PRESERVATION AND MANAGEMENT OF LOCATION PRIVACY IN THE INTERNET OF THINGS

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ABSTRACT

The Internet of Things (IoT) connects everyday objects including a vast array of sensors, actuators, and smart devices, referred to as “things” to the Internet, in an intelligent and pervasive fashion. This connectivity gives rise to the possibility of using the tracking capabilities of things to impinge on the location privacy of users. Most of the existing management and location privacy protection solutions do not consider the low-cost and low-power requirements of things; or, they do not account for the heterogeneity, scalability, or autonomy of communications supported in the IoT. Moreover, many traditional location privacy preserving techniques anonymize location information so that adversaries cannot infer or relate location information to specific users. However, these techniques do not consider the case where a user wishes to control the granularity of the disclosed information based on the context of their use (e.g., based on the time or the current location of the user).

To fill this gap, a middleware referred to as the Internet of Things Management Platform (IoT-MP) is proposed in this thesis. The IoT-MP provides users with fine-grained control over the granularity and disclosure settings of their location information in the IoT. It is based on a distributed architecture that utilises an agent, a manager, and a manager of managers paradigm. The IoT-MP adopts an extensible design where things are represented as attributes in a management database located at the manager. In this way, IoT applications can access things transparently over the Internet, irrespective of the underlying used communication technologies. The IoT-MP’s manager comprises several modules. The Privacy Module (PM), which consists of a Context Analysis Component, Privacy Manager Component, and Semantic Obfuscation Component, enables the user to alter the location of things and to control the granularity of the produced location based on a context-aware and policy enforcement mechanism. The obfuscation process is supported by a novel ontological classification of locations based on a geographical knowledge, which takes into account both the user’s informed consent and preferences. Furthermore, the proposed Semantic Obfuscation approach improves the performance of

two major classical location protection methods by making it harder on an adversary to infer the actual location of a device from a received obscured location..

To confirm the effectiveness of the proposed management platform in preserving location privacy in the IoT, a diverse range of experimental and simulation studies are carried out. The experimental studies aimed to demonstrate the capability of the proposed platform in preserving the location privacy of users in an IoT setup which uses physical low-power sensor devices. The setup involved the utilisation of several Bluetooth Low Energy (BLE) sensor devices, the implementations of two mobile applications and a web application. The results collected from the experimental works validate the IoT-MP approach in providing the user with a method that can be used to control to whom, when, and in which context the location information of their sensors is revealed. They further show that the proposed Obfuscation approach has outperformed the performance of the classic Dispersion method. For instance, using "Obfuscation level 3", it is found that the S-Obfuscation has produced better-obscured location by 60% than that of the Dispersion technique and by 50% than that of the Rand technique.

The simulation studies, conducted using the Opnet and NS2 simulation tools, combined several wireless network scenarios which utilise the low-power wireless ZigBee and IEEE 802.11ah protocols as a practical example of a heterogeneous communication network in the IoT. In these scenarios, as per the IoT-MP approach, privacy policies were defined for a group of sensors which took turns in requesting the location of each other. By observing and analysing the traffic stored in the log file of the simulation, specifically, the location information exchanged between the sensors, the privacy-preserving capabilities of the proposed platform in a large-scale heterogeneous network were demonstrated and verified. Additionally, it was found that the application end-to-end delay experienced by the ZigBee network is low. Furthermore, the average consumed energy to send a packet across the network by a ZigBee and 802.11ah node was also within acceptable levels. These performance results clearly show that the approaches of the IoT-MP in preserving the location privacy of things in the IoT has no noticeable impact on the power consumptions and network performance of both ZigBee and IEEE 802.11ah end devices.

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STATEMENT OF AUTHENTICATION

I declare that to the best of my knowledge the work described in this thesis is, except where otherwise stated, entirely my own work and has not been submitted for a degree at this or any other university.

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LIST OF ACRONYMS

.11ah	IEEE 802.11ah
6LoWPAN	IPv6 Low power Wireless Personal Area Networks
AODV	Ad-Hoc On-Demand Distance Vector
BLE	Bluetooth Low Energy
DSSS	Direct Sequence Spread Spectrum
EHR	Electronic Healthcare Record
EIS	Enterprise Information System
EPC	Electronic Product Code
FDMA	Frequency Division Multiple Access
FHSS	Frequency Hopping Spread Spectrum
HTTP	Hypertext Transfer Protocol
ID	Identification
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IKE	Internet Key Exchange
IoE	Internet of Everything
IP	Internet Protocol
IPv4	Internet Protocol Version 4
IPv6	Internet Protocol Version 6
JSON	JavaScript Object Notation
M2M	machine-to-machine
MANET	Mobile Ad-Hoc Network
MoM	Manager of Mangers
MTs	Managed Things
NS2	Network Simulator version 2
PAN	Personal Area Network IID Interface Identifiers
PKI	Public Key Infrastructure
REST	Representational State Transfer
RFID	Radio Frequency Identification
Rx	Receive
SNMP	Simple Network Management Protocol
SOA	Service Oriented Architecture
S-Obfuscation	Semantic Obfuscation
SSL	Secure Socket Layer
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
TLS	Transport Layer Security.
Tx	Transmission power
URI	Uniform Resource Identifiers
USN	Ubiquitous Sensor Networks
WAN	Wide Area Network
Wi-Fi	Wireless Fidelity

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CHAPTER 1- INTRODUCTION

The Internet of Things (IoT) is the future of the Internet. It provides societies, communities, governments, and individuals with the opportunity to obtain services over the Internet wherever they are and whenever they want. The IoT enhances communications on the Internet among not only people but also things. It introduces a new concept of communication which extends the existent interactions between humans and computer applications to things. Things are objects of the physical world referred to as physical things, or of the information world referred to as virtual things [1]. Things are capable of being identified and integrated into the communication networks. Physical things such as industrial robots, consumer products, and electrical equipment, are capable of being sensed, actuated, and connected to the Internet. More specifically, a physical thing can be described as a physical object equipped with a device that provides the capability of connecting to the Internet. The International Telecommunication Union (ITU) defines a device in the IoT as a piece of equipment with the mandatory capabilities of communications and the optional advanced capabilities of sensing and actuating [1]. On the other hand, virtual things are not necessarily physical or tangible objects. They can exist without any association with a physical object. Examples of virtual things are multimedia contents [2] and web services, which are capable of being stored, processed, shared, and accessed over the Internet. A virtual thing may be used as a representation of a physical thing as well such as the use of objects or classes in object-oriented programming approaches [3].

Communications in the IoT can occur between not only the users and things, but also exclusively between things. These include communications between physical things, (also known as Machine-to-Machine communications), between virtual things, as well as among physical and virtual things. This heterogeneity of communications extends computation and connectivity on the Internet to anything, anyplace, and anytime. As a result, the IoT is expected to be used in numerous application domains, including but not limited to, manufacturing [4], smart cities [5], agriculture and breeding [6], environmental

management [7], and smart homes [8]. Significantly, the IoT enables the sharing of information between different domains [9]. For instance, in the healthcare sector, the IoT supports the sharing of medical information among various healthcare professionals, and therefore it enhances the delivery of health services [10]. From a networking perspective, the IoT can be described as a heterogeneous network that connects many wired and wireless networks, including low-power wireless networks and personal area networks, with an increasingly complex structure. This heterogeneous network encompasses devices which connect to the Internet using various types of wireless, mobile and LAN technologies such as Wi-Fi, ZigBee, Bluetooth, and 3G or 4G technologies among other evolving communication technologies.

Therefore, the IoT has the potential to provide an intelligent platform for the collaborations of distributed things via local-area wireless and wired networks, and/or via a wide-area of heterogeneous and interconnected networks such as the Internet [11]. The availability of information coming from non-traditional computer devices in the IoT will change society and transform businesses. In 2010, the IoT market value was estimated to be worth more than 100 billion dollars by 2020 [12]. In 2013, Cisco forecasted that the economic value created by the IoT will exceed 14.4 trillion dollars in 2020 [13]. Cisco increased its forecast in 2014 to 19 trillion dollars [14]. Furthermore, IC Insights predicts that the number of new connections to the IoT will grow from 1.7 billion devices in 2015 to more than 3.1 billion devices in 2019 [15]. On the other hand, Cisco estimates that the number of connected devices to the Internet will exceed 50 billion in 2020 [16]. BI Intelligence also predicts that the number of things connected to the Internet will grow by 35% between the years of 2014 and 2019 [17]. Consequently, these forecasts and predictions highlight the significance and economic value of the IoT, and the role it plays in elevating communications on the Internet.

Beyond the massive technological opportunities and benefits of the IoT, important challenges such as interoperability, security, and privacy arise [18]. Currently, many research studies are involved in developing solutions to solve the various problems facing the IoT. However, the complexity of addressing the IoT challenges lays in the fact that these challenges are correlated together. That is, there is a need to achieve full

interoperability between the various types of things that communicate, seamlessly, over heterogeneous communication networks. This interoperability needs to be achieved while guaranteeing the best possible Quality of Service (QoS) and highest degree of security, trust, confidentiality, and privacy. Additionally, the IoT presents unique challenges for energy-efficient operations [19]. Many things in the IoT need to run for years on batteries [20]. Therefore, until contemporary power sources or energy harvesting solutions are developed, energy consumption remains a challenging issue in the IoT.

In the IoT, things, such as sensor devices, will be integrated into streets, homes, work and recreation places, buildings, shopping centres, cars, and other public environments. They will also be carried by people and communicate with each other locally, or with IoT applications remotely over the Internet. Therefore, things will have the capabilities of automatically sensing, communicating, and processing the information collected from their environments and their users [21], with a high degree of spatial and temporal precision. This information may comprise the exchange of users' personal and contextual information, including their location information. It is likely that new privacy issues will arise with such a deep penetration of technology in our life [22]. Therefore, the diversity of things and heterogeneous nature of the IoT have an impact on the privacy of the users [23]. Public concerns with regard to privacy issues are a major obstacle to the wide adoption of the IoT [24]. Chief among these issues is location privacy. Recent technological advances in wireless communications, location-enabled hardware, and location-identification techniques provide things with the capabilities of acquiring and revealing the location of their users. This gives rise to the possibility of using the tracking capabilities of things for the violation of the privacy of users [25]. Not only is preserving the location privacy of users vital, but also preserving the location privacy of the actual things is of paramount importance [24].

Typically, most location-based services do not require the personal identification of a user [26]. However, even without providing any personal identification, associating the location information collected by things with other inferred personal or contextual information, such as the time and nature of the activity performed, can lead to revealing a user's personal information. Combining the contextual information of things with other

quasi-identification information will infer other types of sensitive information such as, the contexts of things, their activities, and possibly the identity of the user. In the IoT, privacy is concerned not only with hiding the personal information of a user but also with the ability to control how this information is disclosed [27]. There are two major challenges associated with privacy in the IoT. The first relates to the protection of personal information, e.g., location information [28]. The second relates to the issue of profiling the users' information and tracking their movements by a third party without obtaining their consent [29].

Most of the existing privacy protection solutions are designed to work with traditional devices such as computers and mobile phones. They do not consider the low-cost and low-power requirements of things. Other solutions designed for Wireless Sensor Networks (WSNs), such as those in [30], were optimised to accommodate the low-power characteristics of sensor devices. However, they do not account for the heterogeneity, scalability, and autonomy of communications supported in the IoT. Many traditional location privacy preserving methods, such as the K-anonymity technique [31], anonymize location information so that adversaries cannot infer or relate location information to specific individuals. However, these anonymization methods do not consider the case where a user wishes to control the granularity of the disclosed information based on the context. Contextual data plays a significant role in the IoT as they are used to provide tailored services, increase the quality of information, and discover nearby services.

Although current research in the field has introduced some IoT middleware solutions, such as that in [32], these solutions only focused on particular aspects of the IoT; or did not cater for the unique characteristics of the IoT such as the heterogeneous nature of the communications encountered in the IoT. They do not also provide the users with methods allowing them to control the disclosure settings of their location information collected by things in the IoT. Other solutions such as the platform developed by Axeda [33] provides a Cloud-based system for managing things connected to the cloud. It provides security services for securing the communications between things and the cloud system as well. The Kaa platform [34] also offers a middleware solution to connect things to the cloud. However, Kaa requires the integration of a specific microchip in the hardware of the IoT

device. Besides, none of these middleware provide location privacy protection capabilities in the IoT.

To fill this gap, this research proposes the Internet of Things Management Platform (IoT-MP). The IoT-MP is a middleware providing a user with the capabilities needed to manage the location information collected by things in the IoT. The IoT-MP encompasses novel approaches allowing the management and preservation of location privacy of things and hence their users in heterogeneous communications in the IoT.

1.1 Research Questions

As discussed in Section 1.1, the IoT is characterised by its heterogeneous nature regarding its size, diversity of communications, and the variety of devices envisioned in the IoT. Therefore, things in the IoT, which generally have limited resources, may communicate seamlessly with other things or IoT applications in complex and dynamic environments. Specifically, things play specific roles in supplying information about an environment to other things or IoT applications. Also, things may process and receive information or actuation instructions from other things or IoT applications as well. Thus, the flow of information and actuation events, in the IoT, includes the exchange of the users' personal and contextual information including their location information. For instance, many IoT applications require the geographic knowledge about resources or things and utilise the location information in providing IoT services in fields as diverse as transportation, disaster management, utility management, smart cities, and e-health, among others. Therefore, given the rich, heterogeneous, and dynamic nature of communications encountered in the IoT, this research aims to answer the followings research questions:

How to manage the location privacy of things to prevent them from disclosing the location information they collect and carry about their users to unauthorised entities? Specifically, how to protect the location privacy of constrained things and that of their users in situations where decisions about disclosing location information need to be made by things dynamically without or with minimal human intervention?

To answer these research questions, the research investigated the following sub-questions:

- What are the existing techniques in use for protecting location privacy on the Internet? Can they be used, modified or improved to manage and protect location information in the IoT?
- Can an approach be used to control the disclosure and granularity of location information produced by things, given that things may be lightweight, mobile across many heterogeneous domains and networks, and involved in seamless IoT interaction scenarios; and how to accommodate the user's informed consent in this approach?
- Can existing network management solutions be used to manage the location privacy of things in the IoT? How can they be adapted, adjusted or improved to fit the requirements of the IoT?

1.2 Thesis Objectives

One of the main objectives of this thesis is to provide the users with a solution that enables them to manage the location privacy of their constrained things remotely over the Internet with no or minimal disruption to the IoT services. To achieve this objective, a middleware is proposed referred to as the Internet of Things Management Platform (IoT-MP). The IoT-MP incorporates a novel location privacy protection method referred to as the Semantic Obfuscation approach (S-Obfuscation). It relies on geographical knowledge when producing obscured locations.

The approaches provided by the proposed platform give the user the granule control over the disclosure settings of the location information produced or collected by things. They further allow the user to define location privacy disclosure policies that can be assigned to specific contexts, enabling them to control to whom, when, and to which extent and precision their location information is disclosed in the IoT.

1.3 Thesis Contributions

In this thesis, a novel middleware referred to as the IoT-MP is developed. The IoT-MP enhances the management and preservation of location information generated by things, including constrained things, in the IoT. It is well suited to operate in large-scale and heterogeneous communications networks such as those encountered in the IoT. The middleware is a major improvement to tradtional management and privacy protection techniques which were designed to work with conventional devices such as computers and mobile phones. Thus, they cannot be used efficiently to manage and preserve the location privacy of things, specifically constrained things, in the IoT. The proposed platform provides the user with the management and privacy-preserving capabilities over the location information produced by things in rich and dynamic contexts such as in applications where things are involved in seamless communications in the IoT; and in situations where things are moving across several heterogeneous networks, including LAN, Wireless, and Low-power networks.

On one hand, the middleware provides the user with a method to manage the location information of things in heterogeneous networks. On the other hand, the IoT-MP preserves the location privacy of things by incorporating a novel location privacy protection method referred to as the Semantic Obfuscation approach (S-Obfuscation). The S-Obfuscation provides the users with fine-grained control over the disclosure settings of their location information in the IoT. It provisions five levels of location Obfuscation offering the users the capability of controlling the granularity of the disclosed information in specific contexts. Significantly, the S-Obfuscation improves the performance of two major traditional location protection methods by incorporating geographic knowledge in the generation of the altered locations. This makes it harder on an adversary to infer the actual location of things from a received obscured location.

The IoT-MP employs a mechanism that allows a user to create user-defined policies that specify the level of location Obfuscation things should use when revealing their locations to other entities over the Internet. These policies allow the preservation of location information in situations where the privacy-disclosure decisions need to be made without

the real-time intervention of the user. Unless, a user has specifically configured a policy which requests his or her permission in real-time. Thus, the IoT-MP caters for the need to preserve the location privacy of users in seamless communications in the IoT with minimal or no disruption to the IoT services. The results collected from the experiments and simulations, conducted in this research, confirm the effectiveness of the IoT-MP in managing and preserving the location privacy of things, including constrained things, in large scale and heterogeneous networks. The performance results also show that the preservation and management solutions provided by the IoT-MP have no noticeable impact on the power consumptions and network performance of both ZigBee and IEEE 802.11ah end devices.

Additionally, this research makes the followings contributions:

- The establishment and quantification of a context. The proposed platform incorporated a context analysis process which allows users to attach location privacy disclosing policies and an Obfuscation level to a specific context. Thus, a method has been suggested to quantify contexts.
- The development of a privacy manager that enables users to define privacy disclosure policies.
- The development of an experiment that included several implementations and development processes that implemented the proposed IoT-MP. This experiment demonstrated the capability of the IoT-MP in enhancing the location privacy protection of things in the IoT. The experiment validated the possibility of managing efficiently using the proposed platform the location privacy of low-power sensor devices remotely over the Internet using physical sensor devices in real-time setups.
- The simulations of several wireless network scenarios which utilise the low-power wireless ZigBee and IEEE 802.11ah protocols as a practical example of a heterogeneous communication network in the IoT. The simulation work also confirm the capability of the IoT-MP in preserving the location privacy of things in large scale heterogeneous wireless low-power networks with no noticeable impact on the network performance.

1.4 Thesis Layout

The remainder of this thesis is organised as follows:

Chapter 2 provides the backgrounds and motivations of this thesis. It presents the state of the art of the issues challenging the IoT regarding interoperability, management, security and, privacy. The chapter discusses interoperability and its different types in the IoT. It explores the different ways and topologies available for integrating WSNs into the IoT. This is essential to understand and identify the contexts in which location information is used in the IoT. The chapter then moves into identifying the fundamental management challenges and requirements needed for the management of the IoT. Next, the chapter discusses the methods and technologies that can be used to obtain location information in the IoT. It investigates various localization techniques, including that which uses Bluetooth proximity technology, and examine their capabilities and risks in the light of the IoT. This is followed by a study which introduces a new vector of location privacy attacks envisioned in the IoT. The rest of this chapter selects and analyses two traditional Obfuscation techniques. It then outlines the weaknesses identified in these two techniques.

Chapter 3 introduces the wireless enabling technologies in the IoT. It first provides an overview of the contemporary wireless technologies, specifically low-power wireless protocols. This is followed by an analysis of their technical characteristics, including their topology, energy requirements, and their suitability for implementation in the IoT. It then reports on some of the evolving low-power wireless technologies and the issues arising from their use in providing connectivity in the last 100 m of the IoT. Specifically, the chapter provides analytical comparisons among ZigBee, 6Lowpan, IEEE 802.11ah, and other variants of Wi-Fi technology (802.11a/b/g/n/ac), as well as with LTE. It investigates the capabilities of these technologies in view of the challenges discussed in Chapter 2.

Chapter 4 introduces the Internet of Things Management Platform (IoT-MP) and the Semantic Obfuscation approach (S-Obfuscation). It first describes the major components of the S-Obfuscation. It then introduces the architecture of the proposed platform. The

chapter outlines the IoT-MP approach in providing the user with the management capability of their location information. It then presents the three major components of the IoT-MP where the notion of Managed Things, agents, managers, and MoM components are discussed. Specifically, the role of the manager in providing the middleware functionalities is highlighted. The chapter then moves into modelling and presenting the manager's modules. The followings modules are introduced:

1) The Communication Module, which supports the communications between things and the manager;
2) The Things Management Module, which provides management capabilities similar to those provided by SNMP but for things;
3) The Security Module, which leverages the security requirements needed for securing the communications between "things and the manager" and between "IoT applications and the manager";
4) The Database Module, which provides storage services;
5) The API Module, which provides an integrated and enhanced access interface for IoT applications.

The chapter then moves to outlining the Privacy Module, which is used by the user to define location privacy disclosure policies. The chapter also details the process of incorporating the S-Obfuscation into the Privacy Module of the manager. The chapter then highlights the capability of the proposed platform in preserving the location privacy of things and that of their users in the IoT.

Chapter 5 presents the experimental studies conducted in this thesis. They demonstrate and validate the capabilities of the IoT-MP previously proposed in Chapter 4. The chapter first outlines the four stages of the experiment. In the first stage, a setup is created where physical sensors are utilised to communicate sensory information to a mobile device in a piconet. In stage 2 of the experiment, the major modules of the proposed IoT-MP are implemented. It then moves to creating a network scenario where the data collected by the sensors are transmitted over the Internet via a mobile application to a web application implemented in this stage. Stage 3 and 4 report on the implementations carried out to

design an IoT application, which combined various software and hardware setups. This IoT application is used to request the location information of the sensors as part of a service it provides. This allowed the research to verify the effectiveness of the proposed approach in protecting the location privacy of the sensors. The results of several test cases conducted to demonstrate and validate the capability of the IoT-MP in preserving the location privacy of things in the IoT are also reported.

Chapter 6 reports on the simulation works conducted in this thesis. Firstly, it outlines the major aspects of the setups involved in the design of the simulations. It then moves to describe the results of mainly three simulation scenarios. The first scenario involves the design of a ZigBee-based network. The second involves the design of an IEEE 802.11ah-based network. The last scenario combines the previous ZigBee and IEEE 802.11ah simulations into one heterogeneous network. In each of these scenarios, the effectiveness of the proposed IoT-MP in preserving the location privacy of things is evaluated and verified. Also, in each of the simulations described above, the performance of the IoT-MP with regard to the end-to-end delays and energy consumptions are measured and analysed.

Chapter 7 provides the conclusions and future work of this thesis. The chapter mainly discusses the way the research is developed throughout the end and highlights its contributions. It also reports on the limitations of this work. Finally, the potential future directions for this research are illustrated.

CHAPTER 2- BACKGROUND AND CHALLENGES

This chapter presents the background of this work. It starts first by presenting the general issues challenging the IoT. The chapter then moves to study the localization techniques and identify the contexts in which location information is used in the IoT; including the derived and associated privacy issues. It then concludes by analysing the major traditional location privacy protection techniques and discusses their applicability in the IoT.

Section 2.1 discusses the general issues challenging the IoT with regard to interoperability, integration, management, and security. Studying the overall challenges confronting the IoT is essential to identify the factors impacting the preservation and management of location information in the IoT. Section 2.1.1 discusses interoperability and its different types in the IoT, specifically, the challenges derived from integrating Wireless Sensor Networks (WSNs) into the IoT. This section also explores the different ways and topologies available for integrating WSNs into the IoT. The chapter then moves into analysing some of the fundamental management challenges and requirements needed for the management of the IoT in Section 2.1.3. Next, the various security requirements relating to things and IoT applications are outlined and discussed in Section 2.1.4.

Section 2.2 discusses the traditional methods and technologies that can be used to obtain location information in the IoT. It investigates various localization techniques including that which uses Bluetooth proximity technology and their capabilities and risks in the light of the IoT. This is followed by a study which introduces a new vector of location privacy attacks envisioned in the IoT. In Section 2.3, two classic Obfuscation techniques are presented and analysed. The section then outlines the weaknesses identified in these techniques.

2.1 The Internet of Things: Research Challenges

The Internet of Things (IoT) goes beyond the typical computer-based-Internet model to a distributed heterogeneous model of connected things. The state of the art application in the IoT provides IoT services based on utilising and combining data received from various things. It is a complex system that has the capabilities of sensing information about the environment and collecting physiological measurements. It has also the capabilities to collect machine operational data, identify users, animals, other things, events in an environment, and the capabilities of processing and communicating these data with other things. Moreover, it has the capabilities of converting the data into automated instructions that feedback through the communication networks to other things with actuating capabilities. These things will, in turn, actuate other things, eliminating many human interference roles. Clearly, with such a diverse, complex, and heterogeneous model of the IoT numerous challenges arise.

To realise the unique and innovative characteristics of the IoT, management of things should be well thought-out as one of the fundamental enablers of this technology. There is a need to manage the unprecedented number of things connected to the Internet that generates a large amount of traffic, particularly things with low resources. With billions of things equipped with sensors and actuators entering the digital word using a vast array of technologies, incorporated into devices like lights, electric appliances, home automation systems and a vast number of other integrated machinery devices, transport vehicles, and equipment; the overall management of things become a necessity and cumbersome task. Towards this aim, this section reviews some of the significant issues challenging the realisation of the IoT with regard to interoperability, management, and security. Also, many of these challenges bring to light many significant requirements that need to be considered. These requirements relate to the nature and capabilities of things. Generally, things are characterised as low-cost and lightweight devices that communicate using low-power wireless technologies such as ZigBee or IEEE 802.11ah. Therefore, the resources of things such as memory, processing power, and battery consumption are very

limited. This is, in fact, a challenge to the application of many traditional networking, management, security, and privacy techniques.

Table 2.1 Emergent IoT applications and their impact on societies

IoT development in Healthcare	**The Healthcare Personal Area Network Application:** This application involves the use of personal devices in closed or local area setups. Examples are wearable technologies that can be used for the self-monitoring and administrating of a person's health. **Elderly Monitoring:** This application relies on a set of sensor devices which monitor the health condition of an elderly. The system can be used to collect information relating to the physical activities such as dietary and sleep patterns of the elderly as well. **Smart Medicine:** This application involves the administration of medications. It ensures that patients are taking the right medicine, with the correct dose on time as specified by their healthcare professionals. **Community Based EHR:** This includes outpatient care and electronic medical consultation subsystems that involve the digitation of health care operations. **Smart Emergency:** The smart emergency application is centered on collaborations and sharing of information between the various healthcare subsystems. It is an important component in each of the healthcare subsystems described above. Obviously this is due to fact that emergency services, such as calling an ambulance, are required in medical emergencies. However, the smart emergency application operations are not only limited to providing the service of automatically calling an ambulance. They involve other advanced services such as communicating the status of the patient automatically back to the hospital during transport including the required treatment. This process improves emergency services in hospitals as well. It helps with the better allocations and distribution of patients in hospitals in a given geographical area

IoT development in Smart City	**Smart home:** The IoT enables everyday household objects, electronics and appliances to communicate with one another either locally or via the Internet. Thus, it allows the user to control these household items in various ways. **Smart water:** The envisioned developments in water IoT based infrastructure systems are numerous. An IoT based water system can be used to improve water's quality, transportation, consumption, supply and demand, leakage, treatment, pollutions, and storage facilities such as in household tanks or on a larger scale such as in reservoirs. **IoT metering:** IoT metering is concerned with the metering of water, gas, and electricity within a smart home environment or on a larger scale e.g. within a city. Typically, metering applications rely heavily on sensor network technologies. For example, in environmental and agricultural monitoring systems, the IoT system uses wireless sensors for the monitoring of water, gas and electricity consumptions. **Vehicle-to-X Technology:** The IoT offers the capabilities of connecting cars not only to the Internet, but also to their surroundings. Therefore, an IoT smart car may interact with surrounding roads, buildings, traffic lights, pedestrians, emergency and police vehicles and personnel. Also, it interacts with other vehicles and people, in order to provide real time information for better self-car maneuvering. **Other smart city applications:** These include smart parking, smart lighting, structural health, smart environment among many others.

This low-power requirement adds another dimension to the challenges raised above. For instance, it is hard to achieve security on tiny things (e.g., parking sensors) compared to traditional computation devices (e.g., a mobile device). This is because it is infeasible to apply traditional security cryptographic-based techniques on things with low resources especially low computation and power resources [23]. Also, things or groups of things are often deployed in remote areas or in regions where accessibility is an issue [35], which makes changing the batteries of things a difficult task. As such any computation activity that consumes much energy or requires heavy computation is considered unviable. Therefore, addressing these challenges in tandem with the lightweight requirement of

things is essential for the successful deployment and advance of the IoT. The remainder of this section discusses interoperability and its different type in the IoT, WSNs integration issues, management, and the security concerns challenging the IoT. Privacy challenges are discussed in a dedicated section, i.e. Section 2.2.

2.1.1 The IoT Interoperability and Integration Challenges

Interoperability in information technology is as old as the Internet is, if not older. Solutions considering the issues associated with information systems' interoperability can be traced back to 1988 [36], and perhaps even earlier. Wikipedia defines Interoperability as "the ability to make systems and organisations work together" [37]. The IEEE defines interoperability as "the ability of two or more systems or components to exchange information and to use the information that has been exchanged" [38]. Other definitions of interoperability are further tailored according to the particular application's requirements or needs. As a result, different categories of interoperability have been emerging. Technical interoperability [39], Semantic interoperability [40], Syntactic interoperability [41], and Cross-domain interoperability [42] are examples of these categories.

All these types of interoperabilities are needed to support seamless and heterogeneous communications in the IoT. Achieving interoperability is vital for interconnecting multiple things across different communication networks. It defeats the purpose to have billions of sensors, actuators, tiny, and smart devices connected to the Internet if these devices cannot communicate with each other in a way or another. In fact, for the IoT to flourish, things connecting to the communication networks, which can be heterogeneous, need to be able to communicate with other things or applications.

In traditional computer environments, computer devices are treated equally when connected to the Internet. Their functionalities vary depending on how the users use them. However, in the IoT, each device would be subject to different conditions such as power energy consumption restrictions, communication bandwidth requirements, and computation and security capabilities. Additionally, things may be made by various

manufacturers that do not necessarily comply with a common standard. Things may also operate using a variety of communication technologies. These technologies do not necessarily connect things to the Internet in the same way a typical computer device usually do. For instance, we will see in Chapter 3, that 6LoWPAN offers interoperability with other 802.15.4 devices as well as with any IP-based devices using a simple bridging device. However, an advanced application layer gateway is required to bridge between ZigBee and non-ZigBee networks [43].

Moreover, the highly competitive nature of the IoT makes interoperability between things even a more difficult task to achieve. Besides, wireless communication technologies are evolving and changing rapidly. This adds to the complexity of creating interoperable communications in the IoT as well. This raises many integration issues in the IoT. Service descriptions, common practices, standards, and discovery mechanisms are among the many other challenges that also need to be considered before enabling interoperable interactions between things [44].

2.1.2 WSNs Topologies in the IoT

Integrating WSNs in the IoT, where sensor nodes dynamically join the Internet, collaborate or communicate with other similar sensors or other types of things, opens the door to novel challenges. In this section, we will explore the ways in which WSNs could join the Internet as part of the IoT. This will help the research to identify the contexts of communications in which location information is used.

Network-based Integration

In the Network-based Integration topology, the sensors join the Internet through their network gateway as shown in Figure 2.1. In the case of a multi-hop mesh wireless topology, the sensors rely on a base node, also known as a sink, which even possesses gateway's capabilities or have a connection to a gateway. The sensors, in this case, are not directly accessible on the Internet. Communications between a sensor of a particular

WSN and that of another WSN or/and with other things on the IoT are not going to be direct but via the WSN's base node.

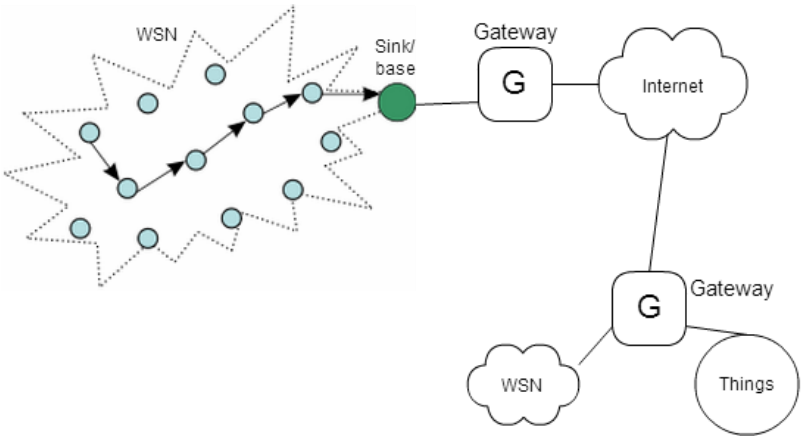


Figure 2.1- Network-Based integration

Independent Integration

In the Independent Integration topology, the sensors can connect directly to the Internet independently from their base point. As a result, the interaction between an independent sensor and other things in the IoT can be established without the need to pass by the intermediate node (i.e. the sink node in the WSN). The topology of such a network is given in Figure 2.2. However, giving an IP address to every sensor, for the purpose of connecting to the Internet, may not be the right approach. This is because wireless sensors are generally characterised by their low-cost and low-power features with packets exchanged across the network periodically and in small sizes [45]. Therefore, it is quite challenging to provide every IoT device with an IP address to connect to the Internet. This is due to the communication and processing overheads associated with the use of the TCP protocol that challenges the capabilities of small and low-cost sensors [46].

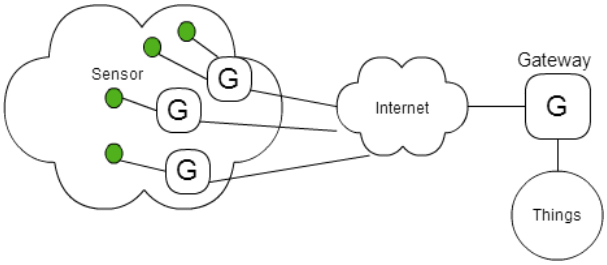


Figure 2.2- Independent integration

Hybrid Integration

Figure 2.3 shows the "hybrid integration" topology. In this topology, the IoT integrates WSNs using a mixture of the previously introduced topologies.

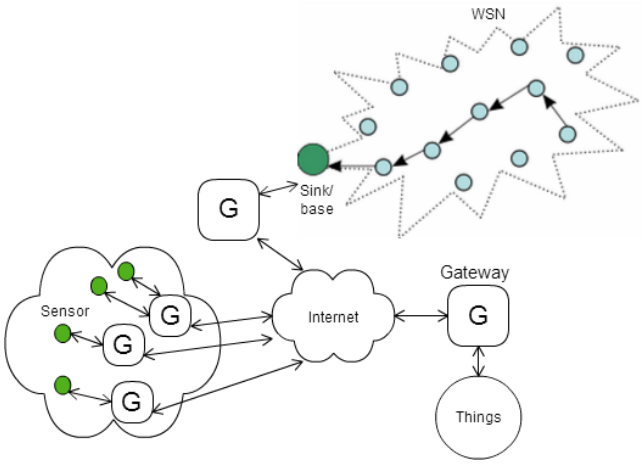


Figure 2.3- Hybrid integration

The wireless sensor nodes involved in each of the network topologies presented in Figure 2.1, Figure 2.2 and Figure 2.3 may have different characteristics. Their technical requirements vary from one to another. For instance, in a Network-based Integration, the sensors rely on a base node when connecting to the IoT. The base node possesses more computational, energy and communication resources when compared with a regular sensor node. A base node connects to the Internet in two ways:

(1) Basic: the base point provides basic gateway services such as protocol translation services and routing [47]. It typically forwards the information collected by the WSN's nodes to a server.

(2) Advanced: In addition to its gateway functionality, the base point has the capabilities of computing, and performing some data analysis. This can help reducing redundancy in the network.

Consequently, at least, the base node in a WSN requires an IP address to connect to the Internet. In the case of a Network-based Integration, there is a need to identify uniquely all the sensors on the Internet. Traditionally, the Internet is designed around an address-centric scheme (IP address) as almost all transactions (e.g., HTTP and email) require information about where the data are hosted [48]. Henceforth, a solution based on globally uniquely identifying things should be explored. Dynamic address allocation schemes similar to DHCP and translation schemes similar to DNS need to be exploited as well.

2.1.3 The IoT Management Challenges

The IoT will certainly include some devices that produce contents that need to be retrieved only by authorised users or things. Searching, finding and accessing things on the IoT require effective addressing policies. Therefore, the identity of Things is an important topic in the IoT that requires further research. Currently, Domain Name service (DNS) is the Internet naming service that translates IP addresses into human-readable names. In the IoT, things will be connected using various technologies and protocols. Some of these protocols are non-HTTP, and some might not even be based on the IP protocol [49]. Therefore, not all devices in the IoT would necessarily have an IP-address. As a result, there is a need to identify uniquely things on the IoT.

Additionally, the characteristics of the traffic exchanged by things, in the IoT, could be periodic and subtle. Further contributions are needed to determine if the TCP protocol is adequate to use in the IoT or if a new concept of a transport layer is required. This is because TCP is a connection-oriented protocol, in which sessions always starts with a connection setup procedure known as the three-way handshakes. Given that some of the communications within the IoT will involve the exchange of an only small amount of data generated from constrained devices, the TCP protocol cannot be used efficiently for transmission control. For example, consider a case where an IoT sensor is to exchange a

small amount of data in a single session with another device or application. In this case, the use of the TCP congestion control mechanism is considered to be ineffective. This is because the whole TCP session will be concluded with the transmission of the first segment and the consequent reception of the corresponding acknowledgment [50]. Interoperability between TCP and future non-TCP enabled devices need to be taken into consideration as well.

On the other hand, the research into device naming or identity management is an active area as well. For instance the work in [46] points out that a device naming scheme should contain key elements of device meta-data such as the device's type and domain information. For addressing purposes, the format should allow accessibility and addressability to the physical world in a granule and efficient way. Profile services are also needed to aid the application query and system configurations such as the device status and presence [46].

Other works on identity management in the IoT are based on the Service Oriented Architecture (SOA) such as OpenID [51]. OpenID describes the process of authenticating users in decentralised systems. These authentication features are necessary for preserving privacy in the IoT. Preserving privacy has to take into account not only the privacy of services or data but also the discovery through user devices. The work in [52] discusses the need to distinguish between connected things and their identities. It proposes the use of tokens. A token is used by a device in an API call when engaging in communications. A user controls the process of issuing tokens. This approach allows the user to impose access control policies as to when that token can be used and how his or her information is shared [52].

2.1.3.1 Network and Device Management Challenges in the IoT

Traditionally, network management solutions are needed to manage network equipment, devices, and services. However, in the IoT, there is a need to manage not only the traditional networked devices and their services but also an entirely new range of things. The enormous number of things and their diversity create many management

requirements. Thus, traditional management functionalities such as remote control, monitoring, and maintenance are considered of paramount significance for the operation of things in the IoT. However, these management solutions need to evolve to cater for the unique characteristics of the IoT. This is because the IoT is of a diverse nature supporting heterogeneous communications and seamless machine-to-machine interactions. This is in addition to the distinctive management capabilities required for managing things in the IoT. For example, self-configuration and network reconfiguration are essential management requirements in the IoT.

Moreover, traditional network management solutions usually aim at providing management information with a minimal response time. However, in some IoT scenarios that may involve lightweight devices, the management solutions should provide comprehensive management information with minimal energy use [53]. Nevertheless, the characteristics of data generated in the IoT are distinct from other data in use today [54]. For instance in [55], IoT data have been described as having five distinct characteristics: Heterogeneity, Inaccuracy of sensed data, Scalability, and Semantics. We add minimally or constrained as another important feature governing data in the IoT as, generally, things in the IoT have limited computation, communication, and power resources at their disposal [56, 57].

Therefore, management solutions are needed to allow managers to perform many maintenance tasks remotely over the Internet and possibly across many heterogeneous interconnected networks. These management capabilities should aim at reducing errors and accelerating response time. The ability to turn things on and off, disconnecting things from specific networks, and monitoring the statuses of things are amongst the important tasks that these solutions should support. Additionally, having a management system deployed in an IoT network helps in eliminating travel's and staff training's costs. Also, it helps in accelerating the response to failure events. For example, a management system that supports the remote monitoring, via the Internet, of sensors or other smart devices deployed in remote locations or a busy city is highly beneficial and essential in emergency applications [58]. Such a system allows managers to control remotely, diagnose errors,

and, troubleshoot IoT devices in real time, reducing costs, and accelerating many maintenance tasks.

Nevertheless, the magnitude of network connections and data associated with the IoT poses additional challenges to the management of data and IoT services. These challenges relate to data collection and aggregation, provisioning of services, and control as well as monitoring the performance of things. In fact, performance monitoring and reporting systems are important to use in IoT applications that deploy things in remote locations where accessibility is an issue. Performance is also considered important in emergency applications where failure can be catastrophic. Thus, management solutions should provide the capabilities needed to monitor the performance of things and the IoT network as well. Performance statistics relating to response time, availability, up and down time, among others are also highly advantageous. Other performance requirements relate to the hardware of things. This is because providing insights into the health of things and their networks are a significant performance activity. For instance, monitoring and reporting the changes in the state of things (e.g., the status of an actuator whether it is running or no), the ambiance's temperature, hardware's temperature, battery levels, among others, are necessary for the overall management of things in the IoT. Table 2.1 describes the major management issues challenging the IoT.

Table 2.2- Management issues

Configuration Management	• How things are set up and by whom? • Connecting to a network. • Self-configuration capability. • Asynchronous Transaction Support. • Network reconfiguration.
Things control	Control issues including turning things on and off, disconnecting things from specific networks, and connecting to other.

Table 2.1 (Continued)

	To effectively control a thing, a prior knowledge of the thing's status is required. Therefore, "Things control" complements "monitoring of things."
Monitoring	It is essential to the operation and monitoring of things to know the status of things e.g., running, listening, down, sleep mode. Therefore, once things are deployed and in use, there should be a way to monitor their statuses. These are in addition to: • Network status monitoring • Network topology discovery. • Notification. • Logging.
Things maintenance:	Detecting the failure of things is important, specifically in an IoT network which might involve a larger number of things. A tool or software is required for detecting and addressing the failure of things. Other issues relate to the general maintenance tasks of things e.g., software update, patch update, protocols version detections.
Things performance	Monitoring the performance of things is needed so sign of stress can be detected before the occurrence of any failure. This is significant for things that might be deployed in remote locations, and essential in emergency applications [58], where availability and other QoS parameters are of high importance.
Things security and privacy	There are basic security challenges such as authorisation, authentication, and access control that need to be addressed. Security bootstrapping mechanisms are also required. Other security issues are associated with things-to-things communications. For instance, if things are to be accessed by applications or software independently from the human users, then there are security measures that need to be enforced to ensure that

	things are not leaking information and disclosing private information to unauthorised things or used miscellaneously. Things have their users and owners. Thus, privacy is vital as well [59].
Energy Management	• Management of energy resources. • Statistics on energy levels e.g., estimated lifespan.

2.1.3.2 Traditional Management Protocols

The purpose of a network management protocol is to transport management information from a device (e.g., a computer or a networked node) referred to as a managed device or object to an application referred to as the manager. Network management protocols are also used to transport control information from the manager to the managed devices. Traditionally, in a client-server scheme, a management protocol is used to transport messages between the manager and the network components. A network component can be a typical network device such as a server, router or a specific network interface on a router. Generally, network management protocols define a static protocol message format and a small set of predefined messages for gathering and posting managed information to and from the managed devices [60]. Emerging standards, which are based on the distributed object-oriented approach, define more complex network management architecture. In this approach, the management protocol is tightly coupled with the management application; thereby facilitating code-on-demand (COD) object transmission, plug-and-play component management, and also defining a rich set of communication primitives between managers and managed devices [61].

The two most widely used management protocols are the Simple Network Management Protocol (SNMP) and the Common Management Information Protocol (CMIP). Although these two protocols have a similar architecture, they vary slightly in operations. Both SNMP and CMIP define a single management device that assumes complete control over all management functions. The manager is an application that interacts with network

agents embedded in each managed device using the network management protocol. In the context of SNMP and CMIP, agents are simple computational entities that provide mechanisms for accessing managed information stored on the managed devices [25]. SNMP's agents store device-specific information in managed information bases (MIB). On the other hand, the CMIP protocol defines a managed information tree (MIT) to store and access configuration information.

The Simple Network Management Protocol (SNMP)

Although SNMP was designed specifically for managing IP-based data networks, it has become the de facto standard for telecommunications network management. The popularity of SNMP is mainly due to its simplicity that allows manufacturers to enhance their products with network management functionality with a minimal effort. This protocol also provides simple and hierarchical management architecture with multi-vendor support.

SNMP aims to unify and minimise the complexity of management functions between various networked and hardware devices. The use of SNMP reduces the cost of management. Significantly, the SNMP's architecture enables the efficient integration of devices across a network. It facilitates seamless integration and management of existing and newly added hardware devices on a network. Additionally, SNMP implementations define a set of management functions that can be easily adopted by network managers and developers of network management systems. Another characteristic of SNMP is extensibility. SNMP's design allows the addition of newly developed extensions with less complexity. The SNMP protocol is a platform independent as well. It supports an array of various network technologies.

The Common Management Information Protocol (CMIP)

Almost in parallel with the development of SNMP, the International Standards Organization (ISO) defined the specifications for the Common Management Information Protocol (CMIP). Unlike SNMP, CMIP is designed to provide network management operations for a wide variety of network architectures [27]. In the open systems

interconnection (OSI) architecture, the fundamental function of network management solutions is to assist with the exchange of management information between the manager and managed devices. This functionality is referred to as the Common Management Information Service Element (CMISE) and is composed of two parts. The first specifies the services provided by the network management, and it is termed as the Common Management Information Service (CMIS). The second part is referred to as the Common Management Information Protocol (CMIP) [26]. It specifies the mechanisms and message format by which the management information is exchanged between the manager and managed devices. The CMIP framework is broken down into three interacting components. These components consist of the Layer Management Entity (LME), the System Management Application Entity (SMAE), and the common management information protocol (CMIP), which facilitates the communication of managed information among the management layer and management devices.

The CMIP implements a much richer set of management functions when compared to SNMP. It organises the managed entities and manager using a hierarchical approach. This allows managed information to be accessed within the scope of the manager. This hierarchical approach significantly increases the protocol's scalability. However, because the services offered by the CMIS entities are considerably more sophisticated than the management functions of SNMP, CMIP protocol is considered harder to implement [27]. For this reason, CMIP has not gained as much popularity as SNMP. Even though SNMP has gained major popularity in network management systems, the IETF designed this protocol to manage TCP/IP-based local area networks. Therefore, the challenges posed by emerging communication standards require a more sophisticated network management approach.

Facing new technologies in the era of the IoT, network management approaches must implement scalable, flexible, robust, adaptive, and automated management architectures. This is because the IoT encompasses several heterogeneous networks consisting of a range of lightweight and more capable devices. This heterogeneity of devices and networks raises some novel management challenges. To address this challenge, studies such as the one reported in [62], examined the possibility of adopting existing network

management protocols for the management of constrained networks and devices in the IoT. It is found, through simulation studies, that SNMP makes efficient use of resources on constrained devices [62]. Future contributions are required to investigate the applicability and performance of traditional network management protocols such as the SNMP in physical IoT setups.

2.1.4 The IoT Security Challenges

The growth in the number of connected devices to the communication networks in the IoT translates into increased security risks and poses new challenges to security. A device which connects to the Internet, whether it is a constraint or smart device, inherits the security risks of today's computer devices. Almost all security challenges are transferred to the IoT. Hence, some fundamental security requirements in the IoT such as authorisation, authentication, confidentiality, trust, and data security need to be considered; which are shown in Figure 2.4.

Therefore, things should be securely connected to their designated network(s), firmly controlled and accessed by authorised entities. Data generated by things need to be collected, analysed, stored, dispatched, and always presented in a secure manner. Nevertheless, there are security risks associated with things-to-things communications as well. This is in addition to the risks relating to things-to-person communications. For instance, if things are to be accessed by things independently from the human users, then there are security measures that need to be enforced. These security measures are necessary to ensure that things are accessed only by authorised entities in a secure manner. Also, they need to ensure that things are not leaking information or disclosing private information to unauthorised things and users, or used miscellaneously. Figure 2.4 shows the inherited security issues that challenge the IoT, which are detailed as follows:

End-to-End Security

It is the process of protecting the communications and data exchanged between both ends of the communication without being read, eavesdropped, intercepted, modified, or

tampered. In the IoT, end-to-end security remains an open challenge for many IoT devices and applications. The nature of the IoT with its heterogeneous architecture and devices involve the sharing of information and collaboration between things across many networks. This poses serious challenges to the end-to-end security.

When devices have different characteristics and operate using a variety of communication technologies (802.11 vs. 802.15.4), establishing secure sessions and secure communications, become a very complex task to achieve. Additionally, not all devices in the IoT are equal. Currently, computers, smartphones, and other computerised devices connect to the Internet via HTTP, SMTP and the like for most of their activities. As such TLS and IPsec protocols are usually used to negotiate dynamically the session keys, and to provide the required security functions. However, some of the devices in the IoT do not possess the ability to run TLS and IPsec protocols due to their limited computation and power capabilities. Additionally, some embedded devices in the IoT have limited connectivity as such they may not necessarily use HTTP or even IP for the communications (e.g., a sensor in a WSN).

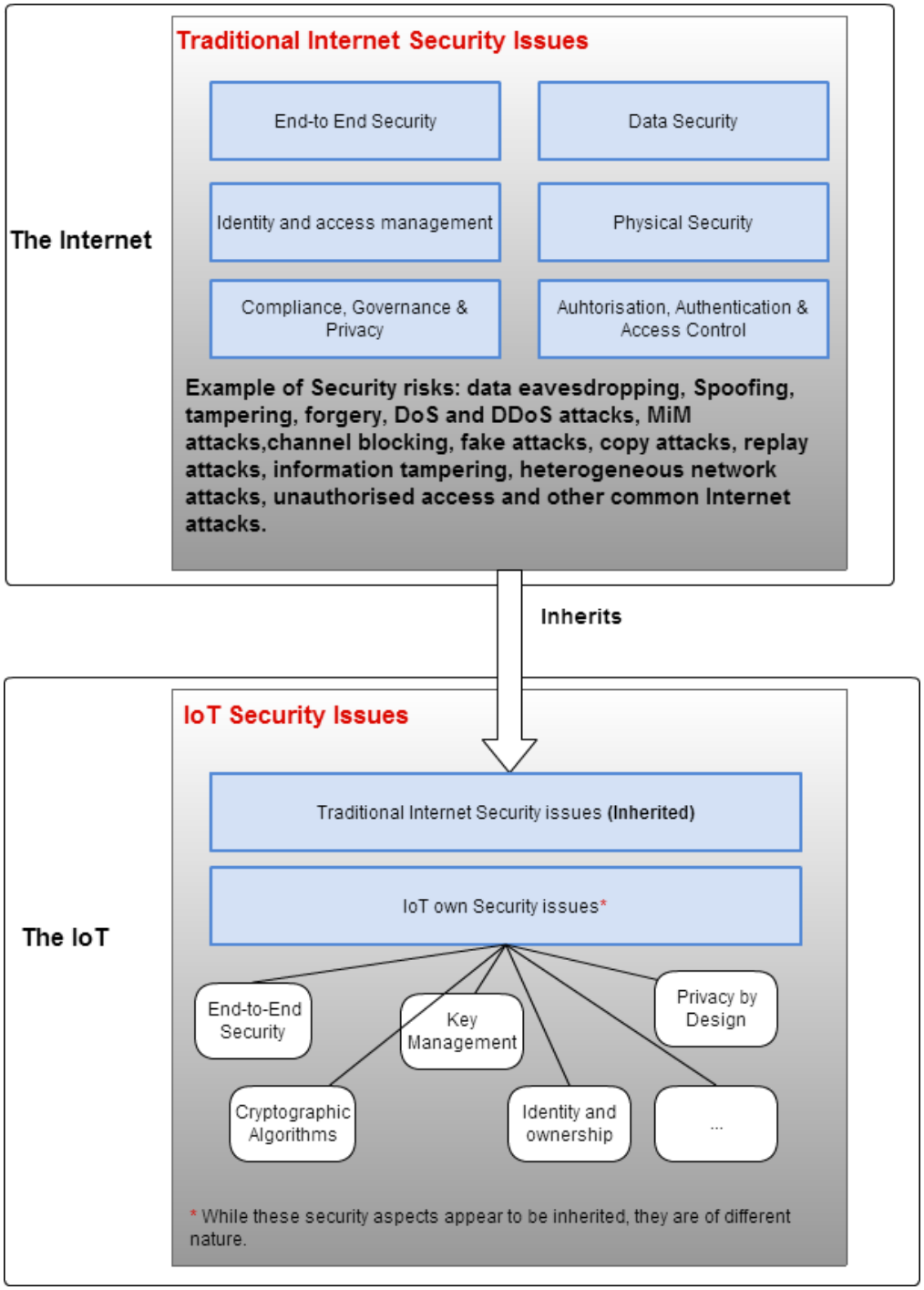


Figure 2.4- Some IoT security issues

Data Security

Data security involves the protection of data during communications and storages. In [63], data security is defined as the process of protecting data from destructive forces or from unauthorised access. Data security also referred to as information security is vital to the IoT security. Data security in the IoT is also associated with safety. Usually, the impact of data security breaches on the human life remained within the scope of hacking the personal information of an individual or getting unauthorised access to sensitive information such as financial data. However, data security breaches in the IoT could pose a serious threat to humans' safety. For instance, the accidental intrusion or malicious access that could interfere or interrupt the operations of a driverless car or a heart pacemaker will threaten the user's life. Security breaches in an IoT forest fire detection system could lead to catastrophic results as well.

Access control

The earliest access control system in use is physical access control. It is the physical access given to individuals based on physical guards. These access control measures are imposed and protected by humans or using devices such as parking machines, locks or keys. Typically, access control means restricting access to resources or physical access to a room or building. However, access control widely covers more than the physical access to a particular system. In some cases, access control is enforced using electronic access system cards, biometric devices, and other electronic methods. An example is the use of biometrical identification systems, such as a fingerprint identification system, to control access to resources. It sets the user privilege based on their biometric identity i.e. their fingerprint. The system controls access to services and networks by issuing access codes to the users. The process of enforcing access control on a resource is typically associated with an authentication and authorisation process. An authentication approval, for example, is based on some security techniques such as digital signatures, passwords, digital certificates, and smart cards.

Role-Based Access Control (RBAC) is a widely adopted access control approach that restricts access to systems or resources to authorised users. RBAC is based on the concept of assigning permissions to roles. However, in the IoT, things, including mobile things (things on the move), and users might require to access data anytime and anywhere from various types of devices. Therefore, the IoT poses new challenges for access control. In fact, the low power requirements of things, limited bandwidth, heterogeneity of communications, and the large scale of devices in the IoT create a unique set of access control requirements. Thus, traditional access control systems in their current status, such as RBAC, might not work efficiently in the IoT. Typically, the advantage of using RBAC in a system is the ability of easily adding access rights to a user, as long as it uses existing roles. In the IoT, as the number of connected devices and networks grow, the number of users and devices requesting access to data and services grow as well. Therefore, an IoT system that comprises thousands of devices would perhaps end up with thousands of roles and permissions that need to be maintained. Therefore, the challenge of managing access control to thousands of devices in the IoT will be simply transformed into a complex task that requires the management of a vast number of roles. This is known as "role explosion" and it is a major drawback of RBAC systems. This is because adding new roles to a system require a system-wide update. Generally, RBAC systems are implemented in a centralised architecture whereas an access control server assigns roles to users and grants them access to resources. Thus, updates at the system level are even harder to implement in the IoT given its distributed architecture.

Attribute-based access control (ABAC) is an access control model that abstracts identity, role, and resources information of the traditional access control into entity attributes [64]. An ABAC system grants access to services based on the attributes possessed by the requester [65]. Therefore, unlike RBAC, the ABAC model uses attributes to describe the requesters and the requested services. The associated attributes of each entity can be defined according to the system needs [66]. Thus, relying on attributes provides a much more fine-grained access control approach. As such access control strategies can be designed to use not only the requester' attributes but also other contextual data e.g., the location of the requester. Therefore, rather than granting or denying access to a resource

based on the role of a user, an ABAC system combines the user's attributes along with other contextual information which provides a way of dynamically generating context-aware decisions for requests [67]. This makes ABAC suitable for adoption in systems that require fine-grained access control such as the IoT. Additionally, the ABAC model suits the access control requirements of the IoT including the dynamic expansion in the number of connected users and things to the IoT.

2.2 IoT Privacy: Threats and Challenges

The convergence of location-based services (LBS) and wireless communication technologies in the Internet of Things (IoT) will enable a revolution in our everyday activities. Location based services are becoming more mainstream. Location-based service technologies play an important role in the IoT. Recent studies on the IoT show the importance of LBS in this domain. Examples are the integration of RFID technology into mobile devices in [68] and LBS into a mobile logistic information system [69], to name a few. While there are apparent benefits in using LBS systems in the IoT [70], they challenge the privacy of users [71]. IoT systems have the potential to enable systematic mass surveillance that could impinge on the personal privacy of users especially their location privacy. Location privacy concerns are not new. What is new is the increased scope of the problem in the IoT.

The automation in gathering and analysing the users' information in the IoT gives location privacy an added dimension. Currently, LBSs have seen a widespread adoption in mobile applications. Applications such as those which run on the iPhone or Android devices provide mobile users with the capabilities to access data anytime and anywhere. They improve the users' productivity in a variety of contexts ranging from personal customization e.g., calendar, work, Mobile banking, health to social networking [72]. Searching for a restaurant nearby, or exploring the area for shopping deals or discounts are some examples of LBSs in use today on almost every smartphone. In early 2000's, a study found that most teenagers use SMS to connect with their friends and arrange meetings [73]. Recently, SMS communications have evolved significantly with the penetration of mobile applications in our life. Nowadays, messaging and VOIP

applications are widely available on iPhone, Android devices, and Windows Mobile. They have taken over traditional SMS. Most of these applications also offer location sharing with friends. Smith refers to them as social location disclosure applications [74]. The cross mobile platform application “Whatsapp” or “Viber”, for example, enables mobile users to exchange, using an Internet connection, text messages, images, audio and video messages, and location information with one another at no cost. Other location based services have emerged and applications such as child location tracking services are becoming popular [75]. Location-aware browsing and geolocation marketing are other examples of LBS [76].

Location information can be obtained using a variety of location positioning techniques, such as GPS systems, cellular tower triangulation, or using the device's media access control (MAC) address e.g., on a Wi-Fi network [77]. In most LBS applications, users are unable to manage their locations disclosure settings effectively as they lack the control over the sharing of their locations. Obviously, the user can decide not to disclose his or her location information, but this limits the disclosure settings to two options “disclose” or “do not disclose.” However, the user may wish to stay anonymous and may not want to be identified by the LBS providers, especially when the information requested are sensitive. Researchers have long been aware of the potential privacy risks associated with the use of LBSs [78]. These risks have received considerable attention from the users and, in some cases, from service providers and government organisations as well. While better services can be provided if personalisation is allowed, not all LBSs require the personal identification of the user. However, the risk lays in the fact that positioning information in the form of a particular location can lead to the personal identification of the user and his or her behavior.

The study in [79] showed that a driver’s home location can be inferred from the GPS data collected from his or her vehicle even if the location information were anonymized. It further shows that the reconstruction of an individual’s route could provide a detailed movement profile that allows sensitive data inferences. For example, recurring visits to a medical clinic could indicate illness. Visits to activist organisations could hint at political opinions. In [79], it has been found that using clustering techniques, sensitive locations

of users can be exposed even when the GPS traces, collected by the location-based services, are anonymized. In [80], it was found that there are ethical issues associated with the use of GPS with the public users. Adequate safeguards need to be in place to avoid the abuse of information gathered through GPS technology. This was derived from an experiment where the authors used a combination of GPS data and diary logs of a volunteer over a period of two weeks. The study aimed at understanding the social implications of tracking and monitoring subjects. In [81], it has been shown that the future movements of a user can be predicted. The study used GPS data from a single volunteer collected over a four month period and used it to derive the location context of the user. They developed an algorithm which extracted locations of importance from the GPS data and used it to design a model that predicts the user's future movements. In a similar study [82], a protocol was developed for the purpose of identifying and inferring the home's location and identities of 172 participants. A reverse geocoder system was able to infer the homes' locations of roughly 5% of the participants correctly.

In the smartphone ecosystem, many mobile applications collect the location information of the users without their consent. For example, TaintDroid project [83], has identified that some Android's applications are releasing users' private information to online advertisers. TaintDroid is developed as a mobile application. It provides real-time monitoring services that monitor the traffics exchanged by other applications installed on the same device. It detects when the user's private information is released by an application to a third party. In a study of the 30 most popular applications, TaintDroid revealed that 15 applications were sending users' geographic location to remote advertisement servers. Another study found that 7.5% of the total applications on the Android market have the capability of accessing the user's stored contacts; while 28% of them had access to the user's location [84]. The study in [85] analysed the 101 most popular smartphone applications running on various mobile operating systems, including Windows Phone, iPhone, and Android. It was reported that out of the 101 applications, 56 were transmitting the unique phone ID to other companies without the user's permission. Forty-seven applications were caught transmitting location information to

third parties. The other five applications were found to be leaking other specific information like gender and age.

Some applications running on the Window Mobile platform had the capability to access the user's picture library, video library, webcam's video feed, microphone's audio feed, location, and other parameters related to the Internet connection [86]. Some of these applications also had the ability to add, change or delete files from both the picture and video libraries. In 2011, another study detailed the vulnerability of the RIM BlackBerry device [87]. The author developed a spyware targeted for Blackberry devices. The spyware was able to access and transfer sensitive data to a remote server without being noticed by the user. The study in [88], showed that a driver's home location can be inferred from the GPS data collected from his vehicle even if the location information was anonymized. The study conducted in [59] also reported on various privacy incidents associated with the use of mobile applications on the Android, Blackberry, iPhone, and Windows Phone platforms. It is concluded that the proliferation of mobile devices, GPS systems and other evolving technologies into our lives has introduced a new set of privacy threats.

Henceforth, given the impact smartphones have on the users' privacy, it is anticipated that the amount of personal data that would be occasionally collected in an IoT environment will be extremely larger than what we have ever experienced before. The IoT highly distributed nature of technologies, such as embedded devices in public areas, creates weak links that malicious entities can exploit and can as well open the door for a mass surveillance, tracing, tracking, and profiling of the users' movements and activities [89]. Moreover, the collection of sensitive data, the tracking of people's movement, data mining, and services provisioning can become automated and unpredictable in the IoT. With the pervasive growth of IoT-connected devices and applications, privacy threats are more likely to increase rapidly.

Consequently, privacy is one of the major implications the Internet of Things develops [90]. Privacy no longer means anonymity in the IoT. Profiling and data mining within any IoT scenario can form a potential harm to individuals due to the automatic process of

data collection, storage and the way personal data can be easily shared and analysed [91]. Also, the foundations, laws, and regulations for digital privacy were established some years ago when the Internet was centralised. These regulations deal, usually, with the collection of personal information, access rights, and ensure their correct handling [92]. This is no longer considered enough in the IoT. By definition, privacy means giving the users the option to control how their collected personal information is used, specifically for secondary usage and third party accesses. As an example, in the online environment, privacy choices are made by the user in real-time by controlling the amount of personal information the user discloses on the Internet (e.g., when filling a form). The concept remained the same in the evolution of social networking websites, where users in Facebook, for example, indicate to whom and to which extent their information can be revealed. These are known as the principles of notice and choice [93].

Conversely, the vision of the IoT allows automated machine-to-machine interactions independently from the user. One of the promising features of the IoT is the ability of devices to observe, sense their environments, and track the user's activities continuously. This poses new risks to the user's privacy. Thus, attackers may configure devices to join a given IoT system or network for the purpose of miscellaneously collecting information about the system environment and the user. The ability of things to participate in communications and exchange information, independently from the user, with each other in the IoT raises many privacy concerns. Smart devices such as smart home appliances, smart cars, and others that log data about their environment, e.g., their locations, constitute a source of risks and vulnerabilities with regard to the privacy of their owners. If these devices are connected, as envisioned in the IoT, and these logs are shared among IoT applications, then there is an increased risk of personal information leakage which threatens the users' privacy.

2.2.1.1 The First Hand Attack

In a first-hand attack, the attacker obtains the information directly from the user. An objectionable disclosure of information can happen accidently, such as the presence of security holes in a system, which leads to a leakage of the information or by tricking the

user. For example, cookiejacking is a form of a first-hand communication attack wherein the attacker can gain access to the session cookies of an Internet Explorer user. Thus, it can be used to gain access to the user's username and password stored in the cookie [94]. Additionally, news on security flaws found on computers', and recently mobiles' operating systems are all on the web. Back in 2003, serious flaws in the authentication and data transfer mechanisms on some Bluetooth enabled devices leading to the disclosure of personal information were reported [95]. Nowadays with the explosion of smartphones technologies, applications installed on the Android, iOS, Windows mobile devices, and others are known to have the capabilities of accessing the personal information of the users including their location information. This could form a vulnerability that may allow an attacker to obtain a live location feed. Bluetooth, NFC, and ZigBee devices are also prone to various security and privacy threats. These are a few examples of the triggers that might lead to a first-hand attack on location privacy. Additionally, numerous electronic devices which provide constant precise location information to location based servers are seen as overly permissive. If this location information is produced by automated devices, then these devices form a source of potential risk to the users' privacy. In a world surrounded by intelligence in the IoT, the threat of disclosing personal information unconsciously via a first-hand communication is significant. At the bare minimum, these concerns must be considered in the IoT.

2.2.1.2 The Gossip Attack

The English definition of the word "Gossip" is an unconstrained conversations or reports about other people personal or private affairs [96]. In digital terms, a gossip attack is relaying personal information from one entity to another unauthorised entity. The main difference between a gossip and first-hand communication is that the user is no longer the direct source of information. Disclosure of the user's personal information can be done without being noticed by the user. This behavior has been already observed in online activities and recently on some portable devices such as tablets' or mobiles' applications that sell the users' location information or their shopping behaviors to advertisement companies. It seems naive not to expect this type of information, which is available via things and fine-tuned by their technological advanced features and automation, not to be

similarly misused. The widespread use of devices and the deployment of IoT networks, such as sensor networks, will lead to an enormous amount of data being captured by commercial and state enterprises. This poses concerns relating to the issue of associating data, including location information, with another set of data. These concerns are related to the collection and appropriate use of this information and the consequence of their leakage on the users' privacy. It is almost ascertained that the more the technology develops, the capacity to gather, organise, and data-mine on the personal information will also develop. Therefore, the disclosure of information is always at risk of leakage whether accidently (via a first-hand communication) or intentionally for someone else's benefit such as in the gossip communication. Currently in the online environment, cautions can be exercised such as controlling the entity acquiring the personal information, and controlling whether the collected information should be transmitted over a secure channel (HTTP vs. HTTPs). In things-to-things communications in the IoT, the user loses this supervisory control role over his or her information.

2.2.1.3 The Inference Attack

Some studies reported the use of recorded personal information to demonstrate a privacy attack, often referred to as an "inference attack." The idea is to build a map reflecting on the activities, mobility behavior, and other patterns of the user's life using the data gathered. An example of an inference attack is the study conducted in [97]. The authors were able to determine the names of the persons stored in their database by observing and noting the location where people spent most of their time in the office building, and by noting who spent more time at their desk. Apart from inferring people's location, some researcher reported the inference of other information based on the observed context. For example in [98], the authors used real-time GPS traces to infer a traveling person mode of transportation (i.e. by car, train, bus, and walking) they were also able to predict the victim's route, based on their movements and historical behaviors. Therefore, the seamless interconnectivity of things envisioned in the IoT will open the door to various inference attacks. When interconnected networks of things in the IoT are capable of tracking the users automatically on an ongoing basis, they generate an enormous amount

of potentially sensitive information leading to possible inference attacks similar to the ones described above.

2.2.1.4 The Automated Invasion Attack

In the IoT, some of the risks associated with automated communications are the compilation of users' profile. After gathering large amounts of information via a first-hand communication, gossip and inference attacks, an automated system can combine these data and perform some data mining or analysis, which lead to a new vector of inference attacks. These combinations of attacks give birth to what we refer to as the "Automated Invasion Attack". An automated invasion attack can be constructed using any of the following gathered information:

- **Current data collected from typical computer usage including the data generated from mobiles' and tablets' application:** This set of collected data is a possible source of information in which the attacker can gather to infer some patterns relating to the user's activities. For instance, the IP address reflects on the location of the user. The time, date, and other parameters can also be collected. Mobile applications can log their location, usage history, and their interactions with a location based server.
- **Current data collected from the Internet or via social networking websites**. The website "Please Rob Me" is an example of how to predict a person presence at home from publicly available information by looking at the places where the users check-in [99]. With the public availability and accessibility of some of the users' information found on various social networking websites, it is possible to infer various data relating to an individual.
- **Data collected on the mobility behavior of an individual**: The movement patterns of a person constitute a form of fingerprinting. This enables an attacker to infer a user's points of interest. The location of the user's kids, school, and the time the victim usually picks up their kids and their Friday weekly social activity locations are all examples of a user's point of interest. Other mobility behavior could hint on other sensitive information. A frequent visit to a political party location or religious group could expose their social, political or religious activities.

- **Data collected from things in the IoT environment:** Whether the user is interacting with a particular device directly or indirectly using another device which they own or operate, there is a threat to the user's privacy. The information generated from these interactions constitute a possible source of information that reflects the behaviors, location, date, timing, shopping habits, and other personal information of the user.
- **Linking the records of things:** Data collected by Things are a possible source of information that the attacker can collect to infer the victim personal information. Additionally, in the IoT, if a device's set of data that contains logs about its use, location, history, and others private information, is linked to the same type of data generated by another device, it could lead to a linking attack. In a geolocation context, a linking attack work by associating the movements of an individual physical belonging device, for instance, his car (stored in log A) with the tracking of their mobile phone locations (stored in another log B). Consequently, an automated invasion attack is an incremental process of inference attacks in which the attacker gradually gathers more knowledge on the victim life or activities throughout the combination and linking of the information collected from the various source of attacks listed above.

In summary, location privacy is one of the major concerns in the IoT. The seamless interconnectivity of things, envisioned in the IoT, highlights the complexity of realising location privacy in this environment. It is clearly evident that it is almost impossible to achieve a complete privacy as long as seamless communications are taking place. When IoT systems, which can operate in an autonomous fashion in the IoT, track the users automatically on an ongoing basis, they generate an enormous amount of potentially sensitive information. This occurs especially when the location information is coupled with identity information. The main location privacy concern with regards to the IoT is that many new automated attack vectors become possible [100]. If effective public records of people's locations are created through systems automation then discrimination against race, religious group and prices, to name but a few, are most likely to occur. Things that log data about their usages, locations, histories, and others sensitive information present an interesting challenge to privacy protection. The amount of

personal data that would be occasionally collected in an IoT environment will be extremely larger than what we have experienced before. In facts, the collection, mining, and provisioning of data in the IoT are at a larger scale from those we experiment with traditional computer devices. The exchange of location information particularly in the IoT can become arbitrary as more devices and applications obtain access to the user's personal information.

Thus, recent technological advances in wireless communications, location-enabled hardware, and location identification techniques extend the location sensing capabilities to several things in the IoT. This gives rise to the possibility of using the tracking capabilities of things for the violation of the privacy of users. Not only preserving the location privacy of users is vital, but also preserving the location privacy of things is of paramount importance. In principle, most location-based services do not require the personal identification of a user. However, even without providing any personal identification, positioning information in the form of a specific location of a thing along with the possibility of associating the location information gathered from another thing or group of things will eventually lead to revealing the movement of a thing or the user; along with other inferred personal or contextual information such as the type and nature of the activity performed. Combining all of this information with other quasi-identification information will infer other types of sensitive information such as, the thing's context, its activities, and possibly the identity of the owners of things.

Consequently, the complexities involved in protecting location information in the IoT demand a new approach to the management and preservation of location information in the IoT. In the search for a solution, the next section (i.e. Section 2.3) investigates the current techniques used to protect location information on the Internet and investigates their applicability to the IoT.

2.3 Measures in Preserving Location Privacy

Current research on location privacy is mainly centered on two main computational protection techniques: anonymity and Obfuscation [101]. Thus, this work reviews two

relevant techniques: the Random and Dispersion techniques, which are discussed in Section 2.3.2. To perform Obfuscation, three key concepts have been widely used, described as follows:

- Adding random noise to location information: The aim is to make it harder on the adversary to infer the actual location of the user;
- Rounding by narrowing the coarse location e.g., by using landmarks to approximate a location;
- Redefinition of possible areas of the location. Example: the use of "invisible cloaking", in which no locations are provided for identified selected areas [102].

Based on these three concepts, most of the computational techniques used for privacy protection alter the location information in a way of reducing the information granularity. This includes the randomization technique, regulatory-based technique, anonymity, and Obfuscation.

The Randomization Technique

Randomization is a core principle in statistical theory. It is the process of making a data stream random. As an example, the study in [103] uses a decision-tree classifier to randomize data. This results in a new data stream that looks different from the original data stream. A reconstructed distributions procedure is proposed to estimate the distribution of the original information accurately. However, the issue with the use of randomization-based methods is that randomization does not offer the flexibility needed in the protection of location information.

Regulatory-based Techniques

This method relies on the government rules and regulations in protecting the personal information of users. The work in [104] reports on the status of privacy legislations and fair information practices in some countries. The problem with relying on regulations for protecting the privacy of the users is that regulations vary from a country to another. They also usually lag behind newly developed technologies.

Privacy Policies

This is a trust-based agreement policy arranged between the user and service provider. However, similar to the regulatory method, privacy policies cannot offer a complete solution since they are vulnerable to malicious disclosure of private information [105]. Privacy policies solutions are often used as part of middleware solutions which improve their efficiencies.

Anonymity

This method uses pseudonyms, normally to hide the identity of a user by anonymizing the user's personal information, e.g., the work in [106]. K-anonymity is another well-established anonymity-based privacy solution [107]. However, the use of anonymity as a privacy protection solution challenges the performance of many personalised services as it eliminates authentication and personalisation options [108].

Obfuscation

The term Obfuscation is introduced in [109]. It is described as the practice of deliberately degrading the quality of location information in some way to protect the privacy of an individual to whom that location information refers. Location Obfuscation is a technique used to protect a user's location by generalising the location information, or using substitution or alteration. The Obfuscation concept can also be linked to the principle of need-to-know. Obfuscation offers a good approach for preserving the location privacy of users. However, obfuscating the location information is ineffective when owners of location information do not wish to obfuscate their location information at all time or in all situations. The challenge is then in providing a solution that would vary the degree of location privacy by using different levels of Obfuscation. Determining the level of Obfuscation is based on the context of the communication and the privacy policies defined by the user.

2.3.1 Privacy Middleware

Developing new middleware solutions for the IoT is an active area of research [110]. Initially, these solutions were designed to support privacy protections in pervasive computing. They are also designed to guide the development and implementation of pervasive systems [111]. In regards to privacy, the physical outreach of IoT makes preserving the users' privacy a difficult task [111]. Typically, privacy is of three types: content, identity, and location [112]. Content privacy is concerned with keeping data or content private. The second type relates to hiding the identity of the user; while, location privacy is concerned with hiding the location of the user. Based on these types of privacy, a benchmark for pervasive computing systems ,which considered two characteristics for privacy models was proposed in [111]. The first characteristic is the user control over his or her private information, which is the model ability to provide content, identity, and location privacy. The second related to the unobtrusiveness of the privacy mechanisms. Pervasive systems in the IoT attempt to provide a seamless user-centric environment, where users no longer need to spend much of their attention to computing machinery. Therefore, unobtrusiveness can be measured by the percentage of time a user consumes on interacting with privacy settings [113].

There is also a challenge of balancing privacy with usability [114]. Traditional models requiring explicit users' input have to be replaced with models that can sense information securely and automatically from the context and environment, and exchange it seamlessly with communicating devices and users. An XML-based User-centered Privacy Model (UPM) for pervasive computing systems that provide content, identity, location, and time privacy with low unobtrusiveness was proposed in [115]. The model consists of three layers: User context layer, Service layer, and Owner layer. It functions as follows: a user sends data to a portal without revealing the user's identity (portals are wireless nodes managing the users' context). Then the portal hides the user's location and forwards the data to an intermediate entity referred to as a lighthouse. A lighthouse is a trusted entity that holds the user's identity information; but it does not have access to user's location, content, and time of the interaction. By doing so, the user portal only knows the user's location and the lighthouse only knows the user's identity. The lighthouse is responsible

for communicating with the service provider. The service provider receives the needed contents from the owners. The authors claim that their UPM model provides the user with control over the content of the information disclosed and the disclosure settings of their identity, location, and time. In [116], the UPM model was evaluated based on the benchmark proposed in [111] as follows: to assess the unobtrusiveness of the privacy policies, the percentage of time the user spends dealing with the privacy subsystem to make a decision was measured. An experiment was designed to show how to measure the model unobtrusiveness. Three tasks with different privacy levels were implemented. The aim is to demonstrate that the privacy files support mandatory and discretionary rules, reflect context sensitivity, handle uncertain situations, and resolve conflicts [116].

In [117], a middleware architecture for privacy protection on the Internet is proposed. The middleware mediates between service providers and users and constitutes a distributed unit of trust that enforces the legal requirements. Before the development of the middleware, the authors classified the data into three types: active data (which are in direct control by the user), semi-active data (users have partial control over them such as RFIDs generated data) and passive data (these data are disclosed without any user's action). Next, the authors proposed a policy framework which incorporated a large set of rules. This framework is used to formalise how users express their privacy preferences. To model the rules, a relevant XML-based language was defined called the Discreet Privacy Language (DPL). To limit the control from the service provider over the user's personal data, a discreet Box was proposed. The Box incorporates the personal data repository that cashes personal data and a policy framework that is responsible for the decisions of personal data disclosure. It serves as the entry point for a service and its operation is similar to a proxy server. While the authors claim that the proposed architecture has numerous benefits, no evaluation has been performed.

Other solutions, such as the mix zone technique [118], were designed to protect the privacy of users in location-aware pervasive computing applications. The mix zone is a middleware, which enables an application to receive and reply to anonymous requests. It passes users' input and output between the application and the user. The mix zone is analogous to a mix node in a communication network [119]. A mix network is a store and

forward network that offers anonymous communication facilities. The proposed technique was applied to location data collected from the Active Bat system installed at At&T Labs Cambridge [120]. The results demonstrated that privacy is low even with a relatively large mix zone. However, this technique could lead to a better privacy if applied over a larger and more populated area. While the mix zone technique provides a way of hiding the location of the users, it does hide their identities. The choices are also restricted to two: anonymized or real location.

Therefore, solutions based on the mix networks, mix nodes model, pseudonyms, and those presented in [97, 121], provide location privacy without addressing the need to provide the user with granule control over the disclosure settings of their information. Other alternative solutions, such as the LocServ model, support location privacy policies that can be checked automatically on behalf of the user [122]. However, LocServe suffers from major flexibility and arrangement limitations and cannot be reliably used in IoT.

2.3.2 The Classical Obfuscation Technique 1: Random

The Random Technique, referred to as Rand in [123], is the simplest Obfuscation technique. This technique alters the original location *L* by a location *L'*. Figure 2.5 (a) shows an example that uses this technique. *L'* is an obfuscated location generated from the original location. The algorithm works as follows:

1) For a location *L*, generate a circular area A with a center *L* and radius *r*. Increasing the radius r will result in enlarging the area around *L*.
2) Generate a random point within the circular area *A* e.g., *L'* from Figure 2.5 (a).
3) Substitute *L* by *L'*, note that a larger *r* implies a larger expected noise in the generated location point *L'*.

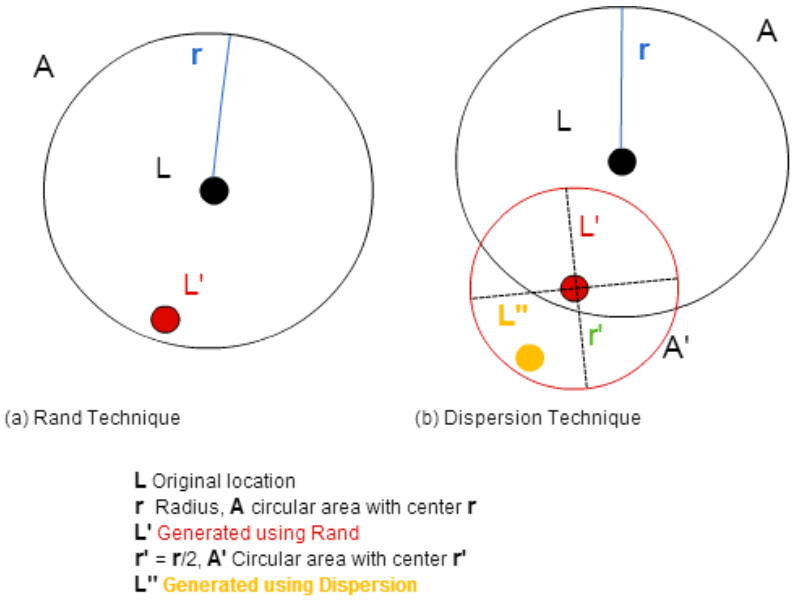


Figure 2.5- Obfuscation Technique

2.3.3 The Classical Obfuscation Technique 2: Dispersion

This technique is a variant of the Rand technique. Instead of using the original location as the centre of the circle, it uses a new location. Let *L* be the original location, *r* a radius to be used to generate the area *A* with the centre *L*. Let *L'* be the obfuscated location obtained using the Rand technique. The following is an example that uses the dispersion technique in generating obfuscated locations:

1) For a location *L*, generate a circular area *A* with a centre *L* and radius *r*.
2) Generate a random point *L'* within the circular area *A*.
3) Generate a new circular area *A'* with a centre *L'* and radius *r'= r/2*. (The size of *r'* is selected randomly).
4) Generate a random point *L"* within the circular area *A'*.
5) Replace the original location *L* with *L*" as shown in Figure 2.5 (b).

The Random and Dispersion Obfuscation techniques serve as a base method for several other Obfuscation methods. For instance, the N-Rand technique is an improved version

of the random technique reported above. The N-Rand introduces a new parameter that allows the selection of location points that are more distant from the original location *L*. The dispersion technique has also been extended in such a way that *L* is also generated as the most distant point to the original location. In [123], these methods were compared and evaluated, and it was found that the N-Dispersion technique produced a larger minimum distance to the original location and the greatest average distance to the original path.

2.3.4 The Weaknesses in the Classical Obfuscation Techniques

As we have seen in section 2.3.2 and 2.3.3, the traditional location Obfuscation techniques, such as the Random and Dispersion techniques, employ geometric methods to generate obfuscated locations. These methods are referred to as the geometric based techniques in [124]. These techniques do not account for geographical knowledge. Thus, they do not take into consideration the actual geographical environment at a generated obfuscated location. In real life, a location may be in a public place, a private location such as inside a building which is closed during that time of the day, somewhere in the middle of the desert, or the ocean. Geometric-based Obfuscation techniques ignore the semantics behind a geographic location. Consequently, the authors in [125] claim that an adversary with sufficient geographical knowledge may be able to infer location sensitive information from obfuscated locations generated by geometric-based technique. Our work aligns with this claim. We will show, through experimentations conducted in Chapter 5, that when a geometric-based Obfuscation technique is applied to a physical environment, certain obfuscated locations are more likely to be identified as fake locations by an adversary. Section 5.2.3.4 describes the experimental works conducted which implement both the Rand and Dispersion techniques. It also reports on the performance results collected for the experiments.

2.4 Summary

This chapter provided discussions and reviews of the major challenges facing the widespread adoption of the IoT including issues relating to interoperability, management, security, and privacy. It highlighted the need for a multifaceted approach to the privacy

preservation and management of location information in the IoT. A new set of privacy attacks were discussed and introduced in this chapter. For instance, the Automated Invasion Attack is described as an incremental process of an inference attack in which the attacker gradually gathers more knowledge on the user's life or activities through the combination and linking of the information collected from various things associated with the user in the IoT. Furthermore, the chapter analysed several traditional privacy protection methods and investigated their applicability in the IoT. It also reviewed two major classical Obfuscation techniques and identified their weaknesses and investigated their suitability for adoption in the IoT. This chapter also highlighted the major role WSNs play in the integration of things and a group of things in the IoT. Specifically, the role wireless low-power technologies play in supporting connectivity of small, low-cost, and low-power things in the IoT.

The investigations conducted in this chapter lead to the following conclusions:

- Several location positioning techniques can be used by things in the IoT to collect the location of a user.
- The disclosure of location information in the IoT can be used to violate the location privacy of things and that of their users.
- The low-cost and lightweight characteristics of things in the IoT challenge the adoptions and implementations of much traditional management and location preserving techniques in the IoT.
- The unique characteristics of the IoT make the preservation of the location privacy of things in the IoT a complex task. This demands a new approach to location privacy protection in the IoT. Such an approach should account for the heterogeneity of IoT communications, lightweight characteristics of things, dynamic and rich interactions between things, and the need to accommodate contextual adaptive privacy policies in the IoT.

The next chapter (i.e. Chapter 3) studies the various enabling wireless technologies in IoT. It conducts several studies on various wireless technologies such as ZigBee, 6lowpan, Bluetooth Low Energy, LTE, and Wi-Fi protocols including the latest IEEE

802.11ah technology. These studies assess the capabilities and behaviors of these wireless technologies and identify their shortcomings, suitability of adoption, and their impact on the preservation and management of location information in the IoT.

CHAPTER 3- WIRELESS ENABLING TECHNOLOGIES FOR THE IoT

As previously discussed in Chapter 2, an interesting aspect of the integration of WSNs in the IoT is the incorporation of multiple long-range and short-range wireless technologies into the designs of IoT applications. For instance, eHealth applications such as body area networks may develop into an autonomous world of small wireless and networked mobile devices attached to their users [126]. They mostly connect to the Internet using a mobile phone as a gateway or via a wireless access point. Wireless technologies in the IoT need to handle a large degree of ad-hoc growth in device connectivity, structure, organisation, and significant change in contextual use, including mobility as well [127]. Many devices will constantly be connected to the energy grid such as smart appliances in the smart home application example [128]. On the other hand, many other IoT devices suffer from limited energy resources as they are powered by small batteries or rely on energy harvesting techniques throughout their lifetime [129]. The need to accommodate the requirements for minimum energy computation, slim and lightweight solutions for the management and preservation of location privacy in the IoT is essential. Therefore, it is vital to understand the networking context and requirements in which location information is exchanged in the IoT. This is because, as identified in Chapter 2, traditional Internet location management and privacy protection techniques cannot be used efficiently in the IoT.

This chapter provides a state of the art on wireless enabling technologies in the IoT. Section 3.1 discusses the wireless protocols available to connect things to the IoT within the last few 100 meters. Section 3.2 reviews the major candidates to providing wireless connectivity in the IoT including the IEEE 802.15.4, Bluetooth Low Energy, and IEEE 802.11 technologies. Section 3.2 provides several analyses and comparative studies between various low-power wireless technologies, particularly ZigBee, 6Lowpan, and IEEE 802.11ah, and the other variants of IEEE 802.11 technology (i.e. IEEE

802.11a/b/g/n/ac), and LTE. These studies examine many parameters of these wireless technologies such as their data rates and ranges, network sizes, transmission powers, security, and significantly their ecosystem and suitability of adoption in the IoT. These are needed to identify the requirements and capabilities of the technologies in which lightweight things use to connect to the Internet. This is in addition to examining the networking contexts and characteristics, in which things exchange location information with IoT applications and with each other.

3.1 Wireless Low-Power Technologies for the IoT

The IoT covers a broad range of applications and devices. The 802.11 protocol with its 802.11a/b/g/n/ac variants, popularly known as Wi-Fi, is among the first obvious technology candidates for the IoT. Examples of Wi-Fi applications in the IoT are presented in [130]. Today, almost every house, workplace, cafe, and university has a Wi-Fi network. Wi-Fi has become the de-facto term when referring to connecting to the Internet via a wireless access point. The widespread adoption of Wi-Fi makes it a first technology choice for many IoT applications. However, in some IoT applications, the choice of technology is limited to the device's hardware capabilities, low-power consumption requirements, and the overall cost. Many IoT devices require the use of a low-cost and low-power wireless technology when connecting to the Internet [131]. Traditionally, energy consumption has always been a limiting factor in many wireless sensor network applications. This limiting factor will continue as a major challenge facing the development of many applications in the IoT. In fact, for the growth of the IoT, low-power consumption is an essential requirement that needs to be met.

In addition to low-power consumption, other associated requirements need to be considered as well. For instance, the cost of technology, security, simplicity (easy to use and manage), wireless data rates and ranges, among others, such as those reported in [132], are essential requirements that require attention. Many evolving wireless technologies such as ZigBee and Bluetooth are competing to provide the IoT with a low-power wireless connectivity solution. Other wireless technologies such as the IEEE 802.11ah and 6Lowpan protocols are emerging as well [133]. They offer similar low-

power wireless connectivity solutions for the IoT. Consequently, there could be many choices of low-power wireless protocols for many IoT applications. Consider, for example, a car-parking system application based on the IoT such as the one presented in [134]. The IoT-based car parking system combines many components together. It combines a variety of devices, multiple networking protocols, several sources of data, and various wireless and generations of technologies. Many of the devices involved in the communications are lightweight devices such as sensors that operate on batteries. They would require a low-power wireless technology to function effectively.

Essentially, low-power wireless technologies contribute to improving not only the way an IoT device connects to the Internet but the efficiency of the overall IoT application as well. A network consisting of low-cost and lightweight IoT devices can be used to monitor relevant operation and contextual parameters. These devices are also capable of making appropriate decisions (based on the occurrence of specific events) while simultaneously communicating with some other IoT devices. In general, a heterogeneous setup allows an IoT system to perform many automated tasks by combining the various data gathered from these IoT devices. In the smart home IoT application example, IoT devices such as wireless sensors can report the ambiance temperatures in various locations in a house to an IoT central device, referred to as the controller, which in turns can make a decision on varying the output of the air-conditioning system. Adding more IoT devices to the IoT system will increase the intelligence of the system as well. For instance, if some other sensors are providing information on whether the house is occupied or not (whether the people occupying the house are out or no), then the controller will be able to make a better decision on when the heating system should be turned on or off. In this smart home example, the IoT devices are in the form of simple sensor devices which have a small bandwidth and low-power requirement. Hence, the need for low-power wireless technologies in this and many other similar applications in the IoT is essential.

3.1.1 Bluetooth Low Energy: A Low-power, Low-cost Solution for the IoT

Bluetooth Low Energy (BLE), also known as Bluetooth Smart and Bluetooth version 4 is an enhancement to the classic Bluetooth protocol [135]. Bluetooth is a packet-based protocol. It implements master-slave communication architecture. A master is a Bluetooth enabled device which has the capability of communicating with a maximum of seven other Bluetooth-enabled devices, referred to as slaves, at a time. In Bluetooth terms, a master is a device that initiates a connection. By agreements, Bluetooth devices can switch roles from a master to slave and vice versa as well [135]. BLE allows devices to communicate with each other when they come within a permitted range, normally up to 100 meters depending on the power classification of the device (more power, longer range). The BLE protocol is designed to have an over the air data rate of 1 Mbps and throughput of around 0.27 Mbps [136]. However, in practical implementations, the data rate and throughput are much lower [137]. The low-power consumption feature of BLE is achieved by putting a BLE device to sleep for a longer period. The device will only wake up for a shorter amount of time when it is sending or receiving data. However, the fact that BLE is only sending a small amount of data at a time with efficient energy consumption makes it a favorable technology choice for several light IoT applications. On the contrary, BLE can be judged as impractical to use in many other IoT applications which may require the utilisation of a more capable technology regarding range and bandwidth such as the IoT application reported in [138].

The throughput, range, data rate, and power consumption parameters of BLE are affected by some other parameters such as the connection parameters. Two important aspects of BLE are the physical channels and events. The physical channel specifies the frequency at which data is sent. An event is the time unit in which data are sent between BLE devices. There are two types of events: advertising events and connection events. Advertising events are used to send advertising packets; while connection events are used to send the actual data. Figure 3.1 shows an example of two connection events and one advertising event. In these events, the slave and master devices are exchanging some packets. The packets of each of the events are sent on a different frequency given that BLE uses frequency hopping technique. Other important aspects that relate to BLE are

the connection interval and slave latency. A connection interval is a period that occurs between two consecutive connection events [136]. The slave latency is a parameter that results in power saving by allowing the slave device to skip some connection events if it does not have data to send [139]. Slave latency specifies the maximum number of connection events that can be skipped [140].

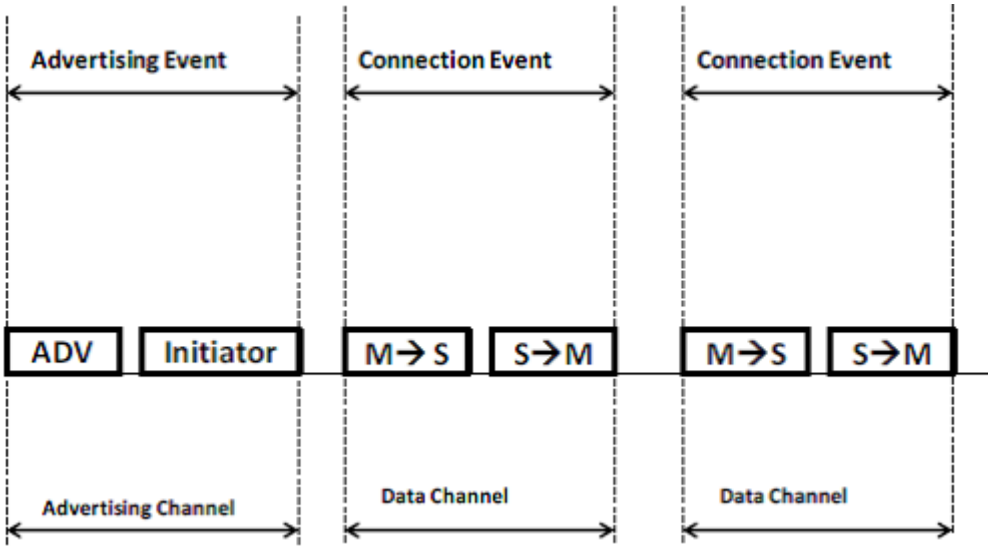


Figure 3.1- Bluetooth connection and advertising events.

The low-power consumption feature of the BLE protocol enables connectivity, monitoring, and sharing of information for many devices, such as home appliances and wearable devices, with a minimal consumption of energy. Significantly, the BLE protocol creates opportunities for a number of IoT applications. It is a strong candidate to be used as a communication protocol in several IoT devices which are limited by their low-power and low-cost characteristics. Examples of these IoT applications and devices range from health monitor devices in e-health, devices in retails applications and home automation systems [141], and smart appliances in smart grid applications [142]. Additionally, the widespread adoption of smartphones and the advancements made by BLE with regard to energy consumption enabled the introduction of many wearables and fitness devices that integrate with smartphones. BLE has a real potential for becoming an essential technology for the “last 100 meters in low-power and low-cost small devices” of the IoT [141]. Using a smartphone or another similar device as a temporary or mobile gateway is

increasingly getting popular in numerous IoT applications. Thus, BLE plays a significant role in providing the communication medium needed between this gateway and the IoT devices. There are also other applications where the same IoT device (e.g., a sensor) is used for both mobile and fixed-location applications such as in the IoT hospital system proposed in [143].

3.1.2 ZigBee IP: an IPv6-based Wireless Mesh Networking Solution for the IoT

ZigBee supports interoperable communications among a broad range of smart and innovative business products that enhance everyday life [144]. The IEEE 802.15.4 is a protocol designed for low-rate wireless personal area networks (LR-WPANs). It defines the physical and media access control layers [145]. The IEEE 802.15.4 is the basis standard for ZigBee [146], WirelessHART [147], and 6LoWPAN [148]. The IEEE 802.15.4 operates in the unlicensed 2.4 GHz band which overlaps with other wireless technologies (e.g., Wi-Fi and Bluetooth) sharing the same band. ZigBee is an extension to the 802.15.4 standard. ZigBee is built on top of the 802.15.4's radio layer. It specifies the application, network, and security layers as described in [149]. Often, the terms 802.15.4 and ZigBee are used interchangeably. However, this may not be correct as ZigBee devices are not necessarily compatible with some implementations of the 802.15.4 standard. ZigBee's data rate is considered low when compared with Bluetooth and Wi-Fi. For instance, ZigBee has a data rate that ranges from 20 to 250 kbps [150]. On the other hand, Bluetooth has a maximum speed of 3 Mbps, and a practical data transfer rate of 2.1 Mbps [151], whereas Wi-Fi has significantly higher data rates when compared to that of Bluetooth. The battery lifetime of Bluetooth classic device is a few days while that of Wi-Fi is a few hours. In some BLE devices, the battery can last for over a year. However, the battery in a ZigBee device may last for five years before having to be recharged or replaced [152]. Although ZigBee does not have the capability of a high data rate and it is not adequate for real-time applications, it is, per se, serves best in applications where both Wi-Fi and Bluetooth are less suitable.

ZigBee IP is an improvement to the standard ZigBee. ZigBee IP has a layered architecture that makes it suitable to work with other 802.15.4 implementations. The design of ZigBee IP accommodates an IPv6 protocol stack. This stack is developed specifically to operate on low-power and low-cost devices. Moreover, ZigBee IP incorporates technologies, such as 6LoWPAN [153], that optimise routing and meshing in wireless sensor networks. It supports the requirements of ZigBee Smart Energy as well [154]. This combination of technologies offers a solution that enables the extension of IEEE 802.15.4 based networks to IP-based networks. With regard to the network size, ZigBee IP network is considered to be highly scalable. ZigBee-IP protocol does not enforce any limitations on the network size. Theoretically, the size of the network is limited by the hardware specifications of ZigBee devices such as the available memory and the amount of data that need to be exchanged across a network. A typical IEEE 802.15.4 network supports a large number of ZigBee devices. Several ZigBee-IP networks can coexist in the same physical area. They can be designed to interconnect at the coordinator level, which allows a network to further increase the number of connected devices. The main advantage of ZigBee-IP compared to other 802.15.4 technologies is its architecture. ZigBee-IP provides a scalable architecture that supports an end-to-end networking based on IPv6. Therefore, many applications in the IoT benefit from this architecture [155].

3.1.2.1 ZigBee Network Topology based on the IoT

A typical ZigBee network consists of a ZigBee coordinator, ZigBee routers, and ZigBee end devices [156]. Each ZigBee device on the network has a specific functionality that is defined by its operational role. The ZigBee coordinator is responsible for controlling the ZigBee network by coordinating the messages between the ZigBee routers and ZigBee end devices [156]. The ZigBee router acts as a message relay that performs like a bridge for ZigBee networks. The ZigBee end devices are standalone devices that participate in the ZigBee network. Figure 3.2 shows an example of a ZigBee network topology, in which the information flow is illustrated. The coordinator may stand for a smart-home control system [157]. The routers can be appliances such as an air conditioner or a thermostat; while the end devices can be security sensors or light switches [156].

ZigBee supports star and mesh topologies [158]. The star topology is used when the devices are close to each other and where the use of one coordinator is sufficient. A star topology can also be a part of a larger mesh network with several routers that connect several end devices. A mesh network is a network topology that allows the nodes to communicate via an alternative path in case there is any failure in one of the intermediate devices in an existing path e.g., link redundancy [156]. ZigBee has two operational modes, i.e., beacon mode and non-beacon mode. In the beacon node, the nodes are aware of when to communicate with one another and the coordinator periodically sends beacons to all devices on the network. The ZigBee nodes, including the coordinator, may sleep between beacons.

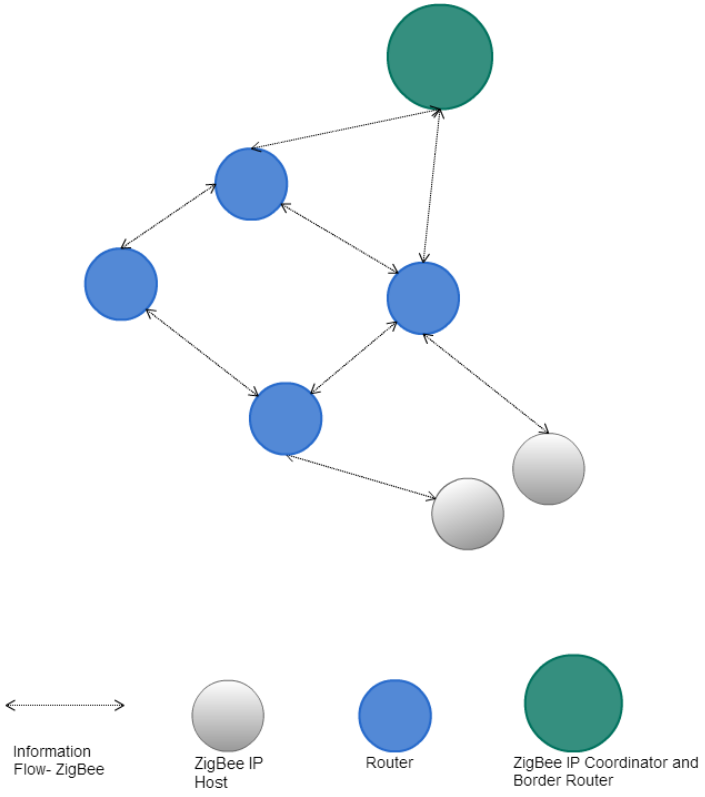


Figure 3.2- ZigBee IP network topology example

The beacons sent by the coordinator check whether there is a message received or not. If there are no messages received, the nodes can go back to sleep mode. On the other hand, the non-beacon mode is characterised by less coordination between the coordinator and

the other ZigBee nodes. Since the end-device nodes only communicate when they need to, the coordinator's receiver is always active which enables it to receive messages from other nodes in real-time. Consequently, in the non-beacon mode, the coordinator consumes more energy since it has to be always listening. In contrast, other ZigBee devices on the network save their power since they do not need to stay awake when they are not engaging in any communication. Therefore, they remain in sleep mode for a longer period. To better understand the differences between the beacon and non-beacon modes, consider the following simple IoT application scenario where the ZigBee network is configured in a non-beacon mode: A wireless switch is used to turn on/off an appliance e.g., a lamp. The switch is battery operated while the ZigBee node i.e. the lamp is connected to the power supply. Therefore, the lamp (the ZigBee coordinator) is always active; while the switch (the ZigBee end device) remains asleep until someone uses the wireless switch to turn on or off the lamp. In this scenario, the switch wakes up and sends a command to the lamp which is always active and listening. The switch then remains active until it receives an acknowledgment from the lamp and then returns to sleep.

3.1.3 Analysis of IEEE 802.11 WLANs for IoT Communications

Wireless Local Area Networks (WLANs) is the dominant technology for indoor broadband wireless access. WLAN products have become commodity items used in professional and consumer products alike. Recently, the propagation of WLANs as extensions of wired networks has been increasing dramatically, and thereby, giving devices equipped with wireless interfaces a higher degree of mobility. The two most common WLAN standards are the IEEE 802.11 standard (commonly branded as Wi-Fi) and the European HIPER (High-Performance Radio) LAN [159]. The IEEE 802.11 defines two types of configurations, the Infrastructure Basic Service Set (iBSS) and Independent BSS (IBSS). In iBSS, an access point (AP) is the central entity of each coverage area with coordination functionality. Additionally, the AP acts as a bi-directional bridge between the wireless network and the wired infrastructure (i.e., typically Ethernet). Stations (STA) are mostly mobile devices equipped with IEEE 802.11 wireless network interfaces. Communication between the AP and the associated stations occurs over the shared wireless medium that carries the data. A station must associate

with an AP for it to transmit and receive data to and from the wired infrastructure, and to communicate with other stations on the same WLAN. A Basic Service Set (BSS) is the term used to refer an AP and its associated stations. In large WLANs, multiple BSSs can be joined using a distribution system (DS), thus providing sufficient coverage for a greater number of stations. This setup of having two or more BSSs is referred to as an Extended Service Set (ESS). The DS is the wired backbone connecting APs and allowing the associated stations to access services available on the wired infrastructure. Therefore, Wi-Fi devices can form a star topology with its AP acting as an Internet gateway. The output power of Wi-Fi is higher than other local area network wireless technologies. Full coverage of Internet connectivity is necessary for Wi-Fi networks, so dead spots which may occur are overcome by the use of more than one antenna in the AP.

Wi-Fi operates in the 2.4 and 5 GHz bands. Its operations in the 5 GHz band allow the use of more channels and provide higher data rates. However, the range of 5 GHz radio indoors (e.g., inside buildings) is shorter than 2.4 GHz. The IEEE 802.11b and IEEE 802.11g operate in the 2.4 GHz ISM band. The IEEE 802.11n improves the previous versions of the standard by introducing the multiple input and multiple output methods (MIMO) [160]. It supports a data rate ranging from 54 Mbit/s to 600 Mbit/s [161]. The IEEE 802.11ac is an improved version of the IEEE 802.11n, and it provides high-throughput wireless local area networks (WLANs) in the 5 GHz band with more spatial streams and higher modulation with MIMO yielding data rates up to 433.33 Mbps [162]. The IEEE 802.11ac provides a single link throughput of at least 500 Mbps and up to 1 gigabit per second. The IEEE 802.11ac has a wider RF bandwidth of up to 160 MHz and a higher density modulation up to 256 QAM [163].

At the other end of the spectrum, the IEEE 802.11ah standard operates in the unlicensed 900MHz frequency band. A wireless signal operating in the 900MHz band can penetrate walls, but it would deliver a limited bandwidth ranging from 100Kbps to 40Mbps [164]. One common IoT application of this technology would be sensors and actuators in homes or commercial buildings. Thus, IEEE 802.11ah could be positioned as a competitor to Bluetooth and ZigBee protocols in the IoT space.

3.1.3.1 The IEEE 802.11ah

Wi-Fi, with its 802.11 a/b/g/n/ac variants, may not be deemed suitable to use in some IoT applications where low-power consumption is a vital requirement. Wi-Fi was originally designed to offer high throughput to a limited number of devices located indoor at a short distance from each other. Therefore, to meet the IoT low-power requirements, the IEEE 802 LAN/MAN Standards Committee (LMSC) formed the IEEE 802.11ah Task Group (TGah) [165]. The task group objective is to extend the applicability area of 802.11 networks. It aims to design an energy efficient protocol allowing thousands of indoor and outdoor devices to work in the same area [166]. The IEEE 802.11ah seeks to support a range of throughput options ranging from 150 Kbps up to 40 Mbps over an 8 MHz band [164]. With regard to the wireless range, the proposed IEEE 802.11ah protocol supports a wider coverage range when compared to that of the IEEE 802.11n/ac protocol. The IEEE 802.11ah supports applications with coverage of up to 1 km in outdoor areas and up to 8191 devices associated with one access point [167]. The IEEE 802.11ah operates in the unlicensed sub-1GHz bands, excluding the TV white-space bands. Sub 1 band provides an extended wireless range when compared to the other bands used by conventional 802.11 Wi-Fi standards which operate in the 2.4 GHz and 5 GHz bands [168]. The IEEE 802.11ah relies on the one-hop network topology and employs power saving mechanisms [164]. Given that the IEEE 802.11ah protocol falls under the overall Wi-Fi umbrella, it is expected that it will be compatible with the existing Wi-Fi infrastructure [169]. The IEEE 802.11ah allows access to more than 8 thousand devices in the range of 1 km within an area with high concentration of small devices such as sensors, and mini controllers. Therefore, the IEEE 802.11ah technology can satisfy the IoT requirements while maintaining an acceptable user experience in parallel with the IEEE 802.11 technologies. One of the interesting functional requirements of the IEEE 802.11ah is to enable coexistence with the IEEE 802.15.4 standard [170].

The IEEE 802.11ah standard includes new PHY and MAC layers grouping devices into traffic induction maps to accommodate small units and machine to machine (M2M) communications [171]. The physical layer allows devices along with the AP to operate over various sub-1GHz ISM bands depending on the regulation of the country [171]. The

900 MHz band is currently used in Europe for GSM 2G cellular facilities. The 900 MHz is used in many devices, and it is suitable for M2M communications specifically in constrained devices such as wireless sensors. In some countries, the frequency bands vary from 902-928 MHz in the USA, 863-868.6 in Europe, 950.8-957.6 MHz in Japan. Other countries are expected to follow in releasing the spectrum once the IEEE 802.11ah standard is finalised.

3.1.3.2 The 802.11ah Power Saving Mode.

The direct advantages of using the sub-1 GHz spectrum, also referred to as Sigsbee, in the IoT is the improvement in the coverage area for IoT devices and applications, in addition to increasing energy efficiencies. Nevertheless, Sigsbee plays a significant role in wireless connectivity. It specifically targets wireless sensor networks. Applications can be found in the home and building automation with intelligent metering instruments such as in [172]. The IEEE 802.11ah protocol implements energy-saving mechanisms which guarantee that the limited energy resources available for a sensor node are efficiently used. A large number of devices can be accommodated by a single IEEE 802.11ah AP due to the infrequent data exchange in some IoT applications. However, the device' activity needs to be properly distributed over time [164].

The IEEE 802.11 standard defines two states for a wireless network interface: awake or sleep. In the awake state, the device's radio is turned on allowing the wireless interface to perform data communications, or just to remain idle [173]. In the sleep state, the radio of the device is turned off, and the wireless interface is put to sleep [174]. This state is specified in the IEEE 802.11 standard as Power Saving Mode (PSM). In PSM, the AP buffers incoming frames destined for mobile stations. It continues doing this until the station wakes up. When the device wakes up, the buffered traffic will be delivered. The station goes back to PSM once the buffered traffic is fully delivered [174]. To achieve this, the IEEE 802.11ah standard defines two classes of signalling beacon frames. The Delivery Traffic Indication Map (DTIM) which informs, which groups of STAs have pending data at the AP. And the Traffic Indication Map (TIM), which specifies which STA in a given STA group has pending data at the AP. Consequently, this new scheme

of PSM, TIM, and Page improves the overall power efficiency of IEEE 802.11ah devices. For further readings on the new proposed PSM scheme the reader is referred to [175].

On the other hand, the IEEE 802.11af also called Super Wi-Fi or White-Fi, operates in the unused TV spectrum [176]. 802.11af coverage can extend up to several kilometres as it operates in the frequency bands between 54MHz and 790MHz. It offers a reasonable throughput, estimated at 24Mb/s. It has similar applications as 802.11ah, providing bandwidth for sensors and other devices of the IoT [177].

3.2 A state of the art on the Adoption of Wireless Technologies in the IoT

There is a growing momentum to embrace and design technologies that adhere explicitly to the IoT requirements. This includes the modification of existing technologies e.g., from Bluetooth classic to Bluetooth smart, and from ZigBee classic to ZigBee-IP or the design of new technologies such as the IEEE 802.11ah. These technologies aim at addressing key IoT wireless and devices' requirements such as low-power consumption, lower computation capabilities, reduced implementation and operational costs, and a wider coverage range. The previous section provided a brief review of the IEEE 802.15.4 technologies, Bluetooth Low Energy, and the IEEE 802.11ah technology. The IEEE 802.15.4 family of technologies, such as the 6Lowpan and ZigBee technologies, are currently used in various wireless sensor network applications. These applications are characterised by requirements similar to those encountered in the IoT. For instance, BLE is widely adopted in wearables and consumer products. On the other hand, the IEEE 802.11ah is a new protocol under development. It is designed to operate in the sub-one-gigahertz (900MHz) band. It has an extended range when compared to traditional Wi-Fi, and it is regarded as a competitor for both ZigBee, 6Lowpan, and the other already-established protocols in this sub-one band.

However, all the technologies above have their weaknesses and obviously their strengths. For example, the gain in range with the use of the IEEE 802.11ah is lost in bandwidth. Whereas, with the use of ZigBee the gain in bandwidth is lost in range. The areas of the

IoT involve diverse sets of devices that use various communication technologies to share and exchange information. Within the IoT, some applications can be in the form of simple peer-to-peer applications. Other IoT applications can also be based on personal area network setups, involving the use of few devices and users. Other complex applications may involve the utilisation of a variety of heterogeneous devices which communicate using a wide array of technologies, in different setups and topologies. Therefore, a technology that can be deemed suitable for a particular IoT application might not necessarily be suited to many others. In fact, the ability to connect and coexist various devices operating using several communication technologies is the vision behind the IoT. Having an ecosystem of coexisted technologies and devices is what enables the IoT vision of extending communications to anything and anywhere.

3.2.1 WLANs: Capacity vs. IoT Requirements

The IEEE 802.11ac and LTE Advanced have the highest data rate among the wireless technologies in use today. The IEEE 802.11ac specification provides a theoretical maximum data transfer speed of more than 3Gbps. It can provide a transfer speed up to 1.3Gbps as well, and supports up to 8 streams [178]. On the other hand, LTE Advanced has a 1 Gbps fixed speed and a rate of 100 Mbps to mobile users [179]. Figure 3.3 compares between various wireless technologies regarding distance coverage in meters, rates, ranges, and power consumptions. In the low-power wireless technology space, Bluetooth Low Energy has the highest data rate of 2.1 Mbps. ZigBee and 6Lowpan technologies, supported by the IEEE 802.15.4 standard, have a data rate of 250 Kbps in the 2.4 GHz frequency band. However, ZigBee's data rate falls to 20 Kbps in the 868 MHz band and to 40 Kbps in the 915 MHz band in some countries [180]. In contrast, the IEEE 802.11.ah has the lowest data rate targeted at 150Kbps with an average of 100 Kbps. As of the theoretical wireless range, as illustrated in Figure 3.3, cellular technologies, e.g., LTE, cover a larger area when compared with other Wi-Fi technologies with IEEE 802.11 variants coming second at an approximate maximum range of a 100 m.

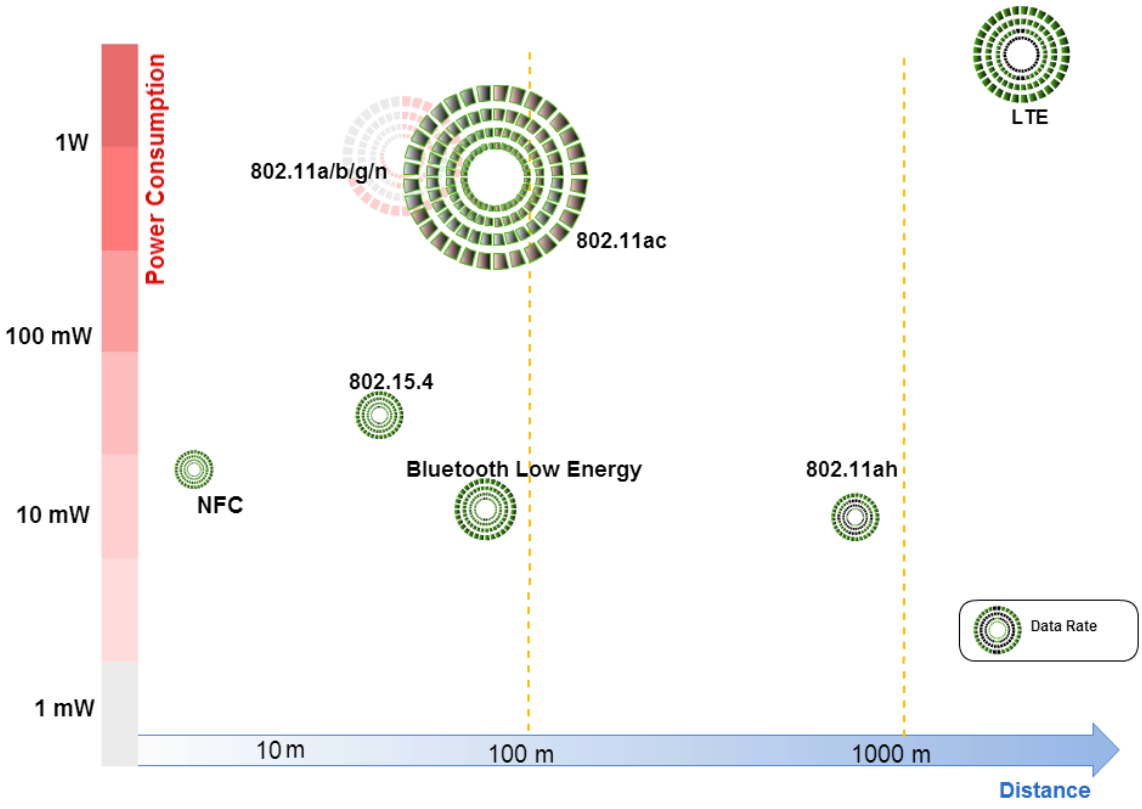


Figure 3.3- A Comparative study of power consumption, distance coverage in meters, and data rate.

As of the range of low-power wireless technologies, the IEEE 802.11ah rules the chart against 802.15.4 and BLE technologies. The 802.11ah coverage range also outperforms that of the other variants of the 802.11 protocol, with a range coverage of approximately 1 km, as shown in Figure 3.3 and Figure 3.4. On the other hand, it should be noted that the 802.15.4 supports mesh networking. In mesh networking, a message is routed through several nodes on a network until it reaches its destination. Therefore, a ZigBee network's range can be easily extended with the use of repeaters in a mesh formation. Data in a ZigBee network "hops" around a mesh of nodes until a route to the host (usually the Internet) is found.

Therefore, repeaters and/or a high density of nodes can be used to extend the coverage of a ZigBee network. Interestingly, the IEEE 802.11ah is under development with meshing in mind as well. Therefore, the choice of technology regarding data rate and range come back to the requirements of the IoT applications in hand.

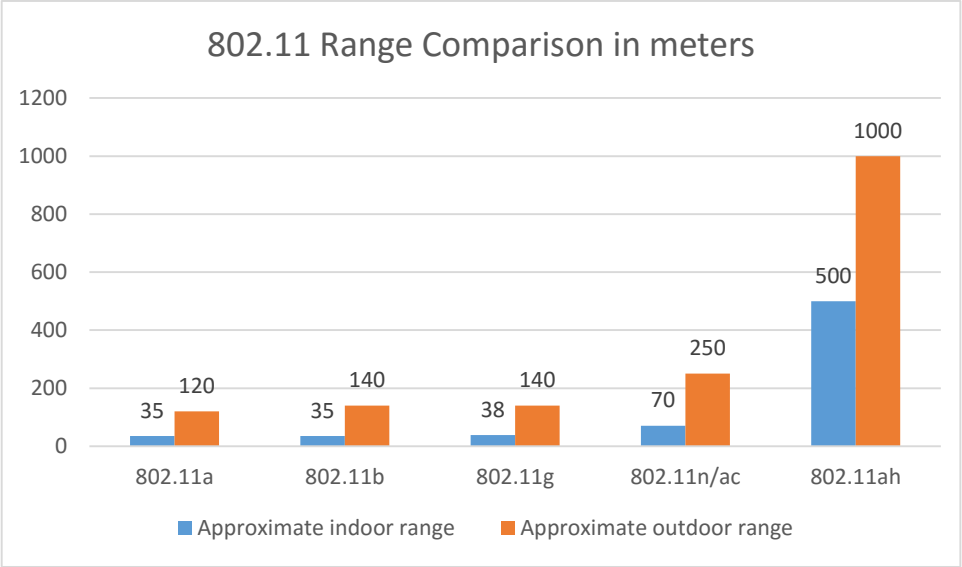


Figure 3.4- IEEE 802.11 technologies Range Comparison in Meters

Accordingly, if an IoT application requires the use of a larger number of nodes and meshing is an option, ZigBee appears to be a suitable candidate given its data rate advantage over its 802.11ah counterpart. On the other hand, IoT applications that require the deployment of fewer nodes with minimal traffic, 802.11ah is a strong contender to ZigBee. This is because 802.11ah has a larger coverage area without relying on any meshing technique. Also, it is intended to be backward compatible with the variants of 802.11 Wi-Fi technologies. However, as we will see in the next subsections that the data rate and range parameters do not provide enough and sufficient measures when comparing IoT wireless technologies as other criteria need to be considered as well.

3.2.2 Network Size Capabilities for IoT Networks

The BLE protocol supports a maximum of eight nodes per network which include one master device and seven devices as slaves. ZigBee can have up to 65,000 nodes per network in a star topology [150]. These technologies can be extended to more sophisticated networks as well. For instance, ZigBee can be extended to a cluster tree or mesh network; while BLE can be extended to a scatternet network. An interconnected piconet consisting of more than eight Bluetooth devices is referred to as a scatternet. It is

the process of connecting two piconets together. A scatternet can be created when a device belonging to one piconet is elected to be a member of the second piconet as well [181].

On the other hand, the baseline IEEE 802.11 standard does not limit the number of devices in the network. However, the limitation can be attributed to the length of some of the fields defined in the management frames of the standard [182]. The Association Identifier (AID) which is a unique value assigned to a station by the AP during an association handshake, is 14 bits long. However, the values other than 1-2007, which are 0 and 2008-16383, are reserved. In particular, AID of value 0 is reserved for group addressing traffic [166]. Therefore, the AID design limits the number of stations that can be associated with an AP to 2007 [166]. Additionally, the Traffic Indication Map (TIM) bitmap enforces the same limit on the number of associated stations as well. The TIM is used for power management mechanisms. It defines the number of buffered frames received from an AP. For these reasons, TGah is extending the range of AID values for 802.11ah's devices from 1-2007 to 0-8191. Also, the IEEE 802.11ah draft standard is increasing the maximal length of the TIM bitmap for 802.11ah's devices from 2008 bits to 8192 bits [166]. Therefore, it is quite obvious that ZigBee and IEEE 802.11ah protocols outperform the classic 802.11a/ac protocol when it comes to the network size requirements. Of course, cellular technologies have an enormous network size. However, cellular connectivity cannot be possible without involving a mobile provider that usually charges a fee per connection. Therefore, while cellular technology can accommodate a larger number of devices, the costs involved are dramatically higher than those associated with other technologies such as ZigBee. Table 3.1 provides a brief comparison between ZigBee, BLE, and Wi-Fi with regard to their network sizes.

Table 3.1- Network Size comparison of ZigBee, BLE, and Wi-Fi

Technology	**Network Size**
ZigBee	Approximately up to 65,000 nodes
Bluetooth	Eight nodes per network/piconet
Wi-Fi (802.11a/ac)	2007 associated with an AP
Wi-Fi 802.11ah	Approximately 8000 nodes

3.2.3 Transmission Power Evaluation

As shown in Figure 3.5 and Table 3.2, the 802.15.4 based technologies, BLE, and 802.11ah all have low power consumption characteristic. The transmission power of BLE ranges from 1 to 10 mW [183]. ZigBee transmission power is very low estimated to be under 1 mW. The Wi-Fi standard has a transmission power of approximately 100 mW. On the other hand, the IEEE 802.11ah has a transmission power of less than 10 mW. It is targeted to be under 1mW with the new proposed PSM scheme which aims for better energy efficiency.

In [184], it was found that with regard to energy consumption, and in the case of a small number of nodes in a low traffic scenario, the IEEE 802.15.4 consumed more average energy for the successful transmission of a packet compared with IEEE 802.11ah. However, in congested networks, the energy consumption of the IEEE 802.11ah was found to be relatively higher than that of IEEE 802.15.4. Therefore, the study concludes that with regard to energy consumption the IEEE 802.15.4 outperformed the IEEE 802.11ah, especially in a dense network with non-saturated traffic characteristics. However, when considering the throughput parameter, the IEEE 802.11ah has a better performance when compared to IEEE 802.15.4. Nevertheless, it should be noted that, at the time of writing, the IEEE 802.11ah standard is still under development. Thus, more simulations and experimental studies are required to determine the performance of IEEE 802.11ah effectively.

Table 3.2- A Comparative study of Low Power wireless technologies

Technology	**Bluetooth Low Energy**	**ZigBee**	**6Lowpan**	**Wi-Fi**
Standard	IEEE 802.15.1	IEEE 802.15.4	IEEE 802.15.4	IEEE 802.11ah
Data rate	1 Mbps	250Kbps	250kbps	150Kbps
Theoretical Range	100 m	10 to 20 m	~20 m	Up to 1000 m
Bandwidth	1 MHz	2Mhz	0.3/0.6; 2 MHz	1,2,4,8,16 MHz
Power consumption	0.01 to 0.5 W	~1mW	~1mW	~1mW
Security	128-bit AES with Counter Mode CBC-MAC and application layer user defined	TLS1.2 AES-128-CCM X.509 v3 certificates and ECC-256 cipher suite	AES link layer TSL/SSL on	Application layer security similar to 802.11

3.2.4 The IoT Ecosystem: Influential Factors and Requirements

When it comes to the ecosystem, The IEEE 802.11ah has the potential to stand out amongst its counterparts. Given that the IEEE 802.11ah is based on the 802.11 protocol, it is expected that it will be compatible with the existing 802.11 infrastructures. So it is expected to be compatible with IEEE 802.11a/b/g/n/ac devices and access points. The IEEE 802.11ah has the potential to grow the Wi-Fi market from its existing computing and mobile platforms for the IoT market significantly. However, given that the IEEE 802.11ah is still in its early stage of development, it is yet to establish itself against already recognised technologies such as BLE and ZigBee. As shown in Figure 3.5, the IEEE

802.11ah implements the full TCP/IP stack when compared to 6Lowpan and ZigBee, which makes it easier to integrate with today Internet systems.

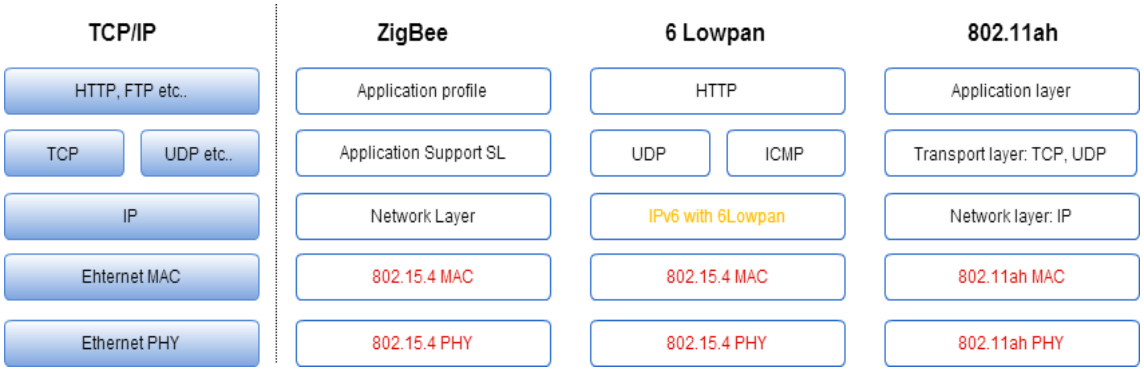


Figure 3.5- Comparative study of TCP/IP stack with ZigBee, 6Lowpan, and IEEE 802.11ah

Nevertheless, ZigBee has been winning grounds in several IoT consumers-based applications including electronics, smart meter infrastructure, and home automation. When meshing is an option, ZigBee's data rate differentiates it against the IEEE 802.11ah. ZigBee's is increasingly being used in various IoT areas such as in automated meter readings application, leading to participation in the smart grid push by utility companies. This has become an especially active area for ZigBee. However, the implementations of ZigBee remain, in greater parts, within closed ecosystems and applications. For instance, the lack of native support for ZigBee in the mobile device domain (e.g., in smartphones, tablets, laptops, smart watches, IT gadgets, and car multimedia) is a major challenge for early IoT adopters. More precisely, in applications where a mobile device is used as a temporary gateway for IoT devices.

On the other hand, BLE is a potential competitor in some IoT areas. It has applications in medical equipment and in remote control applications. BLE has been dominating the consumer electronics market. Additionally, BLE has been increasingly used to eliminate cabling for peripherals. This brings the peripherals closer to the communication networks and allows the management of these devices. Table 3.3 compares the ecosystems of ZigBee, BLE, and IEEE 802.11ah.

Table 3.3- Comparative study of ZigBee, BLE, and 802.11ah based on various criteria

	Security	**Location Detection**	**Low Cost**	**Ease of use**	**Ecosystem**	**Low Power**	**Range**	**Remote control**	**Antenna size**	**Networking size**	**Frequency band**
802.15.4	✓	✓	✓	✓	✓	✓	✓(✓)	✓	✓	✓	✓
BLE	✓	×	✓	✓	✓	✓	×	✓	✓	×	✓
802.11ah	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓(✓)	✓
Comment			Wi-Fi target: as per ZigBee	Wi-Fi target: as per 802.11	- BLE and 802.11ah have larger ecosystems. BLE is established in phones, wearables 802.11ah compatible with 802.11 - ZigBee has a closed ecosystem established in some use cases e.g., smart energy	802.11ah target: as per ZigBee	Criteria: 'home'. ZigBee Mesh will improve range. -BLE: Room range -Wi-Fi: Home range, extendable by mesh		lower frequencies require larger antennas	Criteria: >1000 Nodes per network. ZigBee has an edge of networking size of 65,000 device	802.15.4 and BLE operate at 2.4 GHz; while 802.11ah is fragmented by region

The criteria considered in the rating of technologies provided in Table 3.3 and the conclusions that can be drawn include the followings:

- The wireless technologies surveyed above have built-in link layer authentication and encryption, which most likely need to be completed with an end-to-end security at the application layer.
- Bluetooth Low Energy has the potential for less power consumption compared to that of IEEE 802.15.4 (less overhead).
- The IEEE 802.15.4 lacks the native support in the important ecosystem of mobile devices.
- The ecosystem with phones, tablets, laptops, and phone accessories is driving down the cost of BLE.
- The IEEE 802.15.4 has a data rate advantage over the 802.11ah. With regard to coverage, similarly to 802.11ah, many IEEE 802.15.4 based technologies such as ZigBee support meshing with the use of repeaters to extend the coverage of a network.
- The IEEE 802.11ah can be employed in a variety of existing devices, which will significantly improve the low-power consumption for these devices.
- 6LoWPAN implementations allow a device to communicate with another device over the Internet without having to go through, for example, a ZigBee-to-IP translation layer/device. At the time of writing, it is not clear as yet if the IEEE 802.11ah is backward compatible with existing IEEE 802.11n/ac infrastructure and if any infrastructure update or upgrade is needed. However, the fact that IEEE 802.11 is widely accepted as the dominant indoor wireless technology including IEEE 802.11 based indoor access points (APs) and stations [185], makes Wi-Fi's infrastructure compatibility with IEEE 802.11ah a core aspect of its adoption.
- 6LoWPAN offers interoperability with other wireless IEEE 802.15.4 devices as well as with devices on any other IP network with the use of a simple bridging device. However, a more complex bridging device is needed to connect ZigBee with other types of networks.
- For IoT scenarios that require the use of thousands of devices, ZigBee has a networking size of 65,000 devices. Similarly, the IEEE 802.11ah can also cater for

approximately eight-thousand devices as well. Data rate and the required coverage area play their roles in marking the differences between these two technologies as well.

- The IEEE 802.11ah benefits from the optimal propagation characteristic of sub-1GHz license-exempt frequency bands compared to 2.4 and 5 GHz bands. However, the IEEE 802.11ah frequency band fragmentation across different countries may be an issue for some IoT applications.

3.3 Summary

This chapter reviewed some of the enabling wireless technologies in the IoT particularly, ZigBee, 6lowpan, BLE, and Wi-Fi including the low-power IEEE 802.11ah protocol. It examined these technologies and evaluated their capabilities and behaviours with regard to various metrics including the data range and rate, network size, RF channels and bandwidth, antenna design considerations, power consumption, security, and the IoT ecosystem. The chapter highlighted the unique characteristics of these wireless low-power technologies and the issues about their incorporation in the IoT. The low-power and low-cost characteristics of these technologies and their integration in the IoT demand either new location management and privacy-preserving methods or approaching the prevailing management and location privacy protection systems differently. There is a need to manage the location privacy of an unprecedented number of things connected to the Internet generating a large amount of traffic across heterogeneous networks, particularly those with low-power capabilities such as those examined in this chapter.

The next chapter builds on the studies conducted in this and the previous chapters (i.e. Chapter 2 and 3). Chapter 4 proposes a management platform that provides users with the capability of managing the location information of their devices and preserving their location privacy in low-power wireless network setups similar to those investigated in this chapter. Additionally, the proposed platform incorporates an enhanced novel location privacy Obfuscation technique which addresses the shortcomings of classic Obfuscation techniques identified in Chapter 2.

CHAPTER 4- THE INTERNET OF THINGS MANAGEMENT PLATFORM

This chapter introduces the Internet of Things Management Platform (IoT-MP). The IoT-MP aims to provide users with the capabilities to manage their IoT devices, specifically their location privacy in the IoT. Also, the IoT-MP provides a communication platform enabling IoT applications to support things-to-things communications over the Internet. The IoT-MP offers the users with management capabilities, supervision, and control over things. The platform supports management over services running on managed things, such as sensing, actuating, monitoring, and managing the location information of things, in a local area network or remotely over the Internet. The design of the proposed IoT-MP takes into account the fact that things, in general, have limited power, computation, and communication resources available to them. Significantly, the IoT-MP preserves the location privacy of users and things during communications by supporting a privacy module. In this privacy module, a novel location privacy-preserving technique referred to as the Semantic Obfuscation approach (S-Obfuscation) is implemented which is presented in Section 4.1. The IoT-MP's architecture is presented in Section 4.2. Section 4.3 introduces the various IoT-MP components. The IoT-MP's manager modules are introduced in Section 4.4. Section 4.5 discusses the privacy module responsible for the management of location privacy of things.

4.1 The Semantic Obfuscation Approach (S-Obfuscation)

The Semantic Obfuscation approach (S-Obfuscation) proposed in this work uses geographical knowledge to guarantee that a generated obfuscated location is sensible in the context of the location's environment. That is, the method avoids generating an obfuscated location that could be easily identified as fake by an adversary. For example, if an obfuscated location is in the middle of a lake or sea, then it is easy for the adversary to determine that either the subject is on a boat or the location received is not real. Further knowledge of the geographic location may help the adversary in identifying the received

location as not original or obfuscated (such as whether boats are allowed on that location or no). This is important in the IoT as the physical location of a device is considered sensitive. Thus, there exist situations in the IoT where only specific entities or applications should access the location of an IoT device with greater precision. For instance, a public sensor collecting temperature information in a park or a given street should not reveal its exact location, for example, to everyone. For many IoT applications, it will be just sufficient to know the area where the sensor is located. Thus, by using different levels of proximity to the original location (referred to as Obfuscation levels in this work), we can control the granularity of the disclosed location.

To incorporate local geographical knowledge in the generation of obfuscated locations for a device, a novel method that uses an ontological classification of geographic locations is proposed. Our ontology is based on the one proposed in [186]. In our new approach to Obfuscation, an original location *L*, consisting of longitude and latitude coordinates is converted into ontology as shown in Figure 4.1. Ontologies are used as structural frameworks for organising information and concepts within a domain, and the relationship between those concepts. We use ontology as a form of knowledge representation about the geographic knowledge of a location. The ontology, presented in Figure 4.1, is part of a larger ontology that follows a top-down representation of several classes and subclasses arranged in a hierarchy as shown in Figure 4.2. Note that in Figure 4.1, only a single path of the ontology is presented from Figure 4.2. The ontology classes are constructed based on the naming of the geographic subdivisions used for address purposes in Australia. Therefore, in this work, the scope of the ontology is limited to Australia.

The parent ontological class in the hierarchy has *n* child classes. Each of these child classes is a parent of another set of subclasses, which in turn are more general than their child classes. This top-down hierarchal distribution represents the relative proximity of the obfuscated location to the original true location. The parent class has the widest proximity in the hierarchy while objects of the lower classes represent a smaller proximity. Thus, proximity decreases the further we go down in the hierarchy and increases the further we go up. Ontological classes on the same level of the hierarchy are

considered to be of the same granularity. These classes are structured in a tree starting from the tree root country (1), where 1 is the node identifier, as shown in Figure 4.1 and Figure 4.2. Each class in the tree has a name, an identifier, and a node address. For example, the class “Street (4a)” has the name “Street” and the identifier “4a”. The node address is constructed from the set of identifiers, separated by a dot (.). This node address is used to define the path to the class from the tree root. All classes start with the number 1. For example, the node address for the class with the name ”Street” and identifier “4a” is constructed by following the path starting from “country(1)” through “state(2a)” and “suburb(3a)” down to “street(4a)”. Thus the node address of class “street (4a)” is 1.2a.3a.4a. Thus, this scheme allows the identifications of each of the classes. It also provides a framework for the implementations, given that the scheme is adapting the concept of classes and inheritance from the Object Oriented approach.

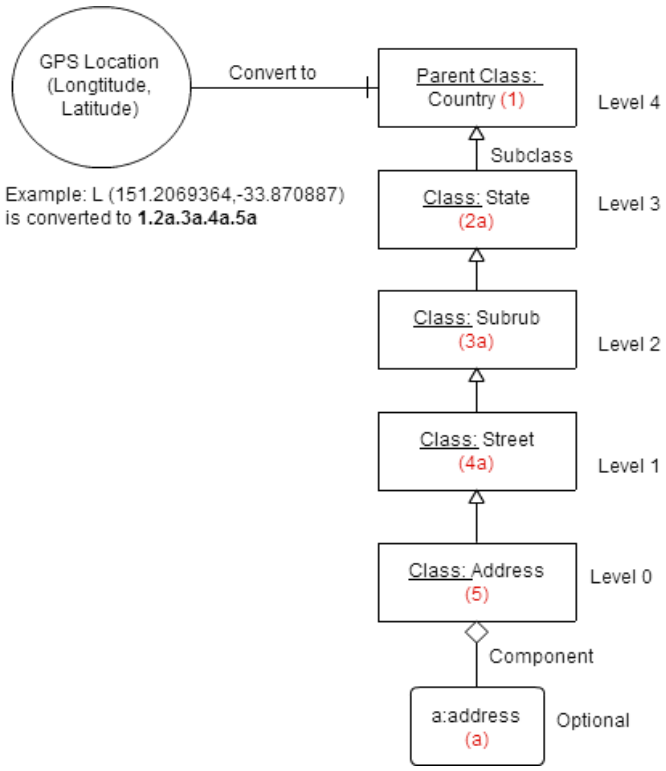


Figure 4.1- The Location Ontology

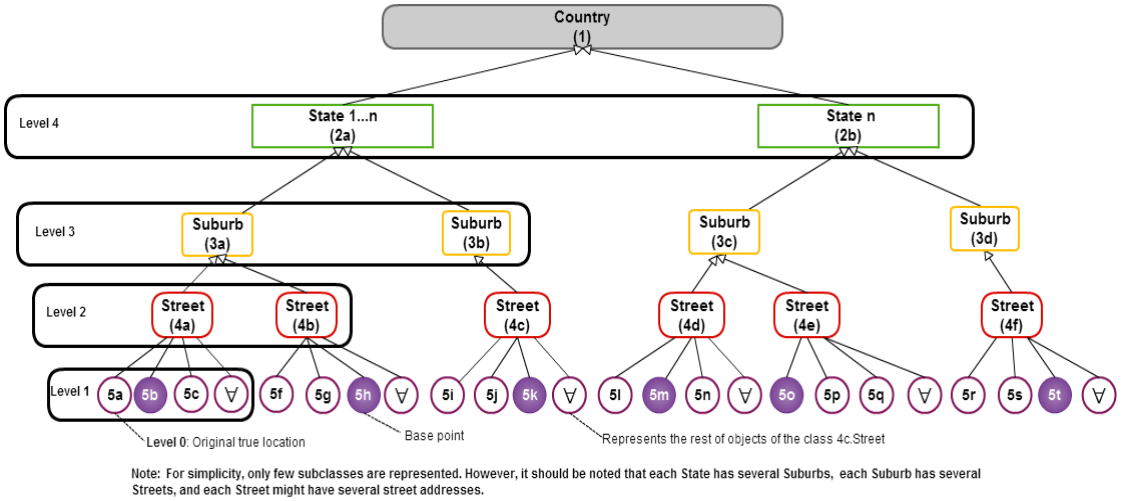


Figure 4.2-Tree Ontology

The S-Obfuscation works as follows: For each object belonging to a class of Level 2, an object from a Level 1 class is selected and defined as a base point (an object is an instance of a class). The base point is chosen based on the geographic knowledge. For example, from Level 2, the class "Street (4a)" has subclasses with the following node addresses: 1.2a.3a.4a.5a; 1.2a.3a.4a.5b; and 1.2a.3a.4a.5c. The object with the node address 1.2a.3a.4a.5b is defined as the base point for all objects of the class "Street (4a)". Similarly, the object with the node address 1.2a.3a.4b.5h is defined as the base point for all objects of the class "Street(4b)" and so on. Therefore, any object with a node address of 1.2a.3a.4a.X (where X represents the identifier of the object of a Level 1 class) will be obfuscated to 1.2a.3a.4a.5b. Similarly, for the class "Street(4b)", any object with a node address of 1.2a.3a.4b.X will be obfuscated to the defined base point 1.2a.3a.4b.5h, and so on.

Consequently, the followings base points are defined for all classes of Level 2: 1.2a.3a.4a.5b, 1.2a.3a.4b.5h, 1.2a.3a.4c.5k, 1.2a.3a.4d.5m, 1.2a.3a.4e.5o, and 1.2a.3a.4f.5t. Defining multiple base points will increase the number of available obfuscated locations that can be used. Also, randomising the appointment of objects as base points will help in addressing historical profiling of locations.

4.1.1 The S-Obfuscation Levels

As discussed in the previous section, there are five levels of Obfuscations: L0, L1, L2, L3, and L4, which are illustrated in Figure 4.3.

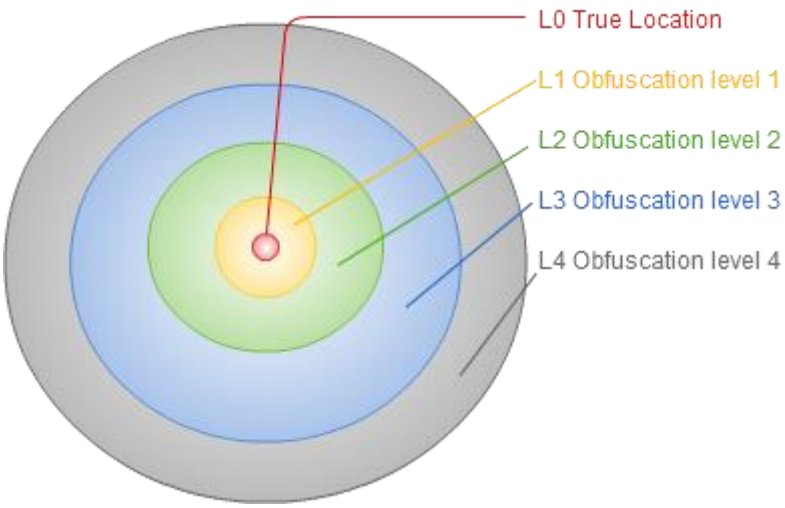


Figure 4.3- The Obfuscation levels

Level 0 (L0) discloses the true location of the object and Level 4 (L4) generates a dummy location. The remaining three obfuscated location levels (L1, L2, L3) are will be described subsequently. The position of any location on earth, on a 2D scale, can be determined using the conjugate graticule, which is where the latitude and longitude intercept. Determining the precise latitude and longitude coordinates of a location is available using many technologies such as a global positioning satellite receiver, which can communicate with satellites over the Earth to triangulate to a certain position. Therefore, an object's location in geographic space can be represented as a point on a map and denoted by L, where L is a 2-tuple (latitude, longitude). Define L to be a member of a set LS such that L∈ LS. LS is a collection of locations (refer to Table 4.1). For every element L∈ LS, define a base point LS (Xsi , Ysj) to represent each L∈ LS. Let the set LS be a subset of another set $\wp$(LS). In turn, let $\wp$(LS) be a subset of a master set $\wp$($\wp$(LS)). Each of these three sets has a base point that can represent L in its correspondent subset. Therefore, by selecting a set, a different base point location can be used and hence different levels of Obfuscation are provided using different base points. Figure 4.4 depicts

this logic. The algorithm, given in Table 4.1, describes how these sets are formulated and how the base points are derived

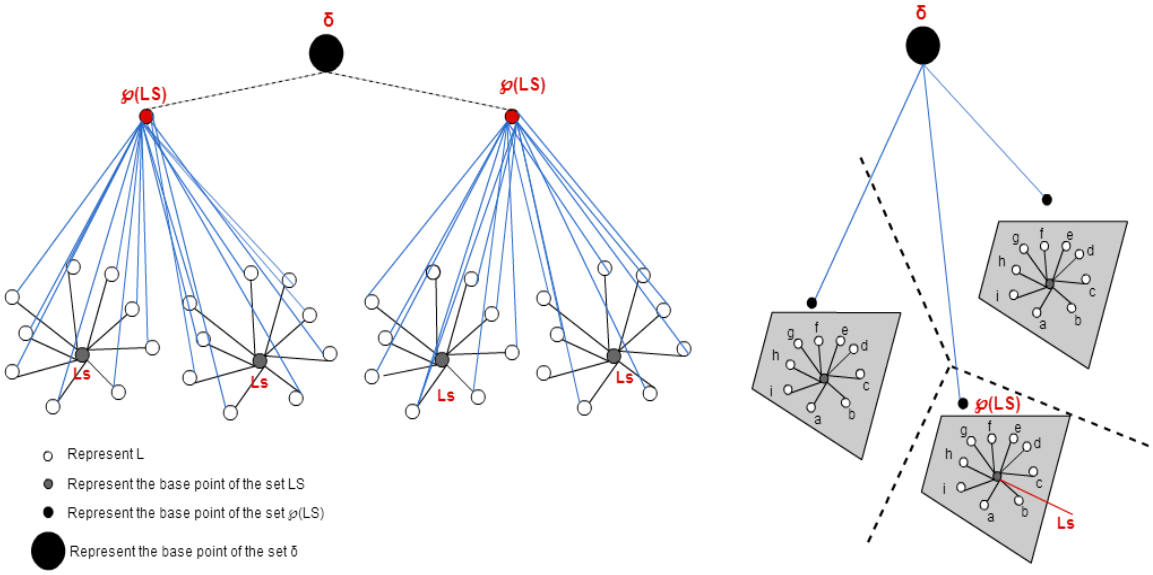


Figure 4.4- Cartesian representation of the three sets

Table 4.1- S-Obfuscation Algorithm

The S-Obfuscation Algorithm
Data: The geographic location of a device L is determined by the longitude *X* and the latitude *Y* and represented by L{X,Y}
Input: $L_i (X_i, Y_j)$ where L_i is the true location with current longitude X_i and latitude Y_j
Output: $L_o (X_i', Y_j')$ where L_o is the obfuscated location where
$L_i (X_i, Y_j) \in L_o (X_i', Y_j')$ and $L_i \subseteq L_o$.
Procedures:
1- Let $L_i (X_i, Y_j)$ be the true location with longitude X_i and the latitude Y_j
2- Let L_S be a set of $\{(X_a, Y_b), (X_c, Y_d) \ldots (X_i, Y_j) \ldots (X_n, Y_m)\}$; Where *n* and *m* are a unique representation of the longitude and latitude of a true location.

Table 4.1 - S-Obfuscation Algorithm (Continued)

That's for a given set of locations denoted by $L_{S1,}$ $\forall (X_n,Y_m)$ $[(X_n,Y_m) \setminus\in L_{S1}]$

where $\setminus\in$ means "strictly an element of"

// A certain location can strictly be an element of the lower subset.

Define the base point 1 $L_S (X_{si} ,Y_{sj})$ to represent any (X_n,Y_m) included in a particular L_S set in a way that:

If $(X_n, X_m) \in L_S$ then $\forall (X_n,Y_m)$ there exist

$(X_{si} ,Y_{sj}) \in L_S$ such that $[(X_{si} ,Y_{sj}) \rightarrow (X_n,Y_m)]$ where "represent any" is donated by $\rightarrow$

3- A collection of sets of L_S is denoted by $\wp(L_S)= \{L_{S1}, L_{S2} \dots L_{Sp}\}$ where *p* is an integer representing the number of subsets in $\wp(L_S)$ such as $\wp(L_S)=\{ Z \mid Z \subseteq L_S \}$

Let $\ddot{Y}= \wp(L_S)$

Define the base point 2 $\ddot{Y} (X_{Ti} ,Y_{Tj})$ to represent any (X_n,Y_m) included in any subset of $\ddot{Y}$ in a way that:

If $(X_n, X_m) \in L_S$ and $L_S \in \ddot{Y}$ then $\forall (X_n,Y_m)$ there exist

$(X_{Ti} ,Y_{Tj}) \in \ddot{Y}$ such that $[(X_{Ti} ,Y_{Tj}) \rightarrow (X_n,Y_m)]$

4- **Define** $\wp(\ddot{Y})$ to be the master set of $\ddot{Y}$ where $\wp(\ddot{Y})= \ddot{Y}_1 \cup \ddot{Y}_2 \cup \ddot{Y}_f$; where f is an integer representing the number of $\ddot{Y}$ subsets available.

Let $\delta = \wp(\ddot{Y})$.

Define the base point 3 $\delta(X_{Ci} ,Y_{Cj})$ to represent any (X_n,Y_m) included in any subset of δ in a way that:

If $(X_n, X_m) \in L_S$ and $L_S \in \ddot{Y}$ and $\ddot{Y} \in \delta$ then $\forall (X_n,Y_m)$ there exist

$(X_{Ci} ,Y_{Cj}) \in \delta$ such that $[(X_{Ci} ,Y_{Cj}) \rightarrow (X_n,Y_m)]$

5- Therefore if $L_i (X_{i,} Y_j) \in L_S$ and $L_S \in \ddot{Y}$ and $\ddot{Y} \in \delta$

There exist: $\forall(X_{i,} Y_j)$ $[(Xsi ,Ysj) \in LS, (X_{Ti} ,Y_{Tj}) \in \ddot{Y}, (X_{Ci} ,Y_{Cj}) \in \delta \rightarrow (X_{i,} Y_j)]$

4.1.2 A Scenario based on the S-Obfuscation

Consider the following typical example where a device requests a location based service:

Let L0 (lon, Lat) be a true original location and L the new obfuscated location. Convert L to ontology with a node address of 1.2a.3a.4a.5a. Suppose Bob is at a location that he considers sensitive. This location has a GPS location of L (151.2069364,-33.870887) which corresponds to the physical address 22 George Street, Sydney, NSW, Australia. The preference is as follows:

Preference 1: Bob, the owner of the sensor, is happy to share the location of the sensor with other IoT applications. While Bob does not mind revealing that the sensor is located at George Street, he prefers not to disclose its exact location.

To do that, Bob uses Level 1 of the S-Obfuscation technique. Therefore using Level 1, for L with the correspondent node address 1.2a.3a.4a.5a, the obfuscated location L' with the correspondent node address of 1.2a.3a.4a.5b will be used (refer to Figure 4.2). Figure 4.5 shows the flowchart representing the actual implementation of this example. It shows that instead of sending the sensor's true location of 22 George Street, Sydney, NSW, Australia, an obfuscated location of 35 George Street, Sydney, NSW, Australia, is used instead. Thus, the base point in this class is 35 George Street, Sydney, NSW, Australia. By obfuscating his true location L with a location L' located on George Street, the sensor can participate in the IoT application and the services it provides without revealing the exact true location of the sensor. In addition, since L' is already carefully selected based on geographic knowledge, Bob is confident that adversaries will not be able to detect if Bob is sending a fake location. In another scenario, Bob preferences are changed to as follows:

Preference 2: Bob does not wish to reveal the sensor's exact location, but he does not mind letting an adversary know that the sensor is located at somewhere in Sydney.

To create this policy, Bob uses Level 2 of the S-Obfuscation techniques. Instead of sending the true location L of the sensor, with the node address 1.2a.3a.4a.5a, Bob is now

able to choose to send an obfuscated location, with a wider proximity to the true location used before. The obfuscated location generated in level 2 is selected based on geographic knowledge as well. Figure 4.6 shows several options for obfuscated locations that Bob can use. Level 3 of S-Obfuscation will allow Bob to choose an obfuscated location with a wider proximity to the sensor's true location than those produced in Levels 2 and 1. This process is illustrated in Figure 4.6. On the other hand, Level 4 of S-Obfuscation will allow Bob to select an obfuscated location with a wider proximity to those generated in Levels 3, 2 and 1.

Figure 4.5- Level one of Obfuscation

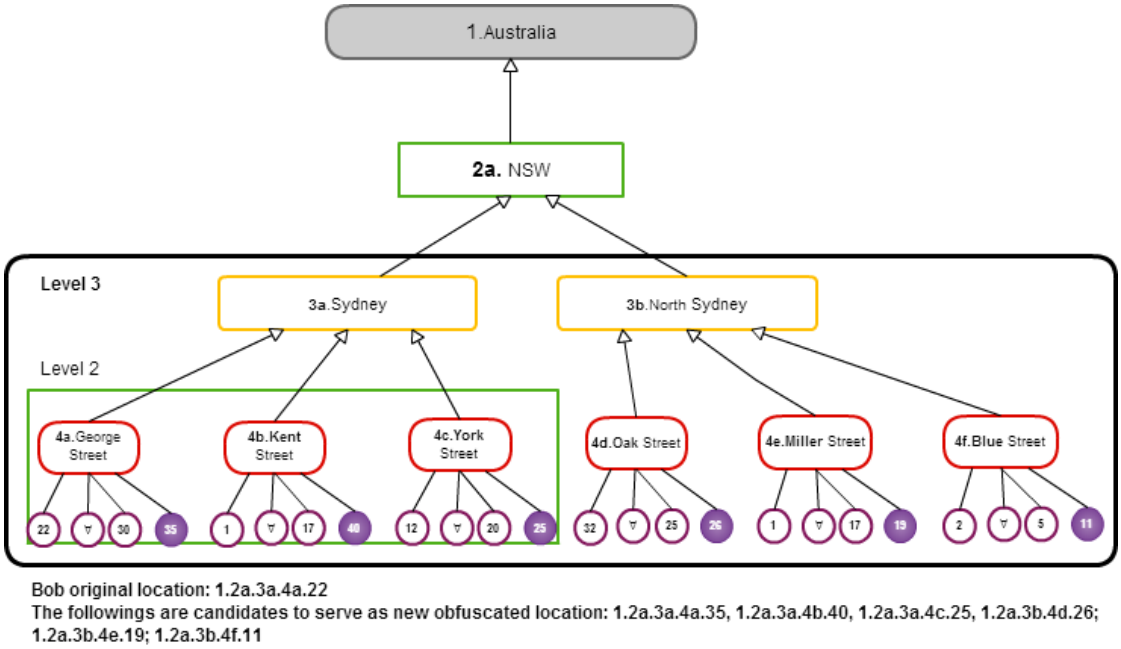


Figure 4.6- Obfuscation Level 2 and 3

The rest of the chapter introduces the Internet of Things Management Platform, which utilises the Semantic Obfuscation approach for the preservation of location privacy in the IoT.

4.2 Architecture of the IoT-MP

The IoT-MP supports the communications among things regardless of their capabilities and the technology they use. The IoT-MP architecture enables heterogeneous communications to occur between the various types of things and IoT applications. Figure 4.7 shows a high-level view of the IoT-MP. It shows four types of things. A general device (things) represents a generic form of physical devices that possess a communication capability as a minimum requirement. The second type of things has actuation capabilities. These are devices which receive remote commands over the Internet. They have the capabilities of modifying the physical environment. Things with sensors collect information from the physical environment and transmit this information over the Internet. The last type of things is a hybrid device which possesses both sensing and actuation capabilities. The IoT-MP acts as a communication bridge between these things.

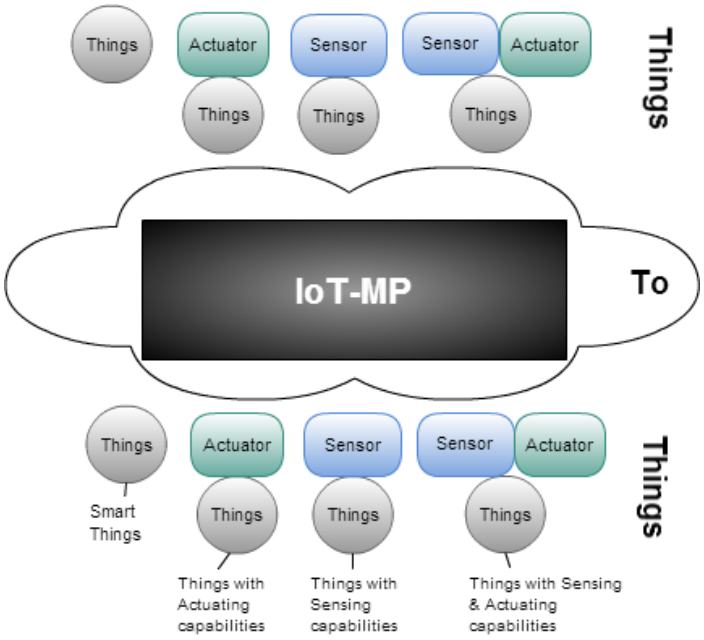


Figure 4.7- A high-level view of the IoT-MP

The architecture of the IoT-MP ranges from a simple two-tier architecture consisting of a manager and its associated agents to a distributed architecture that consists of agents, managers, and a Manger of Mangers (MoM).

In the simple two-tier architecture, as shown in Figure 4.8, the IoT-MP adapts the structure used by traditional network management approaches. The IoT-MP architecture consists of an agent, which resides on a thing and a manager that manages things. The agent acts as a communication agent that has the responsibility of transporting the data generated or collected by things to their manager. The term Managed Things (MT) is used throughout this thesis to refer to an agent and the thing as one entity. The manager manages many managed things in a system. It is a one-to-many relationship between the manager and its associated managed things. Additionally, the manager stores the received data, sent by managed things, in a database.

The IoT-MP provides IoT and management applications, running on top of the manager, access to the data generated by things and stored in the database remotely over the Internet. The details of how IoT applications access the database are discussed in Section

4.4.6. The IoT-MP also provides IoT applications with a mechanism to send instructions to managed things e.g., sending actuation instruction to managed things.

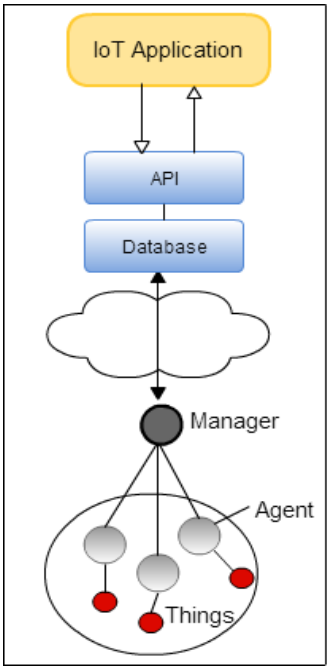


Figure 4.8- IoT-MP Two-Tiers Architecture

In the distributed architecture, a Manager of Mangers (MoM) is introduced. This architecture is provided in Figure 4.9. The MoM is a web application that contains an API referred to as the management API. It allows the MoM to communicate with many managers. The MoM also has a database that stores the addresses of managed things. The MoM database is hierarchical (tree-structured), and each entry relevant to a managed thing is addressed through the Manager unique ID. Thus, the MoM database does not store any information collected from managed things. It only stores their addressing information i.e. through which manager, managed things can be accessed. An IoT application running on top of the MoM can provide services based on combining data collected from various managed things. Therefore, IoT applications and services are built on top of the M2M by supporting communications among things via their respective managers.

Consequently, the architecture of the IoT-MP provides a centralised model of several agents and a manager allowing for central management of things over local area network. On the other hand, the distributed architecture of several managers and MoM creates a distributed system where things communicate in a cooperative fashion rather than stand-alone manner. This flexibility in design caters for the specific communications requirements of the IoT. Given that most IoT devices may play different roles in both centralised and distributed operations setups.

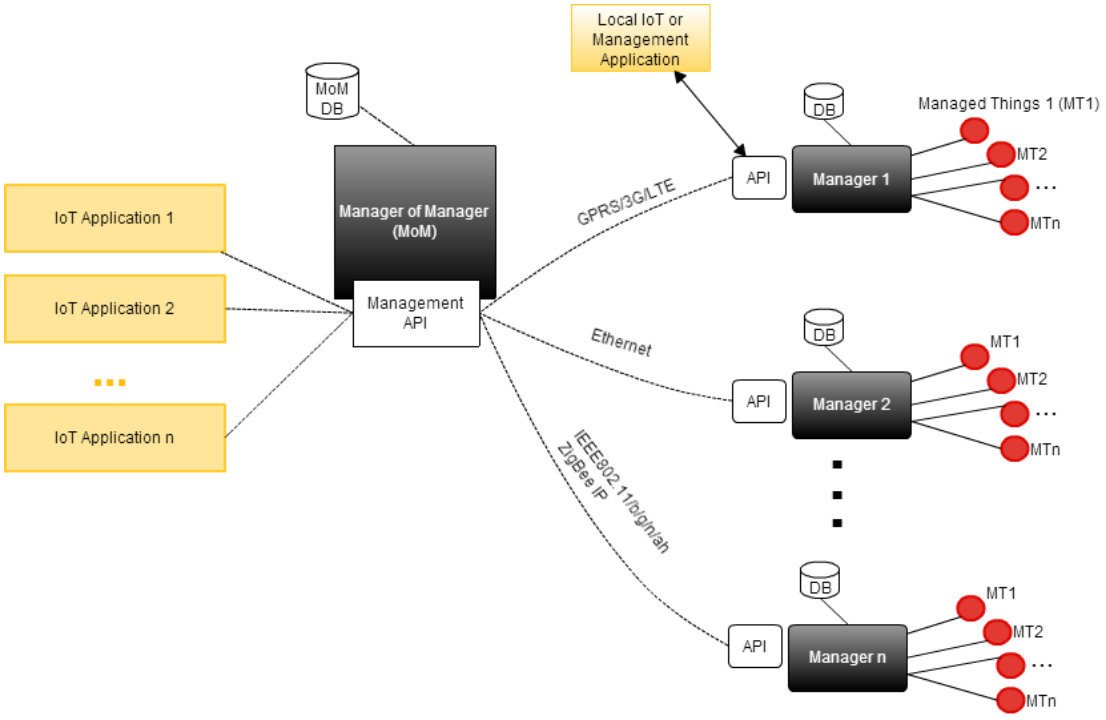


Figure 4.9- Distributed Architecture

4.3 The IoT-MP Components

In this section, the various components of the IoT-MP are introduced.

4.3.1 The Agent and Managed Things Components

Things are virtually represented using attributed on the management database of the IoT-MP and are referred to as “Managed Things”. The management database is discussed in

a subsequent section. The representation of things using attributes is shown in Figure 4.10.

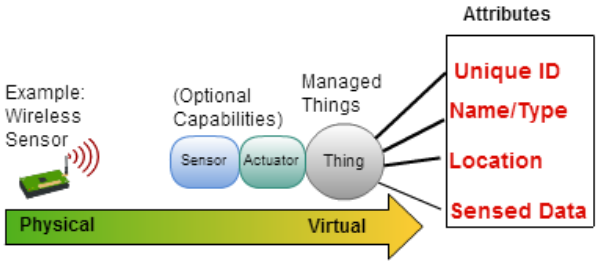


Figure 4.10- The Attribute of Things

More specifically, things are represented using two types of attributes. The first type of attributes is referred to as the management attributes. They are used for the virtual representation of things. The second type of attributes is referred to as the behavioural attributes. These attributes are used to hold the data things sense or collect. They are also used to hold information relating to actuation events. The definition of these attributes provides a way to store information about things and the information they collect on the management database. Table 4.2 provides an example of management and behavioural attributes that represent a wireless sensor device.

Table 4.2- Behavioural and Management Attributes example

Management Attributes	**Behavioral attributes**
• ID • Name • Serial Number • Firmware version • IP, MAC address, network name or others • Battery life • Location (if fixed)	• Temperature • Motion • Sound • Pressure • Water & fire detection • Location (if mobile)

Therefore, we define a Managed Thing (MT) as the entity that represents the device and its agent. Managed Things are accessed via the management database by the manager and

other IoT applications. Managed Things are abstract representation of things that comprises not only the device e.g. a wireless sensor but also the communication module, driver, and software (i.e. the agent) that handles the communications between the device and the manager. In particular, an MT has a name and a unique identifier. The management and behavioural attributes can be optionally defined and implemented for things. From Table 4.2, the management attributes are descriptors of a wireless sensor device. For example, the ID is used to identify uniquely a thing. The name, serial number, firmware version, and the rest of these management attributes are also used as descriptors for things. These attributes are optional, and the decision whether to use them or no is left to the specification of things. For instance, not all things necessary have a firmware version. Thus, a wireless sensor device may elect to use only the ID and location, as an example, from the list of the management attributes. While, a smart enabled Wi-Fi device may utilise more management attributes. Similarly, the behavioural attributes are used as records in the management database. These are also optional as they are inheritably associated with the characteristics of things. For instance, a temperature sensor that has the responsibility for collecting motion and temperature data from a given environment will choose the “Temperature” and “Motion” from the behavioural attributes lists. Other things with a different functionality or scope such as a fire detection sensor will choose the “Fire Detection” from the behavioural attributes. Operators of things may also create new attributes in the management database to represent them.

Figure 4.11 models MTs. It further shows that an agent has two main modules. The communication module is responsible for the communications with the manager. The agent services module is responsible for the execution of services such as generating alerts or processing an actuation instruction. Thus, the agent handles the communications between the manager and thing by forwarding the collected data to the manager and by processing the requests sent by the manager. Further details on how MTs associate with a manager is provided in Section 4.4.3. In summary, the agent has the followings responsibilities:

- Establish communication with the manager.
- Sending data updates from MTs to the manager.

- Handling requests and their correspondent responses from/to managers.
- Receiving actuation instructions from the manager and passing them to the MTs
- Sends notifications to managers

To support the communications between MTs and their manager, a message exchange scheme is defined and discussed in Section 4.4.

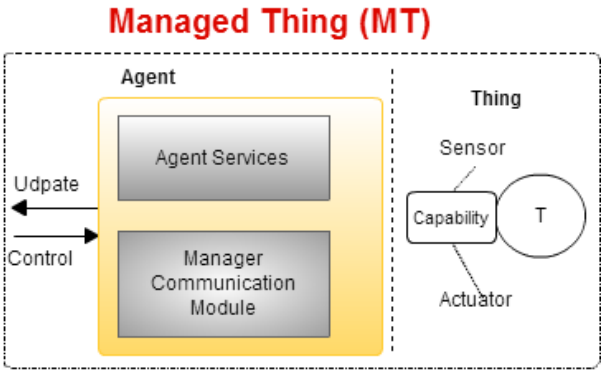


Figure 4.11- Managed Things

4.3.2 The Managerial Components

A manager is an application that performs the operational roles of generating requests to retrieve information from managed things. A manager can also send actuation requests on individual MTs, which have actuation capabilities. A manager receives event-based notification reports on MTs generated by their agents as well. Additionally, a manager issues requests for management's operations on behalf of an administrator or an IoT application and receives notifications from agents. A manager maintains a management database, which stores information about MTs. The manager accesses MTs' data stored in this database.

Significantly, a manager supports a management API which is based on the Restful architecture. This API allows IoT applications to request over the Internet information about MTs, which is stored in the management database. The API also allows management applications to monitor and control MTs. The management API is also used

to communicate topology information about the network to the Manager of Managers (MoM) over the Internet. The MoM is a higher entity sitting on top of the manager. IoT applications run on top of the MoM and send requests to access data of MTs under the manager supervision. Figure 4.12 shows how the manager interacts with things via agents. The manager comprises several modules that provide management, security, and, privacy capabilities among other operational services. These modules are introduced in Section 4.4.

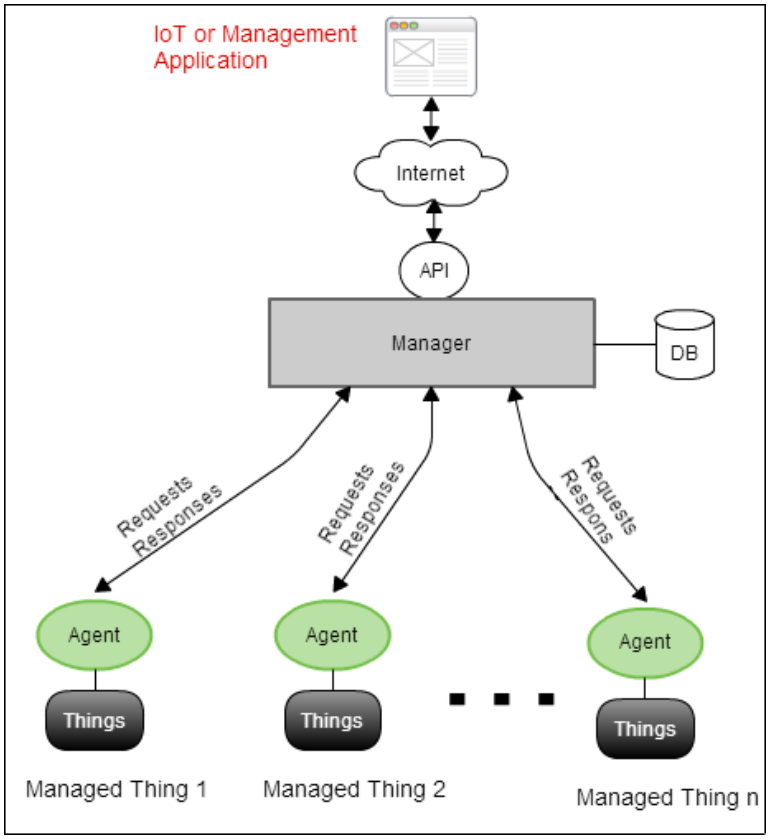


Figure 4.12- The Manager position in the IoT-MP

The Management Database Component

The manager stores the information received from Managed Things in a database referred to as the management database. Therefore, each MT is represented in the Manager's database. An example of how MTs are represented in the database is given in Figure 4.13. The managed attributes describe the MT's type, name, and other descriptors that can be

defined by the administrator. The Behavioural attributes are used to store the data received by the manager from an MT. MTs' information is indexed in the database using the unique ID of the MT. Figure 4.13 shows examples of Managed and Behavioural attributes. For instance, the MTID is used to uniquely identify an MT. The Type, Name, Admin, and AgentID are other examples of managed attributes. The Loc, Sensor Reading A, and B are examples of behavioural attributes entries in the database. The security layer is a pointer to another process that is concerned with security and location privacy protection. This is further discussed in section 4.4.4. The main parts of the database scheme are provided in Figure 4.14. The complete database schema is provided in the appendix.

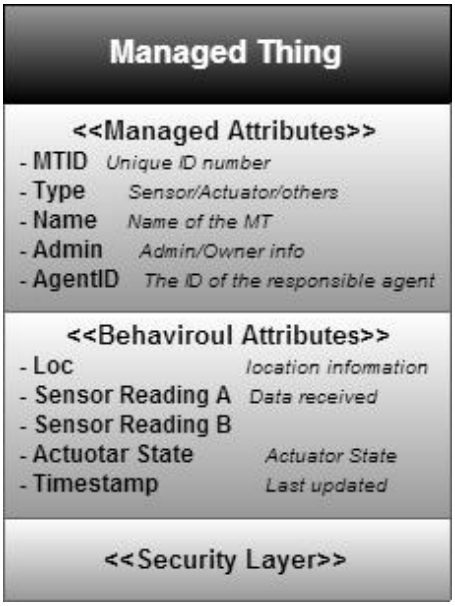


Figure 4.13- MTs Entries

From Figure 4.14- Database Schema, table Managed Thing:

- MTID is an identifier used to uniquely identify things in the IoT-MP. It is assumed that each IoT device (things) is assigned a unique identifier.
- AgentID is an identifier used to identify agents. This AgentID is assigned by the manager. The MTID and AgentID are used to identify an MT. In the case where the agent is residing on the MT, the MTID is used in place of the AgentID.

- The security pointer points to another process that enforces access control disclosures policies on the data of MTs.
- The descriptions of the rest of the entries in the database are provided in Figure 4.14 and are self-explanatory.

Entry	Table Agent: Description
AgentID	Uniquely identify agent
MTID	The Unique ID associated with this manager
Status	Describes the status of agent
ManagerID	used to associate a manager to an agent using the ManagerID

Entry	Table Managed Thing Description
MTID	An ID that uniquely identifies managed things by agents (Hardware ID, Mac/IP)
AgentID	Binds a thing to an agent
Access Type	Read only Read-write (requirePermission)
Status	Describes the last known status of the device
SysDescr	Contains information on the entity administrating the device
Generic	Information publicaly available on the device
SysLoc	Sys Location is an entry which stores the location of a device
TimeStamp	TimeStamp contains the time and date for the last time this table has been updated
Security Pointer	Point to another process which enforces security and privacy on the MT
Data	Array used to store data sent by MTs
Other	Optional entries for behaviroual attributes

Figure 4.14- Database Schema

The Manager of Managers (MoM)

The Manager of Managers (MoM) provides mapping and routing services over the IoT-MP. The functionality of a MoM is similar to a router that performs "traffic directing" functions on the Internet. The MoM forwards data packets between managers' networks and IoT applications over the Internet. An IoT application accesses the MoM remotely over the Internet. It can request information about an MT (belonging to a particular manager's network) or supply information that can be used by other MTs or IoT applications.

As previously mentioned in Section 4.2, the MoM sits on top of the tree structure of the IoT-MP and communicates with many managers. Communications between a manager and the MoM are via their APIs and over HTTPS. The MoM maintains a hierarchical database, which stores the addresses of managed things and their managers. The MoM does not store in its database any operational data on MTs. Thus, similarly to a routing table, the MoM database is used to store information about the topology of the network such as which manager is overseeing which group of MTs. This information is used by the MoM to determine where a request, sent by an IoT application, should be directed within the IoT-MP network.

The MoM database consists of a table which has three fields:

- The ManagerID: i.e. the destination of the manager network
- The IP address of the manager
- The list of MTID belonging to its manager network

The scenario is as follows: the MoM receives a request to access a certain MT data from an IoT application over the Internet (HTTP request). The request must specify at least the MTID of the requested MT and the "AppID" of the application, along with some other credentials used for authentication (this will be described in more details in section 4.4.6). The MoM then lookups the MoM database and retrieves the correspondent ManagerID and its IP address. The MoM forwards the request to the correspondent manager and waits for a response. Lastly, the manager responds to the MoM with either an error message or with the data being requested. This scenario will become clearer once the manager and its components are introduced in the next section (Section 4.4).

In the rest of this chapter, the work assumes that IoT applications communicate with a manager transparently. That is the communication medium is already established between the IoT application and the manager. Thus, instead of passing through the MoM each time a request is issued by an IoT application, we will simply refer to the request as being issued by an IoT application to a manager.

4.4 The Manager Modules

The manager is designed in a modular format, so it is possible to extend its functionalities and capabilities. As shown in Figure 4.15, the manager has seven main modules. These are described in the subsections that follow this section.

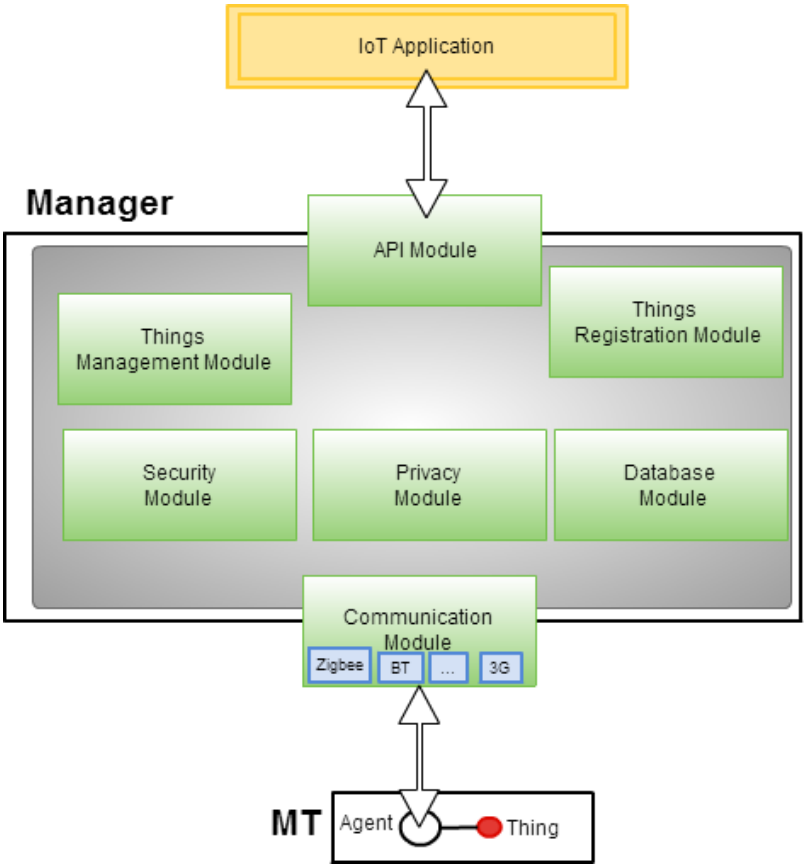


Figure 4.15- The Manager's Modules

4.4.1 The Communication Module (CM)

The Communication Module (CM) is responsible for handling the communications between the manager and managed things. The CM supports the communications of two types of messages: management messages and operational messages. Management messages are handled by the Management Module and are used by the manager to obtain management information such as network status, connection information, and dynamic performance information. These management messages are discussed as part of the

Management Module in Section 4.4.2. Operational messages are mainly used to get status information and updates from managed things. These messages are based on two messages “Get” and “Update”. As their names suggest, the ‘Get’ messages are used by the manager to get information from an MT. The “Update” message is utilised by an MT to send an update to a manager. These messages are defined as follows:

- **Update *(MTID, [AgentID], Array5)*:** The *Update* message is used by an MT to send periodic messages to the manager. The agent can also use this message to send event-based alerts to the manager. It has three arguments: the *MTID,* which stands for the Managed things Unique Identifier ID. The *MTID* is used by the manager to identify MTs. The second argument, *[AgentID]*, is optional and is used to identify the agent. The last argument, *Array[]*, contains the content of the message, in which the MT is sending to the manager, stored in an array format. The format of the message Update is provided in Figure 5.10.
- **GetUpdate *(MTID, [AgentID]):*** This message is used by the manager to request an update from the MT. For instance, GetUpdate(temperature collected by MT) is an implementation example of the message GetUpdate()
- **Response *(MessageID, AgentID, Array[], ErrorIndex)*:** This is a response message to the manager’s message GetUpdate(). The *MessageID* argument in the Response message is used by the manager for matching requests to responses. The *ErroIndex* is a number which points to an error. The *Array[]* contains the content of the message supplied in the reply.
- **Actuate ()**: This message is optional. It is sent by the manager to an MT triggering an actuation event on the MT.

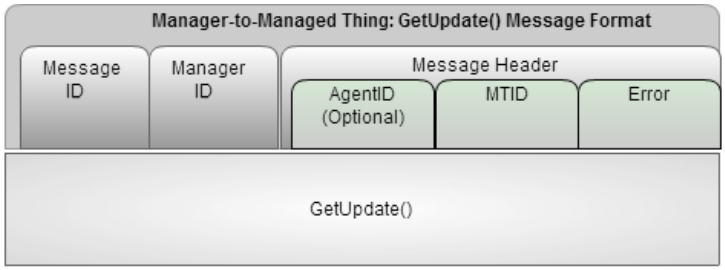
Update Message Format

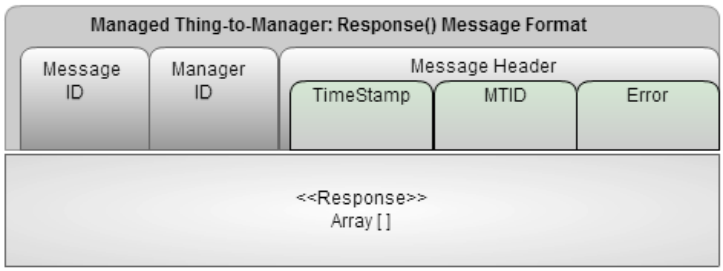
MTID	AgentID	Error Index
Message []		

Error Status

Error Index	Description
0	No errors
1	Agent error
2	Thing error
3	Update Unavailable
4	General error/ Unauthorized

Figure 4.16- Update Message format





Error Index	Description
0	No errors
1	Unauthorised Manager
2	MTID not found or unavailable
4	Agent ID error
5	Unreachable
6	General error

Field	Description
Message ID	An ID used to match the *GetUpdate()* requests to the *Response()* message
Manager ID	An ID used to identify managers by agents
Agent ID	Used to uniquely identify agents. This is optional
MTID	An ID that uniquely identifies managed Things
Error Index	an index that desribes the nature of the error
GetUpdate()	Used to request from an MT update on data. Implementation example: GetUpdate (Location)
TimeStamp	A timestamp in the form of a sequence number added to the message
Array [ ]	In the response message, Array [ ] is used to stored the information being updated and sent by the MT to the Manager

Figure 4.17- GetUpdate Message Format

The *GetUpdate* message is sent by a manager to an MT. It is used to request data update. For example, *GetUpdate(Location)* is used to get an update on the location of an MT. The format of this message is provided in Figure 4.17. It shows the entries for both *GetUpdate* and *Ack* messages. Figure 4.17 contains as well a description of each of the entries of these messages. The message *Actuate()* is an optional message. It is only supported by MTs that have actuation capabilities. The message *Actuate()* has a response message defined as *Ack().* The messages formats of *Actuate()* and *Ack()* are given in Figure 4.18.

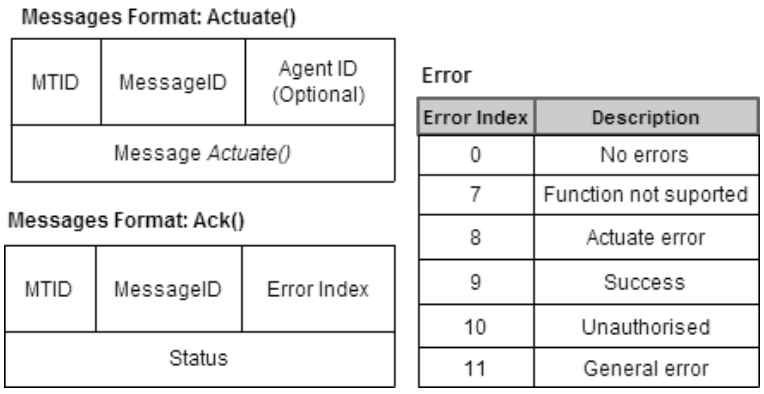


Figure 4.18- Actuate and Ack message format

The entry "Status" reports the current actuator status in the *Ack*() response message to the manager. For example, suppose the actuator of an MT can turn a device ON or OFF. Therefore, the "ON" or "OFF" message will be the status reported back to the manager in the *ACK()* message in this example. Figure 4.19 shows a sequence diagram for the message *GetUpdate*. It should be noted the *GetUpdate* message is initiated by a management application and sent to the manager.

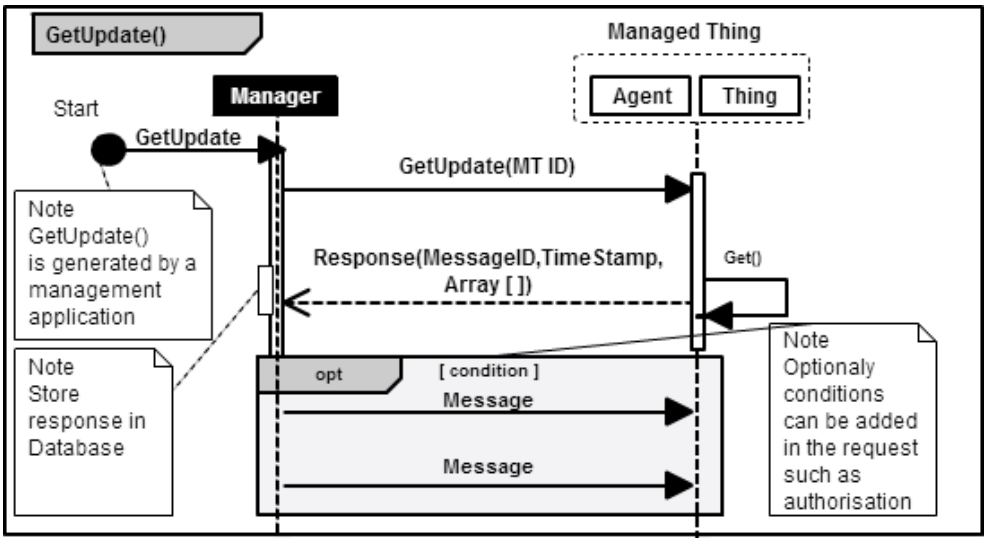


Figure 4.19- GetUpdate Sequence Diagram

Figure 4.20 shows the sequence diagram for the message *Update*, which is initiated by the MT. Upon the receipt of this message by the manager, the manager extracts the data

contained in the *Update* message and updates the relevant records in the management database for the MT using its MTID.

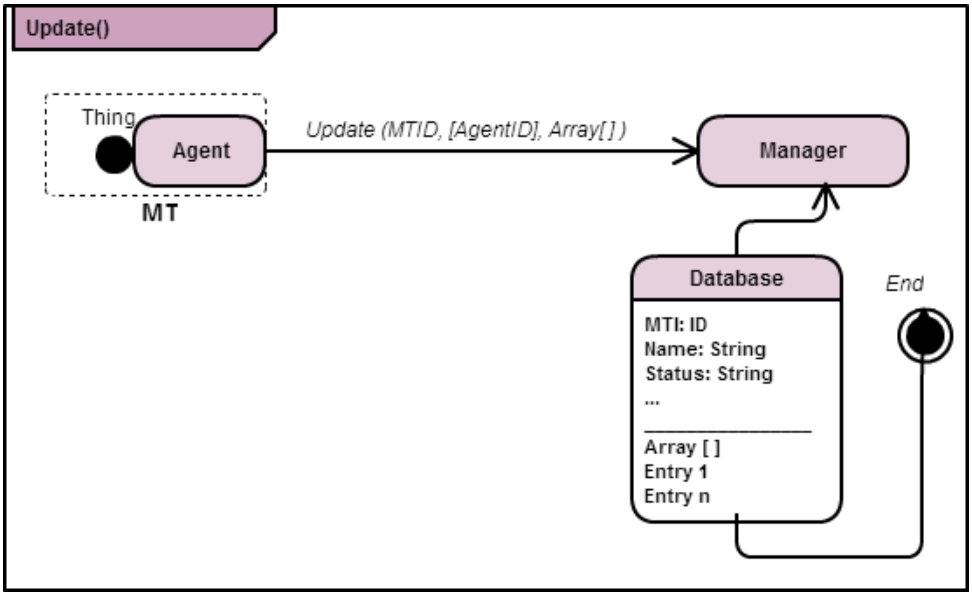


Figure 4.20- Update Message Diagram

4.4.2 The Things Management Module (TMM)

The Things Management Module (TMM) defines the messages used by the manager to manage MTs. These management messages are adapted from SNMP. Mainly, the TMM adapts three SNMP messages: the SET, GET, and Alert SNMP messages. They are used to inspect and communicate information about MTs to the manager. The TMM messages are described as follows:

- *GetMTStatus(MessageID, MTID, [AgentID]):* This message is used by the manager to request information on the status of an MT. The message takes the Managed Thing ID (MTID) as an argument. The AgentID can be optionally specified as well. This message returns an *Update* message (previously introduced in Section 4.4.1) containing the information requested. For instance, a scenario of a GetStatus message is provided in Figure 4.21.

- *GetDeviceMode ([SensorMode], [ActuatorMode], [AgentID]):* The SensorMode and *ActuatorMode* are optional arguments. Their implementations depend on whether an MT possess sensing and actuation capabilities.
- *SetLoc (MTID, Location):* This message is used to set the location of an MT. Mainly, it is used for MTs with fixed location e.g., an item on a shelf in a warehouse.

Other management messages based on the SNMP GET message can also be implemented to retrieve specific information from MTs.

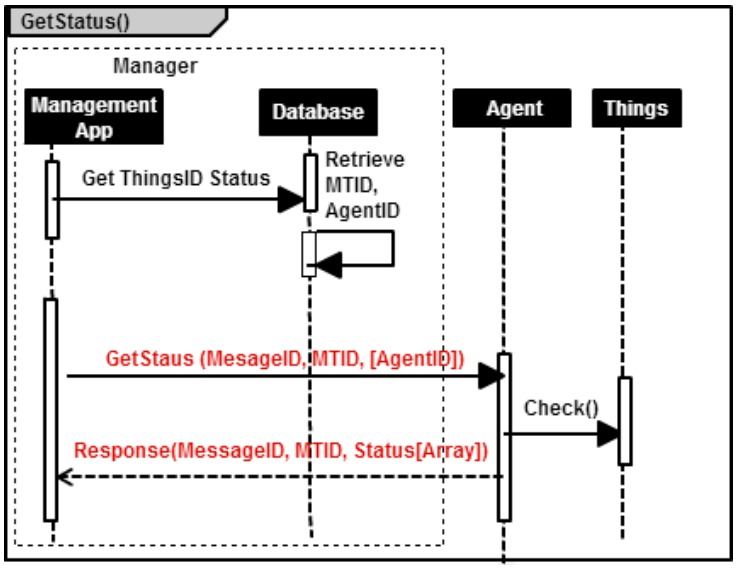


Figure 4.21- GetStatus message

4.4.3 The Things Registration Module (TRM)

The Thing Registration Module (TRM) is responsible for registering things on the IoT-MP. It involves the process of things bootstrapping, connecting and joining the network, and creating an entry for the thing in the database. A thing joins the IoT-MP network and becomes an MT by connecting to a manager using an agent. Thus, it is assumed for the communication to be established with a manager, a thing must rely on an agent that is capable of communicating with the manager. As previously mentioned in Section 4.3.1, the agent is a software that can be installed on the thing, or it could reside on another device in the thing local area network. For example, a Bluetooth slave device (thing) may

communicate with a Bluetooth Master device that implements the agent capability. In this example, the Bluetooth Master device is considered to be the agent. The combination of the master and slave device is referred to as the MT. It is assumed that communications between the Bluetooth Master and Slave devices are already provisioned. Assuming a thing already has an agent capable of communicating with the manager, a thing connects to the manager and becomes an MT using one of the followings three methods:

I. by joining the network directly;
II. by requesting to join the network through associations;
III. by reconnecting to the network.

In the direct joining method I, the thing is pre-programed with the network address of the manager. This allows the thing to send a DIRECT-JOIN request, via an agent, to the manager. In method II, the process of connecting an MT to the manager through an association is similar to that of a Wi-Fi device that associates with an access point. Method III is used when an MT loses its connection with the manager and tries to re-connect. This can happen when an MT moves out of range of the local-area network or when the manager becomes unavailable. In such a case, the MT will try to reconnect and join the network using Method I or II. The difference between method I and II, on one hand, and that of III, on the other hand, is that in method III there is no need to create a new record in the database for the MT. Instead, the manager updates the existing records. The sequence diagrams for the method I and II are provided in Figure 4.22. In the sequence diagram of method II, the security negotiation messages are discussed in Section 4.4.4.

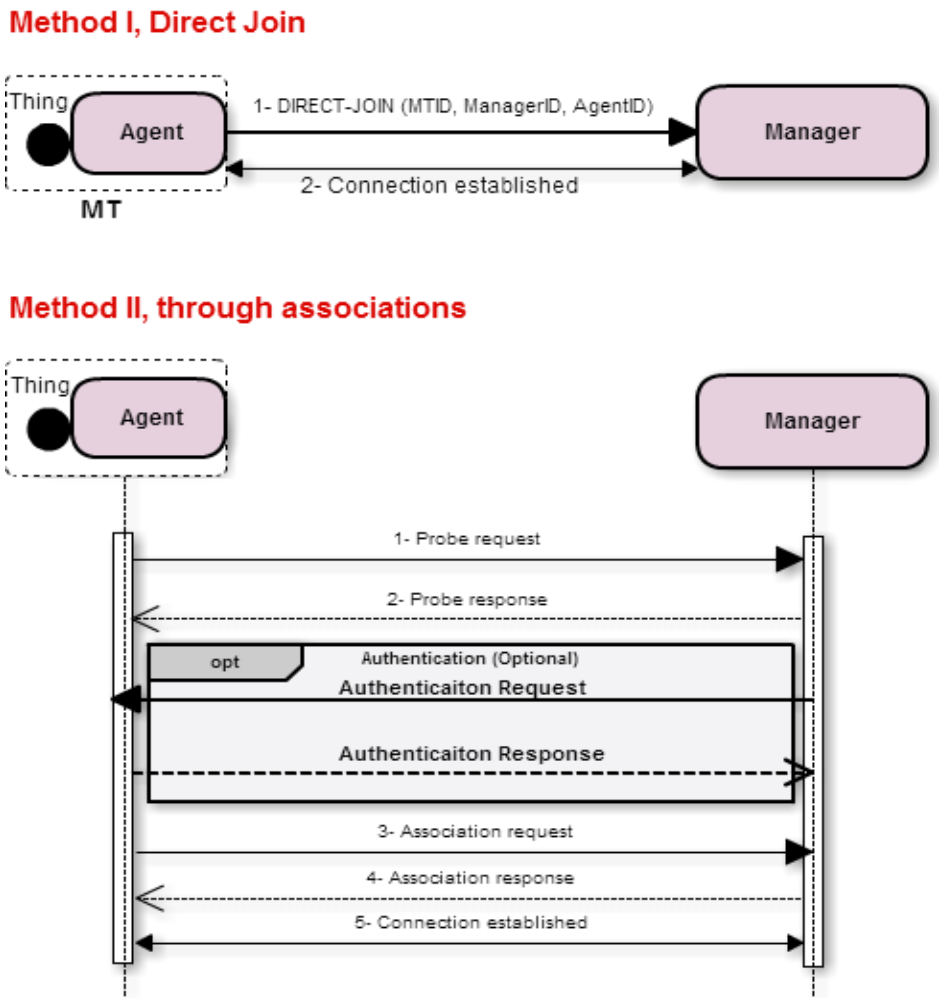


Figure 4.22- Method I and II sequence diagrams

4.4.4 The Security Module (SM)

The Security Module (SM) provides (1) security services between managed things and a manager and (2) security between IoT applications and the manager using a security profile. In (1), the SM enforces that an agent must first be registered with the manager and approved by an administrator. The manager keeps a database of authorised agents using their AgentIDs. Therefore, the SM ensures that only authorised remote agents are allowed to connect to the manager. To achieve this, the SM enforces this two directives:

a) The SM prevents unknown remote agents from connecting to the manager.

b) Remote agents need to be manually approved by an administrator before they can communicate with the manager.

This work assumes that the identity of an agent (AgentID) is unique and protected against classic identity threats such as identity forging, poison attack, and the likes. To relax the condition implied in b,), which requires the manual approval of agents by a human and to automate the process, classical access control and identity management solutions can be employed to preserve the identity of agents. For instance, a digital certificate solution can be combined with an Attribute-based access control (ABAC) system to secure the process of establishing a security association between an agent and a manager. However, identity management is not the focus of this thesis. Therefore, this work assumes that an agent is securely connected to a manager at all time. This includes encrypting the communication channel between these two entities.

In (2), IoT applications can connect to the manager by sending requests over HTTP to the management API. The processes relating to this HTTP request along with the management API are discussed in Section 4.4.6.1. The role of the SM in here is to provide optional security services that protect HTTP sessions using SSL. The SM also contains a security profile enabling owners or admins of MTs to define security disclosure policies. These policies are used to define the authorised entities permitted to access the MTs' data stored in the management database. Thus, the security profile allows the owner of an MT to define to whom the information collected from MTs is disclosed. This is achieved by providing them with a UI enabling them to maintain a list of authorised entities. Furthermore, the security profile is used to create policies that govern whether information collected from MTs should only be disclosed to IoT application over secured channels or no. An activity diagram showcasing the role of the SM and its security profile is provided in Figure 4.23.

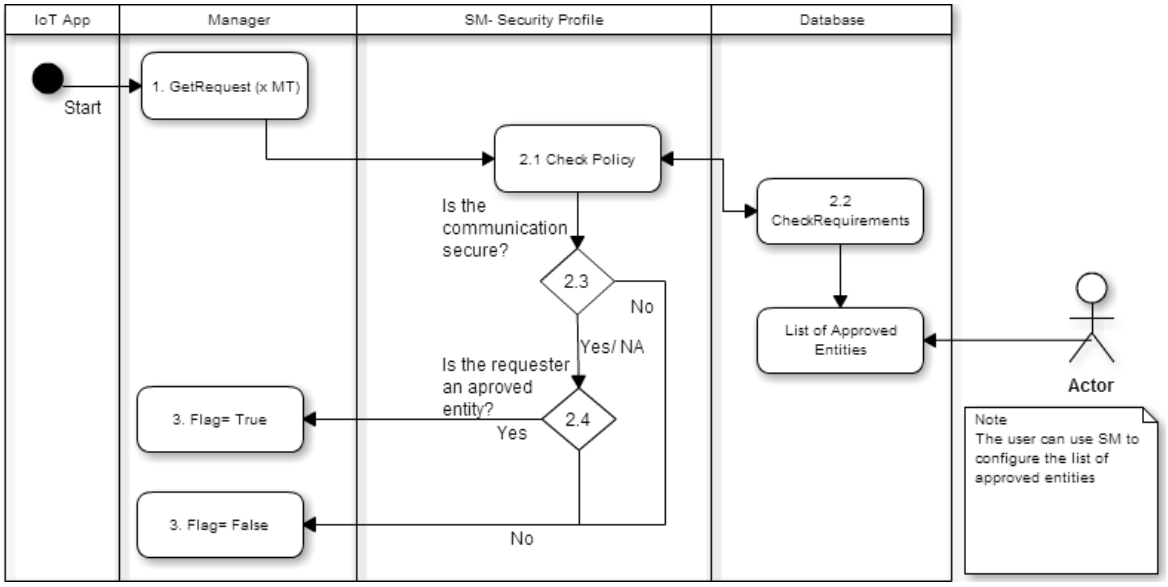


Figure 4.23- SM Activity Diagram

From Figure 4.23, the manager receives a Get Request message from an IoT application requesting some information on an MT. The details of how these messages are processed are provided in Section 4.4.6. Upon the receipt of the message "1.GetRequest", the manager proceeds first into checking whether the requesting entity (the IoT application in this case) is authorised to access the requested MT data. The manager does that by sending to the SM the message "2.1CheckPolicy", which returns a flag that can be either "True" which means the request is approved or otherwise "False". The message "2.1CheckPolicy" has the following sub-messages:

- It starts with the message "2.2 CheckRequirments" that retrieves from the database the security policies stored by the user, which govern the disclosure of the information of the MT under request. Note that in Figure 4.23 the owner or admin of an MT has access to the list of approved entities. This enables him or her to add an approved entity to the list and to indicate whether their MT's data should only be disclosed over secured connections.
- The "Is communication secure" decision point checks whether the policy indicates that the MT's data under request should only be disclosed to authorised entities. If the request does not meet this condition, then the decision point takes the "No" path and

sends a “False” return message back to the manager. If this criterion is met, then the “Yes” path moves to another decision point.

- The “is the requester approved” decision points checks whether the requester (the IoT application is this case) is on the list of the approved entities. If “Yes” then the flag is set to “True”. In this case, the manager receives a return message “True” that indicates that the SM approves this request. Otherwise, if the result is “No” then the request will not be approved, and the original Get Request message will be replied to with an error message. Note that the manager does not disclose the MT’s information in the case of “Yes” yet, as the manager has to obtain an approved message from the Privacy Module as well. This is discussed in Section 4.5.2.

4.4.5 The Database Module (DM)

The database module (DM) contains two types of databases: Data Resource (DR) database and Operational Database (OD).

The DR is used by the manager to store management information of things, their agents, the security profile of the Security Module, and other information relating to the Privacy Module. The DR also stores information relating to architectures, policies, practices and procedures that govern many operations of the IoT-MP. This database is not accessible by IoT applications. It is only accessible by the administrators and/or owners of things. Also, the management API, which is used by IoT applications to exchange messages with the manager, does not have access to the DR database. On the other hand, the OD database is used to store the information sent by MTs to the manager. This database is accessible by the management API whereas IoT applications can request access to the MTs’ data stored in this database over the Internet. The separation of two databases ensures the security of the database module by splitting between the operational data and that of the Data Resource Management.

The database Module (DM) also has an archive database (AD). The DM uses this AD to archive the DR and OD records of MTs, which are no longer connected to a manager. This helps in reducing the amounts of data stored in a database. Figure 4.24 shows the

DM architecture. It illustrates how the management API only has access to the OD. This work assumes that traditional security database management and access control solutions are already employed to secure and maintains the databases included in this module.

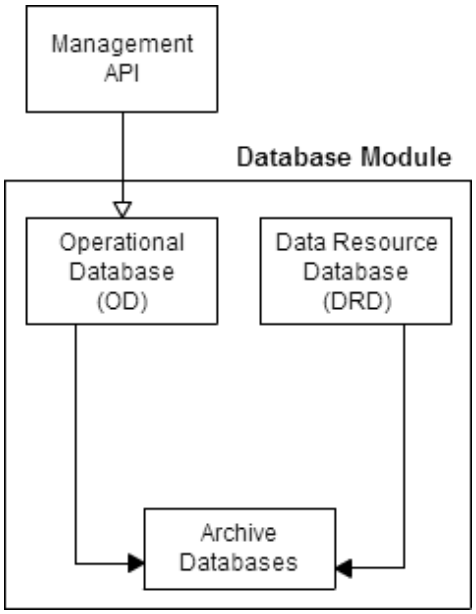


Figure 4.24- Database Module Architecture

4.4.6 The API Module

The API module contains an application programming interface (API), referred to as the Management API. The API provides an integrated and enhanced access interface for IoT applications. It enables IoT applications to participate in communication in the IoT-MP. That is the API allows IoT applications to retrieves MT's data stored in the database remotely over the Internet. It also allows IoT applications to send actuation instructions over the Internet to relevant MTs. The API design is based on the Representational State Transfer (REST). REST implements a set of messages known as HTTP verbs (GET, POST, PUT, and DELETE) as shown in Figure 4.25. It is platforms and languages independent. Thus, it supports multiple platforms (HTML, UNIX, Android, Windows, and iOS.) and does not require the use of a specific programming language (e.g., Java). Hence, theoretically, the API module can support a variety of IoT applications regardless of the platform or programming language they run or use. However, these applications

need to support HTTP. Access to the management API is secured using HTTPS in combination with a token-based authentication mechanism.

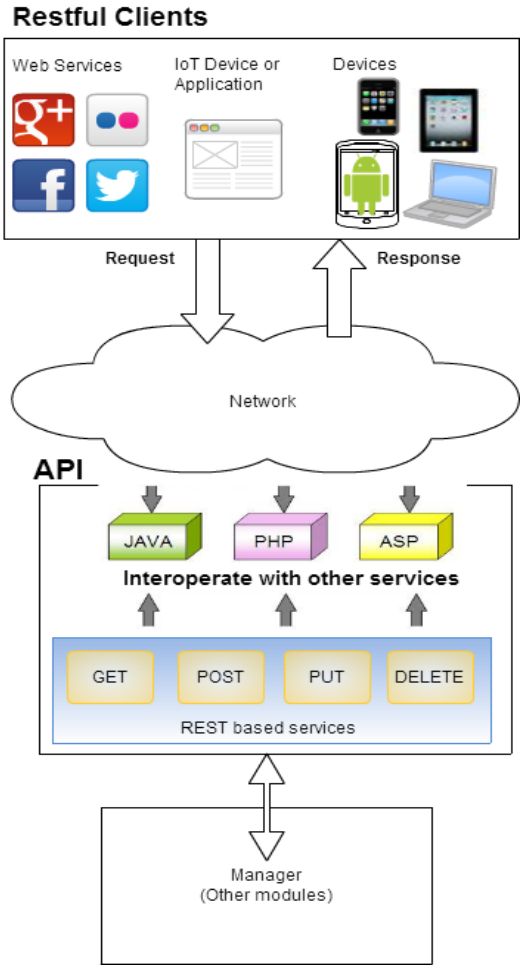


Figure 4.25- The Restful based Management API

From Figure 4.25:

- **GET:** used by an application to request from the manager access to an MT's data that are stored in the management database.
- **POST:** used by an application to send actuation instructions to the manager.
- **PUT:** used for sending inserts and updates commands by a management application to the management database.
- **DELETE**: used by a management application to delete data from the management database.

PUT and DELETE commands are reserved for management applications only. Consequently, an IoT application can only use two commands: GET, which is used to retrieve information about MTs, and POST that is used to contribute with information or to send actuation events.Designing APIs for the Internet of Things is an active area of research. The design of APIs has recently matured a lot in a way it can be used to combine authorisation with authentication. For instance, JSON web tokens can be used with OAuth 2.0 to provide identity delegation services as well. The API designed in this work is intentionally kept simple. This is to avoid drifting into API research and design, which is a research area by itself. The aim is the provision of a valid method to authenticate an IoT application to the IoT-MP. Thus, providing IoT applications with a method to connect to the IoT-MP. Other researchers or future works may look into designing an optimised API for the IoT-MP.

4.4.6.1 Authorizing IoT Application

The IoT-MP requires that IoT applications must be authenticated first by the manager. That is, for an IoT application to send an actuation instruction, contribute with some data, or request access to an MT's information over HTTP, the IoT application must be first authenticated by the management API. This authentication is done by communicating certain credentials to the management API. The authentication process is as follows:

- The administrator or owner of the IoT application must first register the IoT application on the IoT platform using a unique identifier referred to as the "AppID". This "AppID" can be chosen by the person registering the IoT application. However, the API must verify that the AppID is unique. That is, the IoT-MP will verify that no other IoT applications, registered on the IoT-MP, are using the same AppID. Alternatively, an IoT application can utilise a unique AppID automatically generated by the API registration interface.
- Upon successful registration, the IoT application will be issued with a unique "Secret Token".

For an IoT application to be granted permission to access MT's data, the IoT application must authenticate itself by sending a valid access token in the HTTP request header to the manager along with its AppID. The access token is, in fact, the Secret Token, which was assigned to the application upon registration. The supplied credentials will then be used in the authentication flows between an IoT application and a manager. The authentication flow starts with the manager validating the Secret Token initially passed in the request. After the Secret Token is validated, the manager uses the Secret Token to establish a security context for the IoT application. That is, if the IoT application is successfully authenticated, then the request moves to another stage of authorisation conducted by the Security Module (SM). The SM has to responsibility for checking whether an IoT application is on the list of approved entities by the owner of the MT under request. This process is done using the function CheckPolicy() from the security profile as previously described in Section 4.4.4. Unauthenticated requests issued by the IoT application will be replied with an *HTTP 401 Unauthorised* response message and will not reach the authorisation stage.

The design of the API is based on the JSON web API. The main parts of the API design are summarised to as follows: The format of the JSON based web token is three strings separated by a dot (.). Example: stringA.stringB.stringC. StringA is the header. StringB is the payload and stringC is the signature. The header specifies the type of the request and the hashing algorithm in use, which is SHA256. The payload carries the "AppID" and "Secret Token". The last part, stringC, is the signature, which is a hash that combines the header, the payload, and a secret. The secret is the signature held by the manager. It allows the manager to verify existing tokens and sign new ones.

To this end, the work has introduced the IoT-MP and all the main components of the manager, except the Privacy Module (PM). A state diagram that consolidates the communications containing the modules involved in processing a request to access an MT data, sent from an IoT-application to the IoT-MP, is shown in Figure 4.26. It is essential to understand the roles and responsibilities of each of the modules introduced so far and illustrated in Figure 4.26 before proceeding into presenting the architecture of the PM.

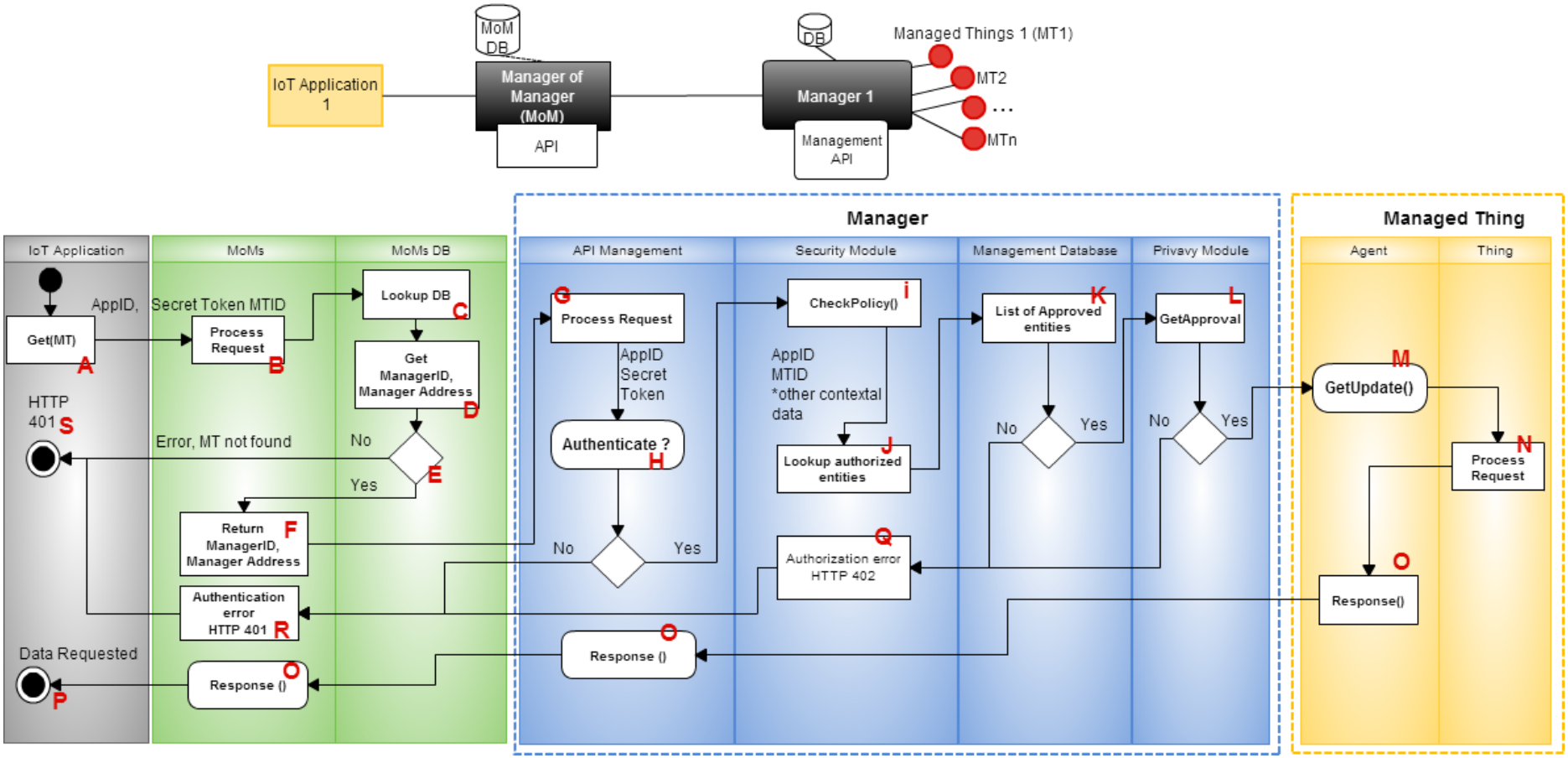


Figure 4.26- Consolidated Activity Diagram

From Figure 4.26, an IoT application sends a request to access MT's data to the IoT-MP, specifically to the MoM API. This request is sent using HTTPS over the Internet. To begin, the IoT application needs to be authenticated first. This is done by sending to the MoM the "AppID" and "Secret Token" of the IoT application (A and B in Figure 4.26). To process the request, the MoM needs to find first the correspondent manager. Using the MTID supplied in the request, the MoM lookups its database to find the address of the manager responsible for the MT (C and D Figure 4.26). If the MoM failed to find in its database a manager associated with the MTID, the decision point, shown in E in Figure 4.26, sends an HTTP 401 error message back to the IoT application and the process terminates here. If a match for a manager is found then, the request is forwarded to the manager using the manager address (F and G Figure 4.26).

The manager proceeds into the authentication process by validating the AppID and the Secret Token. If the request is unauthenticated, the process is halted, and a 401 error is sent back to the IoT application (H, R, and S Figure 4.26). If the request is authenticated, then the manager moves into obtaining approval from the Security Module (SM). The SM lookups the management database. It verifies whether the requested entity (the IoT application) is on the list of approved entities to access the MT's data (H, I, J and K in Figure 4.26). If the IoT application is unauthorised to access the MT data, the request is halted, and a 401 error message is sent back to the IoT application (Q, R, and S in Figure 4.26). If the request is authorised, then the manager moves into obtaining approval from the Privacy Module (PM). The details of this approval will be discussed further in Section 4.5 once the PM is introduced. For now, let's consider if the PM did not approve the request, a 401 error is replied to the IoT application (L, Q, R, and S). If the PM approves the request, then a "GetUpdate" message is sent from the manager to the MT to request a fresh update on the data collected by the MT (L, M, N and O). The response message containing the data initially requested by the IoT application is sent back from the manager to the MoM and then to the IoT application (N, O, and P from Figure 4.26).

4.5 Managing Location Privacy through the Privacy Module (PM)

The Privacy Module (PM) provides the owner or administrator of an MT, referred from now on as the user, with an added layer of privacy protection. As shown in Figure 4.26, obtaining approval from the PM is the last criterion that need to be met before providing an IoT application with access to an MT data. The PM enables the user to define privacy disclosure policies. These policies are used by the manager to determine whether "to disclose" or "not disclose" the location of an MT when an IoT application request access to it. The decision to reveal the location is not simply based on a "Yes" or "No" basis but involves several processes in which an obfuscated location is computed and used in the reply to the request. The PM has three main components: the Context Analysis, Privacy Manager, and Semantic Obfuscation components.

When an IoT application requests the location of an MT, the request is first authenticated, authorised and then forwarded to the PM to be processed. The PM then processes the request and replies with a response message, which even contains a location output or an error message. The architecture of the PM module is provided in Figure 4.27. It shows that the context analysis component has four layers, which are described in Section 4.5.1. The Privacy Manager component stores two types of policies: User's defined policies and default policies. These are discussed in Section 4.5.2. Figure 4.27 also shows that the S-Obfuscation component produces four levels of obfuscated location, which are introduced in Section 4.5.3.

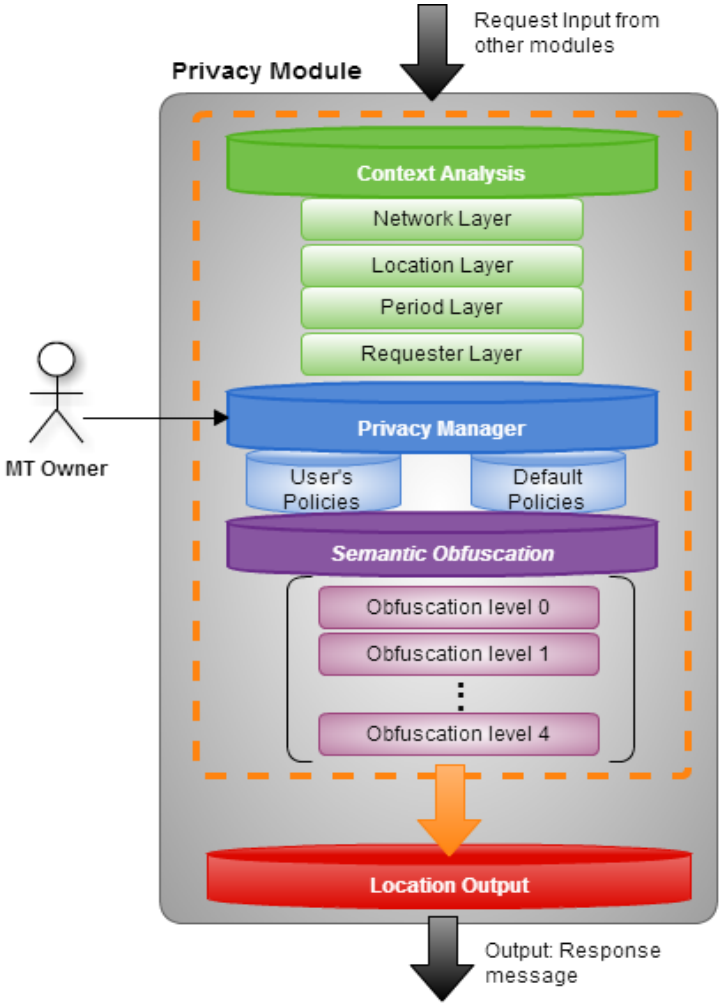


Figure 4.27- Privacy Module

4.5.1 The Context Analysis Component (CAC)

In the IoT, the user is no longer the implicit source of information; and therefore, privacy choices cannot explicitly rely on the users' decisions in real-time. Hence, the challenge is in providing privacy solutions that autonomously adapt to variations in contexts. To achieve this, this work provides a method to formulate contexts. The formulation of contexts is based on the concept that a user makes privacy choices based on some contextual parameters. For example, the user may choose to hide its location at a particular time of the day, from specific entities, and at a precise location. The user may also elect to reveal their location to other specific entities at a given time and location. Thus, the user's decision depends on the context of use of their information. This work

defines a context using the contextual parameters of four layers: the Network, Location, Period, and Requester layers as shown in Figure 4.28.

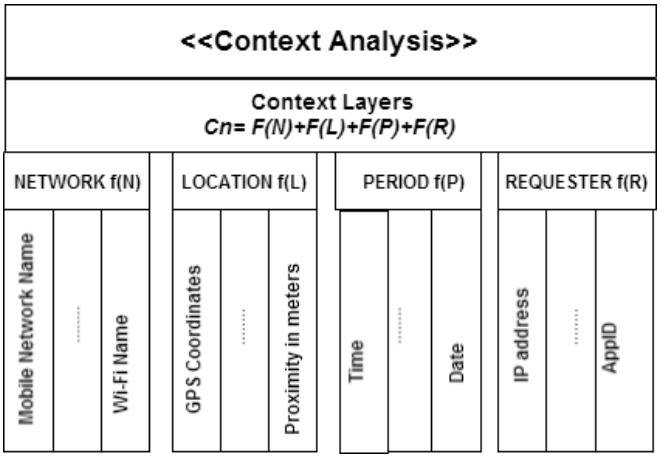


Figure 4.28- Context Analysis Layers

Thus, for a given scenario *n*, a context denoted by *C* is defined using the following statement:

$$Cn = F(N) + F(L) + F(P) + F(R)$$

- F(N) represents the contextual parameters related to the network settings e.g., a mobile network name or Wi-Fi network name.
- F(L) represents the current location of the device.
- F(P) includes the time and date of the interaction.
- F(R) contains parameters that identify a requester. For instance, the "AppID" or the IP address are the parameters used to identify an IoT application requesting access to the location of an MT.

With this formulation of context, we can quantitatively identify a context of interaction in the IoT. This opens the door to numerous opportunities such as providing services based on specific contexts, restricting services to a particular context, and building automation services based on predefined settings. The four layers of the CAC provide the user with a method to attach a user's defined policies to a specific context using the Privacy Manager Component (PMC) discussed in Section 4.5.2. The policies can then be

appended to a variety or combination of contextual parameters such as the user's and the device's attributes.

4.5.2 The Privacy Manager Component (PMC)

The Privacy Manager component (PMC) provides the user i.e. the owner or admin of an MT with a method to define privacy disclosure policies that govern the location privacy of their things. Specifically, the PMC has two main modules: the User Policy Module, which is used to create user's defined policies. A user's policy is defined by the user by specifying the level of Obfuscation used in a particular context for a specific MT. The second module, the Default Policies Module, is used to create default policies that rule the disclosure of an MT location in the absence of a user's defined policy.

The PMC allows the user to define location privacy disclosure policies for each of their MTs. Thus, it provides the user with the granule control over the location privacy of their MTs including to whom, when and in which context the location of their MT is revealed. To do that the user creates policies that attach an Obfuscation level to a context using the contextual parameters defined in CAC. An example of a user's defined policy is provided in

Figure 4.29. It shows how a user uses the privacy manager to select an Obfuscation level (from Figure 4.29, step 1- Select Obfuscation level) and then attach it to a C1 (Figure 4.29, steps: 2.1, 2.2, 2.3 and 2.4) before associating it to an MT (Figure 4.29, step 3- associate with an MT). This policy example is formulated as follows:

P1= Attach (*Obfuscation level 1*) to *C1 (F (N1) + F (L1) + F (P1) + F (R1))* for *MT1*

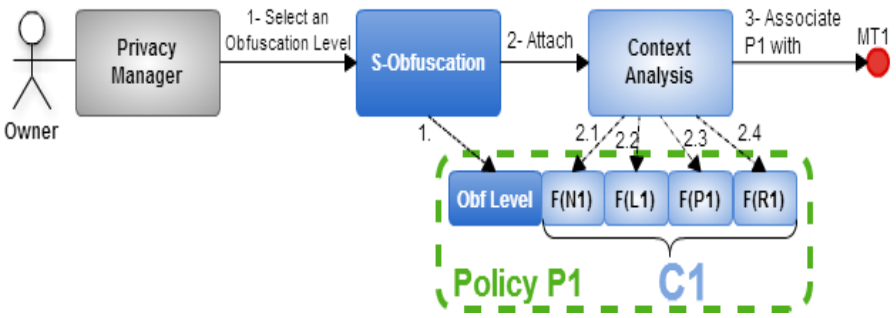


Figure 4.29- Policy P1 example

Consequently, the PMC allows the user to attach several users' defined policies for each of their MTs. The ability to attach more than one policy to a specific MT where each of these policies is coupled to a context provides granule control over the disclosure settings of an MT and allows for greater flexibility. Figure 4.30 shows three examples of policies attached to one MT along with a default policy. For instance, P1 enforces that Obfuscation level 1 should be used when the MT is on Vodafone network, located in X Location and the time of the request must fall on a weekday between 09:00 and 17:00 i.e. any day between Monday and Friday at any time between 09:00 AM and 17:00 PM. Note that P1 is also enforcing this policy to a specific IoT application using its AppID i.e. AppID=123. P2 and P3 enforce a different level of Obfuscation for different contexts. However, the DefaultPolicy enforces Obfuscation level 4 for all other contexts.

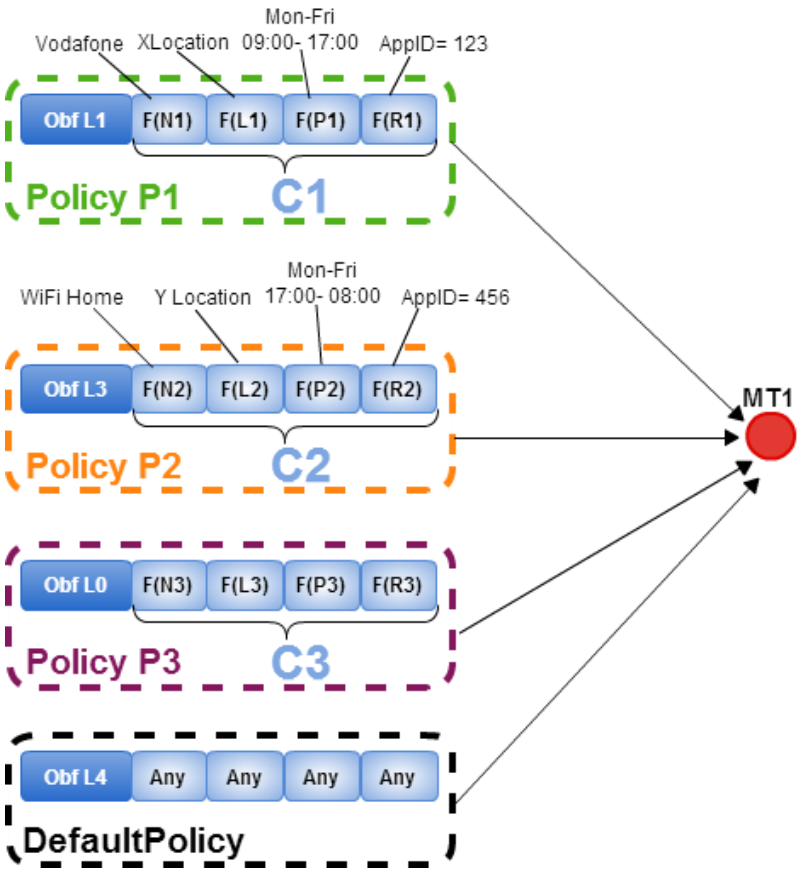


Figure 4.30- An example of three policies associated with one MT

Figure 4.30 shows two examples of policies attached to two different IoT applications (AppID=123 and AppID=456). However, it is also possible to associate more than one policy to one specific IoT application. For instance, an additional Policy denoted by P4 can be defined to attach an Obfuscation level 0 to AppID=123 when F(L) is at ZLocation instead of XLocation or when the time of the request is set to be in a different time frame from the one defined in F(P) in P1.

On the other hand, the default privacy module allows the user to define a default policy for an MT. Below are some examples of default policies:

Example 1: DefaultPolicy 1= Use Obfuscation level 2 for MT1 in C1

Example 2: DefaultPolicy 2= Do not disclose location for MT1

Example 3: DefaultPolicy 3= Request User's permission for MT1

In the example provided in Figure 4.30, the Obfuscation level 4 for MT1 is used as the default policy. Thus, in the absence of a user's defined policy or in the case where a user's defined policy was not met for a particular request, then the DefaultPolicy will be called. Therefore, the location of the MT will be obfuscated using Obfuscation level 4. Similarly in Example 2, the default policy is set to "Do not disclose" the location of MT1. The DefaultPolicy 3, defined in Example 3, is set to request the user's permission before disclosing the location of MT1. Hence, there are two possible options for policy: (1) define a policy and attach it to a context, and (2) define a policy that prompts the user and requests his or her permission. Additionally, in the absence of policy, the default policy is used.

Consequently, the formulation of contexts as part of CAC allows for the integration of Attribute-Based Access Control (ABAC) policy-based system in the PMC and the possibility of adding other systems to be integrated with modules as well. For instance, the work in [187] expanded on our work, which was published in [188], by proposing a rule-based agent that integrate our proposed CAC with behaviour modeling and community-based reputation system in the algorithm of the agent.

4.5.3 The Semantic Obfuscation Component (SOC)

As previously discussed in Section 4.1, the Semantic Obfuscation approach (S-Obfuscation) proposed in this work is an improvement over classic Obfuscation techniques. Consider, for example, a public sensor collecting temperature information in a park or a street. The sensor should not reveal its exact physical location to everyone. For many IoT applications, it will be just sufficient to pinpoint the location of the sensor to a specific area only. Other applications, such as fire detection applications, may require access to the exact location of the sensor. Hence, the S-Obfuscation provides the user with this granule control over the location disclosure of their things. It does that by providing 4 levels of Obfuscation each representing a different degree of granularity or location precision, which was previously introduced in Section 4.1.1.

The S-Obfuscation Component (SOC) incorporates the S-Obfuscation approach in the Privacy Module (PM) of the manager. Figure 4.27 shows that the PM has the following components: The Context Analysis Component (CAC), the Privacy Manager Component (PMC), and The Semantic Obfuscation Component (SOC). The SOC is used by the user to attach an Obfuscation level to a context when creating a policy as seen in

Figure 4.29. The Obfuscation levels range from L0 (true location) to L4 (an obfuscated location with a wider proximity). Therefore, the SOC allows the user to indicate the level of Obfuscation used when defining a policy.

The Location Output, shown in red in Figure 4.27, is the last process in the PM. It is responsible for generating a response to the input request received by the PM. Figure 4.31 shows a flowchart that details how the Privacy Module approves a request to access the location of an MT and the processes the PM goes through before generating a response message. It should be noted that the response message is the same one previously illustrated in step L of Figure 4.26.

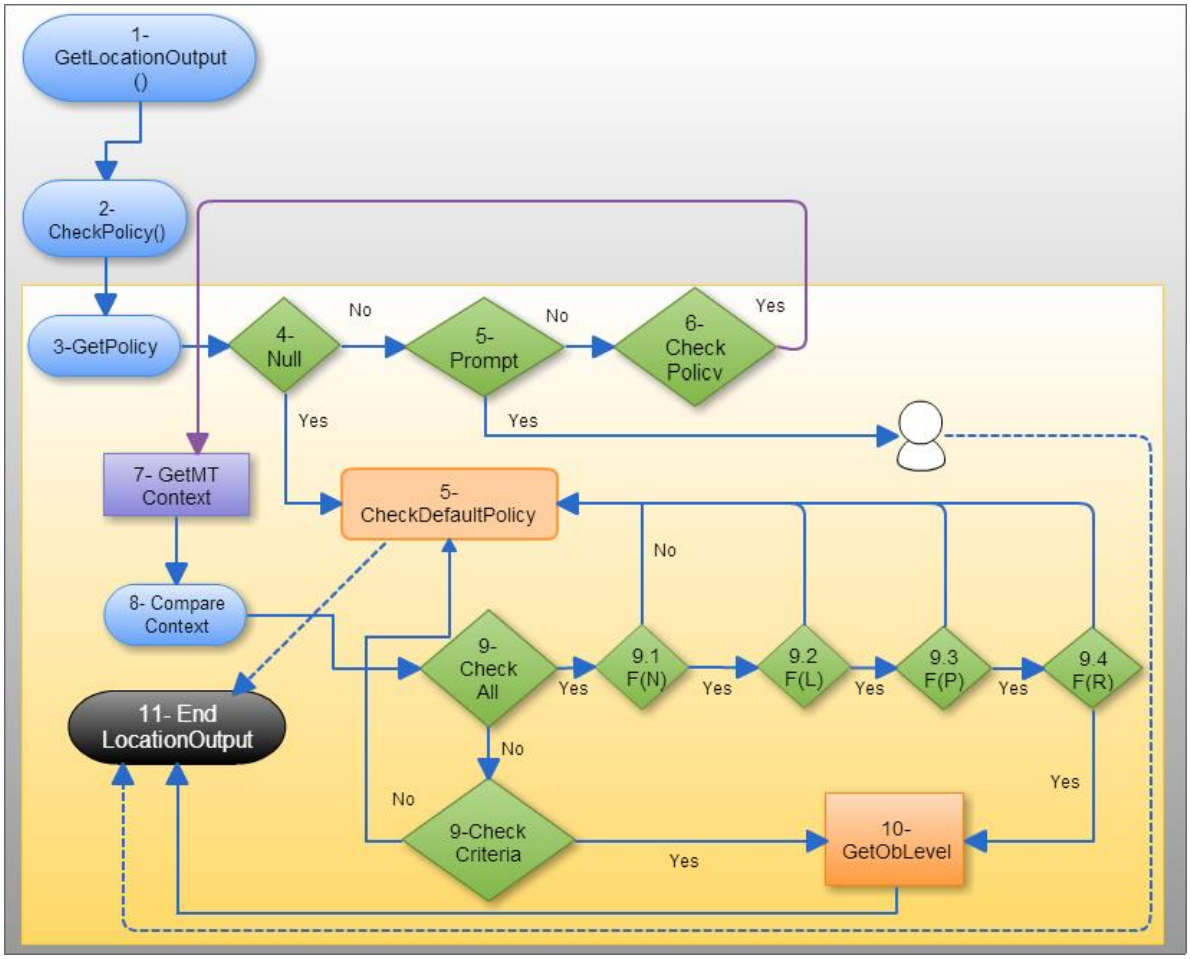


Figure 4.31- PM flowchart process

The PM flowchart process is as follows:

1. A "get LocationOutput" request is placed to the PrivacyManager. In this request, two arguments are passed: the MTID, which is the ID of the MT in which its location is required and the "AppID" of the requesting IoT application
2. The PrivacyManager in "2- CheckPolicy()" check if there is a user's defined policy for the MT in which its location is under request.
3. In "3- GetPolicy" the PM lookups if there is a defined policy for this particular IoT application using "AppID". From here, there are decision points that will dictate how the process continues:
    a. Firstly, if there is no policy found (step 4) the decision point takes the yes path to "5- CheckDefaultPolicy". The PM then proceeds in using the Obfuscation

level as defined in the Default policy and generates an obfuscated location for the MT under request and uses it as a location output (11- End LocationOutput).

b. If in Step 4 a policy is found then the PM examines whether this policy is set to request permission from the user. If yes, the decision point in Step 5 "Prompt" requests from the user the level of Obfuscation that should be used for the location output. If no (the policy is not set to seek permission from the user), then the PM proceeds, in step 6, to check the user defined policy.

4. In step 7 "Get MTContext", the PM requests from the manager the current context of MT. This context is compared to the context defined in the policy.
5. The comparison between the contexts is made in Step 8 "Compare Contexts". The process is as follows:
    a) Firstly, the PM checks if the user has indicated in this policy that all the contextual parameters need to be satisfied (F(N), F(L), F(P) and F(R)). These are the steps in 9, 9.1, 9.2, 9.3 and 9.4. If one of the criterion did not match the one defined in the policy, the process will be halted, and No path will be taken by the decision point to 5- "CheckDefaultPolicy". The obfuscated location defined in the default policy will then be used.
    b) If each of the contextual parameters defined in the policy matches those of the current context, the process then proceeds into getting the location Obfuscation level required from the S-Obfuscation Component in Step 10 "GetObLevel". If one of the parameters does not match the one supplied in the request, it will use the default location.
    c) Step 9 "CheckCriteria" is used by the PM in case the user has indicated in the defined policy that only specific criteria from the context analysis layers need to be met.

To this end, this section has introduced the modules of the manager along with the components contained in each of these modules.

4.6 Summary

A middleware referred to as the Internet of Thing Management Platform (IoT-MP) is developed in this chapter. The IoT-MP provides users with a method to manage the location information generated by things and their privacy across various heterogeneous networks such as those discussed in the previous chapter (Chapter 3). The proposed platform is specifically designed to work with things, which have limited communication, processing, and power capabilities. The IoT-MP uses a distributed architecture consisting of agents, managers, and a Manager of Managers. This architecture is based on an extensible design where things are virtually represented using attributes in the management database. These attributes are accessible via the IoT-MP and are used by IoT applications to control and access things remotely over the Internet. In this way, IoT applications can access things transparently, irrespective of the underlying used communication technologies. This eliminates many of the interoperability issues challenging the IoT and facilitates thing-to-thing communications.

The various modules of the IoT-MP's manager, presented in this chapter, guarantee that the location information of things are only disclosed to authenticated and authorised entities while preserving the location privacy of things and that of their owners. Specifically, the Privacy Module (PM) ensures that an IoT application has sufficient access rights to remotely access the location information of things. The PM consists of three components: The Context Analysis Component, The Privacy Manager Component, and the Semantic Obfuscation Component. These components are used by the user to create privacy disclosure policies that govern accesses to the location information of things based on some identified contextual parameters. This enables the user to define context-aware adaptive policies. These policies utilise different levels of location Obfuscations providing protection for the location information of things. The novel S-Obfuscation approach, incorporated in the IoT-MP platform, enhances the performance of two classic Obfuscation techniques. They rely on a geographic knowledge when producing obscured location.

In the next two chapters (i.e. chapter 5 and 6), a range of experimental and simulation studies are conducted. They aim to validate and demonstrate the efficiency of the proposed IoT-MP in managing the location information and preserving the location privacy of things in the IoT. Chapter 5 demonstrates and confirms the capabilities of the IoT-MP and its new approach to privacy management and protection in an experiment that utilises physical low-power and low-cost sensor devices. On the other hand, Chapter 6 supplements the experimental studies, conducted in Chapter 5, by demonstrating the capability of managing the location information of things and protecting their location privacy in large-scale heterogeneous low-power wireless networks similar in scope, complexity, and size to that envisioned in the IoT.

CHAPTER 5- THE EXPERIMENTAL STUDIES

This chapter describes the four stages of the experimental studies. It reports on the implementations of the Internet of Things Management Platform (IoT-MP) previously introduced in Chapter 4. The purpose of these implementations is to demonstrate that the IoT-MP enhances the management and preservation of location privacy of things and that of their users in a physical IoT setup. The experimental studies also aim to demonstrate and validate the feasibility of incorporating a location protection technique i.e. the proposed Semantic Obfuscation approach, introduced in Chapter 4, into an IoT application that utilises low-power and low-cost sensor devices.

Section 5.1 provides an overview of the experiments and outlines their objectives. Section 5.2 discusses the architecture and design of the four stages of the experiments. Section 5.2.1 describes the developments and implementations carried out in stage 1 of the experiments that involved the setup of a Wireless Personal Area Network using BLE 4.0 sensor devices. Section 5.2.2 reports on stage 2 of the experiments, which included the implementation of an LBS web application. This section also describes the implementations of the various modules of the IoT-MP previously introduced in Chapter 4. Section 5.2.3 discusses the stage 3, which involved the developments of a mobile application and a web application. The mobile application provides users with a user interface allowing them to create location privacy-disclosure policies as an implementation of the IoT-MP's Privacy Manager Component. The web application is used to issue a request to access the location information of the BLE sensor devices over the Internet. In addition to implementing the proposed S-Obfuscation approach, this section also implements the two classical Obfuscation techniques previously described in Section 2.3 of Chapter 2. Thus, in stage 3, the work evaluates the S-Obfuscation and reports on its performance against the two selected classic Obfuscation techniques.

Section 5.2.4 reports on the implementations carried out in stage 4 of the experiments. In this section, an IoT application is developed as a practical example of an application that supports interactions between various devices operating using two different communication protocols. The works conducted in stage 4 expand on the three previous stages of the experiments by adding a Wi-Fi enabled bulb to the experimental works. The 4 stages of the experiments allowed the development of an IoT application in which the status of a Wi-Fi device was automatically manipulated based on the location of a specific BLE sensor device. By implementing the approaches proposed by the IoT-MP and that of its S-Obfuscation, we were able to evaluate and demonstrate the capability of our new approach to management and preservation of location privacy of things in a physical setup that uses low-power and low-cost devices.

5.1 Overview of the Experiments

The main aim of the experiments is to demonstrate the capability of the IoT-MP in providing the owners or administrators of things, referred to as users, with the management of their location information and that of their things. Also, to demonstrate the capability of the IoT-MP in preserving the location privacy of constrained things in the IoT. The experiment mainly has two key purposes:

1. To technically evaluate the IoT-MP, proposed in Chapter 4, under realistic conditions using physical low-power constrained sensors, which are powered by batteries;
2. To assess the performance of the Privacy Module, introduced in Section 4.5, in physical environments that involve dynamic changes in context, interactions and, importantly, mobility. As discussed in before, the IoT-MP encompasses an approach where decisions to disclose location information are based on policies that vary based on the context of their use (e.g., the current location of the Managed Thing, users' preference among the rest of the contextual parameters discussed in Section 4.5.1). Thus, it is important for the research to generate and model a variety of contextual and dynamic interaction scenarios so the proposed IoT-MP can be effectively evaluated.

The experiments involved the followings setups:

- **Designing a testbed based on the concept of WSNs**: The testbed brings a WSN setup to the Internet.
- **The use of Low-power sensor devices:** this involves the utilisation of low-power and low-cost IoT sensor devices. Specifically, BLE sensors are used.
- **The design and implementation of an IoT application:** this involves the design of scenarios that use location information of the BLE sensors as part of the service and information being exchanged. These scenarios model the envisioned interactions between sensor devices and an IoT application.
- **Generating different contextual scenarios:** varying the parameters of the experiments to produce different contextual data including location inputs. This is necessary to test the validity of the proposed approach in various contexts.
- **Implementing the IoT-MP:** this involves the implementation of the IoT-MP entities i.e. the agent, manager, and the management database and the rest of the modules previously introduced in Section 4.3.
- **Implementing the Privacy Module:** Implementing the privacy module, described in Section 4.5, including the implementation of the S-Obfuscation, context analysis, and privacy manager components for the purpose of protecting the location privacy of BLE sensors during communications.
- **Implementing the classical Obfuscation technique:** these implementations are used to compare and evaluate the S-Obfuscation performance against the classic Obfuscation techniques.

5.2 The Four Stages of the Experiment

A high-level view of the experiment architecture is provided in Figure 5.1. The scenarios conceived in this experiment are summarised as follows:

A group of Bluetooth Low Energy (BLE) sensors sends sensory information to an Android mobile application over BLE 4.0. This mobile device acts as an IoT gateway and a backhaul to the Internet. This is in line with many other recent experiments and setups

that utilise a smartphone as an IoT gateway such as the studies conducted in [189-194]. The mobile application receives the sensor's data, computes the location of each sensor, using Bluetooth proximity, and sends this information, remotely over the Internet, to a web application acting as the manager. The web application, shown in Stage 2 of Figure 5.1, is a PHP web application hosted on an Apache server. It has a MySql database that is used to store the information sent by the mobile device in Stage 1. This MySQL database is an implementation of the management database previously described in Section 4.3.2. Additionally, the web application includes the implementations of the rest of the manager's modules and their components as described in Section 4.4. IoT applications can send requests to access the management database remotely over the Internet using the management API.

Stage 3, shown in Figure 5.1, implements a PHP web application hosted on another Apache server. This web application referred to as the Location Based Service application (LBS application), is used to send requests to access the location of a sensor over the Internet to the manager application. The manager application then checks the user's defined policies and either approves the request by responding with a message containing the location of the requested sensor, or replies with an error. The user's defined policies are configured by the user, using a mobile application that connects to the management application through its management API. In the last stage of the experiment, Stage 4 shown in Figure 5.1, instead of simply requesting the location of a sensor, we made the experiments more complicated. In Stage 4, an Android mobile application is used. This application is initially implemented by Belkin so a user can use it to remotely turn on or off a Wi-Fi connected lamp. We adapted this application in our experiment by implementing a condition where the mobile application turns on the Wi-Fi lamp once a certain criterion is met. This criterion is based on the location of one of the BLE sensors.

The design and setup of the four stages shown in Figure 5.1 are described to as follows:

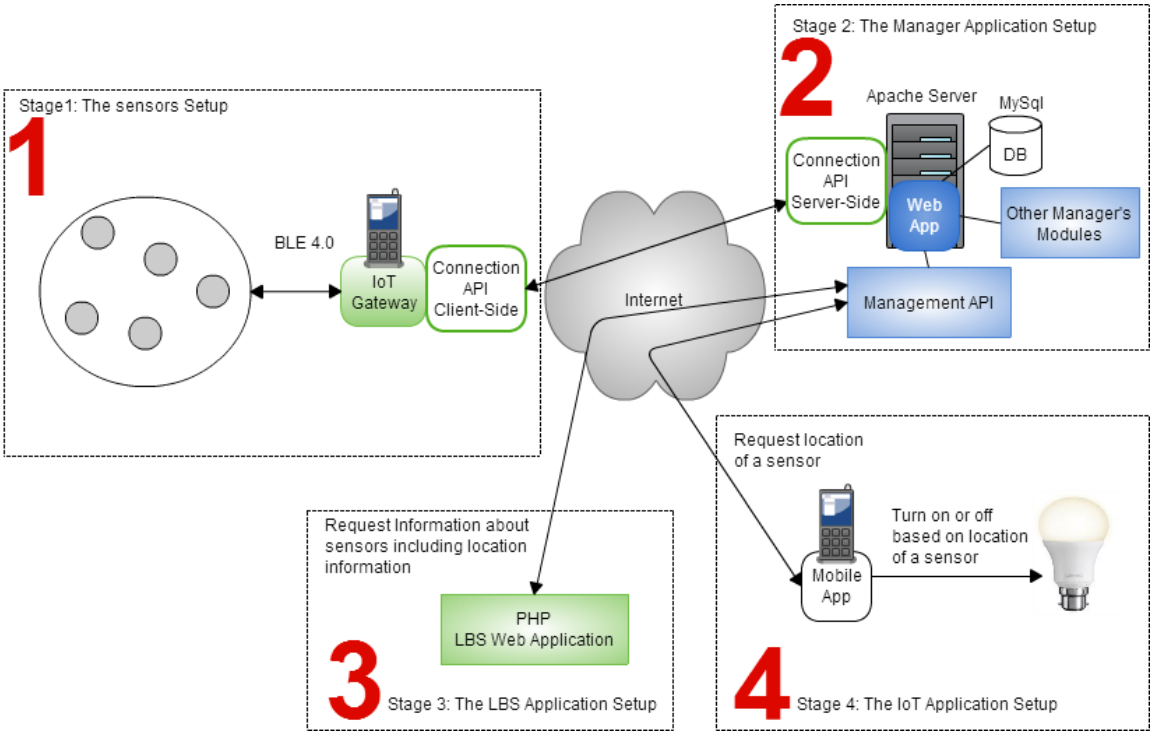


Figure 5.1- Experiment Architecture

Stage 1- The sensors setup: Some Bluetooth Low Energy Sensor devices in a piconet setup (piconets were discussed previously in section 3.1.1) are configured to collect some sensory information e.g., temperature. The basic topology is a star network where five sensors communicate with a single gateway that provides the backhaul to the Internet. This gateway is referred to as the IoT gateway as shown in Figure 5.1. The IoT gateway is an Android mobile device which has a mobile application implemented specifically to support the communications with the BLE sensors. The mobile application is developed to collect the location information of the connected sensors using Bluetooth proximity technology. Also, the application implements a Restful API, referred to as the "connection API". This API allows the mobile application to transmit the collected sensory data over the Internet to a remote web application hosted on an Apache local server. As with any typical API design, the connection API has two parts: the client side API, which is implemented in the mobile application, and the Server side API, which is implemented in the web application.

Stage 2- The manager web application Setup: As discussed in Stage 1, the sensory data collected from the BLE sensors, along with the location information of each sensor are transmitted over the Internet to a web application hosted on an Apache server on our domain. This web application hosts the server-side implementations of the connection API. The connection API is responsible for establishing communication with the Android device. It acts as a web service. It handles the incoming and outgoing communications between the web application and the mobile application. Additionally, the web application has an attached MySQL database. This database is used to store the information sent by the Android application. Mainly, the database stores the followings data: sensory data and the GPS location of the Mobile device and proximity of each of the BLE sensors to the mobile device in meters.

Significantly, the web application represents the manager that was discussed in Section 4.3.2. The web application hosts the implementations of the manager's modules including that of the Privacy Module, described in Section 4.5, and its major components such as the S-Obfuscation component that was introduced in Section 4.5.3. Additionally, the web application includes the implementation of the management API (described in Section 4.4.6). The management API is used to receive requests for sensors' data and respond to these requests by IoT applications over the Internet using HTTP. That is, to access the sensors' data over the Internet, HTTP requests must be placed on the web application using its management API. The Web application then responds to the requests for information about the sensors. Decisions about disclosing sensory and location information are computed using the various modules of the manager as previously discussed in Section 4.5.

The management API should not be confused with the connection API. The connection API is an implementation specific. It is specifically implemented for establishing communications between the mobile device and the web application over the Internet, and it is not part of the IoT-MP components. On the other hand, the management API is used to provide a method to access the management database over the Internet. The management API is one of the manager's modules as discussed in Section 4.4.6.

Stage 3- The Location Based Service (LBS) application setup: In this stage, a Location Based Service (LBS) web application is developed. This LBS application is designed to model the operations of an IoT application that provides services based on the location of a BLE sensor. This application is used to request the location of a BLE sensor using the unique sensor ID (UID) over the Internet by sending an HTTP request to the management application. The purpose behind the design of this LBS application is to simulate the behaviour of a Location Based Service provider that provides localised services based on the location information supplied in the request.

Stage 4- The IoT application setup: To make the experiment more interesting, the developments carried out at this stage have the purpose of simulating the behaviour of an IoT application. For example, an IoT smart home application requests the location of an IoT device (device A) and performs some operations on another IoT device (device B) based on the location of device A as part of the service it provides. Therefore, in this stage, an IoT application is developed to turn on a Wi-Fi connected lamp based on the location of one of the BLE sensors. To achieve this, we modified an Android mobile application developed by Belkin. Usually, the Belkin application is used by a user to control a Wi-Fi connected lamp over the Internet. This experiment adapted this mobile application by automating the process of turning the lamp on once a certain condition is met, which is when the BLE sensor location is within 100m of any GPS coordinates that correspond to Sydney.

As an example, the scenario is set up as follows: if the sensor with the ID 1 is at 100 m from X location, then a Smart light connected via Wi-Fi to the mobile application will be turned on. Manipulating a device or service based on the condition of another device/service is also known as If This Then That (IFTTT). IFTTT is a web service that allows users to create chains of simple conditional statements triggered based on changes to other web services [195]. Thus, the work implemented in this Stage uses the IFTTT concept. In fact, our work is an improvement over IFTTT by providing the user with more control over the disclosure decisions of their personal information including their location privacy and by connecting low-power devices into the service.

5.2.1 Stage 1- The Sensor Scenario Setup

The experiment uses Bluetooth Low Energy sensors developed by Texas Instrument [196]. The sensors have the following sensing capabilities: temperature, proximity, pressure, accelerometer, gyroscope, and magnetometer. The sensors use Bluetooth Smart, also known as Bluetooth 4.0, in a star topology. The technical specifications of these sensors are provided in Table 4.2 and Figure 5.2. According to the manufacturer, the onboard battery attached to these sensors last up to two years in operation [196].

Table 5.1- Sensors' specifications [196].

Frequency	2.4 GHz
Range	~60 m
Flash size (KB)	256
RAM size (KB)	8
Operating Temperature Range (C)	-40 to 125
Addressing	Unique 48-bit IEEE Address
Data Rate (Max) (kbps)	1000
Sensors on board	Temperature, proximity, accelerometer, gyroscope and magnetometer.

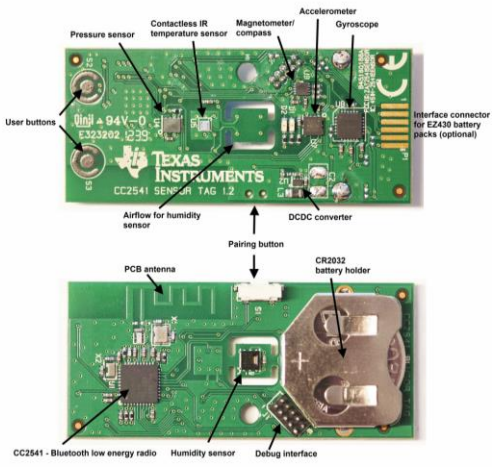


Figure 5.2- The BLE sensor board

To create a realistic setup we attached the sensors to some home appliances to obtain physical data. Figure 5.3 illustrates this smart home setup. The sensors attached to the appliances collect sensory information. For example, the sensor attached to Microwave Oven collects the following information: the room temperature and the oven temperature. The sensor connected to the keys, as another example, provide accelerometer, proximity and, magnetometer readings as well. The sensors send over BLE the collected data to an Android mobile app developed by Texas Instruments. The mobile application allows the user to access the received sensor data in real-time. The screenshots of the mobile application developed by Texas Instruments are provided in Figure 5.4. This application provided a way to receive the data collected from the sensors over Bluetooth. However, the setup remained in the form of a local area network or more specifically a closed Personal Area Network (PAN). To access the sensor information, the user must be present within the transmission range of the sensors and uses the mobile application to connect to the sensors. Consequently, the implementations carried out in Stage 2 improved on the mobile application developed by Texas Instruments. We added to the application the capability of sending the collected information from the sensors over the Internet to a web application hosted on our server.

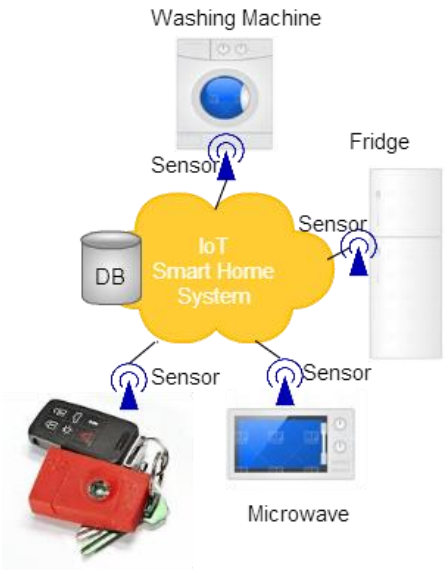


Figure 5.3- Smart home setup

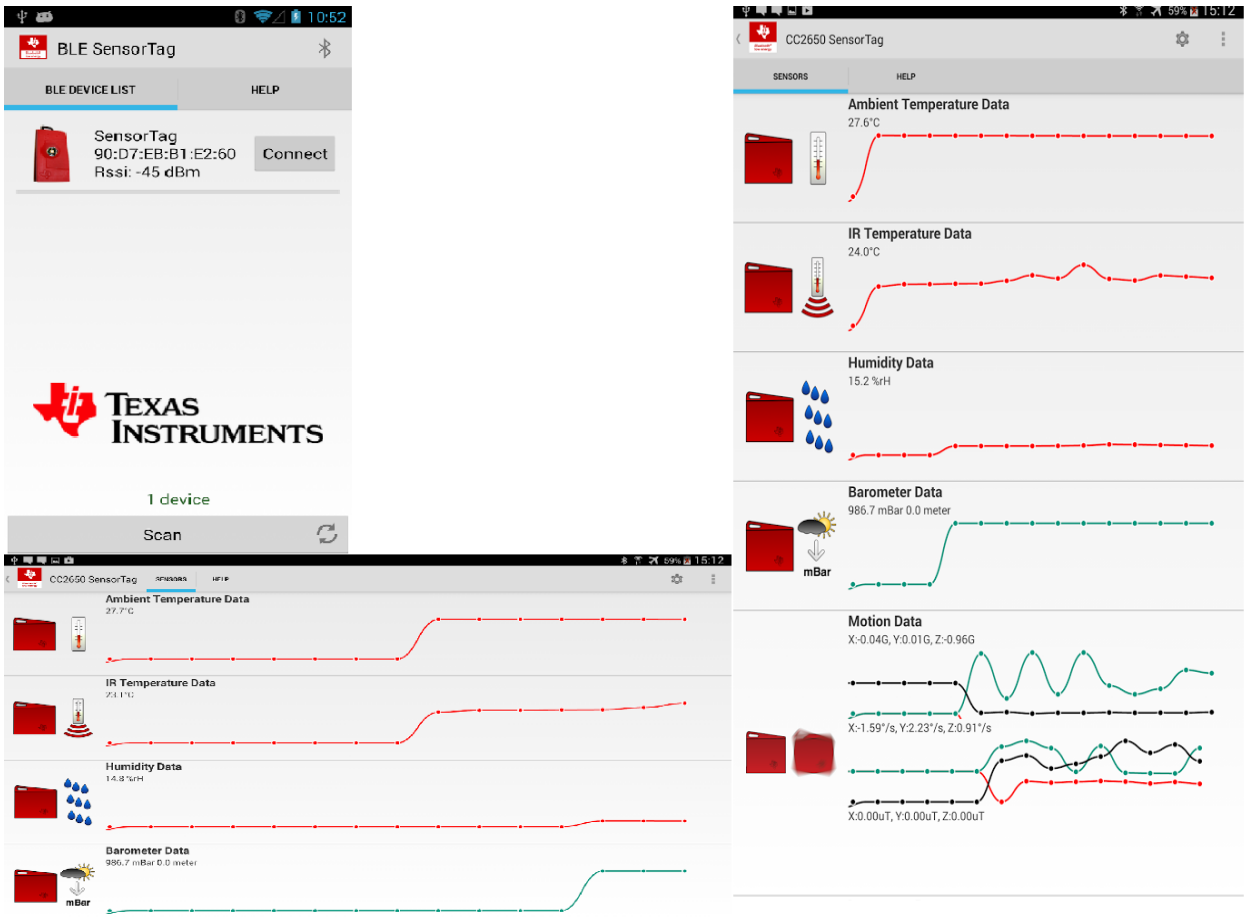


Figure 5.4- Texas instrument application

5.2.2 Stage 2- The Web Application and Database Setup

Additional implementations took place to connect the Bluetooth network to the Internet. To achieve this, an API and a web application attached to a database were implemented. The API is a software incorporated in both the mobile and web application. The API, referred to as the connection API as stated earlier, has the responsibility for sending the collected data from the sensors to the web application, periodically, over the Internet. The Web application stores the received data into the database. The database is an online MySQL database that can be accessed via the Internet. To provide this functionality, an open web service based on Restful API architecture [197] referred to as the management API is also implemented. The management API allows other devices and applications to access the database and hence the sensory data over the Internet. The purpose behind

these implementations is to create a more complex IoT setup. Consequently, the components of the IoT-MP were implemented as part of this IoT experiment.

Figure 5.5 shows how the experiment used the IoT-MP's agent-manager architecture to make the information available on the Internet. The agents are software applications that could even run on mobiles, tablets or computers (mobile phone is used in this experiment). This software has Bluetooth functionalities implemented allowing it to establish communications with Things (the sensors in this experiment). On the other hand, the manager is implemented as part of a server application that resides on a web server. Communications between the mobile device and the web application are secure and encrypted using the SSL3.0 protocol. The Bluetooth communications between the sensors and the mobile device are encrypted using 128 bit AES supported by BLE 4.0. Figure 5.6 shows the additions made to the application provided by Texas Instruments.

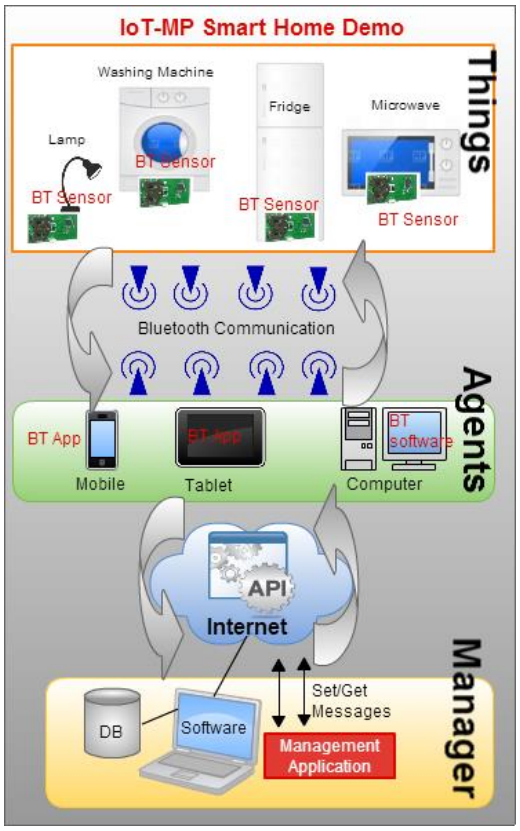


Figure 5.5- IoT Smart home demo

Therefore, Figure 5.6 shows that the improved mobile application has added the capability of sending the sensor data over the Internet to be stored in a database as part of a web application. The design of the management API is provided in Figure 5.7. It shows how the API is allowing IoT applications to access the database over the Internet.

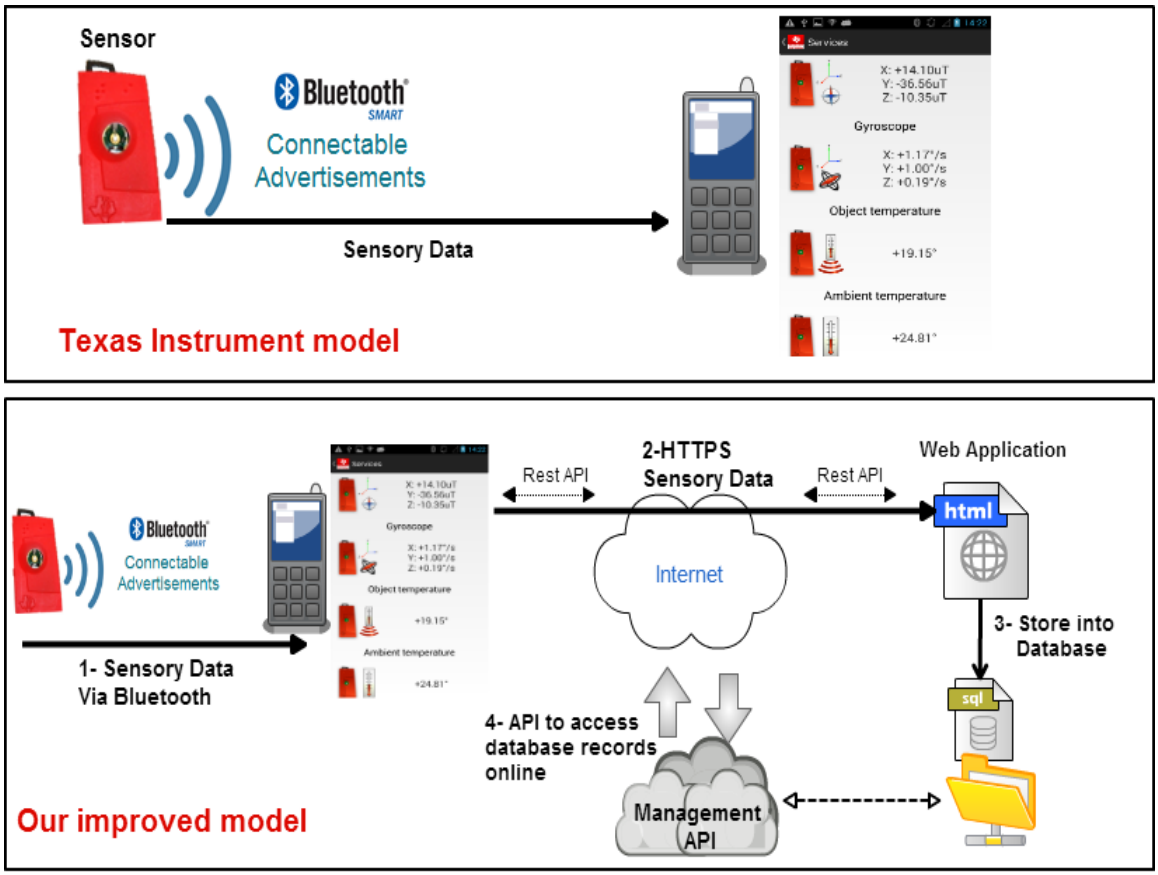


Figure 5.6- The Improved Model

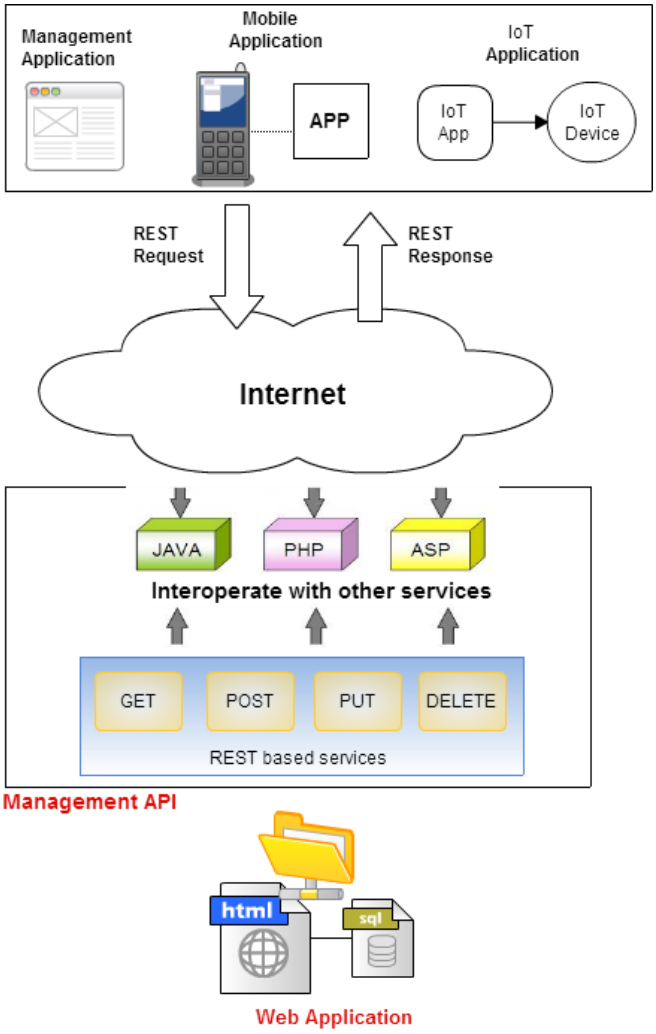


Figure 5.7- Management API

5.2.2.1 The Connection and Management APIs:

As stated earlier, the connection API is used to establish a communication channel between the mobile and web applications by supporting the exchange of HTTP messages. It allows the mobile application to send the received sensory data over the Internet to the Web application. It also allows the web application to send requests to the web application. On the other hand, the management API allows applications running to access the sensory data stored in the database, remotely over the Internet. While both APIs use the Restful architecture, they differ in implementations and complexity. The connection API is simple. It is implemented in a closed architecture, and it is commonly

used to relay information from mobile applications developed on the Android platform to web applications over the Internet. Therefore, the connection API is not accessible to the public or any other applications. It has the sole purpose of sending the data over HTTPS from the mobile device to the Web application. However, the management API is more complex as accessing the database is not straightforward and requires permission from the PM.

The Connection API uses a well-defined Restful structure that utilises the URL scheme. Normally, the API's URL structure depends on the type of the operation requested and on how these requests are processed. These operations need to be defined in the API to be able to receive and parse requests. For that purpose, the JavaScript Object Notation (JSON) is used [198]. JSON is a lightweight data interchange format. JSON is built into two structures: A collection of name/value pairs and an ordered list or an array of values. Therefore, JSON presents a method for handling arrays. It also defines a structure on how to read and parse the value from an array. The connection API re-uses the messages and the methods defined in the HTTP protocol. These are the GET, POST, PUT, and DELETE methods. These methods will cover all the requests needed for transferring the data from the mobile application to the web application. The communication is as follows:

- The mobile application receives sensors' readings (e.g., temperature) and put them in an array. The array includes a unique ID, which represents each of the Bluetooth sensors. This part of the implementations is already provided in the original application implemented by Texas Instruments.
- Next, our work added to the array the followings parameters:
    1. The location proximity of the sensor to the mobile device using Bluetooth proximity technology.
    2. The location of the mobile device. This has been obtained using A-GPS, which combines technologies that extract the location of a device using GPS and cellular network localisation techniques.
    3. The mobile device IMEI number (The International Mobile Station Equipment Identity). This is a unique ID that uniquely identifies the mobile device. This helps

in uniquely identifying the IoT gateway. It also serves as the AgentID in the IoT-MP architecture.

4. A timestamp is finally added to the array. The array is then sent over HTTPS to the web application.
5. The web application receives the request (the array containing the data) and responds to the mobile application. The response can even be an OK (HTTP status code 200), which means the data are successfully inserted into the database or 'Bad Request', which means the data were not inserted into the database. Therefore, the web application relies on the HTTP status codes [199] when generating a reply to the mobile application. A "401" response code sent from the server side application to the client side application indicates that authorisation has been refused. The connection with the web application is established using the HTTPS Post method:

```
private final static String url ="https://elkhodr.com/ci/index.php/welcome/insert_reading";

…

htttpsPost = new HttpsPost(url);
```

The following code extract shows the data being stored in the array using JSON.

```
jsonReq.put("reading", value);
jsonReq.put("imei", getImei(context));
jsonReq.put("deviceid", deviceid );  jsonReq.put("ble.getloc", loca );
jsonReq.put("lat", locLat);
jsonReq.put("lon", locLan);
Calendar rightNow = Calendar.getInstance();
jsonReq.put("timestamp", ( rightNow.getTimeInMillis() / 1000) );
postParams.clear();
postParams.add(new BasicNameValuePair("jsonstr", jsonReq.toString()));
```

From the above code:

- The "reading" is an array that holds the sensory readings.
- The "imei" is the mobile device unique ID. This represents the agentID.
- The "deviceid" is the unique ID of the Bluetooth sensor.

- The “loc” is the location of the sensor. It is calculated using the method BLE.GetLoc(), which returns three possible values: 10 (which means the sensor is within 10 meters proximity), 50 (within 50m proximity), and 100 (for any distance over 50m of proximity).
- The “lat” and “lon” are the GPS coordinates of the mobile device.
- The “timestamp”, as the name suggests, adds a timestamp to the received readings.

The function used to obtain location is adapted from the Android iBeacon Code developed by David Young [200]. Our work improves this function by pinpointing the proximity of a sensor to a range within 10m, 50m, or 100m from the GPS location of the mobile device. The mobile device in this experiment calculates the proximity of the BLE sensor by estimating the distance to the sensor (more specifically the transmitted beacon). It does that by comparing the signal level with the level of that of the reference signal. For instance, consider that a BLE advertisement packed was received by the mobile device and had a signal level of -70dBm. Assume the calibration value of this packet is -62 dBm. Then the method concludes that the sensor is more than one meter away since the signal of -70dBm is weaker than the reference signal. Therefore, each time a location estimate is calculated a formula is called that compares the signal level with that of the reference signal level. As noted by many other researchers, it is feasible to estimate if the sensor is within a meter or two rather than 20 meters away. However, it is difficult to compute whether the sensor is 5m or 15 meters away. For these reasons, our method provides three values estimate for locations: within 10m, 50m, and 100m. The purpose behind this generalisation is to obtain a valid location input that can be further used in the experiment. Also, since indoor positioning technology is outside the scope of this work, the focus was on getting a real location input rather than studying or improving the accuracy of BLE proximity technology. We are confident that, in the future, Bluetooth and other low-power wireless technologies will mature to provide the capability of accurately locating a device. Readers interested in reading more on the performance of BLE proximity location are referred to [201].

5.2.2.2 Evaluating the Performance of BLE Proximity Positioning

For this work, we kept the deployment of the sensors simple. The sensors were deployed in an open air flat hall 100m *40m. The experiment used 5 BLE sensors positioned at approximately 1m high. The mobile device used was Nexus 5 running Android 5.1. The hall had no moving objects that might interfere with the sensors' signal. The mobile application was configured to scan for beacons every 2 seconds for 5 minutes. We initially conducted 20 tests and few others when we implemented the S-Obfuscation approach. In the first 20 test cases, we measured the performance of the application in locating the sensor devices. In each of these tests, the sensors were placed at a predefined distance from the mobile device. We used a combination of schemes and we noted the results. Table 5.2 shows an example of the test cases.

Table 5.2- An example of the test cases

	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5
Test 1	1m	15m	3.5m	30m	48m
Test 2	5m	5m	5m	5m	5m
Test 3	0.5m	12.2m	22m	30m	55m

Figure 5.8 and Figure 5.9 show the results of the test cases reported in Table 5.2. While Figure 5.10 compares the results of the expected sensors' locations against the location computed by the application for the 20 test cases.

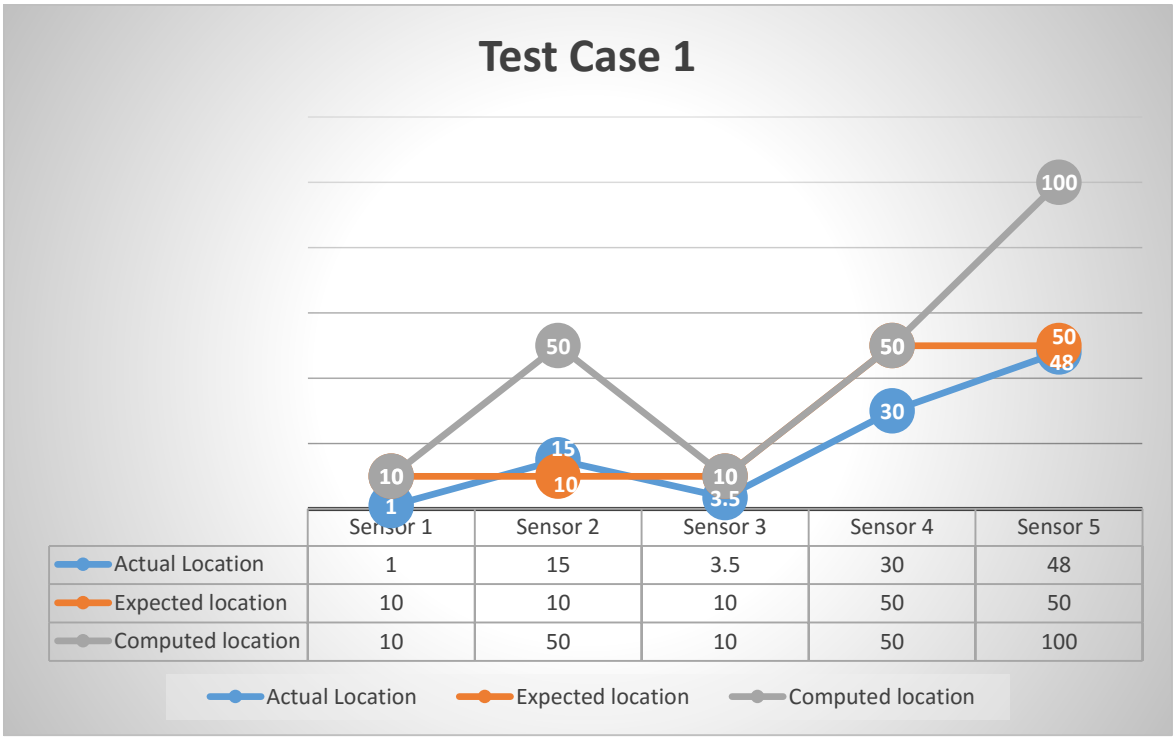
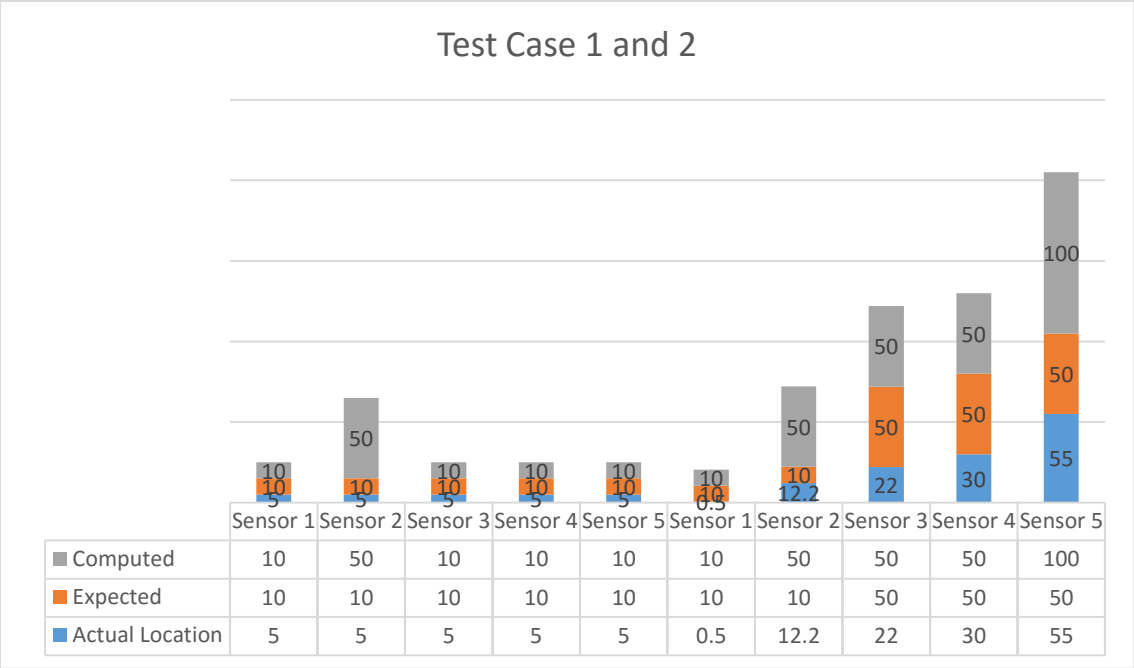


Figure 5.8- Test case 1 results



	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5
Computed	10	50	10	10	10	10	50	50	50	100
Expected	10	10	10	10	10	10	10	50	50	50
Actual Location	5	5	5	5	5	0.5	12.2	22	30	55

Figure 5.9- Test case 1 and 2 results

The actual location is the true location of the sensor. The expected location is the location calculated as expected by the formula with null errors. The computed location is the actual location resulted from the experiment. Figure 5.10 shows the results of 20 test cases.

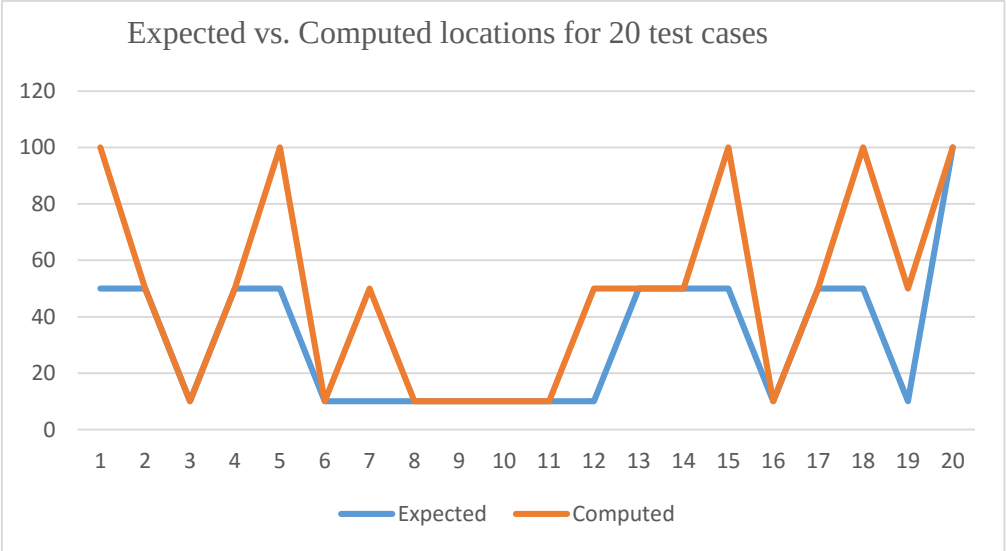


Figure 5.10- Expected vs. Computed Locations

It shows that our approach to generalising the location of a sensor has improved the proximity calculation of the sensors location. However, we are still far from accurately positioning the location of the sensor. Our results correlate with those reported in the literature and demonstrate that BLE is best fit to proximity localization rather than accurate positioning. They show that it is more accurate to determine if a sensor is located within few meters of the mobile device or no. However, when it comes to measuring how far the Beacon from the mobile device is, the formula used to calculate the proximity proved to be unreliable. In some cases, the formula was able to correctly position the Beacon within 50 meters. In other cases, the formula failed to do so. For example in text case 1, sensor 5 was located at 48m from the mobile device. The formula should have calculated the location of the sensor to be within 50m. However, the computed location was 100m. Also, we observed that some factors affected the performance of the signal and that of the formula performance including the position in which the sensor's antenna is directed, the height of the sensor, how many people are in the room, and whether Wi-Fi devices are active in the same room. This is an interesting area that can be further explored by the research committee.

To this end, we have completed the part where the data collected by the sensors along with the location information of the sensors and that of the mobile device are transmitted over the Internet to the web application. Therefore, at this stage, the sensory information is successfully stored in the database. The activity diagram for this interaction is provided in Figure 5.11. Figure 5.12 shows the interaction between the sensors, mobile device, and the web application as per the IoT-MP architecture.

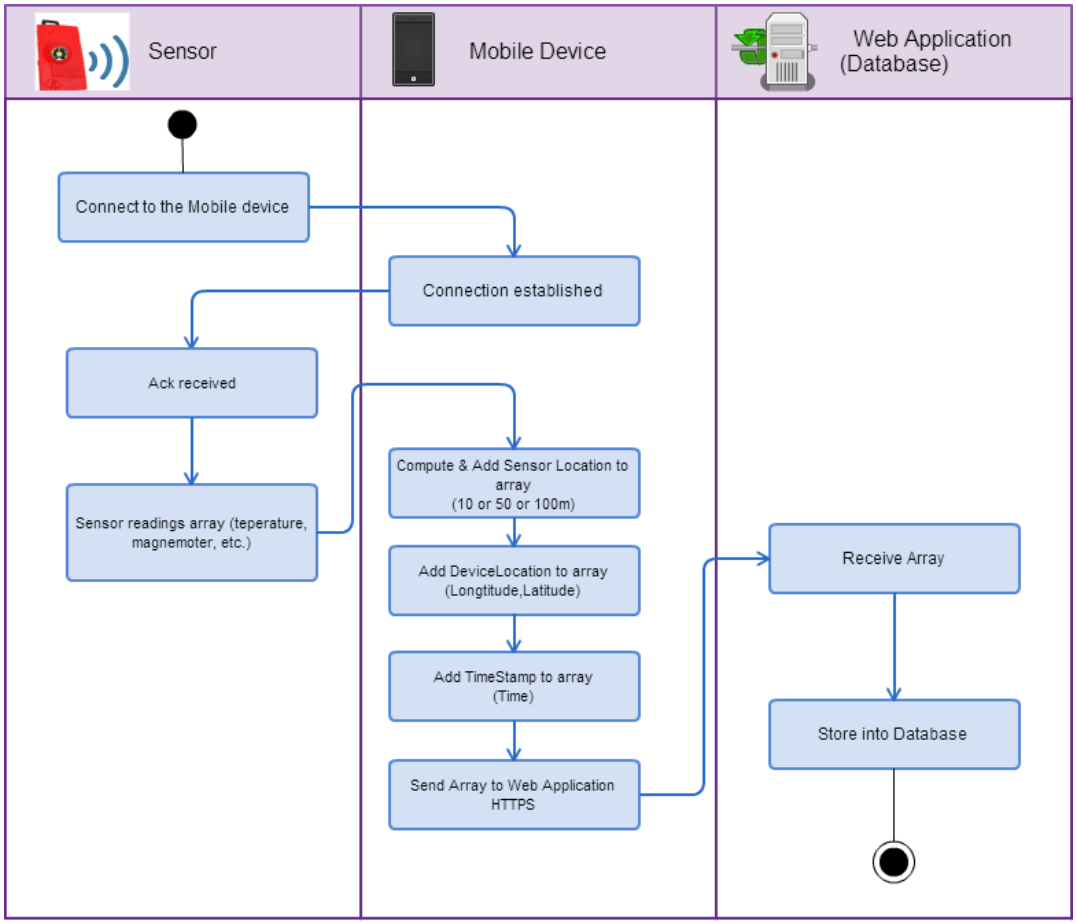


Figure 5.11- Activity diagram: Storing sensors' data into the database

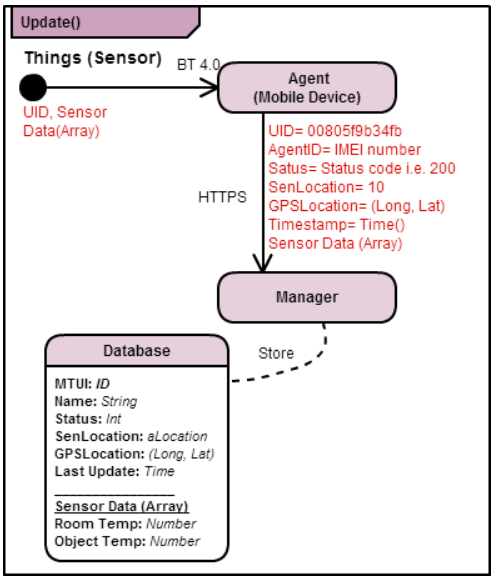


Figure 5.12- State Machine Diagram as per the IoT-MP

5.2.2.3 Scope of the Experiment Designed in this Stage

This experiment uses Bluetooth Low Energy as the communication medium between the sensors network and the IoT gateway (the mobile application). However, the concept of using one of the nodes as the gateway to the Internet is also used in other low-power wireless technologies such as ZigBee IP, 6Lowpan, and 802.11ah; which were reviewed in Chapter 3. Figure 5.13 shows that the use of the technology does not affect the architecture of the model. This is because most wireless low-power technologies follow the same architecture of using a node as a backhaul to the Internet when connecting devices to the Internet, with few implementation differences. For instance, in the case of a ZigBee Smart network, the gateway will have the capability of communicating with the sensors using ZigBee protocol. On the other hand, the gateway connects to the Internet in the same fashion an 802.11 based access point connects to the Internet. Typically, the gateway provides embedded bridging services such as translation, repackaging, and reformatting of packets. In fact, commercialised ZigBee gateway which provides this functionality have started to gain popularity such as the Xbee hub [202].

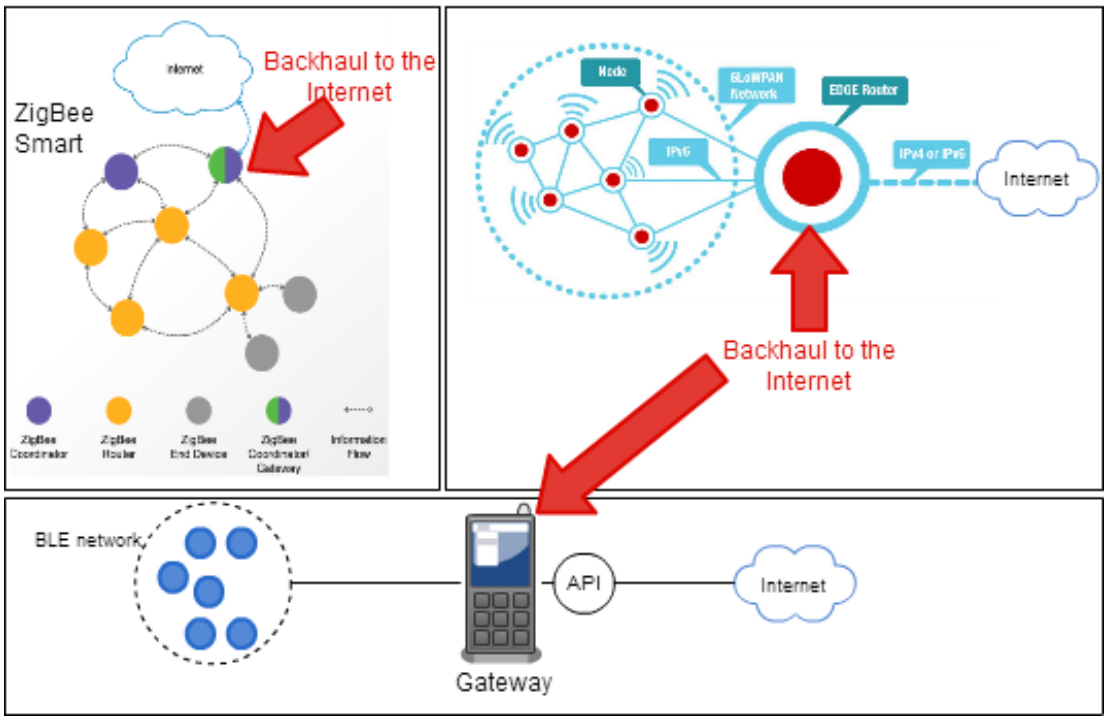


Figure 5.13- Applicability to other Low-Power Wireless network

5.2.2.4 Implementing the PM

As discussed in Section 4.5, the location disclosure decisions are made by the Privacy Module (PM). The PM involves three main components: The context analysis, the S-Obfuscation, and the privacy manager. That is the PM computes whether "to disclose" or "not disclose" the location of a device based on the context of the request and the privacy rules set by the user. Moreover, the privacy manager module has also an important role in determining the level of Obfuscation used for each context.

5.2.2.5 Implementing the Context Analysis Component

Table 5.3 presents a compressed pseudo code of the implementations of the context analysis component.

Table 5.3- Context Analysis pseudo code

Context Analysis Pseudo Code

Begin:

Input: *DeviceID, RequesterID*

Output: *LocationOutput*

```
//Privacy Module receives getLocationOutput(DeviceID, RequesterID) request
on data from third entity. The request includes the DeviceID of the sensor
being requested i.e. Sensor's UID and the ReqeusterID of the requester.

//omitted some housekeeping code and definitions

GetLocationOutput(DeviceID, RequesterID){
    C(context)=ContextManager.getContextOf(RequesterID)
    var RequesterID=C.getRequesterID()
    var SNetworkName=C.getNetworkName()
    var SLocation=C.getRLocation(Long,Lat)
    var Date=GetDate()
    var Time=GetDate()
```

Table 5.5 - Context Analysis pseudo code (Continued)

```
    Call CheckPolicy()

//function to get the RequesterID. In case, the requesterID cannot be
obtained or not supplied use null as the ID
Function getRequesterID(int, RequesterID) {
    if(C.getRequesterID != null)

    {
        return RequesterID;
    }

    else {return null;}

//function to get the Requester network name and type. In case, the network
name cannot be obtained or not supplied use null as the network name

Function getNetworkName(String, SNetworkName) {

        if (C.getNetworkName != null)

        { return SNetworkName;}

        else{return null;}

//function to get the Requester location. In case the Rlocation cannot be
obtained or not supplied use null as the value for the location
Function getRLocation(array, SLocation[Long,Lat]) {

        if (C.getSLocation != null)

        { return SLocation[Long,Lat];}

        else{return null;}

Function CheckPolicy()

P (Policy)= PrivacyManager.getPolicy(int,RequesterID)

//PrivacyManager is class described in Algortihm 2
Switch (p)

case 1 (p==null && PrivacyManager.UseDefault())
    {p=PrivacyManager.getDefaultPolicy.getDefaultLocation();
        (location) LocationOutput= p.getDefautlocOutput(long, lat, SenLoc)
                return locationOutput;
```

Table 5.5 - Context Analysis pseudo code (Continued)

```
        break;}
//Check if the policy is set to Prompt the user. If so, the function will
ask the user for permission to reveal the location//
  case 2(p=="prompt")
    {//post to the user the detail of the request along with those of the
requested resource and then get user permission
   userInterface.postToUser(requesterID, SNetowrkName,SLocation,Date,
Time,DeviceID,Device.UUID.getCurrentLoc());
        userInterface.promptUserAgree(notify(boolean));
        if (notify){
        userInterface.AssignRule(agree, rule)
                //if the user agrees to reveal the location, get the
Obfuscation level to be used and save it as a new policy
        userInterface.AssignObfLevel(promt(obfLevel))
        behaviourModelling.registerAction(Register(rule))}
        //the method register(rule) create a rule which assigns an
Obfuscation level to the current context
        else //if the user did not approve the request, the code will then
proceeds in using  a default location from the default policy
            if (PrivacyManager.getDefaultPolicy.useFakeLoc())
                (location) LocationOutput=
PrivacyManager.getDefaultPolicy.getFakeLoc()
        return locationOutput;
        break;}
//This is the case where a policy has been found for the current context.
The code will then proceed into checking if the parameters supplied in the
request matches the conditions set in the policy.

case 3 (p!=null){
         if (p.checkAllrequired()){
             var error
             if (RequesterID==null)
                 error= "error" +RequesterID+ "required";
             if (SLocation==null)
                 error= "error" +SLocation+ "required";
             if (RNetworkName==null)
                 error= "error" +SnetworkName+ "required";

             return error;}

else if (RequesterID==p.getRequesterID() && SLocation==p.getRlocation &&
$SnetworkName==p.getRName)&&(c.sensorID.getLocation()==p.getLocation() &&
checktime(p) && checkdate(p)) (location) LocationLevel= p.getObfLevel(long,
lat, SenLoc)(location) LocationOutput=Generate (LocationLevel, RLocation)
     return locationOutput;}}
```

Therefore, the "getLocationOutput" defined in Table 5.3 returns a locationOutput. This is a response message to the request "GetLocation" of a specific sensor. The locationOutput can have one of these three values:

1. An assigned obfuscated location based on the level indicated by the user-defined policy. This is done using the method *"PrivacyManager.getPolicy"*. This could be anything from L0 (true location) to L5 fake location. An obfuscated location is used when the privacy manager approves the context of the request.
2. A default location is used. This is the case when the privacy manager does not approve the context of the request. In this case, the user has configured the policy in a way it uses the default policy for unauthorised requests.
3. An obfuscated location is provided, in real-time, by the user. This happens when the user's defined policy is configured to prompt the user for permission.

5.2.2.6 Implementing the Privacy Manager Component

Table 5.4 presents a compressed pseudocode of the implementations of the context analysis component.

Table 5.4- Privacy Manager-Selected Pseudocode

Privacy Manager Pseudo Code

Class PrivacyManager{
Define Context{
int RequesterID;
string SNetworkname;
string SLocation(var long,var lat);
Function CheckAllrequired()
P= Policy;
flag=false;
if (p.SNetworkname!=null)
flag= true;

Table 5.6 - Privacy Manager-Selected Pseudocode (Continued)

```
        if (p.SLocation!=null)
            flag= true;
    //do the rest for all condition

        return flag;

Define ContextManager (c context){
            function getRequesterID(){
                return c.RequesterID();}
            function getRNetworkname(){
                return c.SNetworkname();}
            function getSLocation(){
                return c.SLocatione();}
            Function getContextof(RequesterID)
                    return (getRequesterID(), getSNetworkname(),
getSLocation())
        }

Define Policy{
     Policy (C,deviceID,UserPolicy){
        C=GetContextof(RequesterID);
        deviceID= GetContextof(deviceID);
        UserPolicy=Set {
                    SNetworkname=User.NetworkInput
                    SLocation= User.LocationInput
                    TimeRestriction= User.TimeInput
                    Date.Restriction= User.DateInput}

Call registerAction(RegisterRule())

}}

    Define DefaultPolicy {
        Function UseDefault(){
            GetDefaultPolicy.FilterBy(DeviceID)
            GetDefaultPolicy.getDefaultLocation(){
                return SObf.default(DeviceID)}}

//user interactions omitted
```

This is an implementation of the context analysis component introduced in Section 4.4.1. Table 5.4 should be read in conjunction with Figure 4.31.

5.2.2.7 Implementing the S-Obfuscation Component

The Semantic Obfuscation Component described in Section 4.5.3 is implemented as part of the management application discussed in Section 5.2.2. The implementations conducted in this section alter the location of a BLE sensor to a base point based on the S-Obfuscation level indicated by the user in the policy. The process is as follows:

The connection API forwards the location of the sensor along with the GPS location of the IoT gateway to the management application to be stored in the database. The management application then sets the current true location as L0 and generates a dummy location to be used for Level 5 (L5). The PM then proceeds into finding the coordinates of the three base points' corresponding for the three levels (L1, L2, and L3). To do that, the management application sends the GPS location of the sensor to Google Geocoder API [203] in the format of (X, Y) where X and Y are the integers representing the latitude and longitude. Google API converts these coordinates into readable addresses in the format of (Street Name, Suburb, State and Country). For Example: Convert the GPS location of L (-33.870887, 151.2069364) to 452 George Street Sydney NSW Australia). Following the ontology proposed in Section 4.1, the process starts by extracting the classes, their identifiers, and the node address of the converted GPS address. The PM then performs a tree search and identifies the classes. Suppose level 2 Obfuscation is used, the management API accesses the database and retrieves the base point correspondent to the class suburb of this location. It then communicates back with the Google API to extract the coordinates of each these base points using reverse lookup. With this method, the PM is able to identify four coordinates that can be representing the current location each in a different set (given L0 is the true exact location). The fake location L5 is generated by randomising the latitude and longitudes values.

To simplify the complexity involved in implementing the S-Obfuscation, the scope of the implementations was restricted to a limited geographic area i.e. Sydney CBD. More specifically, the implementations were limited to George Street Sydney and surrounding streets. George Street was selected for the experiment as it is one of the busiest streets in Sydney. Sydney CBD is a coastal city as well.

Consider the following exemplary address: 452 George Street Sydney NSW Australia, which corresponds to Australia (1), NSW (2a), Sydney (3a), George Street (4a), 452. Therefore, the node address is 1.2a.3a.4a.452. Based on the Obfuscation level indicated by the user, a base point will be selected from the ontology. Suppose the user has selected Obfuscation Level 2 then the node address will be shortened to 1.2a.3a. Then, a search for base points is conducted on all subclasses that start with a node address of 1.2a.3a. The search will return all base points defined below the subclasses with the identifier "3a". Next, a base point is randomly selected, e.g., 1.2a.3a.4a.5b or 1.2a.3a.4b.5h. To reduce the implementation complexity, we manually populated the database with an address for each Obfuscation level. This allows the management database to simply lookup the correspondent table for the base point address assigned to each level.

Finally, the selected base point is then converted, using Google Map API, to a GPS coordinates and used as an obfuscated location for the original location. It should be noted that Google Geocoder API is only used as a service for converting the coordinates into a possible readable address. The Google Geocoder API is not made aware of the true location of the device nor its identity. The relevant code is provided in Table 5.5. The code is adapted from Google Maps Geocoding API [203].

Table 5.5- S-Obfuscation codification extract

S-Obfuscation codification

```
<?php

/*

* For a true GPS location of a sensor, return the longitude and latitude using The Google Geocoding API V3

**/

function Get_Loc($address) {

    $Loc = urlencode($Loc);

    $url = "http://maps.googleapis.com/maps/api/geocode/json?address=$address&sensor=false";

    // Make the HTTP request
```

Table 5.7 - S-Obfuscation codification extract (Continued)

```
    $data = @file_get_contents($url);
    // Parse the json response
    $jsondata = json_decode($data,true);
    // If the json data is invalid, return empty array
    if (!check_status($jsondata))   return array();
    $LatLng = array(
        'lat' => $jsondata["results"][0]["geometry"]["location"]["lat"],
        'lng' => $jsondata["results"][0]["geometry"]["location"]["lng"],
    );
 return $LatLng;
}
/*
* Check if the json data from Google Geo is valid
*/
function check_status($jsondata) {
    if ($jsondata["status"] == "OK") return true;
    return false;
}
```

5.2.3 Stage 3- Developing a Mobile Policy-based Application and LBS Web Application

As mentioned in Section 5.1, the LBS application models the operation of an IoT LBS application whereas a service is provided based on the location of a sensor. So the LBS web application is used to request the location of a sensor. This enables the research to observe the received location and determine whether the PM was successful in preserving the location privacy. However, for this to work, a user-defined policy or a default policy must be first configured and defined in the management application. Therefore, before

developing the LBS web application, we needed to implement another mobile application. This mobile application referred to as the Policy-based app is used by the user to create and assign policies to a particular BLE sensor (Figure 5.14 step 5). The steps 1, 2, 3 and 4 were already done in Stage 1, 2 and 3 of this experiment.

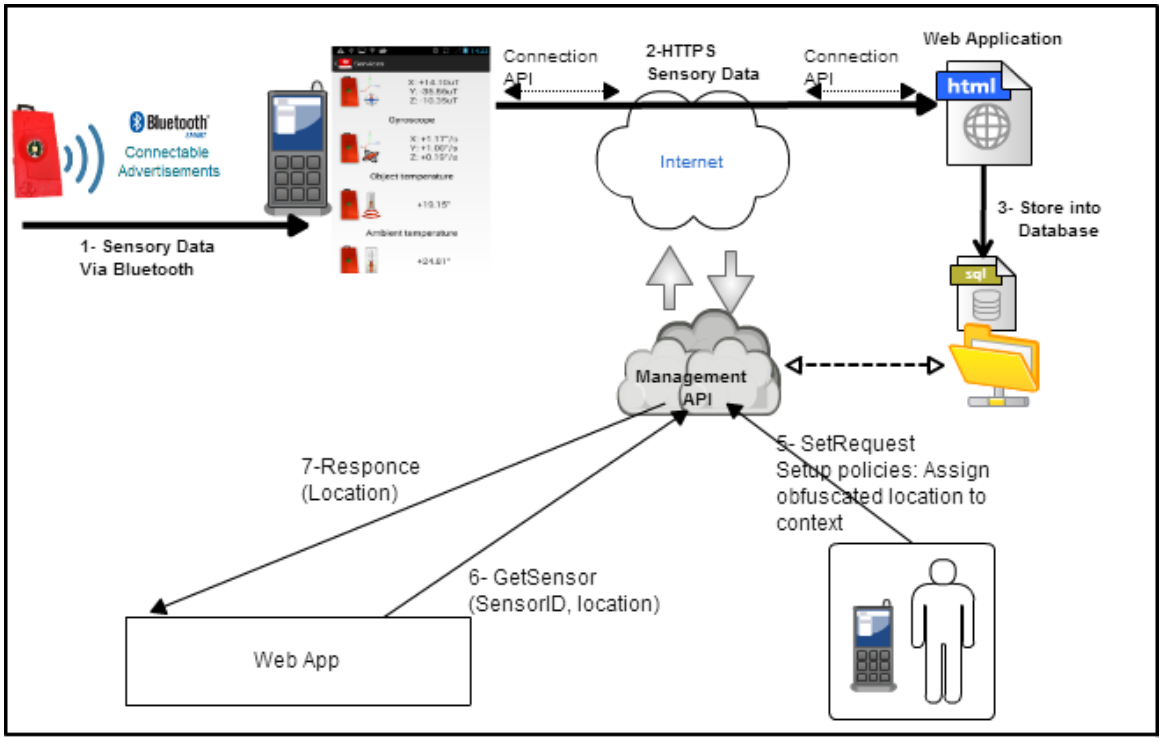


Figure 5.14- Web application requesting the sensor location

5.2.3.1 The Development of a Policy-based Mobile Application

The mobile application, implemented in step 5 of Figure 5.14, provides the user with a UI that allows him or her to define a policy and to assign it to a specific context using the followings criteria:

- Network restrictions: This feature enables the user to define a policy restriction on a particular network e.g., mobile network or Wi-Fi.
- Time restrictions: It is where a limitation on time can also be enforced e.g., between 9:00 AM and 17:00 PM.

- Date restrictions: It is where a limitation on the weekdays can be enforced as well, e.g., Monday to Friday.
- Location restrictions: This is a policy which enforces a specific Obfuscation level.
- Objects restrictions: This allow the enforcement of the policies mentioned above to specific entities.
- Default settings: Allows the enforcement of a set of configurations (restrictions) as a default profile. This default profile is used in the absence of specific policies that govern specific sensors.

For example, using this mobile application the user can create the following policy:

Policy 1: If my sensorID 1 is currently connected to the Internet via Home Wi-Fi (the sensor relies information to the management application through a mobile application), and it is Sunday between 8:00 AM and 6:00 PM then only reveal the suburb as the location of the sensor (which correspond to Obfuscation level 2). The default policy is configured to as "Do not disclose the object's location.

Therefore, if an entity requests the location of sensor ID 1 and its context matched the one defined in the policy, then it will receive a location narrowed to a suburb granularity. Else, if the context does not match the one defined in the policy, then a fake location is used instead. The screenshot of the mobile application used to create the user defined policy is given in Figure 5.15. It shows how the user of a sensor device can attach restrictions to a location output by setting restrictions on the network, time, days, location and, a device identity.

This mobile application offers users with a UI enabling them to assign an Obfuscation level to a context based on some contextual parameters. However, the actual computations are done in the background on the server side (the management application).

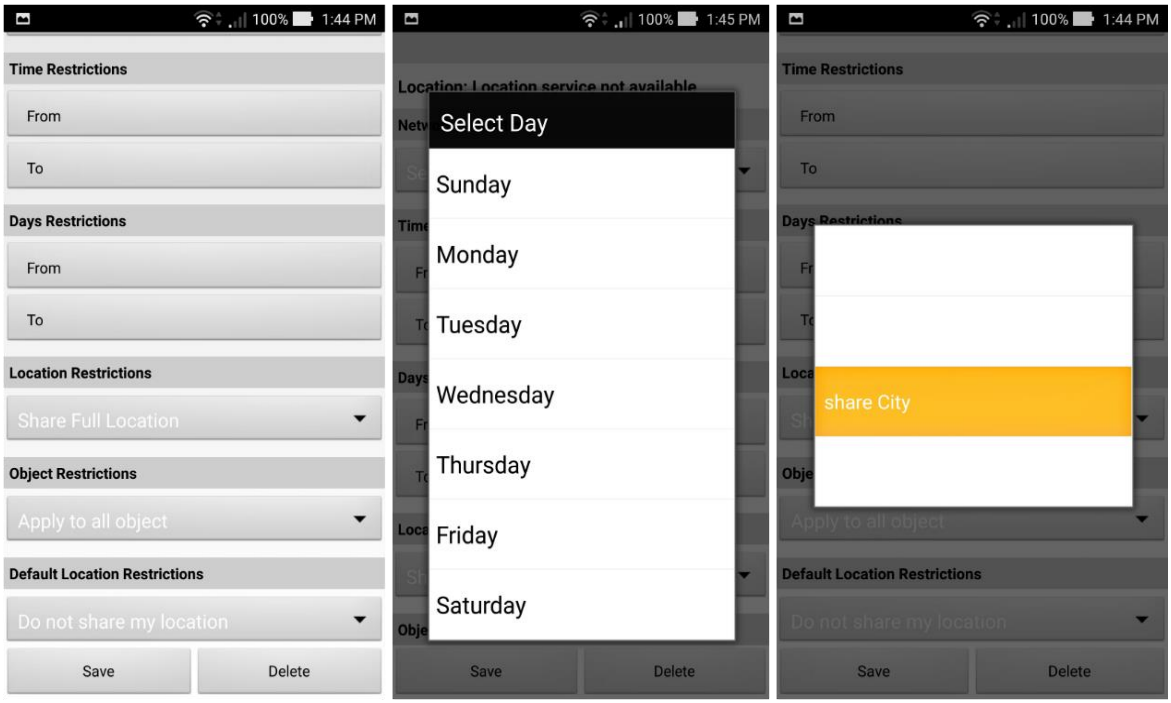


Figure 5.15- UI for defining policies

5.2.3.2 The Implementation of a Location Based Service Web Application

The Location Based service (LBS) has a simple user interface where the user can request the location of a sensor using the sensor ID. Requests are sent to the management application via HTTP. The management API receives the HTTP request, extract the sensorID and checks the PM for any defined policy in the database. Next, the management API replies to the request with an obfuscated location also using HTTP. The LBS web application then plots it on a map. Figure 5.16 shows the sequence diagram for this interaction. It starts by the message getLocation that takes the sensorID and requesterID as arguments. It then proceeds by a GetContext message, which creates a context for the request using the context parameters previously described in 5.2.3 (e.g., time, date, or location). This message triggers another message called Checkpolicy().The steps of the function Checkpolicy are illustrated in Figure 4.31. The interaction then finishes with a return message i.e. the obfuscated location of the sensor that can be anything from true location to a fake location.

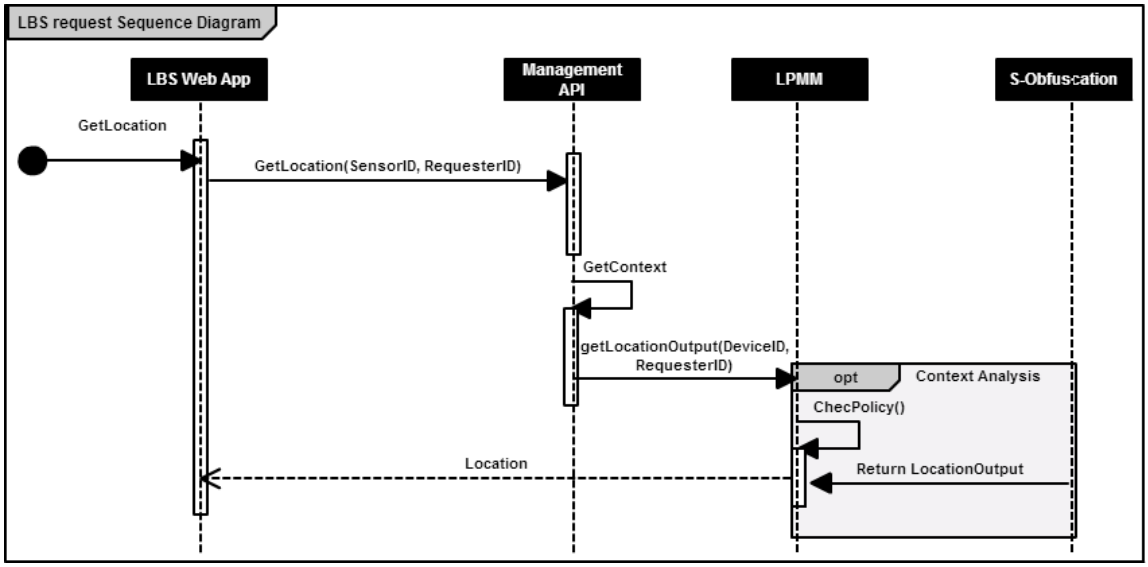


Figure 5.16- LBS request Sequence Diagram

The implementation of the LBS web application is based on the CodeIgniter web framework [204]. It uses the Model View Controller (MVC) approach. The concept behind MVC is the separation between logic and presentation, which is exactly what was needed in our case since much computation related to the PM is done in the background.

5.2.3.3 Test Case Design and Collection of Results

To demonstrate and evaluate the performance of the experiment developed in stage 1, 2 and 3, a test plan is designed. The test plan included twenty test cases in which the generation of each of the Obfuscation levels is tested. Table 5.6 shows the results for three test cases. The location inputs were automatically selected from various addresses within Sydney and the surrounding suburbs. By comparing the current location (location input) against the expected location and the location received (this is the location received by the LBS web application), we were able to verify if the location outputs were successfully generated for a given context.

- Location input: represents the actual location of the sensor
- Expected location: represents the location computed by the s-Obfuscation with nil error.

- Location output: represents the received location as observed in the test.

Table 5.6 Test cases

Location input	**Obfuscation level**	**Expected output** **(Refer to Fig 19)**	**Actual output**
10 m of GPS (-33.870887, 151.2069364) Readable GPS: 452-456 George St, Sydney NSW 2000, Australia	Level 1	10 m of GPS (-33.873961, 151.20569) Readable GPS: within few addresses of 35 George St, Sydney NSW 2000, Australia	GPS (-33.873939, 151.205645) Readable address: 37 George St, Sydney NSW 2000, Australia
50 m of GPS (-33.870887, 151.2069364) Readable GPS: 452-456 George St, Sydney NSW 2000, Australia	Level 2	Two additional base points were defined in the database: 50m of GPS (-33.8593221, 151.20360619999997) within few addresses 40 Kent St, Sydney And 50m of GPS (33.8657357, 151.20360619999997) within few addresses 25 York St, Sydney	GPS (-33.8684743, 151.20601750000003) Readable address: 26 York St, Sydney NSW 2000, Australia
	Level 3		

100 m of GPS (-33.870887, 151.2069364) Readable GPS: 452-456 George St, Sydney NSW 2000, Australia		In addition to those defined in level 1 and 2: 100m of GPS (-33.837634, 151.20496926) Within few addresses of 26 Oak St, North Sydney NSW 2060, Australia And 100m of GPS (-33.842064, 151.206189) Within few addresses of 19 Miller St, Lavender Bay NSW 2060, Australia 100 m of GPS (-33.841122, 151.20751) Within few addresses of 11 Blue St, North Sydney NSW 2060, Australia	GPS (-33.840858, 151.206849) 48 Blue St, North Sydney NSW 2060, Australia

Figure 5.17 visualises the expected location and actual location. It shows that the original location of "452-456 George St, Sydney NSW 2000, Australia" has been successfully obfuscated to "37 George St, Sydney NSW 2000, Australia" (Just 2 addresses from the base point "25 George St, Sydney NSW 2000, Australia").

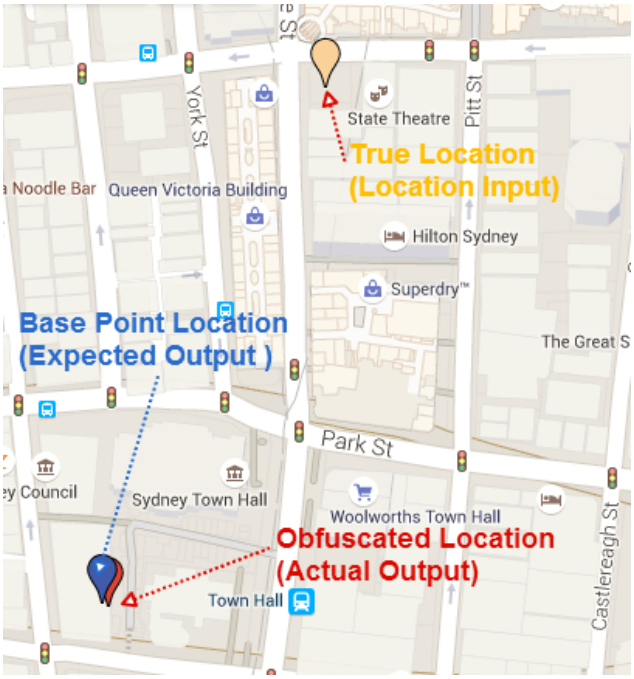


Figure 5.17- Test Case1

The differences between the base point and actual location are because the sensor is located at 10m of the original location (location input). Figure 5.18 visualises the test case 2 from Table 5.6. The S-Obfuscation has two base points' choices when using Obfuscation level 2 (as discussed in Section 4.1.1). The base point is hence randomly selected.

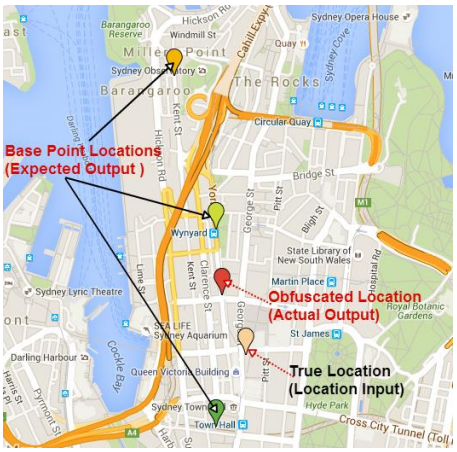


Figure 5.18- Test Case 2

Therefore, in this test case 2, as shown in Figure 5.18, using Obfuscation level 2 the original location of “452-456 George St, Sydney NSW 2000, Australia” has been successfully obfuscated to the “26 York St, Sydney NSW 2000, Australia”. The rest of test cases that used level 2 Obfuscation produced results near Kent St and York St as well. This is because the S-Obfuscation selects a base point from the available ones randomly. Figure 5.19 visualises the test case 3 from Table 5.6. In this case, a wider proximity to original location is used (Obfuscation level 3). This provides the S-Obfuscation with a higher number of base point choices.

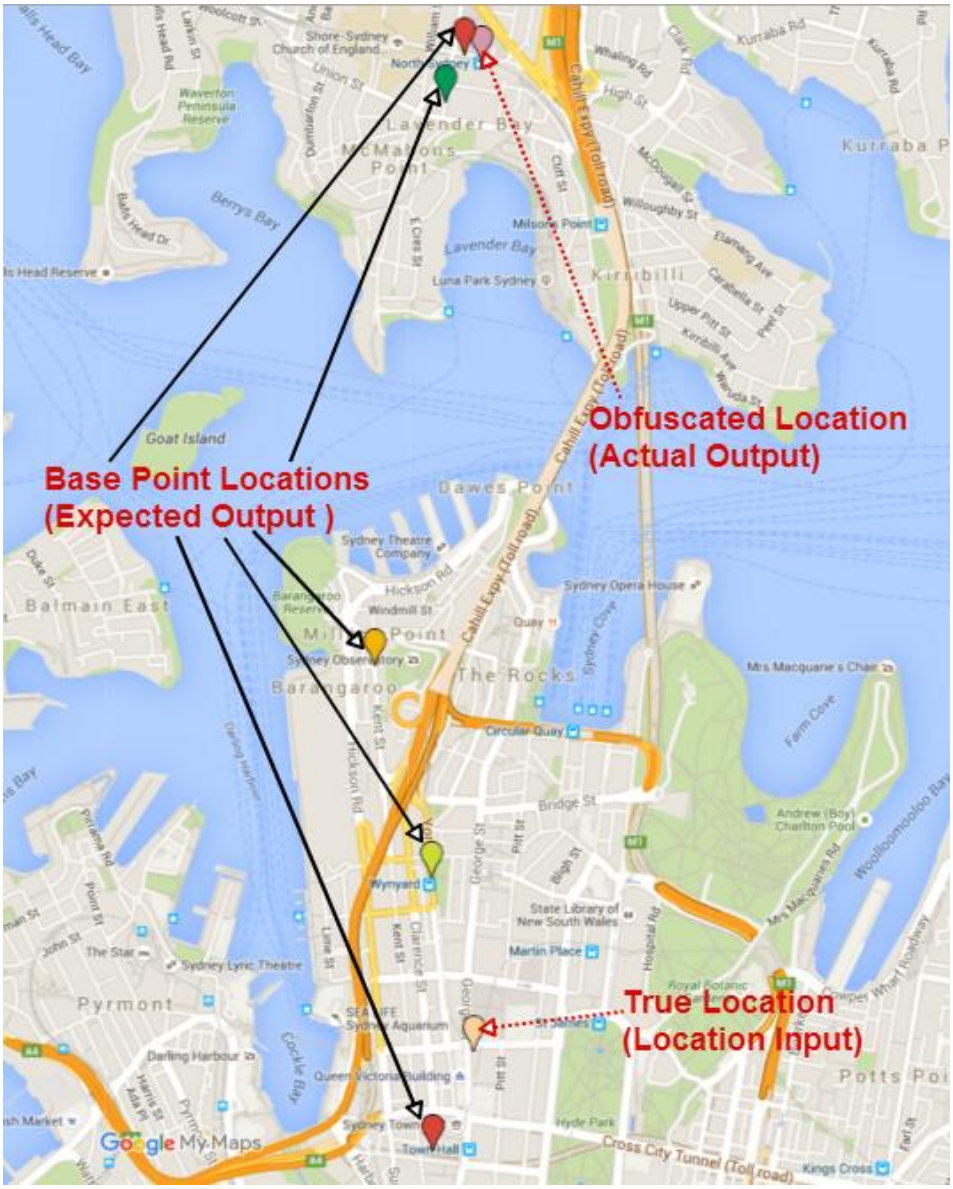


Figure 5.19- Test case 3

Figure 5.20 and Figure 5.21 show the results of test case 2 which was repeated twice. As the base point is selected randomly, we can notice that the obfuscated locations (actual location) are produced each time differently in each of these figures.

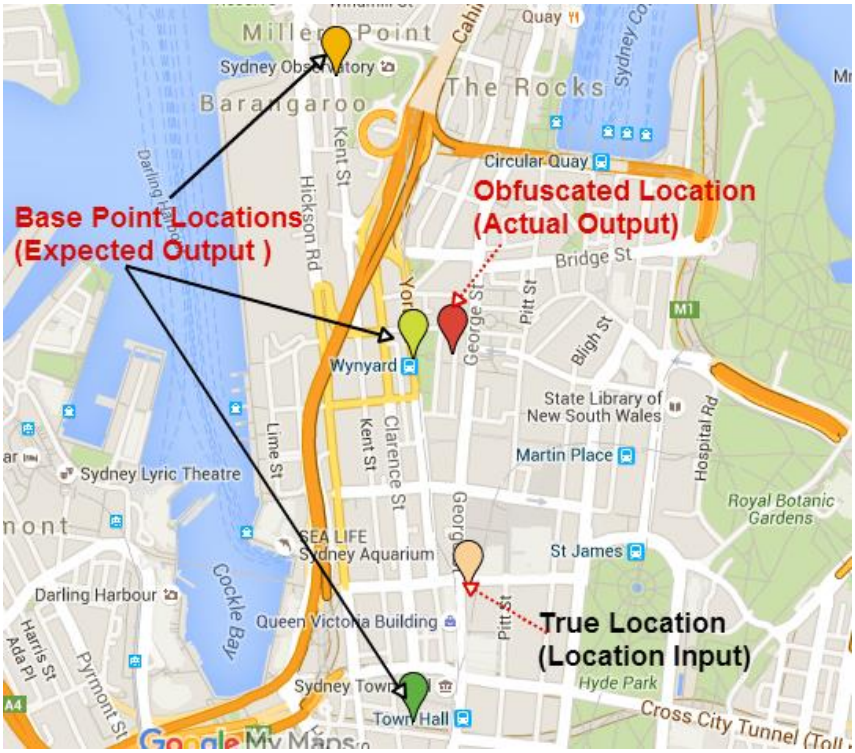


Figure 5.20- Results of test case using Obfuscation level 2(1st round)

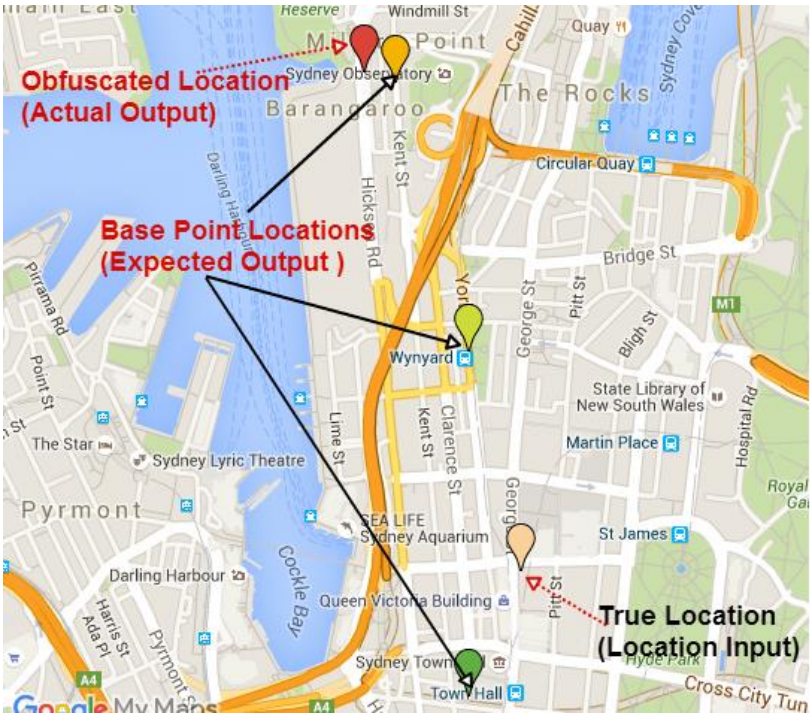


Figure 5.21- Results of test case using Obfuscation level 2(2nd round)

5.2.3.4 Evaluating the Performance of the S-Obfuscation against the Classic Methods

In this section, the performance of the S-Obfuscation in comparison with the Rand and Dispersion Obfuscation techniques is evaluated. The performance metric measured in the experiment is the prediction rate. A prediction rate is the ability of an adversary to detect if a received obfuscated location is real or fake. To determine if an obfuscated location is real or fake, the obfuscated location is converted using the ontology to a real address and the node address of the obfuscated location is examined. If the node address is less than three levels down from the root node, then the obfuscated location is deemed as fake. For example, converting an obfuscated GPS location to a precise address with enough geographic knowledge would look like: Australia, NSW, Sydney, George Street, and Street number (where the street number is optional). If the obfuscated location does not possess enough knowledge to position a location to a street address, then the location is considered to be too ambiguous. Therefore, the obfuscated location is judged as fake. This process is illustrated in

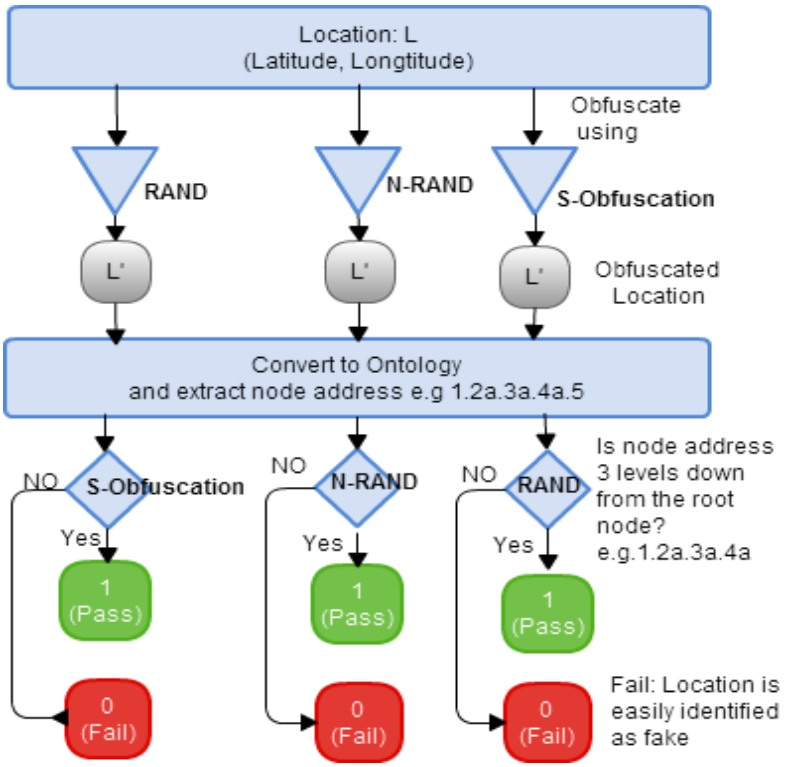


Figure 5.22- Evaluation process

5.2.3.5 Implementing the Rand and Dispersion Techniques

The Rand and Dispersion techniques described in Section 2.3 were implemented as part of a web application. This application is used to test and evaluate the obfuscated location generated by these techniques. It allows the user to randomly generate obfuscated location for specific GPS coordinates. The implementations of the Rand and Dispersion Obfuscation Techniques are publically available online using an open source license. They can be accessed via this link http://elkhodr.com/obf.html . These implementations provide the user with a method to vary the radius of the area where obfuscated locations are generated. Table 5.7 shows the main parts of the code used to implement the Rand technique. The Dispersion technique is based on this code as well.

Table 5.7- The Rand technique selected codes

```
//Generate Random Numbers between -1 and 1
 var u= ((Math.random()*-1)+1)*1; var v= ((Math.random()*-1)+1)*1;
r= Number(r) /111300;
var w = Number(r) * Math.sqrt(u);
var t = 2 * Math.PI * v;
var x = w * Math.cos(t);
 var xx = x / Math.cos(y0)
var y = w * Math.sin(t);
//Generate the new location using the above
var xnew=Number(x0)+Number(xx);
 var ynew=Number(y0)+ Number(y);
```

To compare the performance of the S-Obfuscation approach against the Rand and Dispersion techniques, three obfuscated locations for a given GPS true location have been generated. The three obfuscated locations are then plotted using Google map and converted to real addresses as shown in Figure 5.23. Next, the prediction rate of each of the obfuscated location is calculated using the process described in

Figure *5.22*. The experiment used a sample of 20 GPS coordinates randomly selected from areas within Sydney CBD in Australia, and the results were noted. The results show that the S-Obfuscation approach has outperformed both the Rand and Dispersion techniques regarding prediction rates.

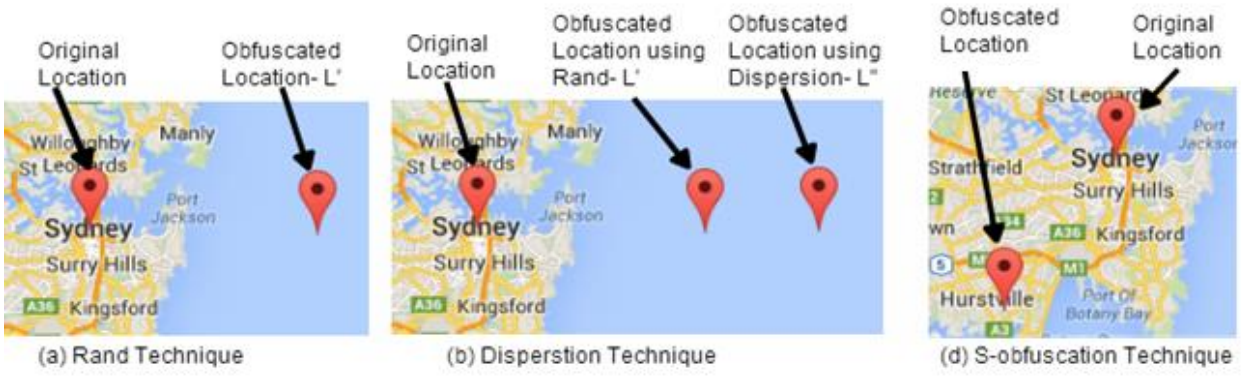


Figure 5.23- Performance example

As shown in Figure 5.23 (a) and (b) the obfuscated location were positioned in the ocean. This is because the classic Obfuscation techniques rely purely on a mathematical calculation when producing obfuscated locations. On the other hand, Figure 5.23 (c) shows that the produced obfuscated location is associated with a geographic knowledge. It represents a GPS location that can be mapped into a readable address.

5.2.3.6 Test Cases Design and Results Analysis:

In this section, we compare and evaluate the performance of Rand, Dispersion, and the proposed S-Obfuscation approach. In each test case, we selected an Obfuscation level and a correspondent radius, and we used these three methods to obtain an obfuscated location. The results were then evaluated using the method described in

Figure 5.22.

Test case 1: Using Obfuscation level 1

Parameters of the test:

Input Address: GPS (-33.870887, 151.2069364)

Readable Address: 452-456 George St, Sydney NSW 2000, Australia

Radius used for Rand and Dispersion methods: 2000 meters

S-Obfuscation level: level 1.

Visual results

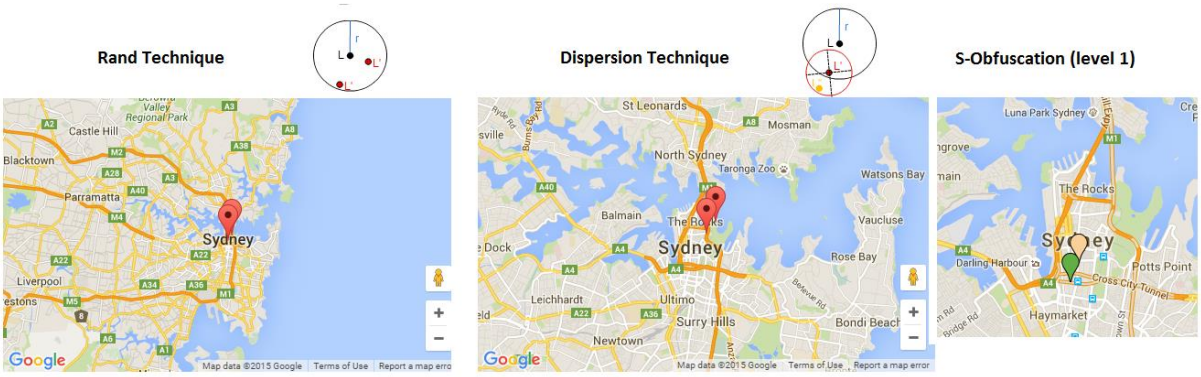


Figure 5.24- Results of the evaluation test case 1

As shown in Figure 5.24, with a smaller radius of 2KM the Rand and Dispersion techniques both produced obfuscated GPS locations that can be converted to readable addresses.

Evaluation

Given that all three methods, in this test case, produced obfuscated locations that can be mapped to readable addresses, then using the evaluation flowchart shown in

Figure 5.22, all methods score 1.

Test case 2: Using Obfuscation level 2

Parameters of the test:

Input Address: GPS (-33.870887, 151.2069364)

Readable Address: 452-456 George St, Sydney NSW 2000, Australia

Radius used for Rand and Dispersion methods: 10,000 meters

S-Obfuscation level: level 2.

Visual results

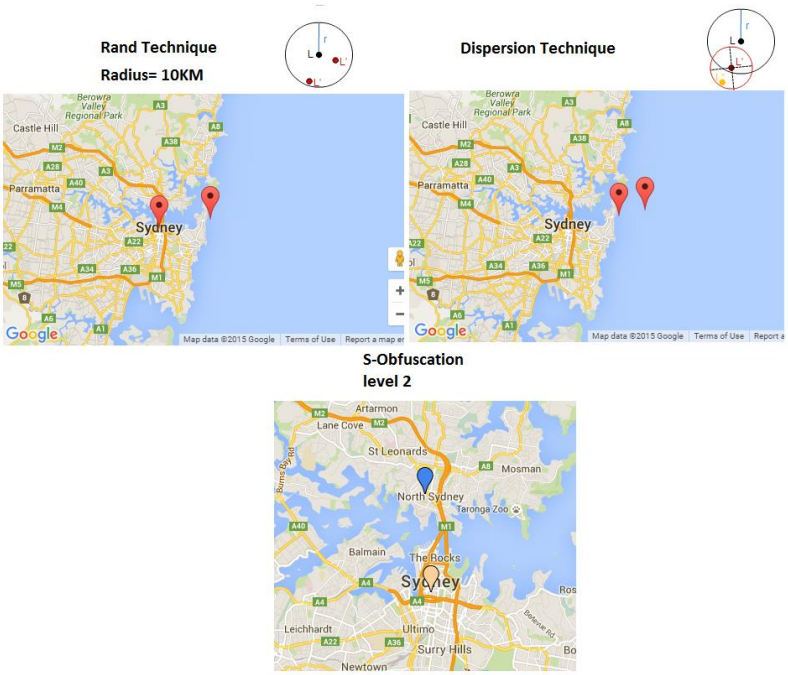


Figure 5.25- Results of the evaluation test case 2

Evaluation

As shown in *Figure 5.25*, with a larger radius of 10KM used in the Rand and Dispersion techniques, both methods produced unacceptable obfuscated locations when compared to that of the S-Obfuscation. These tests can be verified at http://elkhodr.com/obf.html. However, it should be noted that repeating the experiment will not produce the same location outputs since they rely greatly on randomization when selecting obfuscated locations. So by using the same radius of 10KM, in some cases, the Rand and/or the Dispersion method will produce acceptable obfuscated locations; while in other cases they will produce results similar to those shown in *Figure 5.25*. However, repeating the test a few times will help to verify the results visualised in *Figure 5.25*. Table 5.8 reports the evaluation results of ten test trials conducted using a radius of 10 KM.

Table 5.8- Results of 10 others test trials conducted using a radius of 10 KM

Test case Radius 10 KM	**Rand**	**Dispersion**	**S-Obfuscation**
Trial 1 score	1	0	1
Trial 2 score	1	1	1
Trial 3 score	1	1	1
Trial 4 score	1	1	1
Trial 5 score	1	1	1
Trial 6 score	1	1	1
Trial 7 score	0	0	1
Trial 8 score	1	0	1
Trial 9 score	1	1	1
Trial 10 score	1	1	1
Total	9	7	10
Prediction Rate	90%	70%	100%

Table 5.8 shows that using a radius of 10KM, in ten test trials, the Rand method produced 90% of obfuscated locations that can be mapped to readable addresses (prediction rate of 90%). Similarly, the Dispersion technique produced a prediction rate of 70%. While, the prediction rate of the S-Obfuscation was 100%.

Test case 3: Using Obfuscation level 3

In this test case, we used a radius of 50 KM for the Rand and Dispersion technique and Obfuscation level 3 in the S-Obfuscation. Table 5.9 shows the evaluation results of another ten trials conducted in test case 3.

Table 5.9- Results of 10 others test trials conducted using a radius of 50 KM

Test case Radius 50 KM	**Rand**	**Dispersion**	**S-Obfuscation**
Trial 1 score	1	1	1
Trial 2 score	0	0	1
Trial 3 score	0	0	1
Trial 4 score	0	0	1
Trial 5 score	0	0	1
Trial 6 score	1	0	1
Trial 7 score	1	1	1
Trial 8 score	1	1	1
Trial 9 score	0	0	1
Trial 10 score	1	1	1
Total	5	4	10
Prediction Rate	50%	40%	100%

Table 5.9 shows that the S-Obfuscation approach has again outperformed both the Rand and Dispersion methods with regard to the prediction rate. The Dispersion method was the lowest performer with a prediction rate of only 40% (only 40% of the produced locations were successfully mapped to readable addresses). The Rand come second at 50%; while the S-Obfuscation scored 100%. These results were expected given the S-Obfuscation selects a predefined well-chosen base point when generating obfuscated locations.

To this end, the Random and Dispersion techniques, implemented in this work, employ geometric methods to generate obfuscated locations. In real life, a location may be in a public place, a private location such as inside a building, which is closed during that time

of the day, somewhere in the middle of the desert, or the ocean. Geometric-based Obfuscation techniques ignore the semantics behind a geographic location. Consequently, the authors in [205] claim that an adversary with sufficient geographical knowledge may be able to infer sensitive location information from obfuscated locations generated by geometric-based techniques. The results of the experiments show that when a geometric-based Obfuscation technique is applied to a physical environment, certain obfuscated locations are more likely to be identified as obfuscated locations by an adversary. This is because they do not point to a readable address. Figure 5.26 summarises the results of this evaluation regarding the Prediction Rate.

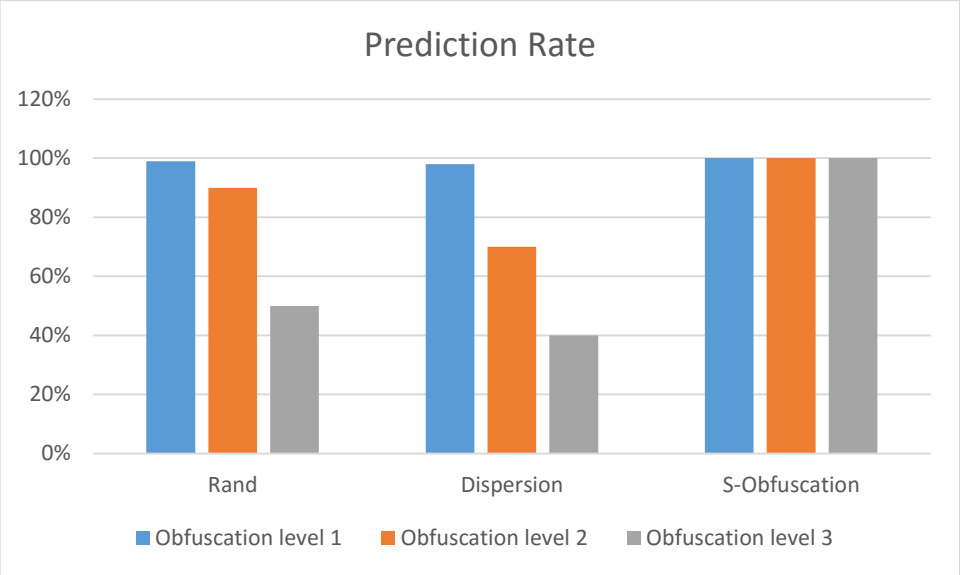


Figure 5.26- Prediction Rate results

5.2.4 Stage 4- The Design and Implementations of an IoT Application

The web application developed in Stage 3 provided the research with a method to request the location of a sensor and to display the received location on a map. This enabled the reserach to validate the operation of the PM and to verify specifically whether the received locations were successfully obfuscated or not. In this stage 4 of the experiment, as mentioned in Section 5.2, to increase the complexity of the experiment, an IoT application is designed and implemented. This application is a practical example of an application that supports interactions between various devices operating using two

different communication protocols. This IoT application is designed to support automation and things-to-things communications seamlessly while, importantly, preserving the location privacy of a BLE sensor. Particularly, in preserving the location privacy of a BLE sensor in scenarios where the location of the sensor is used to make an automated decision on whether to change the status of a smart lamp, which is accessible via Wi-Fi. Figure 5.27 depicts the architecture of the developments added in stage 4 to the experiment.

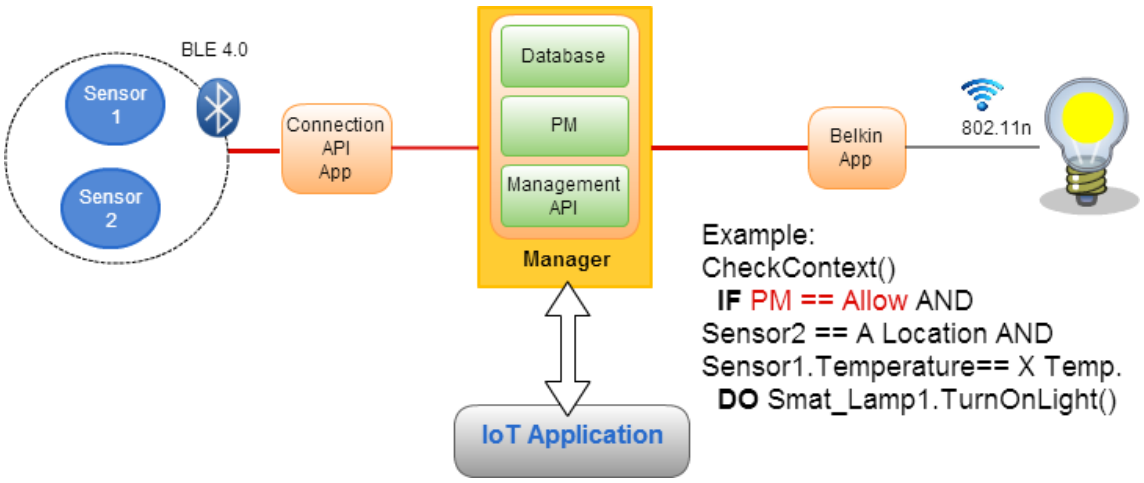


Figure 5.27- Stage 4 of the experiment

From Figure 5.27:

The sensors 1 and 2 are the BLE sensors developed by Texas Instruments. In stage 1 and 2 of this experiment, the data collected using these sensors along with their locations were transmitted and stored in the management database in the web application (the manager). The lamp showing in Figure 5.27 is a smart light developed by Belkin (commercially known as WeMo) and has Wi-Fi capabilities. Belkin has developed a mobile application that allows users to control, via Wi-Fi, their WeMo bulb. This ability is provided using an API developed by Belkin, which supports both Android and iOS devices. Therefore, the experiment reused and adapted Belkin's mobile application in order to integrate the WeMo into the IoT-MP. This has saved us much time and efforts given that building automation is not the aim of this thesis. Instead, the goal is to create a simple and practical example of an automated scenario where the location information of a BLE sensor is used

to make a decision to whether the WeMo bulb should be turned on or no. To achieve this, we modified the Belkin Android application by adding a function that can be used to receive and extract the HTTP requests sent by the management API over the Internet. These HTTP requests are sent by a specially designed PHP function hosted by the management web application server.

The scenarios illustrated in Figure 5.27 are further described as follows:

Sensor 1 and 2 are collecting temperature information and sending this information to the manager via an intermediate mobile device. The manager stores the information received in the database along with the location information of each of the sensor (using the method described in stage 1 and 2). An IoT application is implemented and hosted by the management application (the manager). This IoT application sends a request over the Internet using HTTP to the WeMo bulb. These requests are used to change the status of the WeMo bulb (on/off) based on a predefined Flag (the Flag will be explained subsequently). However, this app does not know the status of the WeMo Bulb. It only supports one-way communication, which is sending a message to the WeMo Bulb. Thus, the Bulb does not initiate communication with the web application or acknowledge any received messages. Instead, the IoT application is only capable of sending a request using the method SetDeviceSate supported by Belkin SDK implementations to WeMo. We did not go into the details of how this request is processed through Belkin API as this is not the focus of our work. We only needed to achieve the capability of changing the status of the bulb (on or off) when a Flag is changed (True or False). Readers interested in further readings on the Belkin API are referred to [206].

The Flag is a Boolean variable set by the CheckFlag() function that consists of a set of conditions, which the user can define. The parameters of the function CheckFlag() was hardcoded and manipulated manually when testing the app. A compressed pseudocode of the CheckFlag() function is provided in Table 5.10.

Table 5.10- CheckFlag() Code

CheckFlag() Function Pseudo Code

Function CheckFalg() {
 	
Flag= False;
 	
Location=CheckPM(sensor 3)
 	
if location= X *// X is for a given GPS address*
 	
and Sensor1.temp< Y *//given temperature*
 	
Then Flag=True;
 	
If (Flag)
 	
Device1.Change_Status }

Firstly, the function CheckFalg() initialises the Flag variable. The function CheckPM checks if the requester (in this example, the IoT app) has permission to access the location of sensor 3 within the requested context. This function calls the message *getLocationOutput(DeviceID, RequesterID)* and passes the argument sensor 3 as the Device ID. The function *getLocationOutput* returns an obfuscated location of the device under request as previously described in Table 5.3. This location can range from a precise location (level 0) or a location that was obfuscated using one of other four levels of the S-Obfuscation approach. Therefore, the function CheckPM (sensor 3) has a return message consisting of the location of sensor 3 as outputted by the PM. Importantly, it should be noted that sensor 3's location was disclosed based on the user's defined policy. Therefore, the actual location of the device is disclosed only if the defined user's policy permit to do so. To this end, the location of sensor 3 is received. The code then moves into comparing the received location against a condition that can be used to trigger the change in the Bulb status. Additionally, the code compares two other conditions including that of sensor 1. If these conditions are met, then the Flag is set to true. If not, the Flag remains set to false. Next, the code completes by checking the status of Flag. If it is true,

then the function *Change_status* is triggered which turns on the WeMo bulb. We repeated the experiment several time by manually altering the parameters including the GPS location used for the comparison. We also manipulated the policies defined by the PM on sensor 3. This allowed us to observe the change in the status of the bulb in different contexts.

In the first test case of this stage of the experiment, we configured the PM to skip the context analysis and to use the default policy. In the default policy, the policy governing the location of sensor 3, was set to reveal the true location (L0) of sensor 3. This is to reduce the complexity involved in the testing and to see whether the WeMo light is successfully turned on when simple configurations are used. However, the experiment did not work. After some diagnosis, we realised that it is inefficient to obtain a GPS reading that can be compared with a hard coded GPS location. To overcome this challenge, instead of comparing the two GPS coordinates, the CheckPM() code was updated to calculate the distance between the two GPS coordinates instead of comparing if they are equal. Thus, if the difference between the two compared GPS locations was found to be less than 100m, then it is assumed that the two GPS locations are matching. The code is adapted from the Haversine Formula [207]. We made some additions to the Haversine Formula to compare the calculated difference in distance between the two GPS coordinates against the number 100 (representing 100m). Fortunately, the Haversine formula has solved the issue and test 1 run successfully. The IoT application was successful in turning on the WeMo light based on the location and parameters of a BLE sensor, autonomously while preserving the location privacy of the BLE sensor.

5.2.4.1 The IoT Application: Test Case Design and Results Analysis

This section reports on the design the test cases. Each of these test cases used a different set of configurations. The dependent variables being manipulated are:

- The location and temperature of the BLE sensors;
- The user-defined policy settings ;
- The level of Obfuscation assigned to the policy.

Table 5.11 shows an exemplary of a test case designed to verify the operation of the IoT application.

Table 5.11- Test Case Design

Test Case ID: WeMo_1
Test Title: Verify WeMo is turned on with simple PM configurations
Description: Verify WeMo is turned on when sensor 3 is at 25 George St, Sydney NSW and temperature of Sensor 1 is below 25 C. Policy defined by the user is to bypass PM context analysis process and always to disclose the true location of sensor 3.
Pre-conditions: 1. Sensor 1, 3 and device 1 are running 2. User has configured a valid policy that reveals the true location of sensor 3 3. Sensor 1 temperature is set to be below 40C 4. The light of device 1 is turned off 5. Hard code the comparable variables in CheckFlag function to match those configured in the pre-condition 1 and 2
Dependencies: 1. Sensor 1 and 3, Device 1 2. PM settings 3. CheckFlag variables **Post-conditions:** 1. WeMo light is turned on

Step	Test Steps	Test Data	Expected Result	Actual Result	Status (Pass/Fail)
1	Set policy for sensor 3 to be null	P=null	WeMo light should turn on	WeMo light is on	Pass
2	Verify Sensor 3	25 George St,			

Table 5.15 - Test Case Design (Continued)

	location	Sydney NSW			
3	Create Default Policy	LocationOutput =L0			
4	Verify Sensor 1 temperature is below 40C	Check stored value in the database			
5	hardcode comparative variable 1	X= GPS address			
6	hardcode comparative variable 2	Y= 40			
7	Verify WeMo bulb is powered on and connected via Wi-Fi to the Mobile App	Manually set WeMo status to off			
8	Run the IoT app	Verify IoT app can access the database			

5.3 Summary

In this chapter, the Internet of Things Management Platform has been evaluated through experiments about its capabilities in preserving the location privacy of things in a physical setup. The experiments incorporated several stages of experimentations that involved the implementation of an IoT application and several mobile and web applications. Through the use of physical GPS location coordinates collected in real-time, the experimental studies demonstrated the capability of the IoT-MP in preserving the location privacy of BLE 4.0 sensors. They also demonstrated that it is possible for users to manage the location privacy of their devices by configuring location disclosure policies that can be attached to specific contexts. Furthermore, the experiments confirmed that it is possible to preserve the location privacy of a sensor in scenarios where the sensor is participating in a seamless and autonomous communications as part of an IoT application.

Additionally, in this chapter, two classic Obfuscation techniques (i.e. the Rand and Dispersion techniques) were implemented and their performances were compared to that of the proposed S-Obfuscation approach. Unlike the classic Obfuscation techniques that employ geometric methods to generate obfuscated locations, the S-Obfuscation relies on a geographic knowledge to produce obfuscated locations that are harder to be detected as fake or obfuscated. The results show that the performance of the S-Obfuscation approach has outperformed that of the two classic techniques under comparison. For instance, using "Obfuscation level 3", it is found that the S-Obfuscation has produced better-obscured location by 60% than that of the Dispersion technique and by 50 % than that of the Rand technique.

While the experimental studies allow for the practical evaluation of the IoT-MP on physical hardware devices in contextual and physical setups, they suffer from few limitations. These limitations mainly relate to the scalability of the experiments. The experiments validated and provided feedbacks on the performance of the IoT-MP and that of the S-Obfuscation approach when using BLE sensor devices, but on a limited scale. Thus, the experiments cannot be used to assess the performance of the IoT-MP in large-scale heterogeneous networks. To address these shortcomings, several simulations studies are conducted in Chapter 6. These simulations aim to complement the experiments by assessing the performance of the proposed IoT-MP in setups which combine various low-power wireless networks together using a large number of low-power sensor devices.

CHAPTER 6- THE SIMULATION STUDIES

This chapter reports on the simulation studies that supplement the experiments previously reported in Chapter 5. They demonstrate the capability of the IoT-MP in preserving the location privacy of things in large and heterogeneous environments similar in scale and complexity to those envisioned in the IoT. Section 6.1 provides an overview of the simulation studies. It outlines the three major parts of the simulations, which are the ZigBee, Wi-Fi, and the heterogeneous network scenarios. Section 6.2 discusses the simulation of IEEE 802.15.4 network scenarios. These scenarios included the implementation of the IoT-MP in a ZigBee WSN. Section 6.2.3 reports on the simulations of IEEE 802.11 networks. Section 6.3 discusses the development of a large-scale heterogeneous network. Section 6.3.4 reports on the simulations conducted to integrate the IEEE 802.11ah, ZigBee, and the other IEEE 802.11 scenarios, previously simulated in Section 6.2 and 6.3, in one large heterogeneous network consisting of thousands of nodes. In each of these scenarios, the approaches of the IoT-MP in managing and preserving the location privacy of things are simulated, and their performances are noted. Additionally, the network performance of each of these simulations about the end-to-end delays and power consumption at the end host devices are also reported.

6.1 Overview of the Simulations

The simulations aim to evaluate the effectiveness and scalability of the IoT-MP in protecting the location privacy of things. That is, they aim to validate the capability of the IoT-MP in a dynamic environment that encompasses heterogeneous communications among large numbers of devices engaged in seamless interactions. The simulation scenarios are divided into three major parts as follows:

- 802.15.4 based-network scenarios
- 802.11 based-network scenarios

- Heterogeneous network scenarios based on different technologies

Each of the above scenarios has several sub-scenarios or stages of simulations. The simulation's setup of the technology used in each of these scenarios and the details of some other parameters such as the number of nodes and the application setups are discussed in the next sections. Some performance related parameters relevant to the work, such as the delays and energy consumptions, are also reported.

6.2 Network Scenarios based on IEEE 802.15.4

The aim of this IEEE 802.15.4 simulation also referred to as ZigBee simulation throughout the rest of this Chapter, is to validate and test the applicability of the proposed IoT-MP in a low-power and low-rate wireless network. The simulated scenario consists of several devices that communicate over ZigBee. It is based on the scenarios provided in the ZigBee IP technical specification report [208]. Thus, the network setup of this scenario consists of several ZigBee devices acting as smart appliances, smart plugs or simply temperature sensors in an IoT Smart Home example. These devices communicate sensory data to a ZigBee router device, which in turn routes the data to a ZigBee coordinator device. The router device, as described in the ZigBee IP specification example, can be any device that has an additional function of routing the data to the network. On the other hand, the ZigBee coordinator can be a programmable communicating thermostat with advanced support for an in-home display system [208]. We simulated the scenario provided by ZigBee Alliance in their ZigBee IP documentations by porting the model into the IoT-MP [208].

As discussed in Section 3.1.2.1, ZigBee is based on the IEEE 802.15.4 standard for Low-Rate Wireless Personal Area Network (LR-WPAN). It is well-suited for IoT devices that transmit smaller packets over a network. Typically, ZigBee's transmission range is within few meters at a maximum data rate of 250Kbps. The network simulator NS2 version 2.35 was used to design, develop, and implement the simulation scenarios carried out in this research. The simulator supports a class hierarchy in C++ (compiled hierarchy), and a similar class hierarchy within the OTcl interpreter (interpreted hierarchy). The two

hierarchies are closely related to each other. From the user's perspective, there is a one-to-one correspondence between a class in the interpreted hierarchy and one in the compiled hierarchy [209]. In NS2, the advance of time depends on the timing of events that are maintained by a scheduler. An event is an object in the C++ hierarchy with a unique ID, a scheduled time, and a pointer to an object that handles the event. The scheduler keeps an ordered data structure with the events to be executed and fires them one by one by invoking the handler of the event [209]. Table 6.1 shows the ZigBee configurations parameters used to set up the simulation in NS2. Figure 6.1 describes the ZigBee stack adopted in this work.

Table 6.1 ZigBee Configurations

Channel Type	Channel/Wireless Channel
Radio-propagation model	Propagation/TwoRayGround
Physical Layer Technology	IEEE-802.15.4 PHY
MAC Layer Technology	Mac/802_15_4
Interface queue type	Queue/DropTail/PriQueue
Link layer type	LL
Antenna type	OmniAntenna
Max packet	10
Number of nodes	7
Area of Network Deployment	*100x100 meter square*
Network layer Routing protocol	AODV
Traffic type used	CBR UDP/FTP

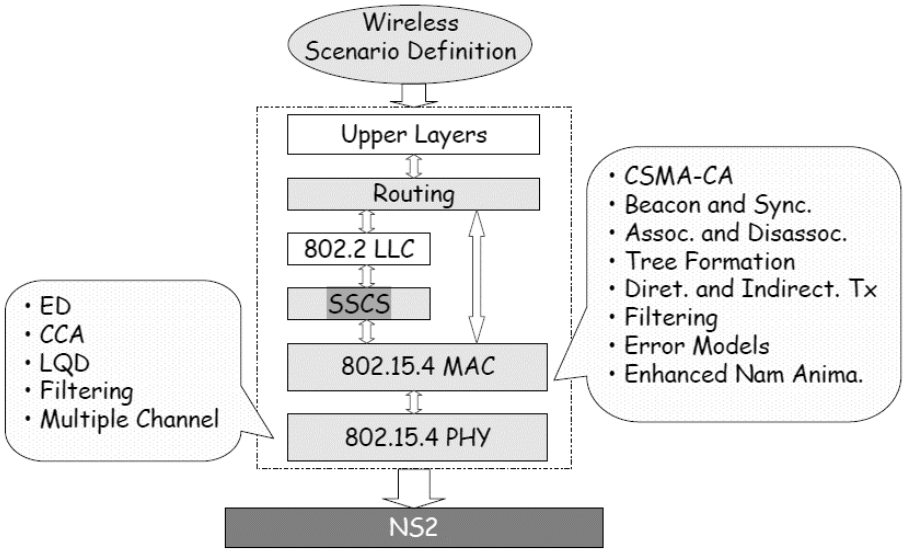


Figure 6.1- ZigBee Stack

The topology of the simulated network is given in Figure 6.2. The simulation includes the following nodes that communicate over the IEEE 802.15.4 standard:

- ***ZigBee Coordinator (Manager):***

A ZigBee coordinator has the responsibility for controlling and monitoring the other sensor nodes. A ZigBee coordinator can be configured in two different types: an ordinary coordinator that operates within the scope of a cluster, and a PAN coordinator that acts as a coordinator for the entire PAN network. In this simulation, node ID 0 is configured as a PAN coordinator. It is referred to as the manager (represented by the green circle in Figure 6.2). This manager will have additional functionalities than those provided by a general ZigBee PAN coordinator as we have implemented the PM and attached a database to it.

- ***Full Function Device (Agent)***

A ZigBee Full Function Device (FFD), representing an agent, supports all the 49 primitives defined by the IEEE 802.15.4 standard [210]. An agent acts as a routing device or intermediate node to relay and forward the sensor's data to the ZigBee coordinator. Simply, it can be described as a communication agent. Node 1 and 2 are configured as

ZigBee full functioning devices. They are referred to as an agent and represented in the blue circle in Figure 6.2.

- ***Reduced Function Devices (Things/ Sensor)***

A reduced function device (RFD) is a ZigBee device with reduced and limited functionalities. That is, an RFD only functions as an end device. RFD's capabilities are limited to collecting and transmitting sensory information. In this work, RFD devices represent IoT devices (things) in the IoT. Things have the capability of communicating only with an agent. Their functionality is extremely low. Their interactions are limited to sending sensory information to their respective agents at a regular time interval. Figure 6.3 shows that Node 3 and 4 are configured as sensors in the grey circle. An RFD is intended for very simple applications and can only communicate to FFDs (denoted as agents in this experiment). On the other hand, FFD can operate as a coordinator or as an RFD. It can communicate also with RFDs or other FFDs.

- ***Requesters (acting as management or IoT application)***

Requesters are nodes that play the role of an IoT application. A requester has the responsibility of requesting information about a sensor from the manager, including the sensor's location information. A request can be made locally within the same PAN network or via the Internet depending on the application design. The requesters are implemented in this simulation for the purpose of simulating requests to location information and, therefore, to verify the capability of the PM in preserving the location privacy of things and their users. We will see later how the requesters are used to demonstrate the location privacy feature of the IoT-MP.

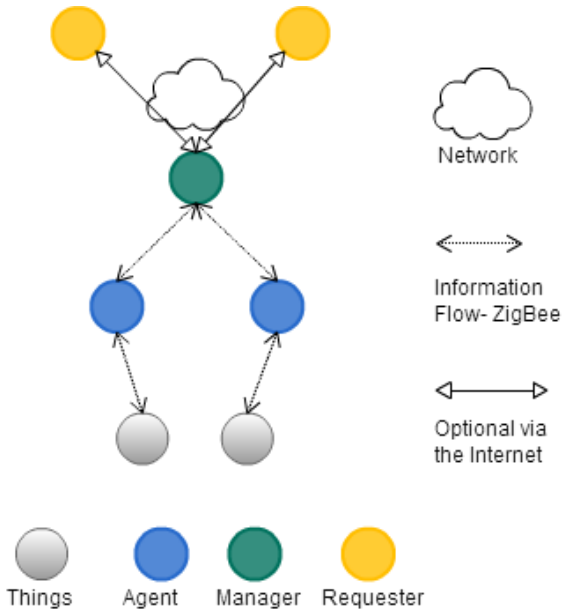


Figure 6.2- Network Topology of the ZigBee Simulation

```
$ns_ at 0.0 "$node_(0) NodeLabel Manager"
$ns_ at 0.0 "$node_(0) sscs startPANCoord 0"
$ns_ at 1.5 "$node_(1) NodeLabel Agent"
$ns_ at 1.55       "$node_(1) sscs startDevice"
$ns_ at 1.7 "$node_(2) NodeLabel Agent"
$ns_ at 1.75       "$node_(2) sscs startDevice"
$ns_ at 1.9 "$node_(3) NodeLabel Sensor"                ;
$ns_ at 1.95       "$node_(3) sscs startDevice 0"
$ns_ at 1.9 "$node_(4) NodeLabel Sensor"
$ns_ at 1.95       "$node_(4) sscs startDevice 0"
```

Figure 6.3- ZigBee nodes definitions from NS2 Tcl file

6.2.1 Network Design and Simulations using NS2

The Network Simulation tool NS2 implements a generic ZigBee stack (module). It provides basic configuration files that can be used as a base template to create ZigBee simulations. Therefore, this work adapted this generic ZigBee module for the implementation of the IoT-MP architecture. Mainly, the following modules have been modified:

- In the AODV module the following packages: Aodv.cc, aodv.h, aodv_packet.h, aodv_rtable.cc and aodv_rtable.h
- packet.h from the Ns2.35 common module

Briefly, these implementations are mainly concerned with the creation of packets at the sensors, transmission of packets from the sensors to agents, and from agents to managers. They also support the receipt of packets on the manager side. This involves extracting the data from a packet and storing them in the manager's database. The packet's structure of the communication is defined by the IEEE 802.15.4 coordinator. The network operates in beacon mode as shown in Figure 6.4. In this mode, the coordinator (manager) sends out periodic beacons throughout the network. This is to enable all nodes to sleep between beacons and to wake up when the beacon timer expires. This is obviously to reduce the energy consumption of RFDs.

```
name_[PT_DCCP_ACK]="DCCP_Ack";
name_[PT_DCCP_DATA]="DCCP_Data";
name_[PT_DCCP_DATAACK]="DCCP_DataAck";
name_[PT_DCCP_CLOSE]="DCCP_Close";
name_[PT_DCCP_CLOSEREQ]="DCCP_CloseReq";
name_[PT_DCCP_RESET]="DCCP_Reset";

name_[PT_NTYPE]= "undefined";
//sensor data
name_[PT_SENSOR]= "sensor";
```

Figure 6.4- Beacon using direct transmission definition

In the file "packet.h", a new data type packet is defined. This packet is used by the sensor to create a beacon. There is no predefined method in which two nodes in a ZigBee network can communicate. However, the suitable methods of transmission can be achieved using mutual synchronization techniques, or direct transmission using un-slotted CSMA-CA. The simulations used the direct transmission method as it is less complex to implement.

Creation of Timers

The FloodTimer, shown in Figure 6.5, implements a timer for the simulation. Using this FloodTimer, a sensor and agent nodes can periodically send updates to the nearby higher authority (sensors to agents, and agents to the manager). Also, it is used by the requesters to send periodic requests to the manager. The sensors and requesters are configured with different time interval when calling this function. This is to ensure that there are data already communicated by the sensors to the manager before requesting access to them. Consequently, after defining the packet (beacon), we next defined the "transmission" and "receiver" functions. The transmission function is used by a node to send packets across the network. The receiver function is used by the node to receive the packets. As already mentioned, transmissions are periodic using the *FloodTimer* function.

```
class FloodTimer : public Handler {
public:
FloodTimer(AODV* a): agent(a){}
void      handle(Event*);
private:
AODV      *agent;
Event      intr;
};
```

Figure 6.5- FloodTimer

Definition of the Transmission Function (WSN TX)

The function *AODVFloodRREQ*, shown in Code Snippet 2, is used to initiate transmission of information. The *FloodTimer* function, described earlier, calls this function internally to transmit data over the network. This function takes *nsaddr_t dst* as an argument that includes the destination node ID. It is used by a requester in the network for placing periodic requests for data to the manager.

Code Snippet 2- Transmission function Void AODV::FloodRREQ(nsaddr_t dst)

Definition of the Receiver Function (WSN Receive)

The *AODVrecv* function, shown in Code Snippet 3, enables a node to receive and process a packet. A packet must first be sent using the *AODVFloodRREQ* and *FloodTimer* functions described earlier. Packets are routed across the network using the destination ID. Packets are also differentiated using their packet's type.

Code Snippet 3- Receive function Void AODV::recv(Packet *p, Handler*)

For instance, the Code Snippet 4 shows how a node processes a packet. It first examines the destination ID, if it matches the node ID then it checks the type of the packet. Once the manager receives a packet from its intermediate agents, it extracts the data and stores them in the management database.

```
 //If the packet is a sensor type and not from the self
if((ch->ptype() == PT_SENSOR)&&
   (ih->saddr()!= index))
```

Code Snippet 4- Packet Type

Defining the Database

The database is used by the manager to store the information it receives from the agent nodes. For simplicity and to avoid the complexity associated with integrating SQL databases with NS2, an array is used instead as shown in Code Snippet 5. It shows the stored entities. This array is implemented in the manager module in C++.

```
struct SensorAgent_Database
 {
 public:
  int received_sesnsorID;
  int sensor_Temp;
  int received_AgentID;
  char AgentNsensor_Loc[20];
  double Agent_Timestamp;
};
struct SensorAgent_Database samdb[10];
```

Code Snippet 5- Packet Type

6.2.1.1 The Design of the Network Scenarios

As mentioned before, the network setup of this scenario consists of ZigBee end devices that send sensory data, routed by ZigBee routers, to the ZigBee coordinator as described in [208]. Consequently, the manager and agent functionalities, as presented in the proposed IoT-MP architecture, have been implemented on the coordinator and router nodes respectively. The ZigBee end devices are implemented as Managed Things (MTs). Therefore, using the IoT-MP platform, the ZigBee devices (MTs) periodically send data updates via their respective agents to the manager, which stores the received information in the manager's database. This distributed architecture allows a user to monitor and control the operation of things remotely over the Internet or within the same PAN network. It provides users with management capabilities of the ZigBee network. Figure 6.6 shows the simulation while running. From Figure 6.6, node 3 and 4 represent the sensors. Node 1 and 2 are agents while node 0 is the manager. The manager has a database as well. Node 5 and 6 are management applications in the form of requesters. They request information from node 3 and 4 including their statuses.

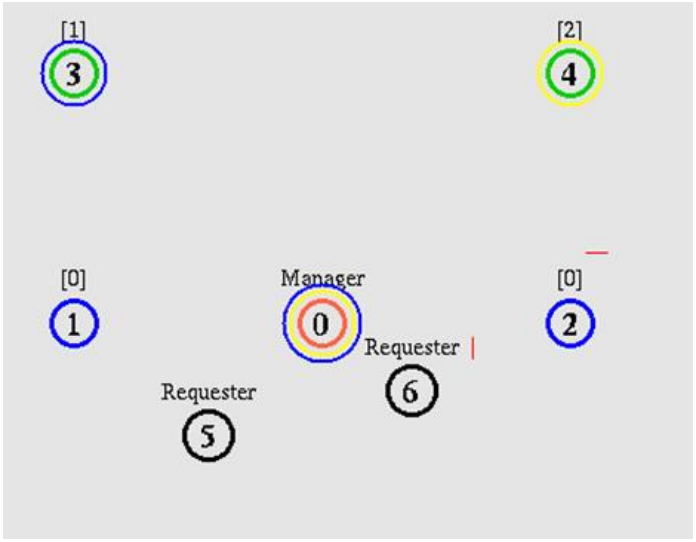


Figure 6.6- Sensor Node 4 is sending status update to Manager via Agent Node 2 (Traffic in Red Line)

Communications in the network are described as follows: Nodes 3 and 4 periodically transmit specific data, which are the SensorID, temperature, and location using ZigBee

respectively to nodes 1 and 2 within their hearing range. Next, the agent nodes process the received messages by adding their own data, specifically the Agent ID, a Timestamp and location in the form of X and Y coordinates. It then forwards the message to node 0 (the manager) also over ZigBee. The manager processes the message and stores the information extracted in its local database. At a given time, nodes 5 and 6 (requesters) request node 3's and 4's locations and statuses updates from the manager. The manager can respond by retrieving, from the database, the last received updates from the sensors (node 3 or 4). Alternatively, a real-time status update can be requested by a sensor as shown in Figure 6.7. Alerts can also be configured to be triggered based on particular events, e.g., an alert can be created once the temperature of node 3 (the sensor) drops below a certain threshold.

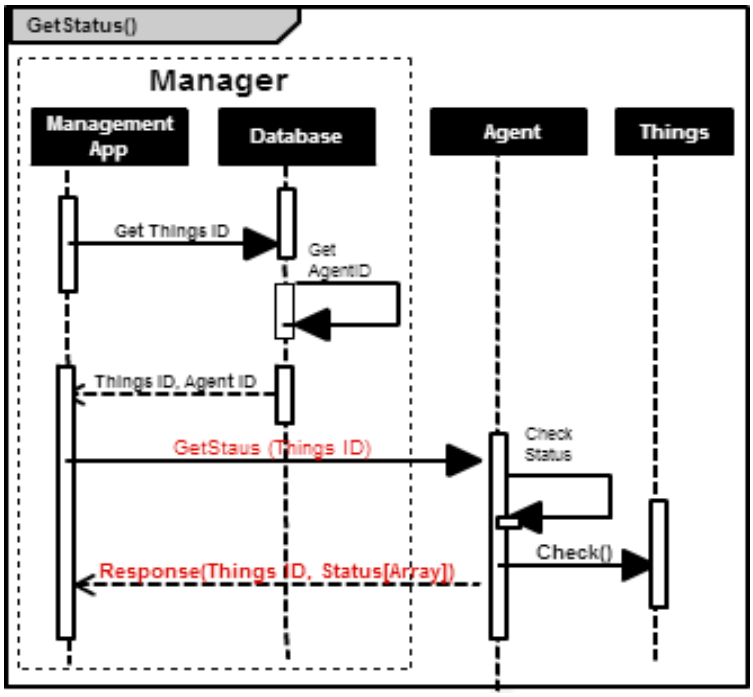


Figure 6.7- A real-time status request of Node 3 initiated by Node 6 sequence diagram

6.2.1.2 Updating the Database

Code Snippet 6 shows the database update process. The function first checks if the agent and sensor are already registered in the database. If they are registered, then their latest parameters will be updated. If not, then a new entry will be created for them in the array.

```
if(samdb[i].received_AgentID==ch->Agent_ID)
 {

printf("EXISTING Agent \n");
samdb[i].sensor_Temp=ch->sensed_Temp;
samdb[i].Agent_Timestamp=ch->AgentTst;
memcpy(samdb[i].AgentNsensor_Loc,ch->Agent_Loc,20);
samdb[i].received_sesnsorID=ch->sensor_ID;
printf("MNANGER received Agent ID %d \n ",samdb[i].received_AgentID);
printf("MANAGER received Sensor ID %d \n ",samdb[i].received_sesnsorID);
printf("MANAGER received Sensor temp %d \n ",samdb[i].sensor_Temp);
printf("MANAGER received SensorAgent Location %s \n ",samdb[i].AgentNsensor_Loc);
printf("MANAGER received Agent TimeStamp %f \n ",samdb[i].Agent_Timestamp);
return;
 }
```

Code Snippet 6- Updating the database

The function SendRequester, shown in Code Snippet 7, is the response message sent by the manager to the requesters. The requester can request an update from the manager using the *FloodTimer* message. Additionally, this response message is associated with another function that implements the Privacy Module (PM). The PM has the responsibility for checking if the requester has enough privilege to access the requested information. Location information is also subject to an Obfuscation process using the S-Obfuscation approach as per the user's defined policy as earlier described in Chapter 4.

```
void SendRequester(nsaddr_t rqsterID,nsaddr_t sensorID);
```

Code Snippet 7- Response message

Implementing and Simulating the PM

Code Snippet 8 shows parts of a policy defined by the user for two requesters identified by ID 6 and 7 respectively. For instance, in this policy example, the requester with the ID 6 has access to the temperature data of sensors 3 only. However, the requester with the ID 7 can access the sensor's temperature, as well as the sensor's location. In this policy, requester 6 has no access to location information.

```
//Manager sending data to requester
if(rqsterID==6)
{
 printf("Manager sending data to requester \n ");
      for  (i=0;i<10;i++)
      {
           if(samdb[i].received_sesnsorID==sensorID)
           {
                ch->sensed_Temp=samdb[i].sensor_Temp;
                goto LABEL1;
           }
      }
)
if(rqsterID==7)
{
     for  (i=0;i<10;i++)
      {
           if(samdb[i].received_sesnsorID==sensorID)
           {
                ch->sensed_Temp=samdb[i].sensor_Temp;
                ch->Agent_ID=samdb[i].received_AgentID;
                memcpy(ch->Agent_Loc,samdb[i].AgentNsensor_Loc,20);
                goto LABEL1;
           }
      }
)
```

Code Snippet 8- PM implementation code extract

6.2.1.3 Running the Simulation

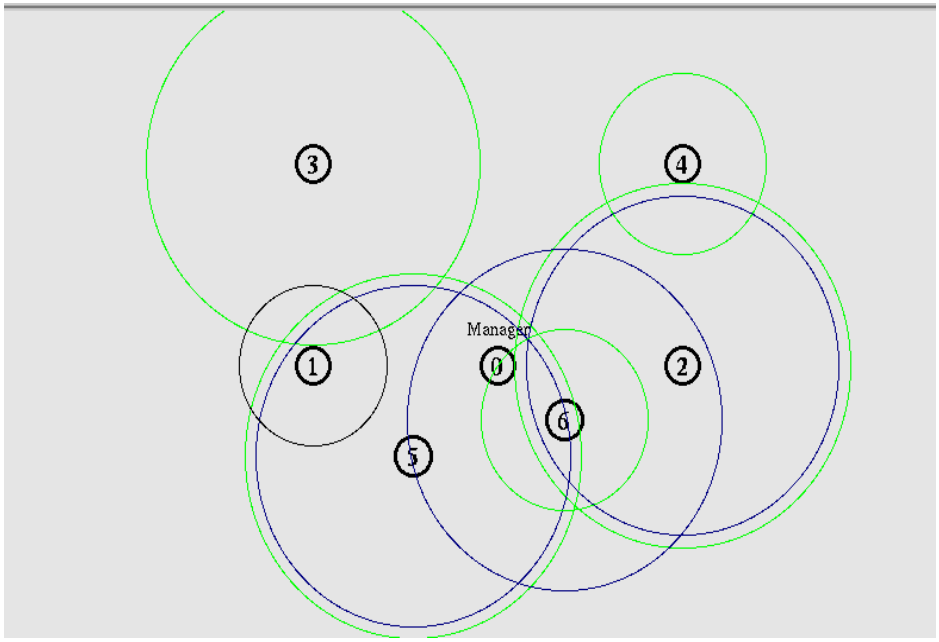


Figure 6.8- Nodes are exchanging messages

From Figure 6.8, this setup represents the initial network scenario where all three types of nodes are initiated and respectively configured to join the network. The manager joins

the network first, followed by the agents at 1.5 sec and then sensors at 1.9 sec. The blue, green and black circles are illustrations of the hello messages exchanged among the nodes. These hello messages are used for node discovery. They are also used to maintain the network connectivity and build the routing table necessary for data transmission.

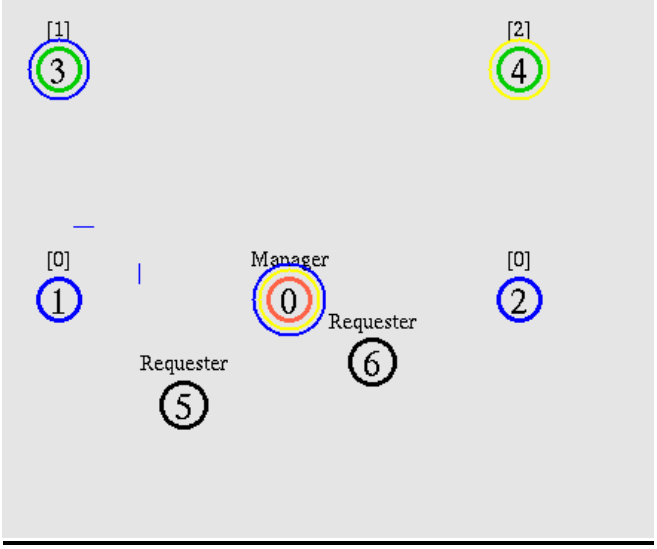


Figure 6.9- Sensor Node 3 is sending status to Manager via agent Node 1 (Traffic in blue line)

Figure 6.9 shows the data being transferred from the sensor nodes to the manager via agents. The agents in this setup are acting as intermediate relay nodes. The sensor node 3 and 4 are updating their status periodically to the agent. This periodicity is configurable, and it is set to 5 sec for the current simulation. Likewise, the agents are also forwarding their sensors' data after adding their own information (i.e. agentID, timestamp, and location) to the manager as soon as they receive updates from the sensors.

At *t'* time, the nodes 5 and 6 (requesters) request node 3's and 4's location from the manager. According to their conditional access right, each requester node will receive specific location information based on the user's defined policy. This policy is configured in the PM hosted at the manager side. However, in contrast to the experiment, in this simulation the location information of the sensors is hard coded. Thus, for each sensor, a hard coded value for a location is configured for each obfuscated level.

6.2.1.4 Analysing the Simulation Traffics by Examining the Log file

We examined the log file generated by the simulation to view the traffics exchanged among the nodes. The log file can be used as well to observe the response message generated by the sensors. This allows the verification of the location output received by checking if the location was disclosed in the response message generated by the sensors.

```
packet received from sensors in node 1
 senseor temperature 23
 AGENT received Sensor ID 3
 AGENT received Sensor temp 23
 packet received from sensors in node 2
 senseor temperature 29
 AGENT received Sensor ID 4
 AGENT received Sensor temp 29
```

Figure 6.10- Traffic from sensors to agents

```
MNANGER received Agent ID 1
 MANAGER received Sensor ID 3
 MANAGER received Sensor temp 23
 MANAGER received SensorAgent Location BRISBANE
 MANAGER received Agent TimeStamp 10.000000
```

(a) Traffic from agent 1 to the manager

```
MNANGER received Agent ID 2
 MANAGER received Sensor ID 4
 MANAGER received Sensor temp 29
 MANAGER received SensorAgent Location QUEENSLAND
 MANAGER received Agent TimeStamp 10.000000
  simulation running.....
```

(b) Agent2 traffic to the manager

```
Packet from REQUESTER
Manager sending data to requester1

Packet from REQUESTER
Manager sending data to requester2
```

(c) Requester 2 is requesting Sensor 3 status from Manager

```
 Requester1 received Sensor ID: 3
Requester1 received Sensor temp 23
```

(d) Requester1 is receiving sensor Information from Manager

```
Requester2 received Sensor ID: 3
Requester2 received Sensor temp 23
Requester2 received SensorAgent ID 1
Requester2 received SensorAgent Location BRISBANE
```

(e) Requester2 is receiving sensor3' temp and location from Manager

Figure 6.11- Log file output

The results validated the approaches of the IoT-MP in preserving the location privacy of the sensors in a large scale heterogeneous network. Figure 6.11(a) and (b) show that the manager has successfully received data from sensors 3 and 4 that were routed via their respective agents (Agent ID 1 and 2). Figure 6.11(c) shows that requesters 1 and 2 (ID 6 and 7 respectively) are requesting, from manager1, access to the sensor 3 and 4 data. Figure 6.11(d) and (e) show that only requester 2 is receiving location information update on sensor 3. This is because the policy is configured to deny requester ID6 the right to access the sensors location. Several other tests were also conducted. Each time a different

policy was configured with different access right. In each test case, the traffics stored in the log file were examined. The results confirmed the successful deployment and operations of the IoT-MP including that of its privacy module.

6.2.2 Simulation Results and Performance Analysis

This section reports on the performance results collected from the 802.15.4 simulation. Figure 6.12 shows the overall network throughput experienced by the MAC layer of all the nodes is around 80Kbps, which is considered to be acceptable in typical ZigBee simulations. The overall ZigBee application end-to-end delay is measured at 7ms in this simulation as shown in Figure 6.13. Figure 6.14 reports the Media Access Delay. It indicates the total of queuing and contention delays of the data frames transmitted by all the 802.15.4 MAC. For each frame, this delay is calculated as the duration of the time when the frame is inserted into the transmission queue, which is the arrival time for higher layer data packets and creation time for all other frames types, until the time when the frame is sent to the physical layer for the first time. The results also confirm that the experienced MAC delays are insignificant.

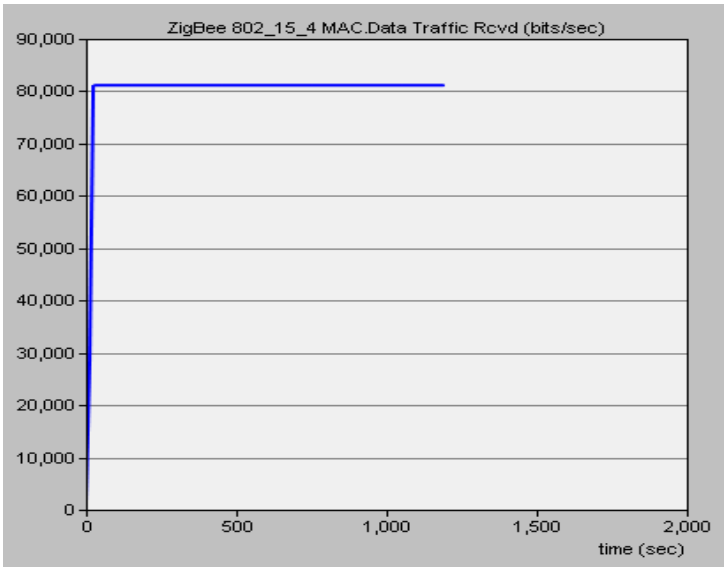


Figure 6.12- MAC layer throughput

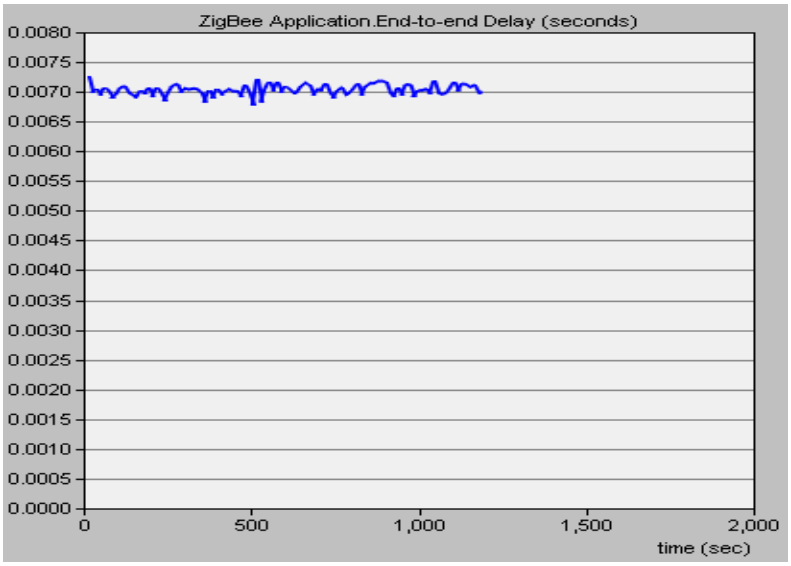


Figure 6.13- Application End to End Delay

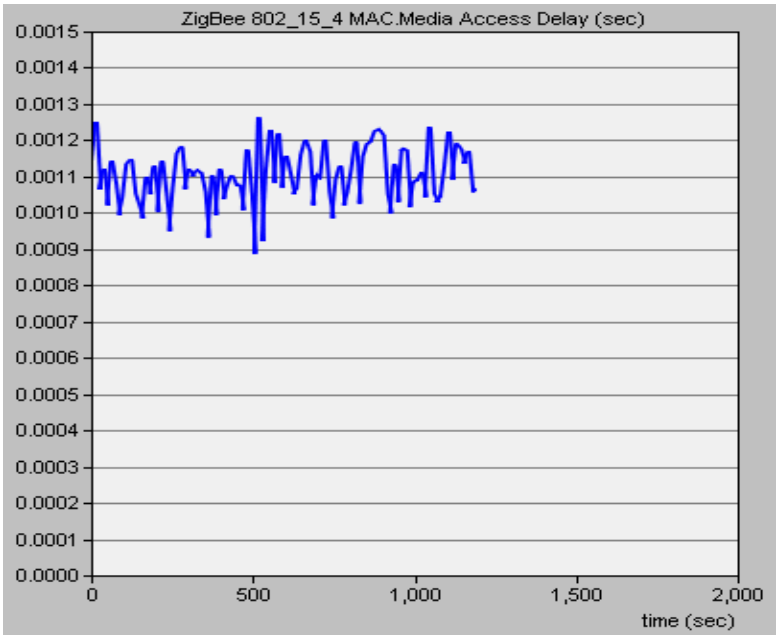


Figure 6.14- Media Access Delay

6.2.3 Network Scenarios based on IEEE 802.11

The previous simulated ZigBee scenarios consisting of a manager, agents, and sensors were also simulated using IEEE 802.11 technology. The performance is measured with

regard to the throughput, total traffic received, and network delays as well. Table 6.2 shows the simulation parameters.

Table 6.2- 802.11 parameters

***802.11b* Parameters**	**Respective value**
Radio propagation model	*Two Ray Ground*
Transmission Power	*1.3962527e-2*
Frequency of Operation	*2.4 Ghz*
Preamble Length	*144 bits*
SIFS	*10 us*
Physical Layer Technology	*IEEE-802.11 Wireless Phy*
PLCP Header Length	*48 bits*
Slot Time	*20 us*
Receiver Sensitivity Threshold	*1.309573e-10*
MAC Layer Technology	*IEEE-802.11 MAC*
Network Layer Routing Protocol	*AODV*
Number of Nodes	*7*
Area of Network Deployment	*500x500 meter square*
Antenna Type	*Omni Directional*
Data Rate	*1 -11 Mbps*
Interface Queue type	*Drop Tail /Priority Queue*
Traffic Type used	*Cbr / poisson /ftp*

The transmission path between the simulated nodes (sensors, agents, and manager) can vary from simple line of sight to dense area with obstacles. A deployment area which includes obstacles presents more challenges to the network such as signal fading and reflection. Therefore, to avoid the multipath effect that can be caused by ground reflections of the radio wave, the two Ray ground model was used in this simulation. This

is because the work does not aim to optimise transmissions within the network. It simply seeks to simulate a network where location information is exchanged and requested. This is to test the location privacy preserving capability of our proposed approach. Therefore, we repeated the same scenario conducted in the ZigBee simulation in this 802.11 simulation. The log file shows that it is also possible to manage the location privacy of 802.11 nodes in an 802.11 network. Figure 6.15 shows that only requester 2 has received location information of sensor 3.

```
 Requester1 received Sensor ID: 3
Requester1 received Sensor temp 23
```

```
Requester2 received Sensor ID: 3
Requester2 received Sensor temp 23
Requester2 received SensorAgent ID 1
Requester2 received SensorAgent Location BRISBANE
```

Figure 6.15- From the log file: Only Requester2 received location information

Evaluating the Simulations Results of ZigBee and 802.11

Figure 6.16 provides energy consumption statistics for both ZigBee and 802.11 network devices. Due to ZigBee low-energy characteristics, ZigBee devices are drawing only up to 100 mW of power. This shows the efficiency of the IoT-MP with regard to power consumption. On the other hand, WLAN device is consuming much higher power of about 700-800 mW.

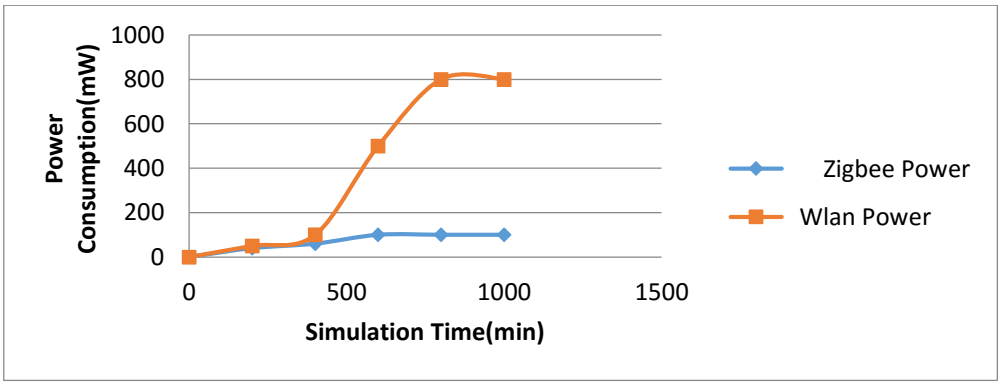


Figure 6.16- Comparison of Power consumed

Figure 6.17 compares the delays achieved post-simulation between the two protocols under comparison. The 802.11 network experienced delays of less than 1ms compared to that of 7ms in the ZigBee network.

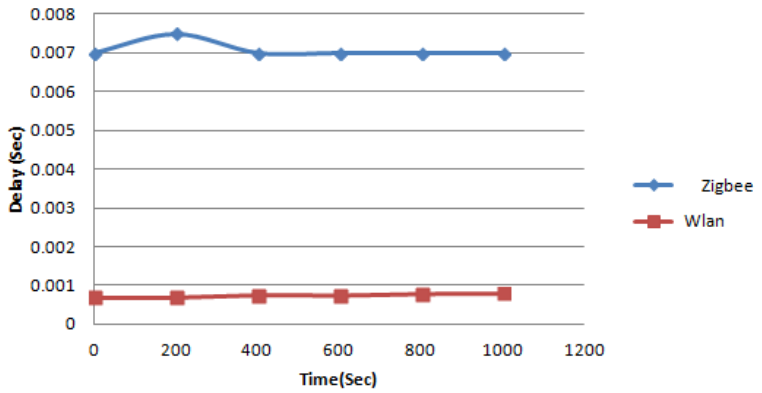


Figure 6.17- End to End delay comparison

The overall network throughput achieved for both protocols is shown in Figure 6.18. It shows that there are not many variations in throughput. This is because the overall amount of data transmitted over the network is small. This also validates that the IoT-MP did not add much of overhead to the sensor network. Both simulations provided a throughput of 80 Kbps initially, but later WLAN throughput slightly came down to 70 Kbps.

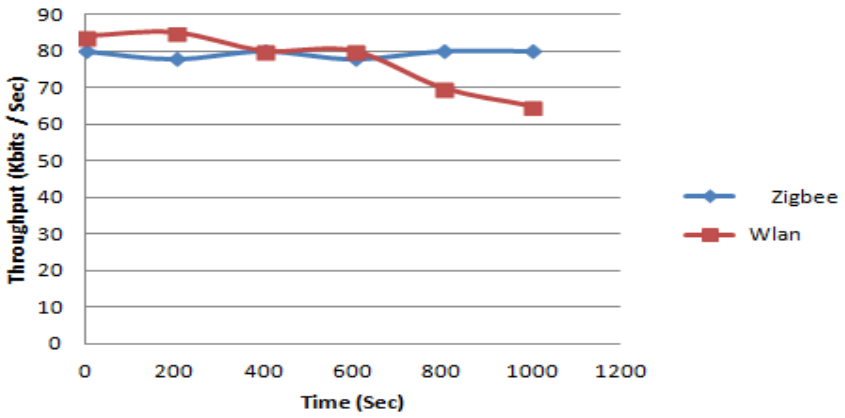


Figure 6.18- Throughput Comparison

These results show that the IoT-MP message scheme added little to no overheads to the sensor network. They also validate the power efficiency of the proposed approach.

6.3 The Heterogeneous Network

The heterogeneous network simulation involves 802.15.4, 802.11n, and 802.11ah technologies. The simulation is designed in the context of a WSN. This simulation encompasses scenarios which expand on the size, scale, and complexity of the two ZigBee and 802.11 scenarios previously reported. The core architecture of these scenarios is based on the IoT-MP. The aim of these extended network scenarios is to test the capability of the IoT-MP in preserving location privacy in different network setups that utilise a large number of devices. In other words, it aims to verify the scalability and flexibility of the proposed IoT-MP. The development of the heterogeneous network scenario is the results of several other sub-scenarios that were designed and simulated. The work gradually expanded the size of the ZigBee scenario, reported in section 6.2.1.1, from few nodes to few thousands of nodes. It also progressively increased the complexity of the overall simulation. Thus, to arrive at the final heterogeneous network simulation, several scenarios were designed as follows:

1. Increased the size of the ZigBee simulation from few nodes to few hundred.
2. Increased the size and complexity of the ZigBee simulation by creating two clusters of ZigBee networks and connecting them together.
3. Further increased the scale of the ZigBee scenarios.
4. Implemented sensors' mobility between different ZigBee clusters.
5. Introduced 802.11ah scenarios to the simulation.

6.3.1 Network Design and Simulation using Opnet

The design of the heterogeneous network was conducted using the Opnet simulation tool. This is because, with the increase in the complexity of the simulation, Opnet supports an intuitive GUI, which facilitated the deployment of a large number of devices. Also, NS2 did not offers efficient and bugs free implementation for 802.15.4 application and network layers (only PHY and MAC layers). For the design of the 802.11 based scenarios, we used the model provided by Opnet as it was well established. For the ZigBee network design, we used the open source "Open-ZigBee toolset". On one hand, this is because the

code of the application layer of that of ZigBee, provided by Opnet, is hidden. On the contrary, Open-ZigBee is a very well established open source model. It provides many implementations and model skeletons. It also provides a well-matured energy consumption monitoring model. Open-ZigBee has been used in some Ph.D. theses such as in [211] and in many other research papers such as in [212]. Consequently, the first step in this network design is to setup the basic nodes of the ZigBee network. The simulated scenarios use the same nodes previously implemented in NS2, but this time in Opnet. The initial setup is provided in Figure 6.19.

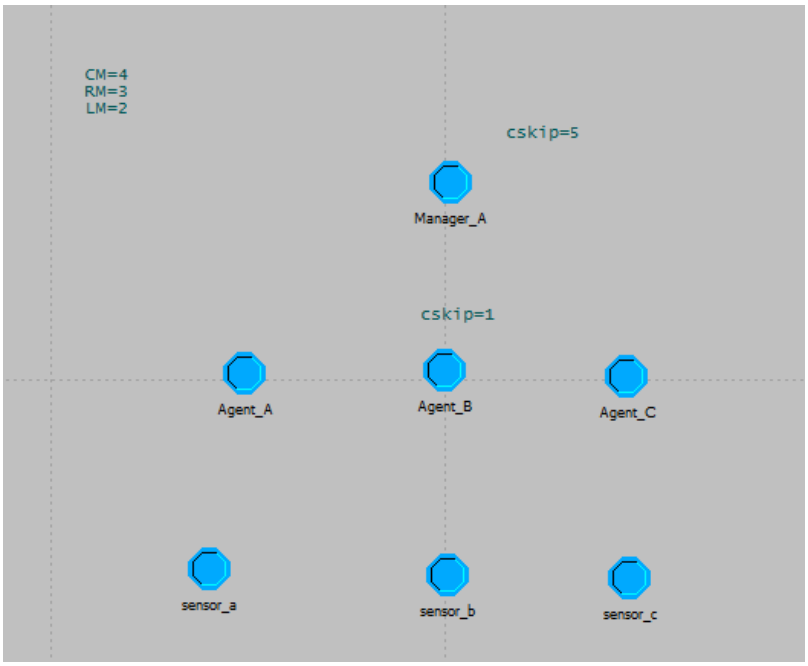


Figure 6.19- ZigBee using Opnet

The ZigBee nodes were deployed using structural tree routing scheme. This scheme provides a very efficient method to implement the architecture of the IoT-MP. In this tree routing scheme, the manager is defined as the parent for agents and agents are defined as parents for sensors. For instance, from Figure 6.19, Agent_A is the parent of sensor_a. Agent_B is the parent of sensor_b and Manager_A is defined as the parent for all agents. This parent addressing scheme is defined using the Mac address of the ZigBee node and network parameters as shown in Figure 6.20.

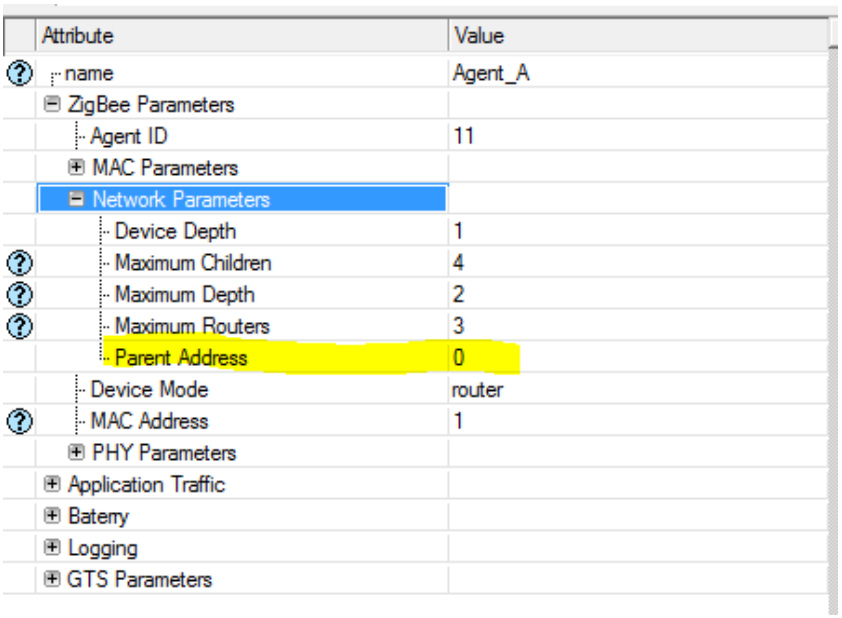


Figure 6.20- Parent address configuration

Next, to implement the IoT-MP message scheme, further implementations of the application layer were needed. This is to add the required functionalities such as adding a Unique ID to the sensor nodes and adding agentIDs to the agent nodes communication. The traffic configured for this simulation is the best effort traffic. Hence, we needed to modify the packet and traffic to insert the data into the communication exchanged between the nodes. The code relevant to the creation of the new packet is provided in Figure 6.21. Also, Figure 6.22 shows the new packet format.

```
op_pk_nfd_set (packet_MSDU_ptr,  "Sequence Number" , sequence_number);

/* Generate a NSDU size outcome */
nsdu_size = (int) ceil (oms_dist_outcome (rt_packet_size_dist_ptr));

/* Size of the NWk header */
header_size = (int) op_pk_total_size_get(packet_MSDU_ptr);


/* 0 <= nsdu_size <= (aMaxMACSafePayloadSize_Octet*8-header_size) */
if (nsdu_size > (aMaxMACSafePayloadSize_Octet*8-header_size))
    nsdu_size = (aMaxMACSafePayloadSize_Octet*8-header_size);   /* The size of generate

if (nsdu_size < 0)
    nsdu_size = 0;

/* unformatted payload  */
packet_NSDU_ptr = op_pk_create (nsdu_size);

op_pk_nfd_set_pkt (packet_MSDU_ptr, "NSDU", packet_NSDU_ptr);

/* send the MSDU via the stream to the network layer    */
```

Figure 6.21- Creating a new packet

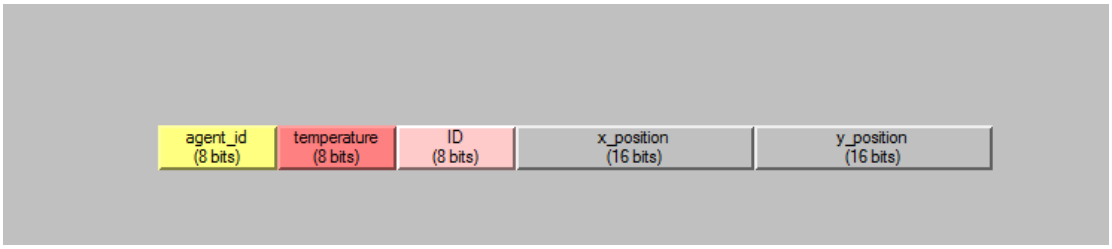


Figure 6.22- Packet format

These packets are updated using the best effort function. The code shown in Figure 6.23 generates a formatted payload, which is then inserted into the Mac frame and sent across the network. Only the agent_id is not set at this stage as it will be set by the agent at the network layer. Next, the packet will be received by the network layer of the agent. The agent checks the destination address to see if this packet is destined for itself or no. Since the packet is destined to the manager, the agent updates the agent_id and forwards it to the manager. The manager then receives the packet at the application layer. The application layer extracts the values from the packets. Then, it sends the pointer to the payload packet to the *set_database* function, which inserts the values in the database (an array is used in this scenario as well). Figure 6.23 shows a sample extract of the code relevant to this process.

The implementations of the PM are similar to those reported in the Section 6.3.1. However instead of creating requesters nodes, we used the actual ZigBee sensors to request temperature and location information from other ZigBee sensors.

```
            op_ici_install (OPC_NIL);
        } else {
            /* I am not destination - route packet */
            next_hop_address = wpan_next_hop_get (dest_nwk_address);
            /*****************************************************************************************************

            op_pk_nfd_get_pkt (packet_MSDU_ptr, "NSDU", &packet_NSDU_ptr);

            op_pk_nfd_set (packet_NSDU_ptr, "agent_id", agent_id);



            /*****************************************************************************************************
            /* Update ICI */
            op_ici_attr_set (iciptr, "Next Hop Address", next_hop_address);

            op_pk_nfd_set_pkt (packet_MSDU_ptr, "NSDU", packet_NSDU_ptr);
```

```
    nsdu_size = 0;

/* Formatted payload    */

packet_NSDU_ptr = op_pk_create_fmt ("payload");
op_pk_nfd_set (packet_NSDU_ptr, "temperature", temp);
op_pk_nfd_set (packet_NSDU_ptr, "ID", ID);
op_pk_nfd_set (packet_NSDU_ptr, "x_position", x_coord);
op_pk_nfd_set (packet_NSDU_ptr, "y_position", y_coord);

op_pk_nfd_set_pkt (packet_MSDU_ptr, "NSDU", packet_NSDU_ptr);


/*****************************************************************************************************************/
```

Figure 6.23- Packet creation code

6.3.2 Scalable ZigBee Simulation

This section describes the work carried out to increase the magnitude of the simulation works and their complexity. This was achieved in several stages where the simulated scenarios were gradually expanded. In each stage of the simulation, we evaluated the capability of the IoT-MP in preserving the location privacy of the sensors. The evaluation process is similar to those described in section 6.2.2. This section also reports on the performance of these simulations. In the first stage of this simulation, we expanded the ZigBee scenario from few nodes to 500 ZigBee nodes. All the ZigBee nodes are operating as part of a one ZigBee cluster (under the authority of one manager) as shown in Figure 6.24. We then run the simulation and conducted few test cases where a sensor requested the location of another sensor within the same ZigBee cluster. The simulation demonstrated the capability of the IoT-MP in preserving the location privacy of things in a ZigBee network that included a larger number of nodes.

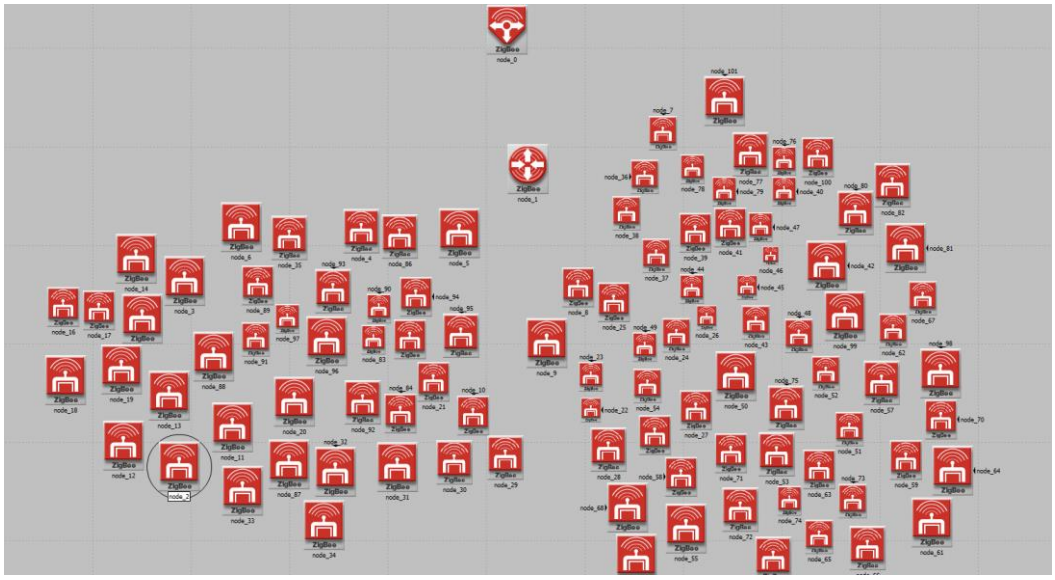


Figure 6.24- Increasing the size of the ZigBee simulation within one cluster

In the next stage of this simulation, the scenario depicted in Figure 6.24 were further expanded to encompass three clusters of ZigBee networks. The new modified scenario is shown in

Figure 6.25. In this new scenario, each cluster has its ZigBee coordinator (manager). The managers of each of these clusters were connected through the manager of managers (MoM) (previously described in Section 4.3.2). The MoM is a ZigBee coordinator node configured as a parent node for the managers of each of these clusters. Therefore, by the IoT-MP architecture described in Section 4.2, the manager of each group manages the nodes in their cluster and acts as an agent to the MoM. Consequently, the MoM has also its database. It keeps tracks of the nodes structure and hierarchy within the tree structure. The MoM oversees the whole network and can communicate with the ZigBee sensors through their managers. This architecture of managers to MoM allows other ZigBee clusters to join and participate in the network using a designated manager. Significantly, this demonstrates the capability of the IoT-MP in connecting ZigBee networks together and in providing users with a method to manage the location privacy of their ZigBee devices. In this simulation, the communications between the managers and MoM are implemented in a fashion where the managers send periodic updates to the MoM. The connections are made at the application layer via a designated function.

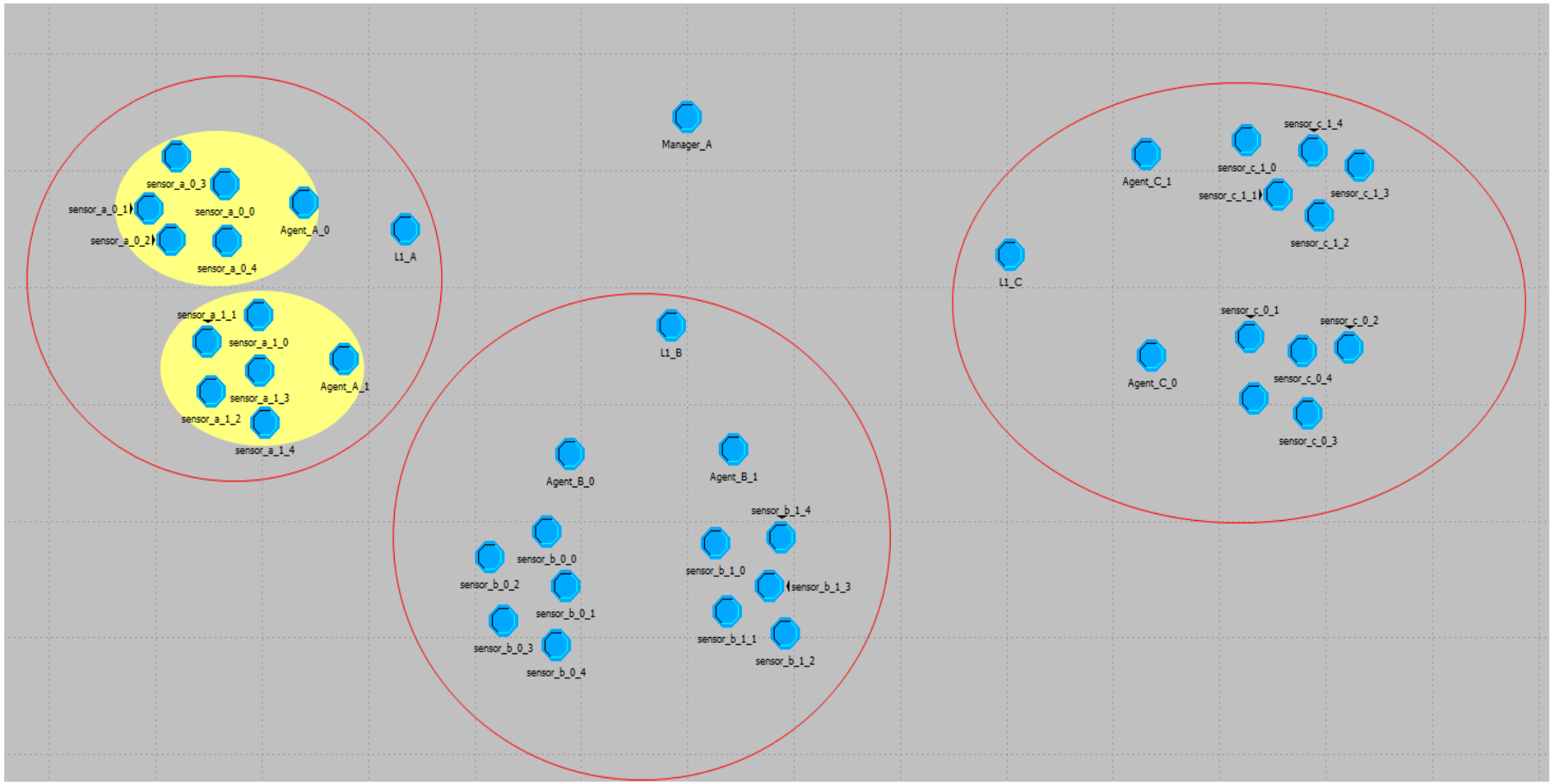


Figure 6.25- Three Clusters of ZigBee network

Ultimately, this structure provides IoT applications with a method to access the data of things operating on separate ZigBee networks. In physical networks and setups, the MoM can be implemented as software that is capable of communicating with the ZigBee coordinators. As discussed in Section 3.1.2, ZigBee IP coordinators act as a gateway that integrates ZigBee networks and IP-based networks. Therefore, the MoM can simply implement an API that connects to the Internet to several other ZigBee gateways. Figure 6.26 shows the application end-to-end delays and application traffic received relevant to this network.

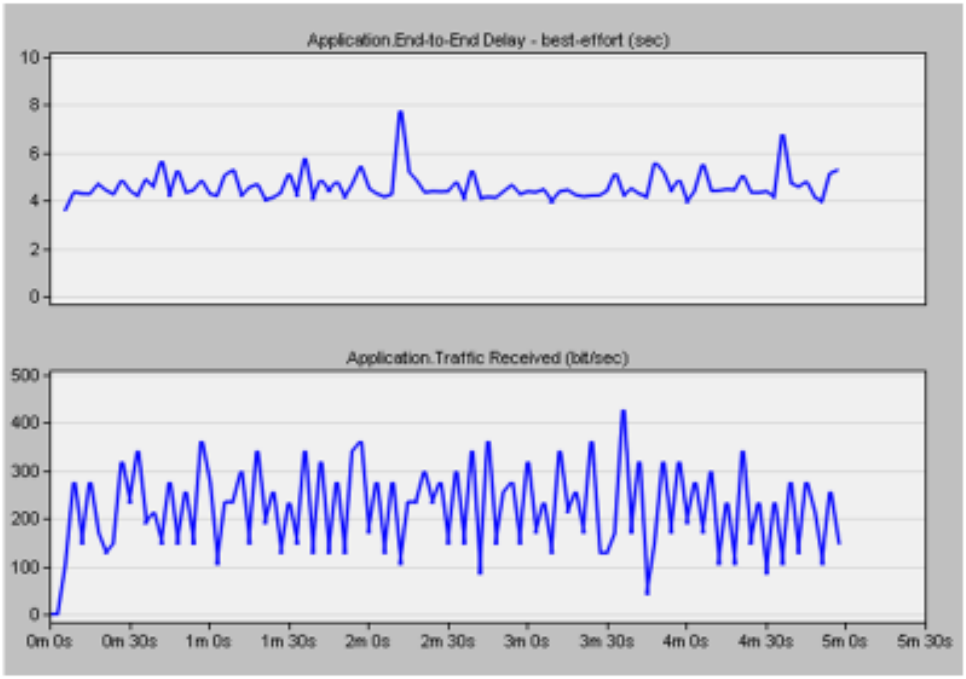


Figure 6.26- Performance results

Figure 6.27 shows the battery consumed energies for the sensors devices. It reports that the sensors consumed an acceptable level of energy. Figure 6.29 shows that the simulation was further expanded into 5 other ZigBee clusters each consisting of 500 ZigBee nodes. Each of these ZigBee clusters can be an independent ZigBee network that connects to the Internet, not necessarily in the same geographic location or as part of the same

application. Figure 6.29 shows an example of an IoT application that connects 5 different IoT applications together.

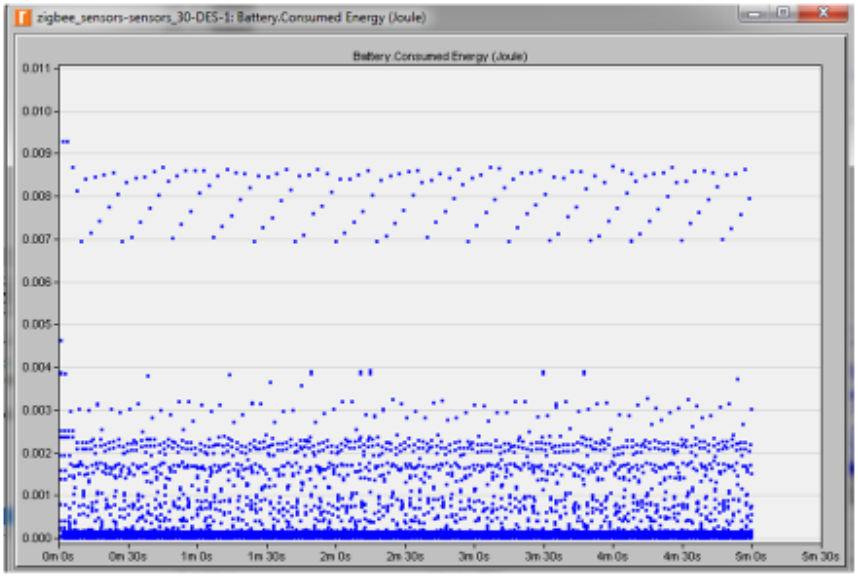


Figure 6.27- Battery consumed energy in Joule

These are the ZigBee home automation, ZigBee retails services, ZigBee smart energy, ZigBee building automation, and ZigBee healthcare services. It illustrates how the IoT-MP architecture connects the independent ZigBee clusters together. By implementing the PM, users of each of the sensors in a cluster can define policies which govern how, when, to whom, and to which extend the location of their devices are revealed. The nodes in blues are sensors and routers devices. The nodes in yellow are the managers of the clusters. The node in red is the MoM. Figure 6.28 also visualises the communications across the network. The communications follow the approach previously simulated. That is, at a given time a ZigBee node requests the location of another node. We configured a few policies where a group of specific sensor nodes was configured to reveal the node locations while a group of other nodes was configured to hide the location information. We ran the simulation and examined the traffic exchanged using the log file. The results also demonstrated the capability of the IoT-MP in achieving location privacy in a heterogeneous ZigBee network.

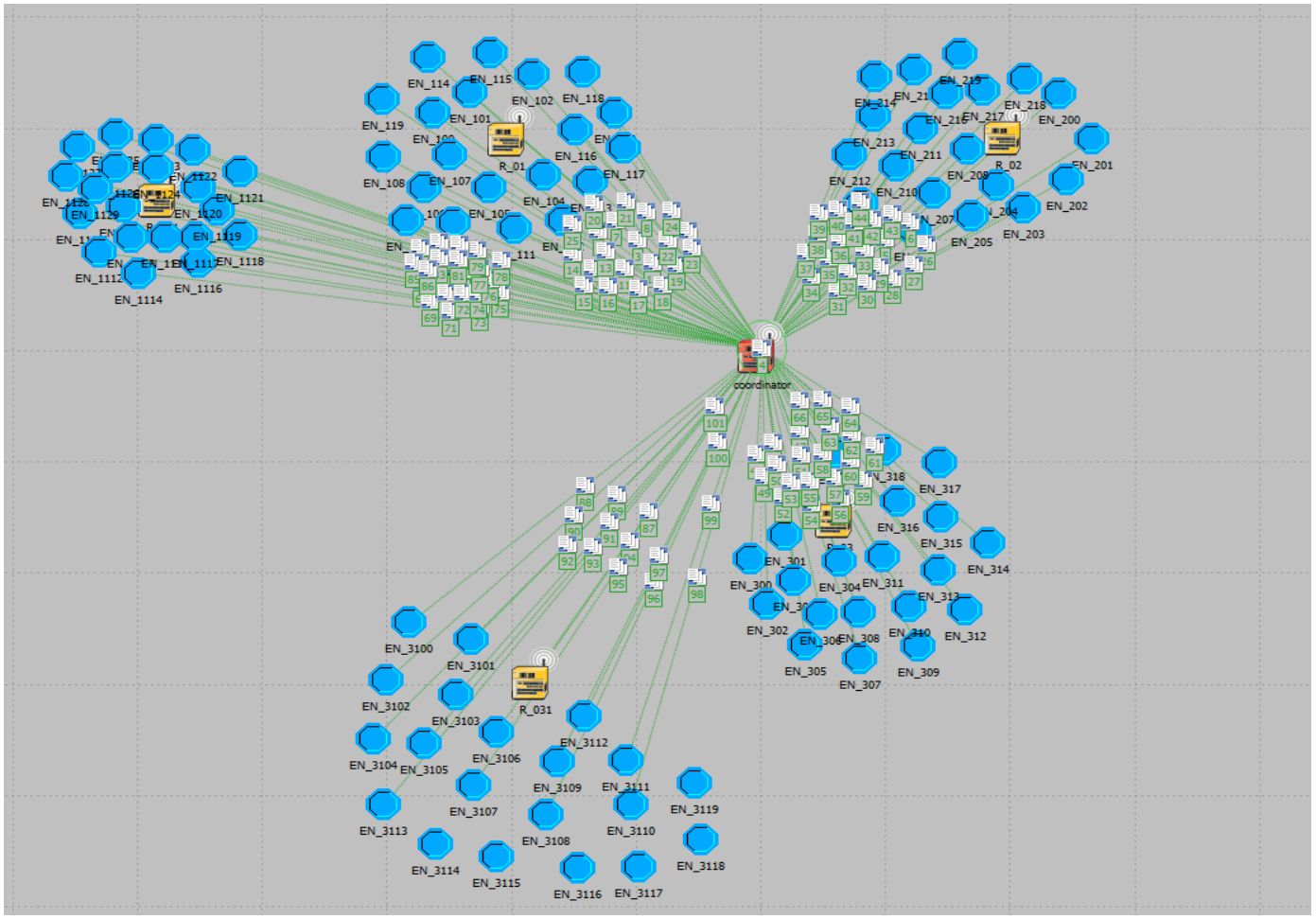


Figure 6.28- Large Scale Simulation

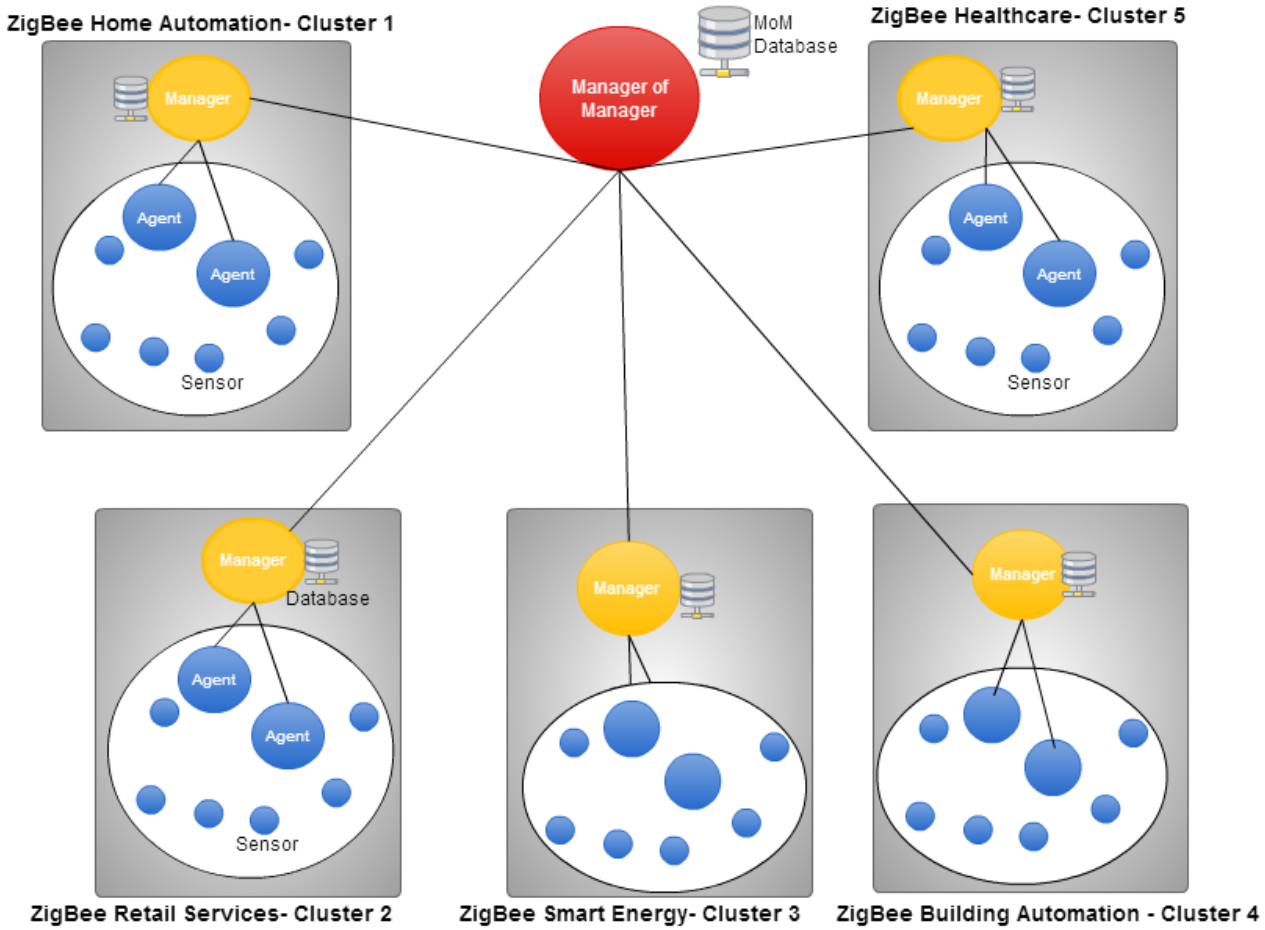


Figure 6.29- Larger scale simulation of hundreds of ZigBee nodes (figure adjusted to fit screen)

6.3.3 Network Scenarios based on IEEE 802.11ah

The IEEE 802.11ah is the new low-power approach to Wi-Fi. In contrast to classic Wi-Fi (802.11/a…ac), 802.11ah uses a sub-l GHz frequency band. The 802.11ah is IEEE attempt to cater for IoT devices, specifically low-cost and low-power devices. Therefore, it is empirical for this research to verify the capabilities of the proposed IoT-MP in a .11ah setup. Hence, this stage of the research simulated the IoT-MP in an IEEE.11ah network. We repeated the exact scenario previously designed using ZigBee but this time with .11ah used as the communication technology. As IEE802.11ah is still in development stage, there are no established models that can be used to simulate this new technology. To overcome this challenge, and since 802.11ah is based on the general 802.11 protocol, we modified the base model of 802.11 in Opnet to model the behaviours of 802.11ah. The common settings for this simulation are provided in Table 6.3. These are based on the 802.11ah simulation works reported in [213]. Mainly, in this simulation, the work has reduced the data rate and receiver's power of the base 802.11 protocol along with changing few other parameters. The simulation calculated the average consumed energy to transmit a packet by a node, which contained the sensorID and the temperature, to another node. It is shown in Figure 6.30. It is noted that the energy consumed by the sensor to send a packet are slightly lower than those reported in [213]. This is attributed to the small size of the packet used in our simulation. Readers interested in a performance comparison between 802.11ah and ZigBee are referred to [213].

Table 6.3- 802.11ah Simulation Parameters

Data rate	250 kbps
Physical Header	5 Bytes
MAC Header	10 Bytes
Receiver sensitivity	-92 dBm
Frequency	900 MHz
Traffic	Uplink
Deployment size	200m*200m
Number of nodes (including AP)	20

Importantly, this stage of simulation demonstrated the successful deployment of the IoT-MP in an 802.11ah network. The results relating to location privacy were identical to those collected from the ZigBee simulations. This also confirms the capability of the IoT-MP in preserving location privacy in low-power wireless networks, specifically in ZigBee and 802.11ah.

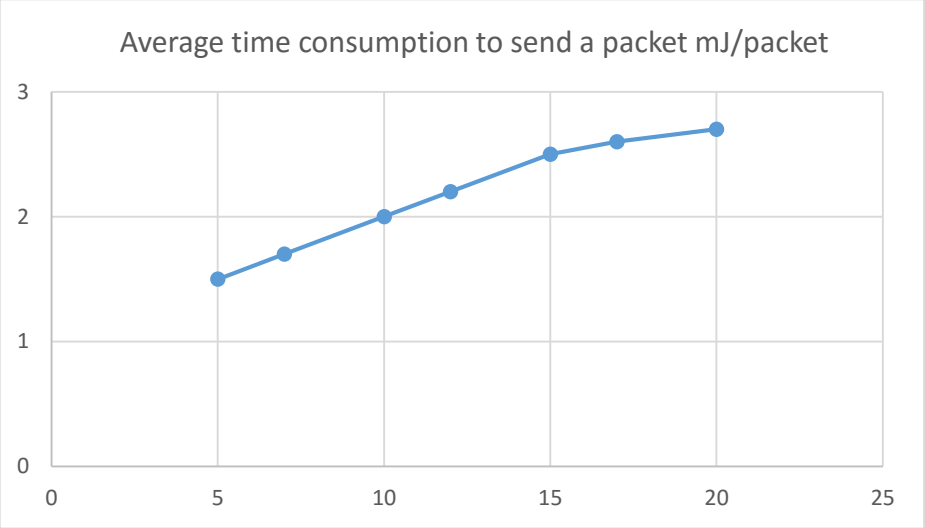


Figure 6.30- Energy consumption: 802.11ah

6.3.4 The Integration of 802.11ah and ZigBee Scenarios in one Heterogeneous Network

Figure 6.31 shows the previous simulation scenarios, reported in Section 6.2.3, were further expanded to incorporate an 802.11ah network to form a heterogeneous network. It is noted that with the increase in the number of devices, the overall end-to-end delay of the ZigBee network has increased as well.

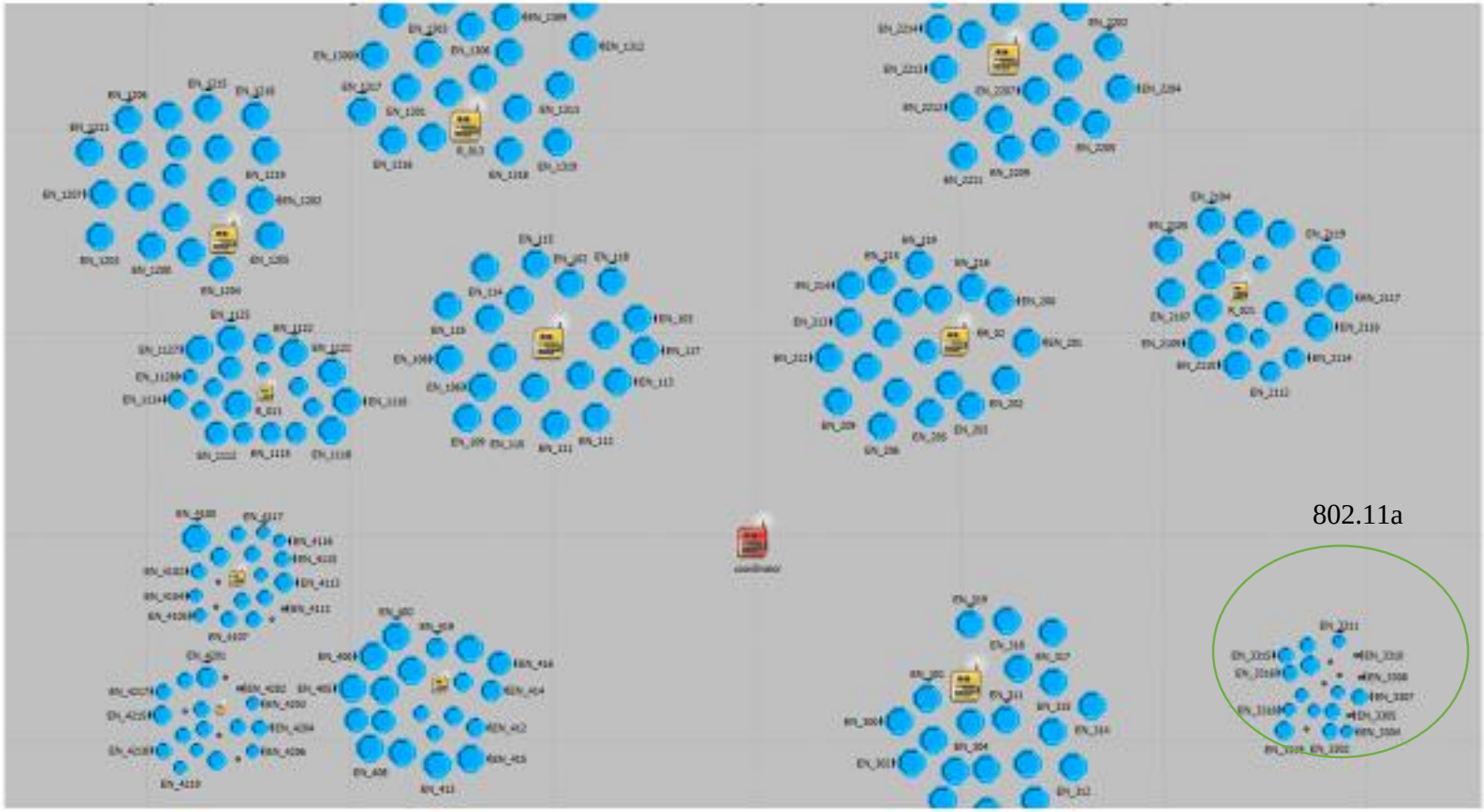


Figure 6.31- Larger scaled with thousands of devices

Also, we observed that the queuing delay at the agents has increased with the rise in the number of connected sensors as shown in Figure 6.32. This is caused by the dramatic increase in the number of nodes in the network as well.

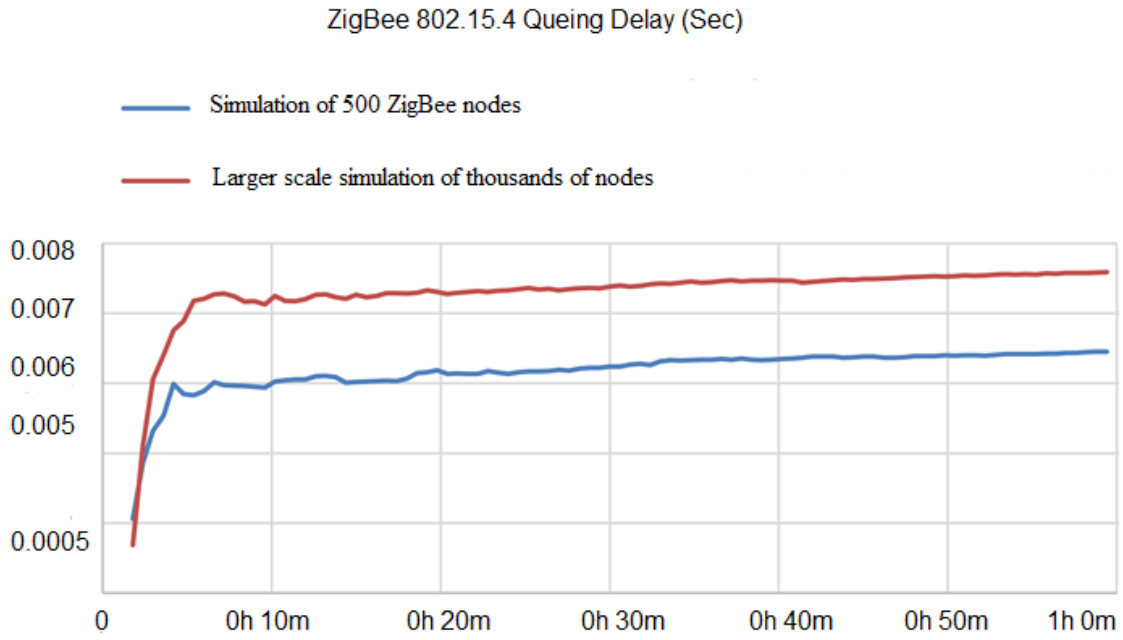


Figure 6.32- Delays Comparison

In each of the simulations described above, a group of nodes (from both ZigBee and 802.11ah networks) were configured to request the location of other nodes at *t''* of the simulation. Each time we repeated the test with different policy configurations which involved the use of a different set of ZigBee and .11ah nodes. The results were verified by examining the log file that shows the traffics exchanged among the nodes. Figure 6.33 is an extract of the log file. It shows that Manger_A is sharing sensor_a X and Y coordinates (location) with sensor a_1_3.

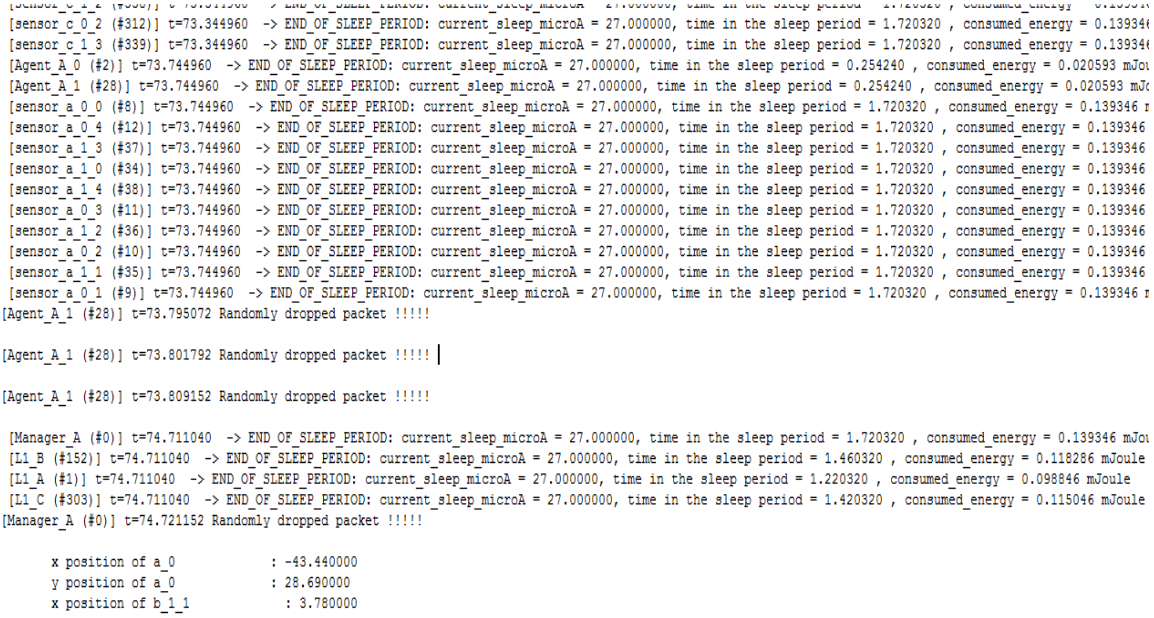


Figure 6.33- Log file

6.4 Summary

In this chapter, the proposed Internet of Things Management Platform has been evaluated using various simulations studies. Through different simulation scenarios and results analysis, the capability of the proposed platform in preserving the location privacy of things in the IoT was assessed. The research started by simulating the IoT-MP in a ZigBee WSN network that comprised few sensor nodes. Then the work increased the size of the ZigBee simulations from few nodes to few hundred. Additional simulations were also carried out to increase not only the size of the ZigBee network but also its complexity, by creating two clusters of ZigBee networks and connecting them together. This also included the simulations of sensors' mobility between the different ZigBee clusters. Lastly, the research introduced the IEEE 802.11ah scenarios to the simulations creating large scale heterogeneous network scenarios. In each of these scenarios, a group of sensor nodes were configured to request the location of other sensor nodes. By observing the traffics exchanged among the nodes in the network, the work verified and demonstrated the capabilities of the IoT-MP in preserving the location privacy of the sensors in a heterogeneous network.

Additionally, the results collected from the simulations studies confirm that using the approaches proposed by the IoT-MP, it is possible to provide the users with a method that allow them to manage the location privacy of their devices. Specifically, in large scale low-power wireless networks with no noticeable impact on the power use and response time of the network. For instance, the scenarios implemented in this chapter show that it is possible to preserve location privacy in networks that utilise the ZigBee wireless technology. It was found that the application end-to-end delay experienced by the ZigBee network is below 7.5ms. This is achieved without affecting the performance of the network with regard to power consumptions. Likewise, the results were verified in a network scenario that uses the 802.11ah protocol as well. For example, it is found that the average consumed energy to send a packet across the network by a ZigBee and 802.11ah node was fewer than 3mJ. Lastly, the capabilities of the IoT-MP in supporting a large scale of devices in a heterogeneous network were also confirmed. The results demonstrated that using the IoT-MP, the protection of the location privacy of things can be achieved in heterogeneous networks with negligible impact on the network performance.

CHAPTER 7- CONCLUSION

The Internet of Things (IoT) foresees the interconnection of billions of things by extending the interactions between humans and applications to a new dimension of communications via things. Rather than always interacting with the human users, things will be interacting with each other autonomously by performing actions on behalf of the users. This will result in the IoT being pervasive in many different areas. Thus, the potentially massive number of things, their diversity, and the seamless and heterogeneous nature of communications encountered in the IoT challenge the privacy of the users. Data collected by a single IoT device may not infringe on the privacy of the users. However, many envisioned IoT applications will require the automated sharing of the users' information collected by things including their location information. The aggregation of this information, gathered from a large number of things and exchanged over various heterogeneous networks, can impinge on the privacy of the users, specifically their location privacy. For this reason, the development of solutions to support location privacy preservation is a key factor for the widespread proliferation of the IoT. Various privacy protection methods have been proposed in the literature to deal with the location privacy issue. However, most of these methods did not consider the low-cost and low-power requirements of things, or the heterogeneity, scalability, and autonomy of communications supported in the IoT. To address these shortcomings, this thesis proposed a middleware solution that enables the management and preservation of location privacy of things in the IoT.

The thesis started first by examining the research issues challenging the IoT, specifically the location privacy issue. It examined the methods and various localisation techniques that can be used to obtain location information by things in the IoT. The research then reviewed the capabilities of these methods and analysed the risks they pose from their usages in the IoT. It was found that the flow of information and actuation events in the IoT may comprise the exchange of personal and contextual information supplied by things, including location information. It was further identified that the disclosure of

location information in the IoT gives rise to the possibility of using the tracking capabilities of things to impinge on the location privacy of users. The findings of these analyses also highlighted the necessity of embedding privacy preservation methods in the design of IoT applications. The research then moved to examine the traditional location privacy protection methods and their suitability for implementation in the IoT. The characteristics, technical parameters, and the challenges about the use of various low-power wireless technologies in the IoT were also studied. The results of these examinations and analyses have clearly pointed to the need for a lightweight solution that supports the preservation of the users' location information in heterogeneous networks in the IoT. It was further found that the deployment of solutions to warrant location privacy protection in the IoT can be quite different in each specific context. Consequently, the research has attributed the complexity of protecting the location privacy of users in the IoT to two main factors. The first is derived from the heterogeneity of the communications encountered in the IoT. The second relates to the unique characteristics of things such as their low-power and low-cost requirements. In fact, these factors highlight the infeasibility to preserve the location information of things and that of their users using traditional privacy protection methods such as anonymization.

To accomplish one of the main objectives of this research in finding a solution to enhance the preservation and management of location privacy in the IoT, a middleware referred to as the Internet of Things Management Platform (IoT-MP) was proposed in Chapter 4. The middleware encompassed context-adaptive approaches that enable the user to manage the location information disclosed by things based on a context-aware and policy enforcement mechanism. This mechanism takes into account both the user's informed consent and preferences. The IoT-MP has a distributed architecture consisting of agents, managers, and a Manager of Managers. The various modules of the IoT-MP's manager guarantee that the location information of things are only disclosed to authenticated and authorised entities while preserving the location privacy of things and that of their owners. Specifically, the Privacy Module (PM) provides fine-grained features for adapting the users' defined policies and location information granularity to specific contexts dynamically. It is shown through experimental and simulation studies that the IoT-MP has managed to preserve the location privacy of users in the IoT. The privacy

preserving capabilities of the IoT-MP were also supported by a novel Obfuscation technique, referred to as the Semantic Obfuscation approach (S-Obfuscation). The research has also shown that the S-Obfuscation has enhanced the performance of two classic Obfuscation techniques by relying on a geographic knowledge when producing obscured location.

Therefore, the validities and effectiveness of the proposed platform have been illustrated through different experimental and simulation studies. The experimental studies, reported in Chapter 5, comprised scenarios that involved the utilisation of some Bluetooth Low Energy (BLE) sensor devices, and the implementation of two mobile applications and a web application. The reported results, collected from the experiments, confirmed the effectiveness of the proposed platform in preserving the location privacy of low-power sensor devices in physical environments, which use physical location information including GPS coordinates. In the experiments, the S-Obfuscation was shown to have better performance than that of the classic Dispersion method. The improvement in the performance was over 50% in cases where a wider proximity to the original true location was used.

On the other hand, the results collected from the simulations, discussed in Chapter 6, also have shown that using the proposed platform, it is possible to achieve location privacy in a heterogeneous and low-power network similar in scope and size to that usually employed in the IoT. Several network scenarios based on ZigBee and the IEEE 80211ah protocols, which used more than three thousand things, were simulated in Opnet. To simulate communications among IoT devices over the Internet, a group of sensors took turns in requesting the location of other sensors in the network. The traffics correspondent to the information exchanged between the sensors in the simulations were analysed. The results have demonstrated the IoT-MP capabilities in preserving the location privacy of the sensors in a large scale heterogeneous network. Additionally, the performance results collected from the simulations have clearly shown that the use of the IoT-MP had no noticeable impact on the power consumptions and end-to-end delays of both ZigBee and IEEE 802.11ah end devices.

Consequently, this thesis has answered the research questions by demonstrating that it is possible to provide the users with a method that enable them to control the granularity of the location information disclosed by constrained things in heterogeneous networks. The research has further demonstrated that it is possible to improve location privacy protection in the IoT by incorporating a location Obfuscation approach in a platform that uses an architecture adapted from traditional network management approaches. The IoT-MP has made some significant improvements to the preservation of location privacy of things, and that of their users in seamless and heterogeneous communications in the IoT as set out by the objectives of this research as well.

It should be noted that this thesis has made some assumptions. In the simulations, it was assumed that an IoT device is already associated with an agent in the IoT-MP. It was also assumed that only authorised IoT applications are connected to the manager in the IoT-MP. Additionally, the research also suffers from a few limitations. The IoT-MP relied on an API module to securely connect things and IoT applications to the IoT-MP network. However, the security services provided by the API module have not been validated. Additional simulations or experimental studies are needed to test and validate the effectiveness of the IoT-MP in securing the communications between IoT applications and the IoT-MP's manager over the Internet. Although, a behaviour modelling and reputation system have been suggested by other researchers [187] to improve the authorisation mechanism of the IoT-MP, other aspects of security such as authentication remain unresolved and are left for future works.

Furthermore, to reduce the complexity of the simulations, the data sent from the sensors to the manager in the simulations were only stored in an external file in the form of an array. Thus, this thesis did not consider the problems and associated delays that could arise from storing thousands of sensors' data over a longer period in the manager's database. The long-term impact of the IoT-MP's management and operational messages on the power consumption of things has not been evaluated as well. Therefore, future works should investigate whether it is needed to optimise the communications between the entities of the IoT-MP. It is essential that communications between things are efficient especially in terms of energy consumptions and latency. Therefore, it is important for

future works to look into ways to reducing the overheads on the communications and improving the overall energy efficiencies as well. Future works should also consider extending the location privacy preserving capability of the IoT-MP to protect the privacy of other sensitive information of the user as well. The research conducted in [214] has already done that but on a small scale. The challenge, however, remains in validating the effectiveness of the extended IoT-MP privacy preservation capabilities in heterogeneous, large-scale, and dynamic networks environments.

The future of communications in the Internet of Things envisions the pervasive interconnection of things across several heterogeneous networks. Therefore, the challenge of provisioning interoperability between IoT networks and devices remains unanswered. Consequently, some of the new research questions arising from this thesis are as follows: How to create an ecosystem of coexisted devices that could connect to the Internet using various wired and wireless protocols? And how to achieve interoperable communications between these devices, in addition to maintaining scalable, private, secure and trustworthy operations in the IoT. With regards to privacy, this thesis provided a context-aware privacy solution that enhances the preservation and management of location privacy of users in the IoT. However, the challenge remains in designing privacy protection solutions for the IoT that balance between the users' privacy requirements and the need for the IoT to know and learn more about the users' daily activities and lifestyle.

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APPENDIX

The codes, software packages, and tools relevant to the experiments and simulations are available to download from http://elkhodr.com/phdappendix.html

The Experiments

- **The Android Mobile Application that connects to the BLE sensors**

  Download Zip Folder

- **The PHP web Application**

  Available at URL: http://elkhodr.com/ci/welcome/display_data

  This webpage displays in real-time the data read and transmitted by the BLE sensors. To repeat the experiment you have to first download the BLESensorTag Mobile application and connect it to the BLE sensors. The BLE sensors can be purchased from http://www.ti.com/tool/cc2650stk

- **The Codeigniter framework used for the IoT web application.**

  Download Zip Folder

  For this application to function, an active Google play services account is needed. The Codeigniter framework should be installed on the server/domain first as well. More details can be found at https://www.codeigniter.com/docs

- **The Android Application used to configure users' defined policies**

  Download Zip Folder from URL: Download APK, Download Source Code

  For the App to run make sure you are logged in to Google Play and Google play services are running. Also, location should be enabled on the mobile device. This app was tested on Nexus 5 handset running Android 5.0

- **The Modified Belkin Wemo Android Mobile Application**

  Download Zip Folder

  For this application to run, all previous applications should be set and running. Specifically, the BLE sensors should be running and transmitting their location to the PHP web application. The Belkin Wemo Android app changes the status of the Wemo light based on the location of the sensors. Some values were hardcoded and may require alteration to work again (depends on the location of the sensors).

- **The Rand and Dispersion Obfuscation Technique codes**

  Available at URL: http://elkhodr.com/obf.html

The Simulations

- **NS2 ZigBee Simulation**

  Download Zip Folder: WLAN and ZigBee

- **Opnet large scale ZigBee simulation.**

  Download Zip Folder

  Note this requires the Open ZigBee framework to be installed and configured first in Opent. Details at www.open-zb.net