The suitability of WiFi infrastructure for occupancy sensing

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September 2014
Declaration

I, Melanie Delport hereby declare that the dissertation entitled “The suitability of WiFi infrastructure for occupancy sensing”, is my own original work and has not already been submitted to any other university or institution for examination.

_______________________
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Signed on the 1st day of September 2014, at Potchefstroom.
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I would be honoured to dedicate this dissertation to my personal source of strength, Jesus. All thanks to Him for pulling me through personal difficult times.

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Lastly, I would like to give an early thank-you to my examinators for baring through this lengthy dissertation.
Abstract

The focus of this study was to investigate an alternative and more cost effective solution for occupancy sensing in commercial office buildings. The intended purpose of this solution is to aid in efficient energy management. The main requirements were that the proposed solution made use of existing infrastructure only, and provided a means to focus on occupant location.

This research was undertaken due to current solutions making use of custom occupancy sensors that are relatively costly and troublesome to implement. These solutions focus mainly on monitoring environmental changes, and not the physical locations of the occupants themselves. Furthermore, current occupancy sensing solutions are unable to provide proximity and timing information that indicate how far an occupant is located from a specific area, or how long the occupant resided there.

The research question was answered by conducting a proof of concept study with data simulated in the OMNeT++ environment in conjunction with the MiXiM framework for wireless networks. The proposed solution investigated the fidelity of existing WiFi infrastructure for occupancy sensing, this entailed the creation of a Virtual Occupancy Sensor (VOS) that implemented RSS-based localisation for an occupant’s WiFi devices. Localisation was implemented with three different location estimation techniques; these were trilateration, constrained nearest neighbour RF mapping and unconstrained nearest neighbour RF mapping. The obtained positioning data was interpreted by a developed intelligent agent that was able to transform this regular position data into relevant occupancy information. This information included a distance from office measurement and an occupancy result that can be interpreted by existing energy management systems. The accuracy and operational behaviour of the developed VOS were tested with various scenarios. Sensitivity analysis and extreme condition testing were also conducted.

Results showed that the constrained nearest neighbour RF mapping approach is the most accurate, and is best suited for occupancy determination. The created VOS system can function correctly with various tested sensitivities and device loads. Furthermore results indicated that the VOS is very accurate in determining room level occupancy although the accuracy of the position coordinate estimations fluctuated considerably. The operational behaviour of the VOS could be validated for all investigated scenarios.

It was determined that the developed VOS can be deemed fit for its intended purpose, and is able to give indication to occupant proximity and movement timing. The conducted research confirmed the fidelity of WiFi infrastructure for occupancy sensing, and that the developed VOS can be considered a viable and cost effective alternative to current occupancy sensing solutions.

Keywords: Building Energy Management, Location Estimation, MiXiM Framework, Occupancy Sensing, OMNeT++ Simulations, RF Fingerprinting, WiFi Infrastructure.
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<th>Description</th>
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<tbody>
<tr>
<td>AOA</td>
<td>Angle of Arrival</td>
</tr>
<tr>
<td>AP</td>
<td>Access Point</td>
</tr>
<tr>
<td>APIT</td>
<td>Approximate Point-Intriangulation Test algorithm</td>
</tr>
<tr>
<td>BEMS</td>
<td>Building Energy Management System</td>
</tr>
<tr>
<td>COS</td>
<td>Custom Occupancy Sensor</td>
</tr>
<tr>
<td>DNS</td>
<td>Domain Name System</td>
</tr>
<tr>
<td>FTP</td>
<td>File Transfer Protocol</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphic User Interface</td>
</tr>
<tr>
<td>HTTP</td>
<td>Hyper Text Transfer Protocol</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heating, Ventilation and Air-conditioning systems</td>
</tr>
<tr>
<td>IA</td>
<td>Intelligent Agent</td>
</tr>
<tr>
<td>IDE</td>
<td>Integrated Development Environment</td>
</tr>
<tr>
<td>IP</td>
<td>Internet Protocol</td>
</tr>
<tr>
<td>LAN</td>
<td>Local Area Network</td>
</tr>
<tr>
<td>LOS</td>
<td>Line-of-Sight</td>
</tr>
<tr>
<td>LQI</td>
<td>Link Quality Indication</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Control</td>
</tr>
<tr>
<td>MF</td>
<td>Mobility Framework</td>
</tr>
<tr>
<td>MMSE</td>
<td>Minimum Mean Square Error</td>
</tr>
<tr>
<td>NED</td>
<td>Network Description file</td>
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<tr>
<td>NIC</td>
<td>Network Interface Card</td>
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<tr>
<td>NLOS</td>
<td>Non-Line-of-Sight</td>
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<tr>
<td>OR</td>
<td>Occupancy Result</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
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<tr>
<td>PHY</td>
<td>Physical Layer Control</td>
</tr>
<tr>
<td>PIR</td>
<td>Passive Infrared sensors</td>
</tr>
<tr>
<td>PoI</td>
<td>Point of Interest</td>
</tr>
<tr>
<td>RAM</td>
<td>Random Access Memory</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RSS</td>
<td>Received Signal Strength</td>
</tr>
<tr>
<td>RSSI</td>
<td>Received Signal Strength Indicator</td>
</tr>
<tr>
<td>RTT</td>
<td>Round Trip Time</td>
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<tr>
<td>SMTP</td>
<td>Simple Mail Transfer Protocol</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>TDOA</td>
<td>Time Difference of Arrival</td>
</tr>
<tr>
<td>TOA</td>
<td>Time of Arrival</td>
</tr>
<tr>
<td>ToF</td>
<td>Time of Flight</td>
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<tr>
<td>VLAN</td>
<td>Virtual Local Area Network</td>
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<td>VOS</td>
<td>Virtual Occupancy Sensor</td>
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1 INTRODUCTION

The topic of energy efficiency has developed into a dominant public interest and high priority for policy makers. This trend is set to continue into the future as a result of rapid growth in energy demand and environmental concern. The prospect to gain cost and competitive advantage through the more efficient use of energy will guarantee that research in this field sustains its relevance since energy efficiency is a by-product of energy intelligence.

In [1] Zavalani defines the intelligent use of energy as smart energy saving accompanied by enhanced ease-of-use and sustained cost saving. There have been various goals and provisions for the enhancement of energy efficiency by incentives for investments in modernisation of energy infrastructure. This is due to the cost of generating energy being greater than the costs of implementing energy saving techniques.

Commercial and residential buildings are considered some of the main and fastest growing energy consumer sectors in both today’s major and rising economies. Building energy consumption is anticipated to grow by 45% in the next 20 years. Efficient energy management in these sectors, thus, bid a momentous avenue for inquiry and improvement [2].

1.1 ENERGY WASTAGE IN BUILDINGS

In order to improve on energy efficiency in commercial buildings, the consumption and wastage of energy need to be investigated.

Three factors influence optimal energy management in buildings; outer environment, inner occupants and provided facilities [4]. The environment contributing to energy spent on climate control and lighting applications that are mostly needed to cater for the comfort of occupants or the cooling of equipment. Energy consuming facilities in commercial buildings are mostly provided to aid occupants in tasks they need to perform, and to facilitate business processes.

In typical commercial buildings up to 50% of energy is consumed by heating, ventilation and air-conditioning (HVAC) systems. This figure is raised to 60% when adding water heating.
Office equipment and lighting in buildings consume another 20% of the overall building energy [5]. Altogether these “basics” account for up to 80% of the total energy consumption of a commercial building.

According to Yuan et al. in [4] the behaviour of occupants have a great deal of influence on the energy consumption in commercial buildings. The neglect of occupants to switch off unused devices contributes a noteworthy fraction. As a result of this neglect, a significant amount of energy is wasted by supplying climate control services and energy consuming facilities in unoccupied building areas. In [6] Meyers et al. mention that 39% of building energy in the US is wasted due HVAC systems left switched on in unoccupied rooms, and in the UK 23%-30% due to lighting left switched on in unoccupied building areas [7].

The above indicates that occupants play an integral role in building energy consumption. Simply put this means that, indirectly, building occupants are the main reason for the vast consumption of energy in buildings as well as the main cause of wastage. From an energy conservation and efficiency perspective it would make sense to monitor occupant presence in commercial buildings. Furthermore, if the physical positions of building occupants are obtainable it would present a means of making intelligent occupancy decisions.

1.2 CURRENT SOLUTIONS

Solutions to integrating occupancy information for efficient energy management can be categorised into occupancy monitoring, occupancy estimation or a combination of both.

Occupancy estimation can be done by the use of techniques such as genetic algorithms, fuzzy-logic, neural-networks and Intelligent Agent (IA) techniques [8]. These techniques require a vast range of suitable data to learn from before occupancy estimation can commence. This range may include data on weather patterns, occupancy schedules, indoor climate, energy usage patterns and occupant behaviour patterns. Suitable data for these occupancy estimation techniques can be found from simulated occupancy models or occupancy monitoring. Due to the vague nature of occupancy and ample fluctuations seen over various time-scales, it is considered extremely difficult to predict occupancy ahead of time based on anticipated building use. Thus far, real-time monitoring of occupancy has proven to be the best option.

The standard solution for building occupancy monitoring is to implement custom occupancy sensors (COSs). COSs are sensory devices consisting of dual-technology sensors that offer sensing capabilities for more than one occupancy indicating factor, and is created by the fusion of several sensors into a single device. COSs can, however, also be a series of different, standalone but integrated sensors.
Typical sensors types incorporated in an occupancy sensor may comprise of:

*Passive/Pyroelectric Infrared (PIR) sensors* that detect movement based on temperature differences are popular for occupancy sensing and are mostly used in lighting applications.

*Microphonic sensors* that monitor occupant activities by means of sound distinction are implemented in [9].

*Ultrasonic sensors* that make use of high frequency ultrasonic waves to detect movement are widely applied in the field of occupancy sensing [8], [9]. These sensor types are also very typical in automobile alarm systems.

*Optical tripwires*, detecting if a zone-threshold is crossed are used to determine room level occupancy [8].

*Intelligent video camera architectures* with people counting abilities can also be implemented [8].

Other occupancy monitoring solutions range from wearable radio frequency (RF) sensors to a combination of closed circuit television and biometric systems [8].

All of these sensor types and intelligent applications have their own limitations and implementation fitness for occupancy sensing.

In [9] Brown *et al.* state that existing occupancy monitoring technologies are plagued with numerous issues like unreliable data, sensor drift, short term financial pressures, inefficient commissioning and low quality parts. Sensor specific issues of the above mentioned sensors will now be examined.

PIR sensors are not considered an effective occupancy monitoring solution because these sensors fail to detect presence when occupants are stationary [6]; this leads to untrustworthy occupancy data and many logged false positives due to sensors registering movement not indicating occupant presence.

Microphonic sensors fail in noisy environments and may not detect the presence of an occupant typing on a computer. This sensor type also relies on very distinct characterisation of sound sources to be effective [8].

High frequency ultrasonic sensors are particularly sensitive and react to minute disturbance in the wave [7]. A vast number of false-positives is registered as a result of this oversensitivity.

Optical tripwires used to count the number of occupants crossing a zone, also suffer from false counts and need to be implemented at all zone entrances.
Furthermore, these sensors need to incorporate two beams or wires to determine if the occupant is entering or leaving a building zone. Lastly, intelligent video camera architectures are considered an unmerited invasion of the privacy of building occupants. In order to function efficiently, this architecture requires continuous real-time streaming that consume a significant amount of network and energy resources.

All of the above sensors types need to be implemented per building zone or even per room to provide effective occupancy monitoring services. This also entails custom and time consuming installations and extensive calibrations in every zone/room, plus the loss of productivity while occupants are inconvenienced by this process. Furthermore, the implementation of COSs add to the total energy consumption of a building. The additional energy required to power the sensors and to compensate for the phantom power load created by sensors in standby mode are not attractive prospects for companies wanting to save on their energy bill. COS solutions may be a viable option for large corporations able to spend the money needed to achieve energy efficiency, but this is, unfortunately, not the case for smaller companies and businesses that would also benefit from more efficient energy usage.

The main limitation of COSs is that they only monitor environmental changes that may or may not indicate the presence of an occupant and not the physical location of the occupants themselves. Thus not providing sufficient information for making intelligent occupancy and power management decisions, such as if the occupant is close to or far from an office area or how long the occupant has been absent.

The discussed limitations provide strong grounds for research into possible alternative solutions that are more affordable, can be more easily implemented, and offer efficient means of occupancy monitoring. This lead to the following research question:

### 1.3 RESEARCH QUESTION

*Can existing infrastructure present in most commercial buildings be used to provide an alternative and more cost effective means of building occupancy sensing?*

This research question is answered in the form of a proof of concept investigation. This investigation will consider simulated data to construct an alternative occupancy sensing model that can be used for efficient building energy management. The concept of the proposed solution will now be elaborated upon.
**1.4 PROPOSED SOLUTION**

Investigations into existing infrastructures offering potential management opportunities that can be exploited for the purpose of occupancy sensing is needed. One infrastructure that is present in most office buildings is an Internet Protocol (IP) network that consists of wired and wireless technology.

This research aims to exploit management opportunities found in the combination of WiFi capable user devices and the existing IP network infrastructure to provide an alternative solution to energy resource management in office buildings. This alternative solution is offered in the form of a Virtual Occupancy Sensor (VOS) and focuses on occupant location rather than environmental changes. The virtual occupancy sensor should be able to establish the location of an occupant while only utilising these existing infrastructures.

In the information age of today, an individual can own between two and five WiFi capable smart devices including smart-phones, tablets and laptops. Individuals or in this case occupants almost always have one or more of these devices, especially smart-phones, on their person or in close proximity at all times. From this, a primary research assumption has been made that the physical location of the occupant can be estimated as the physical location of the occupant’s device.

Localisation, when performed for an occupant’s personal WiFi device, will thus give an indication to the position of the occupant within the building. Position-awareness will provide the ability to focus on occupant location rather than environmental changes. This will allow for various intelligent occupancy decisions to be made based on the proximity of an occupant to a building zone/room, while also taking into account the time spent in the specific zone. Localisation thus plays a fundamental role in the functionality provided by the proposed solution, and sets it apart for current occupancy sensing solutions.

Localisation of radio devices is relatively common, and there are a number of parameters used globally for this task. One such parameter is the Received Signal Strength Indicator (RSSI) of a received radio signal. Time-of-Flight (propagation time from A to B) is also widely used. Both of these parameters can easily be related to distance for use with localisation algorithms. In [10] it is said that most current wireless communication standards which define physical (PHY) and medium access control (MAC) layer protocols offer support functions for RSSI measuring. RSSI measurements are consequently obtainable for localisation purposes without any specialised measuring equipment.

Physical locations of WiFi capable devices can be found by the application of several different methods that include localisation algorithms such as triangulation and trilateration.
Other techniques like RF-mapping are also becoming more widely used. The above mentioned technique entails creating a map of the RF environment and then comparing live RSS readings to mapped readings in order to determine the location of the live radio source. This technique, although it requires calibration, has proven to be very accurate. The accuracy depending mostly on the granularity of the created RF map.

Implementation of Intelligent Agents (IAs) will be used to handle the task of collecting and integrating this localisation information and presenting it in such a way that it becomes useful occupancy information. This occupancy information will be produced by evaluating localisation information with a set of simple logical rules and dependencies.

The IA will require a building occupant to register his/her personal WiFi devices and assign each with a priority based on the fitness of the device to correctly reflect the occupant’s location. The highest priority device should be the one the occupant is most likely to have on his/her person at all times, for example, a smart-phone. The IA will then link all registered occupant devices to the occupant’s specific office location and monitor time-periods spent in building energy zones. By doing this, the IA will be able to provide user-centric localisation for each occupant office and surrounding areas as well as make intelligent energy saving decisions based on the proximity of the occupant to his/her office. Thus meaning that the IA will be able to use this proximity measure combined with the elapsed time, as measured in a particular proximity zone, to distinguish between short, medium and long-leave events. This will prevent the occupant’s office from powering down when quickly leaving for the bathroom as well as ensure that the office does power down when attending a long meeting in the boardroom next door.

The IA will provide the following output information:

- Coordinates of each occupant’s physical location for a given time.
- The proximity of the occupant to his/her office.
- The elapsed time spent in a proximity range.
- An occupation result – numerical value indicating if the occupant’s office should remain powered up, be powered down or monitored.

This occupancy information can then be interpreted by an existing building energy management system (BEMS) connected to a smart-grid for regulating power supply to the building energy zones.

This implementation of localisation-based occupancy gives way to a range of additional benefits. The proposed solution will produce intelligent and more trustworthy occupancy results that take into account the movement of occupants and simple occupancy rules. This would give the proposed solution advantage over current occupancy solutions and also provide the ability to add a range of location-based and other functionalities.
1.5 RESEARCH METHODOLOGY

The diagram presented below details the followed research methodology.

![Research Methodology Diagram]

Figure 1.1 : Research Methodology
The research methodology flow diagram depicts the followed research process as well as the corresponding chapters in which the full discussion of each phase is presented. A brief summary of the research process will now be given:

**Phase [a]** – In the research commencement and motivation phase background literature is provided on the research problem, the research question is defined and a solution to the research problem is proposed. This phase is detailed in chapter one of this dissertation and serves as inception and incentive for the conducted research.

**Phase [b]** – The literature survey firstly serves as a reference with regards to knowledge contributed by predecessors in relevant research fields. This includes research on existing occupancy monitoring solutions, localisation techniques and IP network infrastructure. Background on the OMNeT++ simulation package and MiXiM extension for wireless network simulations are also provided. The literature survey can be found in chapter two and will be concluded with a review of the techniques chosen for implementation.

**Phase [c]** – This research phase makes out the first part of chapter three and involves the generation of RSSI data for use with the occupancy model. The data is generated from simulations of a wireless network implemented in MiXiM. The modelled network consists of three RSSI measuring APs and is compiled for different scenarios. Simulation event logs containing measured RSS, as well as the device's actual position coordinates is uploaded to a self-constructed parser for importing relevant data into a database for use and evaluation by IAs.

**Phase [d]** – In this phase the data imported from the simulations is re-worked and organised by IAs to relate registered occupants to the simulated devices. Thereafter the IA attempts to localise all simulated devices by the execution of three different localisation algorithms; trilateration, constrained mapping and unconstrained mapping. The IA calculates the estimated coordinates, estimation errors and various statistics for each of the three algorithms. This phase is also part of the third dissertation chapter and will be discussed there in full detail.

**Phase [e]** – This section of chapter three starts with implementation of logical rules and constraints to make occupancy based decisions. The decisions lead to an occupancy result that indicates the power state of the occupant’s office. The IA then performs algorithms for analysing and comparing occupancy results, localisation algorithm performance, localisation accuracy and loading handling. This crucial phase serves as foundations for the research outputs and fitness of implementation of the proposed VOS.

**Phase [f]** – This phase represents the last part of the experimental implementation chapter and provides visualisations of occupant movement within the building, the found occupancy results and office power state.
This functionality is provided by the IAs along with the option to generate automated graphs and statistics for each represented device, all devices and all simulations.

*Phase [g]* – These calculated statistics and created graphs will be represented in chapter four and serve as the primary research results. This chapter will be used to analyse and interpret the above mentioned graphs and statistics in order to determine if the found occupancy results accurately reflect the simulated scenarios.

*Phase [h]* – This phase contributes to chapter four and provides insight into the correctness of the results with respects to estimated occupant locations as determined by validation techniques, the fitness of implementation for real-world scenarios and overall fitness for efficient energy management as determined by verification methods.

*Phase [i]* – The final research phase and final dissertation chapter server to provide the overall research findings, limitations and recommendations. In this phase, the research question will be interpreted and the fidelity of the created occupancy model will be defined. This phase then also provides the final closing comments and concludes the undertaken research.

### 1.6 OUTLINE OF DISSERTATION

The following represents a high level summary of the chapter content of this dissertation.

*Introduction* provides insight into the research question, current solutions and the limitations thereof. A research methodology diagram is also presented.

*Literature survey* serves as a point of reference with regards to existing research in the fields of occupancy monitoring, RF localisation techniques and network simulation software.

*Experimental Implementation* details the processes and methods that were applied in order to achieve the research outcomes.

*Results* section presents all of the obtained results and statistics, and provides analysis and interpretation of the results;

*Conclusion & Recommendations* provides the final summary of the research in question as well as a critical evaluation of the obtained results.
2 LITERATURE SURVEY

This chapter provides the relevant context and theoretical setting within which this research is completed. This chapter starts off by looking into existing infrastructure that can be exploited for the use of energy efficiency management within commercial buildings. A brief overview of indoor radio propagation is then provided followed by a detailed section on possible localisation methods to implement for the purpose of determining the physical locations of WiFi devices. A brief investigation into traffic monitoring is conducted to determine the suitability thereof to aid in dynamic radio mapping. Lastly, an overview of the general structure of the simulation packages identified for data generation is provided. The chapter is concluded by a summary section highlighting the main points as discussed within this chapter, as well as selected implementation principles.

2.1 EXISTING INFRASTRUCTURE

As stated in chapter one, an IP network infrastructure is present in most existing office buildings. This study aims to exploit management opportunities identified within this infrastructure for the more efficient management of building energy resources.

An Internet Protocol network is a network of hosts that share a physical connection and is used for network layer communication that incorporates 32bit IPv4 or 128bit IPv6 addresses as unique identifiers for network devices [11]. In order to do this, IP defines datagram structures that encapsulate the sent data, as well as IP source and destination addresses.

The IP addresses are then used by the network layer for routing data packets across networks (over the internet) [3], [11]. IP can run on top of different data link interfaces like Ethernet and WiFi.

2.1.1 ETHERNET

Ethernet forms the base of link layer networking and uses MAC addresses as assigned to the devices’ network interface card by the manufacturer. A network node’s IP address can be used for querying its MAC address with the Address Resolution Protocol (ARP) for IPv4 and Neighbour Discovery Protocol (NDP) for IPv6 [11], [12].
2.1.2  WIFI

WiFi is a technology that enables devices to communicate wirelessly over computer networks using the 2.4 GHz or 5.8 GHz radio bands. WiFi can be seen as a less expensive alternative to, or extension of wired networks and offer mobility to network users. WiFi devices connect to a wireless local access network (WLAN) via a wireless network access point (AP) and transmit data in packets called Ethernet frames. WiFi, like Ethernet, also makes use of MAC addresses to uniquely identify devices [11], [12]. An IP address is assigned to a device when connecting to a WLAN. By using both the IP and MAC addresses of a device, it is possible to know to which AP the device is connected.

Furthermore, local network IP addresses for both wired and WiFi devices can be used to give an indication as to the physical position/location of the device. It is this indication and unique device identification of the IP-Network infrastructure that offer potential management opportunity for occupancy monitoring.

The physical location of wired network devices can be found by the combination of lookup table information, switch port mapping and logical Virtual Local Area Network (VLAN) configurations.

Switch port mapping is used to identify devices that are physically connected to switch ports and stores information such as IP and MAC addresses, Domain Name System (DNS) names and VLAN information [12]. Available switch port mapping tools give network administrators a clear overall graphic view of the relation between this stored information for each device connected to the switch. These tools are especially useful for translating the necessary VLAN configurations to the device’s IP address, offering visualisation of the virtual network layer, sub-netted sections and overall fit on top of the physical network configuration. In [13] Rong et al. state that VLANs can be sub-netted to reflect specific building zones or floors and IP addresses can be allocated strategically to be matched to specific office locations [12].

Taking this implementation to the next logical phase Imielinski et al. in [14] proposed a range of protocols and addressing methods to integrate global positioning system (GPS) data into the Internet Protocol for mobile networks. These IPv4 based methods made use of GPS coordinates as address identifiers and divides the GPS addresses into two by using \langle\text{latitude, longitude}\rangle as the addressing model. This integration of GPS into the Internet protocol can thus provide physical location as well as sign location as positioning results. Where the latitude and longitude represent the physical location result and the sign result can be described by a symbolic logical location such as the building room number [13].
Furthermore, these positioning results are said to be interchangeable for location determination purposes in order to offer best suitability for the installation environment of the IP network. This indicates that, with this addressing scheme, the physical office locations of occupants within a building can be represented by a specific device’s IP address in the form of either coordinates within the building or the logical corresponding room number.

These location based IP addressing methods, however convenient, may not be implementable solutions for most existing buildings and their current IP network configuration and can entail addition costs and extensive time spent on logically configuring the network’s VLAN.

This process can, however, be handled by IA linked to a database storing all additional relevant information needed to give indication to physical device locations. Typical data that would be stored would include the devices’ MAC and IP addresses and physical location information such as the coordinates or floor and office number of network devices as well as the locations of installed APs.

Furthermore, from the above literature it is clear that present solutions in IP network configurations can function sufficiently for determining the physical locations of wired or stationary devices without the need of various additional systems. For WiFi devices, this would only give an indication as to the location of the AP to which the device is connected to; entailing that more information would be required to determine the device’s physical location. The integrated GPS scheme can, however, provide these services for mobile devices if the device is configured to use GPS information to determine its own position [14].

This requires the device to compute localisation algorithms to find its own position coordinates, and thereafter communicate this information to the addressing system in order to receive an IP address corresponding to its physical location. This intelligent process will be able to locate the device with an accuracy equivalent to that of the GPS; which is known to function poorly, if at all, indoors.

In order to provide occupancy monitoring for mobile devices in indoor building environments it is thus necessary to consider qualities of radio signals, specifically WiFi signals that can be used for localisation computations.

### 2.2 INDOOR RADIO PROPAGATION

Considering that radio propagation varies greatly between indoor and outdoor environments it is necessary to investigate this concept in order to determine if the localisation of a radio device, or more specifically, a WiFi device would be accurate enough in indoor building environments. The following table gives a comparison of indoor and outdoor radio environments and propagation characteristics [15]:

---

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Table 2.1: Comparison of Indoor and Outdoor Radio Propagation

<table>
<thead>
<tr>
<th>Path-loss model</th>
<th>Outdoor</th>
<th>Indoor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>Linear</td>
<td>Affected by multi-path effects and shadowing</td>
</tr>
<tr>
<td>Space</td>
<td>Wide and not limited</td>
<td>Small and mostly rectangular</td>
</tr>
<tr>
<td>Deployment</td>
<td>Random and ad-hoc</td>
<td>Can be planned in advance</td>
</tr>
<tr>
<td>Transmission power</td>
<td>Maximum to maintain Link Quality Indication (LQI)</td>
<td>Adjusted to avoid interference</td>
</tr>
<tr>
<td>Height of reference nodes</td>
<td>Ground</td>
<td>Ceiling</td>
</tr>
<tr>
<td>Map</td>
<td>Global</td>
<td>Local</td>
</tr>
</tbody>
</table>

As indicated by Table 2.1 indoor propagation of radio signals are influenced by many factors such as multi-path effects, fading and shadowing. All of these influences can be directly constituted to factors in the indoor environment. Radio waves in indoor environments have to propagate through and around obstacles such as walls, furniture and moving occupants. Signals are also reflected and refracted off of surfaces to travel in multiple paths and at different angles than that of the original transmitted signal. Furthermore, signals in an enclosed space tend to have a greater level of interference with other signals within range.

Both previously conducted as well as modern-day research has provided several RF models that calculate, for a given propagation environment, the average path loss of the transmitted signal. These calculations allow for the prediction of the average received signal strength for a given receiver [16]. This prediction process was developed through investigated into the intrinsic channel and topology characteristics of an implemented RF model [17].

According to Chrysikos et al. in [18] existing research exhibits an increasing interest in measurements and model specification of the 2.4 GHz radio band.

Four key indoor RF models are used for prediction of the average signal strength at 2.4 GHz for commercial topologies: the Free Space Model, the One-Slope Model, the Log-Distance model and the ITU indoor path loss model.
2.2.1 LOG-DISTANCE MODEL

The Log-Distance path loss model is most widely implemented as an indoor propagation model and incorporates a variable for expression of the average-value of the shadowing phenomena [17]. The value of this variable is determined directly from the shadowing deviation (in dB). The Log-Distance path loss model is thus better equipped for the representation of path loss in non-line-of-sight (NLOS) environments where signals encounter many obstacles. Log-Distance path-loss can be calculated by:

\[
P_{L(d)} = P_{L(d_0)} + 10n \log\left(\frac{d}{d_0}\right)
\]  

(2.1)

Where \(P_{L(d)}\) is the path-loss as calculated at a distance \(d\) in meter between transmitter and receiver, \(P_{L(d_0)}\) the reference path-loss at a reference distance \(d_0\) (usually 1m) and \(n\) the path-loss parameter.

2.2.2 FREE SPACE MODEL

In contrast to this, the Free Space model as derived from the Friis equation is better equipped for representation of path-loss in line-of-sight (LOS) indoor environments. This is given by the following expression [18]:

\[
P_L = K + n \log_{10}(d)
\]  

(2.2)

Where \(P_L\) is the calculated path-loss, \(d\) the distance between transmitter and receiver in meters and \(K\) the reference path-loss at a distance of 1 meter. With \(n\) once again representing the path-loss parameter.

The loss of an isotropic radiator in free-space is represented by the following equation:

\[
P_r(d) = P_0 - 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) \text{[dBm]}
\]  

(2.3)

Where \(P_0\) is an empirical constant and \(\lambda\) the wavelength is calculated as:

\[
\lambda = \frac{c}{f} = \frac{3 \times 10^8 [\text{m/s}]}{2.4 \text{ GHz}}
\]  

(2.4)

With \(c\) the speed of light and \(f\) the radio frequency. \(P_0\) can then be selected as reference signal strength at a distance of one meter.
2.2.3 ONE-SLOPE MODEL

The One-Slope model is an adjusted power law model and is represented by the following expression:

\[
P_r(dBm) = P_t(dBm) + K(dB) - 10n\log_{10}\left(\frac{d}{d_0}\right)
\]  

(2.5)

Here \( P_r \) represents the received power of a received radio signal and \( P_t \) the transmitted power in \( dBm \). \( K \), the reference path-loss (1 meter for receiver) is used as \(-39 dB\) by the authors of [18]. The path-loss parameter \( n \) is determined by the minimum mean square error (MMSE) fit to the empirical data. Lastly \( d \) represents the distance from the transmitter to the receiver and \( d_0 \) the reference distance, both in meters.

2.2.4 ITU INDOOR MODEL

This model is also better suited to implementations where the environment is such that small-scale propagation effects dominate the propagation characteristics. The ITU indoor model for path-loss is described by the following equation [19]:

\[
P_L = 20 \log_{10}(f) + N \log_{10}(d) + L_f(n) - 28dB
\]  

(2.6)

Where \( N \) is the power decay index, and \( L_f(n) \) the floor penetration factor.

The ITU indoor model and the Log-Distance model would thus be better suited for characterising path-loss in commercial office buildings that have a partitioned layout.

2.3 LOCALISATION OF RADIO SIGNALS

This section aims to provide insight into techniques, radio propagation variables and implemented hardware used for determining physical locations of radio devices. A classification of the above will first be presented, followed by a detailed section on each contributing aspect.

From a technology point of view, classification of localisation methods can be categorised in a tree diagram as shown in Figure 2.1.
This classification assumes four aspects namely positioning, measurement variables, ranging and hardware devices.

The positioning aspect defines four types of location estimation techniques that can be applied for the purposes of localizing WiFi signals. Calculations to compute location estimation require measurements of specific RF variables such as indicated by the variable aspect in Figure 2.1.

To measure these variables a collection of techniques (as listed in the ranging section) can be implemented. The final aspect that forms part of the localisation methods is the device aspect, this classifies the physical hardware tools needed to conduct these measurements and consist of three types of equipment, antenna arrays, RF transceivers and ultrasonic transducers.

### 2.3.1 POSITIONING

The first classified aspect that makes out the top level of radio localisation methods is positioning. This entails the actual estimation of the position of a Point-of-Interest (PoI). Positioning techniques are further classified as course-grained or fine-grained depending on the level of accuracy by which the PoI can be estimated.
The simplest positioning technique is proximity estimation. This course-grained technique is defined as a detection based, or range-free technique that can only indicate the presence of a signal but is unable to compute literal location coordinates [20].

In contrast, range-based techniques like trilateration and triangulation offer the means to compute the three dimensional location coordinates of a signal source and are considered fine-grained estimation methods. Triangulation estimation calculates location coordinates based on trigonometric angles between a PoI and known reference points whereas trilateration makes use of distance measurements between PoI and reference points.

Lastly, RF mapping is a technique where an array of RF signal strength values is stored for each pair of possible location coordinates within the physical environment. A live signal’s received signal strength (RSS) can be compared to the mapped values where the closest matched value indicates the estimated location coordinates of the live signal.

Each of these four positioning techniques will be discussed in greater detail, in the later sections of this chapter.

2.3.2 RF VARIABLES

RF variables commonly used for localisation purposes include: signal strength, time-of-flight (ToF) from the transmitter to the receiver and the received angle. Measurements of received angles are used for triangulation estimation. Signal strength and propagation time as indicated is used for trilateration purposes.

Trilateration requires these variables to be relatable to the distance between the PoI and several reference points. Since the propagation speed of a signal through a medium is constant, it is possible to relate the propagation time to the actual distance between transmitter and receiver [22].

The transmitted signal strength of a radio signal, on the other hand, attenuates over the physical distance of the path from transmitter to receiver. Using this relationship, it is possible to find the distance by evaluating the total attenuation within the signal [22].
2.3.3 RANGING

The ranging aspect defines four types of measurement for the use with localisation methods:

**AOA – Angle of Arrival**

The angle of arrival of a received signal is measured and compared to the reference orientation of the receiving antenna [22]. Measurement of these arrival angles requires the use of specialised equipment that does not come standard in all WiFi technologies.

**TOA – Time of Arrival**

Time-of-arrival, also referred to as time-of-flight, is the measure of the elapsed time a signal takes to travel from sender to receiver and is mostly implemented when centralised communication is possible. Two approaches can be followed for this method, the first requiring a signal to be sent to many receivers where after each receivers’ measured time of arrival is processed by a centralised system. Another approach entails many transmitters sending to one receiver that then measures the time of arrival of each signal [23]. This measurement method can, however, give way to many complications such as multiple signals arriving at the exact same time. This may result in lost signals and need to retransmit the original message adding additional load to the network. Furthermore, this method requires strict synchronisation between the sending transmitters to give an accurate indication of the time of arrival. In order to achieve the suitable level of synchronisation, equipment with very low clock-drift would be required. To implement accurate TOA measurements, regular calibration of the clocks will also be required.

**TDOA – Time Difference of Arrival**

This measurement process is an improvement on the previously mention TOA method that introduces mechanisms to compensate for induced losses and required synchronisation precision. This process is implemented by sending two signals from a transmitter, with different propagation speeds. The difference between the two arrival times is then calculated by the receiving antenna [22]. This difference can then be used to determine the propagation time, or Time-of-Flight (ToF), of the signal as it travels from transmitter to receiver.

Research conducted by Koenig et al. in [25] proposed the use of Round Trip Time (RTT) instead of ToF measurements. RTT is defined as the time difference between the transmitter sending the original message and receiving an acknowledgement reply divided by two. This allows for the time offset between two devices to be ignored.
Calculations for RTT are given in [26]. This defines the time at which device A sends a frame as $t_{sa}$, and the time B receives the frame as $t_{rb}$. The time at which B replies with a frame is then $t_{sb}$ and the time A receives the reply is $t_{ra}$ such that $t_{sa} < t_{rb} < t_{sb} < t_{ra}$ for the round trip. Then A is measuring $t_A = t_{ra} - t_{sa}$ and B is measuring $t_B = t_{sb} - t_{rb}$.

ToF for this RTT is then calculated as:

$$ToF = \frac{t_A - t_B}{2}$$

(2.7)

ToF can now be converted to distance by the use of the following equation:

$$ToF(d) = \frac{c}{\sqrt{\varepsilon_r}} \times ToF$$

(2.8)

Where $\varepsilon_r = 1.00059$ (Permittivity of air) and $c = 300 \times 10^6$ m/s (Speed of light). The indicated permittivity can prove suitable for open-space office building or can be adjusted to a higher value suited for office buildings incorporating many enclosed spaces. This would need to be determined from site-specific measurements.

**RSS – Received Signal Strength**

RSS measurement provides a method to determine the propagation distance of a signal using the attenuation introduced over the propagation path. If the transmission power is known, the total attenuation of the signal propagating through the path can be calculated by subtracting the received power from transmitted power [22], [25]. This is graphically presented in Figure 2.2.

![Figure 2.2: Radio Propagation Attenuation](image)
The represented occupant is moving a distance $d$ away from the access point in a straight line with velocity $\omega$. $P_t$ represents the transmitted signal power and $P_r$ the received signal power. The inverse-square relationship of received power to distance is given by the following equation [3], [22]:

$$P_r \propto \frac{1}{d^2} \quad (2.9)$$

Considering that different elements within the environment have an effect on the path loss, it is necessary to characterise the environment in terms of a suitable path loss model. Various path-loss models suitable for indoor propagation, as discussed in section 2.2, may be implemented.

### 2.3.4 DEVICE

The last aspect of localisation methods classifies the equipment used for RF variable measurement. These include antenna arrays, RF transceivers, and ultrasonic transducers.

Antenna arrays are used for AOA measurements and works by comparing the phase difference between the measured angles of signals received by several antennas. The multiple reflections and refractions lead to unpredictable phase changes. Thus measuring the AOA does not make sense for indoor purposes.

RF transceivers are used to measure the received signal strength of a radio signal for RSS ranging. This low-cost equipment makes out a fundamental part of all RF devices and offers a dedicated register for storing a value called the received signal strength indicator (RSSI) as defined by the device manufacturer. Arrival time of signals can also be measured by RF transceivers for the calculation of TOA.

Ultrasonic transducers are also used for the measurement of signal arrival times (TOA). If RF and ultrasonic equipment are used in combination, signals propagating at different speeds are produced. Therefore, the time difference between two signals (TDOA) can be measured by starting a timer upon arrival of the RF signal and stopping the timer upon arrival of the ultrasonic signal [22].

Having looked briefly into the different localisation methods, measurements, needed equipment and processes required for their implementation, more detail will now be given on the positioning techniques and algorithms they used for determining physical location coordinates.
2.3.5 PROXIMITY ESTIMATION

As mentioned previously this technique is not able to provide exact location coordinates. The provided information can however give an indication as to the locations of surrounding devices with known or previously determined locations. This makes application of this method unsuitable for location tracking, but it is considered good for localizing devices in large scale networks [21].

Many different approaches to proximity estimation exist. The classic and authoritative range-free location estimation schemes include the DV-hop scheme, the centroid algorithm, and area-based approximate point-in-triangulation test (APIT) algorithm [22].

The centroid algorithm and DV-Hop scheme requires that all devices are able to communicate with each other in order to exchange location information. This makes these two techniques suitable for applications like localisation of sensor-nodes within a sensor network. This is however not the case for WiFi networks since all devices are not set by default to communicate with all other devices. Furthermore WiFi networks usually make use of APs as the only location aware reference nodes within the network. This would make implementations of the mentioned algorithms insufficient for estimating proximity of target nodes.

To aid in solving the problem of having very few reference nodes Huang et al. in [21] proposed the area-based range-free APIT localisation algorithm. This approach allows for target nodes to be localised with the use of only three reference nodes by dividing the service area into many triangular regions. The first defined region being the triangle created by the three reference nodes. It can then be determined if the PoI resides on the inside or outside of this region. This is illustrated in Figure 2.3 below:

![Figure 2.3: APTI Localisation Concept](image)
After the possible region containing the PoI is reduced, smaller triangles can be constructed using the coordinates of previously localised nodes as reference nodes. This process continues until the possible region of the PoI is considered small enough for accurate location estimation.

### 2.3.6 TRIANGULATION

This trigonometric estimation technique is used to find the location of a PoI based on two measured angles and the distance between them. This approach can be implemented in a centralised fashion where angle measurements are collected from distributed reference nodes (APs) or by the target device itself depending on the architecture of the localisation system. In the centralised system case, the APs would measure the angles of the received signal of a broadcast message sent by the targeted device. This is then forwarded to a centralised system for computation of the location of the PoI. The triangulation concept is illustrated in Figure 2.4 below:

![Figure 2.4: Triangulation](image)

As seen in Figure 2.4, at least three reference nodes are typically required to form a horizontal and vertical baseline [22]. The baseline distance \( d_b \) between the two reference nodes can be measured in preface and committed to memory. From both the \( x \) and \( y \) axis two angles \( \alpha_1 \) and \( \alpha_2 \) are measured between the baseline and the line formed by the reference node to the target node.

As seen, the reference nodes, AP1 and AP2, form the baseline of Y-axis and AP2 is reused along with AP3 for the X-axis baseline.
Based on simple triangulation, the coordinates \((x, y)\) of the PoI within this area can be calculated by the following two equations [15]:

\[
x = \frac{d_{by}}{\tan^{-1}(\alpha_{y1}) + \tan^{-1}(\alpha_{y2})} \tag{2.10}
\]

\[
y = \frac{d_{bx}}{\tan^{-1}(\alpha_{x1}) + \tan^{-1}(\alpha_{x2})} \tag{2.11}
\]

This very basic form of two dimensional triangulation works well for simple localisation purposes where the number of devices to localise is small, and other factors like device battery life and network overhead are not of grave importance.

### 2.3.7 TRILATERATION

Trilateration estimation in contrast to triangulation considers the measured distance between reference and target nodes for coordinate location estimation. In this range-based technique, the measured distance is related to radii of several circles with centres at the measuring reference nodes (APs). The location of the PoI can then be estimated by solving the equation representing the intersection of these circles. The concept of trilateration estimation is represented by Figure 2.5 below:

![Trilateration Estimation Concept](image)

Figure 2.5 : Trilateration Estimation Concept
Figure 2.5 shows an ideal situation where the three circles intersect in one point; this is not the case in realistic scenarios but is shown here for clarity.

In Figure 2.5, three APs are implemented as reference nodes and a WiFi device as the PoI moving freely within the WiFi service area. The coordinates of the PoI can be found by using the three pairs of AP coordinates and the respective distances as measured between each AP and the PoI.

This can be achieved by making use of the Euclidean distance theorem to construct expression for each of the three circles [15]:

\[ d_1^2 = (x_1 - x)^2 + (y_1 - y)^2 \]
\[ d_2^2 = (x_2 - x)^2 + (y_2 - y)^2 \]
\[ d_3^2 = (x_3 - x)^2 + (y_3 - y)^2 \]  \hspace{1cm} (2.12)

To solve for \( x \) and \( y \) equation 2.12 can be rearranged as follows:

\[ x = \frac{AY_3 + BY_1 + CY_2}{2(x_1y_3 + x_2y_1 + x_3y_2)} \]
\[ y = \frac{AX_3 + BX_1 + CX_2}{2(y_1x_3 + y_2x_1 + y_3x_2)} \]  \hspace{1cm} (2.13)

where

\[ A = x_1^2 + y_1^2 - d_1^2 \]
\[ B = x_2^2 + y_2^2 - d_2^2 \]
\[ C = x_3^2 + y_3^2 - d_3^2 \]  \hspace{1cm} (2.14)

and

\[ X_{32} = (x_3 - x_2) \]
\[ X_{13} = (x_1 - x_3) \]
\[ X_{21} = (x_2 - x_1) \]  \hspace{1cm} (2.15)
\[ Y_{32} = (y_3 - y_2) \]
\[ Y_{13} = (y_1 - y_3) \]
\[ Y_{21} = (y_2 - y_1) \]  \hspace{1cm} (2.16)
Trilateration localisation coordinates can also be determined by the use of a more convenient matrix expression:

\[
\begin{bmatrix}
X \\
Y
\end{bmatrix} = \frac{1}{Pol} \begin{bmatrix}
y_2 - y_3 & y_3 - y_1 \\
x_3 - x_2 & x_1 - x_3
\end{bmatrix} \begin{bmatrix}
x_1^2 - x_3^2 + y_1^2 - y_3^2 + d_3^2 - d_1^2 \\
x_2^2 - x_3^2 + y_2^2 - y_3^2 + d_3^2 - d_2^2
\end{bmatrix}
\]  
(2.17)

where the Pol is given by:

\[
Pol = 2 ( (x_1 - x_3) \times (y_2 - y_3) - (x_2 - x_3) \times (y_1 - y_3))
\]  
(2.18)

Making use of trilateration estimation for localizing WiFi devices is rather convenient considering that the distances \(d_1, d_2, d_3\) can be obtained by ranging techniques for RSS measurement. This measurement is performed as a rule by all WiFi equipment in order to determine if the signal quality is sufficient for communication.

Furthermore, this localisation method is sufficient for use with very few location aware nodes (at least three) and will thus function correctly if only wireless APs are used as reference nodes for localizing all other WiFi target nodes.

### 2.3.8 RF MAPPING

Radio frequency mapping or otherwise known as RF fingerprinting is a technique used to create a probability distribution of signal strengths at a given location and uses a map of these distributions to predict a location given signal strength samples. A typical fingerprinting map making use of RSSI values looks as follows:

![Figure 2.6: Typical Fingerprinting Map for RSSI](image)

Fingerprinting consists of two phases, an offline or mapping phase and the online or localisation phase.
In the offline phase, the mentioned radio map is created for an area based on the RSSI data from several access points. This data is used to generate a probability distribution of RSSI values for all given \((x,y)\) locations found within the WiFi service area.

Live RSSI values as measured from target devices are then compared to the fingerprint map to find the closest match. This match value’s corresponding coordinates is then used as the estimated \((x,y)\) location of the target device [30]. This technique has proven successful in providing room-level accuracy under favourable circumstances.

In order to identify the closest match Navarro et al. in [30] implemented Markov-localisation and the nearest neighbour algorithm. This constitutes the online or active phase of this localisation method.

2.3.8.1 Markov Localisation

To implement Markov localisation, statistical data of the fingerprint is gathered and used to guess the most probable position. This process is conducted in two phases, a prediction phase followed by a correcting phase.

The following expression is used in the prediction phase to determine the probability of a device being in a particular location [30]:

\[
p(L_t) = \sum_{L_{t-1}} p(L_t|L_{t-1}) p(L_{t-1})
\] (2.19)

Where \(p(L_t)\) is the probability of being in location \(L\) at a time \(t\) and \(p(L_t|L_{t-1})\) is the probability of being in location \(L\) at a time \(t\) given the previous location \(L\) at time \(t-1\).

This prediction step is used to constrain the search-space within the RF map to the most probable region. This constrains the region based on what is physically possible considering what is known about the target’s motion.

Leading to the correction step with the following expression:

\[
p(L_t|R[j]) = p(R[j]|L_t)p(L_t) * N
\] (2.20)

Where \(p(L_t|R[j])\) represents the probability of being at location \(L\) at time \(t\) considering the measured RSSI values \(R[j]\) as received at time \(t\). \(p(R[j]|L_t)\) then represents the probability of actually having the measured RSSI values \(R[j]\) for a given location. This is determined from the probability distribution function.

Gaussian distributions are usually implemented for this. Lastly \(p(L_t)\) is the probability of being at the location as calculated in the prediction step and \(N\) is a normalisation factor.
A problem with Markov localisation is encountered within the prediction step. If the location is wrong and the actual location falls outside the constrained search-space, the algorithm can get stuck. Furthermore, it is unlikely that the algorithm is able to recover from a stuck position.

This issue may however be resolved if a better alternative is found for the probability density function that can more accurately represent the variation of RSSI values within environments [30].

2.3.8.2 Nearest Neighbour Algorithm

The nearest neighbour approach basically calculates the Euclidean distances between the live RSSI reading of a target WiFi device and the mapped fingerprint of each reference node (AP) for a given location. The smallest achieved Euclidean distance is then the Nearest Neighbour and the likely $(x,y)$ location of the target device. The Euclidean distance between live and mapped values can be calculated by the equation below:

$$E_d = \sqrt{\sum_{i=1}^{n} (R_i - FP_i)^2} \quad (2.21)$$

Where $R_i$ represents the live RSSI reading for the target device, $FP_i$ the fingerprint RSSI values and $n$ the number of reference nodes (APs).

The Nearest Neighbour approach can be implemented to use either a constrained or unconstrained search-space. As can be expected the unconstrained search-space approach considers the entire fingerprint map to find the closest match. This ensures that all possible locations are considered, and that the algorithm does not get lost within the map. Unconstrained searching will however take significantly longer to compute depending on the number of mapped values and may, therefore, be considered insufficient for very large RF-maps.

In contrast to this a constrained search-space approach will only consider sections of the map within a given distance from a previously predicted location or within a margin of the received live RSSI readings.

The concept that gave way to the use of the first constraint situation is that a moving object can only travel up to a maximum distance from its previous location within the time it takes to collect a live RSSI reading [30].

This would make searching through the entire map unnecessary and also has the effect of ignoring predicted locations that are closer based on Euclidean distance, but physically impossible based on the previous location. This method does however still present the possibility of getting lost within the map if the first location was incorrectly identified.
To completely alleviate this problem, the search-space can be constrained on RSSI rather than location. In order to do this, a constant value is added and subtracted from the live RSSI readings to provide a search range that will definitely contain the live reading. The location information is then queried for this range. If the nearest neighbour found within this range constitutes a physically impossible location based on the previously determined one, the range is simply expanded.

In order to implement one of the two above mentioned techniques, mapping of the physical environment is necessary. This constitutes an offline phase. The mapping process will require measurement of RSSI readings from all APs from reference locations in a grid format. This would entail physically moving a WiFi device around in the WiFi service area and capturing the required RSSI and coordinate values for each reference point location. This is usually done in increments of one meter at a time. and is illustrated in the Figure 2.7 below:

![RF Environment Mapping Process](image)

Figure 2.7 : RF Environment Mapping Process

This mapping process may be time-consuming but is considered well worth the while for the accuracy of this method for indoor localisation purposes. If per meter accuracy is not considered necessary the mapping process as described above may be conducted with larger increments. This will reduce the time spent on the mapping process.

Furthermore, the mapping can be done in such a way that a mapping element is only registered for each enclosed area. For example, the centre point coordinates for each office. This will once again reduce the time spent on the mapping of the physical environment. This per-area mapping will not be able to track the exact position of a WiFi enabled device, but will still be able to indicate to which mapped building zone or room the device is closest. Another issue that arises from fingerprinting in an indoor environment is the changes that occur in the environment that affect the propagation patterns of signals.
This causes variations in the recorded signal strength that are not reflected in the static mapped values.

When environmental characteristics change, the map may be rendered insufficient for position estimation. Otherwise stated, a radio map collected at one time may be unable to offer accurate positioning at all times [31].

These dynamic environmental changes are caused by a varying number of occupants in a zone, changing humidity levels or structural changes like doors and windows being opened or closed. As result of these changes, the mapping process should be repeated regularly in order to reflect the changed environment.

According to Hansen et al. in [31], research in the field of managing location fingerprinting with these dynamic changes has pursued the approach of introducing additional sensors to capture the dynamics. This solution is not considered because the implementation of sensors is counter to the research objective of making use of existing infrastructure only.

Other related research implements user-contributed signal strength collections for extending the radio map. In these approaches, users are occasionally prompted to contribute to improving the accuracy by indicating their position on a floor plan sent to their WiFi device. From this, the position coordinates as indicated by the user and the corresponding recorded signal strengths are added to an ever-evolving and growing dynamic radio map.

This process will rely strongly on the cooperation of the WiFi users and is not always trustworthy since the issue of handling false classifications (mislabelled location data) always arises when user input is required. These false classifications may come from either malicious users, or users who have inadvertently identified the wrong location on a map [31].

For the purposes of this research, another approach to dynamic mapping exists. Considering that building occupants will be related to their specific office location and each would have a personal wired desktop or laptop computer located in this office, traffic monitoring may be implemented on this stationary device.

The objective of this would be to determine if traffic monitoring is able to give an indication of whether or not an occupant is actively busy on this stationary device. If it is possible to derive such information, and the occupant’s WiFi capable device is on his/her person, RSSI measurements can be collected from the WiFi device to be added to the dynamic map for the location of the office. This will alleviate the need for user-contributed RSSI values for at least the office locations. Considering that offices within a building contain the densest distribution of HVAC systems and power consuming devices, this concept is well worth investigation. This investigation into traffic monitoring is the topic of the following section.
Research on the above dynamic mapping approaches indicated significant improvements over the traditional, static approach. This demonstrates that it is undeniably possible to retain accuracy without the need for additional environment monitoring equipment, thus facilitating accurate and robust ubiquitous positioning.

Another factor that needs to be taken into account when considering a RF mapping approach is the non-homogeneous output power of consumer WiFi devices. An increasingly wide and ever-evolving range of consumer WiFi devices are available in today’s day and age. These devices are manufactured with different configurations and hardware and are produced by independent vendors. This indicates varying RF characteristics and antenna output powers which may lead to a created RF map not being applicable to all monitored devices. This is currently a hot topic in the field of location based services, with most findings indicating that dynamic mapping approaches and device specific contributions hold the most promise [32], [33].

This follows the same logic as the above described dynamic mapping, and relies on user devices to regularly contribute RSS readings to the RF fingerprinting map. As the VOS solution focuses on occupant-centred room-level localisation, it would seem fitting to follow the approach with combined traffic monitoring, as mentioned above, to allow the occupant to contribute RSS data from his/her specific device while in his/her specific office.

This would allow for a dynamically created RF map that is produced to consider the specific output power of a specific occupant’s device while performing occupancy determination for the office in question.

This dynamic mapping approach, in combination with traffic monitoring and device specific contributions is a relevant topic for further investigation and practical testing.

As section closure, RF mapping is widely considered to be the most accurate approach for localisation within indoor environments. Thus, RF mapping and trilateration estimation is considered for implementation of localisation of WiFi devices in this study.

### 2.4 TRAFFIC MONITORING

In order to determine if an occupant is actively busy on the stationary device, user-generated traffic will need to be monitored. User-generated traffic is created when users make use of applications on the network. This includes web-browsing, file downloads, video streaming and email services amongst others. Traffic-wise differentiation of these applications can be found in the IP application layer transfer protocols.
Application layer transfer protocols include the Hyper Text Transfer Protocol (HTTP) for web applications, the Simple Mail Transfer Protocol (SMTP) for email services and the File Transfer Protocol for file exchange. A classification of the various application layer protocols are provide in following table:

<table>
<thead>
<tr>
<th>Transfer Protocol</th>
<th>Addressing</th>
<th>Distribution</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terminal</td>
<td>Telnet</td>
<td>Host</td>
<td>Port 1 - 1</td>
</tr>
<tr>
<td>File system</td>
<td>FTP</td>
<td>Host</td>
<td>Path 1 - 1</td>
</tr>
<tr>
<td>E-Mail</td>
<td>SMTP</td>
<td>Mailbox</td>
<td>MSGid 1 - N</td>
</tr>
<tr>
<td>Usenet</td>
<td>NNTP</td>
<td>Newsgroup</td>
<td>MSGid N - N</td>
</tr>
<tr>
<td>Web</td>
<td>HTTP</td>
<td>Host</td>
<td>URL part 1 - N</td>
</tr>
</tbody>
</table>

Capturing of these traffic types can be done a wide range of available network traffic tools. These include amongst other: Plab based on Libpcap, Wireshark and PacketSniffer.

### 2.4.1 SMTP TRAFFIC MONITORING

An interesting result was obtained for research conducted in [34] on SMTP message-level characterization. It was found that the e-mail trend follows user activity during the day and that the processes of arrivals and departures at servers are Poissonian in nature. Monitoring of SMTP traffic may thus be implementable for determining if an occupant is present at the traffic generating device. This will especially work if an office building makes use of a local mail server.

### 2.4.2 FTP TRAFFIC MONITORING

FTP traffic in contrast to this may or may not indicate the physical presence of a user because this type of traffic may be generated by queued downloads that run while the user is out of office. Thus monitoring of FTP traffic will prove inadequate for this task.

### 2.4.3 HTTP TRAFFIC MONITORING

In [35], research was conducted on the identification of sessions to websites as an aggregation of related HTTP traffic flows. The implemented method relied on the collection of starting and ending timestamps of flows and server IP addresses. The research indicated that HTTP traffic can be matched to identified websites by making use of the site’s server IP address.

Although traffic monitoring could provide the needed information, it is however not a requirement for the purpose of this research topic.
A simpler solution may be to reverse to above described process to log IP addresses of network devices connecting to a specific website or local intranet page. This IP address information should be fed dynamically to a centralised system or IA that can translate these addresses to physical office locations. This would indicate that the occupant was in-office during the time of the connection. RSS measurements of the occupant’s device for this time period can then be added to the dynamic map for the specific office without direct input from the occupant.

This will only be sufficient if the organisation owning the building in question has an official website or intranet site that is used by occupants during office hours and the hosting server is accessible by the IA.

This will not provide continuous dynamic mapping, but the page visits should prove regular enough to aid in the map creation in different time intervals that would reflect a suitable range of environmental variations.

Considering that this is a proof of concept study it was decided that simulated data with respect to RSS and position information will be used. The selected simulation software will now briefly be discussed with respect to general structure and offered functionality.
2.5 SIMULATION PACKAGES

The OMNeT++ simulation framework for communication network simulations was selected in combination with MiXiM. The MiXiM framework is specifically used for mobile wireless network simulations [36], [37]. These frameworks were selected due to the packages being available as open-source software, can that it can run on multiple platforms and offer a small, simple and convenient embedded simulation kernel that does not require massive amounts of RAM and processing power. The following section will provide more detail on these packages.

2.5.1 OMNeT++ SIMULATION ENVIRONMENT

OMNeT++ or Objective Modular Network Test-bed is a C++ based open-source, modular and component-based discrete event simulation environment. OMNeT++ provides strong graphic user interface (GUI) support and an embedded simulation kernel.

The primary application area that was kept in mind for the development of OMNeT++ was investigation into and simulation of communication networks. Thereafter OMNeT++ was successfully implemented for investigation into a vast range of other research areas; this was made possible by its generic and flexible architecture, provided component type architectures for models and the ease of reusability of these models.

As mentioned OMNeT++ is compatible with many platforms and run well on Linux, Win32 platforms and most Unix-like systems.

The OMNeT++ Intergrated Development Environment (IDE) is based on the Eclipse platform and extends it with a range of new editors, views, wizards, and additional functionality. This added functionality, offers creation of network models in network description (NED) files and the configuration of the network in initialisation files. Figure 2.8 shows a screenshot of the OMNeT++ IDE in the graphical NED file editing mode:
As described by the authors in [35] OMNeT++ offers the following remarkable features:

- It is possible to compose models with any granular hierarchy;
- OMNeT’s object-orientated approach allows for flexible extension of base classes for the easy implementation of specific situations to be investigated or simulated;
- The simulation library and user interface libraries are linked to the created simulation model at compilation;
- The extensive simulation library includes support for data collection, statistics, input/output, data structures, random number generation and graphical presentation of simulation data;
- The C++ based OMNeT++ simulation kernel makes it easily embeddable in larger applications;
- Configuration of OMNeT++ models is done in the omnetpp.ini file instead of making use various scripts. This makes it more convenient for configuring various simulations;
- Lastly OMNeT++ offers a model setup wizard with a range of preconfigured networks to select from;
Although OMNeT++ provides a powerful and clear simulation framework, it lacks direct support and a concise modelling chain for wireless communication. MiXiM provides both.

### 2.5.2 MIXIM FRAMEWORK FOR WIRELESS NETWORKS

The MiXiM framework joins and expands several present simulation frameworks developed for wireless and mobile simulations in OMNeT++. It offers detailed models of the wireless channel (fading, etc.), wireless connectivity, mobility models, models for obstacles and a variety of communication protocols specifically at the Medium Access Control (MAC) level.

Further, this framework also provides a user-friendly graphical representation of wireless and mobile networks in OMNeT++, supporting debugging and defining even complex wireless scenarios [37].

The provided detailed models, protocols and supporting infrastructure of MiXiM can be divided into five functional groups [38]:

#### 2.5.2.1 MiXiM Functional Groups

Each of the classified groups will be briefly discussed.

##### 2.5.2.1.1 Environment Models

Environmental models in MiXiM reassure that only the relevant parts of the real world are reflected in the simulation. This includes obstacles that hinder wireless communication.

The environmental model defines a *play-ground* area in which nodes and objects are placed; this area limits the physical space in which nodes can move. The play-ground can be configured to make use of a torus as edge wrapping method so the top and bottom edges and the left and right edges are connected. This enables nodes to move freely within the defined space without border effects dominating the simulation results.

This model also defines a *MobilityUpdateInterval* for configuring the frequency of movement updates of mobile nodes within the environment.

##### 2.5.2.1.2 Connectivity and Mobility

Connectivity and mobility modules handle the movement of nodes and their influence on other nodes within the network. The simulator has to track these changes and provide an adequate graphical representation. Connection modelling in MiXiM is divided into two parts.
The first part, representing the wireless channel along with the attenuation properties of the given channel. The channel models implemented in MiXiM express radio propagation effects as time variant factors of the instantaneous Signal-to-Noise Ratio (SNR). The implemented SNR-based models enable the separate calculation of channel effects and offer the various accepted models for path-loss, large and small-scale fading as well as shadowing effects.

The second part handled by these models in the connectivity between nodes. For connectivity modelling, MiXiM defines the MaxInterferenceDistance parameter as the maximum distance at which a node can possibly disturb the communication of a neighbouring node. This reduces the computational complexity and assumes that nodes can only be connected when within this MaxInterferenceDistance.

### 2.5.2.1.3 Reception and Collision

With the simulation of wireless networks, the movement of objects and nodes have an influence on the reception of a message. Reception handling is responsible for simulating how a transmitted signal is transformed on its way to the receivers, taking transmissions of other senders into account.

### 2.5.2.1.4 Experiment Support

Experimentation support is provided by MiXiM to aid researchers to compare the results with an ideal state, to aid in suitable template selection for a given implementation and also to provide different evaluation methods.

### 2.5.2.1.5 Protocol Library

The protocol library contains a range of previously implemented protocols that can be extended to form new implementation or can be used to compare new implementations to.

These above mentioned solutions are provided by MiXiM by combining the approaches of several existing simulation frameworks into one:

- Mobility support, connection management, and general structure is taken from the Mobility Framework (MF) [39];
- Radio propagation models are based on the CHannel SIMulator (ChSim) [39];
- The presented protocol library is based on a combination of the Positif framework [41], the MAC simulator [42] and the Mobility Framework.
2.5.2.2 General Structure

In this section, an overview of the general structure of the MiXiM framework will be given, and its constituent components will be discussed. An example of a MiXiM network showing all components can be seen in Figure 2.9 below:

![Figure 2.9: Example MiXiM Network](image)

As seen from the above figure MiXiM provides three modules for the overall management of the simulation: the WorldUtilityModule, the ConnectionManager and the ObjectManager.

In the WorldUtilityModule global parameters for the simulation in question are defined. These parameters include network dimensions and environmental models.

The ObjectManager is responsible for managing objects and providing services to the rest of the simulation including calculating which objects interfere within a given line-of-sight between two nodes.

The ConnectionManager module is responsible for dynamically managing the connections between interfering nodes. It is aware of the physical position of all nodes and can query object positions from the ObjectManager.
Furthermore, various network nodes like APs, hybrid nodes and GSM nodes can be defined. The internal structure of all nodes can be sub-classed from the MiXiM *BaseNode* object-class. The structure of a typical node is shown in Figure 2.10 below:

![Figure 2.10: MiXiM Node and Network Interface Card Structure](image)

The *BaseNode* model presented Figure 2.10.(a) incorporates the standard TPC layers of the IP model namely the application layer (appl) and network layer (netw). The MAC layer (mac) and the physical layer (phy) are combined within the Network Interface Card (NIC) within the node model. This is represented by (b) Nic Structure in the above figure.

The adjoining layers are connected by OMNeT++ “gates.” These are used for passing up and down data messages and control messages between nodes. Furthermore, these gates are used for the exchange of control messages between the layers.

The mobility module handles the movement of each specific node or object and can be configured to make use of a variety of mobility models. These motion models are sub-classed from the MiXiM *BaseMobility* module and include simple models like “constant speed mobility,” “linear mobility” and “circle mobility.” Models that parse ANSim trace files [43] and BonnMotion files [44] are also provided.

The node’s ARP module is tasked with handling address resolution and implements the Address Resolution Protocol (ARP) for translation between the network and MAC addresses of network nodes.
The utility module in this node structure is based on the blackboard module pioneered in the Mobility Framework [38]. This module is firstly tasked with providing a general interface for collecting statistical simulation data. This collection process has a negligent impact on the performance of the running simulation and provides flexibility for diverse analysis methods. Secondly, this module is tasked with managing parameters that are needed by multiple modules within the node.

Lastly, a battery module can also be implemented for energy-related issues. The use of this module is especially popular for sensor network simulations for the investigation of battery drainage.

### 2.5.2.3 Base Implementations

In this section, the base implementation concepts of the MiXiM framework physical layer will be discussed. The physical layer can be considered as the foundation of a wireless node in MiXiM. This vital layer is responsible for message sending and receiving, collision detection and bit error calculation [38]. Furthermore, it is tasked with applying the channel models used in the simulation. The function class of the MiXiM physical layer is represented by Figure 2.11 below:

![MiXiM Physical Layer Class](image)

The **BasePhyLayer** of MiXiM is used to supply the interfaces to the MAC layer and the physical layers of other nodes. **AnalogueModels** are tasked with modelling the attenuation factors in received signals, and the **Decider** module is responsible for evaluating noise present in the received signals as well as demodulating the received messages. Both the analogue models as well as the decider are designed as pure C++ classes in order to provide a clear interface and to avoid memory overhead.
2.5.2.3.1 Signal Class

The Signal class aims to handle the complex processes that affect signals during transmission. Each created MiXiM message has an attached SignalObject for the representation of transmission power, attenuation factors and bit-rate in the dimensions of time, frequency and space. The created message with the attached SignalObject is then forwarded to the BasePhyLayer.

2.5.2.3.2 BasePhyLayer

The chief duty of this module is the sending of messages to, and receiving messages from other nodes. Furthermore, this module is responsible for modelling the transmission and propagation delays for the messages it sends out.

As mentioned this module also acts as an interface between the messages from the physical layer (AirFrames) and the neighbouring AnalogueModel and Decider. The BasePhyLayer offers high flexibility and modularity by enabling the plug-in of various analogue models and deciders directly into this module with easy configuration [38].

Lastly the BasePhyLayer stores all messages in the ChannelInfo class. This class is said to be a “service-provider” to keep track of AirFrames on a channel that intersect with a given time interval. This class is then called by the decider module for SNR calculations.

2.5.2.3.3 Analogue Models

The actual receiving power of a signal can be described as a function of (time, space, frequency) to receiving power. This has to be modelled in the MiXiM AnalogueModel since OMNeT++ does not define attenuation. This includes effects like path-loss, fading and shadowing.

The AnalogueModel can be view as a filter class for signals and is used for summing the attenuation over the model to provide the attenuation part of a given signal. This is calculated at the start of message reception.

2.5.2.3.4 Decider

According to Köpke et al. in [38], the decider module is responsible for three functions. Firstly it is the task of the decider to categorise all incoming messages as either receivable or noise. There is a range of ways to accomplish this and all are supported by the MiXiM framework.

The second task is to calculate the bit error for each received message at the end of reception. From this, the previously mentioned ChannelInfo class is called in order to compute the SNR of the received message.
The decider can either make a simple binary decision or calculate bit errors and positions depending on the selected *AnalogueModel*.

The third and final task of the decider is to give information concerning the state of the channel in question. This information is used by the MAC layer routing protocols. This decider class is also identified as the best module for the collection of RSS data as needed for research. Position information, on the other hand, will be collected from the MiXiM *ConnectionManager* module.

The MiXiM model selection and simulation setup parameters that will be used for the simulation will be provided and discussed in the following chapter. The RSS and position data as collected from these simulations will be parsed to a centralised database connected to an IA that will perform the selected localisation algorithms. The IA functioning will also be addressed in the subsequent chapter.

In the next section, a brief overview of the important concepts addressed in this chapter will be given. The selected methods for implementation with respects to propagation models and localisation algorithms will also be reviewed.

### 2.6 CHAPTER SUMMARY

In this chapter, the relevant context and theoretical setting for the research in question were provided.

Firstly existing infrastructure that can be exploited for the use of energy efficiency management within commercial buildings were investigated. An IP network infrastructure that is present in most existing office buildings was studied.

It was found that within the wired and wireless parts of the IP network unique device identification would be possible with the combination of IP and MAC address. It was also found that IP could be configured to present physical device locations. This was not considered since such an implementation would not be possible for all existing IP network configurations.

Thereafter possible radio propagation models were considered. Implementation of the ITU indoor propagation model or the Log-Distance model provided the most promise for the use within non line-of-site (NLOS) indoor localisation.

A classification of possible radio device localisation methods was given and therewith proximity estimation, triangulation estimation, trilateration estimation and RF fingerprinting was discussed. It was determined that trilateration techniques and RF fingerprinting would be best suited for the research objective.
Lastly, an overview of the general structures of OMNeT++ and MiXiM was provided. It was found that MiXiM presents an acceptable level of accuracy for the simulation of various wireless network scenarios as well as support for node mobility. It was determined that both RSS and location data could be obtained from simulation results.

As one of the main aspects of this research, it was determined that it is possible to exploit WiFi infrastructure for positioning. It was found that the immediate benefit is that ubiquitous indoor positioning becomes viable given the ubiquitous deployment of WiFi network infrastructures. Furthermore, no specialised hardware is needed, thus providing a lower barrier of entry for indoor positioning services.

In the following chapter, the focus will be on the experimental implementation of these techniques. The chapter will present assumptions concerning the implementation scenarios and the building occupant. The configuration of the simulation models, the database infrastructure and the IA design will also be discussed.
3 EXPERIMENTAL IMPLEMENTATION

This chapter outlines all of the critical methods, and models that will be configured in this experimental implementation of a virtual occupancy sensor. The first introduction section will provide an overview of this chapter as well as a high level flow diagram of the implementation phases.

3.1 INTRODUCTION

The focus of this chapter is on the experimental implementation of a VOS to enable more efficient power management in existing office buildings. This implementation should meet the requirement of only making use of existing infrastructure.

In the previous literature survey chapter, it was decided that the data needed for this study would be simulated in the OMNeT++ simulation environment in combination with the MiXiM framework for wireless network simulations.

In order to create a realistic simulated environment, investigation into an existing real-world office building was necessary. For this purpose the North-West University’s Electrical, Electronic and Computer Engineering Faculty’s offices, hereafter referred to as the facility, was used.

This chapter will also aim to provide detail on the form, fit and function of the selected models, algorithms and methods as determined in the previous chapter with respects to this experimental implementation.

The provided detail includes the setup of the simulation environment, the configuration thereof, and the selection of simulation parameters for the specific implementation. The subsequent steps involve the extraction and processing of the required data from the simulation outputs.

Thereafter the selected localisation algorithms that need to be executed on the extracted simulation data and their implementation will be discussed. The results from the localisation process are then used to estimate the occupancy of a given building zone or room.
3.2 FUNCTIONAL FLOW

![Diagram of Experimental Implementation Functional Flow]

Figure 3.1: Experimental Implementation Functional Flow
Figure 3.1 showing the functional flow of this experimental implementation will now briefly be discussed where after a table giving indication to the afore mentioned form, fit and function of the implementation phases will be provided.

(A) Implementation Assumptions
In the first phase certain assumptions needed to be made concerning the implementation environment, building occupants and devices. This was necessary to limit the scope of the implementation scenario, and to ensure that the implementation experiment was suitable for investigation of the concept. The assumptions contributing to this phase was made either from investigation into a real-world office building (the Facility) or for the purposes of suitability of the investigation as mentioned. These assumptions were then incorporated throughout the implementation phases where relevant such as in the simulation configuration, simulated scenarios, localisation estimation and occupancy determination.

(B) OMNeT++/MiXiM Simulations
This important phase starts with investigation into a simulation model configuration that can be considered widely accepted for most actual WiFi network implementations. This investigation looked into popular and most used WiFi standards as well as typical AP configurations. This was determined from datasheets of a range of popular commercially available APs suited for office environment deployments. Thereafter all assumption as mentioned was incorporated into this configuration. Various simulation configurations were setup to reflect predetermined scenarios. A sufficient amount of simulations was run for each scenario and relevant data like RSS measurements, positioning information and node identification information was configured to be captured in the simulation output event-logs.

(C) Data Parser
In the next phase a self-constructed data parser is used to identify, extract and order RSS data, positioning data and node identification data for simulated nodes from OMNeT++ event-logs. These event-logs store all events and event timestamps present in the simulation, in a synchronous order. The created parser module also processes this data in a synchronous manner as would be the case in real-world implementations. The parser then also relates this ordered data to corresponding occupants and stores it in the centralised database. Lastly the data parser module sends the ordered data with occupant relation to the IA for further processing, localisation and finally occupation determination.

(D) Intelligent Agent
The final phase of the implementation involves the processing of the data collected by the data parser, as mentioned this is handled by a centralised IA. The created IA constitutes the largest and most critical part of the implementation and is also the part of this research in which a novelty factor can be identified.
The IA is tasked with handling all the complex arithmetic functions and algorithms needed for location estimation and occupancy determination. Furthermore, this agent provides a web-based interface for showing visualisations of occupant movement, and power state of building zones or rooms. Lastly, the agent provides on-demand charts and statistical data for all aspects that were examined in the research. Both charts and statistical data are available per individual simulation as well as for all simulation within a defined category or scenario. The IA design and flow consists of more detailed functional flow phases than presented in Figure 3.1, this will be further sub-classed and discussed in section 3.7.

The following table provides the form, fit and function classification of the functional flow modules as discussed above:

<table>
<thead>
<tr>
<th>Module</th>
<th>Form</th>
<th>Fit</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implementation Assumptions</td>
<td>Extracted in the form of a survey of the facility and incorporated in the form of configuration parameters and logic rules.</td>
<td>The assumptions fit into two different implementation levels and form part of the simulation configurations and also represent logic rules as used by the intelligent agent.</td>
<td>Ensure relation to a typical real-world office building within simulations.</td>
</tr>
<tr>
<td></td>
<td>Extracted from investigations in the form of technology comparisons and implementation scenarios, and is incorporated in the form of configuration parameters and logic rules.</td>
<td></td>
<td>Ensures the suitability for investigation of the concept to be proven.</td>
</tr>
<tr>
<td>Simulation Data Generation</td>
<td>Conducted in the form of wireless network simulations done in OMNeT++/MiXiM. Output presented in the form of event-logs.</td>
<td>This module serves as RSS and actual position data generator and provides the basis on which other the modules are fitted.</td>
<td>The function of this module is to provide input data for testing the functioning of the implemented location estimation algorithms and occupancy determination as well as the VOS concept.</td>
</tr>
<tr>
<td>Data Parser</td>
<td>The data parser is presented in the form of a self-constructed script.</td>
<td>The parser fits in between the simulation environment and the IA.</td>
<td>The function of the parser is to identify, extract and order data from simulation event-logs and save it to a centralised database to be accessed by the IA.</td>
</tr>
<tr>
<td>Intelligent Agent</td>
<td>The intelligent agent takes the form of a variety of interlinked scripts as well as a web-based interface for visualisations, graphs and statistics. Thus also taking the form of a automatic result collection mechanism.</td>
<td>The intelligent agent fits in as the final and most vital piece of the implementation to process the data received from the parser.</td>
<td>The main function of the IA is to compute localisation algorithms and determine the occupancy and power state of building zones and rooms. The IA also functions as result collection unit and handles generation of graphs and statistical data computation.</td>
</tr>
</tbody>
</table>
As seen from Figure 3.1 and Table 3.1, the high-level implementation modules fit on top of each other to form a stack. This makes the flow of the implementation well suited for functioning in a synchronous manner to accommodate the synchronous arrival of RSS data similar to an actual deployment.

3.3 IMPLEMENTATION ASSUMPTIONS

Assumptions concerning implementation scenarios and parameters are detailed in this section. Firstly some physical characteristics of the facility as investigated will be given, and thereafter the assumptions drawn from the investigation will be presented.

3.3.1 THE FACILITY

As mentioned the building model selected to aid in creating a more realistic implementation environment would be based on the offices of the Electrical, Electronic and Computer Engineering faculty of the North-West University. This facility is located on the 2nd floor of building N1 within the engineering complex. The facility provides 38 labelled rooms and 3 APs to service the area. Firstly a floor plan for the facility was obtained, thereafter all rooms/offices were labelled and the centre-point coordinates of each office were determined. This data was then logged to a database. The floor plan with a labelled office layout is presented in Figure 3.2.

![Facility Floor Plan](image)

Figure 3.2 : Facility Floor Plan

The facility provides a range of office spaces and rooms for a variety of different purposes and includes boardrooms, bathrooms, network laboratories a reception area and tearoom, single occupant offices and offices to accommodate up to 8 postgraduate students.
All enclosed rooms within the facility are equipped with air-conditioning systems except for the two bathrooms. The office building is accessible to occupants around the clock but sees the highest occupant presence during office hours from 08:00h to 17:00h. The occupancy of the common areas like the tearoom rising during tea and lunch breaks as expected.

The facility has an open-plan design spanning the different floors with all partitioning within the facility made out of lightweight drywall and 2mm glass. The following table contains the relative permittivities of various materials including those used in typical commercial office buildings.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\varepsilon_r$ (Fm$^{-1}$)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum</td>
<td>1</td>
<td>By definition</td>
</tr>
<tr>
<td>Air</td>
<td>1.00054</td>
<td>Usually approximated to 1</td>
</tr>
<tr>
<td>Glass</td>
<td>3.8 - 8</td>
<td>Varies with glass type</td>
</tr>
<tr>
<td>Wood</td>
<td>1.5 - 2.1</td>
<td></td>
</tr>
<tr>
<td>Drywall</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>Polystyrene</td>
<td>2.4 - 2.7</td>
<td></td>
</tr>
<tr>
<td>Dry Brick</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>4.5</td>
<td>Varies 4-6</td>
</tr>
<tr>
<td>Limestone</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>Marble</td>
<td>11.6</td>
<td></td>
</tr>
<tr>
<td>Fresh Water</td>
<td>80.2</td>
<td></td>
</tr>
<tr>
<td>Sea Water</td>
<td>80.2</td>
<td></td>
</tr>
<tr>
<td>Snow</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Ice</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>Ground</td>
<td>15 (7-30)</td>
<td>Varies with type and humidity</td>
</tr>
</tbody>
</table>

As seen from the above table, the permittivities of glass and drywall are rather low. Furthermore, the partitions made of these materials have a flat surface off of which the indoor radio signals are reflected. Because of this and also to simplify the scenarios to be simulated, all partitioning within the facility and the losses caused thereby will be ignored.

The next step in the investigation was done into the number of occupants per individual office space and the average number of WiFi capable device per occupant. The following table gives a summary of the purpose and number of occupants that are associated with each labelled room within the facility:
### Table 3.3: Summary of number of occupants in facility rooms

<table>
<thead>
<tr>
<th>Room</th>
<th>Purpose</th>
<th>Number of Occupants</th>
</tr>
</thead>
<tbody>
<tr>
<td>201 - 211, 216 – 223</td>
<td>Single Office</td>
<td>1</td>
</tr>
<tr>
<td>212</td>
<td>Reception</td>
<td>0</td>
</tr>
<tr>
<td>213 – 215</td>
<td>Board Rooms</td>
<td>0</td>
</tr>
<tr>
<td>224 – 227</td>
<td>Double Office</td>
<td>1 to 2</td>
</tr>
<tr>
<td>228, 229</td>
<td>Network Labs</td>
<td>0</td>
</tr>
<tr>
<td>230</td>
<td>Tee room</td>
<td>0</td>
</tr>
<tr>
<td>231 - 236</td>
<td>Multi Office</td>
<td>Up to 8</td>
</tr>
<tr>
<td>237, 238</td>
<td>Bathroom</td>
<td>0</td>
</tr>
<tr>
<td>Entire Facility</td>
<td>n/a</td>
<td>Up to 68</td>
</tr>
</tbody>
</table>

Furthermore, it was found that all building occupants possess at least one WiFi capable device with an estimated average of 2 WiFi capable devices per occupant. These devices are usually smart-phones, laptops or tablet computers.

### 3.3.1.1 Derived Assumptions

Assumptions as derived from the investigation into the facility will now be stated and discussed with respects the reasoning behind the assumption as well as how each assumption will be incorporated into the implementation.

*Collection of required data should be done for all 38 labelled rooms as well as all common areas such as hallways.*

This should be done to test the function of the VOS for all possible building areas where occupants can move. To incorporate this assumption, nodes will be created, and their movement simulated for each area. This will be done within the simulation configuration process.

_All unlabelled enclosed areas can be ignored._

This assumption is made to ensure that areas where occupants cannot physically move are ignored.

*Simulations should be done to investigate multiple occupants sharing a multi-office.*

This assumption ensures that real-world scenarios of multiple occupants sharing a physical office location are investigated. This will be incorporated by configuring multiple nodes within an office location, and thereafter simulating and logging both node mobility patterns and RSS measurements.
Each occupant should have at least one WiFi capable device. This assumption is one of the critical assumptions made for this study. This ensures that the physical position of each occupant can be determined in order to determine the occupancy of building zones. This will be realised by creating a WiFi device for each occupant.

Some simulated occupants should have more than one WiFi device. This assumption, made to ensure representation of a real-world scenario, will be incorporated by defining occupants that have multiple WiFi capable devices.

Simulations should be done to test functionality in areas with high occupancy figures. This assumption also aims to provide a real-world feel to the simulation by taking into account that occupancy of an area (tearoom) may vary greatly over the course of a day. This requirement will be adhered to by configuring a high density of nodes within the specific area.

These assumptions were determined from investigations into the facility and its occupants, further logical assumptions and assumptions to ensure the simplicity of the implementation were also made.

3.3.2 LOGICAL ASSUMPTIONS

In this section logical assumption and implementation decisions were made to ensure the simplicity of the created VOS model.

The most basic simulation configuration should be used. This will ensure that focus of the study remains on determining if a VOS is implementable for building energy management. This assumption was kept in mind during the entire design and implementation phase and is incorporated in simulation configuration and IA design.

The selected simulation configuration should correlate to widely accepted and implemented IEEE WiFi standards. This will ensure that the results obtained from the research would be applicable to most existing WiFi networks. This will be incorporated in the simulation configuration by selecting appropriate network models and setup parameters.

At least one occupant should be created to represent each of the 38 labelled rooms within the facility. This will aid in the data simulation process and the organisation of the extracted data. Furthermore, it will enable better result capturing for building zones/rooms. This will be implemented by creating occupants for each room within the database of registered occupants as well as simulating MiXiM nodes for each zone for data collection.
Each occupant should be related to a specific office location. This will ensure that power regulation of a specific office within a building is related to the specific occupant using it as a full time personal office. Furthermore, this will aid in identifying which office should be powered down since other occupants may walk past the office or be in close proximity. This proximity could lead to the IA determining that an unoccupied office should be left power up. This assumption will be incorporated in the occupant registration phase where occupants are linked to their specific office and their personal devices.

The worst case scenario where an office is incorrectly powered down will not be considered as a system failure. Since the goal of such an implementation would be energy conservation, this worst case scenario would not be considered a failure, but rather an inconvenience that would require the occupant to manually switch the power back on. The regularity of this occurrence will be investigated.

Environmental changes and obstacles influencing indoor radio propagation will not be taken into account. Since this is a proof of concept study aiming to determine if a VOS can be used to regulate building energy consumption only very basic implementation and simulation models are required. A simple implementation would prove sufficient to test the feasibility of this concept and other more intricate factors that affect radio propagation can be overlooked.

Occupation results should be able to indicate the occupancy of building zones without revealing the actual position of the occupants. This is necessary to overcome various privacy issues and is incorporated in the IA visualisation function. This function shows both the movement of occupants as well as occupancy and power state of building zones/rooms. This is solely done to show the overall functioning of the implementation, but the occupant tracking can easily be deactivated for privacy sensitive scenarios.

### 3.3.3 OCCUPANT AND DEVICE ASSUMPTIONS

In this section, all assumptions concerning building occupants and their personal WiFi device will be presented.

An occupant will always have a WiFi capable device on his/her person or in very close proximity. From this, it can be interpreted that the physical location of the device would reflect the physical location of the specific occupant. This assumption is made to ensure that the approximate location of occupants can always be determined. This assumption is considered the main assumption made for the purposes of this investigation. This will be incorporated in a very simple manner. Each simulated WiFi device and the measurements collected, therefore, will be seen as data collected for each occupant.
All registered occupant devices should be assigned a priority. This priority indicates the fitness of the particular user device to reflect the actual physical position of the occupant. This ensures that the device the occupant is most likely to have with him/her at all times, is used for location estimation. This is incorporated in the device registry phase.

The active device with the highest priority will be used for localisation. This ensures that position information for mobile occupants can still be collected even if their primary device is not detectable. A scenario such as this may occur when a smartphone runs out of battery power. This selection is handled by the IA.

### 3.4 SIMULATION CONFIGURATION

In this section, the models and parameters used for the simulation configuration will be discussed in detail. This will include selected analogue models, mobility models as well as the overall network type and standard used. Furthermore, various simulation setup parameters such as data rates, maximum transmission power, attenuation threshold and receiver sensitivity will be discussed. Lastly various simulation scenarios will be presented.

#### 3.4.1 OVERALL NETWORK MODEL

As previously mentioned, the overall network model needed to be specific enough to reflect widely implemented real-world technologies. It was decided to make use of the MiXiM `BaseNetwork` model with a network protocol equivalent of an IEEE 802.11 based type network.

Furthermore, the selected model needed to be simple enough as not to complicate the investigation of the concept at hand and also to prove relevant to a variety of existing network configurations. All diagrams and descriptions as provided in this section are based on the MiXiM class references as found in [46]. The following figure shows the usage-diagram of the selected MiXiM `BaseNetwork` model:

![MiXiM BaseNetwork Usage Diagram](image-url)
As seen from the above figure, MiXiM’s *BaseNetwork* makes use of the *ConnectionManager* module described in section 2.5.2.2. This module is tasked with dynamically managing the connections between interfering nodes and tracking the physical positions of all nodes. Parameters for the module are gathered from initial node positions and configurations and movement of the nodes are parsed from the mobility models. Parameters as selected for these modules are summarised in section 3.4.2.

The *BaseNetwork* module is also connected to the *WorldUtilityModule* that manages all global parameters for the simulation that are required by multiple sub-modules. These parameters include the simulation playground size and border wrapping policies. The values of these parameters will also be provided in the setup parameter section.

The MiXiM BaseNetwork module inherits its functionality from a variety of different example networks as setup for a range of real-world protocols. The module also inherits functionality from basic analogue model implementations and connection management classes. A basic inheritance diagram for the *BaseNetwork* module is shown in Figure 3.4 below.

![Inheritance Diagram](image)

Figure 3.4 : Inheritance Diagram

Figure 3.4 confirms that the functionality of the *BaseNetwork* module is inherited from various MiXiM example networks constructed to represent different wireless network protocols. For the purposes of this research, the *BaseNetwork* configuration using the *Mac80211ExampleNetwork* was selected. The IEEE 802.11 protocol is still considered the most widely implemented wireless network protocol and is thus ideal for testing of the concept at hand.
3.4.1.1 Selected Protocol

Implementation of the IEEE 802.11 protocol in MiXiM defines various modules and classes. These include power management modules, MAC layer implementations and also a protocol specific decider module. This is represented in Figure 3.5 below.

![Figure 3.5: MiXiM Classes for Implementation of the IEEE 802.11 Protocol](image)

The functionality provided by this IEEE 802.11 protocol implementation comes as a pre-configured model network. Thus very little user-configuration is needed to setup simulations that make use of the IEEE 802.11 protocol. The only required user-configuration is done in the configuration file. Parameters configured in this file, will be discussed in detail in subsequent sections.

The BaseNetwork module was then configured to offer this IEEE 802.11 protocol functionality by making use of the MiXiM defined Host80211 node type. The MiXiM Host80211 is shown in Figure 3.6 below.
The MiXiM defined Host80211 is sub-classed from the MiXiM BaseNode as discussed in section 2.5.2.2 but defines additional presentation layer, session layer and transport layer implementations as derived from a typical 802.11 protocol network interface card.

Three different nodes types were sub-classed from this Host80211 module for the creation of the needed simulation scenarios. These were access point nodes, smartphone nodes and tablet computer nodes. This was done in the network description file of the implemented BaseNetwork class.

In simulation setup these node were named as indicated in the table below:

<table>
<thead>
<tr>
<th>Device</th>
<th>OMNeT++/MiXiM name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access point nodes</td>
<td>AP</td>
</tr>
<tr>
<td>Smart-phone nodes</td>
<td>Cell</td>
</tr>
<tr>
<td>Cell and Tablet nodes</td>
<td>Tab</td>
</tr>
</tbody>
</table>
This naming convention was introduced in order to represent the individual device with short names for graphing purposes. Note that although the smart-phone nodes are indicated as cell nodes this does not refer to regular GSM-only cellular devices but to WiFi capable smart-phone nodes. When referring to the simulated MiXiM devices in later chapters, the node names as configured will be placed in brackets to avoid confusion.

All three sub-classed node types have the same functionality as the Host80211 module but can now be configured as separate entities. Configuration of these node parameters is done in the omnetpp.ini file and is summarised in section 3.4.2.

### 3.4.1.2 Selected Decider Module

MiXiM implements decider modules along with analogue models to provide functionality for wireless networks to the OMNeT++ framework. This is necessary since OMNeT++ configures node connections as fixed links that are not suitable for representing wireless networks. The MiXiM framework thus fits on top the OMNeT++ framework to provide these additional features. These features include adding attenuation to the signal class of OMNeT++ to represent the path loss of a signal as it travels from sender to receiver. All the functionality that is added is grouped into the physical layer modules of MiXiM. This above discussed MiXiM to OMNeT++ fit is represented graphically below.

![OMNeT++ Layer Architecture MiXiM Infusion](image)

The selected decider module as created for IEEE 802.11 protocol implementations is also sub-classed from the basic decider module of the MiXiM base class and is furthermore connected to a protocol specific power management module.
The decider module calculates the RSS value for a passed interval. This method is called when answering a ChannelSenseRequest.

The module defines a threshold value for checking the SNR-map and a centre frequency value for indicating the frequency on which the decider listens for signals.

This module provides methods for processing new received signals. This function determines if the received power of a signal is strong enough for the signal to be received correctly.

Furthermore, the decider determines if the passed completed Airframe was received correctly. This function implements logic gates to determine if the SNR of a signal is below the defined threshold value.

The decider also implements methods for processing completely received signals. This function creates the SNR-mapping of the signal and compares it to the threshold value. Depending on the outcome of this, the signal is either passed to the MAC-layer or dropped.

The RSS value for passed interval is also calculated in this decider module when answering a ChannelSenseRequest.

From this module, the first part of the required data could then be collected. This was done by making adjustments to the Decider80211 module so that the RSS value is extracted from the decider as an \textit{mW}. This value was converted to \textit{dBm} and piped to the simulation event log.

In the following section the analogue model used for configuration with this Decider80211 module will be discussed with specific focus on the model functionality.

### 3.4.1.3 Path-loss Model

The Decider80211 class, as discussed above, is configured to make use of MiXiM SimplePathlossModel to simulate attenuation in the environment. This very basic analogue model, which is based on the free-space path-loss model, was selected in order to keep simulations simple. Implementation of more complex analogue models proved to significantly increase the simulation run time due to the added complexity of arithmetic that needed to be performed.

Although the SimplePathlossModel would aid in providing rather optimistic results, it was decided that this would be specifically suitable for this proof of concept investigation since a simplistic answer that would be relevant to most implementation scenarios and existing WiFi infrastructure is required.

The class-diagram of the selected SimplePathlossModel is given in Figure 3.8 below.
The SimplePathlossModel’s first task is to determine the start of reception of a signal. Thereafter the movement of the transmitter is queried from the ConnectionManager in order to calculate the distance between communicating nodes. The above information is then used along with other global parameters such as the carrier frequency to add attenuation to a signal over time.

This model defines the following parameters:
- \( \alpha \) – Path loss coefficient.
- carrierFrequency – Carrier frequency of received signal.
- myMove – A pointer to the host move pattern.
- useTorus – Information about the simulation playground.
- PlaygroundSize – Size of the simulation playground.

The model provides the following functionality:
- The analogue model is firstly initialised by extracting the mentioned parameters.
- Calculation of the attenuation value of the implemented path loss is done. This entails determining the square distance between sender and receiver.
- Lastly attenuation for the given signal is determined incorporating the defined path loss value and wavelength.
- The calculated attenuation is then added to the signal in the time domain considering the positions and interference of all nodes as provided by the mobility modules and ConnectionManager.
In the following section, the mobility models used for input into the myMove and other positioning parameters of the implemented analogue model will be discussed.

### 3.4.1.4 Selected Mobility Models

In order to simulate the movement of occupants within the facility, different MiXiM mobility models were selected. These models included the *BaseMobility* model, the *CircleMobility* model, and the *LinearMobility* model. The second set of required data, the positioning data, is generated and extracted from these mobility modules. Configuration of the parameters needed by these mobility models is also done in the configuration file.

The configuration parameters were varied throughout the simulation process to reflect the movement of occupants within the facility. Parameters can be configured for a group of nodes, or for each specific node depending on the scenario.

**BaseMobility- (Stationary)**

This model was implemented for the APs in the simulation configuration. This model only requires configuration of a node’s $x$ and $y$ coordinates since the node remains stationary.

**CircleMobility – (Movement on circle radius)**

This model was used to simulate an occupant moving around within an office. The model is configured by providing centre-point coordinates for the circle, a radius length and starting angle. The centre-point coordinates were configured with respective office centre-point coordinates. The radius length is required to define the path of the circle on which the occupant should move. The starting angle gives indication to the specific angle on the circle at which the initial movement began.

**LinearMobility**

This mobility type was implemented to create the map of the radio environment needed for the selected RF fingerprinting technique and was also used to simulate occupants moving through the facility such as walking up and down hallways. This mobility type took initial $x$ and $y$ coordinates and angle of movement as parameters.

Both implemented mobility types were configured with constant walking speeds as no acceleration was implemented.

All of the implemented mobility models as discussed above were adjusted to make public the current and target positions of all simulated nodes each time a call to the model was made.

These position sets were also written to the simulation event-log in synchronous order as the nodes moved through the environment.
By configuring the simulation to function as described, it was easy to determine from which physical position within the simulation environment a collected RSS value was measured.

These actual position values were used in the later implementation phases by the IA to determine the accuracy of the implemented localisation algorithms.

Having given an overview of the function of the selected network model, the implemented protocol and the modules and classes associated therewith the next step is defining the setup parameters required in the configuration file.

### 3.4.2 SETUP PARAMETERS

The configuration file is used to provide a convenient and centralised method for fast setup of all standard aspects and parameters needed to configure a simulation. This configuration process can be done in text or form based formats and provides sections for the configuration of global simulation parameters, `WorldUtility` parameters, `ConnectionManager` parameters and node specific parameters. The node parameter section is further sub-divided to provide setup for the physical, application and network-layer parameters for each node, as well as mobility parameters. An example of a configuration file for a basic simulation with three APs and one WiFi capable device is provided in Appendix B.

In order to ensure that the simulation model is relevant to existing implemented wireless network technologies, an investigation into specifications of widely used APs was done.

#### 3.4.2.1 Access-Point Comparison

This investigation was done by comparing technical specifications of five common AP manufactures as found from product datasheets. All APs selected for the comparison implemented various IEEE 802.11 protocols and were all specifically designed for use in indoor commercial environments. The comparison is summarised in Table 3.5 below. This comparison was then used to derive suitable values for parameters of the APs configured for the simulations.
As seen from the above comparison, all investigated APs are compliant with the IEEE 802.11 g standard protocol.

Furthermore, it was decided that simulations should be run for different data rates to ensure relevance to most implemented wireless network configurations. For this purpose, a data rate of 6 Mbps and receiver sensitivity of -86 dBm and data rate of 54 Mbps and receiver sensitivity of -68 dBm was selected. All simulated scenarios will thus be run for both configurations to give indication of the sensitivity of the system given this parameter variability.

The other investigated parameters vary significantly. In order to determine suitable values for these greatly varying parameters, it was decided to select a value that falls well within bounds of the maximum and minimum parameter values as presented above. The parameter values as derived from the above comparison are given in table format below:

### Table 3.5 : AP Technical Specification Comparison

<table>
<thead>
<tr>
<th>Specification</th>
<th>DAP 2360</th>
<th>DAP 2310</th>
<th>Aironet 1260 Series</th>
<th>Aironet 2600 Series</th>
<th>AP 110</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>D-Link</td>
<td>D-Link</td>
<td>Cisco</td>
<td>Cisco</td>
<td>Meru Networks</td>
</tr>
<tr>
<td>Frequency</td>
<td>2.4 - 2.4835 GHz</td>
<td>2.4 - 2.4835 GHz</td>
<td>2.4 and 5 GHz</td>
<td>2.4 and 5 GHz</td>
<td>2.4 to 2.471 GHz</td>
</tr>
<tr>
<td>Standard</td>
<td>802.11 b/g new n</td>
<td>802.11 b/g new n</td>
<td>802.11 a/g /n</td>
<td>802.11 a/bg/n</td>
<td>802.11 b/g/ n</td>
</tr>
<tr>
<td>Max Output Power</td>
<td>FCC: 26 dBm/ETSI: 14 dBm (Dual Chain)</td>
<td>ETSI : 20 dBm (Dual Chain)</td>
<td>20 dBm (100 mW) 2 antennas</td>
<td>22 dBm (160 Mw) 3 antennas</td>
<td>17 - 13 dBm</td>
</tr>
<tr>
<td>Number Channels</td>
<td>13 channels (20/40 MHz)</td>
<td>13 channels (20/40 MHz)</td>
<td>13 channels (20/40 MHz)</td>
<td>13 channels (20 MHz)</td>
<td>13 channels (20 MHz)</td>
</tr>
<tr>
<td>Data rate</td>
<td>up to 300 Mbps</td>
<td>up to 300 Mbps</td>
<td>6.5 - 130 Mbps</td>
<td>6.5 - 156 Mbps</td>
<td>6.5 - 130 Mbps</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>5 dBi @ 2.4 GHz</td>
<td>2 dBi @ 2.4 GHz</td>
<td>up to 6 dBi</td>
<td>4 dBi</td>
<td>2 dBi</td>
</tr>
<tr>
<td>Receiver Sensitivity</td>
<td>-82 dBm(6Mbps), -65 dBm(54Mbps)</td>
<td>-89 dBm (2Mbps), -66 dBm(54Mbps)</td>
<td>-92 dBm (6.5Mbps), -74 dBm (130Mbps)</td>
<td>-91 dBm (6.5Mbps), -74 dBm (156Mbps)</td>
<td>-87 dBm (6Mbps), -76 dBm (54Mbps)</td>
</tr>
</tbody>
</table>
This section investigated configuration parameters for the AP to be used within this simulation. Investigation into setup parameters for personal WiFi device were not done in such great detail since these parameters are all manufacturer or device specific and a vast range of different device, makes and models are used by occupants in the real-world. Selection of these parameters, as well as other simulation configuration parameters, is summarised in the following section.

### 3.4.2.2 Selected Setup Parameters

In this section, the setup parameters as used for the simulation configurations are given. The parameters and their selected values are categorised according to the module or class for which they are configured, this is represented in Table 3.7 below. Each category of setup parameters will be briefly discussed in this section going into more detail where needed.

#### Table 3.7: Simulation Configuration Parameters

<table>
<thead>
<tr>
<th>Setup Parameters</th>
<th>Global Parameters</th>
<th>WorldUtility</th>
<th>ConnectionManager</th>
</tr>
</thead>
<tbody>
<tr>
<td>PlaygroundSizeX</td>
<td>100m</td>
<td>useTorus</td>
<td>Variable</td>
</tr>
<tr>
<td>PlaygroundSizeY</td>
<td>60m</td>
<td>use2D</td>
<td>True</td>
</tr>
<tr>
<td>PlaygroundSizeZ</td>
<td>15m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NumNodes</td>
<td>Variable</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Parameters for the Host**

<table>
<thead>
<tr>
<th>Physical Layer</th>
<th>Application Layer</th>
<th>Mobility Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>usePropagationDelay: True</td>
<td>Header Length: 512 bit</td>
<td>AP Mobility: Base Mobility</td>
</tr>
<tr>
<td>useThermalNoise: True</td>
<td>Burst Size: 3</td>
<td>Cell Mobility: Circle/Linear</td>
</tr>
<tr>
<td>thermalNoise: -110 dBm</td>
<td>Packet Time: 1 s</td>
<td>Tab Mobility: Circle/Linear</td>
</tr>
<tr>
<td>AP maxTXPower: 100 mW</td>
<td></td>
<td>Speed: 0.5-1.2 mps</td>
</tr>
<tr>
<td>Cell maxTXPower: 10 mW</td>
<td></td>
<td>Update interval: 0.1 - 1 s</td>
</tr>
<tr>
<td>Tab maxTXPower: 10 mW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity @6Mbps: -86 dBm</td>
<td></td>
<td>Initial X: Variable</td>
</tr>
<tr>
<td>Sensitivity @54Mbps: -68 dBm</td>
<td></td>
<td>Initial Y: Variable</td>
</tr>
<tr>
<td># Radio Channels: 13</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data Rates</th>
<th>Max Output Power</th>
<th>Num Channels</th>
<th>Antenna Gain</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 Mbps</td>
<td>IEEE 802.11 g</td>
<td>100 mW (20 dBm)</td>
<td>13</td>
<td>6 dBi</td>
</tr>
<tr>
<td>54 Mbps</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.4.2.2.1 Global Simulation Parameters & WorldUtility Parameters

These parameters are used to define the size and border policies of the physical area to be simulated in which all nodes will be contained. The number of nodes present in the simulation is also configured here. The playground size selected for use with all simulations was based on the physical dimensions of the facility.

The facility building has a measurement of 68.413 m x 35.985 m at its widest areas. The dimensions selected for the simulations are 100m x 60m to incorporate areas outside the building for testing purposes.

3.4.2.2.2 ConnectionManager Parameters

This section is used to configure parameters as used for management of connections between interfering nodes. This includes maximum transmission power, signal attenuation threshold and path loss coefficient alpha.

The maximum transmission power $p_{Max}$ as defined for the ConnectionManager has to be set to a greater value as that of the maximum transmission power $maxTXPower$ for all hosts as defined in the physical layer host parameters section.

The value of $p_{Max}$ was thus set to 110.11 mW that was also provided as a default value for this parameter by the Host80211 implementation. Furthermore, the connection manager is calibrated to draw the maximum interference distance of all nodes.

Next host specific parameters were configured for use with MiXiM physical layer, application layer and network layer implementations. Most of these parameters are preconfigured for the Host80211 module to reflect the functioning of the IEEE 802.11 type protocols.

3.4.2.2.3 Physical Layer Parameters

In this layer, the maximum transmission power was defined for the three created node types. The transmission power for all APs was set to 100mW, and 10 mW was used for both the smart-phone and tablet node types. Parameter for the physical layer was also set to incorporate thermal noise and propagation delay into the simulation. The amount of introduced thermal noise was set as the default value of -110 dBm as provided by the Host80211 implementation. The receiver sensitivity as selected for the two configurations was applied across all node types.

3.4.2.2.4 Application & Network Layer Parameters

The values for packet header lengths were also configured with the provided IEEE802.11 compliant default of 512 bits. All conducted simulations were run for both the 6 Mbps and 54 Mbps configurations respectively.
3.4.2.2.5 Mobility Model Parameters

The implemented mobility models and the parameters setup required for simulating each specific model were discussed in section 3.4.1.4. These parameters are different for each simulated node, and each tested building zone/room. Furthermore, these parameters were varied throughout the simulation process to reflect specific occupant movement scenarios.

The mobility speed parameter was also varied throughout; this was to represent an occupant moving around at a slow pace within his/her office or occupant pacing through the hallway at an average walking speed of up to 1.2 m/s.

The mobility update interval was varied between 0.1 and 1 s. The selected update interval depended on the type of movement used by a node, the scenario to be simulated and the building area in which the node was located. Smaller update intervals were used for the CircleMobility model as well as for the environment mapping process. LinearMobility models made use of larger intervals up to 1 s.

All of the above discussed setup parameters were configured to create a suitable simulation environment for testing various simulation scenarios. Each of these scenarios is discussed in detail, in the next section.

3.4.3 Pre-Implementation Simulations

In this section, all simulation done prior to the functional implementation of the developed VOS will be explained. The results obtained from these simulations were required to make important design decisions before the full development of the VOS functionality could be done. The pre-implementation simulations included ranging simulations for the two selected receiver sensitivities configurations, simulations for creating the environmental map needed for the RF fingerprinting techniques and simulations to determine the reference path-loss.

3.4.3.1 Mapping Simulations

The first round of simulations that were configured was done for the mapping of the RF environment. This was complete in two steps; The first consisted of running simulations to determine the reference path-loss at a distance of one meter from an AP. This reference value was then used by the IA for the calculation of path-loss as needed for trilateration estimation. The second step focused on mapping the entire RF environment to create the mentioned fingerprinting map as used by the IA for the implemented RF fingerprinting methods.

As the mapping simulations do not form part of the investigation, and the results thereof are needed for the configuration of the VOS, it will be presented in this chapter.
3.4.3.1.1 Reference Path-loss Simulations

In this step, a single smart-phone (Cell) node configuration was used with the CircleMobility type. First only one AP was used in the simulation to determine the reference path-loss without additional interferences. Thereafter, the simulation was reconfigured to function with all three APs at positions as indicated in Table 3.11. The node was then placed at one meter distance from an AP and the reference power measured to investigate the interference created by the addition APs. This process was implemented with the use of MiXiM’s CircleMobility model with the initial circle centre-point set to the coordinates of the AP and the circle radius of 1m. This process was repeated for all APs.

<table>
<thead>
<tr>
<th>Table 3.8 : Path Loss Simulation Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobility Type</td>
</tr>
<tr>
<td>CircleMobility</td>
</tr>
</tbody>
</table>

These simulations were run for a simulation time of 100 seconds and were done ten times per AP. The values as found from these simulations remained rather constant and were not affected by interference from the addition APs. This is due to the decider module only implementing minimal path-loss attenuation for distances of 1 meter or less. The value as determined from these simulations that was used as the reference path-loss at a distance of one meter is given below:

$$P_L(d_0) = 20.4184 \text{ dBm}$$

3.4.3.1.2 RF Mapping Simulations

This entailed configuring a single smart-phone node to move throughout the playground sending broadcast messages. RSS readings were gathered for each position from the three implemented APs.

In this scenario, the node made use the LinearMobility model configured at a mobility speed of 1 mps and a mobility update interval of 1s. This configuration was selected so that the node would move in increments of a meter at a time in a straight line across the simulation playground. The initial position of the node was set to [1,1] as to start in the top left-hand corner of the playground and move at a constant speed towards the right.

After the node had reached the right-hand side the whole process is repeated by incrementing the y-value of the initial starting position by one meter. This process was followed until the entire environment was mapped.
Table 3.9: RF Mapping Simulation Parameters

<table>
<thead>
<tr>
<th>RF Mapping Simulation Setup Parameters</th>
<th>Mobility Type</th>
<th>Mobility Speed</th>
<th>Mobility Update Interval</th>
<th>Initial X</th>
<th>Initial Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>LinearMobility</td>
<td>1 mps</td>
<td>1 s</td>
<td></td>
<td>1 m</td>
<td>10 m</td>
</tr>
</tbody>
</table>

The RSS and position data for this simulation scenario is extracted by a specialised mapping unit of the parser and stored in the database. The data is organised according to the RSS measuring AP to present an RF map of the environment as seen from each individual AP. More detail on the parser unit and database configuration for the mapping process is presented in the subsequent sections.

The RF maps as seen from each of the three implemented APs are presented below. These heat maps were created for the direct area surrounding the facility with the use of the FusionCharts suit.

![HF Fingerprinting Map AP 1](image)

Figure 3.9: RF Fingerprinting Map AP 1

Figure 3.9 shows the heat map for AP1, located at [47 m; 18 m]. As seen, the RF map values range from -30 dBm to -75 dBm and provide the strongest signal and best coverage for the upper-central part of the facility. The placement of AP1 will thus provide RSS readings from which it will be able to identify, to some extent if the PoI is located in the upper or lower part of the building for the central area.

The RF map generated for AP2, located at [65 m; 41.5 m] is presented in Figure 3.10 below, with measured RSS values ranging from -25 dBm to -75 dBm. AP2 provides coverage for the bottom-right area of the facility. Strong readings form this AP will thus suggest that the detected device is located to the right-hand side of the building.
Lastly, Figure 3.11 represents the RF map for AP3, located at [10 m; 41 m]. This AP measures an RSS range of 20 dBm to -80 dBm, and provides coverage for the left-side facility areas. Strong readings from this AP will propose that the detected device is located to the left-hand side of the building.
Using the RSS measurements of the three AP in combination, a unique set of readings can be obtained for all ladled rooms in the facility.

### 3.4.3.2 Ranging Simulations

Ranging simulations were conducted to determine the maximum communication range that would be possible with the selected setup configurations. This range would give an indication to the number of APs that are able to detect a simulated device in various rooms of the facility.

Ranging simulations were conducted for two different configuration scenarios:
- With a data rate of 6 Mbps, and a receiver sensitivity of -86 dBm.
- With a data rate of 54 Mbps, and a receiver sensitivity of -68 dBm.

These simulations involved configuring a single AP and a single smart-phone (Cell) node. The AP was stationary, and the smart-phone (cell) node was configured with `LinearMobility`. The smart-phone then moved away from the AP with a constant speed of 1 mps until it was out of range and broadcast messages could no longer be received by the AP. Setup parameters for these simulations are presented in Table 3.10.

<table>
<thead>
<tr>
<th>Device</th>
<th>Mobility Type</th>
<th>Mobility Speed</th>
<th>Mobility Update Interval</th>
<th>Initial X</th>
<th>Initial Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell</td>
<td>LinearMobility</td>
<td>1 mps</td>
<td>1 s</td>
<td>11 m</td>
<td>41 m</td>
</tr>
<tr>
<td>AP</td>
<td>BaseMobility</td>
<td>n/a</td>
<td>n/a</td>
<td>10 m</td>
<td>41 m</td>
</tr>
</tbody>
</table>

From these simulations, RSS as received by the AP and position information of the moving smart-phone node was captured. Position data was reworked to determine the distance between the smart-phone and the RSS measuring AP.

Results of ranging simulations are presented by the graphs in Figure 3.12 and Figure 3.13. The graphs show the relationship between the measured RSS and distance; a trend-line indicating the distance at which the signal for the smart-phone was lost is also presented.
In Figure 3.12, it can be seen that when configured with a sensitivity of -86 dBm in the 6 Mbps simulation a range of up to 162 meters is possible with signal loss occurring at 163 meters.

This large range is sufficient for the whole area of the facility to be covered by all three APs. A device moving within the facility will thus be detectable by all three APs at any location. All the selected localisation techniques can thus also be performed to estimate the position of the device.
Figure 3.13, however, shows that for the 54 Mbps configuration with a sensitivity of -68 dBm a maximum range of only 40m is possible, with the signal being lost at 41m.

This indicates that devices will not be detectable by all three APs in all areas within the facility. Location estimation of devices in some areas would thus need to be done with RSS measurements from two or only one AP. In the following results chapter, an indication will be given of the number of APs that are able to detect a device in the various defined facility rooms.

In situations as such the use of trilateration estimation would not be possible since this technique requires measurements from three reference nodes (APs). Location estimation of devices that are only detected by one or two APs will thus only be done by the use of the two implemented RF fingerprinting techniques.

Furthermore if a device is only detectable by one or two APs the accuracy of the device localisation would be less. In order to compensate for this loss of accuracy, various techniques were implemented by the IA in the localisation modules to deal with situations as such. These techniques are detailed in section 3.7.1.1 and section 3.7.1.2 describing the functionality of the localisation and occupancy determination units of the developed IA.

This concludes the simulations conducted for determining per-implementation configurations of the VOS. In the next section, simulation as conducted to provide input for testing the finished implementation will be detailed.

### 3.4.4 SIMULATION SCENARIOS

In this section, simulation scenarios incorporating different node mobility patterns as necessary to investigate the functioning of the VOS is discussed. Each presented scenario will provide detail with respects to the actual implemented node mobility and what the scenario aims to represent or investigate. Furthermore, detail will be provided on the run configuration and number of executed runs for each scenario.

All the simulation scenarios made use of 3 configured APs. The physical positions of the APs were the same for all scenarios and is given in the following table:

<table>
<thead>
<tr>
<th>Access Point Positions</th>
<th>AP 1</th>
<th>AP 2</th>
<th>AP 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-coordinate</td>
<td>47 m</td>
<td>65 m</td>
<td>10 m</td>
</tr>
<tr>
<td>Y-coordinate</td>
<td>18 m</td>
<td>41.5 m</td>
<td>41 m</td>
</tr>
</tbody>
</table>
3.4.4.1 Room Simulations

This simulation scenario was run for each of the 38 labelled rooms within the facility to investigate if each specific room could be uniquely identified. Furthermore, this scenario aided in testing the basic functionality of the VOS by simulating occupant presence in a single facility room at a time. This was done by configuring a single smart-phone (Cell) node with CircleMobility and setting the initial position (circle centre-point) to that of each specific office’s centre-point. The setup parameter for this scenario is provided below.

<table>
<thead>
<tr>
<th>Table 3.12 : Room Simulation Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Per Room Simulation Setup Parameters</strong></td>
</tr>
<tr>
<td>Mobility Type</td>
</tr>
<tr>
<td>CircleMobility</td>
</tr>
</tbody>
</table>

These simulations were conducted ten times per individual room and were run until 100 messages were received per simulated node. Simulations as conducted for this scenario were used in a preliminary testing phase to determine the accuracy of the selected location estimation algorithms. Based on the results of this preliminary investigation, one technique was selected to be implemented for occupation estimation.

3.4.4.2 Multi Occupant Simulations

This simulation scenario was implemented for all multi-occupant rooms within the facility and aided in testing if the VOS is able to distinguish between and track multiple occupants in a single room. Furthermore, these scenarios would give an indication to if the overall VOS sensor can work with strong interference created by closely grouped devices.

Smart-phone (cell) nodes configured with CircleMobility were used for the simulations. The number of created nodes varied throughout the simulation of this scenario to represent rooms with two, three or four occupants. Multi-occupant simulations were conducted ten times for each multi-occupant room and were run until 100 messages were received for each simulated node. The scenario specific setup parameters are given below.

<table>
<thead>
<tr>
<th>Table 3.13 : Multi Occupant Simulation Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Multi Occupant Simulation Setup Parameters</strong></td>
</tr>
<tr>
<td>Mobility Type</td>
</tr>
<tr>
<td>CircleMobility</td>
</tr>
</tbody>
</table>
3.4.4.3 Priority Device Simulations

This scenario was implemented to resemble cases where an occupant has more than one WiFi capable device. The aim of this implementation scenario was to test the functionality of the VOS to determine room occupancy based on the device with the highest indicated priority. These scenario simulations were also used to test the functioning of the VOS that indicated if the occupant is close or far from his/her office location. Lastly, the scenario provided data for testing the time an occupant spent away from his/her office within a specific range. If an occupant is, for example, located far from his office and remains there for a certain amount of time, the office of the occupant should be powered down.

Simulations for these priority investigations were done by configuring both smart-phone (Cell) and tablet (Tab) nodes with CircleMobility. The smart-phone nodes, typically considered as the priority device, were placed at initial positions anywhere within the facility except for the specific office location. These initial positions were varied to be near or far from the specific office location. The tab nodes were configured to have an initial position at the centre-point of the specific office location. Thus in the scenarios the top priority smart-phone (cell) node is located out of office and the secondary tab nodes within the office.

A priority scenario where no smart-phone (cell) nodes were configured was also done. This was done to determine if the VOS would be able to reconfigure itself to use a secondary device for localisation and occupancy determination if no primary device is detected. Detail on each specific configuration will be provided with the results obtained from these scenarios in the following results chapter. Priority simulations were conducted 10 times for each specific sub-scenario (close/far from office) unit 100 messages were received for each simulated device. The parameters for this scenario are given below.

<table>
<thead>
<tr>
<th>Node</th>
<th>Mobility Type</th>
<th>Mobility Speed</th>
<th>Update Interval</th>
<th>Mobility Radius</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell</td>
<td>CircleMobility</td>
<td>1 mps</td>
<td>0.5 s</td>
<td>1m / 2m</td>
<td>Out of office</td>
</tr>
<tr>
<td>Tab</td>
<td>CircleMobility</td>
<td>1.2 mps</td>
<td>0.5 s</td>
<td>1 m</td>
<td>In Office</td>
</tr>
</tbody>
</table>

3.4.4.4 Common Area Simulations

This scenario type was used to present occupants moving in the common areas of the facility such as the hallways and right and left-side block areas outside rooms R237/R238 and room R212. These simulations were performed to test the functioning of the VOS when tracking occupants moving between occupancy zones, such as an occupant moving from close to an office, to a location that is classified as far from the specific office.
Furthermore, these scenarios aided in determining whether an occupant walking past various rooms would have an effect on the occupancy of unrelated offices. Smartphone (cell) nodes configured with LinearMobility or CircleMobility were used in the simulation depending on the physical form of the common area in question. These common area simulations were conducted 10 times for each common area, and were run until 100 messages were received for each node, or the physical path, such as the strait of the hallway, was completed. Parameters for the configuration of these scenarios are provided below.

<table>
<thead>
<tr>
<th>Area</th>
<th>Mobility Type</th>
<th>Mobility Speed</th>
<th>Update Interval</th>
<th>Mobility Radius</th>
<th>Start Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hallways</td>
<td>LinearMobility</td>
<td>1 mps</td>
<td>1 s</td>
<td>n/a</td>
<td>Varied</td>
</tr>
<tr>
<td>Block Areas</td>
<td>CircleMobility</td>
<td>1 mps</td>
<td>1 s</td>
<td>1 m - 3 m</td>
<td>Varied</td>
</tr>
</tbody>
</table>

### 3.4.4.5 Loading Simulations

Lastly loading simulations were conducted in order to determine the amount of nodes that can be effectively handled by the VOS. This was done by configuring smart-phone (Cell) nodes with CircleMobility and initial positions of the centre-points of various offices. The scenario was configured for 10, 20 and 40 nodes and was simulated for a simulation time of $T=3600$ simulation seconds.

<table>
<thead>
<tr>
<th>Mobility Type</th>
<th>Mobility Speed</th>
<th>Mobility Update Interval</th>
<th>Mobility Radius</th>
<th>Initial Pos</th>
</tr>
</thead>
<tbody>
<tr>
<td>CircleMobility</td>
<td>0.5 mps</td>
<td>1 s</td>
<td>1 m</td>
<td>Various offices</td>
</tr>
</tbody>
</table>

In this section, a discussion was provided on the implemented simulation model and the configuration and functioning thereof. Each of the scenarios that were simulated was discussed according to the reasoning behind the simulated scenario and what the scenario aimed to investigate. Furthermore, scenario specific setup parameters were provided as well as detail on the run configuration of each scenario.

In the following section the created data parser that is needed to extract the required data from these simulations will be discussed.

### 3.5 DATA PARSER

The self-created data parser module is tasked with collecting RSS, node identification and node positioning data for the conducted simulation scenarios. This parser was created to provide a web-based interface for loading the various event-logs containing this data as generated for the conducted simulations.
The parser was developed with the use of various programming languages and includes HTML, PHP and JavaScript code segments. The event-logs were saved in a text file format.

Figure 3.14 below provides a functional flow of the created parser module, each of the parser sub-modules will be briefly explained.

As seen from Figure 3.14, the parser module constitutes various sub-modules that offer different processing trees for parsing mapping simulation data and other scenario simulation data. In the implementation setup phase, the parser was used to load the mapping data from the RF mapping simulations. This was done to create the RF fingerprinting map used for the implemented fingerprinting location estimation techniques.

After the mapping process was completed the parser was used to upload all other simulation event-logs, extract the relevant data and store this data in a suitable format for the use with location estimation techniques. Each of the parser sub-modules and the functioning thereof for both mapping data and regular simulation data will now be discussed.
3.5.1 FILE UPLOADER – MODULE A

The file uploader module offers an interface where detail could be provided concerning a simulation. This included detail such as simulation name, run number and description as well as the occupants to which the simulated devices should be related. The simulation event-log could then be selected from any directory and submitted along with the mentioned detail.

Each line of data uploaded from the event-log was stored in the data table of the database, and an index was provided to identify each consecutive line. The structure of the database will be explained in detail in the following section. The interface for the file uploader unit is shown in Figure 3.15 below.

![Figure 3.15 : File Uploader Interface Screen Shots](image)

As seen in Figure 3.15.a the interface for the mapping part of the uploader provides fields to indicate the initial x and y coordinates of the mapping. Although coordinate positions for the mapping process is extracted from the event-logs the first pair of initial coordinates were provided here since the mobility module of MiXiM only send coordinate output to the event-log from when the first move is made. Thus failing to provide coordinates for the first meter of the mapped environment.
Figure 3.15.b shows that, for the scenario simulations, a “Sim Device” and a “MiXiM Device” can be identified. This was done in order to relate the simulated MiXiM nodes to occupant’s devices as registered in the database. This process was necessary since when simulating device in MiXiM the device is labelled according to the amount of devices present. Thus if two smart-phone nodes are configured they would be defined as Cell[0] and Cell[1]. This relation of MiXiM to occupant devices aided in providing clarity on which device belonged to which. This also made it easier to organise the simulations and found results.

3.5.2 DATA EXTRACTION UNIT – MODULE B

This module of the data parser is tasked with the identification and extraction of all the required data, the classification thereof according to the MiXiM/occupant device relation and the storing of the data in the relevant database tables and fields. This is implemented as a single script as to effectively process this sequential even-log data but can be categorised into four functional parts:

Node Identification
In this process, each line of data containing relevant information that needed to be extracted had to be processed in order to determine for which simulated node the data was created.

Node Position Extraction
After identifying the node, the actual position coordinates as outputted by the mobility modules were extracted.

RSS Extraction
The RSS extraction process also differed for the mapping and scenario simulations. RSS extraction for the mapping simulations focused only on the AP receiving the broadcast message. Thus, three RSS measurements (one for each AP) were extracted for each sent broadcast message. Extraction of RSS for the scenario simulations worked similarly except for the relation to the sending node that needed to be added. Furthermore, this extraction unit was created to only extract RSS values as measured from the three APs, all other RSS values received by nodes from AP sending acknowledgements or replies were ignored.

Database Storage
After all the above processes were completed the extracted values were stored in an ordered format in the database RSSI table. The created IA could then access this information from the table to implement the algorithms and logic needed to give an indication to the occupancy of the facility.

The database and tables containing all the extracted data values as well the pre-configured occupant information is the focus of the following section.
3.6 DATABASE SETUP

The database contains 11 tables for the organisation and storage of all extracted data, registered occupants, coordinates as calculated from location estimation and also the found occupancy results.

This database is represented in the form of a relational MySQL database that is connected to the parser module and the created IA module. The IA uses the stored data for processes implemented to realise the VOS.

In the table below each of the database tables will be briefly explained according to the data contained therein and the use thereof for different process of the IA. A relational diagram of the database is presented in Appendix C of this document.

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP (P)</td>
<td>This table contains an identifier field and position coordinate information for the implemented APs. This data is used by IA to determine the distance between the sending node and receiving AP for localisation purposes.</td>
</tr>
<tr>
<td>Device (P)</td>
<td>In this table, data for all registered devices are stored. This includes a unique identifier, device type and priority. Indication to the user of the device is given by a userID field. Data from this table is used by both the parser and IA. The parser makes use of the device’s unique identification for relating MiXiM nodes to these devices. The IA agent also makes use of this identifier along with the device priority for occupancy determination.</td>
</tr>
<tr>
<td>Occupant (P)</td>
<td>This table contains the unique occupant identifier and office location identifier for registered occupants. This data is used by the IA module to generate occupancy information per occupant by relating one or more devices to this unique occupant identifier.</td>
</tr>
<tr>
<td>Office (P)</td>
<td>This table contains the centre-point coordinates for all of the 38 labelled office of the facility. Furthermore, a radius field is defined for each office depending on the size of the office. Data in this table is used by the IA to determine the device’s distance from the corresponding office. The radius length is used for calculating the occupancy result (OR).</td>
</tr>
<tr>
<td>Map (P)</td>
<td>This table contains all the RSS values measured from the 3 APs found for the environment mapping simulations. This map data is used by the IA in the localisation phase where the position of a simulated device is estimated by use of RF fingerprinting techniques.</td>
</tr>
<tr>
<td>Sim (F)</td>
<td>In this table, the details for each simulation as entered from the parser interface is stored. This table provides an identifier for each loaded simulation file that is used by all other modules when working with the data of a specific simulation.</td>
</tr>
</tbody>
</table>
The RSSI table is used for storing data extracted from the simulation files. This table defines a row for each received broadcast message with fields to store data relevant to the sending node, the receiving AP, the measured RSS, the actual position coordinates and the time in the simulation that the message was received. The RSS and node data is then used by the IA for localisation purposes, and the positioning data for determining the error of the implemented localisation techniques.

This table is considered the most important table of all and contains all results obtained from localisation and occupancy determination processes. The table includes fields for storing localisation coordinates and errors for the three location estimation techniques, occupancy data such as the distance of the device from its corresponding office location, the time the device is located in a specific zone and the final occupancy result. The data represented in this table is parsed to both the visualisation unit and the graphing and statistical units of the IA.

This table contains configuration data for the statistical unit. This data defines the fields of the Master table for which statistics should be calculated, whether the statistic should be calculated per device, per simulation or for both. Text headers for the calculated parameters are also defined for the display purposes.

The TempDev table was created to add convenient means of grouping all devices used in a particular simulation; this table was then adjusted to also store some preliminary device specific statistics. The data in this table is used by the statistical unit for further overall statistical calculations.

This table contains values for the statistical calculations as performed by the statistical unit and includes fields for maximum and minimum values, median and mean values, standard deviation, quartiles and variance. The data from this table is presented along with various graphs on the IA results interface.

The tables as presented above can be categorised into three groups namely preconfigured tables (P), functional tables (F) and additional tables (A).

### 3.6.1 PRECONFIGURED TABLES (P)

These tables are configured in the pre-phase prior to the IA initialisation. The information stored in these tables is required by the IA for processing data from scenario simulations. In Table 3.17 preconfigured tables are be identified by (P) these include the mapping table, the AP table and tables for registered occupant detail. To give better insight into the relation of registered device to occupants, and occupants to office locations, a detailed relation is provided in table format in Appendix D.

### 3.6.2 FUNCTIONAL TABLES

These tables are actively used by the IA throughout the implemented localisation and occupancy determination processes and are tasked with storing data for each of these process phases in a suitable format.
3.6.3 ADDITIONAL TABLES

Addition tables are used for the configuration of processes that are implemented by the IA module such as the configuration data found in the GetStat table.

Having looked at the setup of the created database and the data represented in its various tables the next step in this implementation is explaining the developed IA module. This critical module is tasked with doing the actual processing of simulation data to transform it into usable occupancy information. The IA module will be discussed in detail in the next section.

3.7 INTELLIGENT AGENT DESIGN

This highly complex module constitutes the novelty factor of the conducted research experiment by transforming regular location information into usable occupancy information to aid in building energy management.

The IA was developed by the use of several programming languages and applications. This included HTML, PHP, MySQL, JavaScript, Json, HTML5 Canvas and the FusionCharts suit.

The agent module like the parser was created to provide a web-based interface. All complex process was handled behind the scenes with the results thereof being shown in the agent interface.

3.7.1 IA FUNCTIONAL FLOW

The created IA is composed of a range of functional modules; this is illustrated in Figure 3.16 below. This figure represents the high-level function flow of the IA, each of the modules and their process flows will also be presented and discussed in detail.
As seen from Figure 3.16, the IA follows the shown flow process for each broadcast message received from an AP. Information for the broadcast message such as the RSS readings for the three AP, the AP coordinates and the actual physical position coordinates of the sending device is extracted from the relevant database tables. This data is then sent to the localisation unit for processing.
3.7.1.1 Localisation Unit – Module B

This unit performs device localisation by implementing three different location estimation techniques. These are trilateration and two different RF fingerprinting techniques. The implemented fingerprinting techniques both make use of the nearest neighbour method for matching the live values to mapped positions.

The nearest neighbour approach was implemented differently for each RF fingerprinting approaches. In the first approach, an unconstrained search of the map is implemented and in the second constrained search space mapping is used. An estimated device position is then found by each of the three location estimation techniques.

The localisation module also measures the execution time of each of these three implemented algorithms in order to investigate algorithm performance. This data is sent to the graphic and statistical unit for performance result generation. The three implemented location estimation techniques will now be presented in detail.

3.7.1.1.1 Trilateration Estimation – Unit B1.1

The trilateration estimation technique requires ranging to be performed to translate the measured RSS of the three APs to the distance.

In order to do this the reference path-loss, previously determined as -20.4183 dBm, was used in equation 2.3. The calculated distances along with the coordinates of the three APs were used in equations 2.17 and 2.18 to calculate the position of the PoI or WiFi device.

This location estimation process requires RSS readings from all three reference nodes (APs) and was thus not implemented for cases where fewer APs were able to detect a device. The flow of this process is illustrated in Figure 3.17 below.
Experimetal Implementation

Figure 3.17: Trilateration Estimation Process

*Unconstrained Nearest Neighbour – Unit B1.2*

In this implementation of the nearest neighbour approach, an unconstrained search space was used. This entails that the entire RF map as presented in the Map database table is searched for the value closest to the live RSS values measured by the three respective APs. The closest matched value is determined by finding the smallest Euclidean distance (equation 2.21) between the live and mapped values.

Situations where two APs detect the device in question were handled by determining the Euclidean distance only for two pairs of live and mapped values. This is also true for situations where only one AP detects the device, in which case the Euclidean distance is determined only for one pair of live and mapped RSS values.

In this implementation the 5 closest, mapped RSS values were found, and their corresponding coordinate values extracted. The estimated location of the device is then calculated by finding the average $X$ and $Y$ values for the determined five closest coordinate pairs. This process is illustrated below.
Constrained Nearest Neighbour – Unit B1.3

In this unit, a constrained nearest neighbour approach is implemented where the map search space is constrained by defining an RSS search range for each AP. This is done by setting a top and bottom limit for the searched RSS. A fixed value of 1 was added too, and subtracted from the live RSS to form this range.

A MySQL search query is performed to find all the RSS values that fall within the search range. The Euclidean distance between these values and the live RSS values is then determined with the use of equation 2.21. As with the unconstrained nearest neighbour approach the sum of the Euclidean distances is determined for the number of APs detecting the device.

In the cases where less than three APs detect the device an additional measure was implemented. The physical distance between the office centre-point, corresponding to the device, and each of the [x,y] coordinate pairs as determined from the query is calculated.

If this distance is smaller than the defined office radius it would indicate that the queried [x,y] coordinate pair falls within the specific office. If this was the case a fixed value of 0.5 was subtracted from the calculated Euclidean distance for the coordinate pair.
This was introduced to minimise getting lost within the map due to RSS value combinations of wrong positions having a close Euclidean distance match to the actual wanted location.

This is only considered a problem when less than three APs are able to detect the device. This is because the combination of readings from all three APs proves unique for each location although there may be a number of identical readings per individual AP.

This approach would give more probability to mapped RSS and coordinates values found within the office location rather than a close Euclidean distance match found outside the office. Note, however, that this process is implemented only if the device is very close or in its corresponding office location.

After calculating the mentioned adjustment in the Euclidean distance, the position coordinates corresponding the set of RSS map values with the smallest Euclidean distance is used as the estimated position of the device. A representation of this process is given in Figure 3.19 below.
After location estimation has been performed for the device calculations are done to determine positioning errors. This is handled by unit 3 of the localisation module.

**Figure 3.19 : Constrained Nearest Neighbour RF Fingerprinting Process**
Position Error Calculation – Unit B3

This unit of the localisation agent is tasked with performing calculations to determine positioning errors of the estimated device coordinates. In order to do this, the actual position coordinates extracted from the event-logs are used. Performed error calculations include determining the percentage X and Y coordinate error as well as the distance error to indicate the range by which the calculated position is erroneous.

This module adds to the validation and verification process of the localisation module. Comparison of the estimated values with actual values serves to validate the functionality and performance of the implemented localisation algorithms. The process of error calculation is illustrated in Figure 3.20 below.

![Figure 3.20: Position Error Calculation Process](image)

### 3.7.1.2 Occupancy Determination Unit – Module C

The occupancy unit made use of the estimated device coordinates as determined from the constrained nearest neighbour approach. This approach was indicated to be the most accurate of the three implemented location estimation algorithms. This was determined in a preliminary accuracy investigation of the three implemented techniques based on the conducted room scenario simulations. Results of this preliminary analysis are provided in chapter four. Validation of the accuracy of the three algorithms across all simulated scenarios will also be provided in this chapter. This would give an indication if the proper algorithm was selected for use with the occupancy determination unit.

This module transforms the regular location estimation position data into usable occupancy information. This is done by implementing a range of several logical rules. This module takes the estimated device coordinates, coordinates of the corresponding office location and the defined office radius as input.
The first step in this process is to determine if a detected device is the top priority (P=1) device of the occupant in question. If the device is registered as the primary device, the distance of the device from the related office is determined. Depending on this distance, the device is classified to be in one of several zones with respects to the office location.

These zones are defined as in-office, close, far and out-of-office. Furthermore, the time spent in each zone is measured. Timers can be set for both the close and far zones and when this timer elapses the corresponding office’s power status is changed to power down the office. A representation of this occupancy determination process is provided in Figure 3.21 below.

Figure 3.21: Occupancy Determination Process

In Figure 3.21 it evident that if an occupant is located in either the close or far zones, for a period longer than that of the zone’s elapse timer, the corresponding occupant’s office will be powered down. This process then modifies the occupation result (OR) from either 2 (close zone) or 3 (far zone) to 5 as out-of-office. With occupation results ranging from 1 to 3 the occupant’s office remains powered up, when the OR changes to 5 the office is powered down.
Note this approach for the close range is only followed when two or three APs are able to detect a device. When only one AP detects the device the fingerprinting process would be especially inaccurate. This rule is thus not implemented for the close range as to not accidentally power down an occupant’s office if the localisation inaccurately detects an occupant that is actually in-office as being in the close range.

3.7.1.3 Visualisation Unit – Module D

This module provides a visual representation of occupants moving throughout the facility, the presence of occupants in offices and the power status of each office as determined from the occupancy results.

This module makes use of the positioning coordinates and occupation results as determined from the constrained nearest neighbour approach. This approach was selected for use with the visualisation module due to providing the most accurate preliminary localisation results of the three implemented location estimation techniques.

This module was created with the HTML5 Canvas application. All data sent to this application was queried from the relevant database tables and stored in PHP arrays. The arrays were then encoded using the Json encode method to convert the server-side arrays to easily usable client-side JavaScript arrays. These JavaScript arrays were then used to provide the required data to the HTML 5 canvas application. The following screenshot translates the look and feel of the created visualisation unit.

![Figure 3.22 : Screenshot - Visualisation Module](image-url)
The scene as illustrated in Figure 3.22 is a visualisation of a priority device simulation scenario. The simulation was configured to include two nodes; a smart-phone (Cell) node as top priority device and a tablet (Tab) node as secondary device.

In the simulation, the smart-phone node’s initial position was set the centre-point coordinates of office R238 and configured with *CircleMobility* as to represent and occupant leaving for the restroom a distance less than 30m from his/her office located at R207. The secondary Tab device was configured with an initial position of the centre-point coordinates of room R207.

As seen from the screenshot two devices are present, one with a user icon indicating the primary device and occupant position and another labelled P2 to present the secondary Tab device. As derived from the dark blue power-logo above office R207 the occupant/primary device is detected near office R207.

Although the Tab device is located in the office, the occupant is not detected within the office since occupation is based on the primary smart-phone device. The two windows on the right-hand side and bottom of the visualisation confirm that the primary device is located within a range of 30m from the corresponding office location and that the occupant is in close proximity.

This created visualisation unit also contributes to the validation and verification process for the conducted study.

In order to demonstrate the full functionality and potential of the created visualisation unit desktop-record videos were made of some the conducted simulations. These videos are available on the attached disk.

### 3.7.1.4 Graphing and Statistical Unit – Module E

This module was developed for generating performance and accuracy results for the implemented localisation algorithms as well as operational results to analyse the functionality of the implemented experimental VOS.

*Graphing Unit – Unit E1*

The graphing unit of the module was created with the use of HTML, PHP and JavaScript code to provide organised data to the implemented FusionCharts application. This application suite enables the dynamic creation of a wide range of charts and provides easy configuration and string-type data definitions for chart data.

The following table provides detail on the dynamically created charts with respects to chart type and represented data.
Table 3.18 : List of Dynamically Created Graphs

<table>
<thead>
<tr>
<th>Chart</th>
<th>Type</th>
<th>Description</th>
<th>Charted for</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated Coordinates vs. Actual coordinates</td>
<td>Scatter Chart</td>
<td>This XY plot chart shows the position of the estimated coordinates in relation to the actual device coordinates.</td>
<td>Per Device</td>
</tr>
<tr>
<td>Mean percentage coordinate Error per Device</td>
<td>Column Chart</td>
<td>Compares the percentage coordinate error for the X and Y coordinates as determined for each implemented localisation algorithm.</td>
<td>Per Simulation</td>
</tr>
<tr>
<td>Distance error per device move</td>
<td>Line Chart</td>
<td>Shows the distance error between the actual and estimated device locations for all three localisation algorithms for each move of the device.</td>
<td>Per Device</td>
</tr>
<tr>
<td>Mean distance error per simulated device</td>
<td>Column Chart</td>
<td>Compares the mean distance error for the 3 localisation algorithms as calculated per simulated device.</td>
<td>Per Simulation</td>
</tr>
<tr>
<td>Occupation Result per device move</td>
<td>Line Chart</td>
<td>Line chart of the OR for each move of a simulated device.</td>
<td>Per Simulation</td>
</tr>
<tr>
<td>Localisation algorithm execution time per run</td>
<td>Line Chart</td>
<td>Shows the execution time for each of the 3 localisation algorithms for each run of the algorithm in a simulation.</td>
<td>Per Device</td>
</tr>
<tr>
<td>Mean Algorithm Execution time per simulated device</td>
<td>Column Chart</td>
<td>Show a column chart comparison of the mean execution times for each algorithm per simulated device.</td>
<td>Per Simulation</td>
</tr>
</tbody>
</table>

Graphs for all Simulations of a specific scenario

<table>
<thead>
<tr>
<th>Chart</th>
<th>Type</th>
<th>Description</th>
<th>Charted for</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean percentage coordinate Error for all Simulations</td>
<td>Column Chart</td>
<td>This graph shows the percentage X and Y coordinate error as determined for the three localisation algorithms across all simulation of a specific scenario.</td>
<td>All Simulations</td>
</tr>
<tr>
<td>Mean distance error per Simulation</td>
<td>Line Chart</td>
<td>Shows the distance error between the actual and estimated device locations for all three localisation algorithms per simulation of a specific scenario.</td>
<td>All Simulations</td>
</tr>
<tr>
<td>Mean distance error for all simulations</td>
<td>Column Chart</td>
<td>Compares the distance error for the three implemented localisation algorithms for all simulations of a specific scenario.</td>
<td>All Simulations</td>
</tr>
<tr>
<td>Trilateration distance error for all simulations</td>
<td>Box-and-Whiskers Chart</td>
<td>Show a box plot for the distance errors as obtained from each simulation for the trilateration estimation technique.</td>
<td>All Simulations</td>
</tr>
<tr>
<td>U-Mapping distance error for all Simulations</td>
<td>Box-and-Whiskers Chart</td>
<td>Gives a box plot for the distance errors as obtained from each simulation for the unconstrained nearest neighbour mapping technique.</td>
<td>All Simulations</td>
</tr>
<tr>
<td>C-Mapping distance error for all Simulations</td>
<td>Box-and-Whiskers Chart</td>
<td>Show a box plot for the distance errors as obtained from each simulation for the constrained mapping technique.</td>
<td>All Simulations</td>
</tr>
<tr>
<td>Algorithm Execution time for all Simulations</td>
<td>Column Chart</td>
<td>Provides a comparison of the execution time of the three implemented localisation algorithms for all simulations of a specific simulation scenario.</td>
<td>All Simulations</td>
</tr>
</tbody>
</table>
**Statistical Unit – Unit E2**

The statistical unit was created to generate regular statistical parameters such as standard deviation and mean values for all positioning error and algorithm performance data. The data found as output from this process is stored in the database stats table. The following statistical parameters were calculated:

- Mode
- Minimum
- First Quartile ($q1$)
- Median
- Mean
- Third Quartile ($q3$)
- Maximum
- Inter-Quartile Range ($qr$)
- Quartile Deviation ($qd$)
- Variance ($Var$)
- Standard Deviation (Std Dev)
- Variation Coefficient (Var Coeff)

**Figure 3.23 : Statistical Unit Calculations**

The values were calculated in order to create box plots for some of the measured parameters such as the distance error. These plots graphically represent the 5 point statistical summary (min value, first quartile, median, third quartile, max value) as well as mean value and standard deviation. A short description of each calculated statistic is provided in Table 3.19 below:
### Table 3.19: Description of Calculated Statistics

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Name</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode</td>
<td>Mode</td>
<td>Observation with the highest frequency</td>
</tr>
<tr>
<td>Min</td>
<td>Minimum</td>
<td>Smallest observation</td>
</tr>
<tr>
<td>q1</td>
<td>First Quartile</td>
<td>Lower quartile - 25% of observations fall below this value</td>
</tr>
<tr>
<td>Median</td>
<td>Median</td>
<td>Observation in the middle of distribution - 50% of observations fall below this value and 50% fall above</td>
</tr>
<tr>
<td>Mean</td>
<td>Mean</td>
<td>Statistical mean value of all observations</td>
</tr>
<tr>
<td>q3</td>
<td>Third Quartile</td>
<td>Upper quartile (75%) - 25% of observations fall above this value</td>
</tr>
<tr>
<td>Max</td>
<td>Maximum</td>
<td>Largest observation</td>
</tr>
<tr>
<td>qR</td>
<td>Interquartile range</td>
<td>(q3 - q1) The range of observations falling within the center 50% (lower 25% - upper 25%) of the distribution</td>
</tr>
<tr>
<td>qd</td>
<td>Quartile deviation</td>
<td>(qR/2) Measure of absolute dispersion within the range qR</td>
</tr>
<tr>
<td>Var</td>
<td>Variance</td>
<td>Measure of variation of distribution (Average of squared deviation for the mean)</td>
</tr>
<tr>
<td>Std. Dev</td>
<td>Standard Deviation</td>
<td>Measure of spread of the distribution around the mean. (Square root of Variance)</td>
</tr>
<tr>
<td>Var Coeff.</td>
<td>Variation Coefficient</td>
<td>Also known as &quot;relative variability&quot; and represents the ratio of the standard deviation to the mean (Std. Dev/Mean)</td>
</tr>
</tbody>
</table>

The shown mode value is the observation with the highest frequency as mentioned. In cases where more than one mode was identified, the first identified mode value (also the smallest, since sorted data was used for the calculations) was used. This is in line with the way mode calculations are done in spreadsheet programs such as excel.

The statistics calculated by this unit will be delivered in a specific order (Min – Max) to show the spread of the values around the mean. This implies that the values representing by the min, q1, median, q3 and max values of a summarised parameter, should have an increasing magnitude from left to right within the statistical summary table rows. Tables representing the calculated statistics are provided in Chapter 4, the use of these summary tables will be discussed here in section 4.4.1.1.2.
3.8 CHAPTER SUMMARY

In this chapter, all of the critical methods and models that were configured for this experimental implementation of a VOS were detailed. The experimental implementation fulfilled the requirement of making use of existing infrastructure only.

At the beginning of this chapter, the facility was investigated as building model to provide a sense of a real-world implementation to the simulated environment. Detail concerning the investigated facility was provided with respects to the amount of building rooms, occupants and present devices. This data was incorporated into the simulation environment via assumption and configurations decisions made.

Assumptions were also made concerning the devices modelled in the simulations. The main assumption on which all of this research is based is that all building occupants would have a WiFi capable device on their person or in very close proximity at all times. This assumption allows for the physical location of the occupant to be related to the physical position of the device.

After all implementation assumptions were discussed according to the reasoning behind the made assumption, as well as where and how the assumptions would be implemented, the focus was turned to the simulation model configuration.

It was decided to make use of MiXiM implementation of a typical IEEE 802.11 type protocol since these protocols are considered widely used. Furthermore, the MiXiM model does not define a specific IEEE 802.11 protocol but rather provides functionality that is typical of most IEEE 802.11 standard protocols. This allowed for the conducted experiment to be of relevance for a wide range of network configurations.

Three nodes types were configured in MiXiM for the experiment at hand; these were smart-phone (Cell) nodes, tablet (Tab) nodes and AP nodes. All of these nodes shared the same functionality of the MiXiM Host80211 module but could be configured separately. In the conducted simulations, these nodes were configured to make use of different mobility models to simulate movement within the environment. These mobility models provided the actual position coordinates of the moving nodes for calculating position errors in the later phases of the implementation. RSS data for sent broadcast messages were collected from the MiXiM Decider80211 module.

A self-constructed parser was implemented to extract the RSS values and actual position coordinated from the simulation event-logs. The parser module then sorted this data according to related occupant, office location and occupant device as registered with the database in the pre-processing phase.
The last sections in this chapter focused on the functioning of the created intelligent agent. Each of the IA modules and units were presented in detail, and the functional layout of each was graphically presented. Detailed functional layouts were provided for each of the implemented localisation algorithms from which the estimated device coordinates were determined.

The accuracy of these models was determined by calculating position errors for the estimated coordinates. This included percentage coordinate error calculations as well as distance error calculations.

The estimated position coordinates along with the centre-point coordinates of the office location corresponding to the localised device was used for occupancy determination. In this process, the distance at which the device is located from the office location was calculated and classified into proximity zones. The OR was then determined from this.

The localisation and occupancy determination outputs were represented by both the visualisation unit and a graphing and statistical unit.

In the following chapter, the results as outputted by these two modules will be presented. Each of the investigated simulation scenario will be reviewed, and the results obtained from each will be explained in great detail.
4 RESULTS & VALIDATION

In this section, the results obtained from the conducted scenario simulations will be presented. These results will be put forth in the form of a discussion of each scenario, focusing on what the scenario aimed to investigate and whether the expected behaviour could be verified. This is done through statistical analysis of the obtained results and visual confirmation from the visualisation and graphing units.

The simulated scenarios aimed to provide validation of the VOS concept with respects to different tested aspects. This validation and verification process will be discussed in detail in section 4.2. The research process followed for analysing and validating the found results will be presented in the following introduction section.

4.1 INTRODUCTION

Since this is a unique study that entails working with unusual occupancy result data, a process needed to be defined to ensure that analysis of this data is presented in such a way that it will prove relevant for the validation of the developed VOS. In this introduction section, the process followed for analysing and presenting this result data in an applicable format will be outlined and is graphically presented in Figure 4.1.

This figure shows the steps that will be followed for representing the simulation results and the validation and verification of the implemented VOS. This will now be briefly discussed.

Firstly validation and verification of the pre-implementation phases are presented. Thereafter results obtained for the preliminary accuracy analysis of the three selected location estimation algorithms are provided.

The rest of the process will be followed for each of the simulated scenarios and will firstly provide a short section summarising the simulated scenario. Thereafter the aspect the scenario aimed to examine as well the expected outcome is provided.

The next step is to present the results for the individual scenarios by means of graphs and statistical summaries that are suitable to illustrate the investigated aspect. These outputs are provided by the graphing and statistical units. A visual validation of the investigated aspect will also be given by providing screenshots of scenarios as captured from the visualisation unit.

The results will then be discussed in detail with particular attention being paid to the determined outcome and the level of validation and verification provided thereby.
Figure 4.1: Result Analysis Process Outline
Lastly analysis of the overall system functioning and fitness for the indented purpose will be done. This will entail enquiry into the sensitivity and load handling of the VOS model. Furthermore, a final analysis will be conducted to determine the overall accuracy and performance of the three location estimation techniques. This is done to validate the use of the algorithm, as selected in the preliminary analysis, across all scenarios.

All of the above will be discussed in detail with focus on the validated attribute and outcome of the analysis. Indication will then be provided of the overall validity, accuracy and fitness of purpose of the developed conceptual VOS system. This chapter will reach its end with a summary reviewing the main points of focus.

Before starting off with the found results, it is first necessary to have a look at the validation and verification methods that were implemented for the aspects contributing to this proof of concept study.

4.2 VALIDATION & VERIFICATION

In this section, procedures as prescribed by Robert G. Sargent in [47] that were applied for the validation and verification of the VOS is presented. These techniques were implemented throughout the development of the created VOS according to the simple modelling process as illustrated below:

![Figure 4.2: Simplified version of the modelling process [47]](image)

Figure 4.2 defines three main entities, the problem entity, the conceptual model and the computerised model. In this study these entities represent the following:
**Problem entity** – This entity represents the situation to be modelled. In the focus of this research, the problem entity is the concept of a VOS.

**Conceptual Model** – The model serves as a logical representation of the problem entity that is virtualised by the assumptions made for this research.

**Computerised Model** – The model represents a computer implementation of the conceptual model, and was developed throughout the experimental implementation phases.

This simplified version of the modelling process relied on validation and verification to be conducted during the model development phases; this ensures that the created model is fit for its intended purpose.

The terms used for the validation and verification processes in Figure 4.2 are defined as presented by Sargent in [47] and Schlesinger et al. in [48]:

*Model Validation*

“Substantiation that a computerised model, within its domain of applicability, possesses a satisfactory range of accuracy consistent with the intended application of the model” [48].

*Computerised Model Verification*

This verification entails determining if the program of the computerised model and the implementation thereof are both correct.

*Conceptual Model Validity*

Conceptual model validity is established by determining if the assumptions and theories on which the conceptual model is based are correct, and if the created model is a reasonably realistic representation of the problem in terms of the intended purpose.

*Operational Validity*

Operational validity checking is done to validate if the output of the model has sufficient accuracy for the intended purpose and area of application.

*Data Validity*

This concerns ensuring the correctness and fitness of purpose of all data necessary to solve the problem at hand. This includes data needed for development and testing.

In this research, the developed model or VOS was created for the specific purpose (or application) of determining occupancy within a commercial office building. The validity of created model thus needs to be determined with respect to this purpose. The functionality of the VOS model is based on its ability to handle diverse occupant mobility scenarios.
The validity of the model thus needs to be determined with respect to each functional scenario to be able to test the applicability thereof for the intended purpose. In order to do this, evaluations of the various scenarios were conducted until sufficient confidence was obtained that the VOS model is valid for the investigated scenario.

Various subjective and objective techniques exist for evaluating the validity of these scenarios, the overall model, as well as the fitness of purpose. The techniques that were selected for use in this study are shown in the following diagram:

**Figure 4.3 : Model Validation and Verification**

Figure 4.3 will be discussed in detail with respects to how each technique is implemented within this specific study. An explanation of each technique is given in Table 4.1 below, and also offers an indication to the relevance of each of these techniques to the particular study.
Table 4.1: Validation & Verification Technique Description

<table>
<thead>
<tr>
<th>Technique</th>
<th>Description</th>
<th>Relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Animation</td>
<td>Operational behaviour displayed graphically over time.</td>
<td>XXXX</td>
</tr>
<tr>
<td>Event Validity</td>
<td>Comparison of simulation event occurrences to reality or real systems.</td>
<td>XXXX</td>
</tr>
<tr>
<td>Extreme condition testing</td>
<td>Test if model structure and outputs are reasonable for extreme conditions and combinations of factors.</td>
<td>XXX</td>
</tr>
<tr>
<td>Face Validity</td>
<td>Is the model, its behaviour, the logic and input-output relationships plausible and accepted by experts in the field?</td>
<td>XX</td>
</tr>
<tr>
<td>Rationalism</td>
<td>Makes use of logic assumptions to determine validity.</td>
<td>XX</td>
</tr>
<tr>
<td>Operational Graphics</td>
<td>Model performance measures presented graphically over time.</td>
<td>XXXX</td>
</tr>
<tr>
<td>Parameter Variability-Sensitivity Analysis</td>
<td>Change model inputs and internal parameters to determine the effect on behaviour, output and sensitivity.</td>
<td>XXXX</td>
</tr>
<tr>
<td>Predictive Validation</td>
<td>Model is used to predict system behaviour and compared to actual system behaviour to determine if the forecast was correct.</td>
<td>XXXXX</td>
</tr>
<tr>
<td>Traces</td>
<td>Model entity behaviour is traced to determine if the logic is correct and the accuracy adequate.</td>
<td>X</td>
</tr>
<tr>
<td>Statistical Tests &amp; Procedures</td>
<td>Calculating statistical values and presentation of graphs.</td>
<td>XXXXX</td>
</tr>
</tbody>
</table>

As seen from Figure 4.3, the validation and verification process is completed in two phases. The techniques in the first phase are implemented throughout the development of the VOS model. This was done to ensure that the created model is suited for occupancy determination and that all aspects contributing to its creation were validated as the development of the model progressed. This validation and verification phase is the focus of the next section.

4.2.1 VALIDATION & VERIFICATION – DURING DEVELOPMENT (A)

This validation and verification phase constitutes three aspects:

4.2.1.1 Conceptual Model Validation

In this phase validation of implementation assumptions were done with the use of the following two techniques:
4.2.1.1 Predictive Validation

This was done by checking that environmental and implementation assumptions corresponded to a physical commercial office building environment. The made assumption were based on investigation into the facility to ensure the validity thereof.

4.2.1.2 Rationalism

Furthermore, assumptions were made based on logical implementation configurations to rationalise the validity of the created conceptual model.

4.2.1.2 Simulation Data Validity

To determine if the data generated by the OMNeT++/MiXiM simulations can be considered valid, the face validity method was used. This method requires the model (OMNeT++/MiXiM) to be accepted by experts in the field. Since these simulation frameworks are implemented in several accredited research studies, it can be assumed that data generated by these packages is valid.

4.2.1.3 Computerised Model Verification

In this phase verification of the correctness of the generated code and the implementation thereof as a computerised occupancy model is done with the aid of the following two techniques:

4.2.1.3.1 Code Walk Through

This entailed checking the generated code for logical, grammatical and typing errors. This process was executed continuously with the generation of each consecutive code module or added functionality.

4.2.1.3.2 Traces

Traces of the coded functions were done to determine the correctness of the logical functionality of the computerised VOS model. This was also done continuously throughout the model development.
4.2.2 VALIDATION & VERIFICATION OF VOS IMPLEMENTATION (B)

Validation and verification techniques in the second phase are applied to test the validity of the operational behaviour, the correct functioning, and the over model validity of the VOS implementation. This also entailed determining the performance, accuracy and fitness of purpose of the implemented location estimation algorithms.

This process is completed in two stages, first for each scenario and thereafter for overall model.

4.2.2.1 Operational Validity – Simulated Scenarios

Operational validity tests were done to determine if the implemented VOS functions as expected when handling the various scenario simulations, and whether the output suggests sufficient accuracy for occupancy determination. To determine this validity, various subjective and objective techniques were applied.

4.2.2.1.1 Animation Validation

Animation of each simulated scenario is presented by the visualisation unit to show operational behaviour over time. This aids in providing relevant visual confirmation of accuracy and functioning of the model’s operation. This method provides convenient means to validate the operational functioning of the VOS since the movement of occupants, and the effect thereof on the office occupancy and power status, can be visually confirmed.

4.2.2.1.2 Operational Graphics

With this validation technique, several measurements relevant to each scenario are graphically represented over time. A variety of graphs are provided by the created graphing unit for giving indication of the functioning of various measured outputs for each scenario. Only graphs that are considered relevant to the validation of the individual scenario will be presented. Additional result graphs for the scenarios are provided on the attached disc.

4.2.2.1.3 Predictive Validation

This validation is applied for determining the accuracy of the implemented location estimation techniques by comparing the estimated device location to the actual location. The percentage coordinate error and distance error was determined in each case and presented as operational graphics and statistical summaries.
4.2.2.1.4 Event Validity

Event validity was implemented for each simulated scenario by determining if the found outcome was as expected. If a strong correlation was found between the actual and expected behaviour, the tested functionality was considered valid for the particular scenario.

4.2.2.1.5 Rationalism

Rationalism is applied throughout the other implemented validation processes to make a logical decision on whether the found outcome of these techniques is logically sound and valid.

4.2.2.1.6 Statistical Test and Procedures

This validation process was implemented by calculating a range of statistical parameters such as mean, variance and standard deviation for all relevant measurements. This gives an indication to the range and limits of the achievable accuracy of the VOS when handling the specific scenarios.

4.2.2.2 Model Validation – Overall Model

In this phase, the validation process for the overall VOS model is described. The ability of the system to handle extreme conditions, such as large amounts of present occupants and devices, and also the sensitivity of the system when parameters such as the data rate and receiver sensitivity are varied was investigated. These aspects are validated by the application of the following techniques:

4.2.2.2.1 Extreme Condition Testing

Validity of the functioning of the VOS when handling extreme conditions, such as large numbers of nodes, was determined from analysis of operational graphics created for the loading simulation scenarios. If the analysis indicated adequate performance and accuracy with outcome as expected, the VOS was validated for the tested load.

4.2.2.2.2 Parameter Variability – Sensitivity Analysis

As previously mentioned, sensitivity analysis was implemented by conducting simulation scenarios with two different sets of parameters. The first to test functionality with low data rates of 6 Mbps (receiver sensitivity of -86 dBm) and the second with high data rates of 54 Mbps (receiver sensitivity of -68 dBm). The functioning of the system with this implemented parameter variability was investigated for each scenario.
If the VOS functioned with sufficient accuracy and produced outcome as expected for all the scenarios the overall model is considered valid for the investigated sensitivity range.

4.2.2.3 Operational Graphics

Operational graphics will be analysed for parameters as measured across all simulated scenarios to give an indication to the overall system accuracy and performance. This will include analysis of the location estimation errors for the three techniques and the execution time of each. If a sufficient level of accuracy can be identified from this analysis, the overall VOS system would be proven valid for the intended application.

4.2.2.4 Rationalism

As with the scenario validations, rationalism is implemented to make logical decisions on the overall model validity based on presented results.

4.2.2.5 Statistical Tests and Procedures

This validation process was implemented by calculating various statistical parameters such as mean, variance and standard deviation for all measurements that were applicable across all simulation scenarios. This offered an indication into the range and limits of the achievable accuracy of the implemented VOS model. The overall model would thus be considered valid for the intended purpose if a sufficient level of accuracy is indicated by the overall statistics.

This section provided an in depth discussion of the validation and verification techniques that were identified for determining whether the created VOS model is fit for its intended purpose. The application of these techniques was discussed with respects to how they were realised and implemented. In the following section, results as obtained from a preliminary location estimation accuracy analysis are presented.

4.3 PRELIMINARY ANALYSIS - LOCALISATION ALGORITHMS

This preliminary analysis was done before the development of the occupancy determination unit in order to determine which of the three selected algorithms would be most suitable for use. The suitability of each algorithm will be determined based on the achieved localisation accuracy and whether the execution time of the algorithm is considered realistic for this implementation. The analysis made use of the data obtained from the room scenario simulations to test the mentioned aspects. Estimated position coordinates were calculated for each of the three algorithms and compared to actual position coordinates obtained from MiXiM.
The percentage coordinate error and distance error was calculated for each received broadcast message. Furthermore, the execution times of the three algorithms were measured for each performed localisation. This process was repeated for all 38 rooms represented by the room scenarios of both configuration one and two.

As mentioned in the previous chapter, these two configurations offer different maximum communication ranges and coverage of the facility. In order to select the best suited location estimation technique for determining room level occupancy, these differences and the effect thereof on the suitability of the three algorithms needed to be considered. It is thus necessary to revisit the results obtained from the preliminary ranging simulations before a further analysis of the localisation techniques can be done.

The ranging results for configuration one indicated that device movement within all facility rooms could be detected by all three APs. This ensured that all three of the applied location estimation techniques could be used to localise devices for this configuration. Results for configuration two showed that a maximum range of 40 meters is possible, thus entailing that some rooms within the facility would only be detectable by one or two APs. In these cases, implementation of trilateration estimation would not be possible.

In order to determine the amount of APs that would be able to detect a device in a specific office, configuration two room scenario simulations (54 Mbps) were used along with the ranging simulations to create the following coverage map:

![Figure 4.4: Number of Detected APs per Facility Room](image)

As seen from Figure 4.4, only 9 of the 38 rooms are detectable by all 3 APs. Furthermore, 20 rooms are detectable by 2 AP and another 9 rooms are only detected by one AP. This can have a great effect on the accuracy of the implemented VOS, but provides sufficient means for testing the sensitivity of the model.
Keeping this in mind, all three location estimation techniques were analysed for configuration one, while only the two fingerprinting methods were analysed for configuration two. The results of this preliminary analysis will thus first be presented for configuration one and thereafter for configuration two.

4.3.1 CONFIGURATION 1 ANALYSIS – 6 Mbps

The following graphs were created by the graphing unit for this analysis:

![Graphs showing mean percentage coordinate error, mean algorithm execution time, mean distance error per room, and overall distance error for Configuration 1 analysis.](image)

**Figure 4.5 : Overall Operational Graphics - Configuration 1**

Analysis of the chart provided in Figure 4.5.a indicated that as expected the triangulation algorithm performs the poorest of the three with very high percentage $x$ coordinate error. The fingerprinting algorithms perform exceptionally well with mean coordinate error values of less than 5% when compared to the actual positions of simulated devices.

The graphs comparing the calculated distance errors of the three algorithms in Figure 4.5.c and Figure 4.5.d also indicate that triangulation estimation would be the least accurate method to implement for occupancy determination.
Furthermore, these graphs both show that the constrained nearest neighbour mapping approach is the most accurate of the three and will be best suited for implementation with occupancy determination.

To further validate the selection of this algorithm, box-and-whisker plots were generated for the distance error of each of the three location estimation techniques. This provides a visual representation of the spread and standard deviation of the found errors from the calculated mean.

As seen from Figure 4.6, the boxes created from the distance error data of each of the specific rooms vary greatly, and produce an uneven distribution with an intense variance in the mean value. Furthermore, the trilateration distance errors follow a skewed distribution around the mean. This distribution seems to be positively skewed for some rooms and negatively skewed for others.

Since the calculated distance error represents the accuracy of the algorithm, the large variance of the mean value and skewed distribution of data around this mean, indicate that the trilateration estimation technique would be very inaccurate for determining room occupancy.
The box-plot of the unconstrained nearest neighbour mapping algorithm is analysed next. In the analysis of the operational graphics above in Figure 4.5, this algorithm performed second best.

![Box-plot Unconstrained Nearest Neighbour Mapping - Configuration 1](image)

**Figure 4.7 : Box-plot Unconstrained Nearest Neighbour Mapping - Configuration 1**

The mean value of this technique seems to be more evenly distributed, but also indicate a skewed distribution around the mean. The individual distributions are mostly negatively skewed indicating that the majority of calculated distance errors are below the mean value.

The sizes of the individual boxes appear longer in comparison to the trilateration estimation plots. This indicated a larger error distribution with a significant range between the minimum and maximum distance errors.

Since the found distance errors are all less than 6 meters with an average mean value of approximately 1.8 meters, this technique should prove viable for the implementation of occupancy determination.

Lastly, the constrained nearest neighbour mapping algorithm will be analysed. According to the simple mean distance error bar chart in Figure 4.5 this technique showed the most promise. If the analysis of the following box-plot can verify this assumption, the technique in question would be applied for occupancy determinations.
The boxes presented in Figure 4.8 are very evenly distributed, indicating that there isn't significant variance in the range or mean values of the calculated distance errors. Furthermore, the data represented by the individual boxes seem to be evenly distributed around the mean value in most cases. This indicates that the accuracy of this technique does not vary significantly for different locations within the facility, unlike trilateration estimation.

Figure 4.8 also indicates that all constrained mapping distance errors fall within a range of three meters with an approximate mean value of 1 meter.

This box-plot thus verifies the assumption that the constrained nearest neighbour mapping approach would be best suited for implementation with occupancy determination for configuration 1.

As a last validation, a statistical summary of the three techniques are provided:

| Statistical Summary - 3 Location Estimation Techniques |
|---------------------------------|-----------|-----------|-----------|
| Trilateration Distance Error (m) | 14.14     | 13.28     | 3.64      |
| Unconstrained Mapping Distance Error (m) | 1.8     | 0.84     | 0.92      |
| Constrained Mapping Distance Error (m) | 1.04     | 0.17     | 0.41      |
Table 4.2 above confirms that the constrained nearest neighbour mapping algorithm is the most accurate of the three.

The mean distance error for this technique across all rooms in the facility is only 1.04 m with a standard deviation of 0.41 m. This level of localisation accuracy would surely prove ample for the use of room-level occupancy determination.

Having looked into the accuracy of the three location estimation algorithms, it is now necessary to analyse the execution times of each. This is done to make a trade-off between the accuracy and fitness for real-world implementation. The mean algorithm execution time for each technique as measured across all room scenario simulation was given as part of the overall operation graphics in Figure 4.5.

As seen in Figure 4.5.b, trilateration estimation has the fastest execution time of the three algorithms. This would make the algorithm specifically suitable for implementation in scenarios where network resources are scarce. Unfortunately, the accuracy of this algorithm is not sufficient enough to make the fast execution time an attractive aspect.

The mean execution time of the unconstrained nearest neighbour mapping approach is very long as expected. This is due to the whole RF map being searched to find the entry with the smallest Euclidean distance. This long execution time makes this algorithm less suitable for implementation.

Lastly, the very accurate constrained nearest neighbour mapping algorithm shows a very promising mean execution time of about 4.25 milliseconds. This combination of fast execution and high accuracy makes this approach the overall best suited for implementation with occupancy determination.

Having done this preliminary analysis for the 6 Mbps configuration, this process needs to be repeated for the 54 Mbps configuration. The results found from this analysis are presented in the following section in the same fashion.

4.3.2 CONFIGURATION 2 ANALYSIS – 54 MBPS

The previously conducted ranging simulation results indicated that trilateration estimation would not be implementable for the 54 Mbps configuration, consequently only the two RF fingerprinting techniques are considered in the analysis of this configuration. The following operational graphics were generated:
The graphs in Figure 4.9 will now be briefly explained:

Figure 4.9.a indicates that the mean percentage coordinate error as calculated for the constrained nearest neighbour mapping algorithm is far less compared to the unconstrained approach.

This is also the case for the mean distance error as presented in the graphs in Figure 4.9.c and Figure 4.9.d. The bar chart in Figure 4.9.d shows the constrained approach has a mean distance error of only 1.916 meters. This is very accurate compared to the 8.35 meters achieved by the unconstrained approach. This indicates that the accuracy of the constrained mapping approach would also be best suited for implementation of occupancy determination for configuration 2.

Once again the validity of this assumption will be further examined by analysing the respective distance error box-plots of the two algorithms.
The box-plot of the unconstrained nearest neighbour mapping algorithm indicates that the found distance errors range from zero to about 47 meters. The mean values are distributed rather evenly but indicate greatly deviant mean values for rooms 24 to 36. These rooms are all only detected by either one or two APs.

Lastly, the distance error data seems to be unevenly distributed around the mean, this indicates, as for configuration one, that the majority of found distance errors are below the calculated mean value. Since the range of the distance errors is very large (up to 47m from the actual value) it does not seem adequate for implementation with configuration two occupancy determination.

Analysis of the constrained nearest neighbour box-plot will now commence.
The distance error mean values for this box-plot are also rather evenly distributed with a significant level of variance for rooms 24-26 and 33-38. Furthermore, the range of the errors is much smaller than that of the unconstrained approach with a maximum distance error of less than 10 meters.

The errors for the individual rooms seem more evenly distributed around the mean value than those of the unconstrained case.

Analysis of these two box-plots thus also show that the constrained nearest neighbour algorithm would be best suited for occupancy determination. A statistical summary of the two algorithms is presented to give final validation of the algorithm selection.

<table>
<thead>
<tr>
<th>Statistical Comparison - 54 Mbps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Unconstrained Mapping Distance Error (m)</td>
</tr>
<tr>
<td>Constrained Mapping Distance Error (m)</td>
</tr>
</tbody>
</table>

Table 4.3 above confirms that the constrained nearest neighbour mapping approach is the most accurate. The mean distance error for this technique across all rooms in the facility is only 2.01 m with a standard deviation of 1.88 m. The unconstrained approaches, as expected, indicates a high level of variance that is not suitable for occupancy determination with this configuration.

This then validates that the constrained nearest neighbour approach is best suited, accuracy wise, for the purposes of occupancy determination with configuration two.

The trade-off between execution time and accuracy is determined by analysing Figure 4.9.b. This graph shows the mean execution time of the constrained mapping algorithm as 4.65 ms and the unconstrained mapping as 97.98 ms. As expected the constrained approach offers much faster execution.

This makes the constrained nearest neighbour mapping algorithm the best suited approach, both accuracy and execution time wise, for the implementation with occupancy determination for configuration two.

### 4.3.3 CROSS-CONFIGURATION SUMMARY

In this section, a preliminary analysis of the three selected location estimation techniques was conducted to determine which is best suited for implementation with the occupancy determination unit. In this analysis, the accuracy and execution time of the algorithm were compared, and box-plots for each were interpreted.
The result of this analysis was that the constrained nearest neighbour mapping algorithm is best suited for configuration 1 and configuration 2, both accuracy and time wise. This algorithm was then implemented in the created occupancy determination unit.

Although only one of the three location estimation techniques could be implemented for occupancy determination, the performance and accuracy of all three techniques were measured over all the conducted simulations. A brief summary of these measurements will be presented in the overall model validation section of this chapter.

In the following sections, the result of the scenario simulations will be presented. The outcome of applied validation and verification techniques will also be detailed for each scenario.

4.4 SCENARIO SIMULATION RESULTS

In this section, the detailed results and the explanations thereof will be presented for each investigated scenario. This will include a short description of the scenario, what the scenario aimed to investigate as well as the expected outcome of each case. Results will then be provided and interpreted to determine if the outcome correlates with the expected outcome.

With the scenario simulations, individual results are provided for one room or sub-scenario, where after results for the entire scenario will be presented. Only the most relevant graphs and statistic are shown in this chapter. To see all graphs and statistics created for a scenario, please refer to the attached disc.

4.4.1 ROOM SIMULATIONS

Room simulations were conducted for each of the 38 labelled rooms within the facility as described in section 3.4.4.1. This simulation scenario aimed to test if the VOS is able to detect in-office occupancy events for all rooms of the facility.

The excepted system behaviour includes the following:

1. In the visualisations, each simulated occupant should be within his/her office location, and the power status symbol should remain green the entire time.

2. All occupation results (OR) should be constant at level one for the entire simulated time. Thus entailing that the distance from the office (office centre-point) is less than the defined office radius. The maximum defined radius of an office can be up to 8 meters.

3. No timer should elapse – causing the OR to change from one to five and the office to power down.
Results for the conducted room simulations will be provided first for the 6 Mbps configuration and thereafter for the 54 Mbps configuration. Each of these configurations will be represented by results for the simulations of one room as well as overall scenario results.

4.4.1.1  Configuration 1 – Room Scenario Simulations

4.4.1.1.1  Specific Room Simulation Event – R233

The results presented below were obtained from the room simulations done for R233. The following figure shows a screenshot of the visualisation unit animating this scenario:

![Figure 4.12: Room Scenario Simulation - R233](image)

Investigation into this visual representation in Figure 4.12 revealed the following:

- The occupant is in-office – This is seen from the map, and is confirmed by the occupancy result in the bottom occupant bar as well as in the right-hand side office information bar.
- The power status of the office is in powered up mode, indicated by the green power icon.
This gives a visual validation of the VOS being able to correctly handle occupants located in R233. The same was found for all other rooms within the facility for configuration 1.

Graphs created by the IA’s graphing unit that are relevant to room simulation scenario are now presented for R233:

![Graphs](image)

**Figure 4.13 : Room Simulation Scenario - R233 Operational Graphics**

In Figure 4.13.a, the distance of the device from the office centre-point is graphed over the number of device movements for the simulated time. This graph indicates that the maximum distance from the office was less than 1.6 meters. This falls well within the bounds of the maximum distance of 8 meters needed to classify the occupant as in-office. This aids in the validation of the second expected outcome of this scenario.

This distance is then related to the occupancy result (OR) as described in the previous chapter. In Figure 4.13.b, it can be seen that the OR remains constant at a level of one over the entire the simulation.
Thus once again validating expected outcome two and also expected outcome three since the OR was not altered by the elapse of a timer. If a timer had elapsed, the OR should have changed from one to five.

The investigated principles and outcomes as discussed for the room simulation scenario of R233 were also found to be true for all other simulated room scenarios within configuration one.

4.4.1.1.2 Overall Room Scenario Results – Configuration 1

The following statistics were obtained from the IA’s statistical unit across all the conducted room scenario simulations for the 6 Mbps configuration:

| Table 4.4: Statistics across all Room Scenario Simulations - 6 Mbps Configuration |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mode | Min | q1 | Median | Mean | q3 | Max | qR | qd | Var | Std. Dev | Var Coeff. |
| C-Mapping percentage [x] Error (%) | 0.02 | 0.01 | 0.65 | 1.42 | 2.74 | 2.86 | 22.22 | 2.21 | 1.11 | 15.57 | 3.98 | 145.62 |
| C-Mapping percentage [y] Error (%) | 0.08 | 0.08 | 0.67 | 1.66 | 1.9 | 2.74 | 7.51 | 2.07 | 1.04 | 1.95 | 1.4 | 73.74 |
| C-Mapping Distance Error (m) | 0.15 | 0.14 | 0.79 | 1 | 1.04 | 1.29 | 3.02 | 0.5 | 0.25 | 0.17 | 0.41 | 39.26 |
| C-Mapping Execution Time (ms) | 3.08 | 3.07 | 3.73 | 4 | 4.26 | 4.47 | 16.62 | 0.74 | 0.37 | 0.89 | 0.94 | 22.18 |
| U-Mapping percentage [x] Error (%) | 0.01 | 0.01 | 1.02 | 2.2 | 4.68 | 4.73 | 58.75 | 3.72 | 1.86 | 57.09 | 7.56 | 161.56 |
| U-Mapping percentage [y] Error (%) | 0.03 | 0.02 | 1.52 | 3.17 | 3.58 | 5.04 | 14.74 | 3.52 | 1.76 | 6.93 | 2.63 | 73.64 |
| U-Mapping Distance Error (m) | 0.1 | 0.1 | 10.6 | 1.75 | 1.8 | 2.33 | 5.35 | 1.27 | 0.64 | 0.84 | 0.92 | 51.1 |
| U-Mapping Execution Time (ms) | 96.42 | 96.42 | 99.94 | 101.04 | 103.33 | 103.68 | 160.44 | 3.74 | 1.87 | 39.84 | 6.31 | 6.11 |
| Trilateration percentage [x] Error (%) | 0.55 | 0.08 | 20.29 | 27.92 | 30.62 | 31.28 | 78.72 | 11 | 5.5 | 356.3 | 18.88 | 61.64 |
| Trilateration percentage [y] Error (%) | 0.34 | 0.34 | 10.91 | 15.92 | 17.25 | 22.21 | 43.22 | 11.3 | 5.65 | 78.09 | 8.84 | 51.24 |
| Trilateration Distance Error (m) | 4.21 | 4.1 | 11.2 | 15.22 | 14.14 | 17.13 | 20.36 | 5.93 | 2.97 | 13.28 | 3.64 | 25.77 |
| Trilateration Execution Time (ms) | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.23 | 0 | 0 | 0 | 0 | 0.01 | 39.72 |
| Distance from Office (m) | 0.5 | 0 | 1 | 1 | 1.12 | 1.1 | 1.12 | 3.16 | 0.12 | 0.06 | 0.15 | 0.39 | 35.28 |
| Occupation Result (OR) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |

The statistical summary represented in Table 4.4, is that produced by the statistical unit as described in section 3.7.1.4. The values in this table and other statistical summary
4 RESULTS & VALIDATION

tables found in later sections of this chapter should be read row by row; from left to right e.g. the statistics matching the C-Mapping percentage [x] Error (%) heading is provided in the row directly below. These calculated statistics can be read of from the table by matching it with the statistical identifier headings in the first table row.

The most important statistics as provided in Table 4.4 are once again the occupation result and distance from office location. As seen from this table, the occupation result (OR) remained constant with a value of one for all of the 38 conducted room simulation scenarios. This is reflected by the values of all fields, from the minimum value to the maximum value being one, and also by the statistics such as the standard deviation and variation coefficient being zero, indicating that no variation was identified in the occupancy result distribution. This validated the functioning of the VOS to correctly identify in-office occupation events for all rooms within the first configured environment.

The calculated distance from office has a statistical mean of 1.1 meters with a standard deviation of 0.39 meters. This indicates that the created VOS can handle in-office occupation events with good accuracy for the 6 Mbps configuration.

4.4.1.2 Configuration 2 – Room Scenario Simulations

4.4.1.2.1 Specific Room Simulation Event – R214

The results presented below were obtained from the room simulations done for R214. This location is detectable by two APs and was identified from the box-plot in Figure 4.11 as a unique case with large variance in the found distance error. The following figure shows a screenshot of the visualisation of this scenario:
Investigation into this visual representation in Figure 4.14 revealed the following:

- The occupant is visually located a few meters from office R214 due to fluctuation in localisation accuracy identified for this particular office.
- The occupant’s occupation result is registered as in-office – This is indicated by the OR in the bottom occupant information bar as well as in the right-hand side office information bar.
- The power status of the office is in powered up mode, indicated by the green power icon. This validates expected outcome one.

This gives a visual validation of the VOS being able to correctly determine room-level occupancy for R214 even with reasonably inaccurate location estimation results. The same was found for all other rooms within the facility for configuration two.

Graphs relevant to this scenario as created by the developed graphing unit are now presented for R214:
In Figure 4.15.a, the distance of the device from the centre-point of R214 is graphed over the movements of the device. This graph indicates that the maximum distance from the office was less than the 8 meter threshold value needed to classify the occupant as in-office. This contributes to the validation of the second expected outcome of the room scenario simulations.

The occupancy result (OR) as determined from this distance is presented in Figure 4.15.b. This line graph indicates that the OR remains constant at a level of one over the simulation. This indicates that no zone timer had elapsed, and validates expected outcome two and also expected outcome three of the room simulation scenarios.

The investigated principles and outcomes as discussed for the room simulation scenario of R214 were also found to be true for all other simulated room scenarios within configuration two.
4.4.1.2.2 Overall Room Scenario Results

The following statistics were obtained from the statistical unit across all the conducted configuration 2 room scenario simulations:

Table 4.5: Statistics across all Room Scenario Simulations - 54 Mbps Configuration

<table>
<thead>
<tr>
<th>Mode</th>
<th>Min</th>
<th>q1</th>
<th>Median</th>
<th>Mean</th>
<th>q3</th>
<th>Max</th>
<th>qr</th>
<th>qd</th>
<th>Var</th>
<th>Std. Dev</th>
<th>Var Coeff.</th>
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<td>0.86</td>
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<td>18.33</td>
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<tr>
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<td>2.01</td>
<td>2.13</td>
<td>9.47</td>
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<td>3.53</td>
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<td>[y] Error (%)</td>
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</tr>
<tr>
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<td>2.92</td>
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<td>4.02</td>
<td>4.71</td>
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<td>[y] Error (%)</td>
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<td>(m)</td>
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<td>1.5</td>
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<td>0</td>
</tr>
</tbody>
</table>

Once again the most important statistics found in Table 4.5 is the occupation result and distance from office location.

As seen from this table the occupation result (OR) remained constant with a value of one over all 38 conducted room simulation scenarios, and the statistics for the standard deviation and variation coefficient once again being zero all round, indicates that no variation was present in the occupancy result distribution for configuration two.

The calculated distance from office over all the room scenarios has a statistical mean of 2.11 meters with a standard deviation of 1.76 meters. Furthermore, the maximum logged distance is shown to be 7.81 meters. This falls within the bounds of the maximum defined office radius for registering in-office events.

This indicates that the VOS can correctly register in-office events for all room simulation scenarios with the 54 Mbps configuration.
4.4.1.3 Cross-Configuration Validation Outcome

In this section, the functioning and accuracy of the created VOS were analysed for the room simulation scenarios of both configurations. The validation methods applied for testing the behaviour of the VOS when presented with in-office events have provided the following outcome:

- The created VOS can correctly identify all in-office occupation events for both configurations.
- The calculated OR remained constant over all room scenario simulations.
- All distances from the respective office locations were within bounds to register in-office events.
- No zone timer elapse was registered in any of the scenarios.

Since all the found outcome correspond to the expected outcome, it can be subjectively rationalised that the VOS functioning and implementation is valid for all configuration one and configuration two room scenario simulations.
4.4.2 MULTI-OCCUPANT SIMULATIONS

This scenario aims to expand the conducted room simulation scenario by introducing multiple occupants for a single office location. In these scenarios, several occupants were simulated to register in-office events for the various multiple occupant rooms of the facility; the setup configurations for these scenarios were presented in section 3.4.4.2.

The scenario aimed to investigate the same principles as the room simulation scenarios with a multiple occupant scale. Furthermore, investigations included determining if the VOS is able to distinguish correctly between multiple devices. These scenarios would also give an indication to if the VOS sensor can function sufficiently with strong interference of closely grouped devices.

The simulations were conducted to model 2, 3 and 4 occupants in various rooms, the specific configuration is provided in the table below:

<table>
<thead>
<tr>
<th>Case</th>
<th>Room</th>
<th>Devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Occupants</td>
<td>R225</td>
<td>Cell 25, Cell 39</td>
</tr>
<tr>
<td></td>
<td>R227</td>
<td>Cell 27, Cell 40</td>
</tr>
<tr>
<td>3 Occupants</td>
<td>R232</td>
<td>Cell 32, Cell 44, Cell 46</td>
</tr>
<tr>
<td></td>
<td>R233</td>
<td>Cell 33, Cell 46, Cell 47</td>
</tr>
<tr>
<td></td>
<td>R235</td>
<td>Cell 35, Cell 51, Cell 52</td>
</tr>
<tr>
<td>4 Occupants</td>
<td>R231</td>
<td>Cell 31, Cell 41, Cell 42, Cell 43</td>
</tr>
<tr>
<td></td>
<td>R234</td>
<td>Cell 34, Cell 48, Cell 49, Cell 50</td>
</tr>
<tr>
<td></td>
<td>R236</td>
<td>Cell 36, Cell 53, Cell 54, Cell 55</td>
</tr>
</tbody>
</table>

The excepted system behaviour includes the following:

1. In the visualisations, all simulated occupants should be within the same specific office, and the office should remain powered up during the entire scenario. This should be indicated by the power status symbol remaining green.

2. The occupation result (OR) of all device should remain constant at a level of one for the entire simulations. Thus entailing that the distance of the devices from the corresponding office location is less than 8 meters.

3. No timer elapse should occur – This will be derived from the OR remaining constant.

Only a single screenshot is provided for these scenarios as to avoid being repetitive. The following screenshot, showing 4 occupants in room R231, is representative of all the conducted multi-occupant simulation scenarios.
In Figure 4.16 above, it can be seen that the visualisation agent creates an identifiable occupant-image for each present occupant. Investigation into all the created visualisations, graphs, and statistics, proved that the VOS can correctly identify all configured simulated devices. Furthermore, the information bars in Figure 4.16 indicated that all occupants are present in the office location. The power status symbol of the office is green, thus meaning that the office R231 remained powered up.

Screenshots of all other simulated cases can be found on the attached disk. These results all show that the individual offices remain powered up during the entire simulated time. This is true even when interference is presented by the closely grouped nodes.

The simulated scenarios will now be investigated by providing occupancy results for each of the cases.
4.4.2.1 Configuration 1 – Multi-Occupant Scenario Simulations

In this section, the multi-occupant scenario simulations will be analysed and discussed for the three cases (2, 3 or 4 occupants) of configuration 1.

![Occupancy Results - 3 Multi-Occupant Cases (Configuration 1)](image)

Figure 4.17: Occupancy Results - 3 Multi-Occupant Cases (Configuration 1)
In Figure 4.17.a, it is confirmed that the occupancy result remains constant the entire simulated time in this two occupant case. The distance from office is thus less than 8 m for the entire simulation, as expected for an occupancy result of one. Furthermore, the power status symbol indicated that the office was power-up throughout the scenario.

The occupants in this scenario did not seem to have a significant interference effect on each other. Lastly as expected no timer-elapse occurred for any of these two occupant cases.

The occupancy results of the three device case as shown in Figure 4.17.b indicates two peaks, one for Cell[32] and one for Cell[45]. This is due to the device’s measured distances from the office location fluctuating. This fluctuation could signify interference in this stage of the communication. Investigation of the simulation event-logs revealed that an error had occurred with the reception of a packet at AP[1]. This caused the RSS to drop approximately 10 dBm from its average value for the specific location. Analysis of similar cases indicated the same error occurrence.

Although the occupation result peaked due to the presented interference, the office location was not powered down, and the occupation result stabilised. It was determined that the VOS was able to correctly determine the occupancy result 98% of the time for the three occupant configuration one cases. This indicated that the VOS functions with sufficient accuracy in the presence of minor interference.

This interference is also present in the four occupant case of office R236. Here only one peak is detected. The occupancy result of this scenario also stabilised back to one and the corresponding office was not powered down.

This analysis showed that the implemented VOS can correctly identify multiple occupant devices within a single enclosed room. The VOS functions sufficiently with the small amount of introduced interference and congestion created in MiXIM environment. Statistical analysis of all multiple-occupant configuration one scenarios showed a statistical mean OR of 1.01 with a standard deviation of 0.11. All simulated devices were registered as in-office, no offices were powered down and no timer-elapse occurred.

This then validates the VOS function for multiple occupants within the configuration one environment.
4.4.2.2 Configuration 2 – Multi-Occupant Scenario Simulations

Analysis for this configuration will also be done as above. The occupancy results of three multi-occupant scenarios for rooms R227, R231 and R234 are presented below:

Figure 4.18: Occupancy Results - 3 Multi-Occupant Cases (Configuration 2)
In all three graphs of Figure 4.18, the occupancy result of the respective offices remains completely constant with a value of one across the entire simulated time. This is much more accurate than expected from an environment making use of faster data rates and lower sensitivity. This unexpected accuracy is due to the adjustment made to the Euclidean distance to find the closest RSS mapping value from the RF fingerprinting map. This adjustment was implemented for configuration two scenarios to improve on the position estimation accuracy when a device is only detectable by one or two APs. Note this implemented method only boosts localisation accuracy for a specific occupant in relation to his/her specific office. It is expected that it would have the opposite effect when occupants are outside of the in-office threshold distance. This is investigated in the section 4.4.3 of this chapter.

All configuration two simulations conducted for this scenario delivered similar outcome with the occupation result remaining constant at a level of one, all distances from the respective office locations remaining under the threshold value, and no timer-elapse occurrences were registered. The calculated statistical mean of all occupancy results was determined as 1 with a standard deviation of zero. Furthermore, interference between closely grouped devices was not reflected in the found occupancy results due to the efficiency of the implemented Euclidean distance adjustment.

The above validates that the created VOS is especially accurate at determining in-office events for multiple occupants within a configuration two environment, and functions correctly and adequately for this purpose.

### 4.4.2.3 Cross-Configuration Validation Outcome

In this section, the functioning and accuracy of the VOS were analysed for multi-occupant simulation scenarios with both configurations. The validation methods applied for testing the behaviour of the VOS when presented with in-office events have provided the following outcome:

- The created VOS can correctly identify all in-office occupation events for both configurations.
- The calculated OR remained constant at a level of one for all configuration two scenarios with a few fluctuations for the configuration one scenarios. The overall accuracy was found to be very adequate.
- All distances from the office locations were within bounds to register in-office events.
- No zone timer elapse was registered in any of the simulations.

The outcome of the applied validation techniques corresponds to the expected outcome for the scenario. It can thus be subjectively rationalised that the VOS function and the implementation thereof are valid for all multi-occupant scenario simulations.
4.4.3 PRIORITY SIMULATIONS

This scenario aimed to investigate the handling of multiple devices related to a single occupant as described in section 3.4.4.3. In reality, a building occupant may own several WiFi devices that could be localised for the purposes of occupancy determination. This was implemented by defining smart-phone (Cell) nodes as main priority devices and tablet (Tab) nodes as secondary devices.

These scenario simulations were conducted to test the following functionality of the VOS:

- The occupancy of a room should be determined from location data of the primary device.
- If no primary device is detectable, the VOS should make use of location data from subsequent devices with respect to priority.
- The visualisation unit should provide means of distinguishing between primary and lower priority devices.

In order to investigate the above, two base studies were conducted. The first study was done by simulating both a primary and secondary device of an occupant within the corresponding office. This was done to determine if the VOS and visualisation unit was able to distinguish the devices. The second base study aimed to test the functionality of the VOS if no primary device is detectable, entailing that the secondary device should be used for occupancy determination. The results of these base studies are now presented:

4.4.3.1 Base Study – Priority Scenarios

4.4.3.1.1 Two occupant related devices – In office

This study was conducted for rooms R219 and R233 at both configurations. The following figure shows the most important visual validation aspects of this scenario for R219:

![Figure 4.19: Priority Base Study 1 - R219](image-url)
The first validation that is found for this scenario is given by the device marker for the secondary tablet device in Figure 4.19. This device marker is labelled as P2 to aid in distinguishing between primary and secondary device within the visualisation environment. Like the primary device with the user-icon, this secondary device marker also indicates its corresponding user and office location.

Correct identification of the priority devices is evident for both simulated rooms and configurations. This is validated by the information provided in the detected occupants bar. Here both devices are determined to belong to the same user, Cell[19] is the first priority device and Tab[62] the secondary.

This study aided in validating the base concept and implementation of the use of multiple devices per occupant. The second base study will represent a scenario where no priority device is detectable.

#### 4.4.3.1.2 No Priority Device

This base study scenario was conducted for both configurations and entailed simulating a single secondary tablet device to be located outside of its corresponding office. No primary \((P = 1)\) device is detectable.

The expected outcome of this scenario would entail the following:

- The secondary device should be upgraded to primary device status.
- This should reflect in the visualisation unit.
- The upgraded secondary device should be used for occupancy determination.

The following image depicts the occupant of office R210 roaming with only a secondary tablet device (Tab[59]) in office R215:

![Figure 4.20 : Base Study 2 - No Priority Device](image)

As seen from Figure 4.20 above, the secondary tablet device has been upgraded to a priority one device, both on the map and also in the detected occupants bar.
The right-hand side information bar shows that User 10 is close to his/her office location (R210). This then validates that the secondary device is now used for occupancy determination to reflect the location of the occupant in question.

This ability of the VOS to switch between devices used for occupancy determination, may hold many exciting advances that can be introduced into this system for future implementations. An example of this would be to reconfigure the VOS to determine occupancy using the device that indicates movement.

The correct functioning of the discussed reconfiguration validates the use of the VOS in real-world scenarios where occupants own multiple WiFi devices. Furthermore it validates the ability of the VOS to cope with everyday nuisances like running out of battery life in which case a device would become undetectable.

After having conducted these base studies, more intricate scenarios were simulated to test the implemented priority functionality coupled with ranging and elapsing timer scenarios. This was done to illustrate two cases. The case either showed an occupant roaming with a primary device at a close or far distance from his/her corresponding office. Scenario simulations of these cases were done for both configurations.

4.4.3.1.3 Priority Simulations – Close to Office Location

This scenario was implemented for two rooms with both configurations by simulating a secondary tablet device located in-office, and the primary smart-phone (Cell) device located in another room with a close proximity (< 30 m) to the office location. This scenario aimed to investigate if occupancy is determined from location information of the primary device.

Furthermore, this scenario aimed to test the basic ranging principles implemented for close-to-office events and the timer-elapse accompanied therewith.

The following is expected as relevant outcome to validate the functionality tested in this scenario:

- The occupation result of all secondary tab devices should remain one (in-office).
- The occupation results of the primary smart-phone (Cell) devices should be 2, indicating that the occupant is within a 30 meter range of the specific office location.
- Timer-elapse should occur if the device is located in the close-proximity zone for longer than specified. The timer parameters were adjusted to suit the simulation time of a scenario since this does not correspond to real-life seconds. A zone elapse time of 15s was selected for close-proximity scenarios.
• If an occupant (primary device) is only detectable by one AP and is located in the close-proximity zone, no time should elapse. This was implemented to reduce the chance of wrongfully powering-down an office location due to the limited achievable accuracy when only having one RSS reading for mapping a location.

In this section, the results of the two configurations will be presented together as to be able to do better comparison of the accuracy achievable with each. The screenshot in Figure 4.21 below shows occupant 7 (with office location R207) roaming with the primary device (Cell[7]) in R238 while the secondary device (Tab[58]) remains in-office.

![Figure 4.21: Priority Simulation - Close range R207](image)

From Figure 4.21, it is apparent that the primary device is located a distance from its corresponding office location. This is verified by the two detail bars that indicate that the occupant is within a 30m range of office R207. Furthermore, the power status symbol of office R207 is dark blue, registering a close-to-office event.

This thus validates that the primary and not the secondary device is used for occupancy determination of office R207.

The occupation results as calculated for office R207 and office R227 is presented below for both configurations and will be discussed thereafter.
Figure 4.22 : Occupancy Result - Priority Simulations (Close-proximity)

Figure 4.22.a, shows that as expected the occupancy result of the secondary tablet device remains constant at one to indicate an in-office event. Furthermore, the occupation result of the primary smart-phone (Cell[7]) device reflects its position with respects to office location R207 by registering a close-to-office event with an OR of two. This OR then jumps to five as the zone timer elapses at 15 simulation seconds. This behaviour strongly corresponds to the expected behaviour, thus validating the specific scenario.

Figure 4.22.b presents the same scenario as described above for the configuration two environment. The simulation shows the same behaviour in this environment with the exception of no timer-elapse occurring. This is expected since the primary device is positioned in a location that is only detectable by a single AP entailing that no timer-elapse should occur. This thus validates the last expected outcome of this scenario.

The two bottom graphs of Figure 4.22 show the occupation results obtained for R227 of the close range priority scenarios. In this scenario, the occupant was located in the tearoom (R230) while the secondary device remained in office R227.
The graph of the occupancy result of Cell[27] in Figure 4.22.c, shows various downward peaks. This indicates that a miscalculation was made with the mapping algorithm or interference of some kind was once again introduced into the connection. The occupation result started out as expected and after the elapse of the close zone timer these anomalies were detected.

During the detection of this loss of signal, the office was already power down due to the timer elapsing, thus entailing that this did not have an effect on the power status of office R227. This also indicates that an office that has been powered down is configured to not re-power when an occupant returns or gets closer to the location. Although such functionality would be easily implementable, it was considered more energy-wise to have the occupant manually undertake the task of switching on what is going to be used. In this scenario, the occupancy result was determined correctly 97.4% of the time. This accuracy is considered sufficient for the intended investigation.

In the last graph in Figure 4.22.d the occupation results of the same scenario is presented for configuration two. This graph again verifies the exact expected behaviour and since the location where the primary device is located (R230) is detectable by three APs, zone timer-elapse is implemented. This is once again an interesting scenario where the configuration with higher data rates and lower sensitivity produces more accurate results.

This is not due to the implementation of the Euclidean distance adjustment since this is only done when a possible map value is within the threshold distance of the particular occupant’s office. This has no influence when an occupant is further than this threshold from his/her personal office. The higher accuracy can thus be contributed to the fact that with a lower range of receiver sensitivity applied to all devices less interference would be able to affect the devices.

This section verified the correct functioning of the VOS with primary devices located within a close range from the office location. In the following section, analogous investigations were conducted for far-proximity range priority simulations.

### 4.4.3.1.4 Priority Simulations – Far from Office Location

This scenario was also implemented for two facility rooms and investigation thereof conducted for both configurations. In this scenario, the primary device is located at a range greater than 30 meters and less than 80 meters from the corresponding office location. In relation to the previous section, this scenario aimed to test the basic ranging principles implemented for far-from-office events and the timer-elapse accompanied therewith.
The expected outcome of this scenario is stipulated below:

- The occupation result of all secondary tablet devices should remain constant at a level of one (in-office).
- The occupation results of the primary smart-phone (Cell) devices should be 3 indicating that the occupant is in range to register a far-from-office event (30 – 80 meters).
- Timer-elapsed should occur if the device was located in the far-from-zone for longer than 10s as configured for these specific simulation scenarios.
- The timer implemented for measuring time spent in the far-from-office zone should elapse no matter the number of detected APs.

Figure 4.23 below, shows occupant 22 roaming with a primary device (Cell[22]) in room R237, with the secondary device (Tab[63]) located in the corresponding office location R222.

![Figure 4.23 : Priority Simulations - Far-from-Office - R222](image)

The above screenshot image indicates that the occupant is located far from the specific office location of R222. This is once again verified by the information bars as well as the light blue power status icon. This gives visual confirmation of the correctness of the determined occupancy.

Further validation of the VOS functioning for far-from-office events will be done by investigating the obtained occupancy results.
These results were obtained for the scenario described above as well as scenarios where an occupant of R236 is located in the common area, in front of office R212.

Investigation into the graphs presented in Figure 4.24 once again revealed that better accuracy was obtained for the configuration two results.

The occupancy results for the 2 configuration one scenarios again shows fluctuations at certain instances, indicating that interference was introduced. This interference was detected in both samples for both the occupancy results of the primary and secondary devices. The similarity in the shape of the two configuration one graphs as well as identical levels for fluctuation found in these samples validates that this effect is produced within the MiXiM environment. The VOS functioned correctly with the introduced attenuation, as the occupancy results stabilised and remained constant after the far-from-office zone timer elapsed.

In Figure 4.24.a and b, the occupancy results of both secondary devices remains at a level of one, with the exception of the introduced attenuation peaks that lifted the result to 2 and even 3, indicating close-to-office and far-from-office events respectively. The occupation results of the primary smart-phone devices were on average correctly identified at a level of 3, to register far-from-office events.
The timer elapse is also verified by the occupation result increasing from 3 to 5, to indicate that the occupant has been out of office for a specified amount of time and the office cloud be powered down.

The overall results of the far-from-office scenarios for configuration one indicated that the VOS was able to correctly determine the occupation result 96% of the time.

The configuration two scenarios again seemed to reflect the exact expected outcome. These samples showed no introduced interference and the VOS was able to correctly identify the occupancy results for all measured samples. This accuracy can once again be contributed to less interference being possible with this configuration.

The occupancy results of both the secondary tablet devices remained perfectly constant to register in-office events during the entire scenario. The occupation result of the primary devices reflected the simulated scenario perfectly, and remained within a range of between 30 and 80 meters from the specific office location. The OR thus remained constant at a level of 3 to register far-from-office events.

The timer configured for the far-from-office zone was set to elapse no matter the number of APs that were able to detect the device. As seen from the 2 configuration two scenarios, this timer elapsed in both cases, altering the occupation result to 5 to indicate a power-down event.

This validates the correct functioning of the implemented VOS when handling far-from-office events. Investigation into the found results indicated that these events are handled with sufficient accuracy for both configurations.

4.4.3.2 Cross-Zone Priority Validation Outcome

In this result section the validation of the correct functioning of the VOS was investigated with respects to priority selection and zoning of primary devices.

In the conducted investigation it was found that:

- The VOS can correctly distinguish between devices of different priority.
- The VOS determines the occupation of an office location based on the mobility of the primary device.
- If no primary device is detectable the VOS correctly reconfigured itself to make use of the next priority device for occupancy determination.
- The VOS can register close-to-office and far-from office events based on the primary device with accuracy sufficient for the intended application.
- The different configurations for zone timer-elapse were verified, and it was found that timers are implemented in the expected scenarios, and the outcome of timer-elapse correctly registers a power-down event for a specific office.
Since the outcome of the implemented validation and verification techniques are in line with the expected outcome, it can be subjectively derived that the VOS function, and the implementation thereof, are valid for all configuration one and configuration two priority simulation scenarios.

The final scenario simulations, which aided in the parallel investigation of various functional aspects are presented next. These aspects are incorporated in the common area scenario simulations that represent occupants moving throughout the building environment in the four defined building common areas. Investigations aimed to test the functioning of proximity estimation, occupancy determination, power-management and timer-elsepase when presented in a single complex scenario.

4.4.4 COMMON AREA SIMULATIONS

The common area simulation scenarios were also conducted for both configuration environments and entailed simulating a single occupant moving in each of the four building common areas. The simulation configurations for these scenarios were given in section 3.4.4.4. The areas in question are the two hallways and the two open block areas at either side of the facility.

Simulations of occupants moving in the block areas once again made use of CircleMobility, whilst the hallway simulations were configured with LinearMobility.

These scenarios aimed to test the functionality of the VOS when tracking occupants moving between occupancy zones, such as an occupant moving from close to his/her office, to a location that is classified as far from the specific office. Furthermore, this scenario aided in testing if the occupancy of a room is affected by occupants of other offices walking past.

The results of these scenarios will first be presented for the two block areas and thereafter for the two hallways.

4.4.4.1 Common Area Simulations – Block Areas

These scenarios were analysed for two office locations with each configuration. The first scenario represents the occupant of room R208 roaming with a priority device in the block area in front of R212. The results obtained for this scenario, at both configurations will now be presented.

4.4.4.1.1 Right Side Block Area – R 208

Simulation of this scenario was specifically done for office R208 since the simulated movement of the occupant in the selected common area would vary between close-to-office and far-from-office events with respects to office R208.
This will produce an occupation result that varies between two and three for the mentioned range-zones. This was specifically simulated to test the resetting of zone-timers each time a change in zone occurred.

The resetting of zone-timers is necessary to avoid powering down an office when a large amount of movement is detected for an occupant. This is based on the principle that if an occupant is constantly moving into and out of proximity zones the occupant may return at any time. Hence the timers were reset each time the occupant moved into a different proximity zone with respects to the office location.

The specific expected outcome for the scenario is as follows:

- The occupation result should vary between 2 and 3 to reflect the movement of the occupant through the close and far proximity zones.
- No zone-timer elapse should occur – entailing that the timers were reset each time the proximity zone varied. In these scenarios the close-to-office zone timer was set to 20s and the far-from-office zone timer was set to 10s.

The following visualisation agent screenshot represents this scenario for the occupant of R208:

Figure 4.25: Common Area - Right Side Block R208

Figure 4.25 shows that user 8 of office R208 is located in the right side common area of the facility. The power status symbol, as well as the information bars, indicates that the occupant is in close range. These indications changed when the occupant moved around the lift and then indicated a far-from-office event with a light blue power status symbol.
In order to determine the outcome of this specific scenario, the occupation results and distance from office location will be analysed for both configurations. This is shown in the following figure:

![Operational Graphics - Common Area (Right Side Block) R208](image)

**Figure 4.26 : Operational Graphics - Common Area (Right Side Block) R208**

In Figure 4.26.a and b, the occupation result and corresponding distance from the office location are provided for configuration one. As seen the distance from office R208 varies evenly as the occupant moves with CircleMobility around the lift. The distance varies with a range of about 22 to 33 meters indicating that both proximity zones should be represented in the occupancy result. Furthermore, Figure 4.26.b shows that the device moved into and out of the far-from-office zone twice during the simulated time. This is indicated by the number of times the 30 meter threshold value was crossed.

The above is also reflected in the occupancy result showing that the occupant was in the far-from-office zone (OR = 3) twice. Furthermore, since the occupation result it not switched to 5 during the simulation it can be verified that no timer elapse occurred.

The configuration two results, as provided in Figure 4.26.c and d, show rather different activity. The range of the distance from the office location first appears to be larger with minimums of about 23 meters and maximums of up to 38 meters. Furthermore, it is indicated that the devices crossed the proximity zone threshold several times.
This larger range obtained for configuration two is due to the location of the occupant only being detectable by two of the three implemented APs. The estimated positions of the occupant were thus not as accurate as when determined from RSS measurements from all three APs. Since the occupant’s device was not detectable by AP3, that is located at the opposite side of R208 with respects to the device, this could give indication to the distance from R208 being larger to the right side. Nonetheless, this behaviour is correctly reflected in the occupation result showing that the device crossed out of the close-proximity threshold zone numerous times. As in the in configuration one case no timer-elapse occurred.

This analysis validated the expected outcome for the specific scenario since the occupation result correctly reflected the measured movement of the occupant through the proximity zones and no timer-elapse occurred. This validated the last expected outcome that the timers were correctly reset for each crossing into a different proximity zone.

The next analysis was done for the left side common area block of the facility and entailed simulating the occupant of R229 walking about in this area.

4.4.4.1.2 Left Side Block Area – R 229

The occupant was configured to only move within the far proximity-zone at distances of approximately 43 meters from the corresponding office R229. This was done to investigate ranging for this area for the two configurations.

The scenario is depicted in the visualisation agent screenshot provided below:

![Figure 4.27 : Common Area - Left Side Block R229](image-url)
The expected outcome for the scenario is as follows:

- The occupation result should remain constant at a level of 3, indicating a far-from-office event for each device move.
- Timer elapse should occur since the device should not cross into other proximity zones. In this scenario, the far-from-office zone timer was set to 10s.

The screenshot in Figure 4.27 shows user 29 roaming in the specified common area. The determined range for the occupant from the corresponding office location R229 is shown by the information bars as well as the power status symbol as far-from-office. This then visually validates expected outcome of the scenario.

Further validation is obtained by analysis of the occupation result and distance from office measurements for the two configurations.

![Operational Graphics - Common Area (Left Side Block) R229](image)

**Figure 4.28 : Operational Graphics - Common Area (Left Side Block) R229**

Analysis of the operational graphics of configuration one, provided in Figure 4.28 reflects the exact expected behaviour. The distance from the office location fluctuates around 43 meters to continuously register far-from-office events. The fluctuation is created by the movement of the node in a circular path as implemented by the CircleMobility model.
The determined distance is correctly reflected in the occupancy result in Figure 4.28.a, and remains constant at 3 until the far zone timer elapses and alters the occupation level to 5.

The results for configuration two indicate an unexpected occurrence of registering a close-proximity event in the first few device moves. In Figure 4.28.d, it can be seen that the distance from the office location starts off at several meters less than expected and then instantly rises several meters above the expected value for the next move. Investigation into this occurrence revealed that the sent message represented by this occurrence was not received correctly and that an error had been detected. This also explains why the occurrence is not seen again in the rest of the distance data, thus validating that there was not a miscalculation due to the number of detected APs.

The error was reflected in the occupancy result by incorrectly localizing the user in the close-proximity zone. The VOS recovered from the detected error and produced an OR of 3 as expected until the far-proximity zone timer had elapsed.

The scenario can thus be validated for both configurations since the introduced error did not corrupt the overall functioning of the system.

In the next section analysis of the results found for the common area hallway simulations will be presented. These simulations aim to provide insight into the overall correct function of all ranging and timer aspect of the VOS as validated thus far.

4.4.4.2 Common Area Simulations – Hallway Scenarios

This following analysis was performed for the top and bottom hallways with both configurations. The results for the two configurations will first be compared for the top hallway and thereafter for the bottom hallway. In these scenarios a single smart-phone (Cell) node is configured with LinearMobility to walk the distance of each hallway. Note that screenshot images will not be provided for these scenarios since one still image would not be able to reflect the simulated scenario. A range of screenshots presenting the movement of the device down the hallway is provided on the attached disk for these scenarios.

4.4.4.2.1 Top Hallway - R203

In this specific scenario, the occupant of R203 is configured to walk down the entire top hallway from the left side to the right. With this configuration, the occupant passes the corresponding office location with very close proximity.
The following outcome is expected from the analysis of this scenario:

- The occupant should move in a straight line down the hallway.
- The occupancy result should change from 2 to 3 as the device moves past and further away from office R203.
- Timer-elapse should occur where appropriate. The close proximity timer was set to 40s for all hallway scenarios and the far-proximity timer to 20s.

To validate the first expected outcome, Figure 4.29 provides a scatter-plot comparing the estimated coordinates to the actual coordinates for each device move.

![Figure 4.29: Estimated Coordinates vs. Actual Coordinates - R203](image)

When comparing Figure 4.29.a and b, it is evident that the results obtained from configuration one would be significantly more accurate than those of configuration two. As seen from Figure 4.29.a, the estimated coordinates are very closely matched to the actual coordinates. This indicated that estimated device locations were very accurate for configuration one, and that the simulated device walked in a straight line down the hallway. This accuracy is due to all areas of the facility being detectable by all three AP.

The configuration two scatter-plot indicates that the estimated coordinate differs significantly from the actual coordinates in various areas along the top hallway. This is because the sections presenting the deviation are only detectable by two or only one AP.

To investigate the effect this would have on the occupancy result, the following operational graphics were analysed:
As implied by Figure 4.30.b the simulated device, Cell[3], moved down the hallway with a constant increase in distance. The first curved part of the graph indicates that the device started at the left side of the hallway, moved closer and past the corresponding office location, and then continued moving further away from the office in a straight line.

The occupancy result for configuration one confirms this by indicating that the device first registers close-to-office events, and thereafter far-from-office events as the distance between the device and R203 increased. Finally, the far-proximity timer elapsed altering the occupancy level to five.

Furthermore, it is important to mention that the movement of the device down the hallway did not affect the power statuses of other office locations and that R203 did not register an in-office event when its corresponding occupant walked by in close proximity.

This scenario reflects the exact expected behaviour and validates the VOS function with devices moving through occupancy zones in the top hallway for configuration one.
As expected, the incorrectly determined position coordinates for the configuration two case, are reflected in the operational graphics. As seen from Figure 4.30.d, the distance from the office location does not follow a smooth curve as in the configuration one case. This is also reflected in the corresponding occupancy result. Closer inspection of the occupation result in Figure 4.30.c shows that, for the first part of the scenario an in-office event was registered.

This is due to the implemented Euclidean distance adjustment for areas that are not detectable by three APs. As proved in the previous sections, this method offers greater accuracy for registering in-office events, but as expected, this also had an effect on occupancy when the device is located just outside of the corresponding office.

Logically it was decided that it is safer to overcompensate for in-office events than to incorrectly power down an office. Although this compensation is reflected in the occupancy result, it should not have a long term effect on the functionality of the VOS. This is because when occupants are located just outside their office they are either going to move inside or walk elsewhere in the facility, entailing that the correct occupancy zone will then be determined. This behaviour is reflected as soon as the device moves out of the zone for which these distance adjustment are done and is then correctly registered as a close-proximity event.

Furthermore, it is worthy to notice that the incorrectly estimated device positions had very little effect on the occupancy result. The occupancy result follows the expected behaviour as soon as the Euclidean distance adjustment range was passed with the exception of a single incorrect value.

This range of accuracy also proves sufficient for the purpose of implementation and thus validates the functionality of the VOS for the configuration two scenario.

In the following section results will be presented for the simulations of the bottom hallway scenario. This scenario reflects the occupant of room R232 walking down the bottom hallway. Investigation will be done into the same principles that were analysed for the top hallway scenario.

4.4.4.2.2 Bottom Hall – R232

This scenario was similar to the one discussed above with the exception of the walk down the bottom hallway being configured as close to the offices as possible. This was done to test if R232 would register in-office events for both configurations at a closer proximity than simulated above.
The expected outcome for this particular scenario entailed the following:

- The occupant should primarily be registered with a close-proximity event (OR 2).
- When the occupant is located right outside of R323, an occupancy result of 1 is expected for configuration two, and either 1 or 2 for configuration one. This would indicate the severity of the implemented Euclidean distance adjustment. This would also prove to investigate the ideal selection of the office radius parameters as used by the occupancy determination unit.
- As the occupant passes R232 the OR should return to 2 until the occupant reaches the far-from-office zone, 30 meters from the office location.
- When in this zone, the far-zone timer should elapse increasing the OR to 5.

Scatter-plots for the movement down the bottom hallway are presented in Figure 4.31:

![Figure 4.31: Estimated Coordinates vs. Actual Coordinates - R232](image)

The estimated coordinates of the occupant’s journey down the hallway seem to be accurate for configuration one and represents a straight lined path as expected.

In the graph for configuration two, the same miscalculations as found in the previous top hallway scenario, are apparent. The miscalculated positions also correspond to the areas that are not detectable by all three APs.

Analysis of the occupation results and the corresponding distances from the office location will be done to determine the effect of these miscalculations on occupancy of room R232.
Figure 4.32 : Operational Graphics (Bottom Hallway) - R232

Analysis of the configuration one chart in Figure 4.32.b shows that the distance from the office location looks as expected, becoming less as the device approached R232 and increasing again as it passes. The occupancy result for configuration one starts off at a level of 2, indicating close-to-office events and then drops to 1. This implies that the same phenomenon created by the Euclidean distance adjustment in configuration two, can also be mimicked when a device passes the office location at a distance that falls within the defined office radius. Although this behaviour is expected as part of the primarily implemented functionality for registering in-office events, it defines an area where parameter optimisation can be introduced.

After having passed R232, the occupation results reflect the expected behaviour by confirming the increase in distance. This is shown by the OR changing from 2 to 3 as the device enters the far-from-office proximity zone. The office is then powered down with the elapse of the far-zone timer.

With this scenario, the miscalculated position coordinates do have an undesirable effect on the configuration two occupation result. This is evident in the zone jumping that occurs in the occupation result as presented in Figure 4.32.c.
This graph shows that the occupancy result varies significantly between the far and close-proximity zones and only stabilises when reaching the R232 where the Euclidean distance adjustment is implemented.

With configuration two a significant length of the left side of the bottom hallway is only detectable by one AP (AP3), entailing that the achievable level of localisation accuracy within this area would be especially low. After passing R232 the device would first be detectable by all 3 APs, and then thereafter, by two APs. In this better coverage area, the occupancy results seem to hold stable and reflect the expected outcome.

The scenario is thus valid for all the conducted configuration one simulations but seems to produce unexpected effects in the configuration two areas that are only covered by a single AP. This indicates that the accuracy of common area occupancy is directly dependent on the number of APs servicing the area, and thus that more sufficient coverage would produce more accurate occupancy outcome.

4.4.4.3 Cross-Common Area Validation Outcome

In this result section the validation of the correct functioning of the VOS was investigated with respects to occupant moving through occupancy zones.

In the conducted investigation it was found that:

- Configuration one scenarios provided better accuracy.
- Configuration two scenarios reflected the expected behaviour in areas with optimal coverage.
- The resetting of the implemented zone-timers functioned as expected, and timer-elapse was correctly calculated for all common area scenarios.
- In most cases of the configuration two environment, the OR was not significantly affected by instances of incorrectly estimated coordinates. The incorrectly determined OR was compensated for by the resetting of the zone timers that prevented office locations from being incorrectly powered-down.

Since the outcome of the implemented validation and verification techniques reflects the expected outcome, the VOS functionality can be classified as sufficient for the common area scenarios.

This section concluded the analysis of scenario simulations done for testing the operational validity and correct functioning of the VOS. In the following section, investigation will be done into the overall VOS functioning.
4.5 OVERALL VOS MODEL VALIDATION

In this section, investigation will be done into the overall model functionality with respects to the sensitivity of the model, the ability of the model handle extreme loading conditions, and the overall accuracy of the implemented location estimation techniques. Furthermore, a summary of principles investigated in the scenario simulations will be provided.

4.5.1 VOS MODEL SENSITIVITY ANALYSIS

Sensitivity analysis of the VOS model was done by implementing parameter variability for the data rate and receiver sensitivity with which the model functions. The investigated parameter sets were defined as configuration one and configuration two.

Analysis of the system sensitivity was done by conducting all scenario simulations for both of these configurations. The accuracy of the VOS model and the outcome of each scenario were presented in the sections above. This will now be summarised:

The accuracy of the VOS proved to be better with configuration 2 for registering in-office events. This was because less interference was introduced for this configuration because of the lower receiver sensitivity. Furthermore, the accuracy for in-office event registration was significantly boosted in configuration two by the implementation of the Euclidean distance adjustment for areas detectable by less than three APs.

In contrast to this, the VOS seemed to be more accurate at registering close-to-office and far-from-office events with configuration one. This is due to the configuration providing optimal coverage, and all building zones being detectable by all three APs.

To optimise for accuracy it is suggested that the following configuration be implemented for future experiments:

- The Euclidean distance adjustment should be implemented no matter the configuration or number of detected APs.
- At least two APs should provide coverage to all building areas.

Analysis of the scenario simulations also proved that the functionality of the VOS can be validated for both sensitivity configurations. This entails that the overall VOS model would then also be valid for other data rate and receiver sensitivity configurations within the tested range.

In the next section, extreme condition testing was performed on the VOS to determine the device load it was able to correctly handle.
4.5 OVERALL VOS MODEL VALIDATION

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In the next section, extreme condition testing was performed on the VOS to determine the device load it was able to correctly handle.
4.5.2 EXTREME CONDITION TESTING

Extreme condition testing was done on the VOS model to determine the scalability of the developed technology. The configuration details for the loading simulations are provided in section 3.4.4.5 of this document.

In the previous multi-occupant simulation scenarios, the load handling of the VOS was tested with 2, 3 and 4 device. Analysis of these scenarios showed that the model, was, able to function correctly with the simulated number of occupants.

To further investigate load handling, extreme condition testing was done for the VOS model with the use of the conducted loading simulations. These simulations were configured to implement a larger number of devices with each consecutive run. Scenarios representing 10, 20 and 40 devices were configured.

In these simulations, all nodes were configured to be traffic generators. With this configuration all devices aim to transmit broadcast messages at every possible occasion, allowing for large amounts of congestion and interference to be introduced into the model. This enabled the validation of the VOS functioning when presented with such extreme conditions.

4.5.2.1 10 Devices

Loading simulations for the 10 device scenario entailed configuring the 10 occupants of offices R201 – R210 to be in-office. This was done so that the mean occupancy result for the time of the simulation could be investigated.

Results of the simulations, as conducted for 10 present user devices, are given in the form of a statistical summary of the various measured parameters. This statistical summary aims to provide insight into the performance of the three location estimation techniques, the found distance from office across the simulation, as well as the occupancy result.

The trilateration statistics given in Table 4.7 represent the results of all node localisations that occurred in this scenario, for which the algorithm could be applied, indicating that readings were obtainable from all three APs. This means that overall 500 device localizations cloud have been done but trilateration was only possible for 400 of these cases. Cases where trilateration was not possible was logged as an inapplicable results, and were not represented in the statistical summary, as to not influence the calculated results. To indicate that many such instances occurred the mode parameter was logged as “-“ for each such instance. If the frequency of these instance was more than that of other calculated values this was reflected in the summary, as per usual mode calculations.
Table 4.7: Statistical Summary - Loading Simulations (10 Devices)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Min</th>
<th>q1</th>
<th>Median</th>
<th>Mean</th>
<th>q3</th>
<th>Max</th>
<th>QR</th>
<th>qd</th>
<th>Var</th>
<th>Std. Dev</th>
<th>Var Coeff.</th>
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<tr>
<td>Error (%)</td>
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<tr>
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<td>22.28</td>
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<td>10.8</td>
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<tr>
<td>Trilateration Distance Error (m)</td>
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<td>9.7</td>
<td>10.85</td>
<td>11.59</td>
<td>13.73</td>
<td>16.42</td>
<td>4.03</td>
<td>20.2</td>
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<tr>
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<td>0.5</td>
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<td>1.26</td>
<td>2</td>
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<td>1.5</td>
<td>0.75</td>
<td>1.9</td>
<td>1.38</td>
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<tr>
<td>Occupation Result (OR)</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.06</td>
<td>6.48</td>
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</table>

Indicated by this summary, the constrained nearest neighbour algorithm is still the most accurate of the three estimation techniques, with the distance error having a statistical mean value of only 0.73 meters and standard deviation of 1.22, clearly outperforming the others.

The measured distance from the office location fluctuated a bit, showing a rather high maximum value of 33.51 meters, but the calculated statistical mean of 1.26 falls within the expected 8 meter threshold value for registering in-office events. This is also reflected in the occupancy result, indicating a maximum value of 3 but a perfect statistical mean of 1 with a standard deviation of 0.06.

The fluctuation in the OR indicates that there were instances where the OR result was incorrectly determined due to the introduced interference, but considering that a
insignificantly small amount of such instance were registered, and no incorrect office power-down events occurred the functioning of VOS was determined to be satisfactory for this scenario.

This thus validates the ability of the VOS to handle a load of up to 10 devices.

### 4.5.2.2 20 Devices

This scenario was configured in the same fashion as above, and represented the 20 occupants of offices R201- R220 as being in-office. The statistical summary, as produced for the scenario by the statistical unit, is presented below.

As seen from Table 4.8 below, the same behaviour as with the 10 device scenario is observed. The constrained nearest neighbour mapping technique perform the best of the three location estimation algorithms, with a mean distance error of 1.03 meters and standard deviation of 3.01.

The distance from office parameter also indicated fluctuation caused by interference of the multiple nodes within the environment. The statistical mean of 1.88 meters falls well within the in-office threshold value.

The OR of this scenario also indicates fluctuations similar to those note in the 10 device case. The incorrect determined OR values also represented a insignificantly small part of the distribution, and once aging had no incorrect office power-down events as a result.

The mean calculated value of the occupancy result is indicated as 1.02 and has a standard deviation of 0.16. This is acceptable to validate the functioning of the VOS with the use of 20 devices present in the building environment.
## Table 4.8: Statistical Summary - Loading Simulations (20 Devices)

<table>
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<tr>
<th>Mode</th>
<th>Min</th>
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<td><strong>C-Mapping percentage [x] Error (%)</strong></td>
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<td><strong>C-Mapping percentage [y] Error (%)</strong></td>
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</tr>
<tr>
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<td></td>
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<tr>
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<tr>
<td><strong>Trilateration percentage [y] Error (%)</strong></td>
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<tr>
<td><strong>Distance from Office (m)</strong></td>
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</tr>
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<td>157.09</td>
</tr>
<tr>
<td><strong>Occupation Result (OR)</strong></td>
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<td>1</td>
<td>1</td>
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<td>0</td>
<td>0.02</td>
<td>0.16</td>
<td>15.5</td>
</tr>
</tbody>
</table>
### 4.5.2.3 40 Devices

This scenario was configured to represent 40 occupants being in-office, one occupant was simulated for each of the 38 labelled rooms, with an addition occupant configured for office R234 and R236. A screenshot of this scenario is presented below.

![Screenshot of 40 Device Loading Simulation Scenario](image)

As seen from Figure 4.33, all devices are located within their offices and have green power status icons except for Cell[25] of office R225. The power status of this office indicates that the occupant is far-from-office. Closer inspection of the screenshot shows Cell[25] being located in office R209. This is due to the heavy congestion caused by the 40 devices within the environment, incidents like this occurred a few times during the scenario.

In order to investigate the effect of this, the overall statistics for the 40 device loading simulation are presented in Table 4.9 below. The summary indicated that as for the previous two cases, the constrained nearest neighbour mapping algorithm still performs the best, with a statistical mean distance error of 1.44 meters and a standard deviation of 5.37.
The occupation result and distance from office measurements were very accurate considering the large amount of simulated devices. A mean occupation result of 1.03 with a standard deviation of 0.25 was found. This corresponds well with the distance from office results, indicating that a mean distance of 2.59 meters, and standard deviation of 5.2 meters.

As expected OR fluctuations increased in the 40 device case, registering OR of a level of five due the large amounts of inter-node interference present. Despite this, the VOS was able to successfully handle the load and quickly recovered from the incorrectly registered events.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Min</th>
<th>q1</th>
<th>Median</th>
<th>Mean</th>
<th>q3</th>
<th>Max</th>
<th>qR</th>
<th>qd</th>
<th>Var</th>
<th>Std. Dev</th>
<th>Var Coeff.</th>
</tr>
</thead>
<tbody>
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<td>0.99</td>
<td>6.26</td>
<td>2.65</td>
<td>132.4</td>
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<td>1.04</td>
<td>2235</td>
<td>47.28</td>
<td>755.52</td>
</tr>
<tr>
<td>C-Mapping percentage [y] Error (%)</td>
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<td>1.46</td>
<td>139.57</td>
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<td>0.24</td>
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</tr>
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<td>3.11</td>
<td>3.77</td>
<td>4.13</td>
<td>4.38</td>
<td>4.51</td>
<td>23.77</td>
<td>0.74</td>
<td>0.37</td>
<td>1.58</td>
<td>1.26</td>
</tr>
<tr>
<td>U-Mapping percentage [x] Error (%)</td>
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<td>0.06</td>
<td>0.56</td>
<td>1.55</td>
<td>8.38</td>
<td>4</td>
<td>1308.5</td>
<td>3.44</td>
<td>1.72</td>
<td>2728</td>
<td>52.23</td>
</tr>
<tr>
<td>U-Mapping percentage [y] Error (%)</td>
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<td>0.11</td>
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<td>2.13</td>
<td>4019</td>
<td>3.74</td>
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<td>2.48</td>
<td>1.24</td>
<td>91.94</td>
<td>9.59</td>
</tr>
<tr>
<td>U-Mapping Distance Error (m)</td>
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<td>0.08</td>
<td>0.74</td>
<td>1.16</td>
<td>2.42</td>
<td>1.85</td>
<td>85.68</td>
<td>1.11</td>
<td>0.56</td>
<td>42.93</td>
<td>6.55</td>
</tr>
<tr>
<td>U-Mapping Execution Time (ms)</td>
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<td>83.27</td>
<td>100.1</td>
<td>102.24</td>
<td>102.97</td>
<td>103.77</td>
<td>150.03</td>
<td>3.63</td>
<td>1.81</td>
<td>33.76</td>
<td>5.81</td>
</tr>
<tr>
<td>Trilateration percentage [x] Error (%)</td>
<td>-</td>
<td>15.86</td>
<td>26.95</td>
<td>28.76</td>
<td>29.16</td>
<td>108.9</td>
<td>13.3</td>
<td>6.65</td>
<td>396.9</td>
<td>19.92</td>
<td>69.27</td>
</tr>
<tr>
<td>Trilateration percentage [y] Error (%)</td>
<td>-</td>
<td>10.63</td>
<td>14.97</td>
<td>15.71</td>
<td>20.54</td>
<td>46.57</td>
<td>9.91</td>
<td>4.96</td>
<td>76.16</td>
<td>8.73</td>
<td>55.55</td>
</tr>
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<td>Trilateration Distance Error (m)</td>
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<td>9.73</td>
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<td>16.63</td>
<td>43.1</td>
<td>6.9</td>
<td>3.45</td>
<td>21.91</td>
<td>4.68</td>
<td>35.47</td>
</tr>
<tr>
<td>Trilateration Execution Time (ms)</td>
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<td>0.02</td>
<td>0.02</td>
<td>0.05</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>27.24</td>
</tr>
<tr>
<td>Distance from Office (m)</td>
<td>1.12</td>
<td>2</td>
<td>2</td>
<td>2.95</td>
<td>2.06</td>
<td>85.7</td>
<td>0.06</td>
<td>0.03</td>
<td>27.01</td>
<td>5.2</td>
<td>200.7</td>
</tr>
<tr>
<td>Occupation Result (OR)</td>
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<td>1</td>
<td>1</td>
<td>1.03</td>
<td>1</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0.06</td>
<td>0.25</td>
<td>24.3</td>
</tr>
</tbody>
</table>

The accuracy of the overall found results for this scenario was found to be satisfactory, and the functioning of the VOS was validated for the use with 40 present devices.
4.5.2.4 Extreme Condition Testing Outcome

The analysis of the extreme condition testing indicated that the VOS technology provides a good level of scalability, and still functions with relatively high accuracy when up to 40 devices are present.

The following outcome was found:

- The constrained nearest neighbour mapping algorithm provided the most accurate position estimation, in all investigated cases.

- The obtained statistical mean values for the occupancy results were as expected for each case.

- The VOS system was able to function correctly with the levels of interference caused by the number of simulated devices.

The testing of extreme conditions were only done for up to 40 devices since all devices communicate to all AP, and the created load is not split among the three APs. This indicates that each AP was tested with up to 40 connected devices. This amount of connected test devices per AP is considered efficient for testing the VOS function since, in reality, not all devices would aim to communicate continuously.

4.5.3 SCENARIO RESULTS SUMMARY

The functionality of the created VOS was validated for various scenarios, each designed to test a specific attribute. The results of these scenario simulations will now be summarised, and indication will be given to the obtained accuracy and operational correctness. This is represented in the following table:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Accuracy-Mean Distance Error-</th>
<th>Operation Correctness</th>
<th>Occupancy Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room Simulations</td>
<td>1.525 m</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Multi-Occupant Simulations</td>
<td>1.485 m</td>
<td>95%</td>
<td></td>
</tr>
<tr>
<td>Priority Simulations</td>
<td>2.091 m</td>
<td>96.80%</td>
<td></td>
</tr>
<tr>
<td>Common Area Simulations</td>
<td>2.715 m</td>
<td>95.87%</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.10 indicates that the mean distance error, as calculated over all scenario simulations, and both configurations, is less than 3 meters. This is considered very adequate for the purposes of occupation determination. Furthermore, this also indicates that the correct location estimation technique was selected.
The high accuracy of position estimation that is achieved in this study is due to a simulation environment being used for obtaining the required RSS data. In a real life implementation of this concept, less accurate estimation can definitely be expected.

This accuracy level also contributes to the accuracy of the found occupation results. The summary indicates that the occupancy result could be determined correctly at least 95% of the time. Although this is a very high percentage, and the accuracy of the estimation technique does contribute, it is necessary to note the ranging aspects that aid in this accuracy.

Firstly, the determined estimated position is used to calculate the distance from a specific office location. This calculated distance is then grouped into zones, indicating the occupancy zone. Since these zones span several meters, all estimated position falling within each zone will provide the same occupancy result. This would entail a high level of occupancy accuracy, and therefore, correctly determined results. Only if an estimated position is so far out that it falls within another occupancy zone, will the result be incorrectly determined.

This zoning concept should offer a higher level of accuracy even with real-world implementations.

As each of the conducted analysis provided validation of the VOS functioning for the specific scenario and investigated aspects, the overall accuracy and correctness can be seen as applicable across the entire developed model.

In the following section, validity of the choice for the selected location estimation technique will be investigated to add further confidence to the found correctness and accuracy as presented above.

4.6 LOCATION ESTIMATION TECHNIQUES – OVERALL ANALYSIS

A preliminary investigation into the accuracy of the three possible location estimation techniques revealed that the constrained nearest neighbour mapping algorithm is best suited for occupancy determination. This algorithm was then selected and implemented for occupancy determination based on this analysis.

In order to determine the validity of the choice to use the constrained nearest neighbour approach rather than trilateration or the unconstrained approach, analysis of the accuracy of all three techniques were conducted over all simulations.
The following operational graphics are presented as output across all configuration one and configuration two simulations:

Figure 4.34 above shows that the correct selection was definitely made since the constrained mapping outperforms the other two techniques and provides a mean distance error of less than 2.6 meters over all conducted simulations.

The constrained mapping approach also performed very adequately based on the measured execution time with a statistical mean value of less than 5.08 ms for all scenarios.

As a last measure, the performance of the three location estimation techniques will be determined by analysing statistics as obtained over all scenarios.

The parameters for the three location estimation techniques were determined per execution of a specific algorithm. This will provide final indication of the accuracy and performance of the location estimation techniques, as well as provide final empirical evidence that the correct technique was indeed selected for occupancy determination.
Table 4.11: Overall Statistical Summary - Three Localisation Techniques (Configuration 1)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Min</th>
<th>q1</th>
<th>Median</th>
<th>Mean</th>
<th>q3</th>
<th>Max</th>
<th>qR</th>
<th>qd</th>
<th>Var</th>
<th>Std. Dev</th>
<th>Var Coeff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-Mapping percentage [x] Error (%)</td>
<td>0</td>
<td>0.57</td>
<td>1.36</td>
<td>3.24</td>
<td>3.04</td>
<td>871.09</td>
<td>2.47</td>
<td>1.24</td>
<td>217.47</td>
<td>14.75</td>
<td>454.62</td>
</tr>
<tr>
<td>C-Mapping percentage [y] Error (%)</td>
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<td>0.34</td>
<td>1.05</td>
<td>1.45</td>
<td>2.09</td>
<td>67.67</td>
<td>1.75</td>
<td>0.88</td>
<td>5.05</td>
<td>2.25</td>
<td>155.26</td>
</tr>
<tr>
<td>C-Mapping Distance Error (m)</td>
<td>0</td>
<td>0.54</td>
<td>0.83</td>
<td>0.92</td>
<td>1.12</td>
<td>59.44</td>
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<td>2.4</td>
<td>1.55</td>
<td>168.5</td>
</tr>
<tr>
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<td>2.83</td>
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<td>4.64</td>
<td>4.82</td>
<td>17.23</td>
<td>0.79</td>
<td>0.4</td>
<td>1.14</td>
<td>23.15</td>
</tr>
<tr>
<td>U-Mapping percentage [x] Error (%)</td>
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<td>0.94</td>
<td>2.09</td>
<td>5.76</td>
<td>4.57</td>
<td>806.85</td>
<td>3.68</td>
<td>1.82</td>
<td>205.66</td>
<td>14.34</td>
<td>248.79</td>
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<td>U-Mapping percentage [y] Error (%)</td>
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<td>1.47</td>
<td>2.86</td>
<td>3.42</td>
<td>4.53</td>
<td>74.95</td>
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<td>1.53</td>
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<tr>
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<td>1.68</td>
<td>1.88</td>
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<td>123.3</td>
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<td>8.73</td>
<td>392.85</td>
<td>19.82</td>
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<td>9.12</td>
<td>12.59</td>
<td>13.95</td>
<td>17.91</td>
<td>43.22</td>
<td>8.79</td>
<td>4.4</td>
<td>61.05</td>
<td>7.81</td>
</tr>
<tr>
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<td>6.44</td>
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<td>0</td>
<td>0.02</td>
<td>94.27</td>
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</tr>
</tbody>
</table>

The above summary indicates that, as expected, the constrained nearest neighbour mapping approach offers the highest level of accuracy with a mean distance error of 0.92 m, followed by the unconstrained approach with 1.88 m. Trilateration estimation performs the poorest with a mean distance error of 13.37 m.

This validates the decision of implementing the constrained mapping approach for occupancy determination since this approach provided the best overall accuracy. The execution time of this algorithm also proves sufficient for the overall configuration one statistics with a mean value of 4.64 ms.

The overall statistics for configuration two are provided next:
### Table 4.12: Overall Statistical Summary - Three Localisation Techniques (Configuration 2)

<table>
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<th>Mode</th>
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<th>Median</th>
<th>Mean</th>
<th>q3</th>
<th>Max</th>
<th>qR</th>
<th>Qd</th>
<th>Var</th>
<th>Std. Dev</th>
<th>Var Coef.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>C-Mapping percentage [x] Error (%)</strong></td>
<td></td>
<td></td>
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<td></td>
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<td>0</td>
<td>0</td>
<td>0.83</td>
<td>1.86</td>
<td>9.84</td>
<td>8.98</td>
<td>135.91</td>
<td>8.15</td>
<td>4.08</td>
<td>347.42</td>
<td>18.64</td>
<td>189.51</td>
</tr>
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<td><strong>C-Mapping percentage [y] Error (%)</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td>0</td>
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<td>0.7</td>
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<td>3.98</td>
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<td>3.28</td>
<td>1.64</td>
<td>30.6</td>
<td>5.53</td>
<td>152.02</td>
</tr>
<tr>
<td><strong>C-Mapping Distance Error (m)</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>0.79</td>
<td>1.19</td>
<td>2.52</td>
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The overall statistics provided for configuration two further strengthens the fidelity of the constrained nearest neighbour mapping algorithm for occupancy determination. This approach offered accuracy with a mean distance error value of 2.35 meters and standard deviation of 2.77 meters. This then validates the selected algorithm for both analysed configurations.

The developed VOS system technology does, however, have its limitations. These limitations, and the effect thereof on the fitness of purpose of the VOS implementation, will be the focus of the next section.
4.7 LIMITATIONS OF TECHNOLOGY

In this section, the limitations of the developed VOS technology will be discussed. In the previous sections of this chapter, it was stated that the VOS is valid and fit for implementation for the intended purpose. This is true; the developed conceptual VOS is able to provide information relevant to the more efficient energy management of commercial office buildings. The current format of implementation does however have limitations. These will now be discussed.

The VOS was first and foremost designed to determine room level occupancy for commercial buildings in an occupant-centred fashion. This required for an occupant and his/her WiFi capable user devices to be register, and linked to the physical location of the specific occupant’s office location. The VOS then used this data along with measured RSS readings to determine the occupancy of a specific office based on the locations of its corresponding occupants. The approach of linking occupants to offices provided a means of better ensuring the correctness of implemented power regulation.

The first limitation that can be derived from this implementation approach is that the system does not offer the ability to determine occupancy of rooms when occupants are not linked therewith. This implies that if an unregistered occupant or an occupant of another office location is located in officeX, the occupancy of officeX would not register these users as in-office and might power down.

The functionality that would be needed to correct the above limitation would definitely be site-specific and was thus not implemented since this study only aimed to prove the concept of the presented VOS. This limitation could, however, be easily corrected by creating a registry containing a list of “free-for-all” office locations and their corresponding coordinates. If an occupant is then located within one of these offices, the occupant can be added to the office’s watch-list. This will ensure that the office stays power-up during the stay of the occupant. The occupant can be removed from the office’s list as soon as the occupant leaves the location and the first timer had elapsed.

The second limitation is that occupancy and, therefore, power regulation of the common areas takes into account all detected occupants. This would imply that the power to the common areas will only be switched off if no occupants are detected within the facility. Functionality to provide for this shortcoming can also easily be added by defining common area zones, in which case the zone will be powered-down if no occupants are detected within a reasonable range from the specific zone. This implementation is also site-specific and would depend on the power-layout of the building. This is because, in a fair amount of cases, especially in open-plan buildings like the facility, a single common area light switch turns on the lights for the entire floor.

Considering this aspect, and that most power consuming devices like air-conditioning systems are implemented within the enclosed office spaces, this functionality was not implemented.
Another major limitation of any occupancy detection system is site-specific configuration. If the created VOS can be validated for real-world implementation, the configuration thereof could provide some obstacles depending on the existing infrastructure of the site. The configuration process would at least entail the creation of the RF-map, registering of occupant devices and the linking thereof to the specific office location centre-points coordinates as determined from a blueprint of the facility. A more efficient and creative means of configuration is thus worth investigating.

The main limitation of the created VOS technology is, however, that it made use of simulated data for testing the functionality. This was done since the aim of the study was merely to prove that the concept of implementing existing WiFi infrastructure as a VOS system would be possible, real-world validity and testing should definitely be explored.

The last section of this chapter summarises the main focus points as found from the validation and verification techniques applied in this chapter.

### 4.8 CHAPTER SUMMARY

This chapter was initiated by providing an outline of the results presentation that was to be followed. This presentation method was developed to present the unique results obtained for this study in a relevant fashion.

The development model that was implemented to ensure the validity, correct functioning and fitness of purpose of the created VOS, was discussed. The processes applied in the model were outlined as to indicate how they fit into the specific VOS development phases.

Thereafter an in-depth explanation of the various validation and verification techniques implemented for testing the VOS was given. The area of application of each technique was also defined.

In the next section, a preliminary analysis of the accuracy of the three location estimation techniques revealed that the constrained nearest neighbour approach should be best suited for occupancy determination. This technique was accordingly selected for implementation of occupancy determination. This choice was then later confirmed by investigating the performance of each of the location estimation techniques across all conducted simulations.

Results were presented for each of the conducted simulation scenarios, from which the validity of the VOS functioning was determined for the investigated aspects. In several of the scenarios, interference was detected as presented in the MiXiM environment. The VOS was able to function correctly and with sufficient accuracy in the presence of this interference.

Analysis of the scenario simulation results indicated that in each case, the expected outcome was reflected, and the achieved accuracy was sufficient. The VOS functioning could be validated for all conducted scenario simulations.
The determined outcome indicated that the VOS functions correctly when handling multiple devices with different priorities. The VOS can determine the occupancy of a specific office based on localisation of the corresponding top priority device. The VOS was able to determine the occupancy zone in which a device is located with high accuracy and can correctly reflect occupants moving through zones.

The implemented timer elapse and resetting functioned as expected and was able to correctly reflect the time an occupant spent in a zone as well trigger power-down events for the corresponding office when a timer had elapsed. All of the above was also correctly reflected in the occupancy results.

The VOS was able to correctly reflect the specific scenarios and varying parameter within the created visualisation unit that proved to be a very useful analysis tool for this unique implementation.

Lastly, this chapter provided analysis of the overall performance of the VOS by presenting results for conducted sensitivity analysis tests, extreme condition testing, overall accuracy and operational correctness.

Sensitivity analysis was done across all scenarios for configuration one and two. This analysis revealed that the VOS would function correctly for data rates ranging from 6 Mbps to 54 Mbps and a receiver sensitivity of between -86 dBm and -68 dBm.

The conducted extreme condition testing indicated that the VOS functioned correctly with tested loads of up to 40 devices connected to an AP.

The overall accuracy as measured across all conducted simulations proved to be very high since simulated data was used for testing. Furthermore, it was determined that the VOS operated correctly in all scenarios and that the developed model would be suitable for real-world testing.

In the following chapter, a summary of the main focus points found throughout this dissertation will be provided. Conclusions as determined from the results will be detailed along with future recommendations concerning this research.
5 CONCLUSION & RECOMMENDATIONS

This final chapter provides a review of the problem that lead to the conducted research and a summary of the work presented in this dissertation. Interpretation of the research question as presented in the introduction is also provided along with direction for future studies.

5.1 PROBLEM REVIEW

Efficient energy management in commercial office buildings has become an important factor since this sector indicates rapid yearly increases in energy usage. The most widely applied solutions for efficient building energy management focus on occupancy determination. This is to counter neglect of occupants not turning off energy consuming devices in unoccupied areas. The cost and other associated factors of implementing custom occupancy solutions sometimes discourage the use thereof, especially for smaller companies wanting to save on their energy bill. Furthermore, current solutions do not take into account the physical positions of occupants that could provide more accurate and useful occupancy results.

This research thus focused on investigating alternatives to the occupancy sensing problem. One main requirement was that the alternative solution should make use of existing infrastructure only. The concept of creating a virtual occupancy sensor was proposed. This VOS made use of existing WiFi infrastructure to localise occupants based on the RSS as measured from their personal WiFi capable devices. The VOS was also able to provide an indication to the proximity of occupants to specific building areas.

5.2 WORK SUMMARY

In the first chapter, an introduction was given detailing the identified problem and grounds for investigation. A research question was formulated, and the proposed solution to the problem presented. The research process that was followed for this dissertation was also discussed.
In the second chapter, a literature survey was conducted to gain insight into all the relevant aspects that would contribute to the development of the proposed solution. Firstly several functional aspect of typical WiFi infrastructure was investigated to determine the fidelity thereof for the occupancy sensing problem.

This included investigation into addressing schemes and radio propagation. Inquiry into different localisation techniques that could be performed to determine the physical position of RF devices was also made. Lastly a discussion was given on the simulation software that would be used for RSS and position data generation.

The next chapter outlined the work done for the experimental implementation of the VOS. In the introduction section the different functional modules of the VOS were briefly discussed and a form, fit and function analysis of the interaction between the modules was provided. Investigation of a real-world office building was done to aid in making integral implementation assumptions. A section was provided detailing the configuration of the simulation environment and the specifics of the conducted simulation scenarios. This section also provided a preliminary analysis of the conducted ranging and path loss simulations. The different functional IA modules of the developed VOS system were discussed in great detail. This included detail on the created data parser tool, the three location estimation techniques and the occupancy determination unit. Detailed functional diagrams were also provided for each of the modules. Lastly this chapter detailed the added functionality provided by the visualisation unit and the statistical and graphing units.

In chapter 4, the focus was on the presentation of the found results and the validation and verification of the developed VOS system. This chapter firstly outlined the process model that was followed to ensure the validity, correctness and fitness of purpose of the created VOS. The specific validation and verification procedures were then discussed. A preliminary analysis of the accuracy of the different location estimation techniques was presented followed by the results of all conducted experiments. In each result section the determined outcome was compared to expected outcome in order to determine the operational validity of the VOS with respects to the tested scenario. A section focusing on the overall model validity and fitness of purpose was given to provide results for sensitivity analysis and extreme condition testing. This chapter then presented a summary of all the found results that would be used to interpret the research question.
5.3 RESEARCH QUESTION INTERPRETATION

The research question as formulated in chapter one reads as follows:

*Can existing infrastructure present in most commercial buildings be used to provide an alternative and more cost effective means of building occupancy sensing?*

This question was answered by the results and outcome found from the conducted proof of concept study. Analysis of the results as presented in chapter 4 indicated that it would be possible to implement existing WiFi infrastructure as an alternative means of building occupancy sensing. This is based on the ability of the developed VOS to provide significantly accurate room level occupancy determination for all investigated scenarios. This indicated that the developed VOS model is fit for its intended purpose.

The VOS functions well with varying WiFi network configurations and a sufficiently large number of present devices. The operational behaviour of the VOS cloud also be validated for all investigated scenarios.

It is also worthy to state, that in a real-world implementation of the created VOS, the accuracy and factors such as the sensitivity and load handling of the system would depend greatly on the capabilities of the APs in the implementation network.

Studies focusing on WiFi device localisation for the purpose of location based services revealed that an accuracy of 2 meters is achievable with some models. If such high location estimation accuracy is achievable, future real-world implementations of the VOS will definitely be possible and very accurate.

The created sensor comprised of intelligent software elements in combination with existing WiFi infrastructure, thus adhering to the requirement of making use of existing infrastructure only. The implementation of localisation-based occupancy determination provided a means of focusing on occupant location and making use of simple occupancy rules based on proximity. This ability gives advantage to the proposed solution over other current occupancy solutions focusing on environmental changes as detected by sensors.

The VOS, as is, does have some limitations. Functionality for addressing these limitations can, however, be added rather easily if necessary for future site-specific implementations.
5.4 RECOMMENDATIONS

The main recommendation that can be made to further this study is to conduct testing within the physical environment. This would provide the ultimate validation of the VOS functioning and fitness of purpose.

Furthermore, this study revealed a number of areas for future investigation, mostly in the form of optimisation related subjects.

The first subject was identified with closer investigation of the RF map. This revealed that the placement of APs would play in integral part in the ability of the VOS to correctly localise devices. APs within a facility should be placed in such a way that each individual location can be identified by a unique set of RSS values. This should be done since an AP usually measures the same RSS for several positions. Thus, if three APs are used, the combination of the RSS readings should prove unique for a specific location. This then merits the optimisation study of AP placement. It is also recommended that a model is developed to determine optimal placement given the blueprints of numerous buildings.

A second optimisation problem was identified with the selection of the different occupancy ranges and timer-elapsed values. These values would also need to be optimally calibrated for each site-specific implementation. Investigation into the optimisation and easy site-specific determination and calibration of these parameters would thus also prove a relevant study.

Lastly it is recommended that the VOS concept is expanded by conducting further investigation into dynamic RF fingerprinting, able to compensate for non-homogenous WiFi device output power, and to incorporate dynamic mapping and traffic monitoring as described in sections 2.3.8 and 2.4 into the created model.

5.5 ADDITIONAL APPLICATIONS

The occupant-centred nature of this implementation would furthermore lend itself to "anywhere" personal preference configurations. The preferences of an occupant can be logged to the system and applied in any room in which the occupant may reside. These preference configurations may include climate control, mood lighting and other location based services.

Furthermore, the VOS would be highly applicable in emergency situations such as a fire. If the infrastructure remains intact occupancy information from the VOS would be able to assist in determining if occupants are still located within the building and in which area or room.
5.6 CLOSURE

The created VOS system shows promise as an alternative and more cost effective solution for occupancy sensing. Further development of the VOS can be done to include a large range of additional and site-specific functionally.

The developed VOS can be considered a smart solution to the occupancy sensing problem because it repurposes an existing infrastructure for an entirely different function with minimal to zero associated cost.

The value that would be added by the implementation of the developed system can be classified on two levels. Firstly, saving would be possible on costly electricity bills and secondly, conservation of the limited electricity resources would be elevated.

It would thus appear that a successful implementation of the developed VOS would have no significant down-side.
6 BIBLIOGRAPHY


6 BIBLIOGRAPHY


APPENDIX A

Conference Contributions


APPENDIX B

*omnetpp.ini Configuration File*
APPENDICES

[General]
cmdenv-express-mode = true
cmdenv-event-banners = true
cmdenv-module-messages = true
network = NetW2

# Simulation parameters
**.coreDebug = false
**.playgroundSizeX = 100m
**.playgroundSizeY = 60m
*.numNodes = 5

# WorldUtility parameters
**.world.useTorus = false
**.world.use2D = true

# Parameters for the ConnectionManager
**.connectionManager.carrierFrequency = 2.412e9Hz # [Hz]
**.connectionManager.pMax = 110.11mW # [mW]
**.connectionManager.sat = -91dBm # [dBm]
**.connectionManager.alpha = 2.0
**.connectionManager.sendDirect = false
**.connectionManager.cmdenv-ev-output = true

# Parameters for the Host
**.phy.usePropagationDelay = true
**.phy.thermalNoise = -110dBm # [dBm]
**.phy.useThermalNoise = true
**.phy.analogueModels = xmldoc("config.xml")
**.phy.decider = xmldoc("config.xml")
**.AP[*].nic.phy.maxTXPower = 100mW
**.Cell[*].nic.phy.maxTXPower = 10mW
**.Tab[*].nic.phy.maxTXPower = 10mW
**.Laptop[*].nic.phy.maxTXPower = 20mW
**.phy.sensitivity = -68dBm
**.phy.nbRadioChannels = 13

# Application layer parameters
**.Cell[*].applicationType = "TrafficGen"
**.AP[*].applicationType = "BurstApplLayer"
**.Tab[*].applicationType = "TrafficGen"
**.appl.headerLength = 512bit
**.appl.burstSize = 3
### NETW layer parameters

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**.networkType = "BaseNetwLayer"
**.netwl.headerLength = 32bit
**.mac.bitrate = 54Mbps
**.netwl.cmdenv-ev-output = true
```

### Mobility parameters

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**.mobility.cmdenv-ev-output = true

**.AP[*].mobilityType = "BaseMobility"
**.AP[*].mobility.debug = true

**.Cell[*].mobilityType = "CircleMobility"
**.Cell[*].mobility.debug = true
**.Cell[*].mobility.speed = 0.5mps
**.Cell[*].mobility.updateInterval = 1s

#Cell[0]
**.Cell[0].mobility.r = 1
**.Cell[0].mobility.startAngle = 90deg
**.Cell[0].mobility.cx = 47
**.Cell[0].mobility.cy = 18

**.AP[0].mobility.initialX = 47m
**.AP[0].mobility.initialY = 18m

**.mobility.acceleration = 0mpss
**.appl.packetTime = 1s
**.appl.packetsPerPacketTime = 20
**.connectionManager.drawMaxIntfDist = true
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APPENDIX C

Database Diagram
APPENDIX D

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APPENDIX E

Attached Disk