Cape Peninsula
University of Technology

Real-time detection of attendance at a venue using mobile devices

by

KONZI OLIVIER SAGBOZE

Thesis submitted in fulfilment of the requirements for the degree

Master of Technology: INFORMATION TECHNOLOGY

in the Faculty of INFORMATICS AND DESIGN

at the Cape Peninsula University of Technology

Supervisor: Doctor BONIFACE KABASO

Cape Town

May 2017

DECLARATION

I, KONZI OLIVIER SAGBOZE, declare that the contents of this dissertation/thesis represent my own unaided work, and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed **Date**

ABSTRACT

The implosion of the mobile phones, mobile applications and social media in recent years has triggered a great interest for more dedicated user-generated contents. Mobile users being the focal point, these modern virtual platforms depend on and live for collecting, structuring and manipulating the very fine-grained details about users' day-to-day activities.

Since every human activity takes place in a geographical context, location information ranks high among the set of data to gather about user's daily life. User's specific location details can help filter content to serve and retrieve from them. Therefore, location-based services have been developed and successfully integrated into most virtual platforms in the quest for these precious data.

However, location-based services do not fulfil all requirements. They depend on a range of positioning systems which show numerous limitations. None of the existing positioning systems is perfectly accurate. Today, it is therefore difficult to pinpoint a user in a venue using location-based services.

Nevertheless, with the set of existing technology and techniques, it is possible to estimate and track users' whereabouts in real-time. Providing the best possible estimation of user's position within a given venue can help achieve better user engagement. Depending on the gap of accuracy, the end result may actually match the outcome expected from perfectly accurate positioning systems.

In this work, the focus is to develop a prototype positioning system which provides the best estimation of user's position in real-time in relation to a targeted venue or location. Through a series of research and comparison study, the most suited technology and techniques are objectively selected to build the intended prototype.

The challenge of indoor positioning is also addressed in this work – bearing in mind the fact that this prototype is set to work accurately and efficiently in any geographical location and structure. The prototype is evaluated according to a set of predefined standard metrics, and theories are extracted to grow knowledge about this trending topic.

ACKNOWLEDGEMENTS

I wish to thank:

- Doctor Boniface Kabaso, my supervisor since my B-Tech Project. More than just a supervisor, Doctor Boniface Kabaso has been a mentor to me during the last couple of years. Many thanks for easing my understanding of many technical challenges and pushing me to the completion of this work.

- The Department of Informatics and Design of the Cape Peninsula University of Technology for providing me with the platform to express my ideas through this research-based Master's course.

- The DooCoLab Project team 2013, in Malmo, Sweden. Doctor Boniface Kabaso, Jörn Messeter, Rael Futerman, Amanda Bergknut and Micah Donnoli. Thanks for allowing me to be part of the project which led to this Master's thesis topic.

- Baliwe Sagboze, my brother, for technical advices and helping me assemble some of the system components to produce the artefact in due time. Also, many thanks for accepting to be a participant in both experiments conducted in this research project. This achievement would not be possible without your crucial participation.

- Corinne Olofio Sagboze, my sister, for providing me with the necessary moral support when I was down with sickness and really thought I would never get to complete this work. Thanks for pushing me and keeping believing in my potential at all times.

- Tabita Kennedy, my friend, for providing me with moral support at all times and allowing me to share my deepest and dearest thoughts regarding this Master's thesis.

I would like to dedicate this work to:

- My late grand-mother, Marie Olofio MONINGA, for being the driving force behind this work and being my inspiration from the beginning to the end of this project.

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
A-GPS	Assisted Global Positioning System
AoA	Angle of Arrival
API	Application Program Interface
BLE	Bluetooth Low Energy
CSR	Constructive Science Research
FTDI	Future Technology Devices International
GIS	Geographic Information Systems
GPS	Global Positioning System
GSM	Global System for Mobile Communications
IEEE	Institute of Electrical and Electronics Engineers
INS	Inertial Navigation System
IP	Internet Protocol
IPS	Indoor Positioning Systems
IR	Infrared
NS	Natural Science
OOI	Object(s) Of Interest
PIP	Point-In-Polygon
PPS	Precise Positioning Service
RF	Radio Frequency
RFID	Radio Frequency Identification
RSS	Received Signal Strength
SPS	Standard Positioning Service
ToA	Time of Arrival
TDoA	Time Difference of Arrival
ToF	Time of Flight
TTFF	Time-to-First-Fix
TTL	Transistor-Transistor Logic
USB	Universal Serial Bus technology
USB OTG	USB On-The-Go
UWB	Ultra-wide band
WLAN	Wireless Local Area Network

1 CHAPTER ONE: INTRODUCTION

1.1 Background to the research problem

The number of people using smart mobile devices is in constant increase (Hayta, 2013). Smart mobile devices have not only facilitated communication, but they have also eased access to various activities through dedicated mobile software applications - mobile apps (Hayta, 2013).

The Internet and the various applications which make use of it have facilitated many common human activities and transformed traditional processes. They allow a greater accessibility to information and flexibility of processes through the execution of software applications such as Internet-banking or mobile news services.

Location-based applications are some of the most popular mobile software applications (Hwang & Yu, 2012). Embedded in smart mobile devices, they provide locations detection features and navigation capabilities to users.

Location-based services represent a relatively new concept. Kupper (2005) defined them as technology-based services for providing information about current geographical locations of users or mobile objects. Recently, they have been successfully incorporated into social media and their popularity has therefore increased (Hecht & Gergle, 2009).

Currently, people use mobile location-based applications to share their locations, find their friends in remote locations or even find information about activities around their current locations. The integration of location-based services in mobile software applications is no longer just a "cool feature", but rather a useful tool for localisation (Hecht & Gergle, 2009).

Location-based services basically allow people to instantly share their location details online. This promotes an informal kind of user tracking of which a large range of people (or businesses) can take advantage (Wang, Burgener, Flores, Kuzmanovic & Huang, 2011). For example, some businesses use their potential customers' location information to offer a dedicated product or service.

Since their adoption by a large number of users in the society, location-based services keep improving and fulfilling users' needs. Location-based services can presently detect users' current country, city and even district (MaxMind, 2012). The users do not need to search for their current location as the smart mobile devices automatically detect fine details about their locations (Kupper, 2005). A combination of the last two mentioned facts just proves the convenience of location-based services in smart mobile devices.

Hecht and Gergle (2009) believe that location-based services efficiently help bridge the gap between the virtual activities and the physical world. They argued that, through these services, virtual activities can be geographically located, thus, making them appear real.

Despite the great improvements they have brought, location-based services in mobile software applications still display significant limitations regarding the geolocation of users and places. In fact, they do not accurately detect smart devices' position changes in small venues. Consequently, it is difficult to track users' movements in such locations.

However, many important social interactions happen in designated venues such as classrooms or football stadiums (Goldenberg & Levy, 2009). Unfortunately, location-based applications lack the fine accuracy and reliability required to fully support human interactions with dedicated contents at such locations. The current limitations are essentially related to the fact that location-based services depend on a number of technology-based parameters which are still being improved and optimised (Sreder, 2014)

In fact, technologies such as the Global Positioning System (GPS) or geolocation with Internet Protocol (IP) address are the tools behind the efficiency of location-based services. Unfortunately, these technologies have not reached perfection yet. They have limitations and their limitations impact the effectiveness of the location-based services (Sreder, 2014). The most important limitations are their accuracy and reliability (Wang, *et al*., 2011).

In addition, many smart mobile devices are not powerful enough to maintain real-time tracking of users using location-based services. Current location-based services easily drain mobile devices' battery power, and require powerful processors to function (Sreder, 2014).

As a result, it is difficult to design mobile applications and services which cater for responsiveness, accuracy and reliability when virtually mapping small locations.
However, such applications, if enabled, would have a role to play in social interactions.

In fact, increasing the accuracy and responsiveness of location-based services could help improve the "localness" of user-generated contents within venues of dense human activities, such as supermarkets or airport terminals. Therefore, it is important to develop a location-based technique dedicated to near-real-time and accurate tracking of mobiles devices' movements in small locations.

1.2 Problem statement

The problem to be addressed in this research can be summarised as follow: how to detect and actively track the positional changes of a mobile user in relation to a virtually mapped venue and determine if the detected mobile user is currently situated inside or outside the venue. The problem posed in this work is a compound problem. Breaking it down in pieces helped identify and understand each technical challenge in depth.

The problem, as presented in the previous paragraph, can be sliced down in the following order:

1. Virtual mapping of a given venue;
2. Detection of an active mobile user situated within the range of the set location;
3. Real-time tracking of mobile user's positional changes in relation to the location of the venue mapped;
4. Flagging of user's current position as internal or external to the surface of the venue mapped.

The first part of the problem refers to the virtual representation of a location. In the context of this research, this translates into a two-dimensional representation of a venue. Such modelling of a location requires a virtual mapping of its borders. Thereby, the technical challenge of this first part of the problem was to find a location-based technology which makes it possible to map the borders of a location in a format which software engineering systems can depict. This mapping had to be accurate.

The second part of the problem has to do with sensing the presence of mobile users within the range of the location mapped. That is essentially detecting an active mobile device within the perimeter of the venue represented. In the quest of addressing this issue, the technical challenge was to find positioning technology's hardware compatible with mobile devices which can report the current position of an active mobile device. The hardware had to be sensible enough to report slight position changes of the device. An algorithm would then be needed to compute the reported position in relation to the virtual location of the venue mapped.

The third part of the problem is largely an extension and continuous assessment of the second problem. The third problem clearly implies that the mobile user's position is expected to be volatile. Therefore, accuracy and measurements' precision were required to ensure the effectiveness of the real-time tracking.

However, the accuracy and precision emitted by the positioning systems strongly depend on the limitations of the equipment used to build it and the structure of the location in which the object modelled is situated (Alarifi, Al-Salman, Alsaleh, Alnafessah, Al-Hadhrami, Al-Ammar & Al-Khalifa, 2016, p.1-2). That is an outdoor or indoor location. Each kind of these physical structures differently influences the computation of an object's location.

Furthermore, in this context, the objects tracked being mobile devices, the components and techniques used to address problem two and three had to be compatible with mobile devices. The activity of any hardware which may be embedded in mobile devices should not drain the limited power of mobile devices' batteries at fast rate. The power consumption must not be excessive. Also, the developed algorithm's required operations should be within the limits of modern mobile device's processors at an acceptable speed of computation.

The last bit of the breakdown relates to the system's ability to determine whether the mobile device detected is inside or outside the surface of the venue represented. Here, the challenge was to find the specific algorithm which would be used to fulfil the above requirement.

1.3 Objectives of the study

The aim of the research was to develop a positioning system which can be used in location-based services to track, accurately and in real-time, a mobile device's positions relative to a mapped venue, be it an indoor or outdoor venue.

In this research, the idea was to develop and test a system which can detect and actively track the positional changes of a mobile user in relation to a virtually mapped venue and determine if the detected mobile user is currently situated inside or outside the venue. This work also aimed at documenting experiments and producinF theories accordingly. At the end of the research, the objective would be reached if the proof of concept artefact can demonstrate the following achievements in form of data:

- High location accuracy :
  Independently of the venue type (outdoor or indoor), based on the data gathered, the system should be able to determine, with the highest possible accuracy, whether a detected user is currently inside or outside a selected venue. See **Figure 1-1: Illustration of the research aim**.

- Location accuracy not affected by the venue type:

The system should respond to user's devices movements in real-time with the same accuracy, whether the selected location is an outdoor or indoor venue. The proposed solution should address the indoor positioning challenge.

- Regular device's power consumption:
  Within the same timeframe, with comparable mobile device's activities, the produced artefact should not induce the mobile device to consume more battery power than other existing positioning systems.
  This research paper identifies some of the most used positioning systems and techniques, and a comparison is then established to determine which system consumes more battery power.

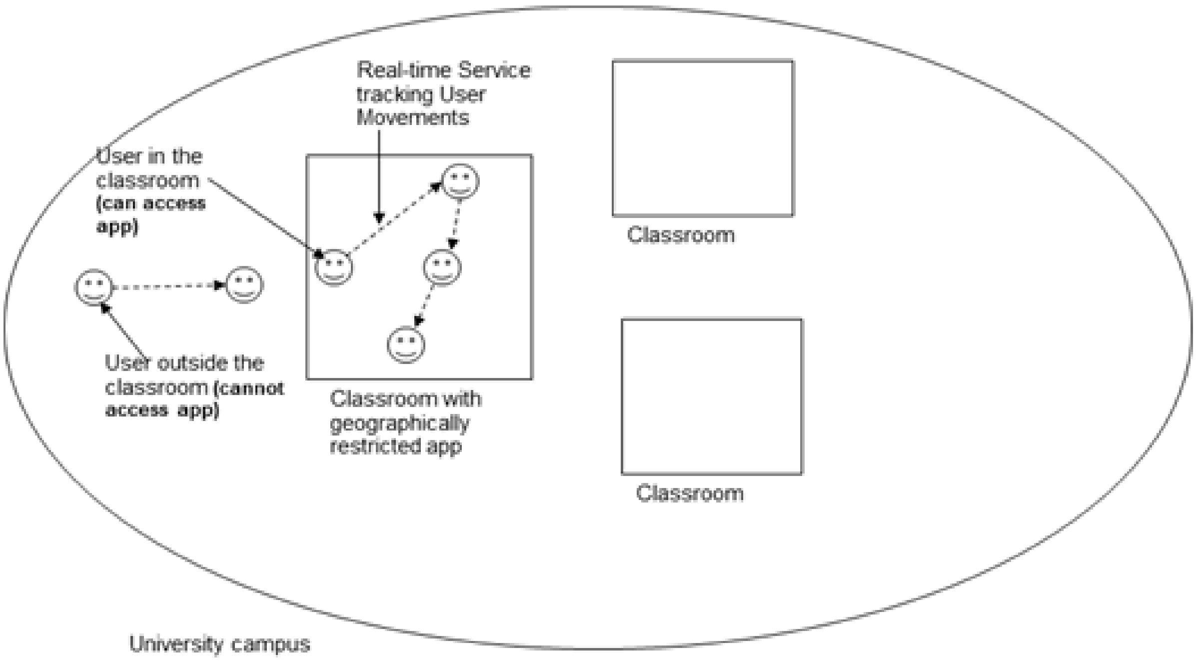


Figure 1-1: Illustration of the research aim

1.4 Research questions

This research addresses the problem raised by providing a clear answer to the following question:

- What positioning system would be best suited to detect, accurately and in real-time, whether a user's mobile device is inside or outside the perimeter of a venue?

This question can be broken down into a few sub-questions targeting the steps to the expected solution. The following sub-questions undertaken sequentially:

- What positioning technology is the most appropriate for a two-dimensional mapping of a venue?
- Is the identified technology as efficient for outdoor venues as for indoor venues?
- Can the identified technology be used with mobile devices?
- What algorithms are needed to produce near-real-time accurate readings of a mobile device's positions in relation to the venue mapped?

1.5 Research methodology

Despite a distant connection to social science, the problem depicted in this research is essentially a computer engineering problem**.** This research was conducted following the Constructive Science Research (CSR) methodology and the research activities of Natural Science (NS). The CSR focuses on building artefacts for communicating findings (Crnkovic, 2010; Oliveira, 2008). This artefact can be theoretical and/or practical depending on the nature of the research problem.

On the other hand, the activities of Natural Science are centred on the "build-evaluate" and "theorize-justify" models (Kabaso, 2014). As explained by Crnkovic (2010), once the artefact is produced, it can be studied by science. In fact, in CSR, building an artefact is the sole way to test hypothesis. Theories therefore result from the evaluation of the artefact (Oliveira, 2008).

Natural science, through its activities, provides a platform for evaluating the artefact and deriving a theory which will essentially represent the knowledge extracted from the work produced by the CSR methodology (Kabaso, 2014).

During the course of this research, an artefact was developed using engineering methods. Therefore, constructive research methodology was adequate for conducting this research and building the artefact. The solution was then evaluated, and the results produced were used to extract knowledge using the "theorize-justify" activity of the Natural Science.

In this work, the evaluation of hypothesises was conducted following an experimental design approach. Referring to the conceptual framework in which the research is conducted, this procedure consists of evaluating hypothesises by determining valid relationships between independent and dependent variables (Key, 1997).

According to Crnkovic (2010), CSR is the paradigm which better suits engineering and science because engineering focuses on creating objects which science analyses.

1.6 Significance of the study

Location-based services in mobile devices certainly represent a great innovation, but they do not fulfil all the needs regarding virtual representation of locations and detection of users' positions. In fact, there are various aspects of the concept which must still be improved.

In addition, the recent integration of these services in mobile devices has shown considerable limitations. These services depend on few methods which are not perfectly accurate and reliable (Wang, *et al*., 2011). These limitations negatively impact the efficiency of the location-based services.

Despite on-going research in the field, detection of indoor positions is still a very complex exercise. In fact, there is still no defined standard for indoor positioning systems (Anthony, 2012). Well-known companies such as Google, Nokia or Broadcom have started developing products based on the IPS concept (Anthony, 2012). However, the proposed solutions are struggling to take off globally due to their complexity and the amount of efforts they require (Anthony, 2012).

Furthermore, location-based services have a considerable impact on mobile devices' components (Zhuang, Kim and Singh, 2010). GPS, the main enabler of location-based services, requires a great amount of power from devices. When used intensively, it can completely drain a device's battery power within a few hours (Zhuang, Kim and Singh, 2010). This represents a major challenge because the battery power of mobile devices is limited.

Therefore, this work enumerates some of the techniques currently used in the industry, and provide a better understanding of some of the challenges met by each of the methods described. An artefact is then set up to resolve the problem investigated in this research, using some of the best technologies currently available.

1.7 Delineation of the study

This work only addresses the problem in its engineering perspective. The social leg of the problem, which consists of improving the “localness” of users' generated contents using location-based mobile applications, is not the focus of this research.

This research strictly focused on developing a positioning system for accurate and real-time tracking of a mobile device's position relative to a mapped venue. The development of a location-based service or a mobile app to prove the effectiveness of the system and technique used within a real-world application was not object of this research.

1.8 Limitations of the study

The literature review does not cover all existing positioning systems, as there are many ongoing research projects in this field, and it is therefore difficult to cover all the latest innovations.
This research only focused on a two-dimensional (2D) representation of a venue. The provided solution was not be tested in a three-dimensional representation of a venue.

In addition, this research only looked at venues in one static position. Venues such as a moving cruising ship or a moving bus did not form part of this research.

The hardware components used in the artefact were the ones in the reach of the researcher, as the project resources are limited.

This research did not compare the proof of concept artefact to all other existing positioning systems because of the timeframe available to the researcher to deliver the paper.

1.9 Thesis overview

This first chapter has given an overview of the problem investigated in this work. The research background, objectives and question have been described. The research significance has also been demonstrated, and the delineation and limitations of the research have been enumerated.

The next section of the paper provides a literature review which is focused on the status of the research area.

Chapter 2: Literature review
This chapter emphasises and explains the context of this research, before presenting some of most used geolocation technologies and techniques. Comparisons is then drawn between the various methods presented in that section.

Chapter 3: Research Design

Research design focuses on naming and describing the approach in which this research is conducted. The research methodologies, process and paradigm is also explained. Lastly, the eventual outputs of this study are discussed.

Chapter 4: Architecture and implementation

In this section, the focus is to elaborate on the conception, development and deployment of the artefact: the prototype of the positioning system set to address the research problem. Every step of the artefact development process is explained, providing the details of all the components and techniques.

Chapter 5: Experimental Setup

This section of the work focuses on the experiments to test the hypotheses and assess the effectiveness of the artefact produced in this project. This chapter is set to provide deep analysis of the results obtained from the experiments.

Chapter 6: Findings, discussion and future work

This chapter summarises the research findings by stating the facts generated from the hypotheses testing process. Furthermore, in this chapter, the consequent improvements and shortfalls of the prototype system are discussed, and finally, theories that may help advance the knowledge in this field are extracted.

Chapter 7: Conclusion.

This section reflects on the entire research project. All the essential steps taken in this project to produce the evidences elaborated at the end of the research are enumerated. The conclusion is essentially a compilation of the main highlights of this work.

2 CHAPTER TWO: LITERATURE REVIEW

2.1 Why real-time detection of attendance at venues

Nowadays, productivity has become the drive of our society. Humankind is in perpetual search to improve every aspect of its living conditions (Hayta, 2013). From prime necessity products to accessories, people are attempting to better what was done before. At the centre of this revolution, computer and technology have opened doors to new opportunities, and new ways of doing life (Hayta, 2013).

The advancements of technology and computer-based solutions have helped increase productivity in several fashions. But the determining factors have been the Internet and mobile devices (Hecht & Gergle, 2009; Poslad, 2009, p.11-12). The coordination of these two components has commanded immediate behavioural changes in our society. Work, hobbies, education or shopping, all human interactions have been affected by emergence of Internet-enabled devices (Hecht & Gergle, 2009; Poslad, 2009, p.11-12; Goldenberg & Levy, 2009).

Today, professionals can work from anywhere; they can attend conferences or training remotely, thanks to their portable devices. New forms of education have been developed, allowing learners to participate remotely using their connected smart devices (Hecht & Gergle, 2009; Poslad, 2009, p.22-30). Even activities such as socializing or shopping have been enabled online. The bottom-line is that people do not necessarily have to travel physically to a location to do something.

This results in speeding up activities, allowing more than one task to happen simultaneously, and therefore, increasing productivity so the spared time can be allocated to other activities. This strategy has certainly been assimilated and individual performances increased. However, physical spaces or locations naturally remain an important part of our lives (Hecht & Gergle, 2009; Poslad, 2009, p.12-25).

In fact, people still need to eat in restaurants, use a kitchen to cook their meals, stay under a roof when it is cold and dark outside, or even find a place to sit to conduct any online activity. Therefore, one can affirm that every activity still requires a venue; meaning a place in the physical or geographical space that makes it possible to conduct the activity. Even firm adepts of the Internet-enabled mobile devices still need a location.

Fortunately, during the past few years, professionals in the technology industry have understood the unavoidable nature of physical locations, and have therefore decided to use it to the benefit of the virtual community (Goldenberg and Levy, 2009). This explains the essence of location-based services.

Embedded in mobile devices, enabled wirelessly using sensors and other positions tracking technologies, location-based services have allowed mobile devices users to locate their online activities in space (Kupper, 2005; Wang, *et al*., 2011). Social interactions or shopping activities can now be located using location-enabled mobile devices. Furthermore, location-based services have made it possible to include global navigation systems into mobile devices.

However, since the apparition of location-based services, the challenge for technology specialists has remained the same: accuracy and real-time representation of the physical space through the services offered (Alarifi, *et al*., 2016, p.1-2; Svalastog, 2007, p.1-5; Wang, *et al*., 2011). Actually, location-based services are nothing other than near-real-time online representations of people and things within geographical spaces. The closer they get to reality, the better they will get used to engage with the intended audience: mobile users (Cisco, 2013).

In fact, in the current configuration of most mobile applications using location-based services, the ultimate purpose can summarised with the following composition: detection – connection – engagement (Cisco, 2013). While “connection” defines the phase where detected users are given access to certain virtual platforms such as a social network or a news service, the “engagement” facet refers to the interactions between the platform and the user, often resulting in the production of some sort of localised user’s personal contents (Cisco, 2013; Svalastog, 2007, p.1-3).

However, none of such exchanges can happen without transiting through the first phase: users’ detection. This is the phase where potential users are tracked on their current location using specialised methods: location-based services. Using mobile devices, location-based services are implemented to sense and discover mobile users. The faster the detection occurs, the more precious it is, since there is no guarantee on the duration of a user’s presence at a given location (Adusei, Kyamakya & Jobmann, 2002; Cisco, 2013).

This explains the importance of real-time detection: location-based services are required to respond dynamically to the mobility of user’s within a geographical setup.

2.1.1 What attendance at stake

When evoking mobile devices, the intended audience has always been mobile users. The term “mobile user” is actually a shorter version of the full term “mobile device user”. In fact, “mobile device” is the centre-piece of this modern expression. Despite being commonly used nowadays, many fail to explain or understand the real meaning of the term “mobile device”.

2.1.1.1 Mobile devices

According to Poslad (2009, p.7-20), the common usage of the term “mobile device” to name portable computing devices is simply wrong because they are not autonomously mobile, but rather rely on the mobility of human beings carrying them. Poslad (2009, p.7-20) explains that only devices which are not physically carried by mobile hosts correspond to the suggested naming. As per Poslad’s view (2009, p.29), devices such as autonomous vehicles or robots are the actual mobile devices, while smart phones or digital tablets should not be called mobile devices.

Nevertheless, the term “mobile device” is mostly used to name modern computing handheld, pocket-sized devices such as smart phones or digital tablets. This naming can be explained by the fact that many people perceive mobility as the devices’ ability to connect wirelessly to cellular networks and the Internet from anywhere. Unfortunately, that common belief does not reflect the reality. Although wireless connectivity can now cover wide ranges, it is not restricted to enabling portable devices’ connectivity (Poslad, 2009, p.346-360; Lee, Su & Shen, 2007).

Wireless networks can actually connect desktop computers as well as the so-called mobile devices. Wireless networks just allow users to afford a certain kind of mobility within a wide ranged area, thus suppressing the dependence on traditional network cables’ length (Lee. *et al*., 2007). Therefore, the perceived mobility does not directly relate to portable computing devices, but rather to the users who carry and use them.

However, in the context of this research, the term “mobile device” was commonly used to designate portable computing devices, cellular system-enabled and capable of supporting location-based services. In fact, the current popularity of mobile devices is explained by the fact that they embed many features easing the activities of their users (Hayta, 2013). The most recent mobile devices offer Internet access, audio system, cameras with photo and video abilities, payment system as well as location detection and navigation system (Hayta, 2013). There are many kinds of mobile devices, but this research essentially concentrates on the most popular handheld, pocket-sized devices which are the smartphones and digital tablets.

2.1.1.2 Mobile users

The attendance targeted by this study was that of the people using mobile devices within a venue. These people are commonly named “mobile users” (Poslad, 2009, p.122).
A mobile user is simply a person or object travelling with an active mobile device within a given space (Svalastog, 2007, p.47). Often, mobile users carry mobile devices to stay connected to other people via the virtual space. This connectivity is needed for business or social reasons (Cisco, 2013).

However, many service providers perceive users’ mobile connectivity as an opportunity for dedicated offerings (Cisco, 2013). The concept of location-based services has found its full meaning in the quest to fulfil that objective. The goal is to represent virtually mobile users’ whereabouts, capture the pattern of their interactions within these locations, and consequently, provide contents which will support their activities in that specific space (Cisco, 2013; Svalastog, 2007, p.47).

In fact, most of the time, mobile users are human beings using mobile devices for various purposes (Svalastog, 2007, p.12). As human beings, mobile users routinely attend a certain kind of location or venue to conduct a certain activity. Data about the undertaken activity at a specific location can be recorded and used to serve different needs. Since most mobile users travel with their portable devices everywhere, service providers are trying to detect users’ attendance at a venue via their devices and use their location-specific data (Poslad, 2009, p.404-410; Hu, 2013, p.1).

The process may appear invasive, but the privacy of users is often respected as agreements are requested before offering services to users (Poslad, 2009, p.404-410). In fact, most mobile users are now firm adepts of the principle, and find the concept very helpful since it helps them in several manners. Location-centred mobile applications allow users to share information about their location with their family and friends, help them find directions to a specific location, and provide information about their whereabouts and so on (Wang, *et al*., 2011).

Mobile users have developed new social behaviours, thanks to location-based services. Today, most of them only hope for the improvement of the location systems, so they can be more adapted to their social interactions and needs (Wang, *et al*., 2011).

Following the above explanation, the term “mobile user” is used throughout this work to name the population who make use of mobile devices for any kind of activity at various venues.

2.1.2 What kind of venues

A venue is a delimitated location where an activity takes place. These delimitations or boundaries can be visible or invisible, physical or virtual. A school, a classroom or a park can be classified as a venue when some kinds of activities are set to happen there. Otherwise, they are just locations in the geographical sphere (Bao, Zheng & Mokbel, 2012). Fortunately, humankind has long since decided to associate each kind of activity with a specific location. This established order has helped keep the society neat and structured.

Therefore, schools have been conceived and built to support activities of learning, while places like public parks are used as playgrounds and locations for relaxing activities and playing. Every delimited location is set to serve a purpose, despite some which do not necessarily fulfil their need and others embed more than a single function (Bao, *et al*., 2012).

Either way, each delimitated location somehow fulfils the role of a venue as per its intended purpose or the activities which it supports (Bao, *et al*., 2012). In addition, since the advent of mobile phones, location-based services and navigation systems, all geographical locations have been technically transformed into effective venues because their virtual representations keep them actively open to virtual activities (Hwang & Yu, 2012).

Being virtual or physical interactions, every time human beings conduct an activity, they need to occupy a geographical space (Goldenberg & Levy, 2009). The activity indirectly qualifies the location where it is undertaken as a venue. This emphasises the importance of a venue in human social interactions.

All venues are equally important as they provide the space for people to conduct activities. However, as per their physical configurations, shapes and representations, venues can be distinctively categorised. A venue can be classified as an outdoor location or an indoor location (Liu, 2014).

This categorisation is important as it influences the detection of mobile users in space (Alarifi, *et al*., 2016, p.1-3; Liu, 2014; Svalastog, 2007, p.1-5). Different detection techniques are used for each type of venue, even though the ultimate goal of the detection remains the same. It is therefore important to know the configuration of the venue to use the most adapted techniques for its virtual representation (Liu, 2014; Svalastog, 2007, p.1-5).

The following points look at describing the above categorisation of venues, name a few examples of locations fitting each category and set a definition for each category in the context of this research.

2.1.2.1 Outdoor venues

The term “outdoor” is commonly used to explicitly describe an activity which occurs outside, rather than inside a building; an open air activity (Carter, 2003). Thus, phrases like “outdoor wedding”, “outdoor event” or “outdoor sports” generally incites people to think of a set of activities taking place at free or open spaces. Despite the fact that it is often associated with a word describing an activity, the term “outdoor” always secretly describes a venue where the activity is taking place.

The term “outdoor” should actually be used to describe a venue rather than the activities set to occur at the venue. An outdoor wedding simply means wedding activities happening at an outdoor venue, while an outdoor sport refers to a sport competition staged outside a building (Carter, 2003). As any other venue, outdoor venues are not boundless. The free or open space is just a perception often associated with the word “outdoor”.

In fact, every outdoor venue needs a set of borders to allow a certain level of control over the activities happening there. These borders can be visible or invisible, physical or virtual, but are important for determining the movement and orientation of the interactions within the location (Bao, Zheng & Mokbel, 2012).

However, the term “outdoor” only applies to a certain kind of location and not to all venues. For example, an uncovered stadium, despite its boundaries, is considered as a venue for outdoor activities, while a covered stadium is not described as such (Goldenberg & Levy, 2009). The main difference between the two venues being the top cover structure, one can define an outdoor venue, not as a free location, but rather as a roofless delimitated location.

Following the above description, a public park, a garden or a street all qualify as outdoor venues as they exhibit roofless structures. In this context, the word “roofless” is used to define the physical structure of a location without a ceiling. In other words, this term describes a physical space with an unobstructed view of the sky, which generally is directly affected by weather factors – storms, winds, snow or rain. A balcony, a veranda or parking bay also fit into this category.

In this research, the term “outdoor venue” was used to describe a delimited physical location without roof and with an unobstructed vertical view of the sky: an open air venue.

2.1.2.2 Indoor venues

The word “indoor” is generally used to describe activities conducted within a building setup, under a roof. “Indoor games”, “indoor sports” or “indoor events” are examples of activities set to take place inside a building, under a roof (Alarifi, *et al*., 2016, p.1-3; Liu, 2014; Svalastog, 2007, p.1-5). However, same as with the adjective “outdoor”, the term is incorrectly associated with activities instead of directly being used to describe a location.

In fact, the word “indoor” describes the kind of physical structure in which an activity is conducted. In this case, “indoor” refers to a venue inside a building. This can be a house, a shopping mall, a classroom or even a covered stadium (Bao, Zheng & Mokbel, 2012). The adjective “indoor” is specifically used to differentiate between an open air venue and a venue covered with a roof or ceiling.

Usually, indoor venues are weather-resistant: people or activities taking place inside the venue are not affected by storms, strong winds, snow or rain (Alarifi, *et al*., 2016, p.1-3; Liu, 2014; Svalastog, 2007). Generally, the material used to build indoor venue’ structures are rigid enough to resist those external factors. The weather is a determining factor as far as the choice of an event’s venue’ structure is concerned.

For example, when organising a wedding party in winter, people tend to choose an indoor venue because of the cold weather which can affect the guests. In this case, a party room within a hotel would be a better choice than a resort’s garden. Indoor venues are simply more convenient when planning an upcoming event taking in consideration the unpredictability of the weather.

Furthermore, indoor venues are often the prime choice when it comes to events for which minimal level of noise is required (Bao, Zheng & Mokbel, 2012). A conference or a training session is a typical example of such an event. These activities require a high level of concentration and are generally conducted indoor to avoid outside noise and disturbance. Built with rigid construction materials such as bricks, concrete, wood and heavy steel, indoor locations are for most exempt of outside noises (Alarifi, *et al*., 2016, p.1-3; Liu, 2014). Those materials easily reduce sounds.

However, indoor venues are not always the best choice for all events. This is true for activities for which fresh air and free space are required. In fact, air conditioning systems are not installed in all indoor venues, mainly because of the cost involved. That is the reason why most sports are practised at outdoor venues, especially in third world countries. Furthermore, indoor venues often come with very limited and narrow spaces compared to outdoor locations (Alarifi, *et al*., 2016, p.11). This is commonly because of the specifications of the specific venue.

Following the above explanation, an indoor venue throughout this work refers to any bounded location covered by a roof or a ceiling, which is barred from a direct vertical view of the sky.

2.2 2. Overview of positioning technologies

All methods, techniques, processes and equipment used to represent or model an object's position in a specific physical space are commonly referred to as positioning technologies (Abdalla, 2016). Positioning systems such as GPS or GNSS make use of these technologies to serve their purposes. Positioning technologies range from components such as satellites or routers to the type of signals used by positioning systems.

The quality of the positioning technologies determines the accuracy, precision, availability and latency of the positioning systems (Adalja, 2013). Core components such as electromagnetic wave frequencies are subject to many processes of improvements as their usage has proven to be efficient in the best rated positioning systems.

This section of the thesis presents an overview of positioning systems, providing details about their core architecture and techniques which are used to implement these systems. The most popular positioning systems are then listed and explained.

2.2.1 Common positioning systems' architecture

2.2.1.1 Positioning systems' architecture

Generally, a positioning system is composed of the objects which are meant to be represented and a defined infrastructure. The objects meant to be represented, also called objects of interest (OOI), can be a device, a human being, a robot or even an animal. The object of interest can essentially be static or mobile. As of the infrastructure enabling the positioning system, it is often composed of transmitters, receivers, computing devices and a set network (Adalja, 2013; Svalastog, 2007, p.12-13).

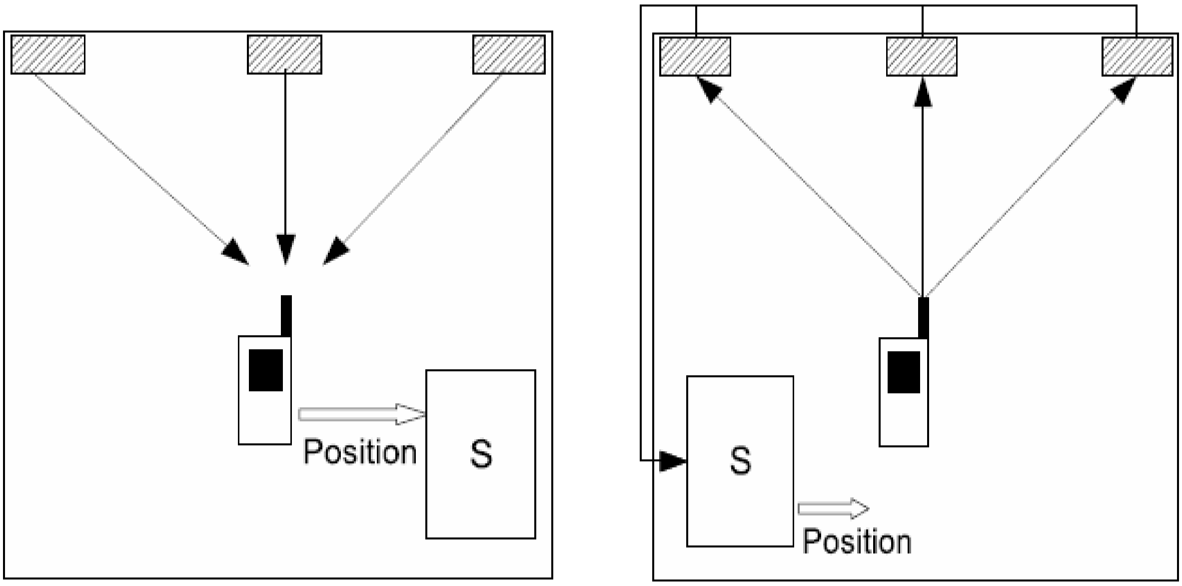
Regarding positioning systems used for mobile devices, the aim is actually to capture the position of mobile users. Instead, the mobile devices (computing devices) are the objects modelled because they are the objects carrying the tag interacting with the specific positioning system. A tag is typically a sensor embedded inside a mobile device, acting as receiver or transmitter for the positioning system. The tag, which is the actual OOI in this case, is often connected to the other components of the system through a wireless network enabled by a specific type of radio waves which is invisible to human eyes (Adalja, 2013; Svalastog, 2007, p.12-13).

2.2.1.2 Positioning systems designs

Positioning systems designs are often determined by the intended usage of the system. That is whether the system is intended for usage by the OOI or the aim is to process the location data remotely. Therefore, based on the interactions between the OOI and the other system components, there are two distinct kinds of positioning system designs: self-positioning and remote positioning system designs (Svalastog, 2007, p.12-13). See **Figure 2-1: Positioning system designs**.

In the self-positioning system design, the system's receivers, which detect the signals by the system's transmitters, are directly linked to the OOI. The OOI is also directly linked to a computing device which computes the OOI's position based on the signals received. In the case of positioning system used for mobile device's location-based services, the system's receiver is a sensor embedded in the mobile device. The mobile device is the OOI and has the ability to compute a positioning algorithm on its own (Svalastog, 2007, p.12-13).

As for the remote positioning system, the OOI is directly associated with the system's transmitters, and the signals' receivers are then set in the environment. The transmitters then send signals to the receivers which, consecutively, forward the signals to the system's central processing unit where they are processed. The central processing unit represents the system's computing device, and is responsible for compiling the OOI's position based on the data received (Adalja, 2013; Svalastog, 2007, p.12-13).



Self-Positioning System Design **Remote Positioning System Design**

Figure 2-1: Positioning system designs

While both system designs fulfil certain requirements, they present some advantages and disadvantages in the context of usage by mobile devices.

The self-positioning system design, by permitting computing of positions to happen on the mobile device end of the system, promotes privacy. Data about mobile users' positions remain on their device, and are not sent to a central server. In the remote positioning context, privacy seems to be compromised by the idea of having personal data being processed by a central computing unit. In any case, by law, any system processing users' personal data should do so following the user's agreement and consent (Farid, Nordin & Ismail, 2013; Svalastog, 2007, p.13).

On the other hand, the remote positioning presents the advantage of requiring less power consumption from mobile devices, since the processing is occurring remotely. Considering the limits of mobile devices' battery power, this represents a non-negligible factor. This type of design could help save mobile devices' power. In remote positioning, mobile devices only play the role of the tag's carrier, and this fact could open doors for mobile devices with less performant processors to take advantage of location-based services (Farid, *et al*., 2013; Svalastog, 2007, p.14).

2.2.2 Positions detection techniques

Positioning detection techniques, also called positioning sensing techniques, are the various methods and measuring algorithms which are used by positioning systems for representing OOI positions. The main techniques can be grouped into four different categories: geometric properties-based techniques, scene analysis, proximity sensing, and dead reckoning (Farid, *et al*., 2013; Svalastog, 2007). In a positioning system, these techniques can be used individually or in combination to compute an object's position. Below is the overview of some of the most popular techniques.

2.2.2.1 Geometric properties-based techniques

Trilateration and triangulation are the two positioning sensing techniques which use geometric properties to determine the position of OOI (Dalce, Val & Van Den Bossche, 2011; Henniges, 2012; Svalastog, 2007). While trilateration uses distances measurements to reach its goal, triangulation uses distances measurements and geometric angles for computation (Adalja, 2013; Farid, *et al*., 2013). However, the two techniques commonly and incorrectly referred to as "triangulation". The following sections addresses this confusion by providing details about the two techniques.

Furthermore, the hypothetical solution to the research problem requires the future artefact to determine whether a mobile user is inside or outside a specific two-dimensional area. That is compiling the position of a device in relation to a two-dimensional representation of a venue. Therefore, it is necessary to visit the algorithms used to solve the Point-In-Polygon (PIP) problem (Sunday, 2012). These are the Ray casting algorithm (also called the Crossing number algorithm) and the Winding number algorithm.

2.2.2.1.1 Trilateration

The trilateration technique measures distances between the OOI and reference points in known positions then uses those measurements to determine the position of the OOI (Adalja, 2013; Dalce, *et al*., 2011; Svalastog, 2007, p.18-19). When the distance of the OOI from a reference point is known, a virtual circle is drawn using the compiled distance as the radius and the reference point as the centre of the circle. The OOI's position is expected to be somewhere on the circumference of the circle (Svalastog, 2007, p.18-19).

This method requires at least three reference points to work in a two-dimensional location setup (Alarifi, *et al*., 2016, p.24). That is because two other reference points are needed from which two other virtual circles are drawn. The intersection of the three circles is then deemed to be the position of the OOI (Svalastog, 2007, p.18-19). However, this description of the technique is based on the assumption that the OOI and the reference points are located in the same plane.

In a three-dimensional location setup, the virtual circles concept is replaced by spheres. In this case, at least four reference points are required to obtain four distance measurements and draw the spheres. Once the spheres are established, their intersection represents the OOI's position (Alarifi, *et al*., 2016, p.24).

This positioning technique may be simplified if there are specific rules about the location represented. The domain-specific knowledge can eliminate the need for numerous radius compilations (Alarifi, *et al*., 2016, p.24). However, there are two main approaches which are used to calculate the radiuses required by the trilateration technique (Adalja, 2013; Svalastog, 2007, p.19). These approaches are: Time of Flight (ToF) and Received Signal Strength (RSS) (also referred to as Attenuation).

2.2.2.1.1.1 Time of Flight

The term "Time of flight" (ToF), also known as "Time of Arrival" (ToA), is the estimation of the time it takes an object to travel between two reference points of interest at a known speed and direction. The speed of an object in a given direction is called velocity (Svalastog, 2007, p.19).

In positioning systems, ToF is often measured using the signal emitted by the transmitter. Time of flight is the timespan between the transmission time and the arrival time of the signal at the receiver. Therefore, for reaching an accurate estimation of the targeted timespan, it is necessary for the transmitter's clock and the receiver's clock to be synchronised (Dalce, *et al*., 2011; Svalastog, 2007, p.19).

The ToF or ToA approach can use a one-way propagation or a round trip of the signal to determine the ToF (Dalce, *et al*., 2011; Henniges, 2012; Svalastog, 2007, p.19). In the one-way approach, it uses the timespan between the signal emission and its arrival to calculate the ToF. In the round trip setup, it uses the timespan the signal takes to reach the receiver, the processing time at the receiver and the total time timespan of the round trip to compile the ToF. The ToF is then used, in conjunction with the speed of the signal, to calculate the distance between the transmitter and the receiver. In this topology, the clocks' synchronisation determines the accuracy of the measurement (Dalce, *et al*., 2011; Henniges, 2012; Svalastog, 2007, p.19).

However, ToF or ToA should not be confused with Time Difference of Arrival (TDoA) which does not rely on the time of the signal transmission to determine the position of an object. The two approaches are equally efficient but use different principles to compile the positions (Dalce, *et al*., 2011; Svalastog, 2007, p.37).

The TDoA approach, also referred to as "Multilateration", is the most commonly used technique in commercial positioning systems (Hu, 2013). It is very similar to ToA (ToF). Clocks' synchronisation is equally important in this topology. However, with OOI being the tag, clocks' synchronisation is not required between the anchors and the tag, but only for the anchors. The difference between the arrival times of the signal at the tag is used to determine the position of the OOI. Depending on the system design used, the tag can be a transmitter with anchors as receivers, and vice versa (Svalastog, 2007).

2.2.2.1.1.2 Received Signal Strength (or Attenuation)

The Received Signal Strength (RSS) method uses the intensity of the signal emitted to measure the distance between a transmitter and its receiver. This method is also called "attenuation" (Svalastog, 2007, p.19). In fact, the distance between the two objects impacts the strength of the signal. The longer the distance between the two objects is, the weaker the signal is compared to its original recorded strength. A specific algorithm using the correlation between the original signal strength and the decreased signal strength is then used to estimate the distance.

The environment is the other factor which can affect the signal strength. Walls or the weather can cause signal strength degradation (Alarifi, *et al.*, 2016, p.11). Fortunately, there are formulas considering signal path loss when compiling the distance.

2.2.2.1.2 Triangulation

The term "Triangulation", often mistakenly used to describe trilateration, is another type of position estimation using geometric properties. Triangulation uses angle and distance measurements to determine the position of the OOI (Henniges, 2012; Svalastog, 2007, p.20).

If the length of a vector's segment is known, the law of sines can then be used to calculate the position of the OOI. In a two-dimensional area setup, two angles measurements and one segment length are required to make triangulation possible (Adalja, 2013; Svalastog, 2007, p.20).

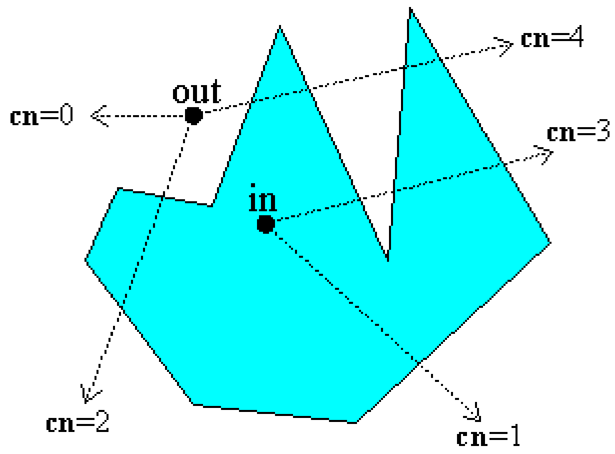
2.2.2.1.3 Point-In-Polygon algorithms

The point-in-polygon (PIP) problem in computational geometry refers to the issue of determining whether a specific point is inside or outside the boundary of a polygon. A polygon is simply a plane figure with at least three straight sides and angles. In geographic information systems (GIS), polygons are used to represent locations or venues (Demsey, 2012; Lawler & Schiess, 2013). This can be a country, a region, a farm or even a building. If each corner of a venue can be identified, the venue can be represented as a polygon.

The PIP problem is generally solved with the following two algorithms: Ray casting algorithm (also called the Crossing number algorithm) and the Winding number algorithm. Many programming languages (e.g. Matlab) have implemented these techniques' and, therefore, provide the ability to solve the PIP problem within a computer program (Sunday, 2012).

2.2.2.1.3.1 Ray casting algorithm (also called the Crossing number algorithm)

The Ray casting algorithm is an technique which draws a one-direction ray from the point evaluated to the edge(s) of the related polygon, and depending on the number of times the ray crosses the polygon's borders, it determine whether the evaluated point is inside or outside the surface of the polygon. If the count is odd, the evaluated point is situated inside the polygon; otherwise, the point is situated outside the polygon (Sunday, 2012). In case the point is situated on the edge of the polygon, the count can return an even or an odd number, depending on the computation rules applied. See **Figure 2-2: Illustration of the Ray casting algorithm**.



"**cn**" stands for "**Count**"

Figure 2-2: Illustration of the Ray casting algorithm

2.2.2.1.3.2 Winding number algorithm

The Winding number algorithm, which is mostly used for complex types of polygons, is based on the count of the number of times the polygon winds around the evaluated point (Sunday, 2012). With this technique, the point is deemed situated outside the surface of the polygon only if the count is equal to zero (wn = 0); otherwise the point is inside. According to Sunday (2012), the Winding number algorithm should always be preferred over the Ray crossing algorithm because it is generally more accurate, although proven equally efficient.

2.2.2.2 Scene analysis

The scene analysis category regroups all the positioning detection techniques which rely on pre-recorded information about a location to achieve an accurate estimation of OOI within the setup (Adalja, 2013; Svalastog, 2007, p.21).

Scene analysis techniques do not depend on geometric properties of elements in the location. With wireless technology, angle or distance measurements happen to be very challenging at times. Instead, with scene analysis techniques, measurements can be done using passive observations and other features unrelated to geometric principles (Dalce, *et al*., 2011).

However, scene analysis algorithms rely on known data about the location and infrastructure used to enable position detection. This dependence makes scene analysis less dynamic than geometric properties-based algorithms (Hu, 2013, p.22). In fact, whenever the environment changes, the system needs to be reconstructed with a new dataset. In addition, with scene analysis, a consequent amount of manual work is required in advance (Svalastog, 2007, p.21).

The following paragraphs describe some of the most prominent positioning detection methods classified as scene analysis techniques.

2.2.2.2.1 Fingerprinting

Sometimes referred to as signal strength profiling, fingerprinting is a form of scene analysis where the strength of the signal from all transmitters in the range of the targeted area is recorded after being measured in certain positions. All measurements along with the associated positions are kept in a database (Hu, 2013, p.19-22).

Thereafter, the positions of an OOI are estimated by comparing the strengths of the signal emitted from the transmitters to the set of data stored in the database.

2.2.2.2.2 Visual scene analysis

This method is essentially based on using a set of cameras or other optical devices in the targeted location to estimate the position of an OOI (Alarifi, *et al*., 2016, p.11; Svalastog, 2007, p.21). Recently, this method has become popular among sports fans as it is now used in many sports to review tight decisions. For example, goal-line technologies in football or the challenge system in tennis make use of visual scene analysis-based techniques.

2.2.2.3 Proximity sensing

The proximity sensing positioning method works by detecting a nearby object from a known position. The nearby objects are detected using wireless signals or simply by a physical contact (Adalja, 2013). This technique is often considered as a technical nightmare as far as its deployment and maintenance are concerned. In addition, the costs involved are quite high (Svalastog, 2007, p.21).

In this wireless signals setup, the accuracy of the targeted position varies based on the number of detectable devices and the length of the coverage area (Svalastog, 2007, p.21). If there are many devices in a short range, the position’s estimation tends to be accurate. On the other hand, if there are few devices in long range, the estimation is less likely to be accurate.

2.2.2.4 Dead reckoning

The dead reckoning technique determines an OOI's current position using an estimated velocity through a precompiled position. In dead reckoning, all computed positions are related. In fact, any current position depends on its predecessor and so on. This can easily cause the method to report errors. This explains the weakness of this technique (Alarifi, *et al*., 2016, p.10; Farid, *et al*., 2013).

.

However, currently, dead reckoning uses other methods as a workaround for its well-known weakness. The secondary method is used to update the positioning system following a pre-defined interval of time, so the dead reckoning method can get back in sync. This also appears to be a weakness as it actually highlights the unreliability and dependence of this positioning technique (Alarifi, *et al*., 2016, p.10; Hu, 2013, p.10).

Despite its shortcomings, dead reckoning has the advantage of not continuously depending on any external presence or wireless signal to determine an OOI's positions (Alarifi, *et al*., 2016, p.10). This makes the positioning process possible even in the case of network failure. Nowadays, many mobile devices use their embedded sensors to achieve OOI's positioning through this technique (Hu, 2013, p.10).

2.2.3 Modern positioning systems

Positioning systems have gained great popularity since the advent of mobile apps and the various location-based services they require. Technologies such as GPS, Wi-Fi, Bluetooth or Infrared, which are currently used to enable positioning systems, are well-known to mobile users and their improvements are closely monitored (Farid, *et al*., 2013). Despite their increased popularity in recent years, positioning systems and their enabling technologies have been around for a long time.

Over thirty years ago, the US military invented the first commonly used positioning system: the GPS (Henniges, 2012). Since then, positioning systems have emerged and today there are many types of positioning systems using different techniques and approach to reach a common goal: identifying objects' locations in specific spaces. Some of these systems focus on the global positioning of objects, by representing objects' position in relation to the world sphere, while others are set to locate objects within a delimited region of the globe.

Based on their utilities, areas of focus and architectures, positioning systems can now be categorised following various criteria. These categorisations allow people to select the most appropriate system for a specific context. Some systems are better suited for indoor locations while others work better in an outdoor setup.

The following paragraphs group and classify systems according to the technologies embedded. A description of each listed positioning system is provided, and its advantages and disadvantages are also discussed.

2.2.3.1 Satellite-based positioning systems

Satellite-based positioning systems are the positioning systems which depend on a constellation of satellites emitting positioning signals (Henniges, 2012). The US Military invented the first satellite-based positioning system: the GPS. The project was launched in 1973 and became fully operational in 1995. Since then, GPS has remained the most prominent satellite positioning system (Huber, 2011; Svalastog, 2007, p.2).

Positioning systems using satellite signals require up to 32 satellites to estimate the position of a Mobile Station (Huber, 2011). These satellites send two types of signals to enable positioning systems: the Precise Positioning Service (PPS), which is reserved for military use only, and the Standard Positioning Service (SPS), which is free and intended for public use.

2.2.3.1.1 Global Positioning System

The GPS is the most popular and prominent positioning system. Most mobile devices today are equipped with GPS receivers to enable navigation and other mobile users positioning needs (Huber, 2011). GPS is deemed accurate enough and adapted for most location's estimation situations. Over the years, GPS has simply become the default positioning system.

GPS satellites signal broadcast time and orbital information, which are needed by GPS receivers to determine positions. In a mobile device setup, GPS receivers require at least four of those signals to provide information about an object's longitude, latitude and altitude. This essentially represents a three-dimensional positioning model. In addition, GPS is very precise, available twenty-four hours and can achieve an accuracy of up to 20 metres (Huber, 2011).

However, the GPS also presents some flaws which have led specialists to develop other positioning systems. Every positioning system developed after the GPS simply tries to cover a certain kind of limitation of the GPS. In fact, GPS requires a lot of electric power to function, takes a long time to boot and read the position (poor latency), and its quality depends on various external factors such as the weather and a clear view of the sky (Huber, 2011).

The latter is one of its worst weaknesses. It has been exploited by competitors to develop other systems. In fact, the GPS needs a clear view of the sky to function well. Therefore, it does not work well in indoor locations (Svalastog, 2007, p.23). The construction material, walls and ceilings make satellite signals unavailable. Despite a few improvements over the last few years, GPS is still not the most appropriate positioning system for indoor locations (Svalastog, 2007, p.2).

2.2.3.1.2 Assisted Global Positioning System

To overcome the poor latency, signals unavailability and the high power consumption challenges, another positioning technique has been developed where the traditional GPS receivers are used in association with cellular positioning methods (Huber, 2011). The data originating from cellular positioning systems are downloaded in the background and used in the gap when and where needed.

This “improved” technique does not solve all the challenges as the data download may fail because of a poor network connection, and the associated method of detection may also require high power consumption (Huber, 2011). However, the latency or the speed of the Time-to-First-Fix (TTFF) has higher chances of improvement than when it depends on the GPS alone.

The GPS used in most smartphones is actually an A-GPS (Huber, 2011). That is simply because cellular phones are in constant need of a cell tower connection. Therefore, it is easier to store and use the cellular data and information they acquire from the cell tower to improve positioning. This saves mobile the mobile device’s battery power, and improves latency and accuracy.

2.2.3.2 Network-based positioning systems

This category defines all positioning systems which depend on a network to position an object. This can be a cellular network, a wireless local area network or any other kind of network which can be used to determine the location of an object.

Often the positioning systems of this category use geometric properties-based algorithms or methods to determine positions. Methods such as trilateration or other types of "Multilateration" with algorithms such ToA, TDoA or Angle of Arrival (AoA) form the basis of network-based positioning systems. In addition, other techniques such as fingerprinting can also be used.

2.2.3.2.1 Cellular network-based positioning system

The Global System for Mobile Communications (GSM) network is the core of cellular network-based positioning systems (Adalja, 2013; Henniges, 2012). GSM are available world-wide and can be used for increasing positions' detection.

The GSM function in specific licensed bands and do not interfere with other devices operating at a similar frequency. Because GSM are available within venues, it is possible to use cellular network-based positioning systems indoor.

The RSS and fingerprinting make it possible to use cellular network-based positioning system indoor. The quality of the indoor service however depends strongly on the network coverage received and the strength of the signal (Adalja, 2013).

However, whether indoor or outdoor, this positioning system is not the most accurate of all. It displays accuracy of 50 to 200 metres (Adalja, 2013). In addition, in cellular network-based positioning systems, the accuracy varies depending on the GSM coverage received. Therefore, it shows better accuracy in urban areas where the coverage is dense and lower accuracy in rural areas where coverage is limited.

Despite these limitations, this positioning system is still widely used in cellular phones and helps to improve the quality of the GPS in the combo positioning system called "Assisted GPS".

2.2.3.2.2 Wi-Fi-based positioning system

Wi-Fi has gained so much popularity in the last years with the ever-increasing popularity of mobile devices (Shah & Shah, 2012). The need for Internet connection on the fly, free of the traditional wire-connected networks, has played in favour of the Wi-Fi technology. Today, public spaces in big cities, restaurants, buses and all other places with a high frequency of human activities all provide users with access to the Internet through hotspots, thanks to Wi-Fi enabled networks (Shah & Shah, 2012).

Despite only being recognised in recent times by the vast majority of the public, the Wireless Local Area Network (WLAN) standard (the IEEE 802.11) was established in 1997. Wi-Fi is the most prominent application of the IEEE 802.11 standard (Shah & Shah, 2012; Svalastog, 2007, p.29; Alarifi, *et al*., 2016, p.9).

Today, Wi-Fi does not just enable wireless connections for Internet users, it is also used in many implementations for enabling objects' location estimation within a defined space. Wi-Fi positioning systems work well in indoor setups, demonstrating good accuracy (Shah & Shah, 2012; Svalastog, 2007, p.29-31; Alarifi, *et al*., 2016, p.9).

Fingerprinting and RSS are well-known for being used in the implementation of Wi-Fi-based positioning systems (Alarifi, *et al*., 2016, p.9). Scene analysis is done in the targeted area and data about various measures are kept in a database. The positioning system is then made available for mobile users in the venue. In 2001, Microsoft RADAR was the first Wi-Fi based positioning system (Dalce, *et al*., 2011).

As per Alarifi, *et al*. (2016, p.9-11) and Dalce, *et al*. (2011), the advantages of the Wi-Fi based positioning systems are:

- Low cost of implementation
- Relatively easy implementation as the material is already available (no extra material other than Wi-Fi network equipment needed)
- Great accuracy and precision

On the other hand, Wi-Fi-based positioning systems are criticised because of the following flaws or limitations (Alarifi, *et al*., 2016, p.9-11; Dalce, *et al*., 2011):

- Limited coverage area
- They depend on scene analysis techniques, which often require complete overhaul when the venue's infrastructure changes
- The more users connected to network, the lower is the bandwidth, and thereby, the availability of the system is affected
- High power consumption

However, great technology firms like Google, Apple or Nokia have adopted Wi-Fi-based positioning systems as a core enabling agent of their location-based services (Huber, 2011). Wi-Fi-based positioning systems are required by those main location-based services to increase accuracy. See **Figure 2-3: Google Maps App requesting user to turn on Wi-Fi on his device for better location accuracy**

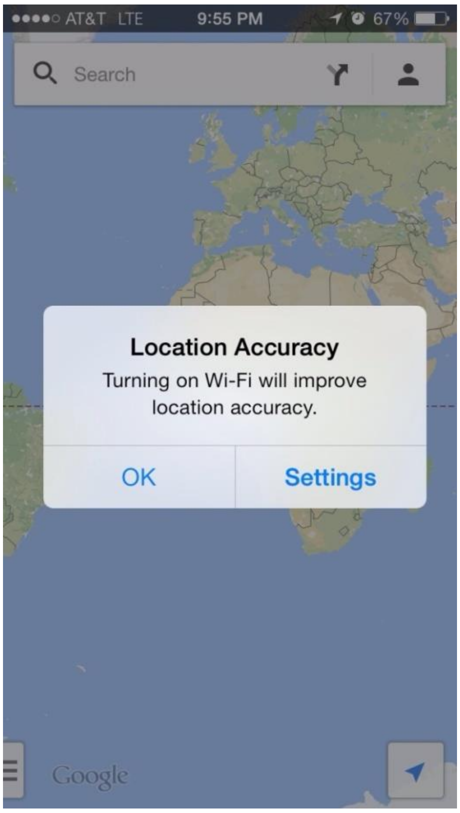


Figure 2-3: Google Maps App requesting user to turn on Wi-Fi on his device for better location accuracy

2.2.3.2.3 ZigBee-based positioning systems

Following the IEEE 802.15.4 standard, the ZigBee-based positioning systems are generally mid-range positioning systems relying on a wireless personal area network to provide information about an object’s location (Chao, Chan, Hsu & Hung, 2007). ZigBee-based positioning systems calculate an object’s position based on coordination and communications between adjacent nodes in the ZigBee network. The RSS positioning technique is often used in these systems (Alarifi, *et al*., 2016, p.9-11).

ZigBee networks were not originally conceived for positioning. Their prime need remains to enable wireless communications for end-users’ devices. ZigBee networks are composed of a coordinator, a router and at least an end-user device. This network can be configured in many topologies (star, bus, mesh, ring or tree), but the mesh topology is the most efficient (Svalastog, 2007, p.33-34).

Relying on ZigBee sensors and network, ZigBee-based positioning systems are considered as a low cost, low complexity, low latency and low power consumption systems (Alarifi, *et al*., 2016, p.11; Svalastog, 2007, p.34). In addition, it is scalable and distributed.

However, ZigBee-based positioning systems suffer from interferences because they operate in the same spectrum as other radio frequency signal types (Alarifi, *et al*., 2016, p.11). Also, ZigBee-based positioning systems are not the most accurate technology for indoor and outdoor positioning. Some commercial positioning systems use a combination of Wi-Fi and ZigBee to achieve better accuracy (Farid, *et al*., 2013).

2.2.3.3 Short-range positioning systems

The short-range positioning systems are those which cover relatively small areas. They often make use of technologies based on radio frequency (Liu, 2014; Tristant, 2009). The radio frequency signals are emitted from three or more transmitters to a multi-channel receiver attached to the OOI. Generally, the positions of the transmitters are known in advance (Liu, 2014; Svalastog, 2007, p.12-13).

Short-range positioning systems are receiving particular attention in the indoor positioning systems sphere (Foerster, Green, Somayazulu & Leeper, 2001). They seem to work better than GPS in indoor setups, and they are regularly improved to solve the different challenges presented by indoor positioning of mobile devices.

This section groups and discusses some of the most prominent and promising short-range positioning systems as per their core technologies.

2.2.3.3.1 Infrared-based positioning systems

The infrared technology was discovered over two centuries ago. Half of the energy of the Sun is said to be reaching the earth as infrared radiation. Infrared or infrared radiation (IR) is invisible electromagnetic radiation with long wavelengths (Adalja, 2013; Rowan-Robinson, 2013, p.13). Since the apparition of smart mobile devices, infrared is one of the most used technologies for enabling wireless communication between devices, and data sharing.

The infrared technology operates well indoor, even though the radiation can be obstructed by walls or other construction materials (Alarifi, *et al*., 2016, p.11; Farid, *et al*., 2013; Svalastog, 2007, p.27-28). Infrared is affordable, displays a simple structure and does not consume much power. In addition, when used in positioning systems, infrared's reported accuracy is really good compared to that of other technologies.

According to Svalastog (2007, p.27-28), infrared positioning systems are enabled by transmitters and receivers. Receivers are attached to OOIs. Infrared can be used as direct IR or diffuse IR. Direct IR functions well in within very short distances while diffuse IR can cover longer distances up to twelve meters. Direct IR is used for point-to-point communication while diffuse IR can be used in multidirectional connections. Geometric propriety-based algorithms such as AoA and positioning techniques such as proximity sensing can be used with IR (Alarifi, *et al*., 2016, p11; Farid, *et al*., 2013).

2.2.3.3.2 Bluetooth-based positioning systems

Invented in 1994, Bluetooth is a standard for wireless personal area networks. Initially conceived as an alternative to traditional data cables, Bluetooth uses radio frequency technology and can connect up to seven devices (Bekkelien, 2012, p.11-12). Bluetooth's power consumption is very low. The Bluetooth sensors operate in the 2.4 GHz spectrum and are not exempt of interferences from other radio frequency technologies (Adalja, 2013).

Initially designed for peer-to-peer connections and data exchanges, in the positioning context, Bluetooth is mostly used with methods like proximity sensing or RSS to determine an OOI's position. But methods like scene analysis and trilateration can also be used (Adalja, 2013; Alarifi, *et al*., 2016, p.11).

While Bluetooth positioning systems work well indoor, they only cover short-range areas (Alarifi, *et al*., 2016, p.11). However, Bluetooth has the advantage of an easy integration with mobile devices because of its small size and simplicity of integration (Farid, *et al*., 2013).

A few years ago, a new feature of Bluetooth, called Bluetooth Low Energy (BLE), was released. The BLE's power consumption is even lower than the previous version of Bluetooth, and its latency is also lower. Although operating in the same 2.4 GHz spectrum, this version of Bluetooth deals with interferences (Alarifi, *et al*., 2016, p.11).

Lately, BLE beacons, also called iBeacons, have received particular attention for indoor positioning systems and the Internet of things. BLE beacons are hardware pre-positioned in a venue to serve as signal transmitters to mobile devices. Companies such as Google, Apple and Nokia have now designed their mobile devices as receivers for open interactions with BLE beacons (Tillison, 2016).

2.2.3.3.3 Ultra-wide band-based positioning systems

Ultra-wide band (UWB) is a radio frequency signal with a bandwidth greater than 500 MHz used as a communication channel sending out large amounts of data at low power consumption. The UWB technology works in a wide frequency band by sending short pulses using methods to spread radio energy with a low power density. The low frequency pulses allow UWB signals to pass through dense physical obstacles (Adalja, 2013; Alarifi, *et al*., 2016, p.9-11; Svalastog, 2007, p.34).

The UWB is a fairly new communication technology, and is currently used in various kinds of location-based solutions' experiments. The UWB is precise and accurate; it does not consume much power, and is relatively easy to implement at an affordable cost (Alarifi, *et al*., 2016, p.9-11; Farid, *et al*., 2013). So far, UWB has also proven to be efficient in outdoor as well as indoor venues. Additionally, it has the power of penetrating walls and other constructions materials which usually affect signals emitted by other kinds of technologies.

In positioning systems, the UWB can efficiently be used with various techniques and algorithms. Geometric properties-based techniques like Trilateration with algorithms such as ToF or TDoA can be used with UWB to determine OOIs' positions (Alarifi, *et al*., 2016, p.11).

The real limitation of UWB is its limited geographical coverage. Using UWB technology in ranges larger than a couple of hundred metres may require extra sensors to be purchased (Alarifi, *et al*., 2016, p.9-11; Farid, *et al*., 2013; Svalastog, 2007, p.34).
Generally, the UWB seems to attract many specialists with its characteristics for the implementation of future indoor positioning systems.

2.2.3.3.4 Ultrasonic-based positioning systems

Ultrasonic-based positioning systems are the ones based on mechanical waves called ultrasound waves (Farid, *et al*., 2013). They do not rely on lines of sight between the transmitters and the receivers. The ultrasonic positioning technology uses the same principle as radars: the distance between transmitters and receivers is measured by the echoes generated by the OOI (Farid, *et al*., 2013; Svalastog, 2007, p.37-38).

Ultrasonic-based positioning systems essentially use triangulation to determine OOI's positions. But methods such as proximity sensing or trilateration can also be used (Alarifi, *et al*., 2016, p.9-11).

Despite generating highly accurate readings ranging in centimetres, ultrasonic-based positioning systems suffer from signal loss because of obstruction, interferences from frequency sounds and false signals caused by reflections (Svalastog, 2007, p.37-38). In addition, the implementations of ultrasonic-based positioning systems are quite expensive.

Crickets, Acitive Bat and DOLPHIN systems are all examples of ultrasonic-based positioning systems (Liu, Darabi & Liu, 2007, p.1067-1079; Mautz, 2008; Svalastog, 2007, p.41-49).

2.2.3.3.5 Radio Frequency Identification-based positioning systems

A Radio Frequency Identification (RFID)-based positioning system is a short-range positioning system composed of RFID anchors, RFID tags and an infrastructure connecting the two types of components (Farid, *et al*., 2013; Svalastog, 2007, p.36-37). The RFID system uses the remote positioning system design with the tags sending radio frequency (RF) signals to the anchors.

RFID positioning systems can use one of two types of tags for positioning: passive and active RFID tags to transmit signals to RFID readers (Farid, *et al*., 2013; Svalastog, 2007, p.36-37). Passive tags work without batteries and are very cheap. Location accuracy is very high using this type of tag. However, they only cover a very short range of up to two meters. On the other hand, active tags use batteries and cover wider ranges, up to a hundred meters. But location accuracy is not as accurate using these tags (Liu, *et al*., 2007, p.1067-1079).

In general, RFID has demonstrated low latency in various experiments. The cost related to its implementation depends on the type of tags used. But the price of the readers (anchors) is expensive. The RFID-based positioning system can determine the OOI position based on trilateration methods such as RSS or ToA. (Alarifi, *et al*., 2016, p.11)

2.2.3.4 Other positioning systems

2.2.3.4.1 Inertial Navigation System

The Inertial Navigation System (INS) is a positioning system based on the dead reckoning positioning technique. Currently in mobile devices, INS is implemented using the device's various embedded sensors. These sensors are accelerometers, gyroscopes and/or compasses (Farid, *et al*., 2013; Hu, 2011). They are all used to compile OOI's positions. In this system, the orientation of the OOI can also be determined.
As explained in a previous paragraph, positioning systems based on the dead reckoning technique are prone to errors and, therefore, can only provide accurate positions for a short time. This positioning system is ideal for use when other reliable positioning systems are unavailable for a while.

2.2.3.4.2 Optical-based positioning systems

This category defines all positioning systems which are image-based, essentially camera-enabled. These kinds of systems use camera placed at specific positions, monitoring the OOI (Alarifi, *et al*., 2016, p.10; Svalastog, 2007, p.21). The other configuration is using a camera attached to the OOI and communicating the position of the OOI visually.

These kinds of systems are very accurate and precise, with low latency. Since most mobile devices are equipped with cameras, this method can be implemented to locate mobile devices. However, they are not really adapted for many types of applications. That is because they are expensive (Alarifi, *et al*., 2016, p.11), they also require a lot of power to function and the level of complexity can escalate quite quickly.

2.2.3.4.3 GeoIP (or Geolocation using IP addresses)

Another form of positioning systems is the GeoIP. GeoIP refers to the system of locating a computing device's geographic location by identifying its IP address. GeoIP can provide a device's location information (country, city, post/ZIP code) using a database of preloaded IP addresses along with their matching locations (MaxMind, 2012).

However, GeoIP is not as accurate as other positioning systems because it does not provide the exact coordinates of the OOI's location. Furthermore, it is also possible for experienced users to camouflage or alter their apparent location in GeoIP systems (Triukose, Ardon, Mahanti & Sethz, 2011).

The most prevalent application of GeoIP involves geo-targeting, or determining a device's location to restrict or allow users' access to content based on their global locations

(MaxMind, 2012). Geo-targeting is most often used for targeted advertising, statistical research, spam prevention, and for restricting access based on location.

2.2.4 Common evaluation metrics

There are various criteria on which positioning systems are evaluated. These indicators are universal and provide systems' users with an overview of their selections. These system's attributes are namely: accuracy, precision, availability, coverage area, latency, scalability, and cost (Alarifi, *et al*., 2016, p.2; Farid, *et al*., 2013; Svalastog, 2007, p.14-17; Liu, *et al*., 2007, p.1067-1079).

This section of the research describes each criterion and provide its expectation in positioning systems being evaluated.

2.2.4.1 Accuracy and precision

While the term "accuracy" refers to the closeness of a measurement to its actual value, the term "precision" refers to the comparison between two or more measurements of the same object with the preconditions (Farid, *et al*., 2013; Svalastog, 2007, p.14).

Although the two terms are often used together or interchangeably, they actually remain independent. A measurement can be accurate but imprecise, and vice versa.
As an illustration of the contrast between the two terms, one can consider a weight scale device. When weighing an object, if the actual weight of the object is 5kg and the device reports 3kg, the measurement will be judged inaccurate. But, if the scale reports the same value for the same object at each measurement, the measurements are then said to be precise.

The same logic applies to the measurements in positioning systems. One system is judged more accurate than the other when it reports a closer gap between the real-world values and virtual values than the gap reported by the other system. On the other hand, a system is deemed precise if it reports measurements' values which are close to each other.

However, accuracy and precision in a positioning system depend on a few factors: the limitation of the hardware used to build the system, the structure of the location modelled and the algorithms used to compile the values (Alarifi, *et al*., 2016, p.2; Svalastog, 2007, p.14).

These elements influence the quality of accuracy and precision reported by positioning systems.

Various kinds of hardware are used to build positioning systems. For example, a satellite is part of the equipment used in the GPS system. A satellite plays the role of a transmitter and a receiver is embedded in the device tracked. Unfortunately, the values emitted by the GPS are not perfectly accurate (Svalastog, 2007, p.2). In fact, no positioning system demonstrates perfect accuracy.

The measurements emitted by positioning systems always differ to their real-world values. For most positioning systems, the range of the gap between the actual values and the virtual values varies from a few centimetres to a good few tens of meters. A few tens of centimetres of gap is often enough to represent the object in location-based applications.

As per Farid, *et al*. (2013), Svalastog (2007), Liu, *et al*. (2007, p.1067-1079), the following levels of accuracy thresholds which are used to evaluate modern positioning systems:

Table 2-1: Accuracy levels thresholds for positioning systems

Accuracy Level	**Margin of Error**
Low	Greater than 5 metres
Medium	1 metre to 5 metres
High	Less than 1 metre

2.2.4.2 Availability

This criterion expresses the average percentage of time in which a positioning system is accessible and not affected by external factors. In fact, apart from the limitation imposed by the hardware and the kind of technology used to propagate signals, the structure of the location in which the object represented is situated sensibly impacts the availability of the positioning system (Adusei, *et al*., 2002; Alarifi, *et al*., 2016, p.6). Whether it is an outdoor or indoor location as described in an earlier section of this research, a venue’s structure encloses characteristics which must be considered when modelling an object’s position.

For instance, when representing the position of an object in an outdoor venue, the weather is a determining factor. A storming weather, rain, snow or wind can easily prevent satellites from transmitting signals needed by certain kinds of positioning systems. Often a clear sky is also a pre-requisite for the best accurate and precise readings in an outdoor setup. Natural obstacles such as trees or mountains also interfere with digital signals and impact availability, accuracy and precision of the systems.

As for indoor positioning, it is a very sensitive trending topic. This is subject to various on-going projects and studies. The representation of an object within an indoor location remains ambiguous. In fact, there is no standard as far as this kind of modelling is concerned. There are various methods of indoor positioning systems, and most of them are quite complex and difficult to implement (Alarifi, *et al*., 2016; Liu, *et al*., 2007, p.1067-1079; Svalastog, 2007).

The availability value indoor is affected by construction materials such as walls, concretes, irons or even dense wood which deteriorate the reception of certain kinds of signals, thereby annihilating signals' transmission or reducing the quality of the measurements emitted by positioning systems (Alarifi, *et al*., 2016).

Generally, the following thresholds are used to evaluate the availability levels of positioning systems:

Table 2-2: Availability levels thresholds for positioning systems

Availability Level	Percentage time of availability
Low	Less than 95%
Medium	Between 95% and 99%
High	Greater than 99%

2.2.4.3 Coverage area

The coverage area simply refers to the physical space or geographical area covered by a positioning system (Adalja, 2013; Farid, *et al*., 2013). Each system covers a certain range. The wider the range of coverage, the more efficient a system is rated.

According to Farid, *et al*. (2013), the levels of the coverage area of positioning systems are classified as per the following three thresholds: local, scalable and global coverages.
Local coverage defines a system's ability to cover a delimited and not extendable limited location such as a building. Scalable coverage refers to a system's ability to extend coverage beyond an area's boundaries, given the necessary hardware to implement such extension. Global coverage refers to the coverage level of systems such as GPS, where coverage is intended for the entire world's sphere.

2.2.4.4 Latency

Latency is the delay it takes for a positioning system to boot before it can make the first reading (Time-to-First-Fix). This interval of time can be crucial in systems where users are allowed to have control over a system's "on and off" switch. Apart from the standalone GPS and Bluetooth at times, most modern positioning systems achieve a latency of 10 seconds or less (Adusei, *et al*. 2002; Farid, *et al*., 2013).

In fact, in positioning systems, the target is to achieve the lowest and shortest latency possible. Other than saving time, short latency also prevents excessive power consumption (Farid, *et al*., 2013). Latency is often measured in seconds. Apart from the technology used, the latency variable greatly depends on the measurement techniques used.

2.2.4.5 Scalability

2.2.4.5.1 Easy deployment, integration and configuration

A positioning system should be easy to build, deploy, integrate into a new or existing environment, and easy to configure and maintain. Deployment and maintenance are facilitated by a reduced number of transmitters and receivers as well as a limited number of wire-based components (Svalastog, 2007, p.15). This explains the preference for wireless technologies in the implementation of modern positioning systems.

2.2.4.5.2 Power consumption

Some of the positioning systems' components require more power than others to function. In fact, in systems which cover wider spaces and make use of a large number of components, the power supply requirement is higher than in relatively small systems (Farid, *et al*., 2013; Svalastog, 2007, p.16). However, excessive power consumption quickly drains power from small components such as mobile devices or other wireless devices where power supply depends on a small-size battery directly attached to the device.

Therefore, power consumption considerations are very critical when designing or evaluating a positioning system. Apart from the technology and sensors used, the methods or algorithms used as well as the interval of data update also affect the systems' power consumptions. In general, power consumption is measured in a Watt (w)-based unit. However, nowadays, most mobile devices can also express power consumption in percentage (%). This expression is easier to understand for end-users.

According to Zhang, Tiwana, Dick, Qian, Mao, Wang and Yang's team (2010), an active GPS consumes 429 milli-watts (mW) from mobile devices, while the Wi-Fi requires about 710 mW to operate. The latter roughly translates into ten percent (10%) of mobile device power consumption per hour. However, when the Wi-Fi is intensively used in dedicated location-based applications, this figure tremendously increases (Carroll & Heiser, 2010).

These figures are still considered high. For comparison sake, when a mobile smartphone is fully awake and idling (not running any application), it only consumes 269 mW (Carroll & Heiser, 2010).

2.2.4.6 Cost

The cost of a system includes costs required for development and installation, any expenses required to maintain the system functionalities, as well as the cost of infrastructure components. This may include the costs of buying components and preparing them, as well as space and energy needed to run those components. The cost at various stages of system's lifecycle must also include the wages of the personnel required to undertake the specific development, installation and maintenance tasks (Alarifi, *et al*., 2016, p.5-6; Svalastog, 2007, p.17; Farid, *et al*., 2013).

The cost is evaluated in terms of money, expressed in a defined currency. The cheaper the system, the better it is for all system's stackholders.

2.3 Comparative study

This section focuses on comparing the various positioning systems and techniques they use to determine OOI's positions. Thereafter, the positioning system better suited to solve the problem raised in this research, along with its associated techniques of position detection, is discussed in details. Finally, a selection of the most recent work addressing similar challenges is listed and discussed.

2.3.1 Positioning systems comparison

In **Table 2-3**, positioning systems based on different technologies using the most relevant performance metrics to this research are compared. This survey is based on the views of the following authors: Alarifi, *et al*. (2016), Farid, *et al*. (2013), Liu, *et al*. (2007), Liu (2014), Mautz (2008), Svalastog (2007) and others.

Table 2-3: Comparison of some of the most prominent positioning systems

Positioning System	Common measurement techniques	Average Accuracy	Availability		Coverage Area	Power Consumption	Cost	Comments
			Indoor	Outdoor				
GPS	ToA, TDoA	Low	Low	High	Global	High	High	Very reliable; slow computation time and high latency
A-GPS	ToA, TDoA	Medium	Medium	High	Global	Medium	Medium	Improved accuracy and latency compared to GPS
Wi-Fi	AoA, RSS, Fingerprinting	Medium	High	Medium	Local	High	Low	Expensive initial deployment , but convenient
ZigBee	RSS, Fingerprinting	Medium	High	Medium	Local	Low	Low	Low transmission rate, complex network design
Cellular-based	RSS, Fingerprinting	Medium	Medium	High	Scalable	Unknown	Medium	Suffer from SIM card dependence
Infrared	Proximity, ToA	Medium	Medium	Medium	Local	Low	Low	Direct line of sight required
Bluetooth	Proximity, RSS	Medium	High	Medium	Local	Low	High	BLE and iBeacons popular indoor; high latency at times
UWB	ToA, TDoA, AoA, RSS	High	High	High	Scalable	Low	Medium	Highly accurate (15 cm) and very precise (99% within 30 centimetres) ; may interfere with GPS signal
Ultrasonic	ToA, AoA	High	High	Low	Scalable	Low	High	Operates unlicensed, sensitivity to environmental noise, but highly accurate – down to a few centimetres
RFID	Proximity, TOA, RSS	Medium	Medium	High	Local	Low	Low	Manual programming, high response time
Inertial Navigation	Dead reckoning	Low	High	High	Global	Low	Low	Prone to bias and drifting

2.3.2 Verdict: UWB-based positioning systems

Location accuracy is at the centre of the solution required to address this research's problem. Therefore, it is necessary to analyse and find the most accurate positioning technology and techniques to possibly serve as the basis for the solution sought in this work.

According to the classification of positioning systems following their performance metrics evaluation, ultrasonic-based positioning systems and UWB-based positioning systems appear to be the most accurate systems among all those listed.
However, ultrasound technology suffers from a great level of interference in its frequency band and cannot pass through obstacles (Farid, *et al*., 2013). Furthermore, the cost of ultrasonic equipment is just so high (Farid, *et al*., 2013; Svalastog, 2007, p.36-37). Therefore, in this research, the choice is ported towards UWB for building a solution to the research problem.

UWB technology is deemed far more accurate than technologies such as GPS, Wi-Fi or Bluetooth (Alarifi, *et al*., 2016, p.11; Farid, *et al*., 2013; Pozyx, 2016; Svalastog, 2007, p.36-37). UWB is accurate in both indoor and outdoor venues. In addition, it works well in small spaces and shows low latency. The latter is needed for fast detection of users in the range of the targeted venue, as required in the research's problem statement.

The UWB technology was first used by the US Department of Defence, and it was made commercially available in 1990 (Bellusci, 2011). As described in an earlier paragraph, UWB is an RF technology which is mostly used for real-time positioning and tracking, for communication and sensors as well as for developing radars. UWB is very accurate in positioning and location estimation.

As presented in the table above, when used in positioning systems, UWB equipment is not very expensive and generally does not consume much power (Alarifi, *et al*., 2016, p.11; Bellusci, 2011). UWB technology covers a good range and does not require a line of sight to function efficiently, since its signals can penetrate obstacles. In addition, UWB-based positioning systems can be developed using various techniques and algorithms.

In fact, UWB-based positioning systems can be built using geometric proprieties-based algorithms and techniques (Alarifi, *et al*., 2016, p.23-24). The UWB system can use both trilateration and triangulation. It can rely on approaches such as ToA, TDoA, RSS or AoA. Furthermore, UWB positioning systems can be developed based on a hybrid algorithm combining any of the above-named algorithms (Alarifi, *et al*., 2016, p.22-29).

UWB can determine objects' positions in a two-dimensional location setup as well as in a three-dimensional setup (Alarifi, *et al*., 2016, p.24; Pozyx, 2016). This all depends on the system requirements and components' selection. In the case of a two-dimensional space representation, UWB requires at least two anchors to determine an OOI's position if the AoA method is used. For methods other than AoA, at least three anchors are needed. When a three-dimension OOI's representation is required, at least three anchors are needed if the AoA method is used. Otherwise, at least four anchors are required. Anchors are also referred to as reference nodes (Alarifi, *et al*., 2016, p.24; Pozyx, 2016).

2.3.3 Related work

Despite being used in various projects since its commercial use release in 1990, the concept of UWB technology for location-based solutions is still quite recent (Alarifi, *et al*., 2016; Bellusci, 2011; Rota & Montalto, 2017). There are a few commercial positioning systems in the market using UWB, but they are not yet popular among end-users. That is because they have not been fully integrated with mobile devices manufactured by leading brands. So, not everyone is aware of the opportunity of improvements offered by UWB.

However, there are very promising on-going research projects using UWB technologies and detection techniques to solve various objects' positioning challenges. In fact, since a few years ago, UWB has proven very useful in the development of the indoor positioning systems (IPS) (Berkeveld, 2016; Kulm, Parv, Rahman & Kuusik, 2016; Rota & Montalto, 2017). In accuracy and efficiency in small spaces occur to be game-changing factors in the race to set IPS standards.

Last year, a young organisation in Belgium was awarded with the Innovation of Things Award for developing a solution based on UWB technology for accurate positioning and motion information of objects within a predefined indoor location. Their award-winning solution is called "Pozyx". The project is still on-going and the product is currently undergoing various improvements (Pozyx, 2016).

Pozyx consists of five components: four (or more) anchors and one tag. The anchors, placed at the centre of each of the walls or borders of an indoor location, are essentially receivers which get signals from the tag which is the transmitter (Rota & Montalto, 2017). The position of the tag is then determined by a central computing unit following the trilateration technique. Pozyx allows real-time detection and can be used to model three-dimensional representation of OOIs (Berkeveld, 2016).

The high positioning accuracy of the Proxy system enables a lot of applications that were not possible before. For example, people can now program a drone or robot to navigate through a building without bumping into things (Pozyx, 2016). Currently, Pozyx is compatible with Arduinos, Raspberry pi and other types of computer using USB.

However, currently, the integration of the Pozyx system with mobile device is simply not realistic. That is because, at the moment, Pozyx is very costly, and its installation, which includes a few hardware components, is deemed too complex (Rota & Montalto, 2017). Furthermore, its size does not fit the specification of most modern mobile devices.

Another UWB-based positioning system project is Kio. Kio is also a scalable, real-time positioning system. Operating in the 31.-4.8 GHz range, Kio is cost-effective and used to locate objects in three-dimensions. Kio claims an accuracy error level below 30 centimetres. Kio is CE and FCC certified and can be used in commercial applications (Kulm, *et al*., 2016).

Kio is easy to setup and has been developed using trilateration with ToF algorithm. Kio comes with a C and C++ Application Program Interface (API) which facilitates integrations with existing systems. Kio can also track OOI in two-dimensional and three-dimensional setups. Kio reports the same high accuracy for indoor and outdoor venues (Kulm, *et al*., 2016).

3 CHAPTER THREE: RESEARCH APPROACH

3.1 Introduction

Oates (2005) believes every research needs to support the aspect of (1) purpose, (2) products, (3) presentation, (4) participants, (5) process and (6) paradigm. This research backs Oates' approach, and is conducted following this approach.

This research work covers Oates' approach as follow:

1. Purpose

   The aim of this research is explained in detail in Chapter 1. The research problem and the research objectives clearly are defined in the previous chapter.
2. Products

   As explained in the previous chapter, a technical artefact was developed as proof of concept to attempt solving the problem raised in this research.
3. Presentation

   This is the object of the publication of a thesis: to present this research, its origins and findings, to the rest of the scientific community.
4. Participants

   In this research, the participants were the people who developed the artefact and the mobile user(s) who tested the artefact.

The last two points of the Oates' approach (2005), process and paradigm, are elaborated in this section of the work. In fact, the choice of a research process and paradigm are often dictated by the type of research.

The problem raised in this research is expected to be addressed by developing a working positioning system with the most appropriate computing algorithms and positioning hardware. Thereby, this research problem can essentially be classified as a computer engineering problem. Computer engineering is a branch of engineering which relies on the integration of computer science and electrical engineering to build systems' software and hardware.

Therefore, this research model is set to address the problem in its two facets: its engineering dimension and its scientific dimension. A third dimension could be added to take on the social leg of the problem and measure the effects of the proposed solution on the "localness" of mobile user-generated digital contents. However, this facet of the problem is beyond the scope of this research.

Engineering is often referred to as the application of scientific knowledge to solve a real-world problem. Engineering generally produces an artefact which science can study and explain how and why the artefact works (Nallaperumal, 2007).

In fact, science focuses on explaining phenomena and extracting knowledge. Logic and mathematics represent the core of all other science disciplines (Freitas, 2009).
See **Figure 3-1: Classification of Sciences**.

The engineering facet of the research is concentrated on producing an innovative artefact following a set of activities defined by a specific problem-solving paradigm. The artefact is then evaluated in a scientific manner to assess its achievements, extract the necessary knowledge and set a platform for future work.

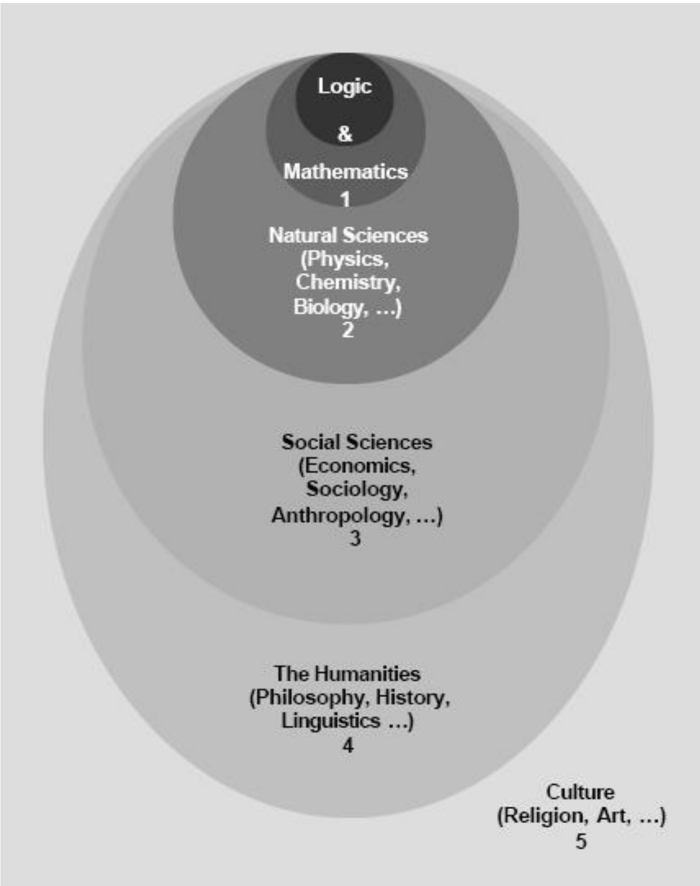


Figure 3-1: Classification of Sciences

3.2 Research paradigm

A paradigm is a framework of assumptions, real-world views and methodologies set to guide a scientific enquiry. According to Oliveira (2008), paradigms support theories based on concepts, phenomena and techniques for explaining new facts or information.

The constructive science paradigm, or constructivism, is the framework elected to conduct this research. According to Kabaso (2014), science can be categorised into three main areas: natural science, constructive science, and human and social science.

Kabaso (2014) argues that philosophy, despite being the basis of the human and social sciences, does not occupy the central place in natural and constructive sciences. In constructive science paradigm, the central point is the practice and what works is largely deemed to be true (Kabaso, 2014). Practice in constructive science is justified by the social world where long-term effects are studied.

Constructive science consists of design, project and prototyping (implementation) of a computer system or device (Oliveira, 2008). The objectives of the constructive science paradigm are to explicitly test a hypothesis and/or solve a real-world problem. Thereafter, a theory or a model is extracted from the artefact's evaluation.

The methods of evaluation include "analysis" and "verification and validation" (Oliveira, 2008). The analysis method consists of deductive reasoning, statistical analysis as well as approximations, while the verification and validation method is done following comparisons with existing prototypes. This is referred to as the hypothetico-deductive method. In constructive science, the end results can be measurement or analytical results. It is important to present the numerical results which verify the thesis (Oliveira, 2008).

3.3 Research process

The research process is a set of closely related steps or activities, sequential and/or iterative, which are followed by the researcher to develop a research project. Computer engineering being the combination of science and engineering, the iterative simplified research process proposed by Oliveira (2008) suits this research. See **Figure 3-2: The Simplified Research Process**

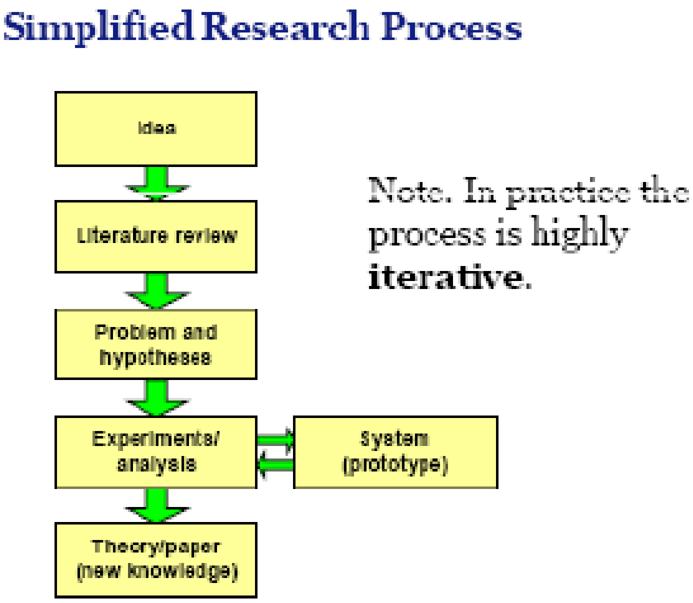


Figure 3-2: The Simplified Research Process

The first activity consists of generating an idea that becomes the centre-piece of the research. In engineering, a research problem can originate from an intuition, an observation, a guess, literature review or by chance. However, the idea emitted must be consistent with accepted facts and related theories, useful, testable and interpretable (Nallaperumal, 2007). This results in the development of a clear problem statement. This phase has been covered in the first chapter of this work.

The second activity is related to the literature review. In this step, the objective is to learn more and acquire more knowledge about the idea generated in step one through active reading. This clarifies the gap between the proposed idea and the current status of the research area (Nallaperumal, 2007). The literature review is a phase that is supposed to overlap with all subsequent phases of the process as it remains active throughout the entire research work. Literature review never ends; there are always new developments about a specific topic, and the researcher must remain an active reader (Nallaperumal, 2007).

This part of the process has been covered in the second chapter of this research. The output is the gap found between various positioning systems through the comparative study. Additionally, a few technologies and algorithms have been identified and used in the development of the artefact expected to test the hypothesis elaborated in this research.

The third activity of this research process pertains to the hypothesis to be tested in this work. The hypothesis is a logical assumption attempting to solve the research problem. It is often extracted from the literature review or from other authoritative sources, and serves as a guideline for the researcher in his quest to solving the research problem (Oliveira, 2008; Nallaperumal, 2007). One research project can generate many hypotheses.

In this research, the research questions elaborated in the first chapter are the framework of the hypotheses of this study. However, the hypotheses are summarised in the other section of the research, right before undertaking the research experiment.

The prototyping phase, which represents the fourth activity of the research, consists of selecting a set of components to develop the artefact. In this computer engineering research, this phase translated into a double activity where the artefact, the positioning system prototype, was iteratively developed and evaluated to minimise the construction errors. The iteration stopped once the artefact had reached a negligible level of construction errors.

The artefact was built based on the constructive science paradigm. Constructivism in this computer system engineering context resulted in the following outputs: system design, system implementation (prototyping) and system testing (evaluation). This fourth activity of the research process constitutes the focus of the very next chapter.

The artefact was then measured against other existing positioning system in a controlled experiment phase. This was the scope of the fifth activity of this project. The sixth and last activity of this research process model was the development of theories or new knowledge derived from the hypotheses specified in the experiment setup. This is the phase which focuses on elaborating theories based on the findings of the experiment exercise. This is the domain area where natural science applies (Kabaso, 2014).

In fact, natural science produces law-like statements and focuses on knowing the general rather than the concrete (Nallaperumal, 2007). Natural science applies the discovery paradigm to the artefact to produce a theory (Kabaso, 2007). In this research, this activity was conducted in Chapter 5, and focused on justifying the findings of the research and, thereby, validating or rejecting the research hypotheses. The resulting theories produced could benefit a future project in the same field.

4 CHAPTER FOUR: ARCHITECTURE AND IMPLEMENTATION

4.1 Introduction

In this section of the work, the focus is to report on the conception, development and deployment of the artefact: the prototype of the positioning system set to address the research problem. In fact, as presented in Chapter 1, this work bets on a dedicated positioning system to deliver a solution to the problem posed.

Following the literature review process, it has become clear that the idea is to create an UWB-based system, centred on its two-dimensional geometric properties-based algorithm for mapping a location and tracking the position of objects located within the location.
The system described in this section is essentially an application of the UWB positioning system.

Thereafter, one of the algorithms used to attend to the Point-In-Polygon problem was used to indicate whether an object is currently situated within the mapped location or not. The assumption is that this proposed system is a viable solution to the technical challenges of this research.

This chapter provides a detailed explanation on the choice and cost of components selected to build the system. The infrastructure and architecture of the system is also explained. Thereafter, the selection of the algorithms used are elaborated. Every step of the development and deployment process are detailed.

4.2 System architecture and infrastructure

The positioning system conceived in this work essentially follows the remote positioning architecture. The choice of this architecture is driven by one of the limitations of this research. In fact, this work does not look into designing an UWB sensor which can directly be integrated into a mobile device and be instructed by the mobile device's processor. This could be subject to another research project. Instead, this research project simply aims at demonstrating that the UWB technology is compatible with mobile devices in terms of power consumption and processing requirements. As a result, the choice of the remote positioning system architecture has been found adequate to serve the purpose of this work.
Additionally, this system architecture is deemed to be less power consuming than the self-positioning architecture (Farid, *et al*., 2013; Svalastog, 2007, p.14). That is because, in this

configuration, most data computation of the OOI position is delegated to a component other than the mobile device itself. The mobile device is not responsible for any data processing. The data collected regarding an OOI at a specific position is sent to a remote server for computation, thereby, allowing the mobile device to save battery power, thanks to limited processing work. Security and privacy not being at centre stage in this research, this architecture choice does not suffer from any side-effect.

This prototype system's architecture consists of one tag, at least three anchors and a remote server. The tag, which is attached to and powered up by a mobile device's battery, is set to send RF signals to each anchor (or receiver). The receiver then calculates its own distance to the tag, and forwards the data to the remote server for further processing. In this work, the anchors were the receivers placed at every designated point of the targeted venue. The number and positions of the anchors are determined by the shape and size of the polygon representing the surface of the location mapped.

In fact, in geospatial information systems, the standard is to represent geometrically real world places or venues as perfect multi-sided polygons (Demsey, 2012; Lawler & Schiess, 2013). That is the standard followed in this project. Each side of the polygon represents a border of the location. Placing the anchors at each corner of a venue helps store the fixed coordinates of a corner and the fixed coordinates of an anchor as a single variable. This eliminates the need of storing extra variables in the system. Furthermore, not only does it ease the computation of the PIP algorithm which serves to determine whether an OOI is inside or outside a mapped area, it also simplifies the computation of geometric properties-based algorithms such as trilateration or triangulation.

In fact, in this setup, trilateration (ToA or TDoA) is an option since the tip point of each corner can be used as the centre point of each virtual circle needed to determine the position of an OOI. On the other hand, triangulation (AoA) can use the angles represented by each corner, in combination with the distance between the tip of each corner and the OOI, to estimate the latter's position.

Furthermore, other points on the perimeter of the polygon can be nominated as additional holders of the anchors' positions if the distance between the anchors at each corner cannot be covered by the UWB sensors in use. The practice would certainly increase the cost of the system's infrastructure, but it would allow the system to fully cover the designated area.

As for the remote server, it is the central processor of the system. The remote server is an isolated component responsible for hosting the system's embedded software which stores predefined variables, computes the location of an OOI and specifies its position in relation to the mapped venue. In this work, the remote server is wirelessly connected to the rest of the system and receives data from the system's anchors at a pre-set interval via Wi-Fi signals. The computed data produced by the server are saved in a database. This data are analysed in a further section of this work.

In **Figure 4-1,** the architecture and infrastructure of this system is summarised.

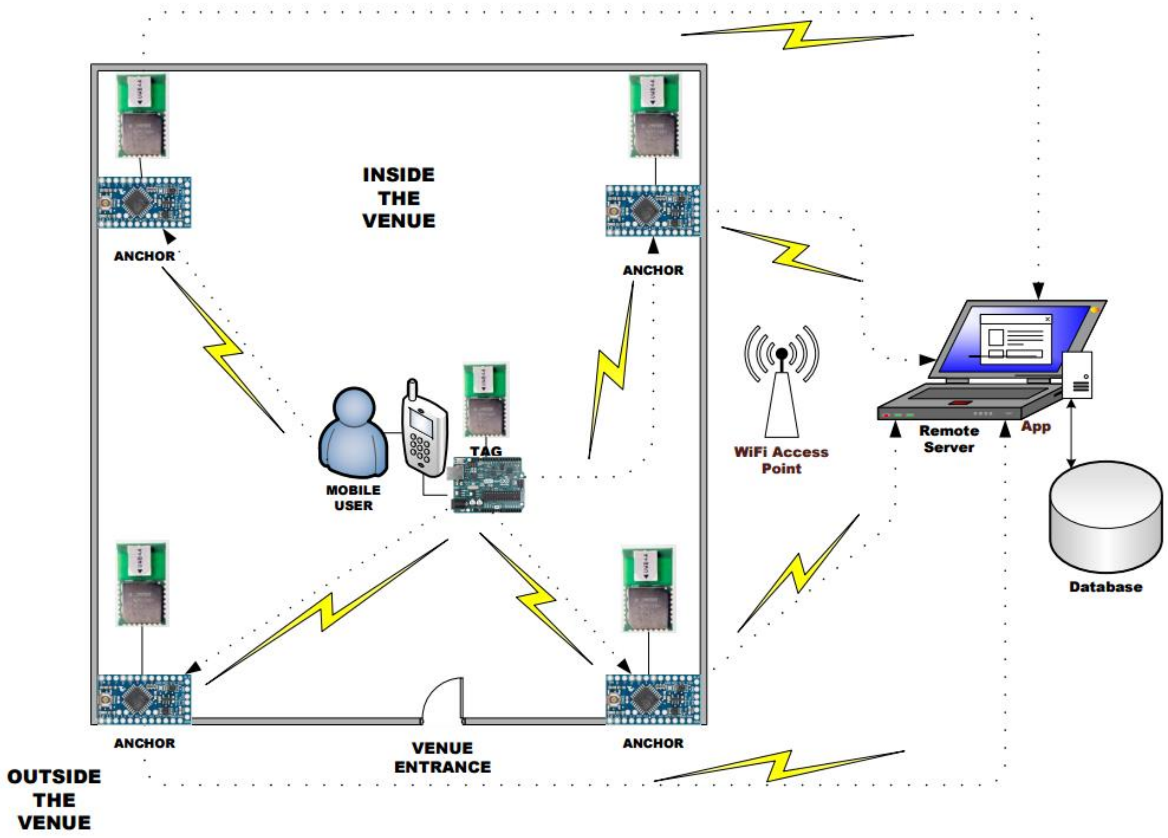


Figure 4-1: System architecture and infrastructure

4.3 System components specifications

The UWB technology is the core enabler of the system built to address the technical challenges of this research. The UWB technology used in this system essentially consists of an UWB sensor configured as the transmitter and a set of UWB sensors configured as receivers.

The UWB transmitter forms part of the tag, which is powered up by the mobile device's battery. On the other hand, the UWB receivers are used in the anchor components configured to receive data from the tag, compute the distance between itself and the tag, and forward the condensed data to the central remote server for further processing.

The UWB sensors used in this system are ScenSor DWM1000 modules. As per the manufacturer (DecaWave, 2013), the DWM1000 module is a low power consumption sensor, small-size IEEE802.15.4-2011 UWB compliant wireless transceiver module, allowing high rate data communication and suited for real-time location systems.

In **Figure 4-2** and **Figure 4-3**, the Arduino Pro Mini and the DWM1000 module used in this system are respectively illustrated.

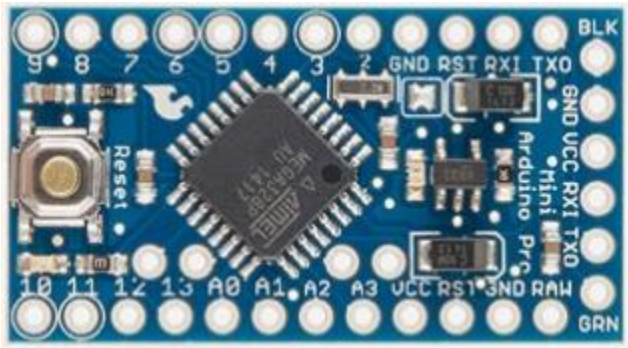


Figure 4-2: Arduino Pro Mini

Figure 4-3: DWM1000 module

In this prototype, the other essential components are the Arduinos used to hold the sensors and read the signals emitted and/or received by the sensors. The Arduino used to build the tag is a 3.3v Arduino Pro Mini. An Arduino Pro Mini is an open source electronic board and hardware which can sense physical real-world objects and control them as inputs and outputs following the user’s instructions via a programming language (Arduino, 2017).

In this context, it is powered up using a SAMSUNG S4 Mini. In fact, a SAMSUNG S4 Mini, with its 3.8v battery, is used as a power source for the Arduino. This has been made possible by using a USB On-The-Go (OTG) cable and FTDI USB to TTL serial cable to power up the Arduino through its serial port. In a future work where an UWB sensor is fully integrated with a mobile device, the mobile device can entirely inherit the responsibility of the role of the tag.

The same kinds of Arduino Pro Minis are used to build the anchors. They are powered up with 3.7 volts Li-ion Battery Dual USB power banks. They receive RF signals from the tag. A specific time of interval is required for data transmission to the server. Note that, in this case, if trilateration or triangulation algorithms are used, the times between all the Arduinos (tag and anchors) used in the system need to be synchronised (Dalce, *et al*., 2011; Svalastog, 2007, p.19).

In addition, the Arduino Pro Minis used for anchors are equipped with ESP8266 Wi-Fi modules. These serial transceiver modules are integrated in the anchor in order to enable wireless data sharing between the anchors and the remote server.

In this artefact, the remote server, which is the central processing unit of the system in this elected architecture, is simply a computer in which the positioning system's main software application is running. The software developed to operate this positioning system is a Microsoft .Net console application which stores computed data in a Microsoft SQL relational database.

The very same database serves as a data store for data sent from the system's anchors to the remote server. These data are used by the system's operating software to compute the current location of the OOI and flag its current position in relation to the mapped venue. All processing activities are set to happen in near-real-time.

Additionally, the software application makes use of various libraries in order to compute algorithms such as PIP algorithms and other geometric properties-based algorithms needed in the system.

4.4 System implementation cost

Building this prototype has only cost six thousands six hundred and four ZAR (R6,604.00). This cost only includes the main components purchased for the development of the artefact. The SAMSUNG S4 Mini mobile device and other cables used for connecting the Arduinos were already available to the researcher.

The details of the cost of each component of the system are provided in **Table 4-1**

Table 4-1: System components cost

System component	Quantity	Unit Price	Total Cost
Arduino Pro Mini	5	R 516.00	R 2,580.00
DecaWave DWM1000 transceiver	5	R 325.00	R 1,625.00
SAMSUNG USB OTG cable	1	R 50.00	R 50.00
FTDI USB-to-TTL 3.3v Cable (serial)	1	R 425.00	R 425.00
ESP8266 Wi-Fi module	4	R 121.00	R 484.00
3.7 volts Li-ion Battery Dual USB power bank	8	R 180.00	R 1,440.00
		Grand Total	**R 6,604.00**

As for the current implementation, with four anchors only, the system's coverage is strictly limited to areas with a radius of hundred and fifty meters or less (area radius <= 150 m). This coverage can scale up to cover wider areas, but it would require more funds, time and efforts. There would be a need for a few more Arduinos and sensors to setup more anchors. Thereafter, there would be need for time and efforts to configure and adapt the system to the new requirements. In short, the system cost can easily scale up, should the need to cover wider areas arise.

4.5 System software algorithms

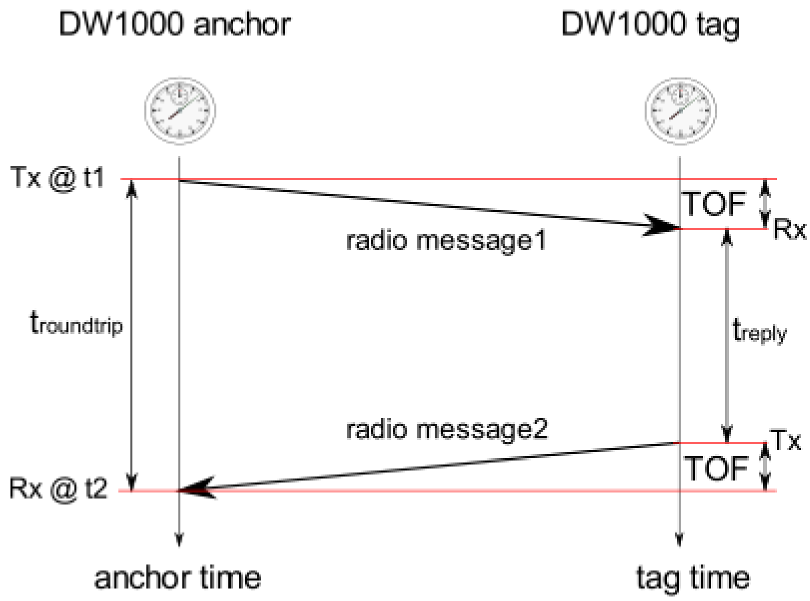
In this designated system design, the software application operating the system is actually the coordinator of all the heavyweight tasks assigned to the remote server. Without this embedded application, the remote server would only serve as a simple data storage box for the data provided by other system components.

In fact, this software application is responsible for reading the data received from system anchors, process it and store the structured data in a relational database. The same data is also used on the fly, or in real-time, to compute the location of the OOI and flag its position in relation to the identified venue. The results, which were used for system analysis and evaluation, are then saved in the database.

For the software application to fulfil its purpose and deliver the expected results, a set of computing steps needs to be executed in a specific order. The set of actions to be followed are the algorithms selected to address the software engineering challenges of this work. These algorithms are all different, serve different purposes, but are equally important. The system's objectives cannot be achieved if any of these steps are omitted.

The algorithms selected to solve this problem are all geometric properties-based algorithms. The Trilateration algorithm, which kicks in at the anchors' level, is used, following its two-dimensional principles, to determine the XY coordinates of the OOI location on the map. In fact, following Thotro Arduino Library (Kang, 2015), each anchor is responsible for compiling the distance between the transmitter and the receiver sensors.
In **Figure 4-4**, a snapshot of how the TDoA algorithm is implemented in this system following Kang's experiment (2015) is provided.

Once the distance is known from at least three anchors in the polygon, the data can be sent to the remote server for further processing. Thereafter, the winding number algorithm, used for the PIP problem, is applied to determine whether the point located is situated inside or outside the polygon representing the venue mapped.



$$TOF = \frac{t_2 - t_1 - t_{reply}}{2}$$

$$Distance = c \times \frac{t_2 - t_1 - treply}{2}$$

c = speed of the light

Figure 4-4: TDoA algorithm computation

The choice of the above algorithms is justified by the particularity of the problem posed. In fact, one of the problem specifications requires the system to work in any kind of location. This can translate into the ability of the system to be easily portable or replicable in other locations. Following that specification, algorithms such as “fingerprinting” or “proximity sensing” do not make the cut as they demonstrate serious complexity in their setup, thereby, requiring a considerable amount of effort and time for system deployment (Svalastog, 2007).

On the other hand, the high accuracy specification has automatically disqualified the dead reckoning technique as it is prone to errors after a certain lapse of time (Alarifi, *et al*., 2016, p.10; Hu, 2013, p.10). This explains the choice of the trilateration technique.

The TDoA algorithm of trilateration has also been chosen over the RSS technique or AoA of Triangulation because it is relatively simple to implement, requires fewer steps than the others and works very well in a two-dimensional setup. Furthermore, TDoA has proven to be more efficient than its ToA counterpart (Alarifi, *et al*., 2016).

As for the winding number algorithm, it has been selected over the ray crossing algorithm to address the PIP problem of this research. This choice can be justified by the fact that the winding number algorithm is adapted to solve the problem for more complex polygons at the same efficiency as the ray crossing algorithm (Sunday, 2012). Built to work in both indoor and outdoor venues of various facets, the system needs to demonstrate a certain degree of reliability in the execution of the algorithms.

Other than these two algorithms, the software application for this prototype uses various other libraries and algorithms to process and store the input and output data generated during various stages of this application processing.

4.6 Main System Development activities

In this section, the main steps taken to build this positioning system are described in the order in which they happened. These activities include logistics setup, hardware setups and configuration, software application development's main algorithms, as well as deployment details.

4.6.1 Step1: Setup UWB sensor board for Arduino

After getting specifications and details about the sensor from DecaWave (2013), it is time to set the module to be used by the various Arduinos needed in this experimental system. In this work, the DWM1000 module compatible board is constructed following the description provided by Kang (2015), for easier and reliable connections. The adapter board is needed for every single Arduino in use in the system. In **Figure 4-5**, an illustration of how the adapter board looks is displayed, with the module attached.

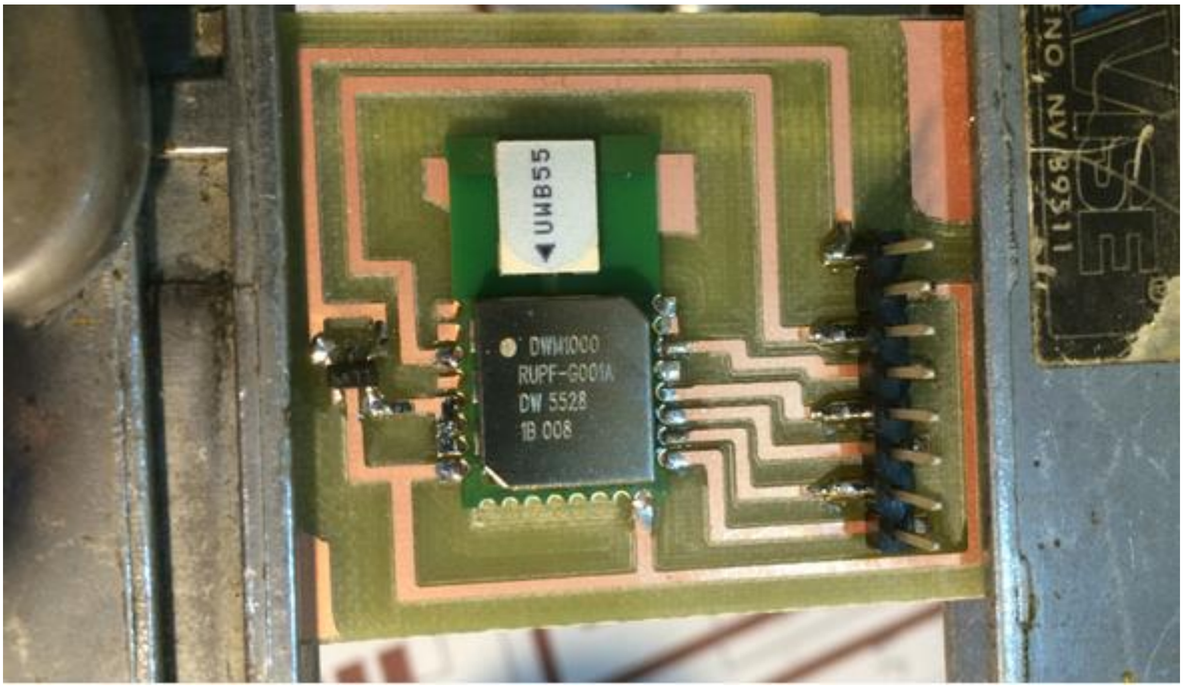


Figure 4-5: DWM1000 adapter board

4.6.2 Step 2: Arduino configuration

Using Arduinos Pro Mini for the tag as well as for the anchors, the next logical step is to configure the Arduinos to transmit and read RF signals transiting between the UWB sensors. Therefore, the Arduino configuration allows controlling the signals transfers between the various UWB-enabled devices.

In this work, the Thotro library has been used to configure and enable Arduinos capabilities of transmitting and reading the RF signals travelling in the system. Furthermore, this library discovered through Kang's blog (2015), provides the TDoA algorithm implementation for compiling the distance between the tag and each anchor in the system.

As described in a previous part of the chapter, the distance calculation is the responsibility of each anchor. It is therefore important to record the coordinates of each identified corner of the targeted venue. That is where the anchors are placed by default in this system. If needs be – in case of a long-range area coverage, more anchors are deployed in other nominated points of the area's borders. These static positions are then used by each anchor to compute its distance to the tag. In **Figure 4-6**, a snapshot of the Thotro code used to coordinate Arduinos activities is seen.

```
void resetInactive() {
    // tag sends POLL and listens for POLL_ACK
    expectedMsgId = POLL_ACK;
    transmitPoll();
    noteActivity();
}

void handleSent() {
    // status change on sent success
    sentAck = true;
}

void handleReceived() {
    // status change on received success
    receivedAck = true;
}

void transmitPoll() {
    DW1000.newTransmit();
    DW1000.setDefaults();
    data[0] = POLL;
    DW1000.setData(data, LEN_DATA);
    DW1000.startTransmit();
}

void transmitRange() {
    DW1000.newTransmit();
    DW1000.setDefaults();
    data[0] = RANGE;
    // delay sending the message and remember expected future sent timestamp
    DW1000Time deltaTime = DW1000Time(replyDelayTimeUS, DW1000Time::MICROSECONDS);
    timeRangeSent = DW1000.setDelay(deltaTime);
    timePollSent.getTimestamp(data + 1);
    timePollAckReceived.getTimestamp(data + 6);
    timeRangeSent.getTimestamp(data + 11);
    DW1000.setData(data, LEN_DATA);
    DW1000.startTransmit();
    //Serial.print("Expect RANGE to be sent @ "); Serial.println(timeRangeSent.getAsFloat());
}

void receiver() {
    DW1000.newReceive();
    DW1000.setDefaults();
    // so we don't need to restart the receiver manually
    DW1000.receivePermanently(true);
    DW1000.startReceive();
}
```

Figure 4-6: Thotro code used to coordinate Arduinos activities

4.6.3 Step 3: Setup remote server

This step consists of selecting a computer box which receives data from the various anchors and carries the computing operations for determining the OOI’s position. This machine needs to be powerful enough to support the required activities.

In the context of this demo, a notebook computer has been elected as the system's remote server. It is a Lenovo X1 Carbon with Core i7-7600U CPU, 1920 x 1080 screen, 8GB of RAM and a 256GB SSD. This choice is motivated by the fact that the system was to be tested in dynamic environments, therefore the equipment needs to be easily portable.

Furthermore, in this demo, the number of anchors used is relatively small, so the processing power required is not excessive. Because of the iteration between system development and system testing, it is important to have a screen directly attached to the server for direct access to the numbers produced by the system. The data storage requirement is largely covered with a 500 GB device capacity.

4.6.4 Step 4: Test the anchors readings

In this part of the setup, it is about visualising the first readings sent over from anchors to the server. These figures represent the distance between each anchor and the tag. If the system comports four anchors, fours values are expected.

First of all, each anchor needs to be placed at a known corner of the targeted venue, and the tag at any position around the targeted venue. This can be inside or outside the venue, as per tester's choice. A participant (person or object) can be asked to carry the tag and move around. In this way, the responsiveness of the components can also be tested.

As for an initial test, readings from a single anchor are enough. Once this happens to provide the right value with reasonable accuracy and precision close to DWM1000 module manufacturer’s claims (DecaWave, 2013), the same process then needs to be repeated with the remaining anchors. This may necessitate a series of calibrations to reach the accuracy and precision level expected.

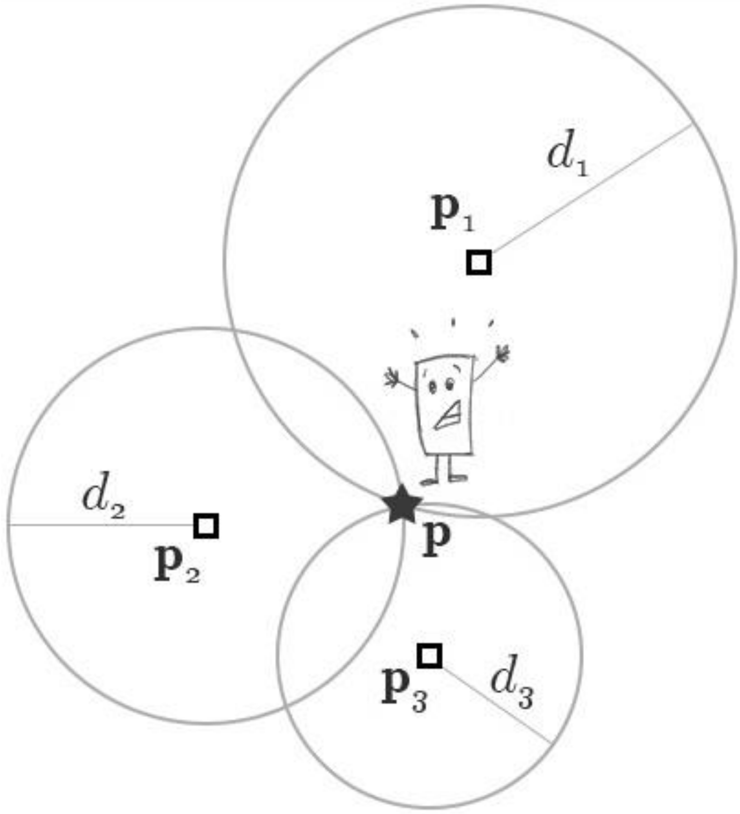
4.6.5 Step 5: Develop the server-side software application

This step could happen in parallel with the other activities. Even though it is dependent on the values emitted by the anchors, it can be developed with static values. Thereafter, the real values can be integrated when they become available. However, this order has been established in this research because the researcher is the only system developer and can only take up a single development task at a time.

In this step, the goal is to complete the trilateration on the remote server side to estimate the location of the OOI, and thereafter, use the winding number algorithm to determine whether the OOI is inside or outside the venue mapped. However, a few inputs are required for achieving this goal.

In fact, the application requires the value of each venue's corners coordinates for the winding number algorithm implementation as well as for the trilateration virtual circles. These coordinates are used as the centre points of each circle. The distances reported by the anchors are also used by the application as radiuses for trilateration's virtual circles.

The principle is that the intersection point of any set of three circles selected on the same floor plan represents the position of the OOI. See **Figure 4-7** for a representation of the ideal trilateration as described by the Pozyx team (2016). However, in reality, the challenge is much more complex.



p = user's estimated position (position of the tag);

d_i = radius (distance between the tag and an anchor);

p_i = position of the anchor (set in advance).

Figure 4-7: Representation of ideal trilateration

In fact, because of the UWB sensors, despite being one of the most accurate positioning technique around, do not report perfect accuracy, it is very improbable that the selected virtual circles would always intersect at a single point (Farid, *et al.*, 2013). There could be as much as three distinct intersection points for any set of three circles selected for trilateration, therefore setting up the intersection as an area rather than a single point.

In that specific case, the exact position of the OOI cannot be pinpointed and therefore remains in the domain of approximation. See **Figure 4-8** for a graphical representation of the case evoked.

However, as explained in the literature review, a predefined set of rules can simplify trilateration and reduce the amount of computation required. In this work, the following rules apply to trilateration of any selected set of three circles on the same floor plan:

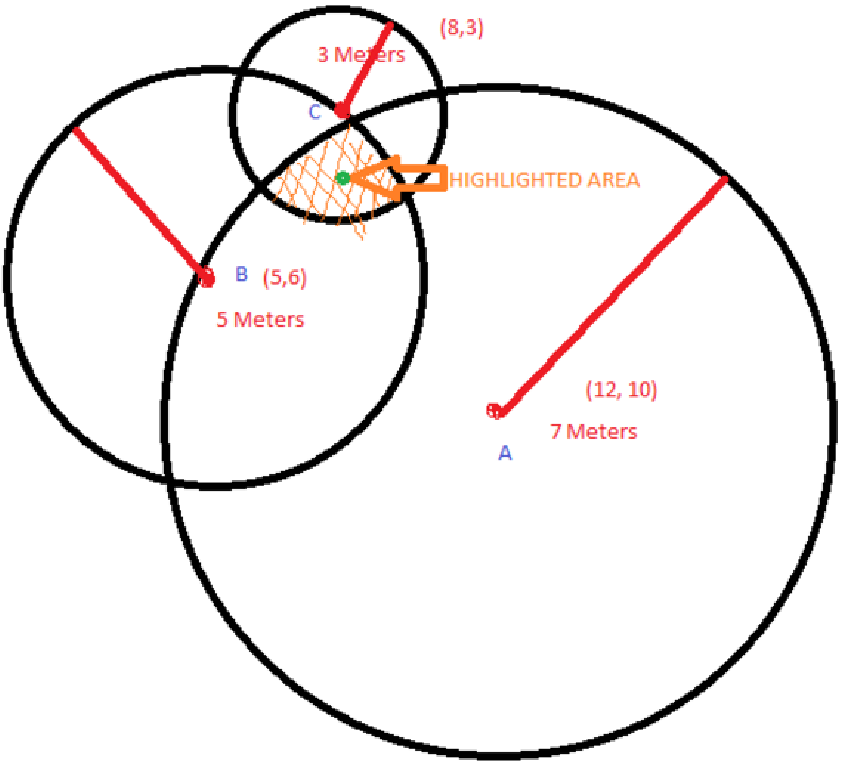


Figure 4-8: Graphical representation of inexact trilateration

- Trilateration is primarily executed based on the intersection of the two circles with the closest centre points, where circle one is drawn based on the shortest reported radius. These centre points are the two closest designated anchors' positions on the polygon representing the venue mapped;
- If the two selected circles do not intersect, the application algorithm selects the second closest circle to the first one selected. In case, there is still no intersection point found, the same logic carries on until all combinations of circles are exhausted. In case no intersection is found, the OOI cannot be determined;
- If two selected circles intersect at a single point, that intersection point is the location of the OOI;
- If the two circles intersect at two points, a third circle is needed to determine which of the two points is the actual position of the OOI. That is the point situated on or inside the third selected circle.

Once the OOI's current location is found, the winding number algorithm can be used to determine the position of the OOI in relation to the targeted venue.
In **Figure 4-9**, a snapshot of the algorithm used to find the location OOI by trilateration is shown, while in **Figure 4-10**, an implementation of the winding number algorithm used to determine if the OOI is currently inside or outside the venue mapped is displayed.

```
// Find the point where the three trilateration circles intersect.
private PointF? FindOOIPosition(
    float cx0, float cy0, float radius0,
    float cx1, float cy1, float radius1,
    float cx2, float cy2, float radius2,
    out PointF intersection1, out PointF intersection2)
{
    // Find the distance between the first two circles' centers.
    float dx = cx0 - cx1;
    float dy = cy0 - cy1;
    double dist = Math.Sqrt(dx * dx + dy * dy);

    // See how many intersection points there are betwwen the first two circles.
    if ((dist > radius0 + radius1) // No intersection, the circles are too far apart.
        || (dist < Math.Abs(radius0 - radius1)) // No intersection, one circle contains the other.
        || ((dist == 0) && (radius0 == radius1))) // No intersection, the circles coincide.
    {
        return null;
    }
    // Find a and h.
    double a = (radius0 * radius0 -
        radius1 * radius1 + dist * dist) / (2 * dist);
    double h = Math.Sqrt(radius0 * radius0 - a * a);

    // Find P2.
    double cxI = cx0 + a * (cx1 - cx0) / dist;
    double cyI = cy0 + a * (cy1 - cy0) / dist;

    // Get the intersection points.
    intersection1 = new PointF(
        (float)(cxI + h * (cy1 - cy0) / dist),
        (float)(cyI - h * (cx1 - cx0) / dist));
    intersection2 = new PointF(
        (float)(cxI - h * (cy1 - cy0) / dist),
        (float)(cyI + h * (cx1 - cx0) / dist));

    // See if we have 1 or 2 intersection point(s).
    if (dist == radius0 + radius1) return intersection1;

    // Find the distance between the first intersection and the center of the third circle.
    float dXI = (float)cx2 - intersection1.X;
    float dYI = (float)cy2 - intersection1.Y;
    double distI1 = Math.Sqrt(dXI * dXI + dYI * dYI);

    // See if the first intersection is inside the third circle.
    if (distI1 <= radius2) return intersection1;

    // Find the distance between the second intersection and the center of the third circle.
    dXI = (float)cx2 - intersection2.X;
    dYI = (float)cy2 - intersection2.Y;
    double distI2 = Math.Sqrt(dXI * dXI + dYI * dYI);

    // See if the second intersection is inside the third circle.
    if (distI2 <= radius2) return intersection2;

    return null;
}
```

Figure 4-9: Snapshot of the algorithm used to find the location of the OOI by trilateration

```
//  Globals which should be set before calling this function:
//
//  int    polyCorners  =  how many corners the polygon has (no repeats)
//  float  polyX[]      =  horizontal coordinates of corners
//  float  polyY[]      =  vertical coordinates of corners
//  float  x, y         =  point to be tested
//
//  (Globals are used in this example for purposes of speed.  Change as
//  desired.)
//
//  The function will return YES if the point x,y is inside the polygon, or
//  NO if it is not.  If the point is exactly on the edge of the polygon,
//  then the function may return YES or NO.
//
//  Note that division by zero is avoided because the division is protected
//  by the "if" clause which surrounds it.

bool pointInPolygon()
{

    int i, j = polyCorners - 1;
    bool oddNodes = NO;

    for (i = 0; i < polyCorners; i++)
    {
        if (polyY[i] < y && polyY[j] >= y
        || polyY[j] < y && polyY[i] >= y)
        {
            if (polyX[i] + (y - polyY[i]) / (polyY[j] - polyY[i]) * (polyX[j] - polyX[i]) < x)
            {
                oddNodes = !oddNodes;
            }
        }
        j = i;
    }

    return oddNodes;
}
```

Figure 4-10: Snapshot of an implementation of the winding number algorithm

Thereafter, all data are saved in the database for future reference. That is for results' analysis and discussion. If available, data are stored in the database every second. Otherwise, the application awaits the interval to extract the next readings.

In this demo application, the database structure is relatively simple. It consists of two tables. The first table (TOF_Result table) keeps track of all TDoA computation results. These data are sent by the anchors. They are the various radius values compiled by the system. This table consists of five rows: an identity field, an anchor name field, the radius value field, the venue name as well as the recorded date and time.

The other table (OOI_Position table) keeps track of rows containing information about an identity field, the date and time of data insertion, the venue name, the radius as well as the coordinate X value and the coordinate Y value of the centre point of each of the three circles selected to complete trilateration, the coordinate X value of the OOI, coordinate Y value of the OOI, and the position of the OOI in relation to the venue mapped - that is the "inside" or "outside" indicator.

As for the "OOI_Position" table, it records a NULL value if an expected value is missing. These data are kept, not only for analysis, but also for replaying at any time the movements of the OOI in relation to the venue targeted.

4.6.6 Step 6: System Deployment

This is the last step of the process. Here, the system is completed. The focus is to install it in a designated venue. For achieving a successful deployment, it is important to carefully gather information about the targeted location. These are a location's structure – an indoor or outdoor venue, and location area size. The latter is important as it provides a good indication of the range to be covered by the system.

Since DWM1000 modules can only cover a distance up to 300 meters (Decawave, 2013), this information is essential for determining how many anchors to use and where on the polygon to place the anchors. The wider the venue, the more anchors are required. This number can quickly escalate and increase the cost of the system.

Once the anchors are installed, data about the anchors' positions recorded and initial tests (Step 4) successfully completed, the rest of the system can be deployed, these being the tag and the remote server. The OOI location and position can then start being tracked in real-time.

5 CHAPTER FIVE: EXPERIMENT SETUP

5.1 Introduction

In this chapter, the focus is on providing details about the hypotheses developed in this work. Later on, the hypotheses were tested against the artefact described in the previous section to determine whether the artefact fulfils requirements or not.

To conduct this experiment, it is important to understand the different variables groups identified in the study (independent and dependent variables) and the hypothetical relationship between them.

Furthermore, the artefact produced was deployed in a real-world setup and its performance measured against one of the most popular real-world location-based applications, which uses different positioning systems. This application was the control experiment selected for this study.

The experiment is conducted in specific locations: an indoor venue and an outdoor venue. These venues are described as part of the experiment scenarios setups. The scenarios setups describe how the prototype system is deployed in venues, and how participants interact with it.

Finally, the results of the experiment are objectively evaluated following the guidelines provided by the hypotheses developed in this study. The comparison with other positioning systems is conducted where possible and necessary.

5.2 Conceptual Framework

5.2.1 Independent variables

The first group of variables are the independent variables. In a scientific research, an independent variable is an object or entity that stands alone and is not influenced or changed by other variables (Graphic Tutorial, 2016). In practice, the independent variables are the ones the researcher conducting the experiment tweaks to test the hypothesis and produce an output.

In the context of this experiment, the independent variables are the positioning technology in use (positioning system's hardware and algorithms), the structure of the targeted venue (indoor or outdoor), the system design and the movements of the OOI.
As described in the literature review section, the positioning technology refers to the hardware (or sensor) and algorithm (or technique) used to develop the positioning system. In the case of this prototype artefact, the UWB sensor, the TDoA algorithm, embedded in DecaWave's DWM1000 module, and the winding number algorithm are the designated technology.

The structure of the targeted venue relates to the fact that a venue selected to conduct the experiment is either an indoor location or an outdoor location. This could affect the accuracy and precision of the system.

The system design, self-positioning positioning system or remote positioning system, is an important independent factor set to influence the security, the power consumption and the responsiveness of the system.

The movements of the OOI, which are unpredictable, volatile and often initiated by a mobile user, mainly influence the real-time capability of the system. In the context of this experiment, a set of fixed points (locations) to place the OOI were used to simulate the movements of the OOI. Furthermore, the real movements of the OOI were also thrown in the equation.

5.2.2 Dependent variables

The second group of variables in this experiment are the dependent variables. These are essentially the outputs of a hypothesis testing. In fact, the dependent variables are variables which depend on other factors (Graphic Tutorial, 2016).

In this context, as described earlier in the problem statement, the dependent variables are the positioning system accuracy, the real-time (or responsive) tracking of the OOI's location, and the mobile device's power consumption rate.

5.2.3 Hypotheses

In this study, the claims were:

1. If an UWB-based positioning system uses the TDoA and the winding number algorithms, then it will be able to determine, at all time, whether a detected mobile user is currently situated inside or outside a targeted venue.

2. If an UWB-based positioning system uses the TDoA algorithm, then it will be more accurate than the satellite-based and the network-based positioning systems.
3. Whether used in an indoor or outdoor location, if a positioning system uses the UWB technology, then it will still report the same accuracy.
4. If an UWB-based positioning system is built based on the remote positioning system design, then it will require less electric power from a mobile device than the satellite-based and the network-based positioning systems built based on the self-positioning system design.
5. If a positioning system uses the UWB technology, then it will be more responsive to the movements of an OOI than the satellite-based and the network-based positioning systems.

Some of the hypotheses and the relationships between the variables were tested in the experiment. The results justify or reject the claims.

5.3 Evaluation

5.3.1 Scenarios setups

This section describes the setups and venues in which the experiments are conducted. The venues selected for this experiment are:

- The indoor entertainment area at Quick Merlin Software premises (Software company in Cape Town, South Africa) – the researcher's workplace;
- A playground at L'Afrique Eco village, a residential complex in Table view, Cape Town, South Africa – the researcher's residential address.

In each scenario, the following equipment and entities are used:

- The complete artefact: with a tag, four anchors and a remote server on which runs the software application computing the tag's position in real-time;
- A male human being of 37 years old who has accepted to play the role of the mobile user in these experiments. He is the only active participant who is responsible for carrying the tag in and out of the designated venues;
- A SAMSUNG S4 Mini powering up the tag, which is also composed of Arduino Pro Mini and a DWM1000 module;
- A USB OTG cable and FTDI USB to TTL serial cable to power up the Arduino from the mobile phone through its serial port;
- A set of 3.7 volts Lithium Ion power banks to power up the anchors, which are also composed of Arduino Pro Minis, ESP8266 Wi-Fi modules and DWM1000 modules;

- The researcher who gathers information about the venues. He is responsible for deploying the positioning system and oversees the system's operations. He also ensures that all the experimental data are correctly recorded.

5.3.1.1 Indoor venue

The indoor entertainment area (or employees' canteen area) at Quick Merlin Software premises is an indoor venue selected to conduct this experiment. Quick Merlin Software office is situated in a ground floor building in Plumstead, Cape Town. The venue selected for this experiment is a fifty square meters (50 m^2) room separated from the rest of the office by three brick walls, a glass wall and a concrete ceiling. The room's floor plan is a perfect rectangle of ten meters (10 m) length and five meters (5 m) width. The room is equipped with a large rectangular table and chairs around the table. There is also a pool table, a television, a PlayStation console, two fridges and other furniture in the room.

5.3.1.2 Outdoor venue

The outdoor venue selected for this experiment is at L'Afrique Eco village, a residential complex in Table view, Cape Town, South Africa. This is a typical green park where residents from complex can be seated, relax and play. This is an open play location of two hundred square meters (200 m^2). The venue's shape is of a perfect four-sided-polygon, a trapezoid.

The trapezoid's base (longest side of the trapezoid) measures thirty metres (30 m) while the opposite side measures twenty metres (20 m). The two equal sides of the trapezoid are seventeen metres (17 m) long. The venue is delimited by four walls and has a single entrance. However, it has no top cover or ceiling.

5.3.2 Control experiment

A control experiment is essentially an experiment set to assess the result of another experiment by adding, removing or changing variables operating in the other experiment (The American Heritage, 2002). The results of the comparison are generally a good measurement of the effect of the variables concerned.

In this context, the control experiment was conducted using Google Maps for Mobile, a mobile location-based application developed by Google. Google Maps for Mobile makes use of A-GPS or Wi-Fi technology to locate OOIs and suggest routes and directions to mobile users.

The choice of this application for the control experiment was motivated by its versatility. In fact, Google Maps for Mobile can make use of a Wi-Fi-based positioning system or an A-GPS to estimate OOIs' locations. When the Wi-Fi setting is switched off on the user's mobile device, Google Maps for Mobile is strictly available in its A-GPS format. When the Wi-Fi setting is turned on, users have access to the Wi-Fi version of Google Maps for Mobile.

Furthermore, when making use of the Wi-Fi-based positioning system, Google Maps for Mobile uses the RSSI and fingerprint positioning technique to determine an OOI's location. When the A-GPS positioning system is used, the technique used to estimate the location of an OOI is the trilateration using the TDoA algorithm.

The application's versatility was needed to collect data from two of the most popular positioning systems, and use the data as a basis of comparison for the newly implemented UWB positioning system. Since Google claims better accuracy using the Wi-Fi positioning system (see **Figure 2-3**), it was deemed necessary to assess the difference in accuracy of both systems in relation to the accuracy data of the UWB system produced in this work.

Additionally, the interest for comparing the rate of power consumption and assessing the effects of locations' structures in all three systems also led to the choice of this multi-facet location-based application to be used in the control experiment.

The control experiment was conducted in both scenarios setups described earlier, and the results were stored for comparisons with the UWB positioning system. The results collected were restricted to the dependent variables deemed relevant for this study. These are the system accuracy, the real-time (or responsive) tracking of the OOI's location, and the mobile device's power consumption rate.

In the A-GPS setup, the independent variables used were: the A-GPS's technology (with the TDoA algorithm), the venue structure – indoor and outdoor – depending on the scenario setup, the movements of the OOI following a set of designated locations in the venue, and the system design – Google Maps uses the self-positioning system design. In the Wi-Fi-based setup, all the independent variables remained the same, except for the technology: the Wi-Fi technology used with the RSSI and fingerprinting methods replaced the A-GPS's technology.

5.3.3 Experiments

5.3.3.1 Introduction

After a quantitative approach of data collection, data extracted from of each experiment were used in statistical comparisons between the prototyped UWB system and the designated control experiment as addressed in the very next section of the thesis. However, if necessary, qualitative approaches of data collection such as observation were used to evaluate the system performance.

Where the hypothesis testing is needed, the P-value approach was used to accept or reject a hypothesis. This approach consists of determining the “unlikely” or “likely” based on the probability generated by observing a more extreme test statistic in the direction of the alternative hypothesis than the one observed, assuming the null hypothesis was true (The Pennsylvania State University, 2017).

When required, the hypothesis testing was separately conducted in the indoor venue and the outdoor venue for a better distinctive interpretation of the results.

5.3.3.2 Venue-level accuracy

In both scenarios setups, indoor and outdoor, the experiment was conducted based on an accuracy of twenty centimetres (20 cm) or less. It is on this basis that the system proceeded with trilateration (TDoA algorithm), computed the location of an OOI and determines the position of the OOI in relation to the targeted venue using the winding number algorithm.

For this experiment, the goal was to detect the movements of the OOI and record its position in relation to the targeted venue. The remote server laptop was placed on the table, close to the middle of the venue. The researcher had visual access to the server's screen. The system anchors were placed at each corner of the room’s floor plan. The mobile user holding the tag was instructed to randomly move in and out of the venue. The positioning system tracked the tag's movements and recorded the data accordingly.

The researcher, who was overseeing the operations, compared the system's reported positions of the tag to his physical observations (by eyesight) of the position of the mobile user, and took notes of situations where the system did not indicate the correct position of the participant. For example, if the participant who was carrying the tag was outside the room and the system reported his position as inside the room, the system reading was deemed wrong and the researcher took note of the defect.

5.3.3.2.1 Results

Despite being considered excellent, the twenty centimetres (+-20 cm) accuracy was not good enough to consistently determine the position of the OOI in relation to a venue. In both scenarios setups, indoor and outdoor, when the OOI was positioned close to the borders of the venue (inside or outside the venue), the system had sometimes incorrectly flagged the position of the OOI as inside or outside the venue.

Therefore, based on the researcher’s observations, one can affirm that, using the TDoA and the winding number algorithms in an UWB-based positioning system does not guarantee that the position of the OOI will always be correctly flagged as inside or outside a venue.

5.3.3.3 Overall accuracy

As explained in the introduction, the success of the solution provided for this research problem largely depends on the accuracy achieved by the system. The smaller the gap to the real-world value, the better is the system. In this part of the experiment, the focus was to demonstrate that the value of the accuracy indicator directly relates to the technology and technique used to determine the OOI's position.

Through a series of activities in selected locations, the accuracy levels of the UWB-based positioning system were estimated. Once the values were determined, the accuracy values were collected both indoor and outdoor, and they were compared with the accuracy recorded in the control experiment.

To test the accuracy levels, the set of activities consisted of defining and drawing a set of nine successive points (or locations) on the floor of the venue selected to conduct the experiment. The points were set in a linear fashion, with a half-a-meter (0.5 m) interval between each point and its successor.

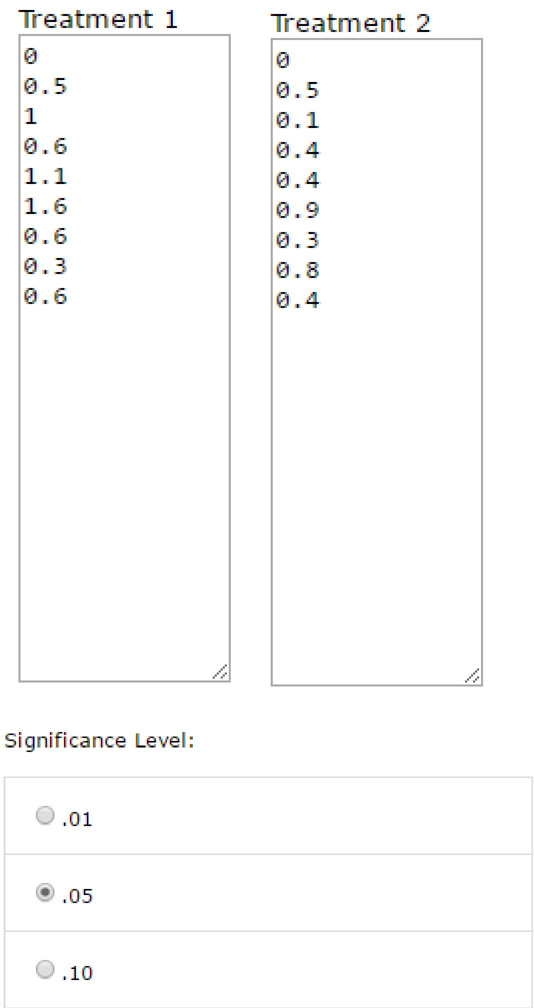
The mobile user (or participant) holding the OOI was instructed to move from a point to another when given the signal to do so. The system then recorded data about these activities.

To assess the UWB-based positioning system accuracy level against the Wi-Fi-based positioning system and the A-GPS used in the control experiment, the hypothesis testing was conducted based on the P-value approach as implemented in the One-Way ANOVA Calculator (Stangroom, 2017).

5.3.3.3.1 Control experiment results: Wi-Fi-based positioning system vs A-GPS accuracy levels

5.3.3.3.1.1 Results indoor

Treatment 1 = accuracy level data collected for the A-GPS indoor;
Treatment 2 = accuracy level data collected for the Wi-Fi-based positioning system indoor



Summary of Data						
	Treatments					
	1	2	3	4	5	Total
N	9	9				18
ΣX	6.3	3.8				10.1
Mean	0.7	0.4222				0.5611
ΣX^2	6.19	2.28				8.47
Std.Dev.	0.4717	0.2906				0.406

Result Details				
Source	***SS***	***df***	***MS***	
Between-treatments	0.3472	1	0.3472	$F = 2.26244$
Within-treatments	2.4556	16	0.1535	
Total	2.8028	17		

The *f*-ratio value is 2.26244. The *p*-value is .152027. The result is *not* significant at $p < .05$.

Figure 5-1: Control experiment accuracy levels indoor

As expected, referring to the literature review, the A-GPS and Wi-Fi-based positioning system's accuracy levels are similar in the indoor venue.

5.3.3.3.1.2 Results outdoor

Treatment 1 = accuracy level data collected for the A-GPS outdoor;

Treatment 2 = accuracy level data collected for the Wi-Fi-based positioning system outdoor

Treatment 1	Treatment 2
0	0
0.3	0.5
0.6	0.3
0.48	0.43
0.35	0.35
0.45	0.83
0.4	0.38
0.4	0.87
0.6	0.36

Significance Level:

- ○ .01
- ◉ .05
- ○ .10

Summary of Data						
	Treatments					
	1	2	3	4	5	Total
N	9	9				18
ΣX	3.58	4.02				7.6
Mean	0.3978	0.4467				0.4222
ΣX^2	1.6854	2.3672				4.0526
Std.Dev.	0.1807	0.2673				0.2228

Result Details				
Source	***SS***	***df***	***MS***	
Between-treatments	0.0108	1	0.0108	F = 0.2066
Within-treatments	0.833	16	0.0521	
Total	0.8437	17		

The *f*-ratio value is 0.2066. The *p*-value is .655551. The result is *not* significant at $p < .05$.

Figure 5-2: Control experiment accuracy levels outdoor

As expected, referring to the literature review, the A-GPS and Wi-Fi-based positioning system's accuracy levels are similar in the outdoor venue.

5.3.3.3.2 Hypothesis testing: UWB-based positioning system vs Wi-Fi-based positioning system vs A-GPS accuracy levels

Practically, this experiment consisted of testing the following hypothesis through a test of significance: if an UWB-based positioning system uses the TDoA algorithm, then it will be more accurate than the satellite-based and the network-based positioning systems. This represents the alternative hypothesis (H_1) that this experiment wants to validate.

Here, the null hypothesis (H_0) is that an UWB-based positioning system using the TDoA algorithm is not more accurate than the satellite-based and the network-based positioning systems.

5.3.3.3.2.1 Results indoor

Based on the data collected from the ranging tests performed in the controlled experiment indoor, it appeared that the average of data collected about the accuracy levels of the Wi-Fi-based positioning system and the A-GPS was 0.56cm. Therefore, $H_1 = \mu < 0.56$cm and $H_0 = \mu \geq 0.56$cm. The significance level for this experiment is 0.05 (or 5%).

Treatment 1 = accuracy level data collected for the A-GPS indoor;

Treatment 2 = accuracy level data collected for the Wi-Fi-based positioning system indoor;

Treatment 3 = accuracy level data collected for the UWB-based positioning system indoor.

Treatment 1	Treatment 2	Treatment 3
0	0	0
0.5	0.5	0.05
1	0.1	0.2
0.6	0.4	0.1
1.1	0.4	0.2
1.6	0.9	0.2
0.6	0.3	0.1
0.3	0.8	0
0.6	0.4	0.1

Significance Level:

- ○ .01
- ● .05
- ○ .10

Summary of Data						
	Treatments					
	1	2	3	4	5	Total
N	9	9	9			27
ΣX	6.3	3.8	0.95			11.05
Mean	0.7	0.4222	0.1056			0.4093
ΣX^2	6.19	2.28	0.1525			8.6225
Std.Dev.	0.4717	0.2906	0.0808			0.3971

Result Details				
Source	***SS***	***df***	***MS***	
Between-treatments	1.5924	2	0.7962	$F = 7.61985$
Within-treatments	2.5078	24	0.1045	
Total	4.1002	26		

The *f*-ratio value is 7.61985. The *p*-value is .00274. The result is significant at $p < .05$.

Figure 5-3: Hypothesis 2 acceptance test indoor

5.3.3.3.2.2 Results outdoor

Based on the data collected from the ranging tests performed in the controlled experiment outdoor, it appeared that the average of data collected about the accuracy levels of the Wi-Fi-based positioning system and the A-GPS was 0.42cm. Therefore, $H_1 = \mu < 0.42$cm and $H_0 = \mu \geq 0.42$cm. The significance level for this experiment is 0.05 (or 5%).

Treatment 1 = accuracy level data collected for the A-GPS outdoor;
Treatment 2 = accuracy level data collected for the Wi-Fi-based positioning system outdoor;
Treatment 3 = accuracy level data collected for the UWB-based positioning system outdoor.

Treatment 1	Treatment 2	Treatment 3
0	0	0
0.3	0.5	0.03
0.6	0.3	0.1
0.48	0.43	0.05
0.35	0.35	0.05
0.45	0.83	0.11
0.4	0.38	0
0.4	0.87	0
0.6	0.36	0.03

Significance Level:

○ .01
◉ .05
○ .10

Summary of Data						
	Treatments					
	1	2	3	4	5	Total
N	9	9	9			27
ΣX	3.58	4.02	0.37			7.97
Mean	0.3978	0.4467	0.0411			0.2952
ΣX^2	1.6854	2.3672	0.0289			4.0815
Std.Dev.	0.1807	0.2673	0.0414			0.2579

Result Details				
Source	***SS***	***df***	***MS***	
Between-treatments	0.8822	2	0.4411	*F* = 12.50437
Within-treatments	0.8466	24	0.0353	
Total	1.7289	26		

The *f*-ratio value is 12.50437. The *p*-value is .00019. The result is significant at $p < .05$.

Figure 5-4: Hypothesis 2 acceptance test outdoor

5.3.3.3.3 Overall results

Following the comparison of data displayed in **Figure 5-5** and **Figure 5-6**, it is evident that the prototype produced in this work demonstrates high accuracy. In fact, in both scenarios, while conducting the initial ranging tests as required by Step 4 of the system development activities, the system had constantly reported a difference of twenty centimetres (20 cm) or less with the real-world value of the distance targeted.

Furthermore, when comparing the accuracy of the UWB-based system with the accuracy of the Wi-Fi-based positioning system and the A-GPS through the test of significance, it is evident that the UWB-based positioning system demonstrates a far better accuracy than the two others. **Figure 5-3** and **Figure 5-4** are a perfect illustration of this evidence.

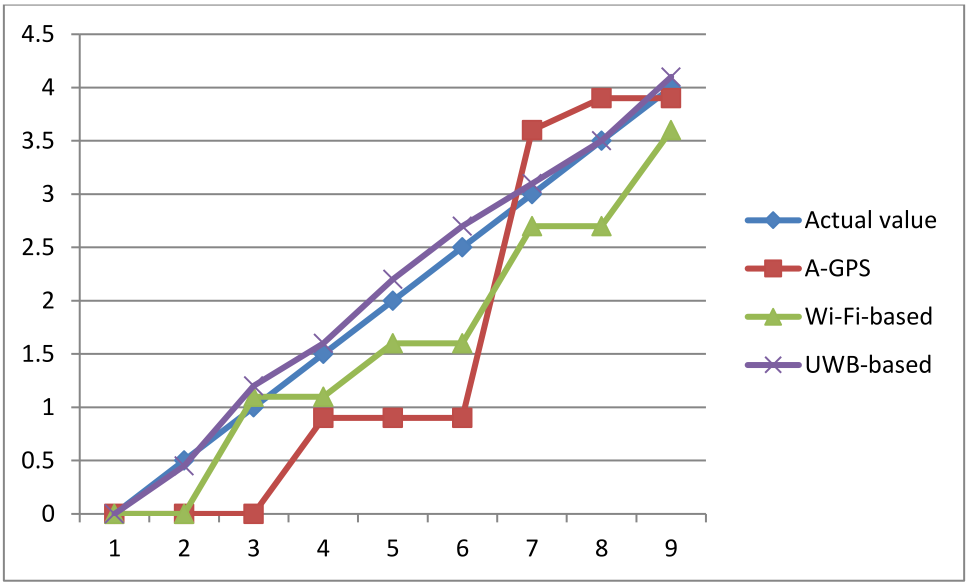


Figure 5-5: A comparison of positioning systems in the nine designated linear points test indoor

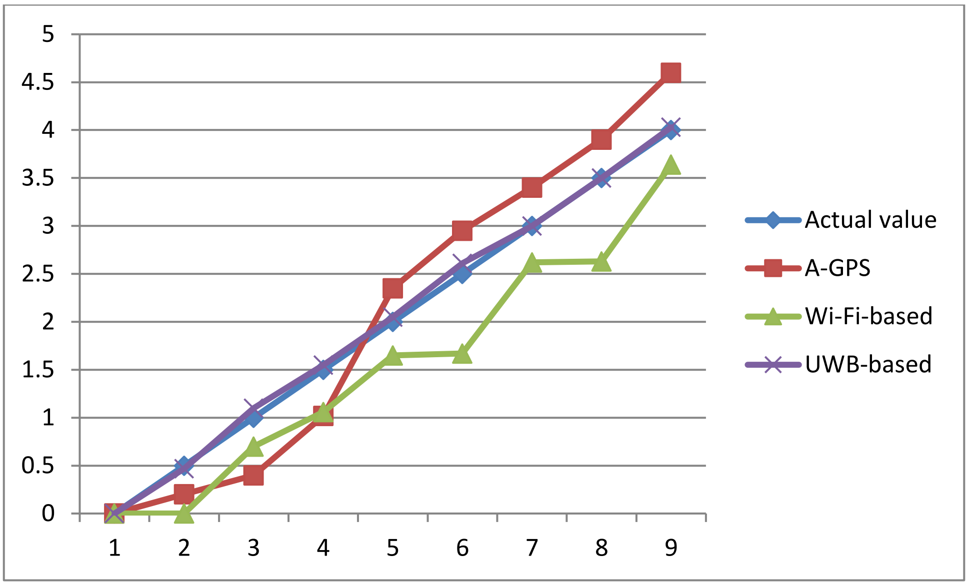


Figure 5-6: A comparison of positioning systems in the nine designated linear points test outdoor

5.3.3.4 Outdoor vs indoor accuracy

In this phase of the experiment, the goal was to determine whether the UWB-based positioning system works with the same accuracy in indoor venue and outside venue. In fact, the most prominent positioning system, the GPS, is affected by the structure of the venue in which it is used. When used outside, the GPS happens to report better accuracy than when it used inside. Therefore, the GPS cannot be used for indoor location-based application.

If the UWB-based positioning system works with the same accuracy in outdoor location as in indoor location, it could be considered as a serious contender to address the indoor positioning challenge. In fact, even though the Wi-Fi-based positioning system and A-GPS represents an important improvement from the GPS when considering indoor positioning (see **Figure 5-5**), they have not yet reached the standard required by most innovative indoor location-based applications.

Practically, this experiment consisted of testing the following hypothesis through a test of significance: whether used in an indoor or outdoor location, if a positioning system uses the UWB technology, then it will still report the same accuracy. This represents the alternative hypothesis (H_1) that this experiment wants to validate.

Here, the null hypothesis (H_0) is that an UWB-based positioning system's accuracy levels indoor are not the same as its accuracy levels outdoor.

5.3.3.4.1 Results

Based on the data collected from the ranging tests performed in the controlled experiment indoor, it appeared that the average accuracy levels of the Wi-Fi-based positioning system outdoor was 0.04cm. Therefore, $H_1 = \mu = 0.04$cm and $H_0 = \mu \neq 0.04$cm. The significance level for this experiment is 0.05 (or 5%).

Treatment 1 = accuracy level data collected for the UWB-based positioning system outdoor;
Treatment 2 = accuracy level data collected for the UWB-based positioning system indoor.

Treatment 1	Treatment 2
0	0
0.03	0.05
0.1	0.2
0.05	0.1
0.05	0.2
0.11	0.2
0	0.1
0	0
0.03	0.1

Significance Level:

- ○ .01
- ● .05
- ○ .10

Summary of Data						
	Treatments					
	1	2	3	4	5	Total
N	9	9				18
ΣX	0.37	0.95				1.32
Mean	0.0411	0.1056				0.0733
ΣX^2	0.0289	0.1525				0.1814
Std.Dev.	0.0414	0.0808				0.0705

Result Details				
Source	***SS***	***df***	***MS***	
Between-treatments	0.0187	1	0.0187	$F = 4.53675$
Within-treatments	0.0659	16	0.0041	
Total	0.0846	17		

The *f*-ratio value is 4.53675. The *p*-value is .049045. The result is significant at $p < .05$.

Figure 5-7: Hypothesis 3 acceptance test

As demonstrated in **Figure 5-7**, the UWB-based positioning system did not suffer of the location's structure effects. The system worked with similar accuracy levels in both indoor and outdoor setups. The results in the indoor scenario correlate with those in the outdoor scenario experiment. Therefore, one can attest that the UWB-based positioning system works with high accuracy whether it is setup in an indoor or an outdoor venue.

Furthermore, when comparing the results obtained from the UWB-based positioning system to those obtained in the control experiment (using the Wi-Fi-based positioning system and the A-GPS), the graphs (**Figure 5-5** and **Figure 5-6)** show that the UWB-based positioning system outperforms the other systems in terms of accuracy levels in both indoor and outdoor setups.

5.3.3.5 Power consumption

The scope of this section of the experiment was to determine how much electric power is required to operate the UWB-based positioning system produced in this work. More than simply identifying the electric power required for the system to be operational, the idea was to monitor and record the power consumption of the system over certain period of time following a set of predefined movements.

Afterwards, the data collected could be used to compare the UWB-based system with its Wi-Fi-based positioning system and A-GPS counterparts. In fact, the UWB-based positioning produced in this work uses the remote positioning system design, while Google Maps for Mobile, the application used in the control experiment, uses the self-positioning system design. Should the power consumption be proven to be lesser in the UWB-based system, it would confirm that, not only UWB is an efficient power-saving technology, but also that the remote positioning system design lessens device's power consumption.

In fact, when running the control experiment, the same set of activities were undertaken to monitor and record the levels of battery's power consumption generated by the Wi-Fi-based positioning system and the A-GPS.

To test the power consumption levels, the set of activities consisted of defining and drawing a set of nine successive points (or locations) on the floor of the venue selected to conduct the experiment. The points were set in a linear fashion, with a half-a-meter (0.5 m) interval between each point and its successor.

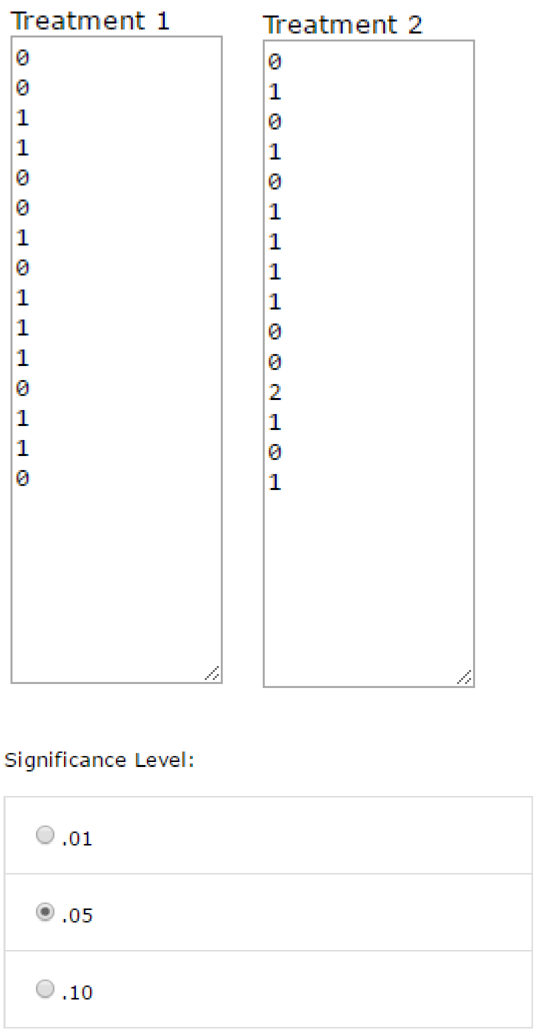
The mobile user (or participant) holding the OOI was the instructed to move from a point to another at his normal walking speed for fifteen minutes. Every minute, the researcher then recorded data about the mobile device's power consumed. The mobile device was charged at full capacity (100%) in the beginning of each system's testing. The mobile device's power consumption is recorded in percentage (%).

To assess the UWB-based positioning system's power consumption rate against the Wi-Fi-based positioning system and the A-GPS used in the control experiment, a test of significance was conducted based on the P-value approach as implemented in the One-Way ANOVA Calculator (Stangroom, 2017).

5.3.3.5.1 Control experiment results: Wi-Fi-based positioning system vs A-GPS power consumption

5.3.3.5.1.1 Results indoor

Treatment 1 = mobile device’s power level data collected for the A-GPS indoor;
Treatment 2 = mobile device’s power level data collected for the Wi-Fi-based positioning system indoor



Summary of Data						
	Treatments					
	1	2	3	4	5	Total
N	15	15				30
ΣX	8	10				18
Mean	0.5333	0.6667				0.6
ΣX^2	8	12				20
Std.Dev.	0.5164	0.6172				0.5632

Result Details				
Source	***SS***	***df***	***MS***	
Between-treatments	0.1333	1	0.1333	$F = 0.41177$
Within-treatments	9.0667	28	0.3238	
Total	9.2	29		

The *f*-ratio value is 0.41177. The *p*-value is .526294. The result is *not* significant at $p < .05$.

Figure 5-8: Control experiment power consumption indoor

As expected, referring to the literature review, the A-GPS and Wi-Fi-based positioning system require similar levels of the mobile device's battery power in the indoor setup.

5.3.3.5.1.2 Results outdoor

Treatment 1 = mobile device's power level data collected for the A-GPS outdoor;
Treatment 2 = mobile device's power level data collected for the Wi-Fi-based positioning system outdoor

Treatment 1

0
0
1
0
1
1
0
0
1
0
1
1
1
1
2

Treatment 2

0
1
0
0
1
1
0
0
0
1
0
1
1
1
2

Significance Level:

- .01
- .05 (selected)
- .10

Summary of Data						
	Treatments					
	1	2	3	4	5	Total
N	15	15				30
ΣX	10	9				19
Mean	0.6667	0.6				0.6333
ΣX^2	12	11				23
Std.Dev.	0.6172	0.6325				0.6149

Result Details				
Source	***SS***	***df***	***MS***	
Between-treatments	0.0333	1	0.0333	*F* = 0.08537
Within-treatments	10.9333	28	0.3905	
Total	10.9667	29		

The *f*-ratio value is 0.08537. The *p*-value is .772307. The result is *not* significant at $p < .05$.

Figure 5-9: Control experiment power consumption outdoor

As expected, referring to the literature review, the A-GPS and Wi-Fi-based positioning system require similar levels of the mobile device's battery power in the outdoor setup.

5.3.3.5.2 UWB-based positioning system vs Wi-Fi-based positioning system vs A-GPS power consumption

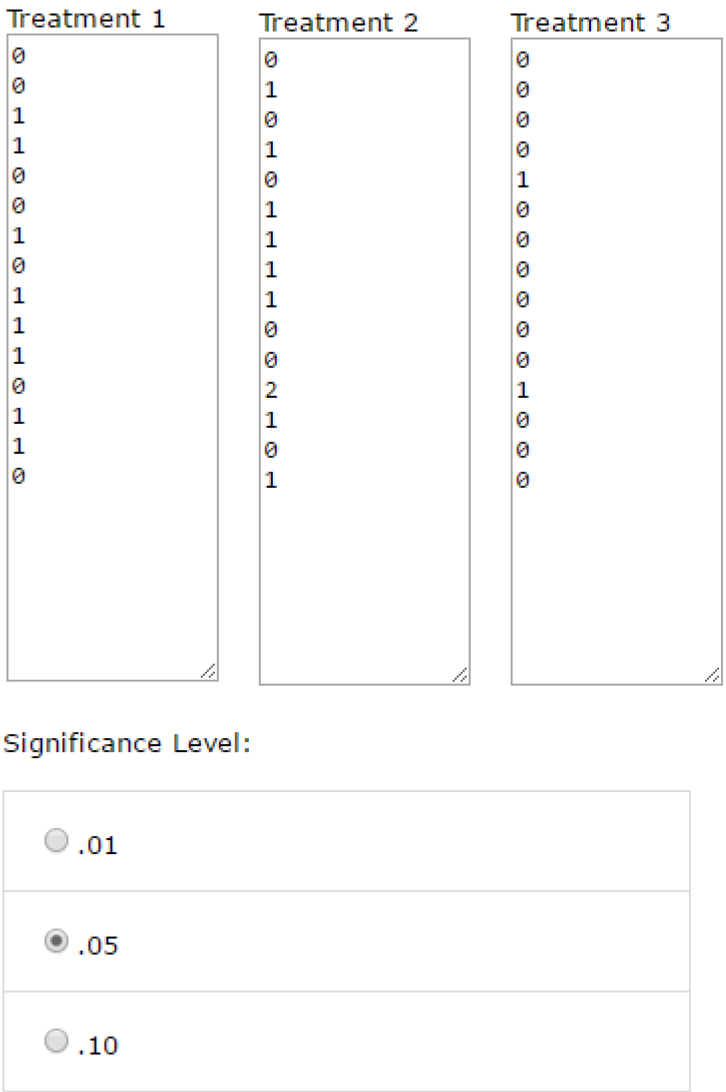
Practically, this experiment consisted of testing the following hypothesis through a test of significance: if an UWB-based positioning system is built based on the remote positioning system design, then it will require less electric power from a mobile device than the satellite-based and the network-based positioning systems built based on the self-positioning system design. This represents the alternative hypothesis (H_1) that this experiment wants to validate.

The null hypothesis (H_0) is that an UWB-based positioning system built based on the remote positioning system design does not require less electric power from a mobile device than the satellite-based and the network-based positioning systems.

5.3.3.5.2.1 Results indoor

Based on the data collected in the controlled experiment indoor, it appeared that the average per minute of data collected about the power levels of the Wi-Fi-based positioning system and the A-GPS was 0.6%. Therefore, $H_1 = \mu < 0.6\%$ and $H_0 = \mu \geq 0.6\%$. The significance level for this experiment is 0.05 (or 5%).

Treatment 1 = mobile device’s power level data collected for the A-GPS indoor;
Treatment 2 = mobile device’s power level data collected for the Wi-Fi-based positioning system indoor;
Treatment 3 = mobile device’s power level data collected for the UWB-based positioning system indoor.



Summary of Data						
	Treatments					
	1	2	3	4	5	Total
N	15	15	15			45
∑X	8	10	2			20
Mean	0.5333	0.6667	0.1333			0.4444
$\sum X^2$	8	12	2			22
Std.Dev.	0.5164	0.6172	0.3519			0.5459

Result Details				
Source	***SS***	***df***	***MS***	
Between-treatments	2.3111	2	1.1556	*F* = 4.49383
Within-treatments	10.8	42	0.2571	
Total	13.1111	44		

The *f*-ratio value is 4.49383. The *p*-value is .01704. The result is significant at $p < .05$.

Figure 5-10: Hypothesis 4 acceptance test indoor

5.3.3.5.2.2 Results outdoor

Based on the data collected in the controlled experiment outdoor, it appeared that the average per minute of data collected about the power levels of the Wi-Fi-based positioning system and the A-GPS was 0.63%. Therefore, $H_1 = \mu < 0.63\%$ and $H_0 = \mu \geq 0.63\%$. The significance level for this experiment is 0.05 (or 5%).

Treatment 1 = mobile device's power level data collected for the A-GPS outdoor;
Treatment 2 = mobile device's power level data collected for the Wi-Fi-based positioning system outdoor;
Treatment 3 = mobile device's power level data collected for the UWB-based positioning system outdoor.

Treatment 1	Treatment 2	Treatment 3
0	0	0
1	0	0
0	1	0
0	0	0
1	1	1
1	1	0
0	0	0
0	0	0
0	1	0
1	0	1
0	1	0
1	1	0
1	1	0
1	1	0
2	2	0

Significance Level:

- ○ .01
- ◉ .05
- ○ .10

Summary of Data						
	Treatments					
	1	2	3	4	5	Total
N	15	15	15			45
∑X	9	10	2			21
Mean	0.6	0.6667	0.1333			0.4667
$\sum X^2$	11	12	2			25
Std.Dev.	0.6325	0.6172	0.3519			0.5878

Result Details				
Source	***SS***	***df***	***MS***	
Between-treatments	2.5333	2	1.2667	$F = 4.2$
Within-treatments	12.6667	42	0.3016	
Total	15.2	44		

The *f*-ratio value is 4.2. The *p*-value is .021737. The result is significant at $p < .05$.

Figure 5-11: Hypothesis 4 acceptance test outdoor

5.3.3.5.3 Overall results

When comparing the end results of the control experiment to those of the UWB-based system (see **Figure 5-12),** there is no doubt that the UWB-based positioning system requires less electric power from the mobile than the Wi-Fi positioning system and the A-GPS.

In fact, after fifteen minutes of intense activity in each scenario (indoor and outdoor), the fully charged SAMSUNG S4 Mini, with its 3.8 volts (v) and 7 watts per hour (Wh) battery, was respectively at 98% of power left in the indoor experiment, and 98% in the outdoor experiment.

The above results did not take into consideration the fact that the mobile device was not just powering the DWM1000 sensor, but also the Arduino which held the DWM1000 sensor and broadcasts the RF signal to the anchors. The resulting data completely back the low power consumption claim by the DWM1000 transceiver manufacturer (Decawave, 2015).

When the same experiment was done with the Wi-Fi-based positioning system, the fully charged SAMSUNG S4 Mini, with its 3.8 volts (v) and 7 watts per hour (Wh) battery, was respectively at 90% of power left in the indoor experiment, and 91% in the outdoor experiment. In the A-GPS context, the SAMSUNG S4 Mini reported respectively at 92% of power left in the indoor experiment, and 90% in the outdoor experiment.

Furthermore, the tests of significance results in **Figure 5-10** and **Figure 5-11**, which use all data recorded during the different power consumption-related experiments, have demonstrated and confirmed that the UWB-based positioning system requires less electric power from the mobile device than the Wi-Fi-based positioning system and the A-GPS in both indoor and outdoor setups.

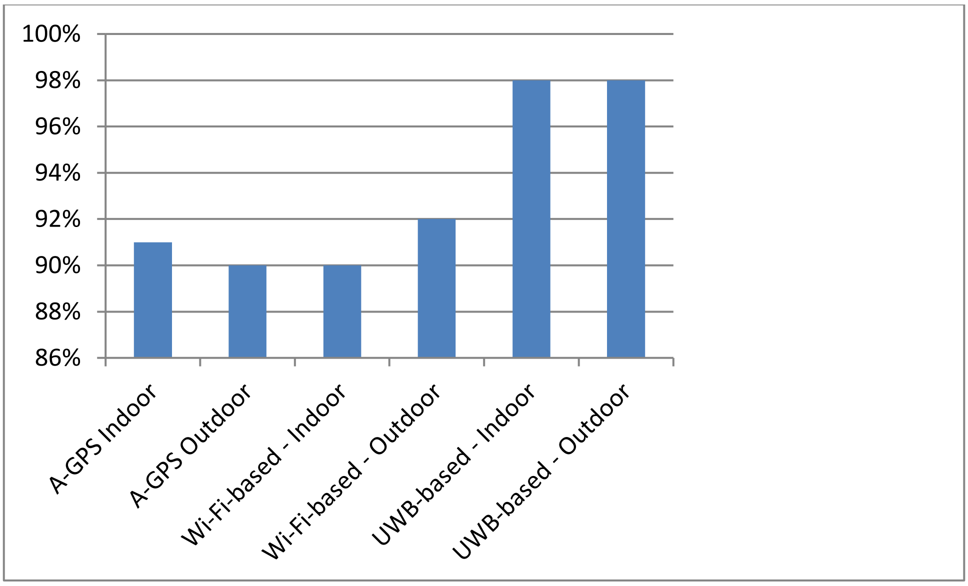


Figure 5-12: A comparison of the SAMSUNG device's remaining battery power after fifteen minutes of activity with different positioning systems

5.3.3.6 Responsiveness to position changes

This facet of the experiment focused on assessing the responsiveness of the UWB-based system when the OOI is moving, and compared the data collected to those recorded in the control experiment. The ultimate purpose of this test was to determine whether an UWB-based positioning system is capable of fulfilling the “real-time” requirement raised in the problem statement.

In this experiment, two set of activities was set to assess the responsiveness of the system to the OOI’s position changes. In the first assessment, a set of nine successive points (or locations) were drawn on the floor of the indoor venue selected for this experiment. The points were set in a linear fashion, with a half-a-meter (0.5 m) interval between each point and its successor.

The mobile user (or participant) holding the OOI was the instructed to move from a point to another when given the signal to do so. The system then recorded data about these activities.

In the second set of activities, the mobile user (or participant) holding the OOI was the instructed to move from a point to another randomly at his normal walking speed. The system then recorded data about his movements. Here, the goal was not only to observe the responsiveness of the system, but also to observe the effect on the accuracy of the systems.

5.3.3.6.1 Results

The following observations were made during the above experiment:

- When the OOI was slowly moving from one point to another as per the first assessment instructions, the UWB-based system accurately responded to an OOI’s position change in less than a second delay.
- When taking up the second assessment, with the walking speed increase, the system still responded with the same accuracy and the same time delay.

In the control experiment, the following results were observed:

- When the OOI was slowly moving from one point to another, the Wi-Fi-based system seemed to be responding only after every third move with a delay close to one second (1s), while the A-GPS responded to few moves after a longer delay.

- When taking up the second assessment, with the walking speed increase, the Wi-Fi-based system responded with a longer delay than at the previous assessment, while the A-GPS delay largely increased. However, both the Wi-Fi-based positioning system and the A-GPS appeared to report inaccurate data about the OOI's position.

According the researcher's observations, the UWB-based positioning system backs the claim suggesting it is more responsive than the Wi-Fi-based positioning system and the A-GPS. Therefore, the UWB-based positioning system is found to be good enough to fulfil the "real-time" requirement evoked in the problem statement.

6 CHAPTER SIX: FINDINGS, DISCUSSION AND FUTURE WORK

6.1 Introduction

This section focuses on the theories extracted from the above experiments. The theories or facts are set to advance the knowledge, and provide a platform to future research projects in the field. In this chapter, the theories are established based on the quantitative and qualitative validations of the hypotheses generated, and a discussion is set around the consequent system's improvements and shortfalls. Few suggestions for future work are also enumerated.

The theories filtered from this work are for most related to the technology and infrastructure used to implement the artefact. The theories are generated from the overall achievements and shortfalls in the performance of the system, as well as the effectiveness of processes and methods used in its development. The goal of the theories in this context is to verify the hypotheses and advance the knowledge in the field regarding technical challenges encountered in this project. Each theory generated directly or indirectly responds to a hypothetical path proposed to solve a challenge of the research problem.

Furthermore, in this section of the work, the future system improvements are discussed, providing a few recommendations and guidance for future work. The discussion is essentially based on the views and observations of the researcher, solidly backed by the results extracted from the experiments described in the previous section of the work. The discussion covers a summary of actions which can be taken to improve the overall performance of this system.

6.2 Research findings

All of the research hypotheses have been tested through the experiments documented in the previous section of the work. The results have given clarity on all the challenges posed by the research problem.

6.2.1 Practical contributions

In practice, the results obtained from the experiments conducted in this work have proven the following facts:

1. Based on the researcher’s observations, an UWB-based positioning system using the TDoA and the winding number algorithms is not consistently capable of determining whether a detected mobile user is currently situated inside or outside a targeted venue.
2. Based on the P-value hypothesis testing, one can affirm that an UWB-based positioning system is more accurate than the satellite-based and the network-based positioning systems.
3. Based on the P-value hypothesis testing, one can affirm that, whether used in an indoor or outdoor location, an UWB-based positioning system still reports the same high accuracy.
4. Based on the P-value hypothesis testing and the researcher’s observations, one can confirm that an UWB-based positioning system built based on the remote positioning system design consumes less electric power than the satellite-based and the network-based positioning systems built based on the self-positioning system design.
5. Based on the researcher’s observations, an UWB-based positioning system is more responsive to the movements of an OOI than the satellite-based and the network-based positioning systems.

6.2.2 Theoretical evidences

In the context of this research, when analysing the above facts as a whole and correlating them to the problem posed at the beginning of the research, the following theories can be extracted from this study, summarising all the findings:

1. To build a positioning system capable of consistently, accurately and reliably flagging the position of an object in relation to a venue based on single technology and method, the selected piece of technology needs to report perfect accuracy at all times. In fact, currently, even one of two most accurate positioning technologies (UWB) combined with one of the most efficient positioning algorithms (the TDoA and the winding number algorithm) is incapable of consistently pinpointing the position of an object in a venue. It works at times, but the level of errors still needs serious improvements before reaching the target required for this kind of systems.

2. Near-real-time tracking of objects using mobile devices is a reality. Current mobile devices processors' speed of execution combined with low power consumption sensors as well as adapted infrastructure allow for such high system

responsiveness without draining mobile devices' batteries. Additionally, the choice of the system design and architecture also helps keep low levels of devices' power consumption. Therefore, it is possible to follow and report every positional change of an object in near-real-time. Currently, the term "near-real-time" is the most appropriate to describe this on-going tracking process as it has not yet reached the actual real-time level.

3. It is possible to develop positioning system which works with the same high accuracy and precision in indoor and outdoor locations. The artefact produced in this work backs the claim. Even though the UWB is mostly used to implement indoor positioning systems, this technology can be used for an outdoor system in need of higher accuracy. GPS is certainly still considered as the standard for outdoor positioning mostly because of its global coverage, but its accuracy is not comparable to the accuracy achieved in this work. However, this kind of system can only be used in-request for now, since it requires quite a bit of investigation beforehand. In fact, anchors need to be placed at certain specific positions of the targeted venue.

6.3 Discussion and future work

Despite proving somewhat successful, the prototype developed in this research only looks at the problem in its simplest form. The complexity such as a three-dimensional representation of venues and OOIs, combining positioning technologies and techniques for better results, or the full integration of UWB sensor in a mobile device motherboard have not been addressed in this research.

Furthermore, the accuracy errors reported in the end results of the experiments have also been overlooked by this work. The full range of the UWB has also not been tested and the impact of a longer range or distance on UWB effectiveness is still unknown.

The work covered in this research only looks at the problem in its two-dimensional perspective. But actually, location and positioning problems for most involve a three-dimensional challenge: length, width and depth. Unfortunately, in this work, there is no boundary set for location depth. The assumption is that all activities happen on the same floor plan in these set experiments. An extension of this work will consist on adapting the same principles in a three-dimensional context and checking if the results correlate.

Another important point consists of trying to integrate other sensors with the UWB and see how that improves the accuracy of the system. This technique has proven efficient in the Pozyx project (Pozyx, 2016). However, the Pozyx project is based on a three-dimensional representation of the tag, the anchors and the venues. In future, the interest will be finding the necessary sensors and algorithms that could bring improvements in the current system setup.

This may consist of trying other positioning techniques with UWB, or even replacing UWB with another accurate technology such as Ultrasound and see if it improves the system. The integration of other kinds of systems (network-based positioning systems or optical-based positioning systems) with this prototype is also option to experiment.

Furthermore, the balance between the advantages and disadvantages of some short-range positioning technologies compared to other short-range technologies is one of the reasons for which there is still no reference or reputed standard as far as indoor positioning systems are concerned.

The recent interests for short-range technologies to address the indoor positioning systems challenges are explained by the accuracy and precision of these technologies. In fact, short-range technologies such as the UWB demonstrate a very high level of accuracy never achieved by technologies such as GPS.

However, each technology has its pros and cons. The technology to use in a specific instance gets selected according to the requirements and priorities set for a system. These priorities can be accuracy and precision (as is the case in this work), security, coverage area, power consumption, cost, or even a combination of many of these attributes. In these circumstances, there is no way of valuing any technology as better than the other. The same applies to the techniques, methods and algorithms used in the systems.

Another interesting project would be integrating an UWB sensor in a mobile device and getting the mobile device processor to directly provide instructions to the tag. That way, the system eliminates the need for an Arduino to hold the sensor. That will further simplify the system and provide more autonomy to mobile devices in the system.

In fact, it is quite hard to believe that, despite the numerous advantages presented by the UWB (accuracy, precision, low power consumption), it has not yet been integrated into mobile devices conceived by the big firms such as Apple or Samsung. Furthermore, it is not yet supported by operating systems such as iOS and Android. However, the popularity of the

UWB is more likely to increase in the coming years. Before that, it will be interesting to fully study the integration of the UWB into mobile devices.

Besides, the accuracy errors reported in the end results of the experiments conducted in this work also deserve a deeper investigation to determine their causes. According to Kang (2015), these errors originate from a limitation of Arduinos used in the project. However, the claim has not been verified in this work. Therefore, it is worth setting up an experiment which will result in approving or rejecting Kang's claim.

On the other hand, Decawave (2014) explains that those errors relates to clock drift and to an incident signal level at the anchors. Additionally, Decawave (2014) provides ways of overcoming these ranging errors. In this work, Decawave's recommendations have not been implemented. However, they are worth pursuing and report on the eventual improvements they bring to the system, even though they appear to be theoretical add-ons rather than definite solutions to the ranging errors.

On the same topic, the representation of venues or locations as polygons following GIS standards certainly works great for areas which are perfect polygons (as the ones used to conduct experiments in this project), but tends to misrepresent areas with more rounded shapes. This also impacts on the accuracy of object’s position in some instances. This inconsistency needs to be addressed.

Finally, the recent increase in the implementation of short-range positioning systems sets the scene for eventual RF interferences all over venues in the near future. In fact, the deployment and emplacements of these short-range technologies-based positioning systems need to be coordinated in order to avoid the physical and virtual chaos of having anchors or beacons placed all over the globe, with systems virtually interfering with each other.

7 CHAPTER SIX: CONCLUSION

In this work, the idea was to find a way to detect users in venues using technology, especially technologies which are compatible with mobile devices. The purpose of achieving such detection is explained by the need for increasing the quality of user-generated contents through location-based services used in mobile apps. Accurate detection of users in their current locations would more likely improve the quality of real-time engagements between users and service providers. The latter could be the object of a complete social science research project.

This work, however, has set focus on addressing the practical side of the target: the real-time detection of users. Accordingly, mobile devices, which are the most common piece of technology carried by users at any time anywhere, has been identified as the best suitable proxy through which the targeted detection process could operate. However, there are some critical challenges preventing mobile devices to be used for such accurate and responsive detection of mobile users. These challenges are linked to:

- The limited accuracy of the most popular positioning systems;
- The limitation of core positioning technologies in certain types of the venues or locations (indoor or outdoor);
- The limitation of mobile devices' power supply.

All the above-listed challenges being of technical nature, it has become evident that the problem undertaken in this research is essentially an engineering one. Therefore, the research was aimed at finding ways of overcoming these challenges.

In the quest for eventual solutions to address the identified issues, a few hypotheses have arisen. These hypotheses have required a detour of the systematic literature review to gather key information and knowledge regarding the topic.

The system literature review process has consisted of finding how other studies have done to overcome or address similar challenges, comparing various existing technologies and methods, and finding the most suited practices to approach this research problem. Thereafter, the implementation of an artefact using the literature review findings was proven necessary to test the effectiveness of these findings in this context.

In the literature review process, the UWB technology gathered much attention because of the level of accuracy and precision it demonstrates. The cost, low power consumption and its availability in the market are a number of factors which led the researcher to nominate UWB as the most adapted technology on which to build the artefact set to address the research problem. In addition, the TDoA algorithm, which is a geometric-based technique of position detection, has been found to be appropriate to use with the UWB in this context to produce a sample of the targeted positioning system.

The concept of building an artefact to test a hypothesis and produce a theory has been extracted from the CSR methodology. Also referred to as constructivism, CSR has been selected as the research paradigm to produce the artefact. Furthermore, Oliveira's (2008) simplified research process has been identified as an adequate process to conduct this work. Thereafter, the development of the artefact, the prototype positioning system built in this work, became the centre-piece of this research project.

On completion of the artefact development, some of the performance metrics used to evaluate various positioning systems in the comparative study elaborated in the literature review section of the work was used to evaluate the prototype produced in this work.

Furthermore, a few experiments were set to test the hypotheses developed in this study. The evaluation of the experiment results and the analysis process found the artefact to be somewhat adapted for the research problem stated in the introduction.

However, a few important improvements are desperately needed to make this prototype bulletproof. Additionally, in the process of addressing the research problem, this work has also revisited the indoor positioning systems challenge and brought a contribution to the real hot topic of the moment.

The following evidences have emerged from the research results:

- Currently, achieving perfect accuracy in positioning systems is not possible using a single technology and positioning technique. Even if they are the best set of technology. Especially, the kind of system targeted by this work, if based on a single piece of technology and method, requires the selected piece of technology to consistently report perfect accuracy.
- Real-time detection of objects using mobile devices is achievable using the right set of existing technologies. These are mobile devices with powerful processors, low power consumption positioning technologies such as UWB and an adapted infrastructure. Furthermore, the choice of the positioning system architecture can help keep power consumption at low levels.

- Using existing technologies and techniques, it is possible to build high accuracy positioning systems suited for use in indoor and outdoor locations. The range of these technologies is certainly limited, but they help achieve better accuracy than the GPS or Wi-Fi-based positioning systems.

At the end of the research, a few discussion points have proven that there is still a lot to do in the field to build the ideal positioning system set to attend to the social aim and prime objective of the problem: the improvements of the quality of user-generated contents using location-based technologies.

BIBLIOGRAPHY

Abdalla, R. 2016. *Introduction to Geospatial Information and Communication Technology (GeoICT)*. Switzerland: Springer International Publishing, 2016.

Adalja, D.M. 2013. *A Comparative Analysis on indoor positioning Techniques and Systems*. International Journal of Engineering Research and Applications, 3(2):1790-1796, March-April 2013.

Adusei, K.A., Kyamakya, K. & Jobmann, K. 2002. *Mobile Positioning Technologies in Cellular Networks: An Evaluation of their Performance Metrics*. London: IEEE, British Crown Copyright.

Alarifi, A., Al-Salman, A., Alsaleh, M., Alnafessah, A., Al-Hadhrami, S., Al-Ammar, M.A. & Al-Khalifa, H.S. 2016. *UltraWideband Indoor Positioning Technologies:Analysis and Recent Advances*. Sensors 2016, 16(707), May 2016.

Anthony, S. 2012. *Think GPS is cool? IPS will blow your mind*. [Online]. Available from: http://www.extremetech.com/extreme/126843-think-gps-is-cool-ips-will-blow-your-mind [Accessed: 22/05/2014].

Arduino. 2017. *Arduino Pro Mini*. [Online]. Available from: https://www.arduino.cc/en/Main/arduinoBoardProMini [Accessed: 08/04/2017].

Bao, J., Zheng, Y. & Mokbel, M. F. 2012. *Location-based and Preference-Aware Recommendation Using Sparse Geo-Social Networking Data*. Redondo Beach: ACM SIGSPATIAL GIS'12, November 2012.

Bekkelien, A. 2012. *Bluetooth Indoor Positioning*. Master of Computer Science: University of Geneva.

Bellusci, G. 2011. *Ultra-Wideband Ranging for Low-Complexity Indoor Positioning Applications*. Doctoral Thesis: Wireless and Mobile Communications department in the Faculty of Electrical Engineering, Mathematics and Computer Science.

Berkeveld, R.A.J. 2016. *Design and implementation of unicycle AGVs for cooperative control*. [Online]. Available from: https://pure.tue.nl/ws/files/46945898/855665-1.pdf [Accessed: 07/12/2017].

Carroll, A. & Heiser, G. 2010. *An Analysis of Power Consumption in a Smartphone*. [Online]. Available from: https://www.usenix.org/legacy/event/atc10/tech/full_papers/Carroll.pdf [Accessed: 23/05/2016].

Carter, E. 2003. *LANDSCAPES FOR CELEBRATION: An Investigation and Design of Wedding Gardens*. A thesis submitted in partial fulfillment of the requirements for the degree of Master of Landscape Architecture: Landscape Architecture in the Faculty of the Virginia Polytechnic Institute and State University.

Chao, Y., Chan, L., Hsu, J. & Hung, Y. 2007. *IMPROVING LOCATION ACCURACY BY COMBINING: ZIGBEE AND VISUAL POSITIONING TECHNIQUES*. Taiwan: Graduate Institute of Networking and Multimedia, Department of Computer Science and Information Engineering, National Taiwan University.

Cisco. 2013. *Cisco Connected Mobile Experiences*. At-A-Glance, Cisco, Janvier 2013.

Crnkovic, G.D. 2010. *Constructive Research and Info-Computational Knowledge Generation*. [Online]. Available from: http://www.mrtc.mdh.se/~gdc/work/MBR09ConstructiveResearch.pdf [Accessed: 21/05/2014].

Dalce, R., Val, T. & Van Den Bossche, A. 2011. *Comparison of Indoor Localization Systems Based on Wireless Communications*. Wireless Engineering and Technology, 2, 240-256, October 2011.

DecaWave. 2013. *PRODUCT INFORMATION: DWM1000*. [Online]. Available from: http://www.decawave.com/sites/default/files/product-pdf/dwm1000-product-brief.pdf [Accessed: 08/04/2017].

Decawave, 2014. *SOURCES OF ERROR IN DW1000 BASED TWO-WAY RANGING (TWR) SCHEMES*. [Online]. Available from: http://www.decawave.com/sites/default/files/resources/aps011_sources_of_error_in_twr.pdf [Accessed: 14-04-2017].

Demsey, C. 2012. *GIS Data Explored – Vector and Raster Data*. [Online]. Available from: https://www.gislounge.com/geodatabases-explored-vector-and-raster-data/ [Accessed: 10/04/2017].

Farid, Z., Nordin, R. & Ismail, M. 2013. *Recent Advances in Wireless Indoor Localization Techniques and System*. [Online]. Available from: https://www.hindawi.com/journals/jcnc/2013/185138/ [Accessed: 13/03/2017].

Foerster, J., Green, E., Somayazulu, S. & Leeper, D. 2001. *Ultra-Wideband Technology for Short- or Medium-Range Wireless Communications*. USA: Intel Technology Journal Q2.

Freitas, R. 2009. *Scientific Research Methods and Computer Science*. Porto: Universidade do Porto.

Goldenberg, J. & Levy, M. 2009. *Distance Is Not Dead: Social Interaction and Geographical Distance in the Internet Era*. Jerusalem: The Hebrew University.

Graphic Tutorial. 2016. *What are independent and dependent variables?*. [Online]. Available from: https://nces.ed.gov/nceskids/help/user_guide/graph/variables.asp [Accessed: 05/04/2017].

Hayta, A.B. 2013. *A study on the effects of social media on young consumers' buying behaviors*. International Association of Social Science Research – IASSR.

Hecht, B. & Gergle, D. 2009. *On the "Localness" of User-Generated Content*. Illinois: Northwestern University.

Henniges, R. 2012. *Current approaches of Wifi Positioning*. Berlin: Service-Centric Networking.

Hu, B. 2013. *Wi-Fi Based Indoor Positioning System Using Smartphones*. A thesis submitted in fulfilment of the requirements for the degree of Master of Applied Science: School of Mathematical and Geospatial Sciences College of Science, Engineering and Health, Royal Melbourne Institute of Technology (RMIT) University.

Huber, D. 2011. *Background Positioning for Mobile Devices - Android vs. iPhone*. Berlin: School of Electrical and Computer Engineering, Technical University Berlin.

Hwang, S. & Yu, D. 2012. *GPS Localization Improvement of Smartphones Using Built-in Sensors*. South Korea: Catholic University of Pusan.

Kabaso, B. 2014. *HEALTH INFORMATION SYSTEMS INTEROPERABILITY IN AFRICA: Service Oriented Architectural Model for interoperability in African context*. Thesis submitted in fulfilment of the requirements for the degree Doctor of Technology: Information Technology in the Faculty of Informatics And Design at the Cape Peninsula University of Technology.

Kang, H. 2015. Test DWM1000 UWB module with Arduino. [Online]. Available from: http://khjtony.github.io/project/2015/05/15/Test-DWM1000-UWB-Module-with-Arduino.html [Accessed: 10/02/2017].

Key, J.P. 1997. Research Design in Occupational Education. [Online]. Available from: https://www.okstate.edu/ag/agedcm4h/academic/aged5980a/5980/newpage2.htm [Accessed: 07/12/2012]

Kulm, T., Parv, L., Rahman, A. & Kuusik, A. 2016. *Precise Ultra Wideband Indoor positioning System*. Tallinn: Eliko.

Kupper, A. 2005. *Location-based Services: Fundamentals and Operation*. London: John Wiley & Sons Ltd.

Lawler, J & Schiess, P. 2013. *Introduction to Geographic Information Systems in Forest Resources. The GIS Spatial Data Model*. [Online]. Avalaible from: https://courses.washington.edu/gis250/lessons/introduction_gis/spatial_data_model.html [Accessed: 10/04/2017].

Lee, J., Su, Y. & Shen, C. 2007. *A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi*. Taipei: The 33rd Annual Conference of the IEEE Industrial Electronics Society (IECON), November 5-8.

Liu, H., Darabi, H. & Liu, J. 2007. *Survey of Wireless Indoor Positioning Techniques and Systems*. IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS—PART C: APPLICATIONS AND REVIEWS, 37(6):1067-1079, November 2007.

Liu, J. 2014. *Survey of Wireless Based Indoor Localization Technologies*. [Online]. Available from: http://www.cse.wustl.edu/~jain/cse574-14/ftp/indoor/index.html [Accessed: 13/03/2017]

Mautz, R. 2008. *Combination of Indoor and Outdoor Positioning*. Zurich: 1st International Conference on Machine Control & Guidance, June 24-26.

MaxMind. 2014. *Web Services*. [Online]. Available from: http://www.maxmind.com/en/webservices [Accessed: 07/05/2014].

Nallaperumal, K. 2007. *Engineering Research Methodology: A Computer Science and Engineering and Information and Communication Technologies Perspective*. [Online]. Available from: https://www.researchgate.net/publication/259183120_Engineering_Research_Methodology_A_Computer_Science_and_Engineering_and_Information_and_Communication_Technologies_Perspective [Accessed: 23/03/2017].

Oates, B. J. 2005. *Researching information systems and computing*. Thousand Oaks: Sage Publications Ltd.

Oliveira, E. 2008. *MSR- Methodologies for Scientific Research*. [Online]. Available from: https://web.fe.up.pt/~eol/MSR/MSR_09_10/Aula1/Methods_1.pdf [Accessed: 05/03/2017].

Poslad, S. 2009. *Ubiquitous Computing: Smart Devices, Environments and Interactions*. London: John Wiley & Sons Ltd.

Pozyx. 2016. *Pozyx accurate positioning*. [Online]. Available from: www.pozyx.io [Accessed: 04/03/2017].

Rowan-Robinson, M. 2013. *Night Vision: Exploring the Infrared Universe*. Cambridge: Cambridge University Press.

Rota, D. & Montalto, S. 2017. *ON THE USE OF BEACONS AND UWB TECHNOLOGIES FOR INDOOR NAVIGATION SYSTEMS*. Milan: School of Industrial and Information Engineering, Dipartimento Di Elettronica, Informazione E Bioingegneria, Politecnico Di Milano.

Shah, D. & Shah, K. 2012. *Basic of Wi-Fi based positioning system*. [Online]. Available from: https://www.researchgate.net/publication/232729025 [Accessed: 15/03/2017].

Sreder, A. 2014. *Android: GPS positioning and location strategie*s. [Online]. Available from: https://blog.codecentric.de/en/2014/05/android-gps-positioning-location-strategies/ [Accessed: 23/5/2014].

Stangroom, J. 2017. One-Way ANOVA Calculator. [Online]. Available from: http://www.socscistatistics.com/tests/anova/Default2.aspx [Accessed: 05/05/2017].

Sunday, D. 2012. *Inclusion of a Point in a Polygon*. [Online]. Available from: http://geomalgorithms.com/a03-_inclusion.html [Accessed: 01/04/2017].

Svalastog, M.S. 2007. *Indoor Positioning - Technologies, Services and Architectures*. Cand. Scient Thesis: Department of Informatics at the University of Oslo.

The American Heritage. 2002. *Control experiment*. [Online]. Available from: http://www.dictionary.com/browse/control-experiment [Accessed: 05/04/2017].

The Pennsylvania State University. 2017. *3.2 - Hypothesis Testing (P-value approach)*. [Online]. Available from: https://onlinecourses.science.psu.edu/statprogram/node/138 [Accessed: 05/05/2017].

Tillison, J. 2016. *Bluetooth BLE Beacon Pseudo-Standards (Apple iBeacon, Google's Eddystone, AltBeacon)*. [Online]. Available from: http://www.eedneurope.com/blog/bluetooth-ble-beacon-pseudo-standards-apple-ibeacon-googles-eddystone-altbeacon [Accessed: 05/04/2017].

Tristant, P. 2009. *Ultra Wide Band (UWB) and Short-Range Devices (SRD) technologies*. ITU/WMO Seminar on use of radio spectrum for meteorology: Weather, Water and Climate monitoring and prediction, September 2009.

Triukose, S., Ardon, S., Mahanti, A. & Sethz, A. 2011. *Geolocating IP Addresses in Cellular Data Networks*. Australia: NICTA.

Wang, Y., Burgener D., Flores M., Kuzmanovic A. & Huang C. 2011. *Towards Street-Level Client-Independent IP Geolocation*. Illinois: Northwestern University.

Zhang, L., Tiwana, B., Dick, R.P.,Qian,Z., Mao, Z.M., Wang,Z. & Yang, L. 2010. *Accurate online power estimation and automatic battery behavior based power model generation for smartphones*. 2010 IEEE/ACM/IFIP International Conference on Hardware/Software Codesign and System Synthesis (CODES+ISSS), October 2010

Zhuang, Z., Kim, K. & Singh, J.P. 2010. *Improving Energy Efficiency of Location Sensing on Smartphones*. California: MobiSys'10.