Living Lab, iLabO, Laurea Living Lab	Innovation process	Token gift, Recognition. [84]. Learning, Curiosity, Entertainment [85]	Voluntary Contribution	Crowd-Innovation
Micro-Mappers, Standby, Taskforce, Digitalhuma-nitarinism.com Ushahidi, Rappler	Crisis management	Get help and helping in crisis situations [55]	Crisis management	Crowd-engagement

5.2.2 Compensation mode

Crowdsourcing initiatives, focusing on compensation for the crowds' efforts, are usually driven by an intermediary platform owner, such as for instance Amazon Mechanical Turk, ClickWorkers or Freelancer, who matches the need of a requester with the competence and skills of a provider and after the work has been done, they are compensated for their efforts [57]. Hence, the platform is usually rather complex and the support is on a spot market, matching skills and tasks. Compensation in this mode usually refers to monetary compensation where the provider gets a fee for her efforts depending on the problem that has been approved by the requester [69]. Another dimension related to the mode of compensation are initiatives such as Airbnb, Uber and iStockphoto where the crowd use the platform as a mean to offer its resources to potential buyers. At Airbnb the provider offers a place to rent and at iStockphoto, they offer pictures. These initiatives differ from the more traditional compensation initiatives, since they do not have a clear requester that is triggering the process. Here the platform has the role of being a market place where providers and buyers can easily meet.

The common motivator between these different crowdsourcing initiatives is the desire to earn money (e.g. [66] [88]). In the more labour oriented initiatives, the crowd is also motivated by having fun (or killing time) and develop their career since the tasks they do help them also to develop their skills and they can do something they like to do [69]. In initiatives such as iStockphoto, the crowd is motivated by their opportunity to develop their creative skills and get peer recognition. This is somewhat different from the crowds who test new innovations. These crowds seems to be more motivated by the possibility of being a forerunner and making a difference in the society [89]. Hence, the role that the crowd has related to the crowdsourcing initiative, seems to influence its motivations to contribute. In a more sharing economy-oriented crowdsourcing initiative, such as AirBnb (overnight renting) and Uber (car-pooling), the crowd is usually motivated by the opportunity to earn money, unfreeze capital and being able to decide on how to use the things they own [90]. Other cases include more ideological motives such as sustainability [91]. In this work, we have chosen to exclude collaborative consumption initiatives that focus on swapping, lending and donating since these are more focused on peer-to-peer consumption, which is outside of the scope of this work. Table 5.2 summarizes and categorizes the *compensation crowdsourcing mode*.

Table 5.2: Compensation Crowdsourcing mode

Example of Platforms	**Action in Focus**	**Crowd Motivator**	**Crowd Role**	**Crowd labelling**
iStockPhoto, Zazzle, Dreamstime	Creative creation	Peer recognition, Develop creative skills Make money, Peer recognition and the opportunity to learn new skills, Sheer enjoyment of participating at iStockPhoto [66]	Creator	Crowd-production
Airbnb, Ueber	Sharing resources	Earing money, Avoid costs, Decide over the things you own, Unfreeze capital	Resource provider	Crowd-production
Testbirds, Testbats	Testing	Financial compensation, Being a forerunner, altruism, curiosity, making a difference [89]	Tester	Crowd-testing [92]
Amazon, Clickworkers, Spudaroo, Freelancer	Micro-Tasks	Payment, Fruitful way to spend free time [69]. Earn money, Better working conditions than in their own country, Develop their competence [88]	Work for hire	Crowd-work

5.2.3 Competition mode

The third proposed mode of crowdsourcing is the competition mode, which refers to initiatives, that create competition for a crowd to solve a problem. This mode is one of the most traditional ways of crowdsourcing. This was, for instance, the starting point for InnoCentive, which focus on solving complex problems. In their "common"crowd, many researchers are active, but there are also other people who want to contribute to different challenges which help creating a better world [60]. In this mode, the process usually starts with a requester having a need that she describes in an open call through a platform provided, for instance by XPrize, 99designs or Topcoder. The requester describes the prize and defines the criterion for the competition and then the task is published through the platform to the crowd. Afterwards,the crowd providers develop their solutions to the suggested problem or task and upload them onto the platform. These are then gathered and sent to the requester who chooses the winning contribution and awards the provider with the prize. This approach is rather beneficial for the requester since she gets several perspectives and suggestions to solutions for a problem, and only one award has to be given to the selected winner [57]

Here, we have chosen to include categories that have the most apparent competitive mode since many crowdsourcing initiatives have a competitive touch, such as Quirky and Freelancer. However, for those it is not the driving force behind the initiative. Consequently, in this mode, we have chosen to include initiatives such as the Topcoder, InnoCentive, NineSigma and XPrize that have focus on solving problems where the best solver wins a prize. However, we also include initiatives such as the Threadless, eYeka and 99design where the crowd is engaged as creative designers. The common motivator in this mode is the challenge of either being selected, as in Threadless (t-shirt design) or the challenge in the problem to be solved (InnoCentive and TopCoder) [93]. Other motivators are the enjoyment and fun [94], [82] part of competing and learning, and also the possibility of winning the reward [93]. In initiatives focusing more on crowd-creation, as in 99designs and Threadless, the crowd is also motivated by the possibility to develop their creative skills and for the love of the community “Threadless is kind of an addiction” [67]. Table 5.3 summarizes and categorizes the *Competition Crowdsourcing mode*.

Table 5.3: Competition Crowdsourcing mode

Example of Platforms	Action in Focus	Crowd Motivator	Crowd Role	Crowd labelling
Topcoder	Computer programs	Enjoyment based motivation, community/obligation based motivation, Immediate payoffs, Delayed payoffs [82] [94]	Problem solver	Crowd-labour
InnoCentive, NineSigma, Ideaken, xPrize	Complex problem solving	Challenging monetary rewards, Joy of solving scientific problem, Having free time to kill [93]	Expert problem solving	Crowd-wisdom
ThreadLess, Speradshirt, 99designs, eYeka	Creative creation	Challenge to be selected, Financial rewards, Communicating with like-mineded people, Fun,Career [82]. Opportunity to make money; to develop one's creative skills, The potential to take up freelance work, The love of the community [67]	Creator	Crowd-creation

5.3 Methodology and Survey

The methodology for this work started with a literature review in which motivators and crowdsourcing were in focus. The literature was then combined with a netnographic study of the different crowdsourcing initiatives mentioned in this chapter to get a good view of the essence of the initiatives, using a snowballing approach. We started by analysing the most common crowdsourcing sites such as InnoCentive, Airbnb and Quirky, and continued to dig further in each mode of crowdsourcing. Hence, we have used a qualitative and reflective approach, meaning that we reflect on the results from one paper or platform and then looked further. To guide our analysis we started by categorizing the initiatives activities, what is the crowd actually doing by means of platform for each initiative. We then analysed the role of the crowd; are there for instance, problems solvers, creators or data providers. Thereafter, we labelled each initiative according to existing categories of crowdsourcing as suggested by [60]. The author in [60] defines four basic categories of crowdsourcing applications: crowd wisdom; crowd creation or user generated content; crowd voting; and crowdfunding. In this process, we identified that these categories did not cover all the different aspects of crowdsourcing that there are available today, hence labels such as crowd-production, crowd engagement and crowd testing emerged. In some occasions, the labels stem from literature, as in crowd-testing [92], and in others we analysed the essence of the crowdsourcing initiative and interpreted the existing four categorizes as inadequate to catch the kernel of the initiative and the motivators related to it. As for instance the crowd engagement; even though the crowd jointly creates the content, the essence of the initiative is to influence the society that does not appear as strongly related to crowd creation, as in Quirky, Threadless or 99designs. The second part in this research was a survey carried out within the realms of a research and innovation project called Internet of Things (IoT) Lab [[38]].

5.3.1 IoT Lab project

The Internet of Things Lab (IoT Lab) is a research and innovation project sponsored by the European Commission (GA No 610477). IoT Lab is a research project exploring the potential of crowdsourcing to extend IoT testbed infrastructure for multidisciplinary experiments with more end-user interactions. It researches and develops crowdsourcing mechanisms and tools enabling testbeds to use third parties resources (such as mobile phones), and to interact with distributed users (the crowd). The crowdsourcing enablers address issues such as privacy by design, identity management, security, reputation mechanisms, and data ownership. In the project, we also explore end-user and societal values by analysing the potential end-users and crowdsourcing participants to propose an optimized model for end-user adoption and societal value creation.

The survey on crowd motivation was carried out within this project. The purpose of this survey was to get insights into what could motivate a potential crowd to take part in crowdsourced driven research projects that in particular focus on crowdsensing. The questions in the survey were designed based on established theories on motivation and values in general (e.g. [95], [96]), knowledge about crowdsourcing and motivation in particular (e.g. [64], [68], [65], [66], [67]). The survey was distributed to the respondents using a snowball approach and 103 people responded it online. The responses have been analysed and interpreted and the results are reported in this chapter.

5.3.2 Results from the survey

The survey was distributed on-line during a two months period and was answered by 142 individuals. 95 completed the survey as a whole, hence, the other responses have been removed from the data. Among these 70 respondents where male and 25 where female, which gave us a rather biased result. The age of the respondents ranged from 18- over 60 years old with most of them being 30-39 years old. The distribution of the crowd that participated is shown in Figure 5.1

After the background questions, the respondents got to read a description of how the crowd-sensing solution we develop within IoT Lab project is planned to function and how the design of the crowd-sourced driven research processes are planned. Thereafter, the respondents were asked to answer on what would motivate them to participate in this type of initiatives. We think that this initiative relates to the mode of collaboration since they would not necessarily get monetary compensation or there might not be competitions involved in the process. Related to this the respondents stated that they where most motivated to participate in such an initiative if they could learn something new, exchange knowledge with others and if they had a personal need related to the activities. From their answers it seems that, the least motivating factors were to get recognition by the requester, to do the same things as their friends and to extend their social network. This also correlates with other studies such as

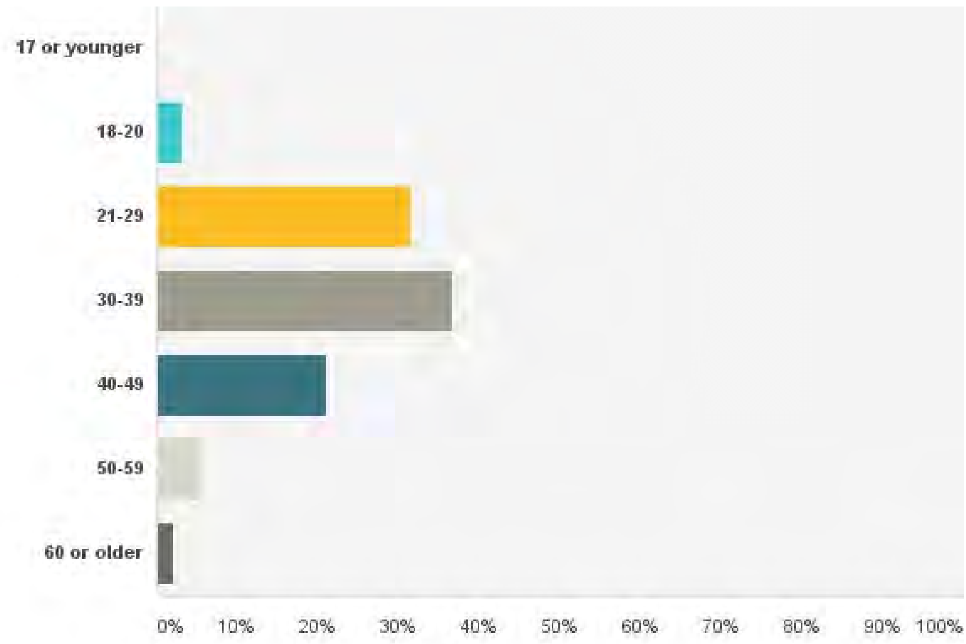


Figure 5.1: Distribution of participating crowd

in [67] where social aspects do not seem to be a motivational factor when it comes to participating in crowdsourcing activities. To understand the motivations more deeply, we also looked into the correlation between gender and motivations. In this analysis we observed that men are more motivated to have an opportunity for radical change in the society, while women are more motivate to participate if they could learn something new. In addition, more women than men are not motivated by the possibility to become visible. In the contrary, men are more motivated when they can become visible. Men also seem to be more motivated by the possibility to get monetary rewards for their effort with 31% being very positive, while among the women, only 24% where strongly motivated by monetary rewards. The same trend is visible in the question about future rewards, where 44% of the men where highly motivated and 28% of the women are highly motivated by future rewards. Even though the sample in this survey is rather small, this shows a trend that men seem more motivated by monetary or rewarding mechanisms.

Analysing the results, we saw that there was also a difference between men and women when it comes to being challenged. 42% of the men answered that would be motivated to participate if they where challenged by the activity, while only 24% of the women would be motivated by a challenge. When it comes to become a trend-setter and be motivated to participate in that, for none of the two genders this was a strong motivator. However, there is a difference in the answers where 24% of the men would be motivated, by this to some extent, while only 4% of the women stated that they would be motivated by being a trend-setter. Here also 12% of the women stated that they would not be motivated at all by being a trendsetter, while 3% of the men were completely demotivated. The same trend is also visible when it comes to getting recognition by the requester; 20% of the women stated that they would not be at all motivated by that, while 8.5% of the men stated the same. Concluding, there are differences in motivators between genders, which have not been investigated in previous studies, but still remain an important factor to consider when engaging a crowd in crowdsourcing initiatives.

5.4 Crowd motivations re-visited

Our study confirms earlier studies on user motivation in innovation communities in general [70], but it also adds to the understanding of what motivates people in crowdsourcing activities in particular. Viewing crowdsourcing from a gender perspective revealed that there are differences in what motivates the crowd members according to their genders. Motivators such as learning, and having a personal need related to the crowd activities were more motivating for women, while men were more motivated by being challenged. There was also a clear difference between genders when it comes to monetary compensation or rewards; men where more motivated by these motivators than women. We want to caution against drawing any general conclusion about this because the sample of the study is rather small. However, there is a visible trend which merits further investigation. We interpret the answers from women as being more modest and mainstream. They stated that they are not motivated by monetary incentives, by being a trendsetter or by getting recognition for their efforts. These are all aspect that might be interpreted as competitive, shallow and status seeking, which might be aspects that women have more difficult to identify themselves with. Men are more motivated by factors such as becoming a trendsetter, get future rewards, get recognition and to do the same things as their friends. These are all motivators that are strongly linked to extrinsic motivators.

Caution is advised against drawing general conclusions based on a study of a crowd has also been highlighted by Brabham [66] who acknowledged that the crowd at iStockphoto mainly consisted of white, middle-aged and middle-class men. Hence, to really understand crowd motivation, it is important to dig into the crowd and understand by whom it consists. People having a steady income from a job they like might not be as motivated by developing their careers or get monetary rewards as people who use crowdsourcing as a source of income or a job.

This also became apparent in this study when comparing different modes of crowdsourcing with each other. In this comparison, our study shows that in the collaboration mode, the crowd is mainly motivated by a will to contribute to a larger cause, for example to a crisis situation where they see the collaboration as a way to reach a larger goal. This is not as obvious in the compensation mode where the crowd is more motivated by the possibility to earn money. While in the competition mode of crowdsourcing the main motivators are the challenge. It can either be the challenge of being selected (as in Threadless) or the challenge in the problem to be solved (as in InnoCentive). What is similar between the modes is the enjoyment, having fun and the ability to kill time with meaningful activities. These motivators can be seen as the most important ones from a general perspective. If the crowd does not enjoy what is doing, it will most probably move to another activity. This enjoyment can be used to learn something new, to develop creative skills or to trigger the crowds' curiosity. Common among the different modes is also the motivator to get some type of recognition, visibility or recognition by peers. The way these motivators appear, depend on the crowd and the platform. In some platforms the visibility is vital to be able to earn money, as for instance in Airbnb and iStockphoto. While in other crowds, getting visibility is more strongly related to intrinsic motivators such as feeling important and being seen by the community.

This can also be explained by the nature of the platforms where some of them support a two-sided market (e.g. amazon mechanical turk, airbnb and iStockphoto) while in others there is no clear buyer and seller relation. These are also factors that influence the motivator for the crowd, while there is a possibility to earn money or the main benefit is to contribute to others.

5.5 Conclusions

The aim of this work was to categorize contemporary crowdsourcing initiatives and identify different motivational factors driving the crowd to contribute to their specific focus. Our study has shown that depending on the modes of the crowdsourcing initiative, the crowd is motivated and behaves differently. In collaborative crowdsourcing, contributing to a larger cause mainly motivates the crowd. In compensation focused crowdsourcing, the crowd is mainly motivated by the possibility to earn money while in competition focused crowdsourcing the main motivator is the challenge.

However, based on our study we can also draw the conclusion that to fully understand the crowds and their motivations it is important to look into the crowd itself. In this study we saw that women are motivated differently than men, hence if the focus for the crowd efforts is to earn money, this is likely to attract more men than women. On the other hand, if the focus for the crowdsourcing is to trigger learning or to contribute to the society, the initiative is more likely to attract women. This is especially important since many researchers are using crowds as sources for data collection, for example in evaluations and tests, where gender might be an influential factor to consider in both construction and use of the crowds.

In practice, this means that by highlighting key motivators, mangers or researchers need to consider and address to specific crowds through IT-based platforms. In that way they can better harvest the potential the crowd can have for their specific crowdsourcing initiative. For instance, the crowd motivators provide a suitable starting point for understanding what incentives engage and motivate crowds. Crowdsourcing capabilities, both in terms of acquisition and assimilation, provide dimensions and examples of IT structures and engagement options that we hope will be proved practical for decision makers and for their strategic development of crowdsourcing initiatives.

6 An IoT Crowdsourced-enabled Experimental Platform Architecture

6.1 Introduction

Exploring direct interactions with the crowd through crowdsourcing and crowdsensing techniques while enabling the crowd to be at the core of the research cycle with an active and participating role in research, from its inception to the results' evaluation, is the main motivation behind the development of the IoT Lab platform - testbed as a service (Figure 6.1) developed by IoT Lab European research project [38, 97]. This platform provides a better alignment of the research within the society, end-users needs and requirements. Crowdsourcing is recognised as a practice of obtaining needed services, ideas, or a content by soliciting contributions from a large group of people and especially from an online community, rather than from traditional employees or suppliers. The crowdsourcing approach can apply to a wide range of activities including crowdsourcing of data, measurements, opinions, solutions and funding. The main focus here is on IoT-related, attractive types of crowdsourcing such as collection of data/measurements and user rates/opinions. IoT today regards every smartphone user as a source of data that is generated and shared via his/her device.

This chapter is organized as follows: Section 6.2 summarizes the related work, Section 6.3 presents the IoT Lab vision and discusses the main challenges; Section 6.4 describes the architecture design approach whilst Section 6.5 gives details about the architectural components. The sequences of using the services are given in Section 6.6 while this chapter concludes in Section 6.7.

6.2 Related Work

There are already a number of crowdsourcing platforms focusing on different ways to empower user participation in the IoT through their mobile phones. While some of the existing platforms might be too specific [98] and only support pre-defined tasks without a possibility to extend them due to the lack of open source code, others might be too general, like Ushahidi [99] that does not support the involvement of participants and only leverages on geo-localized data collection and visualization through maps.

Figure 6.1: IoT Lab "Testbed-as-a-Service"

Platforms like Phonelab [100], provide a model for crowd engagement in the IoT co-creation effort, but no actual application is provided to support this, while on the other hand custom applications are developed and distributed according to the selected use case. There is a number of existing platforms that properly support user participations in IoT experimentation through mobile phones such as in [101] [102] but still lack the ability to fully support the IoT Lab envisioned models for participation and interaction between participants and investigators. Supporting scripting and crowdsourcing on mobile phones is possible through APISENSE [103] but an integration with other IoT Lab provided tools is needed, such as Resource Management and Experiment Management. However, an official version of the platform has not been released at the time of writing this work. Similarly, a set of other existing platforms, fulfilling different needs envisioned by the IoT Lab mobile application, will be investigated further in order to understand how and to what level they could be extended with other IoT Lab tools, so as to achieve a complete IoT Lab platform integration. EpiCollect [104] can be useful for creating a survey and questionnaire, but the lack of open source code limits the possibility of extension and integration. mCrowd [105] seems to better fit participatory sensing applications. However, the lack of APIs and only provided an iPhone version might limit the possibility of integration and extension. Funf [106] and AmbientDynamix [107] represent good frameworks for crowdsensing and crowdsourcing. In particular, the capability of AmbientDynamix to adapt its behaviour to context could allow support of different experiment participation models suitable for the end user perspective. The possibility to integrate it with other envisioned IoT Lab resources should be further investigated. Together with AmbientDynamix, the scope of results are limited to the IoT Lab mobile application. McSense [108] seems to support all the basic functionalities envisioned in the IoT Lab mobile application (actuation and sensing), of which the IoT Lab platform should be comprised, and also includes tools for resource selection, task (and experiments) description and other useful functionalities. The possibility to integrate and extend it with other IoT Lab resources, such as integration with FIRE testbeds Profile Management and the Search and

Communication tools, should be investigated further. For all these reasons, the platforms that should be selected and further analysed to fully understand their potential integration with in the final IoT Lab platform are represented by AmbientDynamix and McSense.

None of the platforms actually foresees the possibility to integrate smartphones with existing FIRE testbeds or in general statically deployed IoT resources, such as smart power meters, home automation control systems and so on. Nonetheless, no effort has been put towards providing virtualization tools that enable heterogeneous IoT resources to be homogeneously available and interoperable with each other. Our contribution to this purpose, is the design of a platform architecture in the context of the IoT Lab project [97]. Our approach of the platform is new and advanced with respect to existing crowdsourcing platforms.

6.3 IoT Lab Vision and Key Challenges

The main aim of the IoT Lab's vision is to enable the FIRE testbeds, which traditionally are comprised of static sensor mote platforms, by utilizing end-user participants' smartphones and relevant mobile/portable devices in order to achieve crowd participation in sensing and actuation operations and thus enable a wide range of multidisciplinary experiments and services.

To achieve this aim, the IoT Lab platform addresses the following objectives:

- Crowdsourcing & crowdsensing mechanisms and tools;
- Crowd-driven research;
- Virtualization of crowdsourcing and testbed components;
- Ubiquitous interconnection and cloudification of the testbeds' resources;
- Testbed as a Service;
- Multidisciplinary experiments;
- End-user and societal value creation;

Through these objectives the IoT Lab platform can achieve its goals in terms of (i) connecting and using existing IoT testbeds which increases the testbed economic sustainability; (ii) proactively involving participation of the public through crowdsourcing, as well as researchers taking part in the IoT experiments which provides closer interactions between experiments and society. The platform also considers issues such as privacy and personal data protection through a 'Privacy by Design' approach and built-in anonymity. There are various stakeholders identified for the IoT Lab "Testbed as a Service" platform with the main ones being: researchers/experimenters; testbed owners; crowd/media; EC; official authorities and potential private customers.

The expected IoT Lab impact is to support experimentally driven research, in particular to conduct multidisciplinary investigation of key techno-socialeconomic issues (i.e. Internet Science), to further exploit any relevant FIRE facilities, to consider benefits for citizens as well as to investigate ethical and self-sustainability aspects of experimental facilities.

The key challenge of the IoT Lab platform is to successfully attract researchers and the general public (crowd) into using the testbed facilities and joining the experiments respectively. A range of incentive and rewarding schemes has also been considered. Furthermore, a wider audience needs to be reached throughout the duration of the project both for IoT Lab sustainability reasons and in order to help the platform mature. Additional technical challenges originate from the IoT Lab platform development process that needs to address heterogeneous identified requirements and to support challenging use cases proposed by the crowd.

6.4 Architecture Design Approach

The preliminary IoT Lab platform architecture design is addressing double challenge: On one hand, it has to integrate diverse IoT-related testbeds located in different regions of Europe. On the other hand, it has to integrate smart phones with existing

FIRE testbed infrastructures, thus representing a novel approach with respect to existing crowdsourcing solutions. The key platform components have been identified and their functionalities, interaction patterns, interfaces and communication links described.

The derivation process followed an IoT-A methodology [109] to support interoperability and scalability and to enable use of a wide range of heterogeneous devices and testbeds from different application domains thus satisfying a high number of requirements. An architecture generation process starts with the analysis of technical and end user related requirements derived from selected use cases. Two scenarios have been proposed. The first one is a "Game and Supermarket Marketing" - a smart city scenario in which users can play a game and participate in experiments, for instance a market survey from a supermarket. The second scenario is "Energy Efficiency and User Comfort Hints" in which crowdsensing methods are used to adapt energy efficiency to human presence and behavior. Moreover, the users can provide feedback on the current devices' setup and set their user preferences representing a Physical Testbed Scenario. These two scenarios have been analysed using the IoT-A methodology and they are here represented using a general use case diagram shown in Figure 6.2.

The analysis of the use cases provided a detailed list of requirements for the IoT Lab platform that can be summarised as follows:

- User profile management for both participants and investigators.
- Experiment Configuration – Investigators must specify a detailed description of their experiments, including needed resources, ethics and privacy concerns, timeline and overall objectives of the experiment.
- Testbed Resources Management – A simple and easy interface that allows testbed managers to configure and make their resources available for experimentation.

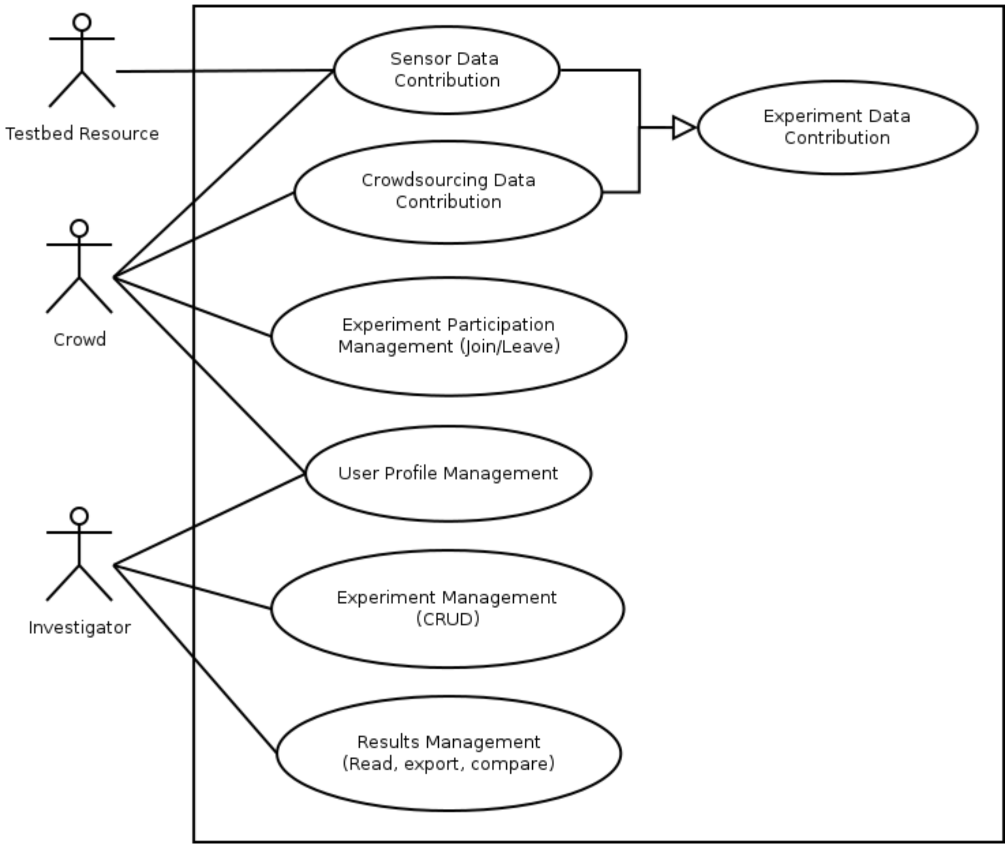


Figure 6.2: IoT Lab General Use Case Diagram

- Crowdsourcing and Crowdsensing provisioning - The platform must provide ways that allow both crowd and testbed resources to provide data which can be sensory data and/or crowd knowledge.
- Experiments Management – The system must provide ways that allow the users to browse and evaluate existing experiments and in the case of the investigators to manage their own experiments.
- Privacy and Ethics – Privacy by design concept is followed; users are requested minimal information and for each of the experiments a clear description of the required data (user and device) is presented. Experiments must be validated before being run.
- Support for incentives – Incentives scheme for crowd and investigators need to be included.

Development of the polyvalent and flexible IoT Lab platform 'Testbed as a Service' that can support a large set of IoT related experiments is guided by several considerations:

- Adopting a modular architecture, that will enable the evolution of individual components without impacting the whole architecture;
- Favouring generic enablers that can be easily used by different experiments;
- Aligning with main stream standards and solutions to ease the integration with third parties resources;
- Satisfying the requirements derived from the most up-voted use case scenarios proposed by the consortium and described above.

Selected real use cases for implementation identified several important experimental approaches including crowd sensing; data collection & processing from different IoT testbeds; the code execution on the participant side and completion of different questionnaires by participants. The generic IoT Lab 'Testbed as a Service' enablers are illustrated in Figure 6.3

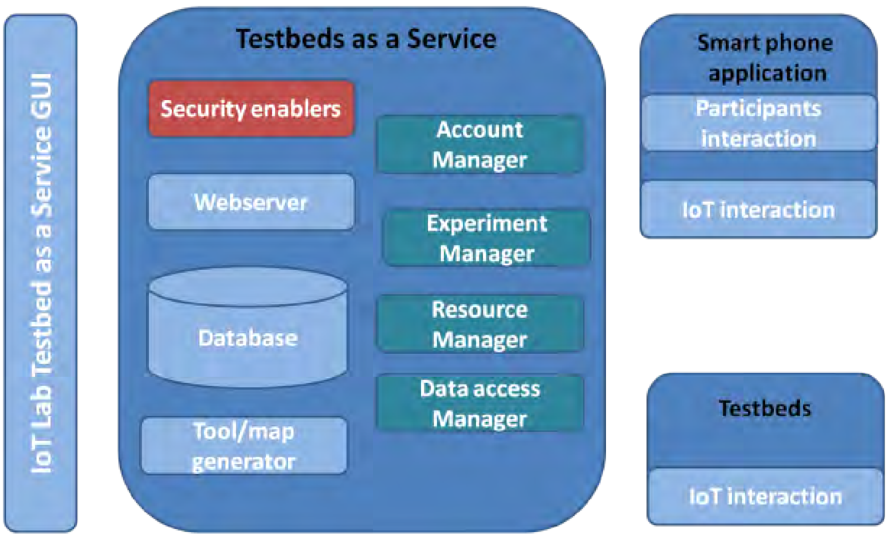


Figure 6.3: IoT Lab enablers – generic

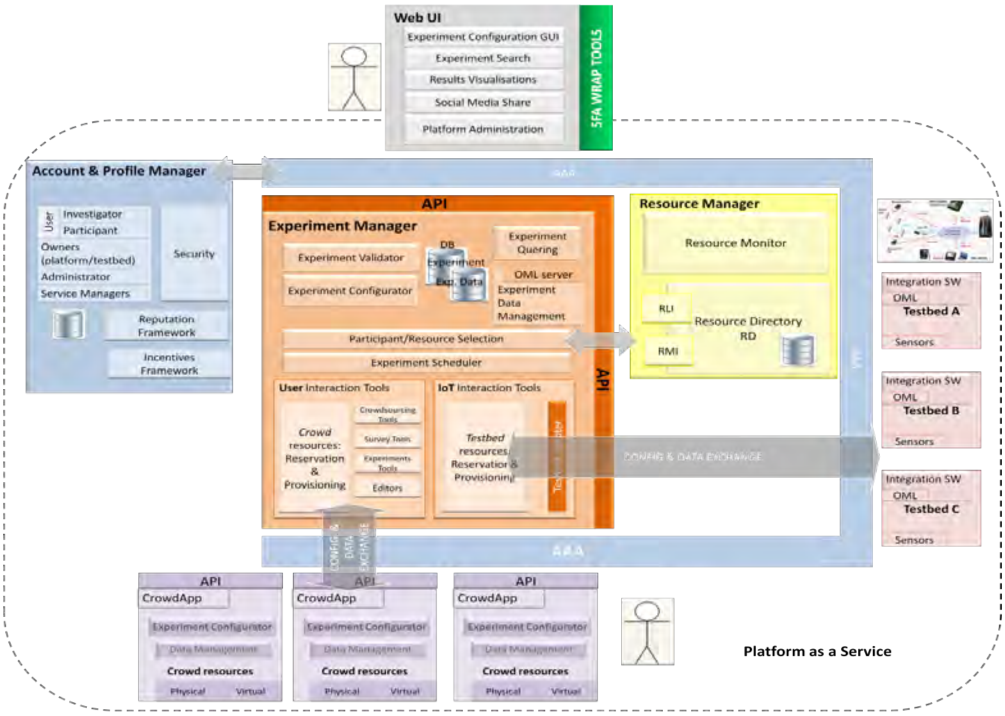


Figure 6.4: IoT Lab Architecture – A deployment view of the proposed concrete architecture

6.5 Architectural Components

The main architectural components of the proposed IoT Lab system are organised in four groups as shown in Figure 6.4 : Account manager, Resource manager; Experiment manager and Web user interfaces.

6.5.1 Account & Profile Manager

The Account Manager group collects components related to different user accounts and assigned users' roles. Two main user categories are Investigators and Participants. Investigators use the IoT Lab platform and tools to set-up their investigations or experiments, recruit participants and collect and analyse results. Participants are all the actors involved in an experiment; i.e. people who use the IoT Lab product(application) and allow the experiment execution on their phones. Other users of the platform include: platform owners, researchers/students, testbed owners, customers, testbed service managers, and administrators, etc.

The IoT lab platform is able to collect different types of data and it will be designed to ensure the privacy and trust of the users. All users have to be authenticated and appropriately authorised to be able to access the system functionalities. The platform will provide the option for data anonymisation as well as for generating identifiers for such accounts. Access to the platform functionality will be controlled by AAA (Authentication Authorization and Accounting) component. The Security component will control AAA mechanisms in the system. All accounts and roles will be persistently stored in a database.

The function of the Reputation and Incentives framework component is to monitor the users' activity and then estimate the users' rating in a semi-automatic way as well as to apply incentives schemes for engaging different end users and crowdsourcing participants in experiments.

6.5.2 Resource Management

The *Resource Management Group* monitors and collects information on available resources in the system. The resource Directory (RD) component provides a persistent storage of resources. It implements the interfaces for the resource management by providing the *create, read, update and delete* (CRUD) functionalities as well as the Resource Managing Interface (RMI) and Resource Lookup Interface (RLI) which are implemented as REST based web services. All resources available in the IoT system should be uniformly described. IoT testbed resources management interface uses Fed4FIRE enablers such as Slice-based Facility Architecture (SFA) Wrap [110] and the *Outline Markup Language* (OML) to enable interactions with IoT components from testbeds and smart phones in a unified way. SFA Wrap enables resource virtualization, federation and integration of testbeds. OML is responsible for data collection from testbeds and crowdsourced devices.

Resource Monitor Component manages resources in the RD by keeping real time information on availability of resources in the system.

Testbeds should implement a resource discovery mechanism that will announce their available resources following the RSpec format of the SFA.

6.5.3 Experiment Manager

The *Experiment Manager Group* aggregates components related to both the experiment management and the experiment data management. An API provides the standardised RESTful interface for component interaction. Several components take part in creating an experiment:

The *Experiment Validator* Component receives a standardised abstract experiment representation and validates the experiment definition. Standardised experiment representation should result from consolidated analysis of use cases and additional user requirements. It can contain code segments that should be performed on the participants' devices involved in the experiment, or a definition of questionnaire forms that should be completed by every participant. All segments of an experiment should be verified and any detected irregularities should be reported before any further processing.

The *Experiment Configurator* Component interprets the received validated experiment definition and stores the standardised experiment representation in an Experiment Database.

The *Participant/Resource Selection* Component detects and selects available resources that match the experiment requirements. This component performs the appropriate query on the RLI interface and receives notifications on availability (and location) of Resources from the Resource Monitor component.

The *Experiment Scheduler* runs the experiment on resources using the Reservation and Provisioning Components for appropriate testbeds.

The *Experiment Querying*, through the *Experiment Manager API*, provides an access to stored experiments. All data provided by the experiment are collected by the Experiment Data Manager component. Testbeds provide streams of experimental data in the OML format.

The *Experiments* are conducted on top of different testbeds. The process of an experimenter discovering, reserving and provisioning the available resources across all testbeds for his/her experiment will be conducted in a standardised way via the SFA Wrap tools and architecture (e.g. an SFA client will be running at the Web GUI). Then, the IoT Lab Experimenting Platform will take care of the particularities of each testbed and will interact with the resources according to the experiment scenario.

The *Crowd Interaction* management interface handles the interaction with the participants. Crowd based experimenting is focused on running the experiments on users' mobile devices. Again, these resources will be exposed by the IoT Lab Experimenting Platform in a standardised way via SFA Wrap.

The *User Interaction* component aggregates components for experiments on top of crowdsourcing smart mobile devices. Several components for survey, crowdsensing and code script execution are involved in experiment execution.

The *IoT interaction tools* control the experiment execution on federated testbeds. All components in the Experiment Manager are accessible through the Experiment manager RESTful API.

6.5.4 Web User Interfaces

The *GUI* access to the system is implemented through components grouped in the Web user interfaces. The Experiment Configuration GUI provides the Web access for designing and initiating the experiment and it should be intuitive. The GUI communicates with the Experiment Manager through a corresponding API to provide the experiment description to the Experiment Validator. This also includes the access to the Survey and GUI editor so the experimenter can set up a specific survey and/or a specific user interface for his/her experiment on the smart phone application.

The Experiment Search Component provides an interface for the experiment querying. This component can query the resources in order to make the access easier for resources in different testbeds

Results Visualisation Component provides the appropriate graphical interpretation of collected experimental data. It will include a maps and graphs generator based on main stream open source solutions, such as OGC SWE and Google maps. It will enable the platform to provide graphical representation and dynamic maps of the results as well as of the live data.

Social media will share components of the Web interface and enable different types of users to publish their experiments and related opinions on popular social networks.

The system management is provided through the Platform Administration Component which enables several functionalities including:

- User Account Administration for the users to log in and manage their personal account and profile.
- Data Access & Management for the experimenter to manage the collected data; delete unnecessary data sets; and/or retrieve filtered data sets.
- Filtering users' personal data in order to ensure full compliance with the personal data protection policy and obligations.

6.6 Use of Services

An overview of the usage of available services within the proposed IoT Lab platform described in the previous section is provided using the Sequence Diagrams, which illustrate three stages in the platform deployment:

- User registration Process shown in Figure 6.5

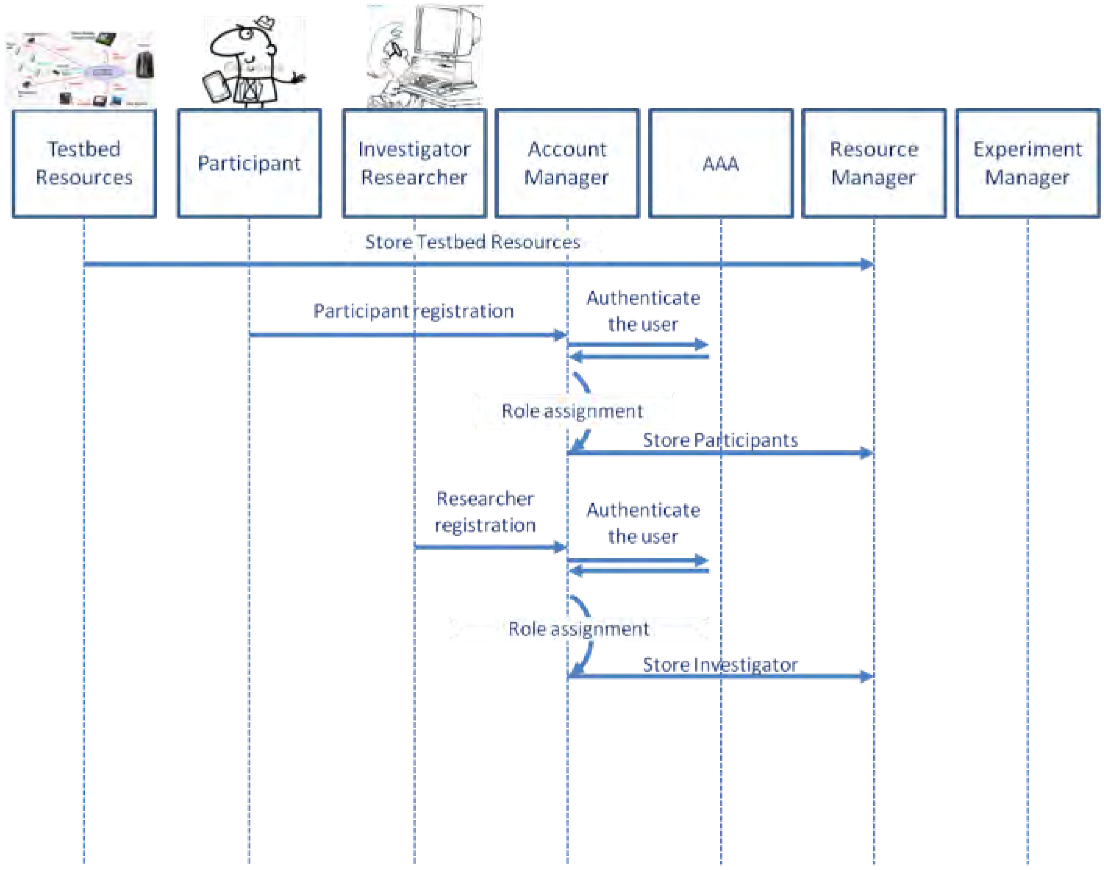


Figure 6.5: User Registration Process (Sequence Diagram)

- Experiment submission–Investigator side shown in Figure 6.6
- Contribution from Crowd shown in Figure 6.7

6.6.1 User Registration Process

Testbed Resources: All available individual testbed resources need to be stored in the Resource Manager following their announcement to the IoT Lab platform using a common description scheme. In this way, the IoT Lab platform will be able to leverage the available resources in a uniform manner.

Users of the platform (participants and investigator researchers) should be stored in a Resource Manager component following their registration in Account Manager, authentication through AAA and the role assignment again in Account Manager.

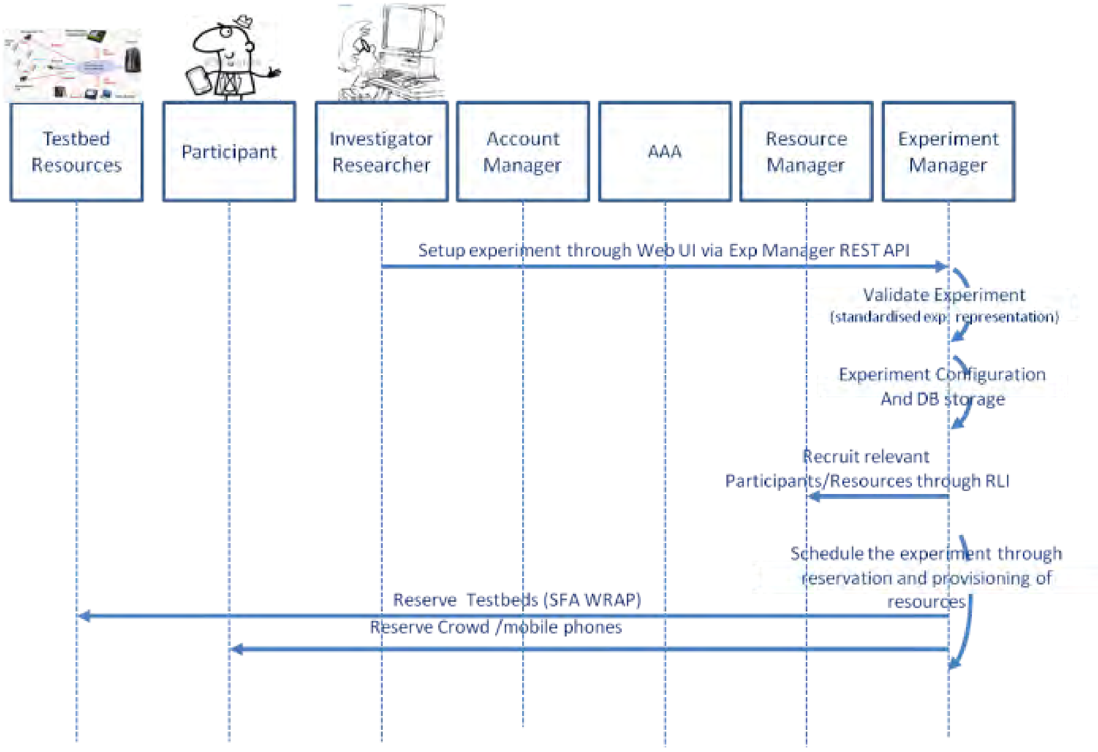


Figure 6.6: Experiment Submission (Investigator side)

6.6.2 Experiment Submission

An Investigator/Researcher uses the Web UI to setup the experiment via the Experiment Manager RESTful API. The experiment is then validated based on standardized experiment representation, interpreted by Experiment Configurator and then stored in an Experiment Database. In addition to automatic validation, experiments are also physically validated as part of a review process involving human resources.

The Experiment Manager is then able to recruit the relevant participants and resources (testbeds) by communicating the Resource Manager through Resource Lookup Interface (RLI). The experiment is then scheduled by Experiment Manager through reservation and provisioning of resources which includes: Testbeds - reserved through SFA WRAP and Crowd/mobile phones.

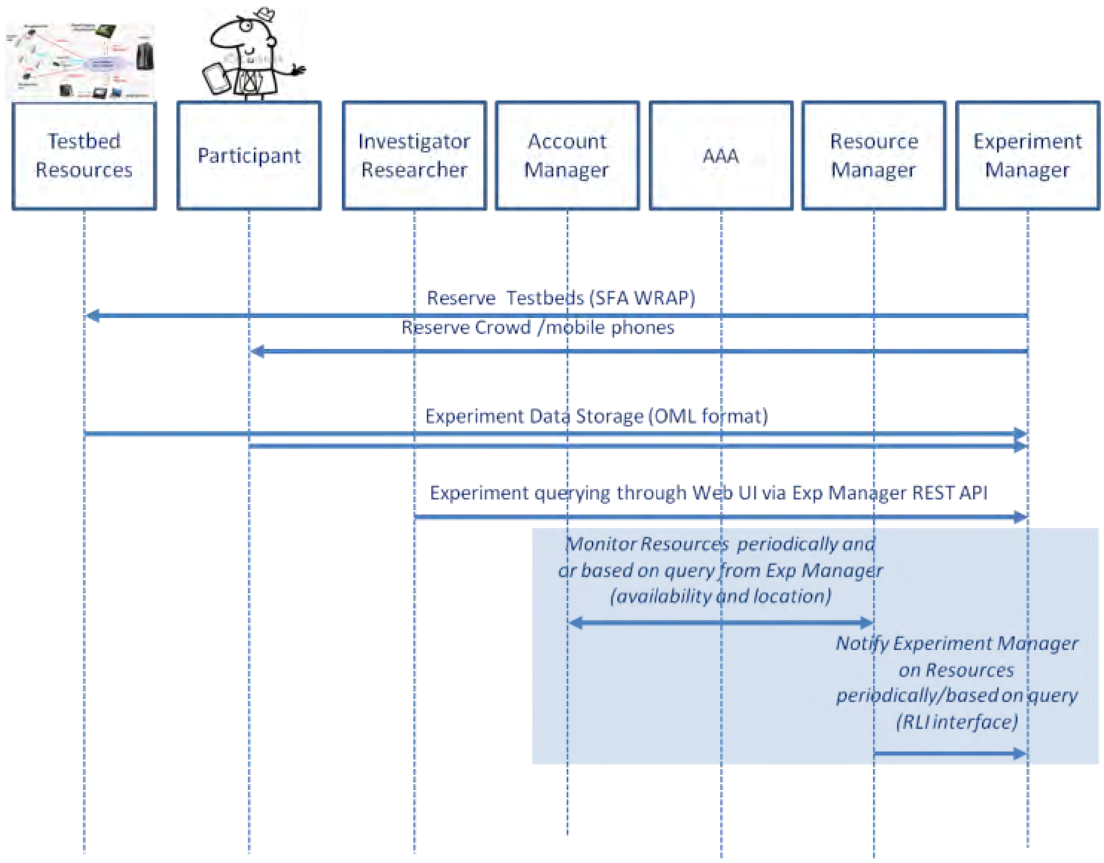


Figure 6.7: Contribution from the Crowd/Testbed Resources

6.6.3 Contribution from Crowd / Testbed Resources

The obtained experimental data from Testbeds and Participants is sent to the Experiment Data Storage within the Experiment Manager in an OML format. An investigator researcher can send the query for experiments through the Web UI via the Experiment Manager RESTful API.

Monitoring the Resources and information about their availability and location should take place either periodically or based on the query from Experiment Manager between the Account Manager and the Resource Manager.

The Resource Manager should notify the Experiment Manager on Resources periodically as well as based on the query through the RLI interface.

6.7 Conclusions

In this chapter are proposed the main components of the IoT Lab platform and described their identified functionalities, interaction patterns, interfaces and communication links. The IoT Lab platform development focuses on:

- Enhancement of existing IoT FIRE testbed facilities which are traditionally built from static sensor mote platforms by including the participants' end user mobile phones and thus achieving a crowd participation in sensing and actuation operations.
- Solutions with built-in reputation and privacy mechanisms as well as procedures for dynamic selection of suitable crowd resources.

The derivation process followed an IoT-A methodology in order to support interoperability and scalability and to enable the use of a wide range of heterogeneous devices as well as the testbeds from different application domains, therefore, satisfying a high number of requirements. Integration of smartphones with existing FIRE testbed infrastructures or any general statically deployed IoT resources represents a novel approach with respect to existing crowdsourcing solutions.

The values that IoT Lab brings in comparison to other existing crowdsourcing solutions are numerous: IoT and crowd sourcing based research and development; access to distributed testbeds; economies of scale; access to innovative service oriented architecture (SOA) technology; a possibility to explore the future now; market insight; crowd interaction and access to wisdom of the crowd; experimental platforms; reduction of development time and time to market; capital expenditure avoidance; cost reduction; access to 'up to date' and evolving IoTservices/ infrastructures; new product experimentation on advanced IoT facilities.

Our future work will focus on further implementing the proposed platform in order to test selected use cases in real situations and get a feedback from participants. Strategies for engaging as many participants as possible will be examined as well as the new components that provide reward mechanisms towards all participants and investigators.

Part IV

IoT, Crodwsensing and Incentive Mechanisms

7 A User-enabled Testbed Architecture with Mobile Crowdsensing Support for Smart and Green Buildings

7.1 Introduction

The Future Internet and the Future Networks are general terms coined to address the major shift in the context and the operation of the Internet that is expected to take place in the near future. This shift is realized by cross-cutting changes in several aspects of the Internet, each one driven by a different factor. For instance, technological advances during the past decade in the field of embedded systems have driven the rise of the Internet of Things (IoT) paradigm. On the other hand, the constantly increasing adoption rates of truly portable hand-held and wearable smart devices (smartphones, smart watches and glasses, etc.) have paved the way for the Mobile Crowdsensing Systems (MCS) that seek to exploit the embedded sensory capabilities of these devices and their intrinsic mobile nature.

Between the first stage of conceiving a new paradigm, by laying down its theoretical foundations, and the final stage of rolling out at full scale a new technology, there lies an intermediate phase where small scale, experimental systems are putting the vision to the test, thus providing valuable feedback. Such testing facilities bridge the gap between abstract assumptions, necessarily present when theoretically analyzing a concept, and implementation-specific limitations that emerge due to technological dependencies and real-life limitations. Various challenges regarding the design of such testbed facilities have been widely highlighted and relevant desired properties have been identified (e.g. see [111], [112] for IoT testbeds). Among these properties, the *realism of experimentation environment, device and service heterogeneity* and *efficient service composition* during the experimentation life cycle are important aspects to improve upon existing testbed facilities.

Increased realism implies matching the experimentation conditions as close as possible to the typically operating situations where the final solutions are expected to be deployed. This way design flaws or imperfections can be earlier detected and evened out, thus reducing the cost of roll out and maturation time. *Device and service heterogeneity* offers experimenters with more experimentation options and captures better how technological environments are expected to mature at later deployment stages. Efficient *service composition* is thus a key requirement for efficient testing facilities. Therefore, mechanisms to control and exploit realistic experimental conditions during the evaluation phase are necessary.

Our contribution. We present an IoT testbed facility for Smart Buildings whose architecture enables the seamless and scalable interaction of crowd-enabled resources provided by the end-users of the facility [113]. This integration increases the awareness of the facility both in terms of sensory capabilities as well as in terms of users' preferences and experienced comfort. Combined with smart actuation, IoT communication and networking technologies, the experimenter is provided with an agile experimenting platform. The facility exposes its operations as services thus greatly facilitating the definition and evaluation of diverse use-case scenarios. In order to demonstrate the use of the facility we design and evaluate several incentive policies in the context of a smart luminance scenario based on Participatory Sensing. First the end-users are incentivised to provide access to their hand-held devices from which data on the ambient environmental conditions are collected and aggregated into live luminance maps. Then, the indoor lighting units are dynamically adjusted based on the luminance maps and the feedback provided by the users to the system on their personal preferences and experienced comfort.

7.2 Related Work

There have been numerous testbed facilities using wireless sensor networks as the main component of their backbone infrastructure. For instance in [27] the authors present Syndesi, a framework for creating personalized smart environments using wireless sensor networks. This framework, among other services provided, is able to identify people and take personalized actions (such as control of electrical devices) based on their personal preferences. As a proof of concept, authors present a real-world deployment, where two use-case scenarios are implemented in the premises of a building. Also, in [114], they first identified some of user and operator testbed requirements, then they introduced the architecture and general concepts of a testbed approach and showed how this architecture meets the requirements of both groups. The main focus of this work was to address the perspective of both users and operators on how to experiment or respectively operate a wireless sensor network testbed based on a specific technology. In [115], the authors present PhoneLab, a smartphone testbed that provides access to smartphone users incentivising them to participate in experiments while simplifying experiment data collection. Three selected results from a usage characterization experiment are presented. In [116], they proposed a comprehensive architecture for managing a cluster of both real and virtual smartphones that are either wired to a private cloud or connected over a wireless link. Also, they proposed and described a number of Android management optimizations (e.g. command pipelining, screen-capturing, file management), which can be useful to the community for building similar functionality into their systems. Finally, they conducted extensive experiments and microbenchmarks to support our design choices providing qualitative evidence on the expected performance of each module comprising the relevant architecture. In [117], the authors developed a distributed computing infrastructure using smartphones. More specifically, they profile the charging behaviours of real phone owners to show the viability of their approach. Furthermore, they present a simple task migration model to resume interrupted task executions. They have also implemented and evaluated a prototype that employed an underlying novel scheduling algorithm to minimize the makespan of a set of tasks. A more diverse approach is presented in [118], where the testbed deployment is focused on smart buildings, a key building block for cities of the future. The presented system combines heterogeneous IoT devices such as a programmable experimentation substrate in a real life office environment while making feasible the experimentations with real end users. Authors present the architecture of the facility and underline the considerations that motivated its design. Using several recent experimental use cases they demonstrate the usefulness of such experimental facilities for user-centric IoT research.

Early after the first smartphones were introduced, research teams started investigating the combined usage of their embedded sensory capabilities. In [119] authors recognize the opportunity of fusing information from populations of privately-held sensors as well as the corresponding limitations due to privacy issues. In this context they describe the principles of community based sensing and they propose corresponding methods that take into consideration the uncertain availability of the sensors, the sensitive context of sensor information and sensor owners' preferences about privacy and resource usage. Authors present efficient and well-characterized approximations of optimal sensing policies in the context of a road traffic monitoring application. In more recent works, the authors in [101] use the notion of Participatory Sensing (PS). They consider the problem of efficient data acquisition methods for multiple PS applications while taking into consideration issues such as resource constraints, user privacy, data reliability and uncontrolled mobility. They evaluate heuristic algorithms that seek to maximize the total *social welfare*, via simulations that are based on mobility datasets consisted of both real-life and artificial data traces. Finally, in [102] the authors propose a utility-driven smartphone middleware for executing community-driven sensing tasks. The proposed middleware framework considers preferences of the user and resources available on the phone to tune the sensing strategy thus enabling the execution of tasks in an opportunistic and passive manner.

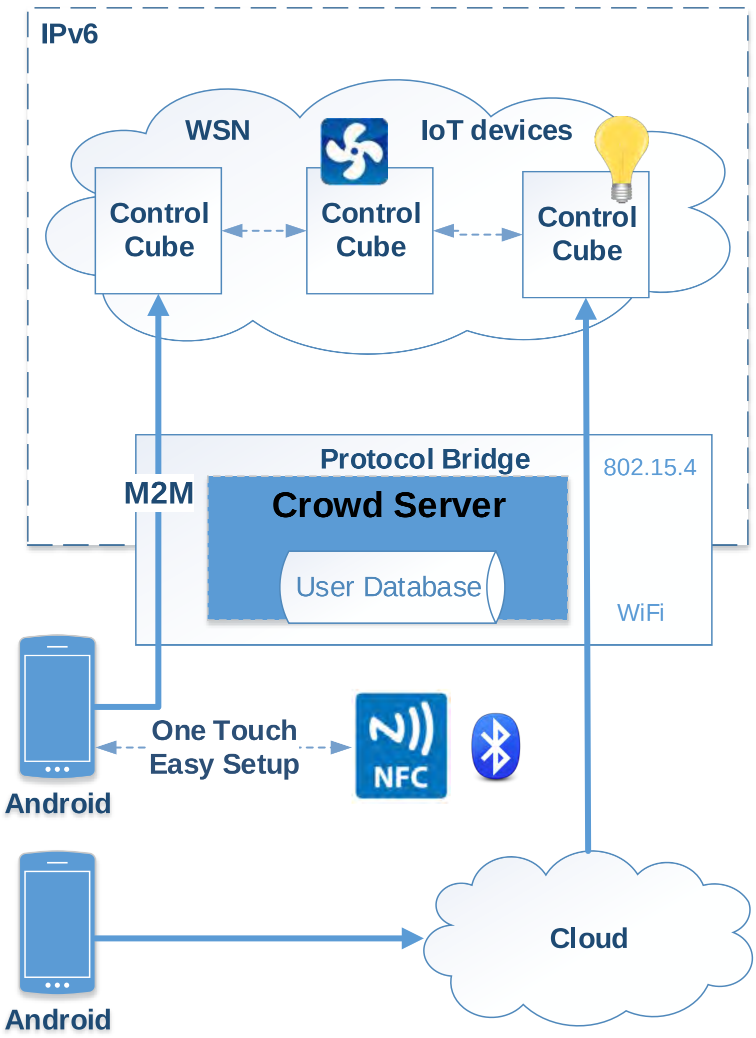


Figure 7.1: High-level architecture

7.3 Testbed Architecture

Figure 7.1 presents an overview of the IoT testbed architecture with Mobile Crowdsensing Support. The architecture consists of Control Cubes for converting electrical devices into IoT smart objects, a networking device operating as a network protocol bridge, Android enabled smartphones and NFC tags. The testbed also runs auxiliary services such as an indoor localization service and a Crowd Server. Below we discuss in detail the components of the architecture.

a) Control Cube: The Control Cube ([120], [121]), is a device that enables every-day, conventional appliances and automations to join the IoT vision. By combining Future Internet Technologies (like IPv6, CoAP and the IPSO Application Framework) and off-the-shelf electrical and electronic components into an open and modular architecture, Control Cube is a low cost, easily deployable, plug-n-play solution that extends the IoT paradigm. Each Control Cube is able to provide meta-data including information on the type of the device, its state and the supported operations. Furthermore, the embedded sensors of the Control Cube are used to monitor ambient environmental conditions (i.e. temperature, relative air humidity and luminance levels). The testbed we deployed and used in this work, consists of four Control Cubes that control: a) four *indoor light units* each one controlled independently b) two *electric curtains* each one controlled independently c) one *air-conditioning unit* with support for temperature and fan control d) one *ventilation unit* with support for fan direction and speed control. The supported devices and sensors of the testbed and their representation are shown in Table 7.1.

b) M2M communication: The testbed combines a diverse set of communication interfaces in order to support different classes of devices. The Control Cubes form an M2M, ad-hoc network, running the IEEE802.15.4 at the physical and MAC layers, the IPv6 protocol over 6LoWPAN and CoAP. On the other hand, Android devices carried by the users utilize the IEEE802.11 at the physical and MAC layers, the IPv4 and CoAP (Californium library, [122]). In order to enable the devices for direct communications with each other without the need for intermediate webservices, we developed a networking device that acts as a protocol bridge. This device is built around a Raspberry Pi micro-computer equipped with a USB wireless card and a TelosB sensor mote. Its role in the testbed is to set-up both a wireless sensor/actuator network and a local Wi-Fi while providing connectivity with the Internet. Consequently, by relaying traffic between the two radio interfaces and performing IPv4-to-IPv6 translation, the protocol bridge enables the ad-hoc communication among the smartphones and the Control Cubes.

Table 7.1: Smart automation and sensing devices and their URI representation.

Device type	States	Control Cube resource
4-bits 2 curtains	left up / `01XX` left down / `10XX` left stop / `00XX` right up / `XX01` right down / `XX10` right stop / `XX00` both up / `0101` both down / `1010` both stop / `0000`	`gpio/dout/0`
1-bit light	on / `1` off / `0`	`bio2/dout/x` where `x` is `0,1,2,3`
4-bits ventilation	off / `0000` blinds open / `0010` airflow out / `0011` airflow in / `1010`	`gpio/dout/0`
Air-conditioning unit	on/off / `0001` temperature up / `0010` temperature down / `0100`	`gpio/pulse/0`
Ambient sensors	sensor value	`sh, st, sv`

c) Indoor localization service: The testbed facility also provides a service for indoor localization for Android smartphone users. The service is based on four Bluetooth beacons [123], deployed at the corners of the deployment space, that act as anchor points. This way, the space is virtually tessellated into tiles [124]. Each smartphone is able to estimate its distance from each beacon via the Android Beacon Library [125] at a refresh rate of 1Hz. Then, it is able to triangulate its position inside the space and identify which tile it occupies.

d) Crowd server: This component is the core of the Mobile Crowdsensing System of the testbed as it implements the Participatory Sensing functionalities. By utilizing the `Socket.IO` websockets [126] the Crowd server maintains a connection with the smartphones that are present in the testbed in order a) to be aware of their distribution via the indoor localization service b) to interact with the smartphones and their users in order for them to declare their preferences on desired luminance and to offer them incentives which they can either accept or reject and c) to collect ambient luminance sensor readings from the smartphones of the users that have accepted the incentive they were offered. Based on these readings, the server constructs detailed luminance maps and combines them with the user preferences in order to adjust accordingly the light units. The main functions of the Crowd server are described below.

`Join.` The Crowd server listens for ”join” messages from the smartphones that are willing to participate. The join message contains the location of the device and the lighting preference of the user.

`Send incentives.` The server calculates the incentives depending on the policy that is defined, according to the devices that have already joined. Then, the server sends the calculated incentives to the corresponding devices.

`Accept.` The server listens for ”accept” messages from the devices that have accepted the offered incentive. The users can accept the offer during a specific time window.

`Decline.` The server listens for ”decline” messages from the devices that have declined the offered incentive. In the cases dome users will not respond to the offer within the available time window they are considered to have declined it.

`Start.` The server sends a ”start” message to the devices that have accepted the incentive offer in order to start sending their sensor values.

`Revoke.` The server sends a ”revoke” message to the devices that have declined or not responded to the offer. Those devices are now waiting for the next round.

`SensorValues.` The server listens for ”sensorValues” messages. Those messages contain the light level that each device measures. The server calculates the average light for each tile and actuates based on the average preference of the users in this tile.

`Stop.` The server sends a “stop” message to the devices that were participating in this round in order for them to stop sending their sensory data. All the devices are now waiting for the next round.

e) Android application: The Android application allows the to control every-day electrical and electronic devices through a friendly user interface. A user can control devices across different facilities by simply connecting to the corresponding black-box. Moreover, the application can be used to retrieve internal (light) or external (temperature, humidity, weather condition) sensor values. Another feature is the ability to communicate with the crowd server using a Socket.IO client [127]. The Android application provides a service that is responsible for listening and responding to messages from the server. At the beginning of every round the service sends the lighting preference of the user and the position of the smartphone inside the IoT testbed. Also, the service receives incentive offers from the server and notifies the user to accept or decline. In case the user accepts, the service begins to send the values from the light sensor to the server.

The testbed also provides an easy and transparent way to the user in order to allow quick set up in the smartphone and start interacting with the testbed. The user simply needs to read an NFC tag or scan a QR code in order to install the application. Then, the user will be able to declare her preferences on ambient conditions, receive and reply to the incentive offers and provide information regarding her location as well as sensory data from her smartphone's embedded light sensor. In the cases where no user is present in the premises of the testbed or no user is connected to it through the application, the ambient conditions of the area are set at a default level defined by the testbed itself based on the history of usage. Furthermore, the architecture of the testbed and its design makes it easily expandable both in terms of network size and in the diversity of measured parameters. In a different scenario the same facility with only minor adjustments, could be used for example for a more enhanced acoustic experience in the event of a concert where the microphones of the smartphones of the crowd could be used to adjust the volume levels of the speakers in the hall.

Table 7.2: Notation used.

S	The planar area of interest
$\|S\|$	Total number of tiles that S is virtually tessellated into
S_i	A tile inside S
$\|\sigma\|$	Total number of non-empty tiles in S
A	Set of agents present inside S
$\|A\|$	Total number of agents in S
A_j	A single agent in S; $j \in \{1, 2, .., \|A\|\}$
A_{S_i}	The set of agents in tile S_i
S_{A_j}	The tile that agent A_j occupies
$\|A_{S_i}\|$	Total number of agents in tile S_i
ΔS_{A_j}	The distance covered by agent A_j (measured in tile-units) between two rounds
q_j	Sensing accuracy indicator of A_j; $q_j \sim \mathcal{U}(0.7, 1)$
r_j	Variable capturing the willingness of agent A_j to contribute to the system; $r_j \in \{0.6, 0.7, 0.8, 0.9\}$
lux_{A_j}	Preferred ambient luminance of agent A_j (measured in lux)
$fame_j$	Reputation indicator for A_j maintained by the system
γ	Adaptation constant of the $fame_j$ indicator
B	Total available budget during one round
I_j	Incentive offered to agent A_j
I_c	Currently used incentive strategy
a_{I_c}	Acceptance ratio of the currently used incentive strategy
δ	Probability adaptation constant used in the mixed incentive strategy

7.4 Mobile Crowdsensing

The aforementioned architecture enables the embedded sensory infrastructure of the facility to be opportunistically augmented by integrating any available smart devices located in its area of operation. Since such devices are carried by people, the system initially incentivises their owners to provide access to their embedded sensors, as well as to provide feed-back to the system. This way the facility raises its awareness on the actual conditions in the building, as well as on the comfort levels the end-users are experiencing.

7.4.1 A crowd-enabled scenario for efficient indoor lighting

In order to demonstrate the capabilities offered by the described architecture, we developed a smart luminance scenario that incorporates Participatory Sensing mechanisms. In this scenario the system tries to optimize the operation of indoor light units in terms of energy efficiency and user satisfiability via Participatory Sensing practices.

For this scenario, consider a planar area of interest S that abstracts a smart room. S is virtually tessellated into sub-regions or tiles each denoted by $S_i, i \in (1,2,..|S|)$. In general we assume that each tile is illuminated by one light unit which may have a binary on/off state or a dimming function. Inside the area of interest S, there is a set of mobile agents A abstracting people carrying smart devices (smartphones, smart-watches, etc). Each agent is denoted by $A_j, j \in (1,2,...|A|)$. Due to the indoor localization capabilities of the testbed, at each given time the tile in which each agent is present is known to the system. Based on how often and for how long each agent is present in the testbed area, we categorize her either in the set of *regular agents* that have a long and concise record of presence or in the set of *visiting agents* that their presence tends to be more ephemeral. Furthermore, each agent demonstrates a level of trustworthiness towards the system in terms of actually fulfilling her commitment to provide access to their smartphone and propagate meaningful data when agreeing to do so in return for an incentive. The system maintains for each agent A_j a corresponding indicator $fame_j$ and initially each agent is equally trusted by the system. Then, depending on whether each agent fulfills her commitment to provide access to her smartphone or not, the system adjusts this indicator. In particular:

$$fame_j^{t+1} = \begin{cases} fame_j^t & \text{, if the agent does not participate} \\ fame_j^t + \gamma & \text{, if the agent participates and fulfills her commitment} \\ fame_j^t - \gamma & \text{, if the agent participates and does not fulfill her commitment} \end{cases} \tag{7.1}$$

where $fame_j^{t+1}$ and $fame_j^t$ denote the value of the indicator for two consecutive rounds (see next paragraph) and γ denotes the adaptation constant. Finally, we assume that the smartphone device of each agent is characterized by an accuracy factor q_j, capturing the quality of sensed data.

The system discretises time in rounds. At the beginning of each round each agent declares to the system her preferred value of ambient luminance denoted by lux_{A_j}. Then, the system computes the average desired luminance at each tile based on the individual preferences of the agents that are present on this tile during this round. Based on the average desired luminance and the ambient light values collected from the smartphones, the system tries to adjust the ambient light conditions to the preferences of the agents by turning the corresponding light units on or off. In order to incentivise the end-users, the scenario follows a gamification approach by using virtual coins. During each round the system has a budget B of virtual coins to distribute as an incentive to the agents; we denote by I_j the incentive offered to A_j on a particular round.

Each agent evaluates the offer I_j she is offered and decides whether she will contribute to the system via a boolean *join function*

$$P_j = r_j \frac{I_j}{B} \tag{7.2}$$

where r_j is a constant capturing the willingness of agent A_j, I_j the incentive offered and B the total available budget. The values of r_j correspond to different levels of agent willingness spanning from *"totally unwilling"* to *"always participating"* agents.

7.4.2 Incentive policies

7.4.2.1 The Flat Incentive

This is a naive strategy used as a baseline in the evaluation of the other strategies in which the system equally distributes the available budget over the set of agents. In particular each agent A_j, currently located in tile S_i is offered:

$$I_j = \frac{B}{|A|} \tag{7.3}$$

7.4.2.2 Presence/Location-aware Incentive

As the system is constantly aware of the location of each agent inside the room, in this strategy, the system equally distributes the budget first over all non-empty tiles and then over all agents of each tile. In particular each agent A_j is offered:

$$I_j = \frac{B}{|\sigma||A_{S_i}|} \tag{7.4}$$

where $|\sigma|$ denotes the number of non-empty tiles and $|A_{S_i}|$ denotes the number of agents located in tile S_i.

A variation of this strategy also takes into account the accuracy q_j of each agent:

$$I_j = \frac{B}{|\sigma||A_{S_i}|} \frac{q_j}{\sum q_j} \tag{7.5}$$

7.4.2.3 Behavioural-aware Incentive

Following this strategy the system maintains an indicator $fame_j$ for each agent based on which her commitment and trustworthiness is rewarded; e.g. how many times has the agent contributed in the past and whether the agent has fulfilled her commitment.

In particular each agent A_j is offered:

$$I_j = B\frac{fame_j}{\sum_i fame_i} \tag{7.6}$$

where

$$fame_j = \sum_{history} \frac{\Delta t}{\Delta T}$$

where $history$ denotes the number of past participations of A_j, Δt denotes the number of epochs the agent actually contributed and ΔT denotes the number of epochs the agent had committed she would contribute. If $\Delta T = 0$ then $fame_j = 0$.

7.4.2.4 Mobility-aware Incentive

Following this strategy the system favours the agents that frequently move inside the room as they are able to provide data corresponding to different subregions. Here each agent A_j is offered:

$$I_j = B\frac{\Delta S_{A_j}}{\sum_i \Delta S_{A_i}} \tag{7.7}$$

where ΔS_{A_j} denotes the distance covered by agent A_j (measured in tile-units) since last round.

7.4.2.5 Mixed Incentive

As the composition of the crowd may change in time in terms of size, distribution in space, willingness to participate, sensor accuracy or mobility the system may need to adapt its incentive strategy. The mixed incentive strategy constitutes a probabilistic combination of the aforementioned "pure" strategies that enables the system to implicitly capture such changes in the crowd. Initially, the system chooses uniformly at random which strategy to follow. If the chosen strategy has been positively accepted by the crowd then the corresponding probability is reinforced over the rest of the strategies and vice versa. This scheme enables the system to dynamically adapt its behavior and eventually converge to an equilibrium among the “pure" strategies that achieves the highest acceptance ratio by the crowd. To summarize, the mixed strategy follows the following procedure:

a) For the first round choose u.a.r. among the ”pure” incentive strategies.

b) For the next round, adjust the corresponding probability of the chosen strategy I_c based on its acceptance ratio a_{I_c} as follows:

$$Pr\{I_c\}^{t+1} = \begin{cases} Pr\{I_c\}^t + \delta & \text{, if } a_{I_c} > 60\% \\ Pr\{I_c\}^t & \text{, if } 40\% < a_{I_c} < 60\% \\ Pr\{I_c\}^t - \delta & \text{, if } a_{I_c} < 40\% \end{cases} \tag{7.8}$$

c) Accordingly, for the next round, adjust the corresponding probabilities of the rest of the strategies I_r

$$Pr\{I_r\}^{t+1} = \begin{cases} Pr\{I_r\}^t - \frac{\delta}{3} & \text{, if } a_{I_c} > 60\% \\ Pr\{I_r\}^t & \text{, if } 40\% < a_{I_c} < 60\% \\ Pr\{I_r\}^t + \frac{\delta}{3} & \text{, if } a_{I_c} < 40\% \end{cases} \tag{7.9}$$

d) Return to step (a) but use the newly adjusted probability distribution.

The reason for choosing the $a_{I_c} > 60\%$ is because in this scenario we wanted the testbed to be "smooth" while transitioning from one incentive to the other. Lower values of a_{I_c}, will result to more even distributions over the "pure" incentives.

7.5 Experimental Evaluation of the Incentive Policies

In section 7.4 we described a personalized energy-efficient use-case scenario for indoor lighting that seeks to optimize the balance between energy consumption and end-user satisfiability. The system tries to do so by offering incentives to the end-users who in exchange they provide personal preferences and ambient luminance data from their smartphones. In this section we describe the experimental evaluation of the incentive policies and the gains on the energy consumption by initially monitoring the conventional use of the testbed facility and then by engaging its smart automations and Mobile Crowdsensing capabilities.

Based on the real-life findings, we investigate the impact of such a smart-system in big buildings via thorough simulations by using real-life datasets on ambient luminance inside big buildings and mobility models that accurately capture human mobility inside buildings.

7.5.1 Evaluation Metrics

For the performance evaluation of the various incentive policies and the efficiency of the overall system, we utilize several performance metrics that capture different aspects of the IoT and MCS components of the testbed facility.

Social Welfare: This metric evaluates the satisfiability and comfort that the end-users (agents) are experiencing while using the smart room. In particular, social welfare measures the average difference of luminance over all agents inside the smart room measured from the preferences of each agent and the final luminosity achieved by the system. For each round, the system computes the following quantity:

$$SW = \frac{\sum_A |lux_{A_j} - lux_{S_{A_j}}|}{|A|} \tag{7.10}$$

where lux_{A_j} denotes the preferred luminance by each agent A_j and $lux_{S_{A_j}}$ denotes the achieved by the system luminance at the tile that agent A_j occupies during this round.

Energy consumption: For each incentive policy we measure the energy consumption of the smart room coming from the indoor light units. This metric is used in order to evaluate the energy efficiency versus the user comfort trade-off for each policy.

Budget spent: For each incentive policy we measure how much of the available budget B the system has actually given to the agents. The various policies differ on how they incentivize the agents in terms of budget generosity as well as in terms of focusing on different aspects and using the available to the system information in different ways. For instance, the location-aware incentive focuses on the distribution of the agents inside the smart room while the mobility-aware incentive focuses on the changes of this distribution.

Acceptance ratio: For each incentive policy we measure how many agents have actually accepted the incentive offered. This metric captures the appeal of each incentive policy to qualitatively different sets of agents; different in terms of agent mobility, sensor accuracy, etc.

Area coverage: For each incentive policy we measure the number of different tiles that the system managed to collect smartphone sensor data from. For this metric, the mobility-aware incentive is expected to outperform all other policies.

Data quality: Each agent is equipped with a smartphone of different quality in terms of sensory capabilities (e.g. the sensitivity and the measurement span of different light sensors may vary significantly). Correspondingly, the data collected by the system can also vary in terms of quality and accuracy and the quality of the estimations made by the system as well. This metric captures these aspects and therefore the variation of the presence/location-aware incentive that takes into account the accuracy of each agent is expected to outperform the other policies.

7.5.2 Experimental Study

We deployed the testbed facility in an office room at the University of Patras premises. The room was virtually partitioned in 4 tiles, each one mapped to an on/off light unit. The Android application was used by 17 users (students, researchers and employees, all of them agnostic about the system). Each user, after accepting to join the experiment, was prompted periodically (each round lasted for 30 minutes) to provide light readings of his current location in exchange for some budget defined by the corresponding incentive policy. Note that the sensor readings were being sent during the entire 30 minute interval and the user's smartphone consumed a percentage of its battery. If a user accepted an offer and for some reason did not succeed in providing useful data (e.g. the user kept her phone in her pocket and therefore no true ambient luminance measurements were collected), then the corresponding budget was not allocated. Apart from using the Android application for the lights actuation, users followed their daily office routine.

The total acceptance ratio over all agents for the entire experiment is shown in Figure 7.2. The total energy consumption for each incentive policy is shown in Figure 7.3. Figure 7.4 depicts the overall coverage for the 4 office tiles, i.e. how many tiles were covered[1] throughout the rounds of the experiment. In Figure 7.5 we see the evolution

[1]Tile coverage refers to the spatio-temporal availability to collect sensory data via the users' smartphones.

Figure 7.2: Acceptance ratio.

Figure 7.3: Energy consumption.

of the budget expenditure during the experiment. In Figure 7.6 we see the social welfare of the crowd for every incentive policy.

Finally, Figure 7.7 is a depiction of the luminance over time for selected users, when using the testbed facility. It portrays the luminance preference set by two users and luminance achieved by the testbed.

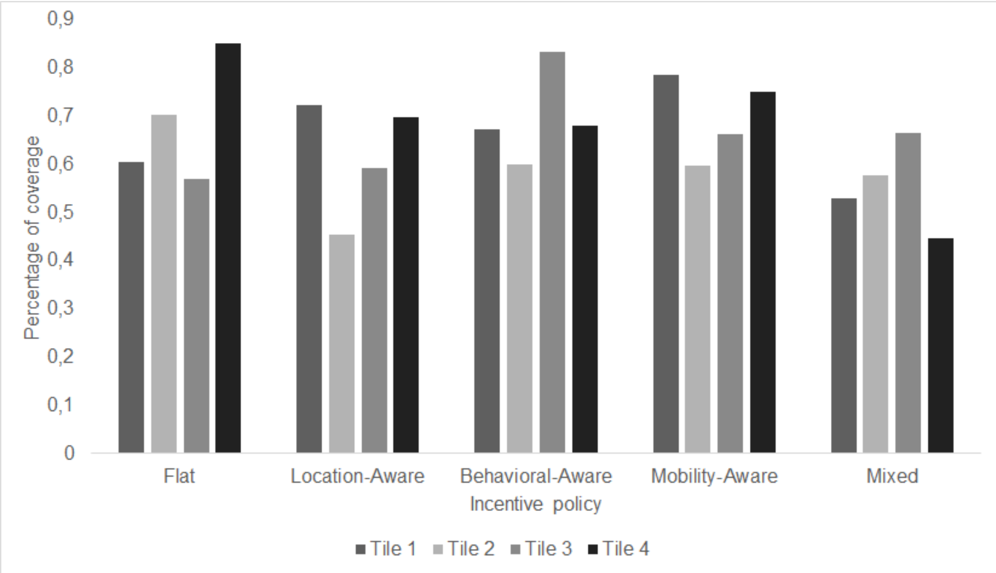


Figure 7.4: Overall area coverage.

We observe that the acceptance ratio and the overall energy consumption follow a similar pattern (Figures 7.2, 7.3). This is natural, since the more users that accept a budget offer, the more lights that are used for continuous time intervals. Regarding tile coverage (Figure 7.4), low values of coverage indicate that either the specific tile was not occupied by the users, or that users in it were not accepting the budget offer. When applying the mobility policy, the users were more confident in covering the whole office area, since the reward was higher. Consequently, the mobility aware policy keeps good coverage levels in all tiles.

We observe that all incentive policies lead to an increasing budget expenditure (Figure 7.5). The mobility and the mixed incentive policies achieve higher budget savings, in contrast to the location aware incentive policy, which spends more of the available budget. In spite of the similarity of the two latter in the budget consumption rate, a closer examination of Figures 7.2, 7.3 leads us to the conclusion that both mixed and location aware policies achieve similar acceptance ratios, but different overall energy consumption during the experiment. This fact makes clear that the location aware incentive policy exploits more efficiently the given budget during the experiment. It also achieves high area coverage, as shown in Figure 7.4.

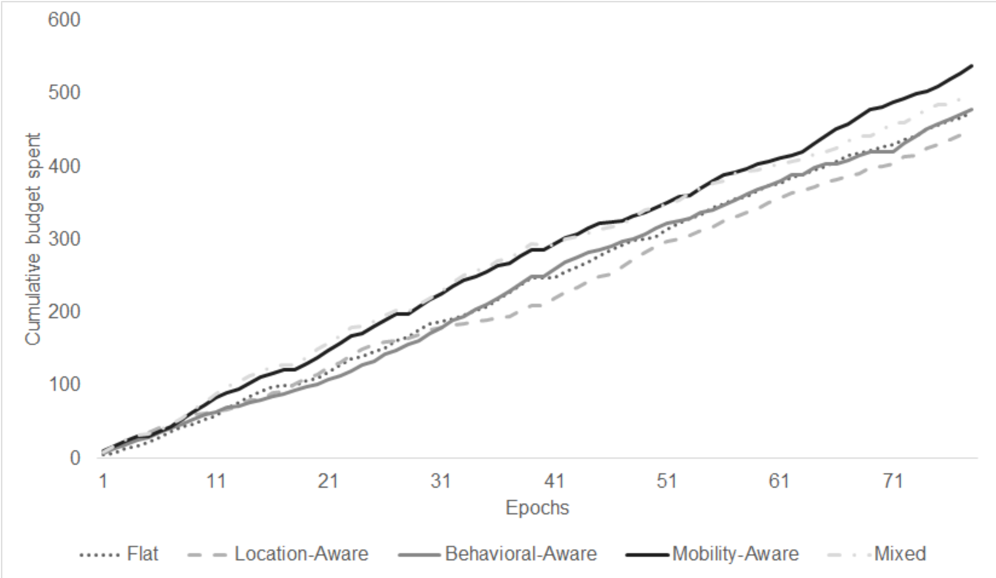


Figure 7.5: Budget spent over time.

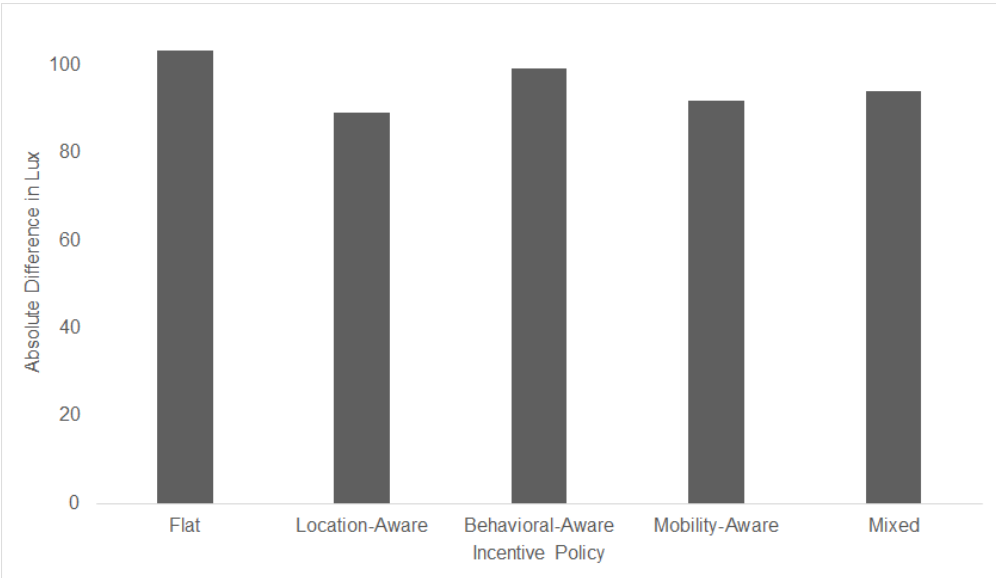


Figure 7.6: Social welfare.

By comparing the impact of the various incentive policies, we conclude that the flat, mixed and location aware incentives, although spending lower budget than the mobility incentive, they result to an uneven coverage of the interest area in terms of measurements. For this reason, they also provide lower energy consumption, since at a given time only a portion of the office lights are on. The behavioural aware incentive

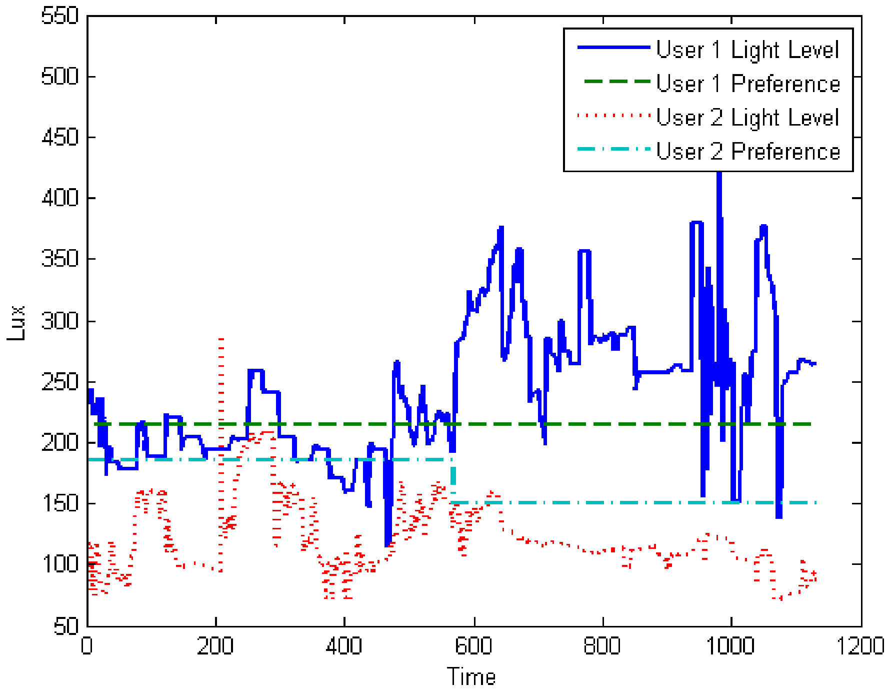


Figure 7.7: Luminance preference/achieved over time.

policy has been proven highly adequate. It consumes relatively lower budget amounts compared to other policies and maintains fair coverage levels in all tiles (Figure 7.4) and high social welfare (Figure 7.6). This is a result of its adaptive nature which is based on the budget distribution according to the crowd's location.

For the sake of comparison between users, we selected two indicative users from the crowd and monitored their comfort levels throughout a working day (flat incentive is used). They were both mainly stationary and the first user was positioned near an office window (i.e. a more luminous point), whereas the second user near a darker corner of the office. Figure 7.7 portrays the indicative light preference set by the users and the achieved luminosity levels. Note that the second user changed his preference at some point. It is easy to see that external lighting is a crucial factor, since in the first case the lighting levels are relatively higher than the user preference, while in the second case they are lower.

Table 7.3: Simulation Parameters

Area $\|S\|$	64 Tiles
Total agents $\|A\|$	20 Agents
Agents absent	$\in$ [0 10]% of Total Agents
Number of epochs	500
Number of experiment iterations	500
Budget B	10^6 Units
Personal preference on lux_{A_j}	$lux_{A_j} \in$ [120 350] lux
Sensor's accuracy q_j	$q_j \sim \mathcal{U}(0, 100)$
Agent willingness r_j	$r_j \in \{0.6, 0.7, 0.8, 0.9\}$
Agent mobility parameter	$\in [0, 0.15, 0.30, 0.45, 0.60]$
Initial $fame_j$	0.5
Adaptation parameter γ	0.1
Adaptation parameter δ	0.05

7.5.3 Simulations

a) Complementary to the real-life experimental study and based on corresponding findings and observations, we conduct simulations (using Matlab R2013b) in order to evaluate the performance of the various incentives for larger buildings and bigger populations of end-users. In particular, by using the smart room infrastructure, we first compile a dataset of ambient light conditions inside the smart room, when the room is empty and no actuation takes place. The dataset consists of light measurements corresponding to ten working-day cycles.

b) Furthermore, in order to abstract human mobility in our simulations we use the Random Waypoint Model, which we enhance to also include a probability for each agent to be absent from the smart room during each round as well as different levels of mobility. These levels of mobility actually correspond to mobility patterns of real users of the smart room, extracted from the experimental study. Table 7.3 summarizes the simulation set-up and the values of the simulation parameters fine-tuned under the light of the experimental study.

Figure 7.8 depicts the acceptance ratio achieved by each incentive policy over the size of the crowd. The mobility aware policy demonstrates the lower acceptance ratio due to the fact that it strongly favours agents characterized by high mobility levels.

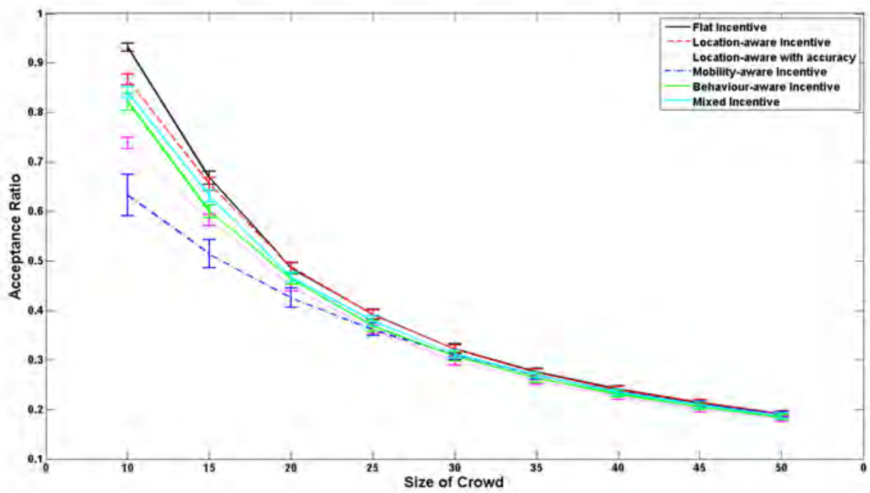


Figure 7.8: Acceptance ratio for various crowd sizes.

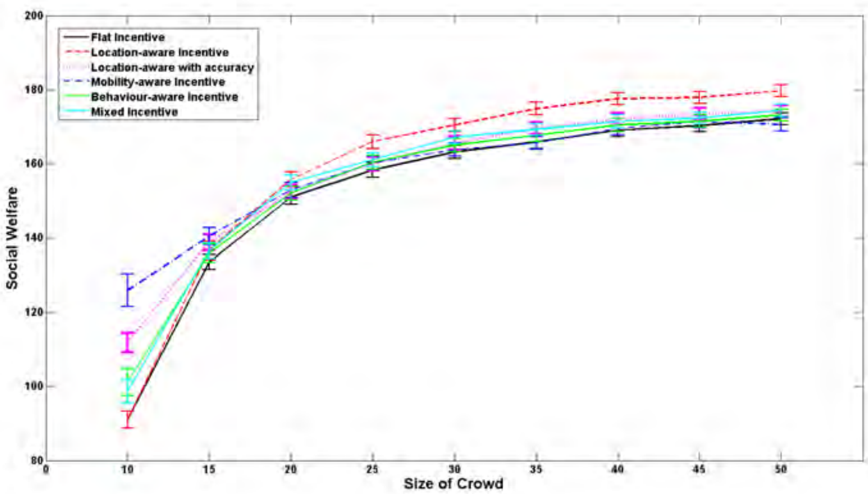


Figure 7.9: Social welfare for various crowd sizes.

Therefore, agents with lower mobility levels, although receiving an offer, the incentive being offered is smaller and thus the probability to eventually reject it is higher. On the other hand, the flat incentive consistently achieves better acceptance ratios due to the fact that it distributes the available budget evenly among the present agents. Two general remarks regarding the acceptance ratio as the size of the crowd increases are the following: a) all policies demonstrate decreasing acceptance ratios and b) they

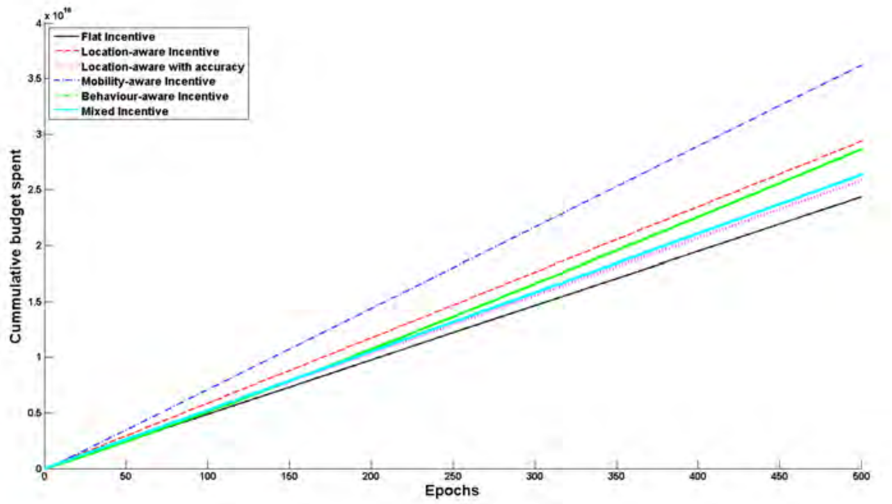


Figure 7.10: Budget spent over time.

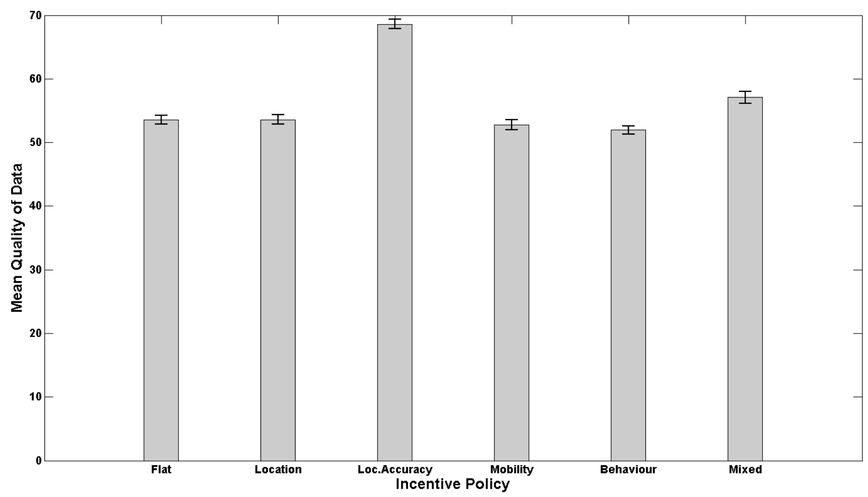


Figure 7.11: Quality of data collected.

all converge to the same ratio. The first remark is due to the fact that as the size of the crowd increases, the system tries to distribute the same amount of budget over more and more agents, thus providing lower incentives that yield lower probabilities to be accepted. The second remark indicates that as the area A is filling-up with people, the different incentive policies loose their sophistication - i.e. if a smart building is fully occupied, then (also intuitively) all light should be turned on. When the number

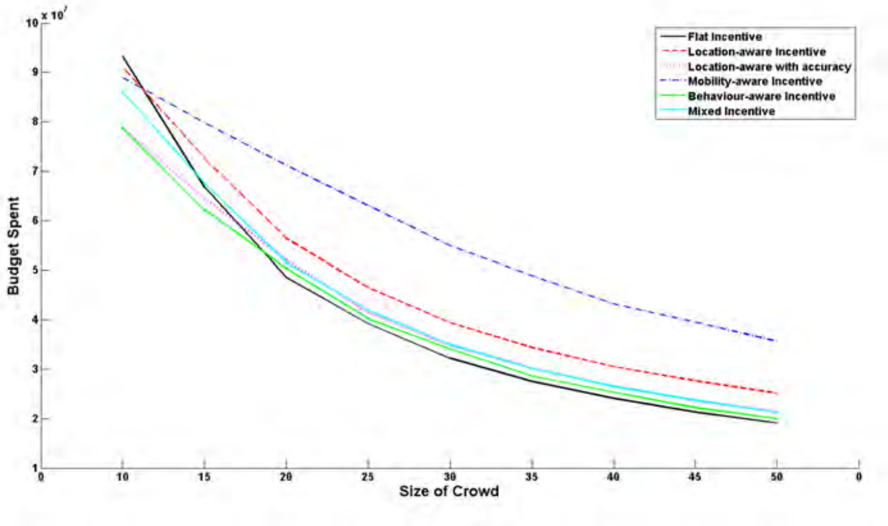


Figure 7.12: Budget spent for various crowd sizes.

of present agents in the area is small, then the system has the ability to successfully apply more sophisticated methods for energy saving. For the same reasons, the social welfare metric (Figure 7.9) demonstrates a similar behaviour as well. Note that social welfare captures the standard deviation of the achieved luminance by the system from the preferences of each user (i.e. the lower the better).

Figure 7.10 depicts the mean cumulative budget spent for each incentive policy. The mobility aware incentive demonstrates the highest budget expenditure due to the fact that during each epoch it focuses on a small subset of the users; those that have moved since the last epoch. These users receive high incentives and therefore the probability that they accept the offer is very high, thus yielding a high cumulative budget. For similar reasons, the location-aware with accuracy incentive also demonstrates a high budget expenditure as it focuses on agents equipped with high accuracy sensors.

Figure 7.11 depicts the mean quality of sensor readings achieved by each policy. Naturally, the location aware with accuracy policy demonstrates the best performance, while the rest of the policies have similar performance as they are sensor accuracy-agnostic. Finally, Figure 7.12 depicts the budget spent by each policy over the size of the crowd. The high acceptance ratios achieved by the mobility-aware incentive (due to the high incentives offered to few agents with high mobility levels) also yield high budget expenditure. As the size of the crowd increases and the corresponding incentives are getting lower, the total expenditure for all policies is also getting lower. However, due to the higher number of present agents, even low acceptance ratios lead to a sufficient number of agents that eventually concise to provide sensory data (intuitively the bigger the crowd, the higher the probability that some agents will concise, even when offered a low incentive.)

7.6 Conclusions

In this work we presented an IoT-enabled testbed for Smart Buildings following an architecture that enables and scalable integration of crowd-sourced resources. We demonstrated its agility via a use-case scenario in which the users first declare their preferences on the ambient luminance levels and then the system offers them incentives in exchange for access to the light sensors of their smartphones. Based on these readings the testbed constructs detailed luminance maps and is able to adjust the indoor lights to the user preferences. By using the testbed facility, we evaluated several incentive policies taking into account diverse aspects of the crowd such as the distribution of the users in the smart room, their mobility, the quality of information they provide and their behaviour in terms of actually providing input to the system. Based on these real life experiments, we extracted a dataset on indoor ambient luminance and user mobility patterns that we used in our simulations for larger buildings with bigger number of users. For future work, we plan to extend the services provided by the testbed to also include privacy mechanisms as well as to implement more complex use-case scenarios.

8 Synergistic User and Context Analytics in Mobile Crowdsensing

8.1 Introduction

New research fields on *(socio-)physical* or *personal analytics* have recently emerged and raised high attention, both from researchers [128–131] and practitioners (mostly startups). The goal is to derive semantically-rich insights about people (high-level activity, preferences, intentions) from low level measurements (location, type of activity etc), from their (online) social interactions, or more compellingly from a combination of these. The results of such analytics could be used to improve customer engagement for businesses, provide space and event planning that accounts for the self-organising phenomena in crowds, and create higher value location-based services for users.

We argue here that people's mobility and behavior are substantially influenced by their broader environment as well. Conditions such as weather, infrastructure state, air quality, radiation level etc. determine to a great extent the way a person moves and acts. For example: on a *rainy day*, someone may decide to take the bus to work, rather than cycle; or during pollen peak times, an allergic person may skip her regular jogging sessions. Moreover, depending on the application scenario, specialized information such as in retail, items currently on sale or number of shop assistants currently available, may also be very meaningful. For example, when analyzing shopper behavior, if a big sale is announced, someone may reschedule her regular shopping to attend the sale. The ever wider availability and usage of smart mobile devices, sensors, as well as their supporting infrastructures, means that such data could be available as more personal, user-centric type of information, for example via crowdsourcing or crowdsensing. In light of this, we argue here for a building with much more comprehensive user context. In this work we propose the concept of *synergistic user* ↔ *context analytics* [132], illustrated in Figure 8.1, as a way to promote the generalized form of an analytic initiative. Synergistic Analytics (SA) is a modular construction, consisting of the above-cited personal analytics core (based on smartphone and online media data), enriched with extra layers of additional information, such as environmental, infrastructure-related or specialized data (e.g. retail). It is a shift from individual analytic disciplines (e.g. prediction of next place or activity, of the next device interaction, mining crowdsensed context data towards a more holistic, yet still user-centric focused perspective. The results of Synergistic Analytics will be much more than the sum of its parts: instead of isolated predictions of limited scope, deeper, semantically richer inferences are possible.

While in some related research privacy is an afterthought, we strongly believe that privacy-protection must be developed alongside and in full synergy with other system's components. More specifically, by viewing the complete system as a graphical model, we can impose different privacy constraints on different parts of the graph. To illustrate our proposal of SA, we present here our ideas and ongoing work on a platform for providing privacy-preserving, location- and context-based services to users. Our platform aims to support a variety of applications, such as highly personalized navigation, user-optimized coupon dispensing, dissemination of localized and user-centric recommendations, as discussed in Section 8.3.

The scenarios for synergistic analytics underscore several scientific challenges to be addressed by relying on the following research pillars, see Figure 8.1: (i) location and activity prediction; (ii) context (environment, infrastructure etc.) awareness via crowdsensing analytics; (iii) social profile and behavioural analytics; and (iv) privacy-preservation methods for each of the above.

The first and third pillar correspond to the aforementioned personal analytics core, while the second pillar represents a first layer of information on the broader context. We present our ongoing work on three main aspects of the platform: a testbed with two components that we aim at integrating (a crowdsensing component with smartphones and an Internet of Things (IoT) component with sensors/actuators) in Section 8.4.1; a data model and storage solution, for efficiently representing and processing the highly heterogeneous information collected from the smartphones and from the sensors in Section 8.4.2; and a predictive analytics engine in Section 8.4.3.

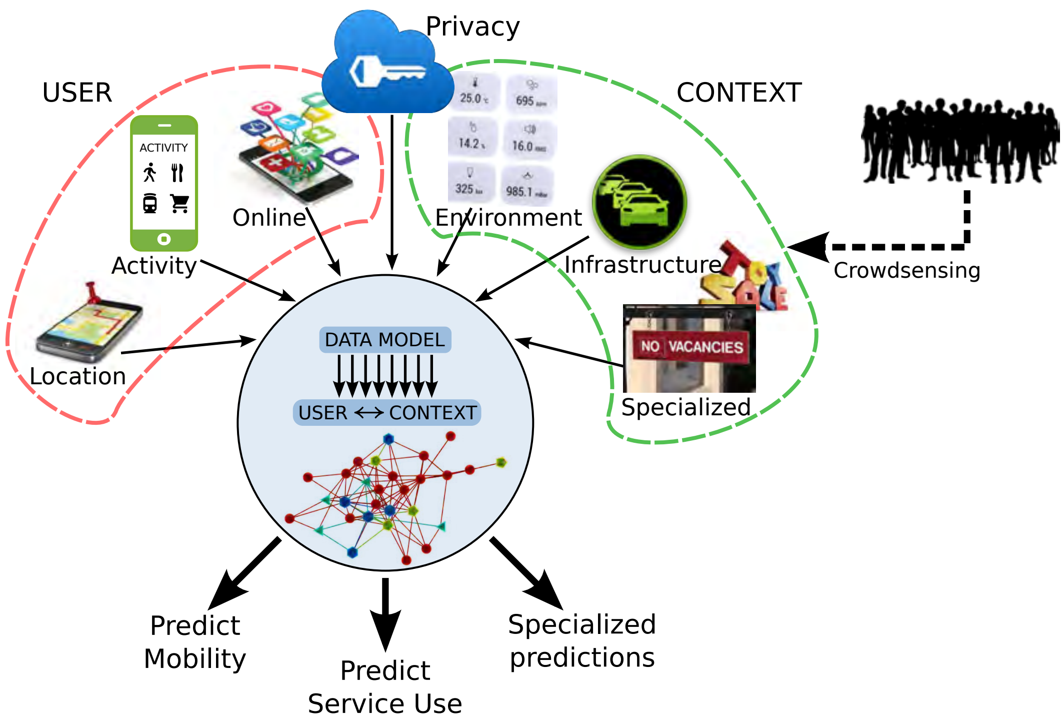


Figure 8.1: Synergistic User ↔ Context Analytics

8.2 Related Work

In this section, we summarize the recent efforts in the area of (socio-)physical analytics as well as research on individual components of physical analytics systems (e.g., crowdsensing, privacy etc.).

(Socio-)physical analytics. The authors in [130] present a system that can integrate mobile sensing data with data from online social networks, in order to provide insights into user mobility and their interactions (both online and physical). *SocialFusion* [128] project focuses on the immediate context of individuals, rather than on their interactions. In [131] a personal analytics engine generates high-level user states (e.g., emotions, preferences), which can be used to intervene in user actions. In [129] authors recognize the importance of a more comprehensive user context (including, weather, light or sound level, scenario-specific data etc.). The paper mainly offers a nice collection of highly specialized use cases, along with preliminary ideas on how to technically realize each of them separately. In contrast, we will describe a more unified and complete system.

Mobile crowdsensing. A user's context consists of many variables: immediate (e.g., location), personal (e.g., activity, heart rate) and of a broader nature (e.g., weather, pollution). Traditionally, these variables are measured via standalone specialized sensors. Through *mobile crowdsensing (MCS)* [133], smart mobile devices can be used to infer or measure the above variables in a broader range and usually also more accurate as well. This is achieved via the devices' sensing capabilities. While this solves the sensing problem, it creates new challenges: resource limitations (energy, bandwidth, computation), privacy and security issues, and the lack of a unifying architecture. The latter is important not only for making the best use of sensor data across applications and devices, but also for guaranteeing privacy and security. A common framework will allow seamless integration of both sensory and security information. We already defined the fundamental components of a mobile crowdsensing architecture and their interactions [113], along with incentives mechanisms for engaging the *crowd*. In [133] an overview is provided of the current state of applications that are based on MCS systems. The main challenges recognized refer to resource limitations, such as available energy, bandwidth and computational power, privacy issues that may arise due to correlation of sensor data with individuals and the lack of a unifying architecture that would optimize the cross-application usage of sensors on a particular device or even on a set of correlated devices (e.g. if they are located in the same geographical area). In [134] authors identify the fundamental components of a Mobile Crowdsensing System - the Crowd, the Server and the Task - and the function set that governs their interactions is defined. Several qualitatively different types of Tasks are identified along with corresponding Incentive Policies the Server may follow in order to engage the Crowd. In [119] authors recognize the opportunity of fusing information from populations of privately-held sensors as well as the corresponding limitations due to privacy issues. In this context they describe the principles of community based sensing and they propose corresponding methods that take into consideration several aspects related to the nature of MCS. One fundamental question is if individuals can make decisions that somehow create the "wisdom of the crowd". This is possible in the setting proposed by [135], where agents wish to maximise their individual payoffs, and a central planner organises them so as to maximum the social welfare, i.e. the average payoff obtained by each agent. Our proposed synergistic analytics platform will tackle the additionally raised issues by integrating and jointly analyzing data from different MCS sensors to extract comprehensive patterns and predictions about user behavior and/or their context.

Privacy and security. Mobile crowdsensing (including location and activity sensing) raises many privacy and security concerns. The *crowd* provides sensed data to a *server*, which may or may not be trusted. If the server is not trusted, computation must be performed on encrypted data, which can be achieved via homomorphic encryption [136] or through secure multi-party computation [137]. Even if the server is trusted, private information may still leak, e.g., when a third party constructs clever queries that, if answered truthfully, will cause the server to divulge private information. A characterisation of resistance to this is given by the concept of differential privacy [138]. These issues have not yet been addressed in the context of mobile crowdsensing, and it is our goal to design efficient algorithms, fitted for these cases. In [139], privacy in social networks is analysed where they observed that simply leaving blank what each user think is private is not enough to guarantee privacy. They proposed a utility-oriented random method to break the label-neighbourhood association in a social network graph. For each conservative users (users who do not want to keep private one attribute) they modify her neighbourhood by randomly changing a number of edges connecting this user to other users having same label. Their work is different than the differential privacy setting. Indeed, instead of making a query private given the data, they made the data publication itself private. Our platform integrates privacy and security seamlessly, by embedding their guarantees within the graph that describes the relations between measured and inferred variables. For privacy, a simple solution is to utilise Bayesian posterior sampling for message passing [140], which allows us to trade off communication costs with privacy and accuracy.

8.3 Synergistic Analytics Use Cases

8.3.1 Highly Personalized Navigation

Current navigation applications are typically limited to a few transportation modes and miss complex context and user related data. Exploiting data on user preferences, transportation modes, and the environment, allows a more effective user-oriented navigation and recommendation system. The information may include real-time traffic data, public transportation, rental vehicles, air quality, weather conditions, safety ratings and user habits. The system suggests places to visit, transportation modes, as well as important traffic and environmental data to city officials. Users benefit by improved social interactions, handling mobility more sustainably and efficiently. Security and privacy issues may arise, such as untruthful users and non-trusted local infrastructure.

8.3.2 User-Optimized Coupon Dispensing

An empirical study in [141] found that *proximity* drives coupon redemption. It considered the behavior of people while moving into the proximity of *Subway* restaurants: the authors showed that the distance to a restaurant is inversely proportional to the amount of monetary incentive needed to prompt people to redeem the restaurant coupons. However, the physical distance to a shop is not the only driving factor for an optimized coupon distribution. In fact, a better insight into potential customers' profile would allow a more effective dispensing. Along with proximity, other user-related information may be important driving factors, for example: *personal preferences* (i.e., a user who likes Italian food is most likely to visit nearby Italian restaurants) and *social network* (i.e., a user tends to go where their friends have already been). Consequently, a coupon distribution service could optimize the process of customer selection and coupon distribution, by exploiting our synergistic platform, for retrieving location- and context-related user information.

8.3.3 Recommendation systems

Synergistic analytics could be exploited to make recommendations to users, according to their location and social profile similarity. For example, in a crowded touristic city, the dissemination of localized recommendations (i.e., interesting events and places in the city) among users would be more effective than static provider-based data distribution, in terms of both resource usage (downlink) and time for the recommendations to reach the target users [142]. Such an environment is usually populated by people with various social profiles and interests. The availability of rich information about users may improve the dissemination of localized recommendations by identifying the people and/or communities with similar profiles and interests.

8.4 Synergistic Analytics: Early Experiences

We present our efforts on three main aspects of the proposed privacy-preserving location- and context-based platform: a testbed with two components that we aim at integrating; a data model and storage solution, for efficiently representing and processing the highly heterogeneous information collected from the smartphones and from the sensors; and a predictive analytics engine.

8.4.1 Data Collection

For our generic platform for location- and context-based services, we need access to real(istic) data and to be able to easily develop, deploy and debug software on real(istic) end devices. We are building VIVO, a novel human- and sensor-based testbed with volunteers.

8.4.1.1 The VIVO volunteer testbed

The VIVO testbed is based on the concept of *enrolled crowdsourcing*, which allows the deployment of several experiments, as opposed to the traditional usage of crowdsourcing for a single experiment. VIVO provides a secure and privacy-respecting platform for *testbed users* to collect social, physical and environmental information. The information can be accessed remotely, as in traditional testbeds. However, VIVO differs from traditional testbeds in that it allows testing algorithms and solutions by scheduling and running them *in real time* on real mobile phones of people participating in the testbed (also called *volunteers*, not to be confused with *users*). Further, the VIVO also provides an emulation environment for *users* to run and test experiments on already existing data, stored in the VIVO database. Unlike LiveLab [143] and SmartLab [144] (where a single specific and static application is installed on each smartphone to constantly save the data collected from the sensors), VIVO aims to offer more flexibility. More precisely, VIVO *testbed users* can dynamically deploy their own application on each *volunteer*'s device, as in

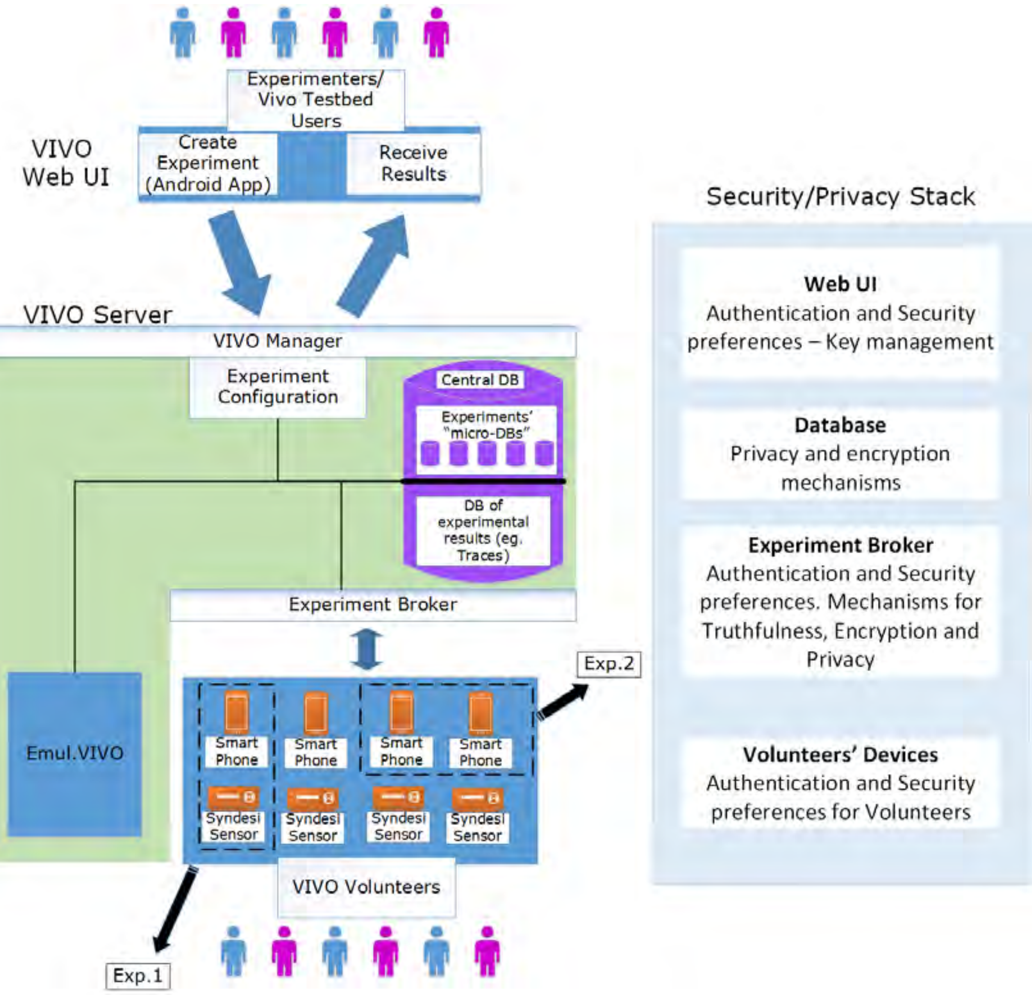


Figure 8.2: VIVO Testbed Architecture

PhoneLab [145]. However, while PhoneLab requires *volunteers* to run a modified version of the Android OS on their mobile (thus limiting the set of potential participants), VIVO applications run on normal Android versions without extra hardware requirements. In addition, VIVO promotes reproducibility of the experiments via its emulation environment.

Figure 8.2 depicts the VIVO architecture. At the top level, experimenters and researchers are provided with a *Web User Interface* for access. They can define new experiments, upload the corresponding source code and parametrise them; e.g. define the number of volunteers to be engaged or the environment in which the experiment will be conducted (indoor, outdoor, in a smart building, etc). At this layer the front-end management of users' authentication takes place and corresponding security preferences are defined. The main back-end platform noted as the *VIVO Server* lies below the Web user interface. It consists of the following elements:

1. The *VIVOManager* handles requests from the testbed users and based on their preferences, forwards experiments to be run either on real devices or on an emulation environment provided by the *EmulVIVO* component. Once an experiment has been completed, it sends the results to the testbed user conducting the experiment in a secured and anonymised way. This component also performs the back-end management of the actual identification keys as well as the authentication and security preferences.

2. The central database of the system constitutes the anchor point via which the other components are able to exchange data. Here, for each defined experiment the corresponding data structures are maintained. Collected data are then provided to the experimenter and are also available for “a posteriori" analysis; e.g. to be stripped from potentially sensitive information and to be stored in a repository for future reference. The database will also be equipped with mechanisms enforcing privacy and handling encrypted data.

3. The *Experiment Broker* provisions and orchestrates the experiments to be conducted by using devices provided by the *VIVO Volunteers*. This component takes care of aspects such as the time scheduling of the experiments as well as load balancing issues among the available volunteers. While the experiments are running, data collected from *VIVO Volunteers* is stored in the corresponding micro-DB of each experiment. At this layer authentication and security issues

related to the *VIVO Volunteers* are addressed. Also, mechanisms regarding truthfulness, encryption and privacy are implemented, thus mitigating such issues from the side of the volunteers.

4. *EmulVIVO* offers an environment to run experiments on existing data, available in the *EmulVIVO-DB*. The reasoning component of this module is the *EmulVIVO Manager*, which is in charge of receiving requests from *VIVOManager*, retrieving the corresponding data from the *EmulVIVO-DB* and allocating the emulation-running environment for the requested experiments.

The final layer includes the *VIVO Volunteers*, who are people equipped with smartphones or other personal devices able to run experiments and who accept to run VIVO experiments. Volunteers provide their characteristics ,socio-economic profile, and also define their availability. The experiments proposed by the VIVO platform must first be checked and validated in terms of respecting privacy and trust issues. Also, authentication and security mechanisms are incorporated in the experiments' source code.

8.4.1.2 The Crowd-augmented Experimenting Facility.

Syndesi 2.0 [113] based on [27] is an IoT testbed architecture for smart buildings, which enables the seamless and scalable integration of crowdsourced resources, provided by the end-users of the facility. The end-users of the smart building are equivalent to VIVO *volunteers*, and different from *testbed users*. End-users are not necessarily VIVO volunteers and vice versa. This integration increases the awareness of the facility both in terms of sensory capabilities as well as in terms of end-user preferences and experienced comfort. Combining smart actuation, IoT communication and networking technologies, the testbed user is provided with an agile experimentation platform. The purpose of integrating crowdsourced resources, such as smartphones and tablets, is two-fold. First, the sensory capabilities of the resources provided by the crowd are combined with those of the building for smart actuations. Second, the system is able to interact directly with end-users, both to incentivize them to provide sensory data from their devices and also to receive feedback. functionalities will be abstracted to the experimenters as services via RESTful APIs, thus enabling their usage in the context of webservices. Given the testbed APIs, an experimenter can use them while being agnostic of the technical details. Such architectures, in which testbed functionalities are exposed as services, have led to the notion of Testbed as a Service (TBaaS). Thanks to its modular architecture, Syndesi 2.0 can be integrated into the VIVO testbed presented above. All testbed resources of Syndesi 2.0, along with the accompanying mechanisms (e.g. defining the incentivizing strategies towards the end-users) are exposed as services via RESTful APIs. These services can be consumed by the VIVO testbed, thus leading to the integration of VIVO and Syndesi.

8.4.1.3 VIVO Privacy and Security.

The security issues facing the VIVO testbed (including the IoT unit) can be defined by specifying different trust models. First, we can assume that the user trust the application, but may not trust the central VIVO Server. The user definitely does not trust the intervening network. The server, on the other hand, cannot be sure that the application (or users) are providing truthful information. Many security components are available to make sure that the system is functioning properly. Mechanism design can be used to give incentives to users to provide truthful information. Differentially private statistical models can be used to optimally trade off user privacy requirements with utility of the barometric service, in a task-dependent manner. Finally, cryptographic methods can be used for secure communication between the server and the users. The particular provisioning of the VIVO testbed for trust and privacy preserving issues along with the capability of supporting a heterogeneous set of information will enable the facility to be used in more diverse experiments, by a higher number of end-users, e.g., for monitoring and collecting data on environmental conditions in outdoor settings (via sensors for ambient noise and luminance levels, pressure, etc.) and their correlation to user preferences. The extracted data can then be utilized in order to emulate and study more populous crowds in the EmulVIVO running environment.

8.4.2 Tackling the Heterogeneous Data Challenge

In addition to the challenges of collecting and unifying the data, our proposed platform also needs an appropriate data model that allows easy and efficient querying, processing and analytics. Efficiently storing, processing and analyzing continuous streams of heterogeneous and dynamic data is a complex task [128, 130, 131]. The goal of analytics is to identify and exploit relationships in data. A graph-based model is the natural data model choice, as widely recognized (e.g. Google's knowledge graph, Facebook's social graph and Twitter's interest graph) Other growing commercial uses include cloud management, bioinformatics, content management, and security and access control.

In the case of Synergistic Analytics, we are dealing with multiple node types (users, locations, activities etc.) and multiple link types ("knows", "is interested in", "is currently at" etc.). In addition, both nodes and links may have attributes, such as demographic information for users, usage for locations or statistical information for links. Finally, while graphs normally only support edges between two nodes, it would be clearly beneficial to be able to represent links among several nodes, forming hypergraphs. For example, as shown in Figure 8.3, an *interest* in art is connected both to the interested *user* and to a *gallery*. Storing this type of information in an efficient, but easy to handle manner is challenging. The two main options are: (i) the new generation (hyper)graph databases and the RDF (Resource Description Framework) databases. Choosing between the two (or additional options) will highly depend on the type of processing to be done on the graph, which we discuss in the next section.

8.4.3 Prediction Tasks

The prediction engine of our synergistic analytics platform enables different types of predictions, such as user mobility, behavior or service use predictions, as shown in Figure 8.1. This engine uses social and physical data, environmental and infrastructure information, and application-specific data to predict the users' next

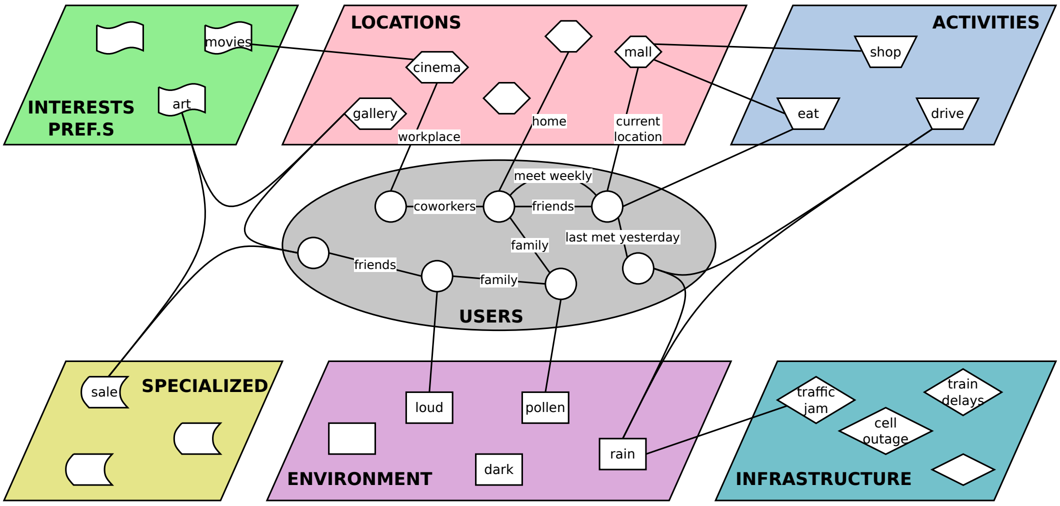


Figure 8.3: Graph model for synergistic user ↔ context analytics

place and behavior, the users' service usage, as well as any required application-specific predictions. Social data mainly consists of the user's social profile (e.g., habits, interests, etc.) and social contacts/activity information. Physical data contains the user's mobility history, activity, sensed data from different embedded sensors in mobile phones and physical contacts with other people. Environmental and infrastructure information may include ambient noise levels, ambient luminance, barometric pressure, public transportation schedules, road traffic data etc. Finally, the application-specific data (e.g., shopping behavior) should be provided by the contracting entity (e.g. retailer, hotel owner).

The heterogeneity of the collected data gives high potential to the prediction engine, which is then able to perform a deeper analysis of the user and context related data. In terms of mobility, it predicts the user's next-visited physical location together with its semantic meaning (i.e., where the user is willing to go), and it predicts the user's next physical contact. The behavioural prediction includes user activity (i.e., what the user is willing to do), mood (i.e., how the user feels), social contacts, and activity (i.e., who the user is willing to meet).

The prediction methodology is based on both historical and current data. The historical data is analysed to create a user-dynamic mobility and behavioural model.

This allows a user characterization in terms of mobility aspects (i.e., more active or sedentary persons) and the identification of the locations that are relevant for both the user itself and the social community he belongs to (according to users' social profile similarities). The model dynamically adequate to changes in the user mobility and behavior. The current data allows adaptivity to the current user's context, providing so more accurate predictions.

The potentials of including social aspects to location prediction was confirmed in some preliminary study: we showed that with the analysis of the user's mobility history we can classify the visited locations according to their relevance to the user. This classification is then used to retrieve the user's mobility and behavioural *characteristics*. Even this simple information about the user profile already improves the next-visited location prediction [146, 147]. The synergistic platform will further combine our initial results with personality and social behavior information to improve the location prediction.

8.5 Conclusions

In this work we introduced *synergistic user and context analytics*, a concept extending recent proposals for (socio-)physical or personal analytics by including more comprehensive data sources. We argued that, in addition to smartphone sensors and (online) social interactions, the environment and application-specific information is valuable for gaining insights into interactions between users and their context. We presented a testbed, based on mobile crowdsensing and the IoT, a data model for representing the different sources of data and their connections, and a prediction engine for analyzing the data and producing the insights.

Part V

Wireless Power Transfer

9 Traversal Strategies for Wireless Power Transfer in Mobile Ad-Hoc Networks

9.1 Introduction

In principle, the theoretical and technological know-how regarding wireless power transfer has been known since the beginning of the previous century. However, only recently, the corresponding technology has become mature enough so as to be used in practice and to be commercialized. In particular, in [148] it has been shown that through strongly coupled magnetic resonances, the efficiency of transferring 60 watts of power over a distance in excess of 2 meters is as high as 40%. Industrial research has also demonstrated that it is possible to improve the wireless transferring of power and in particular transfer of 60 watts of power over a distance of up to two to three feet with efficiency of 75% [149]. As the technology constantly improves, commercial products utilizing wireless power transfer have become more available on the market such as those in [150] and [151]. Apart from its application in micro-electronics, the technology has already started being applied on other, more demanding application areas such as public transportation [152]. The potential of this technology has led to the establishment of corresponding industrial standardization bodies such as the Rezence Alliance for Wireless Power [153] and the Wireless Power Consortium (WPC) [154] that seek to maximize the use of the wireless power transfer.

In parallel, significant research effort is conducted in the context of this technological advance. In the field of ad-hoc networks, a new paradigm has emerged; the Wireless Rechargeable Sensor Networks (WRSN). In WRSNs sensor motes are equipped with fast rechargeable batteries [155] and with specialized hardware components called wireless power receivers. There also exist special mobile entities called Mobile Chargers (MC), that are able to wirelessly transfer power to the sensor motes while traversing the network area. The existence of the MCs enables the detailed and efficient energy management of the network while it also renders obsolete the need of complex and computationally intense energy management algorithms that infer significant computational and communication overhead to the network. However, as hand-held mobile devices demonstrate high acceptance rates by the general public, we believe that research efforts in Wireless Power Transfer (WPT) should not be restricted only to WRSNs but should also address mobile ad-hoc networks in general.

The Problem. We consider a set of mobile agents deployed in an area of interest. The agents abstract moving people that carry portable autonomous devices, such as smartphones, smart-watches or sensor motes, that are capable of wirelessly receiving power and quick charging their batteries. The type of motion of the agents is considered to be diverse and unpredictable. Finally, we consider a single, special purpose mobile entity, called the Mobile Charger (MC), that traverses the networking area of interest and is capable of wirelessly recharging devices that lie in its vicinity.

The problem we study is which traversal strategy should the Mobile Charger follow in order to efficiently recharge the moving agents of the network. We focus on the process of efficiently transferring energy from the MC to the network and therefore the strategies we design and evaluate are agnostic to any underlying, energy consuming tasks.

Remarks. We note that, although the wireless charging problem might look similar to other related research problems (such as aggressive data collection via mobile sinks), it admits special features that necessitate a direct approach. In addition, the optimization of concrete trade-offs and the fine-tuning of design alternatives that arise in wireless charging necessitate the distinct investigation of special protocol design parameters. Finally, we note that Mobile Charger optimization problems are (inherently) computationally hard e.g. in [156] we have formulated the wireless charging problem as the Charger Dispatch Decision Problem - CDDP, and showed that it is NP-complete (via reduction from the Geometric Travelling Salesman Problem, G-TSP; see e.g. [157], p. 212).

Our Contribution. While interesting research has been conducted on the wireless recharge problem and particularly on the scheduling of the Mobile Charger, most commonly a static agent topology is considered. Also, in several of the investigated methods the role of the Mobile Charger is assigned to the Mobile Sink. This way, the two processes, of delivering energy to the network and collecting data from it, are coupled and therefore the efforts are focused on optimizing their coupling. Few previous works have considered settings in which the charged entities are mobile (e.g. mobile and robotic networks). However, in these works either the particular motion of the MC is not directly studied or they provide solutions that are fully centralized and applicable only in small scale networks. Our work here is, to the best of our knowledge, the first one to directly address the traversal strategy of a MC in large scale mobile ad-hoc networks [158]. Our contribution can be summarized as follows: a) We formally define the Charger Traversal Decision Problem (CTDP) and prove its computational hardness. b) We identify four network parameters that affect the MC in choosing its trajectory; the energy needs of the nodes, their energy dissipation rates, their mobility level and their distance from the MC. We define a corresponding weighting function used to prioritise the nodes during the charging process. c) Based on this weighting function, we design three traversal strategies for the MC; a global-knowledge strategy that uses an Integer Linear Program, to compute the MC's trajectory, a global-knowledge strategy that tessellates the network area and prioritizes each tile based on its aggregated weight, and a local-knowledge strategy that uses local network information collected and ferried distributively by the moving agents. d) We evaluate the designed strategies along with two naive zero-knowledge ones; one space-filling deterministic strategy and one in which the MC performs a blind random walk. In our evaluation we use several performance metrics and simulate various network sizes and densities. Our findings indicate that in small networks agnostic strategies are sufficient. However, as the network's size scales up, the use of local distributed network information achieves good performance-overhead trade-offs.

9.2 Related Work and Comparison

There has been much research effort in WRSNs; in particular for the case where the charged entities (e.g. sensors) are *static*. In [159, 160] authors study the cases where a Mobile Charger traverses the network area where a set of static sensors is deployed. In both works, authors focus on some particular aspect of the network (e.g. on the ratio of the MC's vacation time over the cycle time) and provide methods in order to compute corresponding optimal charging tours. In [161] the authors consider a sensor network in which a mobile entity is employed which (in contrast to our approach) serves also as a data collector and as an energy transporter that charges the static sensors on its migration tour. They provide a two-step approach: in the first step the mobile entity selects the maximum number of anchor points such that the sensors located in these anchor points hold the least energy and meanwhile the tour length is no more than a threshold. In the second step they formulate a utility maximization problem on a flow-level network model in order to determine how to gather data from sensors. However this algorithm requires global information, thus making it not very practical in even medium-sized sensor networks. In [162], the authors formulate an energy-constrained wireless charging problem, which maximizes the number of sensors wirelessly charged by a Mobile Charger. The paper proposes heuristic solutions based on the meta-heuristics of Particle Swarm Optimization. However, the model assumes the charger has an extensive knowledge on the network and the performance evaluation is limited to simulations of small-scale networks.

In a previous work of our group in [156], the authors study the impact of the charging process to the network lifetime for selected routing protocols. They propose a mobile charging protocol that locally adapts the circular trajectory of the Mobile Charger to the energy dissipation rate of each sub-region of the network. They compare this protocol against several other trajectories via a detailed experimental evaluation. The derived findings demonstrate performance gains, but are still *limited to uniform network deployments*, in contrast to our approach in this work, where we also consider heterogeneous node distributions.

Alternative versions of the problem have also attracted important research studies. In [163–165] the authors consider the wireless recharging problem, using multiple mobile chargers. In this case, several other interesting aspects emerge, such as the minimum number of chargers that suffice to cover the network area, inter-charger coordination, etc. Few research efforts have also taken into consideration settings in which the charged entities are *mobile*. In [166] authors study the throughput of an energy-constrained mobile network where MCs recharge the battery of each mobile node. However, they do not focus on the traversal of the MC *per se*, as they consider it to perform only a random walk. Also, they assume a naive mobility model for the mobile nodes (they assume identically distributed random processes). In [167] authors consider a small scale network of mobile robots in which the MC needs to rendezvous with the robots in order to recharge them. Authors provide a centralized solution while considering direct-contact charging technologies.

Although these efforts successfully identify and address fundamental aspects of wireless power transfer in ad-hoc networks, they significantly differ from our approach in this work. They mostly consider networks with low dynamics, where the sensor motes are static or small scale networks. Also, motivated by the characteristics of the wireless power transfer via conductive charging technologies that operate efficiently in very small distances (in the order of few centimetres), in most of the previous efforts the charging model considered is point-to-point. On the contrary, we envision a wireless power transfer scheme that is based on *inductive charging*; i.e. the MC is able to simultaneously charge devices that lie inside its charging radius by creating an electromagnetic field.

9.3 The Model

In our model we consider two types of entities: the set of n *mobile agents* $\mathscr{A} = \{A_i \mid i : 1 \le i \le n\}$, that abstracts autonomous devices carried by people (such as smartphones, smart-watches and sensor motes) and a *Mobile Charger* (MC) which is a special purpose entity capable of wirelessly transferring power to devices located in its vicinity while traversing the network area Ω. We discuss below the mobility, energy and charging aspects of our model.

9.3.1 Mobility Models

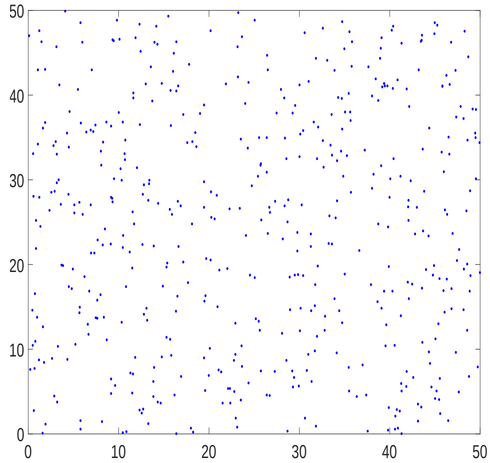
We consider a planar area of interest Ω in which the set of mobile agents $\mathscr{A}$ is initially deployed uniformly at random. The speed at which each agent traverses the network is modelled as a random variable following the Poisson distribution. The corresponding mean value s_i capturing the *average speed* of agent A_i is drawn u.a.r from a set of four indicative values corresponding to four distinct mobility levels $\mathscr{M}_x^i$ $(x \in \{work; walk; bic; veh\})$. Each mobility level captures a different kind of activity such as limited moving in an office environment, walking, riding the bicycle and moving by using a vehicle. As a result, a diverse population of agents is created in terms of mobility in Ω. In order to model the particular *type of motion* of each A_i we use two mobility models, each one leading to a different agent distribution over Ω.

The Random Walk Mobility Model - RWMM. According to this model, the agents are initially deployed uniformly at random inside Ω. Then, each agent A_i performs a random walk independently of the other agents. The motion of each agent in this model consists of consecutive movements of a constant time duration Δt. We refer to these intervals as rounds. In particular, each agent A_i given its current position and its mobility level $\mathscr{M}_x^i$, moves to a new location by randomly choosing a *direction* in which to travel from $[0, 2\pi]$; if the agent's location lies close to the borders of Ω, then the interval is properly adjusted so as to maintain the agent always inside Ω. From a broad point of view, this model over time, results in a uniform distribution of agents over Ω, while at the same time local minima and maxima emerge in the density of the agents.

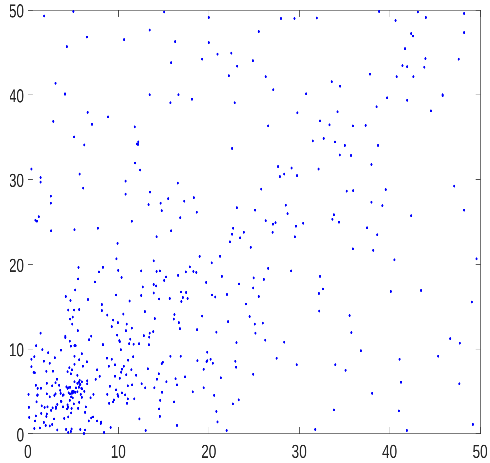
Although similar mobility models to the RWMM (e.g. the well-known Random Waypoint Model) have been proven not so efficient in capturing particular characteristics of human mobility (note we assume that agents abstract people carrying electronic devices), we choose to use this model for its simplicity because it helps us focus and high-light the qualitative characteristics of each traversal strategy during the evaluation process.

The extended Random Walk Mobility Model - eRWMM. To better address the intrinsic social aspects of human mobility, we take into consideration the notion of *social attraction*. Social attraction comes from the field of social network theory and is broadly used in mobility models for Mobile Social Networks [168]. In particular, it is used in *community-based* mobility models in order to capture in a more realistic way the aspects of human mobility [169]. Social attractivity is defined as the aggregate attraction among the agents as well as towards physical locations inside the area of interest. Real-life examples would include the commercial mall of a city or a cafeteria in a university campus.

Towards more heterogeneous and dynamic placements, we expand the RWMM by adding *social hotspots* inside area Ω, where agents are attracted during their network traversal. More specifically, in this extended model each agent randomly chooses a new direction in $[0, 2\pi]$ not uniformly but with a bias factor b towards the hotspots. The value of b affects the impact of the hotspot on the network; higher values result to denser hotspots and thus in more heterogeneous agent distributions in Ω. Figure 9.1(a) depicts a snapshot of a network following the RWMM model while Figure 9.1(b) depicts a network following the eRWMM model.



(a) Snapshot of a homogeneous agent distribution under the RWMM model.



(b) Snapshot of a heterogeneous agent distribution under the extended with social hotspots RWMM model.

Figure 9.1: Example snapshots of homogeneous and heterogeneous agent distributions.

9.3.2 Energy Model

We denote with E_i^t the amount of energy reserves of agent A_i on time t and with E_{max} the maximum amount of energy each agent may have; i.e. when an agent is *fully charged*. Initially each agent is assumed to be fully charged; i.e. $E_i^0 = E_{max}, \forall A_i \in \mathcal{A}$. We also assume that the amount of energy each agent A_i dissipates during a time interval Δt, i.e. a round, follows a Poisson distribution with mean value λ_i. For each agent, λ_i is constant and is chosen uniformly at random from $[\lambda_{min}, \lambda_{max}]$. Intuitively, small values of λ_i correspond to users that mainly perform light activities with their devices (e.g. taking pictures or chatting), while larger values correspond to users that tend to perform more intense activities (e.g. high definition video streaming or GPS navigation).

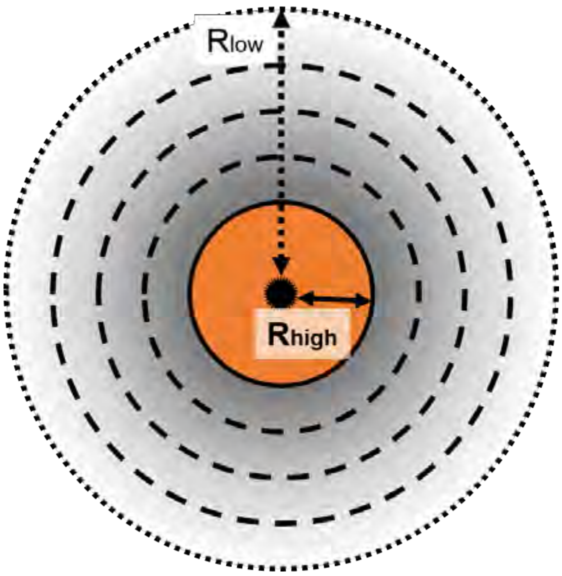


Figure 9.2: Graphical representation of the charging zones around the Mobile Charger. Over all zones, the efficiency of the power transfer reduces sub-quadratically to the distance from the Mobile Charger. However, for distance $d \leq R_{high}$ (central zone) the efficiency of charging is sufficiently high for the MC to fully charge agents in a single round. In distances $d > R_{low}$, efficiency is so low, that no effective charging takes place.

9.3.3 Charging Model

We assume that the Mobile Charger uses inductive charging technology thus being able to wirelessly transmit energy in an omnidirectional way and to simultaneously recharge multiple devices that lie in its vicinity. We identify two *charging zones* around the MC (Fig. 9.2). The first one extents up to a radius R_{high} around the MC. Inside this zone, the charging process is conducted at such a high efficiency that the corresponding agents can be fully charged during a single round. The second zone

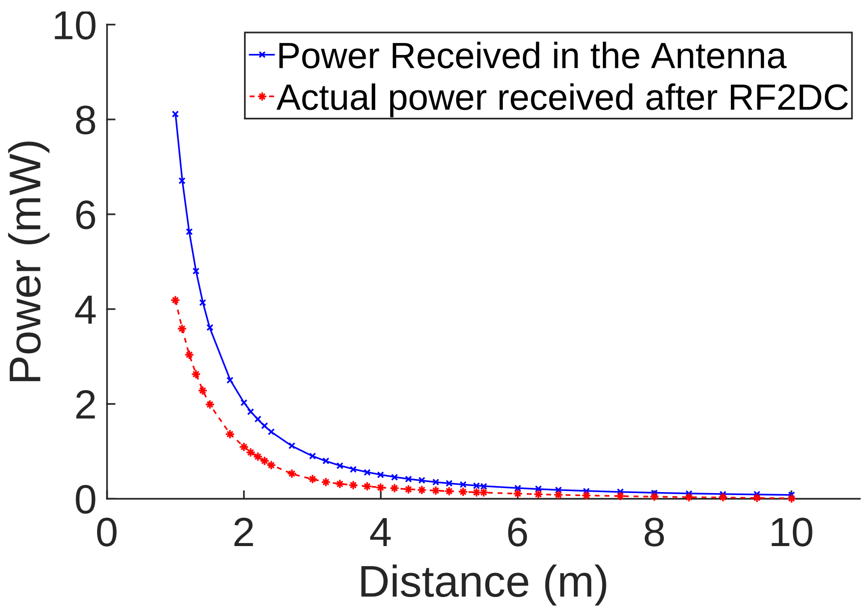


Figure 9.3: Received power using a 3 Watt Powercast charger (transmitter).

lies in distances greater than R_{high} and smaller than R_{low}. In this zone although the devices are being charged, the charging happens with a lower efficiency and therefore an agent may end-up being only partially recharged after a single round (depending of course on its residual energy at the beginning of the round). For distances greater than R_{low}, although energy is still emitted, we assume that charging efficiency is so low that no effective charging takes place.

Based on the specifications of commercially available wireless chargers (such as those in [150]), we assume that the amount of energy each agent receives and eventually stores in its battery per round is reversely proportional to the square of its euclidean distance from the MC. In fact, in order to estimate the amount of the received power, industrial manufacturers make use of the Friis transmission equation. Figure 9.3 shows the theoretical received power rates from the specifications of a 3 Watt Powercast transmitter [150]. In fact, the actual power that can be received by the battery of the receiver is about 50% less than the power its antenna receives in distances up to 6 meters and more than 70% less in distances further than that. This is due to the RF-to-DC energy conversion efficiency.

We consider the energy reserves of the MC to be significantly bigger than those of the agents' or to be easily and continuously replenished during network traversal; e.g. via energy harvesting from the environment (like solar panels) or via more conventional means such as having the charger draw energy from the vehicle it is attached on. Therefore, in this work we consider the energy reserves of the MC to be infinite.

9.4 The Charger Traversal Decision Problem

Based on the model presented in the latter section, we formally define the Charger Traversal Decision Problem and proof its NP-completeness.

Definition 1 (CTDP)**.** *Suppose that we are given a set* $\{A_i \mid i = 1, \ldots, n\}$ *of mobile agents with positions* (x_i^t, y_i^t) *at times* $t = 0, \ldots, T$. *We assume that at initial time* $t = 0$ *all agents are charged up to their maximum energy level of* E_{max} *energy units. The energy dissipation units* EU_i^t *in time windows* $[t-1, t]$ *are known for all agents and times* $t = 1, \ldots, T$. *Furthermore, we are given a mobile charger MC which charges all agents in its range up to radius* R_{high} *in one time unit up to their maximum energy level. All agents with distances greater than* R_{high} *up to* R_{low} *are charged following a rule such that the amount of energy units received by an agent is reversely proportional to the square of its distance from the MC. The additional amount of energy units the agent eventually stores is limited such that the maximum energy level of the agent is not exceeded. The Charger Traversal Decision Problem (CTDP) is to determine whether there is a feasible schedule for the MC to visit points in the plane such that no agent falls below sufficient energy level at any time.*

Theorem 1. *The CTDP is* $\mathcal{NP}$*-complete.*

Proof. Given a schedule S of the MC visiting positions in the plane, we can verify whether all agents have sufficient energy at all times in polynomial time. Let E_i^t denote the residual energy of agent A_i at time t. For all times $t > 0$, we compute the euclidean distances d_i^t of the agents to the MC. Let $E_i^{rec}(d_i^t)$ denote the additional energy units an agent A_i receives reversely proportional to the square of its distance d_i^t. From d_i^t we can infer the residual energy of agent i which equals to $E_i^{t-1} - EU_i^t$, if $d_i^t > R_{low}$; equals to the $\max\{E_{max}, E_i^{t-1} - EU_i^t + E_i^{rec}(d_i^t)\}$, if $R_{low} \geq d_i^t > R_{high}$; or else equals to E_{max}. Note that the value of $E_i^{rec}(d_i^t)$ can be computed in polynomial time in d_i^t. Therefore CTDP $\in \mathcal{NP}$.

Now consider the subclass of CTDP problem instances where the positions of the agents are static; i.e. there exists x_i, y_i such that $x_i^t = x_i$ and $y_i^t = y_i$ for all $i = 1, ..., n$ and $t = 0, ..., T$. Let us denote this subclass by CTDP^{stat}. To proof completeness, we reduce the Charger Dispatch Decision Problem (CDDP), introduced and proven to be $\mathcal{NP}$-complete in [156], to the CTDP^{stat} in polynomial time. In the CDDP, we are given a set of sensors S with a maximum energy deposit of discrete energy units and information of distances between every two sensors in the form of a distance matrix. These sensor motes are the agents in our corresponding CTDP^{stat} instance. Now in the CDDP, for every sensor $s \in S$, we have a list L_s of pairs (t_s^j, e_s^j), $j \geq 1$ in which t_s^j corresponds to the time that the j-th message of s was generated and e_s^j to the energy that the sensor used to transmit it. In the corresponding CTDP^{stat}, we consider these values by setting the energy dissipation units of the agents as $EU_s^t = \sum_{j:t_s^j=t} e_s^j$ (i.e., we are summing up the transmission energy of node s for messages send at time t_s^j). In the CDDP, a charger which can charge a sensor in one time unit to its initial (maximum) energy is given. In order to create the same setting, we increase distances between nodes by a constant factor such that the smallest distance between two nodes is larger that R_{low}. In this way, the corresponding charger in the CTDP^{stat} can charge at most one node per time unit as well. The CDDP is to determine whether there is a feasible schedule for the charger to visit the sensors so that no message is lost due to insufficient energy. This corresponds to the decision problem of the CTDP^{stat} for the created instance. An answer to the CTDP^{stat} would provide an answer to the CDDP, hence the CTDP^{stat} is $\mathcal{NP}$-complete. As all instances of the CTDP^{stat} are in the CTDP, thus the CTDP is $\mathcal{NP}$-complete. $\square$

Note that the CTDP and CDDP differ particularly in the mobility of agents and in the charging range enabling the MC in the CTDP to charge several agents at the same time. In addition, in the CTDP we consider energy dissipation of agents independently of their precedent actions while in the CDDP energy is considered in relation to message transmission.

Distinguishing our work from previous related works, in this work we focus on the investigation of tackling the mobility of nodes in an ad-hoc network while recharging them. In real-life settings, a MC would have limited local knowledge about the decentralized mobile ad-hoc network it traverses; i.e. the charger will only have information on agents it encounters and no exact information on future events. Therefore, our goal is to define traversal strategies that are applicable in such local knowledge online settings.

Ensuing from the CTDP, let us consider the associated NP-hard problem of optimizing the network life time in terms of maximizing the number of agents alive over time. We go directly over to its online problem with global information about the agents and their attributes at the current time only. Further investigation of the offline version of the problem in order to obtain an upper bound for the results of the online optimization is not presented here due to lack of space. In fact, we intent to provide such a solution in our future work. However, we note that experimental results extracted from our detailed simulation study demonstrate that our online heuristics have sufficiently high performance (see section 9.7). In addition, the consideration of the online problem offers valuable insights on optimization aspects when information on the future positions of agents is missing. This insight is then used to define a distributed local knowledge strategy which also has to act online.

9.5 The Weighting Function

As the MC traverses the network area, it needs a way to prioritize the agents in terms of visiting them for recharging. This prioritization will take into consideration several network aspects that affect the evolution of the network over time. For mobile ad-hoc networks we identify these aspects to be:

1. the *energy need* $E_i^{need} := E_{max} - E_i$ (with E_i indicating residual energy) of each agent A_i
2. the mean energy *dissipation* rate λ_i of each agent A_i
3. the *mobility* level $\mathscr{M}_{x(i)}^i$ of each agent A_i
4. the euclidean *distance* d_i of each agent A_i from the MC

However, each one of these aspects is measured in different units and has different ranges. Therefore, the *Weighting Function* (see below) considers their normalized values. We multiply by the factor 100 in order to simplify arithmetics as these values will be used as basis for exponents as follows:

- we normalize the *energy needs* over the maximum energy an agent may store; i.e. $\bar{E}_i^{need} := \frac{E_{max}-E_i}{E_{max}} \cdot 100$
- we normalize the *dissipation rates* over λ_{max}; i.e. $\bar{\lambda}_i := \frac{\lambda_i}{\lambda_{max}} \cdot 100$
- we normalize the *mobility levels* over the maximum mobility level $\mathscr{M}_{max}$; i.e. $\bar{\mathscr{M}}_{x(i)}^i := \frac{\mathscr{M}_{x(i)}^i}{\mathscr{M}_{max}} \cdot 100$
- we normalize the *distances* over the maximum distance possible in the network area d_{max} (e.g. if Ω is a rectangle then d_{max} is its diagonal); i.e. $\bar{d}_i := \frac{d_i}{d_{max}} \cdot 100$

Given these normalized values, the MC will assign a weight to each agent via a *Weighting Function* W^* whose generic form is defined as:

$$W^* : \mathscr{A} \to \mathbb{R}_0^+; \quad W_i^* \mapsto (\bar{E}_i^{need})^\alpha (\bar{\lambda}_i)^\beta (\bar{\mathscr{M}}_{x(i)}^i)^\gamma (\bar{d}_i)^\delta \tag{9.1}$$

The higher the weight assigned to an agent, the higher priority it will have during the charging traversal of the MC. The use of the exponents enables us to fine-tune the significance of each network aspect by adjusting the value of the corresponding exponent. The monotony of W_i^* with respect to each network aspect will help us define the sign of each exponent. In this context we denote the following relations:

1. the higher the current *energy need* $\bar{E}_i^{need}$ of agent, A_i the higher the value of W_i^*
2. the higher the mean energy *dissipation* $\bar{\lambda}_i$, the higher W_i^*
3. the higher the *mobility* level $\bar{\mathscr{M}}_{x(i)}^i$ of agent A_i, the smaller W_i^*
4. the higher the distance $\bar{d}_i$ of A_i, the smaller the value of W_i^*.

While the rationale for relations 1 and 2 is intuitively straight forward, rules 3 and 4 capture the abilities of the MC to react in a timely manner to spatio-temporal dynamics of the network. In the online problem even if the MC has global knowledge, we assume that it cannot infer the exact future positions of the agents; instead the MC has to make decisions based on a “snap shot” of the network at the current time. Rule 3 supports the idea that the smaller the mobility level of an agent the more likely that in the near future the agent will still be in close vicinity to its current positions. Hence, the incentive for the charger to start travelling towards the direction of such an agent is to be successful in actually reaching the agent and charging it. A similar motivation can be used to reason on rule 4 concerning the distance of an agent to the charger; the closer an agent is, the more likely that the MC will reach the agent in the near future.

In the light of the previous discussion the final generic form of the *Weighting Function* (assuming that all exponents are positive) is:

$$W : \mathscr{A} \to \mathbb{R}_0^+; \quad W_i \mapsto \frac{(\bar{E}_i^{need})^\alpha (\bar{\lambda}_i)^\beta}{(\bar{\mathscr{M}}_{x(i)}^i)^\gamma (\bar{d}_i)^\delta} \tag{9.2}$$

As mentioned before, the exponents in the generic form of W enable us to investigate the relationship and importance of individual attributes with respect to the charging process. In order to define the exact numerical values for each exponent, in this work we adopt the One-Factor-At-A-Time (OFAT) methodological approach (see e.g. [170]);

i.e. varying the value of the exponent of one of the attributes at the time, while fixing the others to a base value in order to evaluate the impacts on the performance of the MC.

Experimental findings indicate that the uniform consideration of all network aspects (i.e., all exponents equal to one) already lead to good results in our MC traversal strategies (see details in section 9.7). Fine tuning via more sophisticated methods would only further increase the already high efficiency of the proposed traversal strategies.

9.6 Traversal Strategies for the Mobile Charger

We now discuss five traversal strategies for the Mobile Charger that are qualitatively different in terms of the assumed level of knowledge that the MC has on the network. The first one is a zero-knowledge deterministic space-filling strategy. The second one is a zero-knowledge randomized strategy. The third and fourth ones are online, complete-knowledge centralized strategies integrating the node *Weighting Function* defined above. The last strategy is a reactive one that is based on local network information gathered by the agents in a distributed way.

In terms of network knowledge, complete-knowledge strategies are the most powerful strategies for the MC. At any given moment, the MC is aware of the exact distribution of the agents over the area Ω and is therefore able to choose its trajectory accordingly towards maximizing the number of nodes alive over time while considering the delay between the time of computing positions and the arrival time of the MC in the online setting. Such recharging schemes have the strong assumption that the agents are able to periodically propagate data regarding their position and energy needs to the MC; e.g. over the Internet. The MC is assumed to have the required computational power in order to be able to perform the necessary calculations.

9.6.1 The Space-filling Strategy (SPF)

This zero-knowledge deterministic traversal strategy consists in having the MC to systematically sweep the network area in such a way that no overlaps occur. In particular, according to this strategy the MC is moving along the one dimension of Ω until it reaches its border. Then, it takes a U-turn shifted by a distance of $2R_{low}$ along the second direction. When the entire network area has been covered the process is repeated. This traversal strategy guarantees that eventually all network sub-regions will be covered by the MC and in uniform agent distributions it is expected to have a satisfactory performance. However, in heterogeneous distributions where big numbers of agents are located in confined sub-regions (i.e. the social hotspots) significant latencies in inter-charging times are expected.

9.6.2 The Random Walk Strategy (RAND)

This is a zero-knowledge randomized traversal strategy for the MC. Given its current position, the MC chooses the direction of its next move uniformly at random from $[0, 2\pi]$ and the distance to be covered uniformly at random from $[0, 2R_{low}]$. This strategy assumes zero-knowledge on the network and the distribution of the agents. Therefore, like the SPF, it is characterized by the absence of any overhead as the agents maintain a passive role, simply waiting to encounter the MC in order to be recharged. Moreover, this strategy probabilistically guarantees that eventually all the sub-regions of the network will be visited by the MC, although it may infer long waiting periods for the agents among consecutive charges, particularly for highly heterogeneous topologies.

9.6.3 Global Knowledge ILP Strategy (GK-ILP)

Initially the Mobile Charger is placed at a random position in the network area Ω. At each round, given the current positions of all the agents in Ω and the current values of their network attributes (i.e. $\bar{E_i^{need}}$, $\bar{\lambda}_i$, $\bar{\mathcal{M}^i_{(x)}}$, $\bar{d_i}$), the MC is able to compute the exact location it should visit (or move towards to) at the current time. The MC could do so by finding the center of the circle of radius R_{low} which encircles the agents that cumulatively have the highest node weights with respect to the *Weighting Function*. By the design of the *Weighting Function*, the cumulation of the node weights correctly prioritizes the various areas with respect to demand for being charged. The corresponding non-linear problem formulation is as follows:

$$\max_{x,y,\beta_i,d_i} \quad \sum_i W_i \beta_i \tag{9.3a}$$

$$d_i = (\,(x_i - x)^2 + (y_i - y)^2\,)^{1/2} \qquad \forall\, i \tag{9.3b}$$

$$R_{low} + (1 - \beta_i) \cdot \mathbf{M} \geq d_i \qquad \forall\, i \tag{9.3c}$$

$$\beta_i \in \{0, 1\} \qquad \forall\, i \tag{9.3d}$$

In the problem formulation the i's are the indices of the agents $A_i \in \mathscr{A}$, W_i indicate their weights, β_i are binary decision variables, d_i the distance of the agents to the MC at position (x, y), x_i and y_i are the position coordinates of the agents, and **M** is a very large constant. In (9.3b) we compute the distances of the agents to the MC. In (9.3c) we make sure that if $\beta_i = 1$ (i.e., if the weight of agent A_i is considered in the objective function) then $R_{low} \geq d_i$.

To create an ILP, we approximate d_i. Instead of a circle with radius R_{low}, we look for a rectangle whose sides are at most of length R_{low} and whose center (x, y) is the position of the MC:

$$\max_{x,y,\beta_i,d_i} \quad \sum_i W_i \beta_i \tag{9.4a}$$

$$d_i \geq |x_i - x| \qquad \forall\, i \tag{9.4b}$$

$$d_i \geq |y_i - y| \qquad \forall\, i \tag{9.4c}$$

$$R_{low} + (1 - \beta_i) \cdot \mathbf{M} \geq d_i \qquad \forall\, i \tag{9.4d}$$

$$\beta_i \in \{0, 1\} \qquad \forall\, i \tag{9.4e}$$

In the later equations the constraints (9.4b) can be replaced by linear equations $d_i \geq x_i - x$ and $d_i \geq -(x_i - x)$. Corresponding replacements can be made for (9.4c) resulting in an ILP. By solving this ILP, the MC is able to identify the rectangle that maximizes demands and move towards its center. The MC is updating its directions using the ILP with updated information at each time step.

Note that even for relatively big and dense network instances the ILP can be solved in reasonable amount of time.

9.6.4 Global Knowledge Tessellation Strategy (GK-TS)

In this traversal strategy the MC is initially deployed at a random position inside the network area Ω. First, the MC virtually tessellates the network area in square tiles of the same size. In order to minimize overlaps in the charging areas the pivot of the tessellation is chosen to be equal to $2R_{low}$. Then on each round, given the current positions of all the agents in the Ω and the current values of their attributes, the MC assigns weights to each agent via the *Weighting Function* and computes the aggregated weight for each tile by summing the weights of the agents located in that tile. Finally, the MC chooses to move towards the center of the tile with the highest cumulative weight.

9.6.5 The Reactive Local Knowledge Strategy (RLK)

This is a local knowledge traversal strategy that exploits local information collected distributively. The agents overtake an active role in collecting local network information and informing the MC on the current demands of their neighbourhood (we assume that R_{low} and the communication range of the agents, although not equal, are of the same order). This way the MC is able to identify and serve stressed areas of the network as well as to react to changes of the network topology under a more realistic and efficient distributed scheme.

More specifically, each agent periodically collects information regarding the network attribute values of its neighbouring agents; i.e. each agent poles its one-hop neighbours on their energy needs, their average energy dissipation rate and their mobility levels. Then this information is used to assign to each neighbour a weight via a modified *Weighting Function* that does not take in consideration the distance to the MC. This is due to the fact that the agent is unaware of the actual location of the MC. Instead, the agent associates the assigned weights to its current position for future reference. The modified *Weighting Function* applied by an agent in the GK-TS strategy:

$$\bar{W} : \bar{A} \to \mathbb{R}_0^+; \quad \bar{W}_i \mapsto \frac{\bar{E}_i^{need} \bar{\lambda}_i}{\bar{\mathcal{M}}_{x(i)}^i} \tag{9.5}$$

Eventually, the agent stores in its memory and ferries a tuple consisting of the cumulative weight of its current neighbourhood and the coordinates of the position where this weight was measured. As each agent is moving inside the network area, the quality (in terms of accuracy) of the measurements degrade over time due to the dynamics of the network, such as the mobility of the agents. In order to address this issue we introduce the following ageing mechanism. At every round each agent updates the carried tuples by multiplying the stored aggregated weight with a constant $q \in [0, 1]$. Therefore, after T rounds the corresponding value will have been multiplied by a factor of q^T and will be a percentage of the initial weight. The lower the value of q is set, the more high the reduction over time of the weight stored in the tuple.

On another aspect, as the agent traverses the network, it periodically collects local network information and stores them in tuples in its memory. As new tuples are being created, at each round the agent re-evaluates the already existing ones and compares them to the new tuples. Low weight entries are replaced by higher weight entries once the storage space limit of the agent has been reached. An agent carries stored tuples and opportunistically delivers it to the MC once it encounters it.

Table 9.1: Structure of the tuple each agent maintains.

`tuple.x`	% X coordinates of the measurement location
`tuple.y`	% Y coordinates of the measurement location
`tuple.weight`	% Modified weight of the measured location

The MC is initially placed at a randomly chosen position inside Ω. As the MC traverses the network, it receives and saves tuples from each agent it encounters. Then, the MC uses the information provided in order to solve the ILP introduced in the later subsection thus adjusting its trajectory correspondingly at each time step.

The presented reactive, local knowledge traversal strategy introduces a communication overhead to the network as the agents need to exchange information with each other. However, this overhead is rather small, thus not yielding significant energy consumption for the agents. Further, we note that information regarding network areas with high agent density and/or high energy needs (such as social hotspots) will be carried by the agents for a longer time period and will traverse a longer distance into the network. Finally, the distributed nature of this strategy makes it scalable and applicable in more realistic settings.

9.7 Performance Evaluation

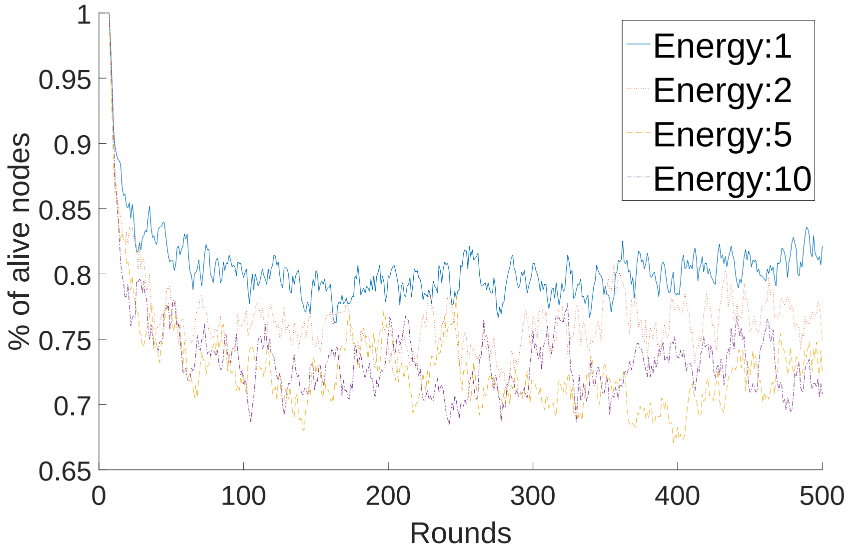
9.7.1 Simulation Set-up

We evaluate the performance of the five traversal strategies by conducting extensive simulation studies in Matlab 2015. We conduct simulations with three different sizes for Ω; a) 50×50, b) 100×100 and c) 150×150 where in each setting 100 agents are deployed. We make this choice as it provide us with qualitatively different sizes and densities of the network in which the agents are distributed enabling us to better study the performance of each heuristic. In terms of speed of movement, we set the mean agent speed for each mobility level to be (all numbers are in space units over time units) $\mathcal{M}_{work} = 2$; $\mathcal{M}_{walk} = 4$; $\mathcal{M}_{bic} = 8$; $\mathcal{M}_{veh} = 16$ and the speed of the MC MC_{sp} =10.

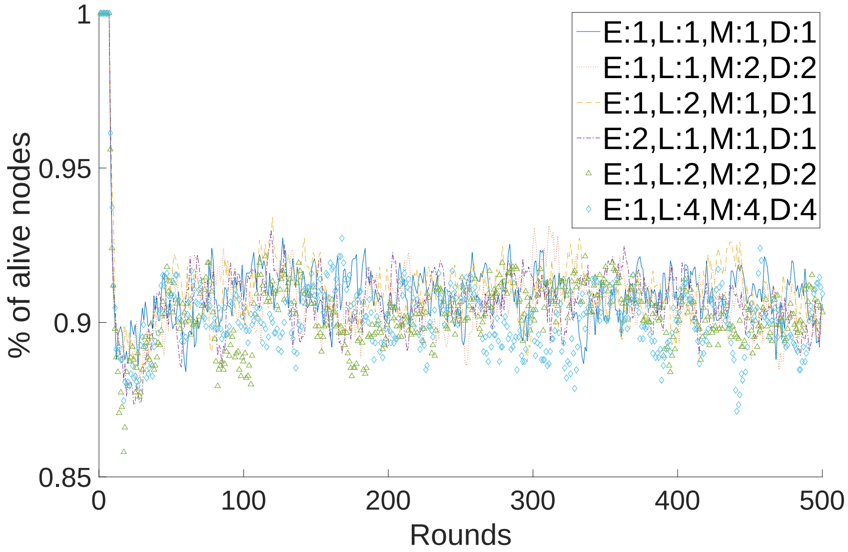
Mobility levels are assigned to the agents u.a.r., thus leading each one to correspond to approximately 25% of the population. We also set the maximum and initial energy for each agent to be E_{max} = 3000 units of Energy. At each round of simulation, the amount of energy that each agent dissipates follows a Poisson distribution whose mean value for each agent is chosen independently and u.a.r. in [20, 80] units of Energy. We study both homogeneous and heterogeneous placements. In the heterogeneous placements three social hotspots are considered each on in different network subregion with a bias factor of: 0.45; 0.15; 0.15 accordingly. Note that the agents are *attracted* towards the hotspots; they do not move directly to them. For each setting we simulate the network for 500 rounds. Each simulation is repeated for 60 iterations and we compute the mean values for each metric; results demonstrate strong concentration around the mean (evaluated via the standard error over the mean).

9.7.2 Preliminary Evaluation of the Weighting Function

Before running the simulations for the evaluation of each strategy we turn to the task of finding appropriate parameter settings for the attribute exponents in the *Weighting Function* introduced in section 9.5. We employ the simple One-Factor-At-A-Time (OFAT) methodology: varying the parameter values of the exponent of one of the attributes while fixing the others to a base value in order to evaluate the impacts on the simulation outputs (see e.g. [170]). OFAT has the advantage of being relatively easily conducted and, as it will turn out, over relatively few trials will provide settings which result in sufficiently high performance. We will leave a more sophisticated analysis of the exponent parameter settings for future work claiming that this would only ameliorate the our findings. For the evaluation of the exponents we measure the performance of varying parameter settings when employing the *Global Knowledge ILP Strategy* as this strategy employs the base version of the *Weighting Function* and in terms of adjusting the traversal strategy of the MC may, out of all of the presented strategies, best exploit the added value of *Weighting Function.*



(a) Evaluation of the *Energy* exponents.



(b) Evaluation of all the exponents of the *Weighting Function*.

Figure 9.4: Evaluation of exponents using the *GLK-ILP* strategy

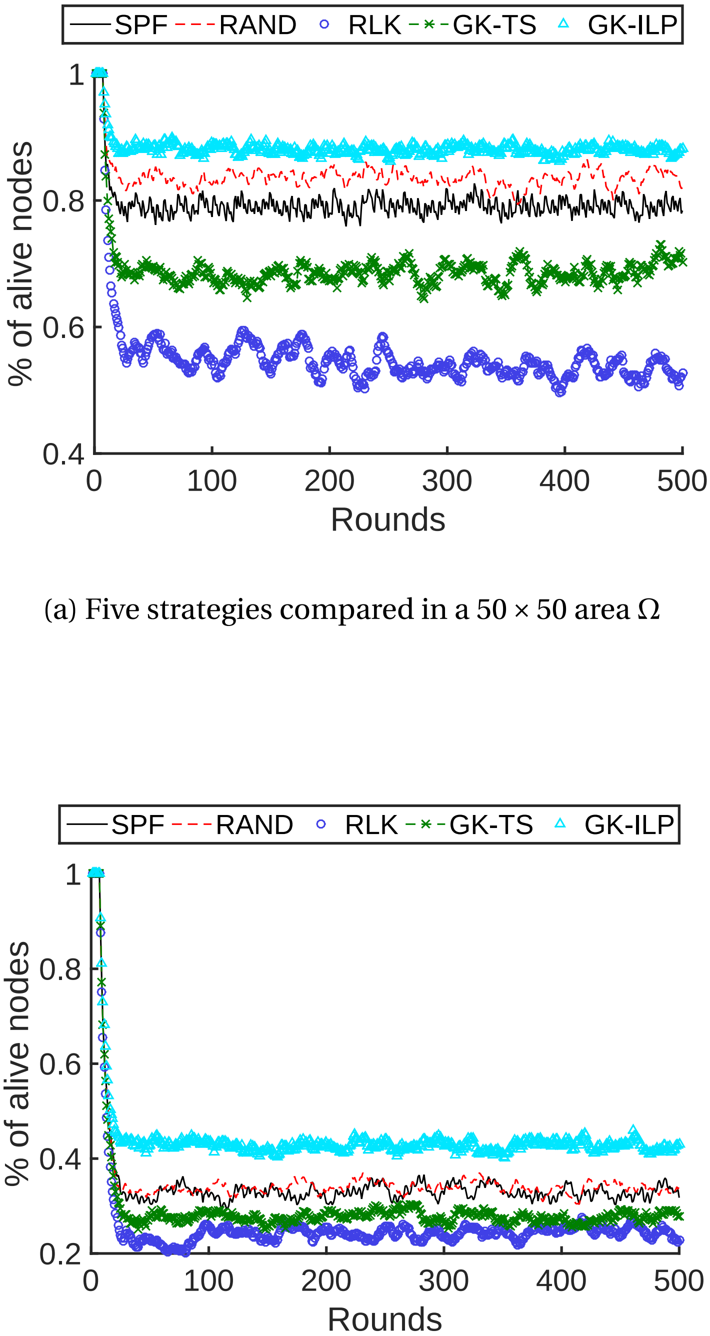
We first evaluated different values for the E^{need} exponent with values ranging from 1 to 10 (keeping the other exponents at 0). Figure 9.4 a) shows the percentage of alive nodes over the number of rounds for different exponents of E^{need} in a 50x50 area with a homogeneous agent distribution. We observe that the more we increase the value of the E^{need} exponent the less alive nodes we have in the area. Similar results are achieved for 100x100 and 150x150. This can be explained by how the *Weighting Function* assigns values with respect to the exponents: the higher the exponent of E^{need} is, the higher the weight distance between two agents, even if their actual energy needs are similar. For instance, for value 10, consider two nodes: one with energy need equal to 2 and one with energy need 2.5. These would end up in receiving weights 1024 vs. 9537. In a network with several nodes the MC integrating the *Weighting Function* with high exponents might focus too much on some few individual nodes.

As E^{need} is the indicative factor for a the survivability of an agent, we conducted tests for evaluating the exponents of pairs of $\{E^{need}\} \times$ *Dissipation, Mobility, Distance*}. Similarly to the tests on using only the E^{need} exponent, the results were changing with respect to changes of the E^{need} exponent only. As such we run tests for evaluating all the exponents by keeping the E^{need} exponent at 1. The results can be seen in figure 9.4 b). Considering the relatively high performance, we used for our strategies evaluation the exponents in a uniform manner (i.e. all exponents equal to 1).

9.7.3 Evaluation of traversal strategies

9.7.3.1 Evaluation Metrics

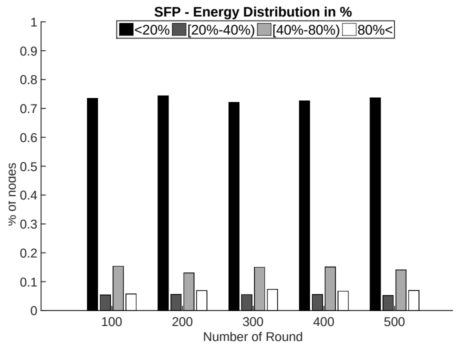
Number of alive agents. In this metric we examine the percentage of alive agents each traversal strategy is able to achieve in a given amount of rounds. We note here that a fully charged agent with highest possible dissipation rate in the absence of the MC will die in 12 rounds. This metric is a good indicator of whether a strategy manages to provide energy to the network where and when is needed.



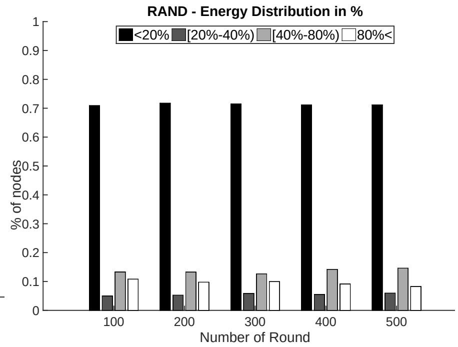
(a) Five strategies compared in a 50 × 50 area Ω

(b) Five strategies compared in a 100 × 100 area Ω

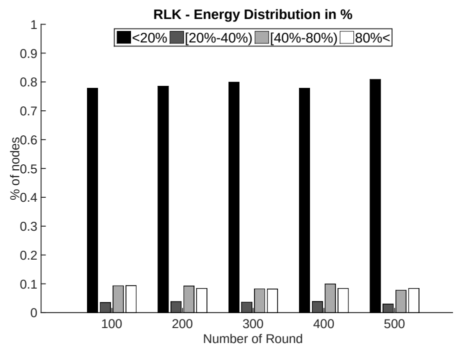
Figure 9.5: Percentage of alive nodes over 500 Rounds in homogeneous setting



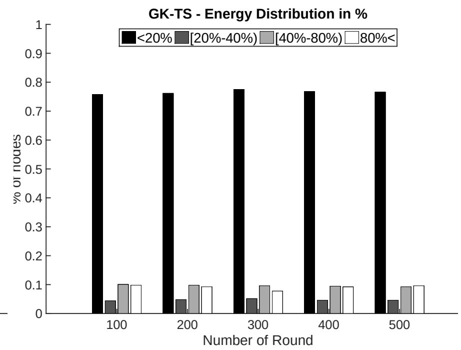
(a) Space-Filling Strategy



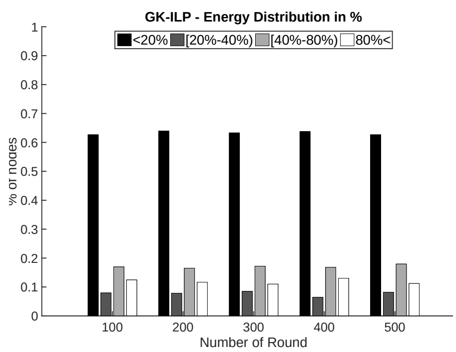
(b) Random Walk Strategy



(c) Reactive Local Knowledge Strategy



(d) Global Knowledge Tessellation Strategy



(e) Global Knowledge ILP Strategy.

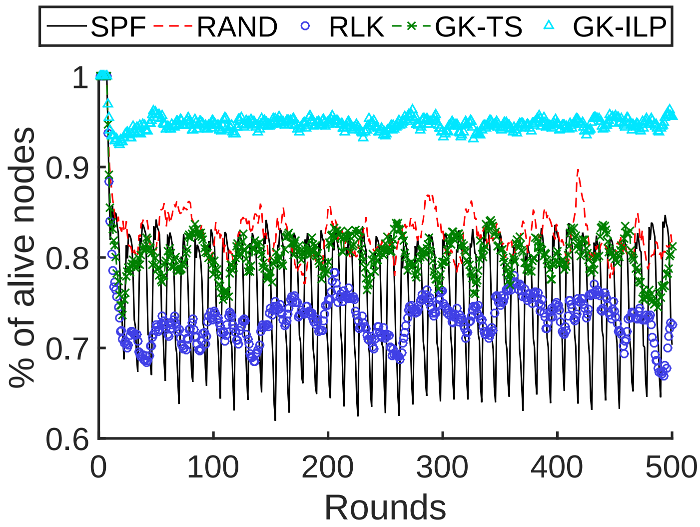
Figure 9.6: Energy Percentage Distribution in homogeneous setting in a 100×100 area Ω.

Energy Distribution. In this metric we examine the energy distribution to the agents by the MC in percentiles over time. In particular, we tessellate the percentage of agents that have residual energy in the ranges of: [0%-20%),[20%-40%),[40%-80%),[80%-100%]. We take some samples of the network in terms of energy distribution and we examine the % of the agents that lie in each of the ranges.

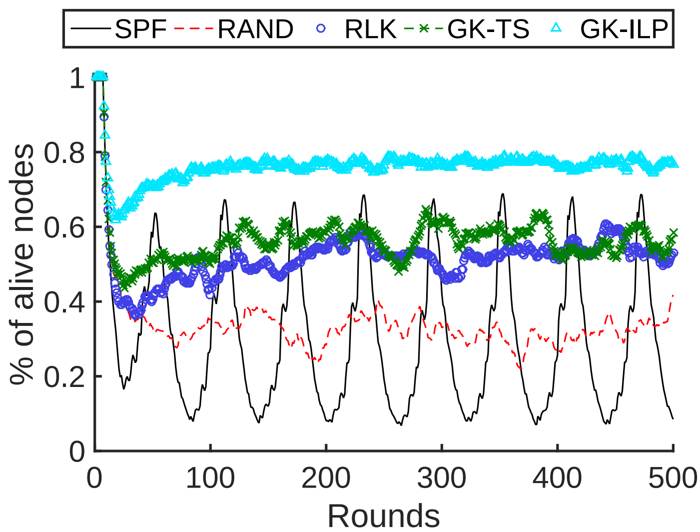
Distance Coverage. In this metric we examine the cumulative distance covered by the MC in the network. This metric although it is not directly correlated with the operation of the network itself, it can lead to useful conclusions regarding the charging process and the efficiency of the route that the MC is following. In addition, this metric is associated to relevant movement costs of the MC.

9.7.3.2 Findings

Homogeneous Agent Distribution. Figure 9.5 depicts the percentage of alive nodes (*survivability of the network*) in an homogeneous agent distribution for a (a) 50×50 and (b) 100×100 area Ω. We observe in the subfigure (a) that the *GK-ILP* strategy outperforms the other ones, as expected. This is due to the knowledge the Mobile Charger has and its ability to best exploit the *Weighting Function.* The second best strategy is the *Random Walk* of the Mobile Charger and this is due to the nature of the homogeneous area and the fact that the random walk probabilistically will eventually visit the entire area. Comparing the *RAND* to the *Space-Filling* strategy, it distributes "more evenly" the probabilities of visiting all the subareas. The *SPF* strategy comes third since the MC is sweeping the network and thus some sub-areas are left without being charged until the MC will revisit them in the next iteration. The *GLK-TS* performs even worse. This may be explained by the limitation of the positions the MC can visit when this strategy is applied, i.e. it may only visit the centres of the tiles of the tessellation. In the case where nodes are positioned towards the edges of the tiles, the MC will not have the chance to fully charge these nodes in one round. We observe that in the homogeneous set-up, the *RLK* strategy has the poorest performance: the MC has limited information about the agents and they are equally



(a) Five strategies compared in a 50×50 area Ω



(b) Five strategies compared in a 100×100 area Ω

Figure 9.7: Percentage of alive nodes over 500 Rounds in heterogeneous setting

distributed over the area Ω. We observe that in all settings of 50×50, 100×100 and 150×150, the strategies follow the same trend. The differences of the strategies in comparison to the topologies lie in the absolute values of % of alive nodes they are able to achieve. In a bigger area with the same MC the distances are longer thus the

MC does not have enough speed and sufficient time to keep a high % of overall alive nodes.
Figure 9.6 shows the energy distribution in percentiles in the homogeneous 100 × 100 area. In general we observe that the performance of all the strategies is stable over time. We note also that even though the *GK-ILP* performance in terms of number of alive nodes is much better than the other strategies, its energy distribution percentiles are only slightly better. The *SFP*, *RAND* and *GK-ILP* have relatively high values for nodes with energy levels higher than 40%.

Heterogeneous Agent Distribution. Figure 9.7 depicts the % of alive nodes in an heterogeneous agent distribution for a (a) 50 × 50 area Ω and (b) 100 × 100 area Ω. In the heterogeneous setting the *GLK-ILP* strategy is again clearly the best in all topologies, as expected. In the 50 × 50 area the *GK-TS* and the *RAND* have almost identical behaviour but in the 100 × 100 area the *RAND* performs much worse. This is explained as follows: since the distribution of the agents in the area is done in a heterogeneous manner and there are three hotspots, when the overall area is small, the MC manages to cover a sufficient area thus charging a relative high number of agents. On the contrary, when the area is relatively big, the random walk of the MC does not manage to cover sufficiently neither the whole area nor the hotspots. The *RLK* strategy in the 50 × 50 area performs weaker again, even though much better in relation to all of the other strategies and much better than the *SPF* strategy in terms of maintaining the agents alive. However in a larger area, its performance increases quite significantly, i.e. in the 100 × 100 area the *RLK* strategy performs similarly well as the *GK-TS* although it is only employing local knowledge collected while traversing the network. At the same setting the performances of both zero-knowledge strategies, *SPF* and *RAND*, drop significantly. Lastly we observe that the *SPF* strategy maintains the least number of agents alive in both topologies and specifically it is following a “wave charging" every time it is passing through the hotspots.
Figure 9.8 shows the energy distribution in percentiles in the homogeneous 100 × 100 area. We observe that the *GK-ILP* manages to both keep a high number of nodes alive and hold a relatively even distribution over them. The *RAND* has a performance

similar to the homogeneous setting but compared to the non-naive strategies, it performs much better. Moreover, we observe that similarly to the performance of the number of alive nodes, the *RAND* and *GK-TS* perform equally good; i.e. both are being successful in keeping a relatively high number of nodes at high energy levels.

9.7.3.3 General Findings

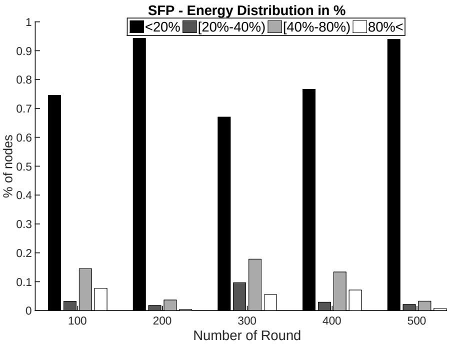
Conclusively, for a homogeneous distribution of agents, our simulation results suggest that when the knowledge of the MC is limited, as in most real world applications for mobile ad-hoc networks, it may be advisable to employ a naive, low-cost *Random Walk* strategy. In the heterogeneous setting, experimental results suggest an outstanding suitability of our local knowledge *RLK* strategy when the area of interest is relatively large. In addition, table 9.2 shows the cumulative distance travelled by the MC in a 100×100 area Ω over 500 Rounds in homogeneous and heterogeneous setting. We observe that the MC, in our *RLK* strategy and in the heterogeneous setting, is travelling the least distance. This is a significant result given that the *RLK* performs also very well in terms of keeping the a high number of agents alive.

Table 9.2: Cumulative distance (Units of Space) covered by the MC in 500 Rounds in 100×100 area Ω.

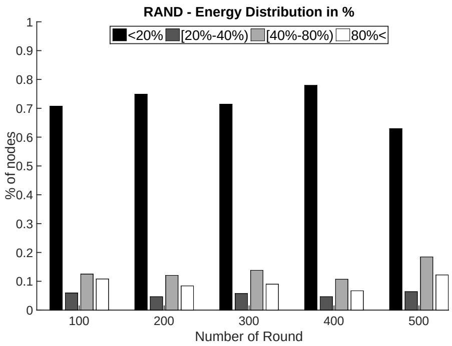
Strategy	*Homogeneous*	*Heterogeneous*
SPF	10800	10800
RAND	12000	12000
RLK	4271	2982
GLK-TS	6553	5387
GLK-ILP	10692	8933

9.8 Conclusions

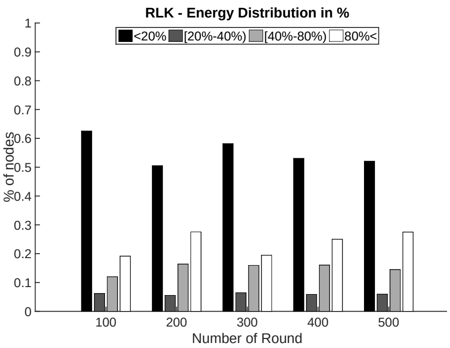
In this work we addressed the Wireless Recharge Problem in mobile ad-hoc networks characterized by diverse and unpredictable spatio-temporal dynamics. First, we defined the charging model and then utilized the notion of social attraction in order



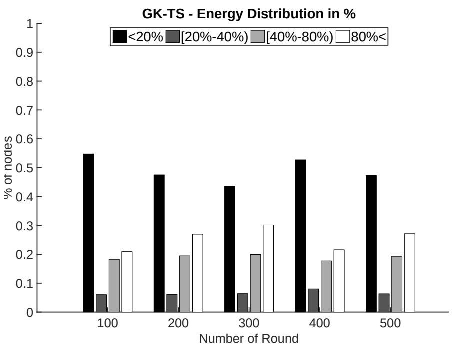
(a) Space-Filling Strategy



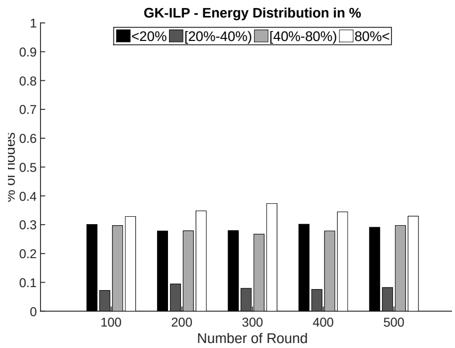
(b) Random Walk Strategy



(c) Reactive Local Knowledge Strategy



(d) Global Knowledge Tessellation Strategy



(e) Global Knowledge ILP Strategy

Figure 9.8: Energy Percentage Distribution in heterogeneous setting in a 100×100 area Ω

to better capture human mobility in our mobility model. We evaluated the performance of five qualitatively different traversal strategies for the MC; a zero-knowledge deterministic space-filling strategy, a zero-knowledge randomized strategy, two complete-knowledge centralized strategies and a local distributed knowledge reactive strategy. Our findings indicate that in homogeneous topologies the added value of the network information is degraded. However, in heterogeneous topologies strategies utilizing local network knowledge can outperform more powerful schemes if they efficiently exploit their knowledge.

In future research we aim at investigating more diverse topologies of the network area, more accurate mobility models as well as coordination schemes among multiple Mobile Chargers. In fact, our aim will be to efficiently coordinate the Mobile Chargers so as their effect on the network to be at least super-linear with respect to their number. Finally, we will also employ more detailed evaluation methods for further fine tuning the *Weighting Function*.

Part VI

Conclusions

10 Conclusions

• WSN, IoT and Smart Environments

In chapter 2 we propose two design approaches for Wireless Sensor Network architectures and related to smart and efficient buildings. The first approach is based around the IPv6 and 6LoWPAN protocol while the second one does not utilize IP protocols. We analyse theoretically the two approaches in a bottom-up analysis and we demonstrate the advantages and disadvantages. Afterwards, we set a use-case scenario and we implement them in order to experimentally evaluate them in terms of memory footprint, energy consumption and latency. Our findings indicate that for large scale WSN and systems with focus in the IoT vision, the IPv6 approach is more suitable.

In chapter 3 after we identified in the previous chapter, that for Smart and Green Buildings in the IoT era the IPv6 approach is more suitable, we present *Syndesi*: a framework for creating Personalized Smart Environments using Wireless Sensor Networks. The framework is capable of integrating several heterogeneous wireless networks comprised of sensors and actuators, electronic and electrical appliances and smart devices. Our framework is designed to provide increased comfort experience to the users, energy savings for the building and personalized services, through a set of UIs and actuation points. From the sensing point of view, the sensors expose their resources to the core of the system as services following the RESTfull architecture style and the CoAP protocol which allows for easy integration and scaling up. At the heart of the system a CoAP to HTTP proxy is implemented for an easy translation to and from Web Services. *Syndesi* is able to provide the personalized services tailored to the preferences of the users automatically or the users can manually interact with it via their smart-device or the WEB. Our proposed framework was implemented in the premises of our building and two scenarios were realized.

In chapter 4 we tackle the problem of air pollution monitoring where we present an automated, near-real time and low-cost pollution measuring system using Wireless Sensor Networks and Unmanned Aerial Vehicles. The architecture of this airborne WSN which we name as *AIRWISE* has advantages compared to other systems in regards to mobility, flexibility, cost and resolution. Air quality sensors integrated with embedded devices enable the measurement of the concentration of several air pollutants and atmospheric parameters in an efficient and highly accurate way. We present a model, two schemes and their respective algorithms for facilitating the monitoring process. The first one is a naive sequential monitoring scheme in which the monitoring of the three dimensional space is done in a deterministic manner, while the later one is a dynamic monitoring scheme where some subregions of the area of interest are dynamically monitored. The use of these dynamics enable a more efficient use of the limited and constrained resources of the airborne WSN.

• IoT and Crowdsourcing

In chapter 5 we introduce the idea of crowdsourcing and we categorize the contemporary crowdsourcing initiatives and identified the different motivational factors which drive the crowd to contribute to its specific focus. The three categories in which we divide the different crowdsourcing modes are the: *collaborative, compensation and competition* focused. We conducted a survey where 95 people answered and from the results we see that in the *collaboration* mode, the crowd is mainly motivated by a will to contribute to a larger cause. In the *compensation* mode, the crowd is motivated mostly by the possibility of earning money, gifts or discount coupons. Lastly, in the *competition* mode, challenge is the main motivator. The common parameter in all the three modes of crowdsourcing we found out that is the interest of the crowd in gaining reputation and recognition and its enjoyment in learning something new or developing a new skill.

In chapter 6 we propose an architecture design approach of an IoT and crowdsourced-enabled platform. The architecture integrates on the hardware level, smartphones, PCs, IoT resources, smart power meters, testbeds, sensors and actuators. On the personal level it interconnects, researchers, testbed owners, experimenters, users and participants via WEB GUI's, visualization tools, smartphone applications and services. All those components are harmonically embedded into our platform in such a way that it enables heterogeneous IoT resources to be homogeneously available and interoperable with each other while at the same time the crowd can actively participate in the research or experiments defined in the platform.

• IoT, Crowdsensing and Incentive Mechanisms

In chapter 7 we introduce the basic concept behind the Mobile Crowdsensing Systems (MCS) in which any smart device with sensory capabilities interconnected to such a system can opportunistically or participatorally augment the information provided to it. In this context we propose an IoT and MCS enabled architecture together with crowdsensing incentive mechanisms. We developed a testbed implementing this architecture in the premises of a building, and through a mobile application we engaged users to participate in a use-case scenario, in order to evaluate both the incentive policies and the behaviour of the testbed. The collected data from the the experimental evaluation fed our simulations where we used the same services and incentive mechanism to scale up the scenario for larger crowd and bigger area. In conclusion, by using our proposed IoT and MCS-enabled system in the context of Smart Buildings we can increase the experience comfort of the people inside it, decrease the energy consumption of the building, and provide the researchers an agile tool for experimenting on different incentive policies.

In chapter 8 we propose the concept of *Synergistic user and context analytics* which extends the recent proposals for socio-physical or personal analytics by including more comprehensive data sources from the field of MCS. We argue that, in addition to the smartphones' sensors and online social interactions, by including environmental and application specific data, we can better capture the interactions between users and their context. We present a privacy-preserving, location- and context-based platform, based on Mobile Crowdsensing and Internet of Things, a data model for representing the different sources of data and their connections, and a prediction engine for analyzing the data for producing useful insights.

• Wireless Power Transfer

In chapter 9 we investigate the problem of wireless power transfer (WPT) in mobile ad-hoc networks. In particular we investigate which traversal strategy should a Mobile Charger (MC) follow in order to efficiently recharge agents that are randomly and dynamically moving inside an area of interest. We first formally define this problem as the Charger Traversal Decision Problem (CTDP) and prove its computational hardness. We then present the models for the problem in regards to mobility, energy and charging. Then we define a weighting function which evaluates several network parameters in order to prioritize the nodes during the charging process. Based on this function we define three traversal strategies for the MC; a global-knowledge strategy that uses an Integer Linear Program to optimize its trajectory; a global-knowledge strategy which tessellates the network area and prioritizes the charging process over each tile; a local-knowledge strategy that uses local network information collected and ferried distributively by the moving agents. We also evaluate two naive zero-knowledge strategies; a space-filling deterministic one in which the MC systematically sweeps the network area and a randomized one in which the MC performs a blind random walk. We evaluate these strategies both in homogeneous and heterogeneous agent distributions and for various network sizes with respect to number of alive nodes over time, energy distribution among the nodes over time and charging efficiency over distance travelled. Our findings indicate that in small networks agnostic strategies are sufficient. However, as the network's size scales up, the use of local distributed network information achieves good performance-overhead trade-offs.

Annex: Publications

Publications which I have co-authored:

- **Orestis Evangelatos**, Kasun Samarasinghe, and José Rolim, *Evaluating design approaches for smart building systems*, 2012 IEEE 9th International Conference on Mobile Adhoc and Sensor Systems (MASS), IEEE, Las Vegas, USA, October 8-11, 2012, pp. 1–7.

- **Orestis Evangelatos**, Kasun Samarasinghe, and José Rolim, *Syndesi: A framework for creating personalized smart environments using wireless sensor networks*, 2013 IEEE 9th International Conference on Distributed Computing in Sensor Systems (DCOSS), IEEE, Cambridge, USA, 2013, pp. 325–330.

- **Orestis Evangelatos** and José Rolim, *Airwise - an airborne wireless sensor network for ambient air pollution monitoring*, 4th International Conference on Sensor Networks (SENSORNETS), Angers, France, 2015, pp. 231–239.

- Constantinos M. Angelopoulos, Julia Buwaya, **Orestis Evangelatos**, and José Rolim, *Traversal strategies for wireless power transfer in mobile ad-hoc networks*, in Proceedings of the 18th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM), Cancun, Mexico, 2015, ACM.

- Constantinos M. Angelopoulos, **Orestis Evangelatos**, Sotiris Nikoletseas, Theofanis P. Raptis, José Rolim, and Konstantinos Veroutis, *A user-enabled testbed architecture with mobile crowdsensing support for smart, green buildings*, in 2015 IEEE International Conference on Communications (ICC) London, United Kingdom, June 8-12, 2015, pp. 573–578.

- Anna Stahlbrost, **Orestis Evangelatos**, Srdjan Krco, Sebastien Ziegler, Constantinos M. Angelopoulos, Sotiris. Nikoletseas, and Theofanis P. Raptis, *Understanding crowdsourcing modes and crowd motivators*, in Proceedings of the 14th International Society for Professional Innovation Management (ISPIM) Conference, Hungary, June 2015.

- Stevan Jokic, Anna Rankov, Joao Fernandes, Michelle Nati, Sebastien Ziegler, Theofanis P. Raptis, Constantinos M. Angelopoulos, Sotiris Nikoletseas, **Orestis Evangelatos**, José Rolim, and Srdjan Krco, *Iot lab crowdsourced experimental platform architecture*, in 5th International Conference on Information Society and Technology (ICIST), Kapaonik, Serbia, 2015.

- Andreea Hossmann-Picu, Zhongliang Zhao, Zan Li, Torsten Braun, Constantinos M. Angelopoulos, **Orestis Evangelatos**, José Rolim, Michaela. Papandrea, Kamini Garg, Silvia Giordano, Aristide Tossou, Christos Dimitrakakis, and Aikaterini Mitrokotsa, *Synergistic user - context analytics*, in ICT Innovations 2015, ser. Advances in Intelligent Systems and Computing, S. Loshkovska and S. Koceski, Eds., vol. 399. Springer International Publishing, 2016, pp. 163–172.

Annex: Projects

Projects in which I have worked for and have partially funded my research:

European Projects

Projects supported by the European Commission in the 7th Framework Programme for Research and Technological Development (FP7):

WISEBED is a European Research project which aims to provide a multi-level infrastructure of interconnected testbeds of large scale wireless sensor networks for research purposes, pursuing an interdisciplinary approach that integrates the aspects of hardware, software, algorithms, and data. *http://www.wisebed.eu/*

HOBNET is a European Research project which main objective is to ease and maximize the use of FIRE platforms by multidisciplinary developers of Future Internet applications focused on automation and energy efficiency for smart and green buildings. *http://hobnet-testbeds.eu/*

IoT Lab is a European Research project which aims at researching the potential of crowdsourcing to extend IoT testbed infrastructure for multidisciplinary experiments with more end-user interactions. *http://www.iotlab.eu/*

National Projects

The Nano-Tera **Wireless Sensor Network Laboratory** aims to use and extend the existing Wisebed wireless sensor network (WSN) testbed facility to support hands-on programming and experimentation exercises in wireless sensor networks. *http://www.nano-tera.ch/projects/332.php*

The **SwissSenseSynergy** is a project funded by the Swiss National Science Foundation (SNSF) which aims to provide a unifying framework for secure localisation and privacy-preserving location-based services. *http://www.swiss-sense-synergy.ch/*

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List of Abbreviations

6LoWPAN IPv6 over Low power Wireless Personal Area Networks

AC Alternate Current
AES Advanced Encryption Standard
ASCII American Standard Code for Information Interchange

Cf Californium
CoAP Constrained Application Protocol
CoRE Constrained RESTful Environments
CRUD create, read, update and delete functionalities

D2D Device to Device
DC Direct Current
DHCP Dynamic Host Configuration Protocol

EEPROM Electronically Erasable Programmable Read-Only Memory
eID electronic ID card
EU European Union

GENI Global Environment for Network Innovations
GPIO General purpose Input/Output
GPRS General Packet Radio System

GPU	Graphics Processing Unit
GSM	Global System for Mobile communications
GUI	Graphical User Interface
HDMI	High-Definition Multimedia Interface
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
HVAC	Heating, Ventilating and Air-Conditioning
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IoT	Internet of Things
IP	Internet Protocol
IPSO	Internet Protocol for Smart Objects
IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6
JRE	Java Runtime Environment
JSON	JavaScript Object Notation
JVM	Java Virtual Machine
LAN	Local Area Network
LLN	Low-power Lossy Networks
LoWPAN	Low-power Wireless Persoanal Area Network
M2M	Machine to Machine
MAC	Medium Access Control
MANET	Mobile Ad-Hoc Network
MAVLINK	Micro Air Vehicle Link protocol
MC	Mobile Charger

NFC	Near Field Communication
NGO	Non-Governmental Organization
OASIS	Organization for the Advancement of Structured Information Standards
oBIX	Open Building Information Exchange
OS	Operating System
OSI	Open Systems Interconnection
P2P	Peer to Peer
PC	Personal Computer
PHY	Physical Layer
PnP	Plug-and-Play
QoS	Quality of Services
RD	Resource Directory
RDC	Radio Duty Cycle
REST	Representational State Transfer
RF	Radio Frequency
RFID	Radio Frequency Identification
RGB	Red,Green,Blue
ROLL	Routing over low-power and lossy networks (IETF WG)
RPL	IPv6 Routing Protocol for Low-Power and Lossy Networks
RSSI	Received Signal Strength Indicator
RTT	Round Trip Time

SA	Synergistic Analytics
SaaS	Software as a Service
SOA	Service Oriented Architecture
SOAP	Simple Object Access Protocol
SQL	Structured Query Language
TaaS	Testbed as a Service
TCP	Transmission Control Protocol
TLS	Transport Layer Security
UART	Universal Asynchronous Receiver/Transmitter
UAV	Unmanned Aerial Vehicle
UDP	User Datagram Protocol
UML	Unified Modeling Language
URI	Uniform Resource Identifier
URL	Uniform Resource Locator
URN	Uniform Resource Name
WBAN	Wireless Body Area Network
WoT	Web of Things
WPAN	Wireless Personal Area Network
WPT	Wireless Power Transfer
WRSN	Wireless Rechargable Sensor Network
WSN	Wireless Sensor Network