Spectrum optimisation for low power wide area network utilisation in smart cities

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DECLARATION BY STUDENT

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ABSTRACT

With the advent of the fourth industrial revolution, demand for spectrum by wireless networks has continued to increase exponentially. As the unlicensed band is a free-to-use spectrum, many networks including LPWANs gain access resulting in overcrowding and congestion. This research focuses on the optimisation of unlicensed spectrum occupied by LPWANs at 868MHz and 915MHz using the Optimised Frequency Hopping Model. The study focuses on these frequencies because these are where most LPWANs are found. The major challenge faced by these unlicensed spectra will continue to impact negatively on the network performance. For instance, there is a noise floor called the ambient noise which is a background noise that is present in the unlicensed spectrum due to signals of different wireless devices making use of these frequencies. On the other hand, Sigfox and LoRa; two of the most popular LPWANs operate at Sub-GHz frequencies of 868MHz and 915MHz in Europe and America. These unlicensed spectrum frequencies are susceptible to different problems like interference due to coexistence of networks and ambient noise. As long as it is a free-to-use spectrum, more devices will transmit at these frequencies below 1GHz causing disruptions to the services of LPWANs. It is therefore imperative to optimise the unlicensed spectrum in order to provide the 'city of the future' with seamless connectivity. Models like Open Sharing Model (OSM), Hierarchical Access Model (HAM), Dynamic Spectrum Sharing Model (DSSM) and Cooperative Spectrum Sharing Model (CSSM) were considered and tested. Their performances in the unlicensed spectrum at the frequencies of 868MHz and 915MHz showed little improvement against ambient noise and interference when compared to the proposed Optimised Frequency Hopping Model. Furthermore, the proposed Optimised Frequency Hopping Model showed a better performance against the troublesome ambient noise and interference, the two major problems associated with an overcrowded unlicensed spectrum. Simulations were carried out using MATLAB and results showed that the proposed method reduces interference at frequencies of 868MHz and 915MHz to the barest minimum. Hence, there is a decrease in latency, increase in channel capacity, high throughput, reduction in degradation of performance and higher quality of service QoS.

CONTENTS

ABBREVIATIONS

AMC:	Adaptive Modulation and Coding
API:	Application Programming Interface
ARQ:	Automatic Repeat Request
ATPR:	Adaptive Transmit Power Control
BS:	Base Steering
CR:	Cognitive Radio
DER:	Data Extraction Rate
GSM:	Global System of Mobile Communication
IoT:	Internet of Things
LoRa:	Long Range
LPWAN:	Low Power Wide Area Network
LTE:	Long Term Evolution
MAC:	Medium Access Protocol
MATLAB:	Matrix Laboratory
MBS:	Multiple Base Stations
NB-IoT:	Narrow Band Internet of Things
OFHM	Optimised Frequency Hopping Model
OSSM:	Optimised Spectrum Sharing Model
QoS:	Quality of Service
SA:	Spectrum Analyser
SAT:	Smart Antenna Technology
SSP:	Spatial Signal Processing
UAV:	Unmanned Aerial Vehicle
Wi-Fi:	Wireless Fidelity
WSN:	Wireless Sensor Networks

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CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Radio spectrum sharing is known to be one of the most important aspects of radio wireless communications. The evolution of different technologies making use of the spectrum is increasing on a daily basis. These emerging technologies bring about innovations that make communication far better than before. Nowadays, Low Power Wide Area Networks (LPWANs) have become an integral part of internet of things (IoT) technologies and their presence permeates every aspect of life. However, the deployment of these technologies faces new obstacles in the unlicensed spectrum because so many other technologies are found there, each causing interference, ambient noise and obstructing proper network communication leading to poor quality of service (QoS). LoRa, Sigfox and NB-IoT are examples of LPWANs that make use of the unlicensed spectrum, operating at low cost and deployed for long distance coverage. In the same vein, smart cities and all its features have become popular around the world due to LPWAN technology adopted and because it boasts of good features like low power, long range, robustness and affordability. Therefore, the utilisation of IoT/LPWANs in smart city focuses on how smart applications can improve the wellbeing of the citizens and improve their quality of lives [1]. The technologies making use of LPWANs are found in the Sub-GHz unlicensed spectrum where many network users can access freely [2]. Due to the importance of LPWANs and its operations in the unlicensed spectrum, they have attracted research interest in both the academia and industry leading to improvement in their overall network performance. Their features can work with different and numerous devices which are interconnected to the IoT networks, enhancing the adoption for smart cities. There are several applications of LPWANs like those found in the Low Throughput Network (LPN), sensors as well as control systems, they continue to have notable impact on day-to-day communication among humans and the immediate environment. Some of the major uses of the LPWANs are found in the transportation management system, a subset of smart cities, where sensors which are placed in strategic locations can detect the working condition of lights on 24 hours basis, thus reducing congestions on the road. In smart cities, smart watering systems feature advanced sensors that instantly detect water leakages and flow-related issues. These sensors promptly alert authorities to any anomalies thereby enabling quick resolution. Overall, this will enhance efficient city water management system [3].

It is important that unlicensed spectrum is available so that LPWANs can function well in the context of smart city applications [4]. The unlicensed spectrum is faced with the challenges of underutilisation as well as overcrowded and sometimes misdetection of available spectrum holes when LPWANs access the spectrum. The reason for this weakness is not far-fetched, because they are installed in the overcrowded unlicensed frequency bands. In these bands, so many network users are transmitting and each user wants a good use of the spectrum so as to have a better communication and because no user is licensed to use them, it becomes more challenging. To address or minimise these obstacles, there is need to optimise the unlicensed spectrum occupied by LPWANs for better performance so as to have efficient communication as well as higher quality of service (QoS). Many authors have talked about cognitive radio as an intelligent radio communication system specifically designed to address the problem of spectrum scarcity or spectrum underutilization, but it also has its limitations [5]. One of the limitations is that there must be proper detection of a vacant holes before communication can be shifted there. Without the efficiency of the spectrum, the noble goals of smart cities may not be achieved.

1.2 MOTIVATION

Today, many cities in the world are becoming smarter because of the need to have efficient cities that will run on modern technologies. LPWAN technology is the technology adopted for smart cities and they are found in the unlicensed spectrum [6]. In the unlicensed spectrum, especially in the ISM frequency bands (433MHz, 868MHz and 915MHz) the challenges of technology coexistence, interference and ambient noise persist. These challenges militate against LPWANs in the smooth running of smart cities. Considering a situation where there is high interference due to another technology deployed at close proximity in the unlicensed spectrum, the LPWAN network could become unreliable leading to loss of important data or information needed for a city's critical decision making [7]. The motivation is to minimise to the barest minimum effects of interference and ambient noise in the unlicensed spectrum occupied by LPWANs.

1.3 PROBLEM STATEMENT

In the unlicensed spectrum, many independent networks are deployed in close proximity and interference between them becomes a problem adversely affecting the performance of LPWANs. As these numerous networks operate in close proximity, ambient noise will also continue to occur, thereby degrading their performances in the unlicensed spectrum. Since these two problems persist, the performance of the unlicensed spectrum becomes unreliable for smart city applications. Furthermore, since LPWAN protocols operate in the unlicensed spectrum under 1 GHz (use case frequencies considered in this study includes 868 MHz and 915 MHz), the continued occurrence of multiple LPWAN networks within the same spectrum mostly leads to low throughput and high latency as well as poor quality of service (QoS). Consequently, overall performance of the LPWAN network systems in the unlicensed spectrum becomes unreliable, unstable and have poor quality of service.

1.4 AIM AND OBJECTIVES

The aim of this study is to design a model that would optimise an unlicensed spectrum to improve LPWAN utilisation for smart city applications. The objectives are:

- To develop a model that will improve unlicensed spectrum at 868MHz and 915MHz frequencies.
- To minimise ambient noise and interference which affect communication and transmission at these 868MHz and 915MHz frequencies.
- Validate the designed model on a coexisting use case network.

1.5 METHODOLOGY

The research methodology adopted was using MATLAB simulations for various network parameters at 868MHz and 915MHz frequencies and developing an Optimised Frequency Hopping Model (OSSM) for unlicensed spectrum at these two frequencies.

1.5.1 Optimised Frequency Hopping Model

We studied other spectrum sharing models in the unlicensed bands and a model known as Optimised Frequency Hopping Model was proposed which showed a better performance of the spectrum at 868 MHz and 915 MHz than other models studied.

1.5.2 Ambient Noise and Interference of Unlicensed Spectrum

The major work of the research is minimising the ambient noise and interference found in the unlicensed spectrum at frequencies of 868MHz and 915MHz. Ambient noise and interference were studied at these given frequencies, and we were able to address it in the course of the research. The Optimised Frequency Hopping Model reduced the two most troublesome phenomenon found in the unlicensed spectrum to the barest minimum.

1.5.3 Validation of the Designed Model

The simulation results showed a significant improvement in the performance of the unlicensed spectrum against interference and ambient noise. The simulation results validate the developed Optimised Frequency Hopping Model as a better optimisation tool at use case frequencies of 868MHz and 915MHz unlicensed bands.

1.6 CONTRIBUTION TO KNOWLEDGE

A model known as Optimised Frequency Hopping Model (OFHM) is developed. This model is preferable to other models for spectrum optimisation. The study began by reviewing research work done in the area of spectrum optimisation, and some models were tested to see their performance in the unlicensed spectrum at the frequencies of 868MHz and 915MHz. Though some showed a better performance, they did not adequately address optimisation in the unlicensed spectrum by minimising the coexistence problems. Therefore, a model is developed that practically minimises the effects of ambient noise and interference at the frequencies under consideration. The developed Optimised Frequency Hopping Model gave the desired results and it is the model that can be adopted for spectrum optimisation of LPWANs (occupying 868MHz and 915MHz frequencies), The research showed that the OSSM produced desirable results with simulations showing low latency, interference reduction and high channel capacity. Results also showed overall improvement in performance of the unlicensed spectrum.

1.7 RESEARCH OUTPUT FROM THE STUDY

Published Conference Papers and Book Chapters

1. Fadeyi Johnson, Elisha Didam Markus, and Adnan M. Abu-Mahfouz. "Technology coexistence in LPWANs-A comparative analysis for spectrum optimization." *2019 IEEE 28th International Symposium on Industrial Electronics (ISIE)*. IEEE, 2019.
2. Fadeyi, Johnson, and Elisha Didam Markus. "A Review of Interoperability of IoT Systems for Smart Cities." *Smart Trends in Computing and Communications* (2022): 747-758.
3. Markus Elisha D., and Johnson Fadeyi. "Smart Cities and Spectrum Vulnerabilities in Long-Range Unlicensed Communication Bands: A Review." *Applied Soft Computing and Communication Networks* (2021): 207-220.
4. Fadeyi Johnson and Elisha Markus, "Spectrum Optimization of Low Power Wide Area Network Utilization in Smart Cities", Maricon ICONIC Conference 8th-9th December 2022.

1.8 OUTLINE OF THE DISSERTATION

Chapter 1 provides an introduction to the study. It lays the foundation for the research work with the motivation for embarking on the study.

Chapter 2 reviews literature in the field and it provides one of the reasons for the study. Here, the works of other researchers were thoroughly reviewed, and the research gap was identified.

Chapter 3 presents the research methodology and a discussion in the area of study.

Chapter 4 takes a look at different simulation results that were obtained and discusses the tests conducted in achieving those results. Also, an explanation of the graphical representation of the simulation results was done in this chapter.

Chapter 5 provides the conclusion as well as future direction for further research.

Chapter 6 presents the references and the acknowledgement of the literature used for this academic work.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

In looking at Low Power Wide Area Networks and its utilisation in smart cities, we considered the roles of unlicensed spectrum. Also, for smart city to function properly, it needs an efficient unlicensed spectrum devoid of any hindrance to its functionality. The work of various researchers in this field were reviewed to see what has been done and the research gaps that needs to be filled.

2.2 A REVIEW OF LPWANS

2.2.1 Sigfox

Sigfox is a popular network technology developed by a French company named Sigfox. It is a narrowband or ultra-narrowband technology that is practically employed to provide long range communications which is highly important for smart city adoption. This technology uses a standard radio transmission method known as binary phase-shift keying (BPSK), and it takes a small portion of the spectrum and changes the phase of the carrier radio wave to encode the data [11]. A drawback for this promising technology is that only one of its networks can be deployed in an area due to exclusive arrangements with the selected network operator. More important is that coexisting with other technology is difficult without interference [12].

2.2.2 LoRa

LoRa is a technology that uses the same radio for a receiver on the base station and at the endpoints. It uses a specific modulation method that is based on the spread spectrum so that it can move on long range which is essential for smart city. Since the cities cover a wide area, it is important that the technology involved covers several kilometers to provide necessary network for transmission of data [13]. Besides, the use of the chips in the LoRa technology helps provide the robustness that is needed in mitigating multi-path fading. The challenge of multipath fading seriously affects signals and passing across information to the desired end. To improve spectral efficiency and increase the network capacity, the modulation of the LoRa technology features six different data rates resulting from orthogonal codes [14 15].

2.2.3 DASH 7

DASH7 is another technology for long communications used in the smart city applications [16]. It is found in the ISM unlicensed bands like LoRa and Sigfox. One unique feature of this technology is that it uses wake up signal to achieve low power, low latency and its architecture. When considering the network configuration, the whole network of devices is considered as transitional and there is no need routing information. Quite recently, it has also found its usage in the smart city, but not as strong as other long range communication technologies found in the unlicensed bands [17]. This technology uses radio frequencies mainly in the 433 MHz, 838MHZ, 915MHz range to provide a bit secure, reliable, and fast wireless connection.

2.2.4 Telensia2

This LPWA technology provides end to end solutions for internet of things applications. It uses an ultra-narrow band (UNB) modulation technique and operates in the unlicensed industrial scientific and medical (ISM) frequency bands at low data rates for long distance. Telensia's areas of strength is in smart lighting, smart parking and smart metering which are all parts of the smart city initiative [17].

2.2.5 Ingenu

Ingenu is formerly known as ON-RAMP. It is another innovation that has made considerable impact on long range communications deployed in smart cities. It uses Random Phase Multiple Access (RPMA) and differentiates itself from the market because of its flexible network system. It is found in the 2.4 GHz of Industrial Scientific and Medical bands and hence is prone to high level of interference. However, it has good Multiple Access Control (MAC) implementation which enables proper transmission at high frequency [18]. At these higher frequencies the propagation path loss is more significant.

2.2.6 IQRF

The technology is found in ISM band of the unlicensed spectrum [19]. A wireless packet communication via the radio frequency, it is for general use where wireless connection is needed. It may be point to point or in a complex network like the internet of things (IoTs) which is what a smart city requires [20 21]. It has a basic transceiver module with built in operating system implementing the link layer and network layer which support mesh network utilisation. However, it supports the mesh topology by default; hence it allows the interconnection of all devices [22 23].

Table 1: LPWAN utilisation and spectrum features in Smart Cities

LPWAN	Key Spectrum Features	Advantages for Smart Cities	Disadvantages for Smart Cities
LoRa	(i) Since this technology uses the unlicensed bands with many technologies, control over bandwidth is lost [24]. (ii) It operates at 868/433MHz and in the US 919 MHz frequency bands.	(i) Low power consumption (ii)Secure bidirectional communication (iii) Low cost (iii)Well secured with encryption and authentication. (iv) Resistant to multipath fading because it uses the chip spread spectrum modulation. (v) Long range capabilities (vi) Cost effective for large deployment.	(i) Limited downlink capabilities (ii) Not open standard (iii) Find it difficult to coexist with other technologies in the spectrum without interference

		(vii) Long battery life	
Sigfox	(i) It cannot force users of the same frequency band in the unlicensed bands to curtail their usage if their behaviors become dangerous to the services rendered by the Sigfox network. (ii) Sigfox operates in the frequency band of 868MHz.	(i) Low cost of network operation and ownership (ii) It can help communicate with buried underground equipment [25]. (iii) Higher budget link for improved coverage (iv) Provides backup connectivity for higher bandwidth devices.	(i) Narrow band spectrum emitted by a single Sigfox end device can cause interference to an existing wide band device. (ii) Supports one-way communication without acknowledgement this is not good enough for smart city that requires two-way communication (iii) Increased power consumption.
DASH 7	(i) Operates in the ISM unlicensed bands (ii) This technology is known to work at 433MHz, 838MHz and 915MHz.	(i) Operates in the ISM unlicensed bands (ii) This technology is known to work at 433MHz, 838MHz and 915MHz.	(i) High signal attenuation (ii) Limited service radius which is not suitable for smart city requiring long range communications.
Telensia	(i) It is found in the unlicensed Sub GHz band. (ii) It is found in the following frequencies.868MHz,915MHz,430MHz	(i) Simpler and less expensive than other LPWANs (ii) Collision avoidance (iii) Low cost	(i) It does not cover a long range like other LPWANs e.g., 1km (i) It consumes more power
Ingenu	(i) Found in the unlicensed 2.4GHz bands.	(i)Very good technology stacks (ii)Very high capacity	(i) Exposed more to interference.

		(iii)Good commercial traction	(ii) The underlying technology takes much more processing power.
IQRF	(i) Works at 868 MHz, 916 MHz and 433 MHz frequency bands (ii) Operate in a multiple channel like 67channels in 100KHz bandwidth	(i) It has a fast response (ii) Better resistance against interference. (iii) Easy interoperability (iv) Extra low power consumption	(i) Low speed and low data volume.
Weightless	(i) It can operate in the sub 1GHz unlicensed band or licensed band.	(i) Good range in urban environment (ii) Coexist with other RF technologies with minimal interference using advanced demodulation (iii) Good uplink and downlink capabilities	(i) Have a low battery life but LPWANs required for smart city need a longer battery life (ii) It requires TV white space spectrum for its operation.

Table 1 demonstrates a review of the various unlicensed band technologies in terms of their advantages or disadvantages in their deployment and utilisation for smart cities. LoRa technology has the most benefit to be considered for the smart city applications. It has bidirectional communication link and a bit secured with encryption like Advanced Encryption Standards (AES) that can make the network safer. Next is Sigfox which also shows some benefits as regards its deployment in the smart city. Considering the cost of deployment, LoRa, Sigfox and Telensia are the best, and mostly suited for larger area of smart cities. In terms of ruggedness against interference, Weightless and IQRF are the best. Also, DASH 7, Telensia and Ingenu prove to be better technologies for smart city adoption because they have high technology stacks.

2.3 CHALLENGES OF SPECTRUM UTILISATION IN UNLICENSED BANDS

2.3.1 Interference

Interference is a major impediment to reliable and efficient wireless transmission and can negatively impact performance and coverage in high-capacity mobile systems. As more spectrums are used in the unlicensed bands, numerous networks with different technologies cause interference to one another making the spectrum underutilised affecting the quality of service [24]. Dealing with escalating levels of interference is a critical issue for wireless systems designers and network service providers alike for smart city adoption. While interference has been an issue affecting the licensed spectrum bands for years, it has now become a serious challenge for unlicensed bands and spectrum utilisation for smart city.

2.3.2 Power Control

Another issue is power control. This adversely affects the utilisation of the spectrum for smart city. It comes in terms of regulation which controls the amount of power that can be used during transmission. Regulations for usage of the unlicensed bands imposes limits on the maximum duty cycle (e.g., the amount of time it is allowed to send and become compared to the amount of time it is required to remain ‘silent’) of a single transmitter. In the long-range networks, mostly found in the unlicensed bands, the restrictions apply equally to the devices and the base stations that feed the devices with the network coverage [26]. Therefore, such networks are much worse at managing power than their licensed counterparts. Clearly, the issue of power will continue to constitute a serious challenge to spectrum usage for effective communications and spectrum utilisation.

2.4 CHARACTERISTICS OF SMART CITIES

The smartness of a city is given by a lot of physical infrastructure and other technological innovations that support the economic development of such cities and to ensure that they are not socially excluded. The environment also needs to be well protected from carbon emissions so that the quality of air is guaranteed as well as water and other environmental conditions. The ISO standard 37120/2014 titled the sustainable development of communities emphasises key indicators that show how cities are performing with regards to urban services and the quality of lives of the city dwellers, ranging from economy to education, environment, finance, transportation, energy and urban planning etc. These indicators about the performance of the modern smart cities will be a reference for city managers, politicians, researchers, travelers, investors and other professionals which will make them put in place policies that help the city become more prosperous and economically attractive. In these cities, the ICT which includes LPWANs are essential for efficiently running the infrastructures that are critical to the sustainability of these cities [27].

Fig 1. Components of smart city [27]

Figure 1 shows the components of smart city where there is smart health, smart energy, smart agriculture, Internet of Things, smart home, open data source, and smart retail. Each component makes use of the sensors attached to them, transmitting data constantly. The transmitted data is interpreted and used for the benefit of smooth running of the smart city.

It can be seen that all critical infrastructures are interconnected and under one roof for the efficient functioning of the smart city.

2.5 LPWANS AND SMART CITIES

Smart city applications are gaining prominence among major cities of the world and LPWANs continue to play significant roles in the realisation of the city of the future. Without this technology, the smart city dream would only be a mirage. Hence, smart city applications require the network coverage to cover the whole of the city and equally provide efficient services. These applications involve the collection of data of many important parameters which will enhance the performance of the city. Such parameters include pollution, waste level, humidity, temperature, mist, fug etc. Obviously, large number of nodes are needed for the proper deployment of the technology as regards smart city, [28] therefore, the network needs to have a large capability and must be scalable. There will always be several nodes of LPWANs deployed in the city so that the whole city can be covered and to ensure there is low consumption of power at a moderate level. As part of the smart city initiative, the ecological balance of the environment can be monitored by smartly placed sensors which will in turn inform the state officials of the pollution monitoring in the environment. In the area of waste bin management, LPWANs will help for proper disposal of the waste bins. The sensors can be placed on the smart waste cans tracking the level of the position of the waste in the cans. When they are full, they can be easily emptied. In the fire protection management systems, LPWANs can help detect fire alarms through sensors and quickly send emergency notification to the department responsible for the task [29].

LPWAN technologies will continue to impact smart city applications in various ways. They provide the ability to connect numerous devices at the same time and share information which are critical to the betterment of the city. As more cities around the world are becoming smarter, they will continue to make use of this great innovation. Moreover, a technology like LoRa can reach several kilometers and a lot of devices connected to each base station. Then it has the capacity to provide large connectivity and penetrating deep into areas which traditional cellular networks will not be able to reach [30] [31].

In some instances, there may be network collisions which occur rapidly and allow the capacity of the network to be filled up quickly. At this stage, monitoring the services is not the only thing that needs to be done, the reliability of the wireless network also needs to be considered to ensure that it aligns with the required parameters of the available network [32]. A model can then be formulated due to the signal strength of the other available networks as well as that of devices. The number of packets generated during this time can be used to compute the PER. The outcome will then have an effect on the network reliability in large geographical areas [33].

2.6 RELATED WORK

Ahmed M. Abass et al in their research talked about NB-IoT and failed to consider other LPWANs in the broader sense. They narrowed their work to smart meter networks in smart cities. In the real sense of it, smart metering is just a component of smart city management. However, their paper introduced a new integrated approach which argued that in the future, more demands for smart meters businesses for maximum use of the resources should be used to serve high numbers of NB-IoT users. Going further, they presented that the management of traffic as regards NB-IoT requires efficient use of spectrum and is a newly opened issue at the IoT 5G. In their work, they achieved spectra efficiency to improve performance of smart meters. They also reduced the signaling burden that occurred during each transmission request for the smart meter businesses. Although, their simulation results showed a great improvement in spectrum utilisation and efficiency, it failed to account for the spectrum utilisation involving other LPWANs. The performance of NB-IoT cannot be used to conclude other LPWANs since their research focused on technology in LPWANs [34]. Also, it was assumed for an ideal propagation without any impairment and in some situations, obstacles like interference will show up, mitigating against efficient propagation of these LPWANs.

In the course of making the spectrum better for improved performance, Weiss eta al proposed a new approach that is known as spectrum pooling. This approach allows public users access to a primary user licensed spectrum. Also, it is applicable to unlicensed spectrum because when one user utilises the spectrum, the other user can wait till when there is a spectrum hole which signifies the availability of spectrum. Moreso, it involves bringing together spectra ranges from various spectrum owners, be it the military or other licensed spectrum owners to a general pool.

This shows that many mobile radio systems can coexist within a particular range of frequency. The overall aim of the spectrum pooling is to enable the spectrum to function efficiently by putting a new mobile communication system which overlaps the previous one with the aim of making no changes to the spectrum of the licensed owner. The method adopted still could not account for the interference that can occur when such communication systems are put together [35].

Besides, Wang et al proposed a method which can quantify the queue dynamics of many secondary users of multiple channel cognitive radio networks. The method designed involves the critical below the layer functioning models which include sensing anomalies in the spectrum, medium access control (MAC) protocols and adaptive technologies like automatic repeat requests (ARQ), adaptive modulation and coding (AMC), and the limited buffer size. To show the impact on quality of service (QoS) performance for secondary users, they modelled it using the Markov Chain (FSMC). Consequently, the throughput and average queueing delay became better which showed an increase in performance as a result of their proposed methodology [36]. It failed significantly to show the impact on latency and channel capacity.

Balapuwaduge et al., [37] proposed two queueing schemes for secondary users. Their proposition is based on a lag in the tolerance of abrupt elastic services. They agreed that in multiple frequency cognitive radio networks, the highest capacity can be achieved by the secondary users by using dynamic channel assembling (CA) methodologies. The drawback of the methodology is that the channel slots suffer from increased blocking and instant stoppage when the primary users become active. According to them, in the multiple frequency network with a lot of network traffics, more than one queue is independently assigned to frequent and non-frequent users.

The frequency access chances are evenly distributed between these many queues in such a way that the frequent receivers have upper access than others. Markov chain access similar to Wang et al approach was used to get the performance of their proposed CA strategy. As can be seen, what these researchers have done was to analyse the performance of one or two LPWANs without considering majority of the LPWANS as regards their performances in the smart city and also how the spectrum will be improved. The research will fill this gap.

Xin Liu et al., proposed an unmanned aerial vehicle (UAV)-based CR is proposed to improve the spectrum sensing performance [38]. The essence of spectrum sensing is to achieve a better spectrum utilisation and ensure good quality of service. They analysed that UAV performs a rotational flight and the primary user is at the center and then the period of the flight is divided into sending radian and the transmission radian. This will enable the UAV to access the spectrum when the absence of the primary user has been detected withing the radian of sensing. When this happens, the spectrum sensing optimisation is proposed as an optimisation problem that need to be removed. However, these steps are taken so as to maximise the throughput of the UAV simply by making the sensing radian better to overcome the constraint of throughput interference. They also proposed virtual cooperative sensing, all in an effort to get a better performance for the spectrum for fading channel. They talked about increasing the number of sensing slots so that the throughput can be increased. They failed to account for spectrum optimisation of LPWANs as it relates to smart cities.

Minho Jo et al. argued that to make the spectrum better utilised, they proposed combined spectrum sharing algorithm. In their research work, it was discovered that many users can access both networks at the same time using the same spectrum resources. The method is such that it reallocates the occupied channel by another user to meet the quality of service of each user. In the proposed algorithm, the spectrum utilisation is enhanced by dividing the entire spectrum into three zones, the determination zones occupied by GSM or LTE users, fixed zones for GSM and the last one for LTE users. Though their work brought about improvement of the spectrum, it only focused on GSM and LTE, it did not account for low power wide area networks (LPWANs) which are utilised for smart cities [39].

Eduardo Sallum et al. proposed how to improve the quality of service in LoRa can be improved using the optimised radio resource management. They argued that improving the quality of service of LoRaWAN can be improved by fine tuning some specific radio parameters. Using their mixed integer linear programming problem formulation, they found optimal setting for spread factor and carrier frequency radio parameters as well as network traffic specifications to improve the Data Extraction Rate (DER) as well as reduce the packet collision rate and the energy consumption in LoRa networks. The effectiveness of their optimisation method was demonstrated by simulations which showed a lot of improvements as noted in the increase in DER and number of collisions. The collision is 13 times smaller than the LoRaWAN random distribution.

Their work only account for LoRa and no other low power wide area networks (LPWANs) and it failed to account for spectrum optimisation for better performance of LoRa and its relationship with smart cities [40]. As it can be seen, there is a research gap created by the work of these authors. None of them addressed the issue of spectrum optimisation in the unlicensed bands at frequencies of 868MHz and 915 MHz for its utilisation by low power wide area networks (LPWANs)

2.7 PERFORMANCE IMPROVEMENT OF SPECTRUM DUE TO OPTIMISATION

Smart city applications are gaining prominence among major cities of the world and LPWANs continue to play significant roles in the realisation of the city of the future.

Without this technology, the smart city dream would only be a mirage. Hence, smart city applications require the network coverage to cover the whole of the city and equally provide efficient services. These applications involve the collection of data of many important parameters which will enhance the performance of the city. Such parameters include pollution, waste level, humidity, temperature, mist, fog etc. Obviously, large number of nodes are needed for the proper deployment of the technology as regards smart city, [41] therefore, the network needs to have a large capability and must be scalable. There will always be several nodes of LPWANs deployed in the city so that the whole city can be covered and to ensure there is low consumption of power at a moderate level. As part of the smart city initiative, the ecological balance of the environment can be monitored by smartly placed sensors which will in turn inform the state officials of the pollution monitoring in the environment. In the area of waste bin management, LPWANs will help for proper disposal of the waste bins. The sensors can be placed on the smart waste cans tracking the level of the position of the waste in the cans. When they are full, they can be easily emptied. In the fire protection management systems, LPWANs can help detect fire alarms through sensors and quickly send emergency notification to the department responsible for the task [42].

LPWAN technologies will continue to impact the smart city applications in various ways. They provide the ability to connect numerous devices at the same time and sharing information which are critical to the betterment of the city. As more cities around the world are becoming smarter, they will continue to make use of this great innovation. Moreover, a technology like LoRa can reach several kilometers and a lot of devices connected to each base station. Then it has the capacity to provide large connectivity and penetrate deep into areas which traditional cellular networks will not be able to reach [43].

In some instances, there may be network collisions which occur rapidly and allows the capacity of the network to be filled up quickly. At this stage, monitoring the services is not the only thing that needs to be done, the reliability of the wireless network also needs to be considered to ensure that it aligns with the required parameters of the available network. A model can then be formulated due to the signal strength of the other available networks as well as that of devices. The number of packets generated during this time can be used to compute the PER. The outcome will then have an effect on the network reliability in large geographical areas [44].

2.8 SPECTRUM OPTIMISATION TECHNIQUES

2.8.1 Cognitive Radio

Many authors have described cognitive radio using different terminologies. Some call it dynamic cognitive radio, intelligent radio technology, intelligent cognitive radio, radio resource management. Irrespective of the name, the concept is the same, which is to dynamically and intelligently optimise the spectrum for efficient use. Admittedly, the industrial, scientific and medical (ISM) radio bands are found in the unlicensed bands of the spectrum though they also have fixed spectrum allocation. Cognitive radio can help overcome some of the challenges faced by the conventional wireless networks [45]. The cognitive radio works when there is persistent interference in the spectrum. It intelligently senses the environment, detects interference and adjusts the network parameters in such a way as to move communications to a clearer portion of the spectrum and continues to monitor interference in the new portion of the spectrum [46].

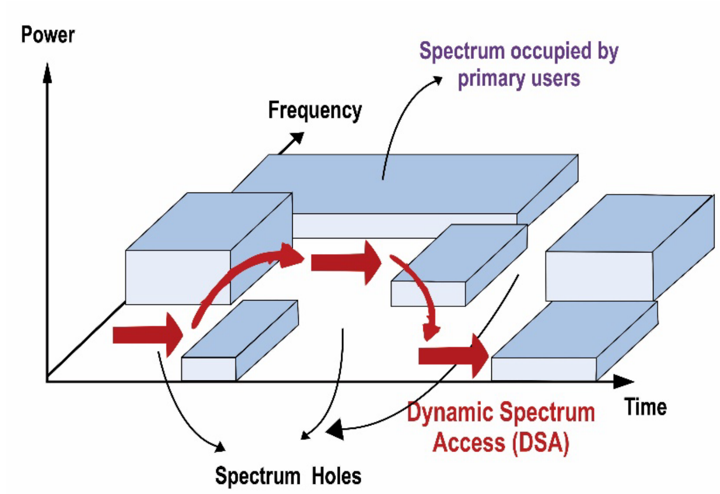

Fig. 2 Access in a cognitive Radio [47]

2.8.2 Spatial Signal Processing

Spatial processing can be used to cancel interference from multiple sources which include mobile transmitters that make use of sophisticated signal processing algorithms. The major advantage of using the spatial signal processing is that it can be used to remove the longer bursts (several milliseconds in duration and longer) which appear on the channel. Burst here refers to interference which is constantly found on the channels as a result of noise and many networks that are closely packed together. Using the spatial signal processing will improve Signal-To–Noise ratio performances of the uplink and downlink of the network [49].

2.8.3 Band Steering

Since some LPWANs use the 2.4 GHz band of the ISM band, there is a congestion as well as interference on the unlicensed band due to massive deployment of different technologies. Band steering can be used to move communication from the 2.4GHz to 5.0GHz frequencies or vice versa and this will mitigate the overload or congestion. Band steering takes into account the adjustments in path loss as communication shifts from more congested 2.4GHz to less congested frequency bands. The transition helps optimize network performance by navigating through different frequency bands based on congestion level. It is crucial to ensure that when the channel bands switch, they do so in a controlled manner. This is necessary to accurately understands the status of the band to which the client transitions. It will give a clear picture of what technology or devices are found making use of the said band [50].

2.8.4 Using Spectrum Analyser

The spectrum analyser is a test instrument which can be used to see signals across different frequencies. The adjustment of the analyser will be done in such a way as to measure energy within group of frequencies contained within a bandwidth i.e., frequency domain measurement. With access to information carrier-to-interference (C/I) ratio from the radio manufacturer and a spectrum analyser with adequate dynamic measurement range and noise floor, the interfering signal level would be measured at the input of the affected receiver. Accordingly, when the source of the interference is located, the polarisation of the antenna will be changed from horizontal to vertical which will then mitigate the effect. A higher antenna with a larger beam width can also be used to resolve the interference problem encountered. By removing the antenna and placing the interference producing signal in the area the main beam and the adjacent lobe of the corrective antenna will mitigate the interference signal enough to allow the network to be strong for higher quality of service [51].

2.8.5 Multiple Base Stations

A high data extraction rate (DER) of a network means the network is performing well under interference and cannot be affected by other interfering networks at close proximity. However, in the work of Thiemo Voigt et al it was said that one of the best ways to eliminate interference is to deploy multiple base stations which will increase the Data Extraction Rate for the particular sensor nodes [52]. The deployment of multiple base stations means that the signal strength produced by these base stations will be strong at the receiver's end. The more the concentrated base stations are, the more the network produced in the location which can serve as many users as possible. A packet transmission is counted as successful when the base stations receive the packet transmission.

2.8.6 Smart Antenna Technology

The smart antenna technology is one of the methods used to overcome the challenges faced by networks in need of a better spectrum for quality services. The smart antenna system consists of multiple antennas at the transmitter or the receiver side of the communication link where the signals at the terminals are processed in such a way the spatial dimension of the radio channel are increased [53]. However, it depends on whether the access and processing are done at the receiver or transmitter end. It thus has a definition in that it makes use of Single Input Multiple Output (SIMO) or MIMO. The network capacity can be improved using the link quality mitigation of a number of obstructions to a good communication access such as multi-path fading and interference. The smart antenna makes use of the concept of diverting all the energy of the transmitted signal to a particular receiver thereby receiving high power antenna gain. The adequate control of the received and transmitted power as well as making use of other properties of the received signal will help mitigate interference [54 55].

2.8.7 Adaptive Transmit Power Control

This is another method used to mitigate interference and ensure spectrum efficiency. The idea is to manipulate the power of the transmitters in such a way that it helps reduce interference between the link and other services [56 57]. When a new communication system is assigned a frequency band close to the continuously functioning band in high density environment, the transmit power of it is adaptively controlled according to the information supplied by the high priority network receiver [58 59 60]. The power should be controlled in such a way it is not too low or too high but balanced to ensure that optimal performance of the spectrum. It is important to calculate the peak allowable transmission power so as to get better network performance. Information such as the position of the interfering transmitters and the victim receivers are important in adjusting power to get the desired result [61 62].

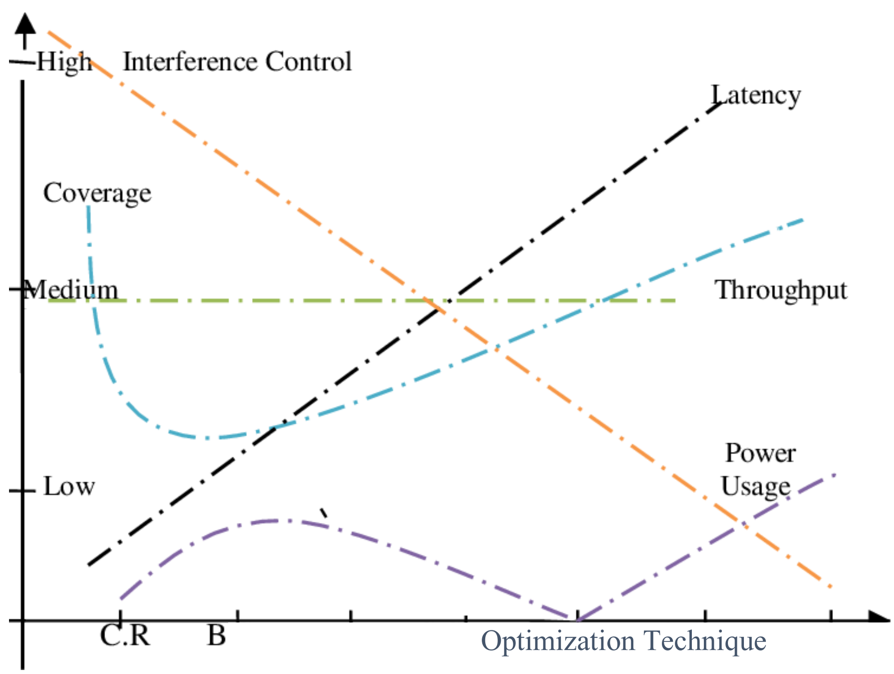

Fig. 3: Various optimisation techniques used for spectrum optimisation in the unlicensed spectrum

Figure 3 shows the various optimisation techniques used for spectrum optimisation and their performance against interference. Cognitive Radio depicted C.R performed well against interference having the highest interreference control compared to other optimisation techniques. Due to its superior interference management, this technique also enables broader network coverage. This means that when the interference levels are low, the network has the capacity to extend its reach over a wider area. It has a moderate throughput meaning that more networks can transmit data in the unlicensed spectrum. Cognitive Radio has the lowest latency showing that data can be transmitted within a short period of time. Then, followed by the Band Steering which also has a good interference control as shown in the figure. It also has a medium throughput which means more networks can be in the unlicensed band when this technique is used for spectrum optimisation. Furthermore, the Adaptive Transmit Power Control is another good technique to mitigate interference. Like the two previously mentioned techniques. It also offers the advantage of lower latency, ensuring that data is transmitted quickly. Smart Antenna Technology comes after in term of interference control showing better performance against interference too. The throughput for this technique is the same for Cognitive Radio, Band Steering, and Adaptive Transmit Power Control. Spatial Signal Processing is also a technique used for spectrum optimisation and can control interference but not like other techniques. The latency for this technique is high meaning that data is transmitted at a longer time. The throughput is the same for it like the other optimisation techniques. Using Spectrum Analyser can help mitigate interference, but not as good as the Cognitive Radio.

Table 2: Spectrum optimisation techniques, advantages, disadvantage and application to smart cities

Spectrum Optimisation Technique	Advantages	Disadvantages	Application LPWANs
Cognitive Radio	(i) It can intelligently and automatically change channels. (ii) The cognitive radio can easily detect interference in the spectrum and adjust the operating parameters of the cell sites throughout the network. (iii) By sensing environmental and inadvertent man-made radio interferences, cognitive radios can select frequency channels with a higher Signal to Noise Ratio SNR thereby improving quality of service. (iv) It also overcomes spectrum scarcity by sensing spectrum utilisation (irrespective of channel allocation), cognitive radios can broadcast on unused radio spectrum.	(i) Needs proper sensing to determine when the spectrum is vacant. (ii) It can cause interference to the primary users. (iii) The data may be eavesdropped or altered without notice. (iv) The channel might be jammed or overused by the adversaries.	It supports IoT and makes spectrum available in the ISM bands used for LPWANs

Band Steering	(i) Easy movement from 2.4 GHz to 5GHz when there is congestion and interference (ii) Simultaneous and optimal use of the two important bands of frequencies. (iii) Only moves clients that has enough strong signal. (iv) With band steering the wireless network will be able to monitor all clients in the surrounding area.	(i) There is always a path loss as the client move from 2.5 GHz to 5GHz which affects signals needed for communications (ii) It does not account for the condition the band it is moving to.	IoT devices are found in 2.4 GHz bands where band steering can easily move devices out if IoT devices cause congestion and interference. LPWANs are found in the 2.4GHz band where congestion occurs.
Using Spectrum Analyser	(i) It can easily locate the source(s) of interference. (ii) Hardware can easily be replaced at the site. (iii) Measure interference across different spectrum and transmit better channel power at the receiver site.	(i) It is too manual and cumbersome. (ii) It causes interruption in communications as	It can be applied to so many LPWANs like Sigfox, LoRa, and NB-IoT base stations.
Smart Antenna Technology	(i) Increase range or coverage. (ii) Lower power requirement and cost reduction. Directing all the transmitted energy towards the user antenna.	(i) Difficult to function well in a multi-parametric continuously changing environment (ii) Implementation cost still very high.	Because of its high data usage, it can apply to critical IoT supported by LPWANs.

	(iii) Improve Link quality and reliability (iv) Saves Power		
Multiple Base Stations	(i) More devices will be connected since the capacity of the network is increased with additional base stations. (ii) Strong signal strength of the available LPWAN networks.	(i) It can cause congestion with time which creates another interference (ii) It is expensive because of the additional base stations or network infrastructure	It was shown that the additional base stations improve DER and hence performance of LoRa network. It can also work for Sigfox and other LPWANs.
Spartial Signal Processing	(i) It can be used to remove larger burst or interference which appears on the channel. (ii) It can cancel interference from different sources (iii) It can increase coverage	(i) There is a problem when the signal is weak. (ii) Increase residual interference at the receiver.	Very viable at 2.4GHz where we have more of LPWANs
Adaptive Transmit Power Control	(i) It reduces average power consumption (ii) It can prolong equipment lifespan (iii) Reduces interference level for a long time.	(i) Difficult to know the extent to which power will be controlled. (ii) Sometimes depend on information from the transmitter that is causing interference.	The antenna of LPWANs base station power can be controlled in such a way to minimize interference to other LPWANs in the same frequency. E.g., Sigfox, LoRa

From Table 2 it is evident that the Cognitive Radio has the best advantage in optimising the unlicensed spectrum than other techniques. This is because, it can intelligently detect interference and move communication to the clearer portion of the spectrum although sensing is needed to know when there is a vacant hole. It has a robust method of managing interference than other techniques especially in the unlicensed bands where interference is very common. It is followed by Band Steering which can also mitigate interference by monitoring all clients in the same area to avoid interference. It can move communication from one band to the other, ensuring that there is little interference while doing that. Another method is the use of Spectrum Analyzer, this tool identifies the source of interference and facilitates the analysis of the type of interference being encountered. This will enable the monitoring of interference across spectrum to transmit better channel power at the receiver's end. Smart Antenna Technology increases coverage, improves link quality and reliability. Multiple Base Stations is another technique that can help reduce interference in the unlicensed band. With this, there will be strong signal strength since many base stations of LPWANs are connected. This will produce strong signals for the LPWANs thereby reducing interference from other network sources. Spatial Signal Processing can be used to cancel interference from different sources and improves performance of the LPWANs against interference. Finally, the Adaptive Transmit Power Control is used to lower the transmission power of the network which minimises interference.

2.8.8 Interoperability and Modularity in Smart Cities

Interoperability and modularity are at the center of smart city development. However, it is worth remembering that for example the global success of the internet and mobile networks was based largely on interoperability and a modular, scalable architecture both on a technical and business level. Many positive things are emerging in major cities across the world and valuable lessons can be learned from these historical examples and leveraged in smart city development. Also, the use of open data and open application programming interface (API) are becoming more common and seems to be a promising trend. In addition to these, additional and other ways to achieve interoperability as well as a multi-buyer and multi-vendor market are being introduced by network operators. An important component of it is the testing and certification of the interoperability of the systems. Recently, using Finland as a typical case, the National Archive of Health Information Services (Kanta) just introduced a testing and certification service, which network suppliers could use to validate system interoperability and enable the transfer of prescriptions from health centers to pharmacies. Obviously, this will have good impact in enhancing quality life of the citizens based on LPWNs/IoT usage. System interoperability could also be enhanced by city procurement. When many cities are procuring systems for similar purposes, they could agree on common principles and interfaces that would be used, but still procure the systems independently, and thus enable the emergence of multi-vendor market [62]. According to IEEE system interoperability is the ability of two or more systems, networks or components to exchange information and use this exchanged information for the purpose of making the system better. It entails more than just making each system relate with each other, it requires reaching some degree of compatibility and common interpretation among the systems involved in the set up. Interoperability can happen in two ways; Firstly, the systems can be designed in such a way that they can interoperate. Secondly, the system can be retrofitted. The first way is easier and not costly in that it can easily operate with other systems based on its initial designs, considering the fact that smart cities are propriety which is owned by different organisations saddled with the tasks of making the smart cities work efficiently, however, they are designed independently without putting into consideration interoperability [63]. The second option requires enormous tasks since it adversely affects the existing systems like system interface or user protocols. The second option is majorly available to be used for smart cities.

Table 3 shows the effects of interoperability in a smart city. When there is interoperability, there will be interoperability at the level of data and good communications, whereas at the city without interoperability of networks, the same services will need to be replicated compared to when there is interoperability among the LPWANs in the smart city. There is high level of reliability in a case where there is interoperability among the LPWANS adopted for smart city.

Table 3: Interoperability in Smart Cities

Without Interoperability	With Interoperability
(i) There is a highly fragmented market, and there are no vendor specific applications.	(i) There is an end-to-end platform for common service capabilities layer.
(ii) Reinvention of the wheel, same services developed over and over.	(ii) Interoperability at the level of data and good communications.
(iii) Each section contains its own technology without interoperability.	(iii) Very seamless and quality interaction between different technologies and devices.
(iv) When one network is down the whole smart city connectivity could go down [64].	(iv) When one network is down, the whole smart city still functions.
(v) Low level of reliability.	(v) Very high level of reliability.

Besides, without interoperability of networks in smart cities, when one network is down, this may affect the whole of the smart city and can have serious disruption to the services being provided. But when there is interoperability among the networks, when one network goes down the other networks can still function well, so this does not affect the smart cities.

2.8.8.1 Benefits of Interoperability in Smart Cities

As indicated in Table 4 there are lots of benefits derived from IoT systems, networks and devices interoperating. The benefits come in terms of operational expenditure and capital expenditure. Lower cost of deployment enables network operators to deploy many sensors and devices making the cost of building infrastructure for smart cities low. The optimization of CAPEX and OPEX helps eliminate barriers to efficient smart city management [67]. [67]. Moreover, there is an efficient communication at the operational expense level; this also brings about smooth running of the smart cities. If network and IoT systems can communicate at different strata of the smart cities, then we are sure of getting the cities we desire. Another benefit of interoperability is in terms of security, the cooperation that comes with different devices will assist in protecting information and data shared. Poor security is a potential symptom of non-standardised communication system [68].

Table 4: Benefits of interoperability in terms of Capital Expenses (CAPEX) and Operational Expenses (OPEX)

CAPEX	OPEX	Effects on Smart Cities
(i) Lower cost of deployment	(ii) Efficient Communication	It helps in easy implementation of smart city initiative. This can help promote smart cities
(ii) Programmers can focus on application	(ii) There is sensor data sharing	It will help in mapping out best application that can suit the smart cities
(iii) Economies of scale for horizontal service layer	(iii) Transport economies. Use best transport for business needs [65]	It creates cross market economies of scale. Allowing more people to invest in smart cities
(iv) Simplify the development of applications	(iv) Reduces the cost of application development	Removes obstacles to efficient smart city management
(v) Reduces the cost for network coordination	(v) Allows easy network coordination	Public authorities can coordinate response from different critical infrastructure allowing smooth running of smart cities.
VI) Reduces the cost of security maintenance	(VI) Helps in security	It enables proper security of smart cities [66]

2.8.9 Security Vulnerabilities of Smart Cities

In the smart cities, Low Power Wide Area Networks LPWANs/Internet of Things involves the connection of machine readable, uniquely identifiable objects or things which are found on the internet. These objects continue to interact with one another exchanging information which is extremely useful in making the city efficient [69]. Moreover, these censors are part of important infrastructure that gathers huge data on specific location, humidity, temperature and pressure of a particular or various locations. Objects that are found in various homes are now becoming smarter than ever before, exchanging useful data and becoming controllable from a distance [70]. This becomes achievable due to LPWANs that are deployed for smart cities. However, the vulnerability of these technologies comes in terms of various degrees of attacks which are enumerated below.

2.8.9.1 ACK Spoofing Attack

In this kind of attack, the protocol of the LPWAN is vulnerable to the attacker. Since the gateway is connected to the internet by any of the interfaces, it makes it susceptible to different malicious attacks. Since the acknowledged (ACK) message does not contain all the messages received, it will confirm the last that is received. The attacker will intercept the message over the LPWAN network and resend the same message to get other messages from the end device [70].

- *Effect on smart cities*

A malicious gateway will therefore harm data exchange over the network. This will cause disruption and Denial of Service (DoS) for future smart cities.

2.8.9.2 Replay Attack

The replay attacks affect the security protocols in that data transmission is resent by a malicious entity which acts as an intruder on the network. What it does is to deceive the module by making use of old data that has been stored on the network. Before this attack is carried out in LPWAN networks, the entity will know the communication frequencies so as to remove data from transmission between many devices found in the network.

- *Effect on Smart Cities*

This attack causes denial of services, disruption in the flow of data from the sensors through the cloud to the servers [71]. Services render by LPWANs in smart cities are severally distorted.

2.8.9.3 Wormwhole Attack

These shows how vulnerable some LPWANs have become as it relates to smart city. In this attack a malicious device tends to capture packets from one device then begin to transmit them to other devices on the same network at different locations to replay the capture packets. This can be done with a malicious entity with or without a prior knowledge of the LPWANs or its cryptographic configuration. It is a dangerous attack that happens in the network layer because it affects network security systems [72].

- *Effect on smart cities*

It disrupts the routing of data communications in smart cities and leads to denial of service for essential services.

2.8.9.4 Jamming Attack

This is one of the problems faced by LPWANs as far as security is concerned. A malicious entity may try to transmit in the proximity of application devices thereby causing a disruption in the radio transmissions. For instance, LoRa as an example of LPWANs adopted in the smart city, when an attacker makes use of Arduino platform that has a LoRa radio module. Anyone with terrible intent can flood LoRa module with messages that have the potential of wiping out an entire transmission.

- *Effect on smart cities*

The radio communication system collapses, which leads to disruption and denial of service [73]. If critical infrastructures like subways and traffic systems managed by these networks are connected in a smart city, there will be traffic shutdowns and even accidents.

2.8.9.5 Eavesdropping attacks

It is an attack that has been disturbing networks for a long time. In this kind of attack, the attacker quietly listens to the communications over the network and has an unauthorised access to the information on the network. This includes information such as node identification numbers, routing updates on the network, and highly critical data. Moreover, attacker can use this information maliciously to harm the network nodes, terminate the routing process and severely compromise the network performance [74].

- *Effect on Smart Cities*

Compromises of services rendered by LPWANs for smart city and performance degradation. The huge data may be lost in the process.

2.9. IMPACT OF WEATHER CONDITION ON LPWANS

2.9.1 Effect of Temperature

Temperature is one of the weather conditions that affect the reliability of LPWANs. Aside from affecting the link quality, it can also affect the performance of the communication hardware. For instance, outdoor antennas can malfunction when there is an excessive heat due to high temperatures [75]. In the experiment carried out by Cattani et al, it was noticed that there was a decrease in antenna performance on the wireless link due to excessive heat, while at the same particular time the indoor antenna was not affected. Also, extreme temperatures and change in temperature rate may seriously affect the noise functioning and at the same time the RF-circuitry [76]. When the experiment was carried out, the power variations that were observed had magnitude that was smaller than link variations observed. Moreso, since there is a relationship between the ambient temperature and received power level, the dominant effect here is the propagation [77].

LPWANs have been developed with variable link performance and propagation effect which will be affected by weather conditions bringing about serious signal deterioration. Since the scalability of some of the LPWANs is being questioned, any increase in range may make it interfere with other nearby networks. The result is a low quality of service. Therefore, understanding of relevant weather-related propagation of LPWANs should always be updated so that good decisions can be made by network providers for urban and suburban areas [78]. There is always a link fluctuation caused by the variation in the refractive index and multipath conditions caused by droplets of water in the atmosphere. It has been discovered that this is a problem for any network designer [79].

A Effect of Temperature on Received Signal Strength (RSS)

At higher temperatures there is an attenuation of the received signal strength. This is because both nodes of the LPWAN networks exhibit a linear decrease in the received signal strength when the temperature of the LPWAN nodes rises due to various reasons. The reason for the attenuation has been explained by various researchers particularly Bannister et al who states that, for a given voltage the high temperature will increase the resistance of the conductors of the LPWAN network nodes while at the same time it reduces the current that passes through the nodes. For instance, with excessive temperature, a perfectly working LoRa nodes and network link can become useless that its performance amount to nothing [80]. Obviously, there is a relationship between temperature and signal strength. When temperature rises, the received signal strength falls and also when the temperature falls the received signal strength rises. The relation between these two parameters varies according to the link as well as the communication channel [81].

B Effect of Temperature on Localisation

In many Low Power Wide Area Networks (LPWANs) and their applications most especially in smart cities, knowing the position or the direction of the nodes is essential to evaluate the network performance. It can help in geographical routing and location-based queries. Localisation approaches have gained prominence recently since the use of more expensive tool of GPS has been sidelined, and more effective solution of localisation has been discovered [82]. Localisation accuracy helps the proximity information helping the nodes to send right information; this connectivity information can be obtained by getting the information between received signal between the pairs and nodes. Therefore, high temperature affects the accuracy of localisation.

C Effect of Temperature on Data Collection

Data collection is an integral part of LPWAN adopted for the Internet of Things. Without the collection of information stored as data for usage in smart applications, it is going to be a big challenge to attain the smooth running of smart cities, smart agriculture, smart health etc. The collection of data is dependent on well-designed architecture. The architectures are placed around two main approaches. They are static network and mobile network. The first approach, static architecture involves the deployment of many sensors in a particular place so as to get information that will be needed [83]. The mobile network architecture means the allocation of sensors in many places to get information. Also, there are two models of architecture, they are static –sink and static sensor architecture. These two models of architecture for data collection have a large number of sensors that can collect and at the same time transmit the data collected in the environment in a specific way. The positions of the sensor nodes are not determined earlier than expected as they can be spread across an area of interest. When the temperature of the nodes is high above the normal temperature that they can hold, there tend to be a serious malfunctioning which can thus affect the data collection process of the nodes [84].

2.9.2 Effect of wind

This is another physical phenomenon that usually affects performance of LPWANs. In this case it usually affects network nodes, causing a negative effect on the performance of their networks. One observation is that the pressure of the wind on the antenna during windstorm or high wind can make the antenna change its position which can lead to malfunctioning. The slightest antenna loss of position can have a significant impact on the LPWAN network nodes. This in turn will cause the signal to drop below an acceptable level. Sometimes the position of antenna nodes can face a direction where there will not be good signal due to the wind shifting the position towards another side. One of the ways to minimise the impact of wind is to ensure that the nodes as well as the antennas are well positioned in such a way that it is well fixed [85].

2.9.3 Effect of humidity

Studies have been carried out to understand the effect of humidity on the network performance of LPWANs. Humidity is the amount of water vapour that is found in the air. When the amount of water vapour in the atmosphere is measured and in the same ratio with the amount of water vapour at the same temperature and pressure, it is known as relative humidity. It can be observed that relative humidity does not have much impact on the received signal strength of LPWANs but only increases the air pressure [86]. The moisture found in the humid air will make it more difficult for the network signal to be sent effectively which can lead to a slower data speed i.e., propagation delay. Due to the fact that LPWANs transmit for long distances, propagation delay will have more severe impact.

2.9.4 Effect of Rainfall and Snowfall

Due to the fact that signals propagate in various media, it is certain that the weather condition at a particular time will have an effect on these signal's movement. Absorption and scattering of waves as well as refraction are important factors that determine how the signal or electromagnetic waves transmit in wireless spectrum which include LPWANs. When an LPWAN network encounters rain, fog, and clouds there is bound to be attenuation in the wireless unlicensed bands [86]. There is going to be a limiting effect because of these factors.

One of the areas in which the rain affects the transmission of LPWANs is the packet data loss. This can be measured using the packet delivery ratio (PDR). The PDR tells how successful data are sent from the end device to the nodes of the LPWANs to deliver this data. For a particular LPWAN, there are two conditions that will be put into consideration when measuring the packet data loss, PDR in the line of sight, and the PDR in non-line of sight. The rain increases the amount of data packet loss because the value of the PDR is lowered when there is high volume of rain. Likewise, when the rain decreases the value of PDR is increased. A high value of PDR means a successful transmission for any particular LPWANs [87]. Furthermore, in the recent research that was carried out on characterisation, it was obvious that snowfall also had detrimental effect on link quality [88]. The packet reception is slightly lower in summer months when compared to winter months, it was observed that for a wireless link that employed an outdoor antenna during a period of significant rain had poor signal quality [89 90], while the signal received by an indoor antenna without rain remained largely un-affected. Snowfall has a similar impact as the rainfall because snowfall contains heavy or tiny droplets of water. They can cover the sensor nodes, thereby obstructing the transmission of data on the LPWAN.

2.10 DISCUSSION AND MAJOR FINDINGS FROM THE LITERATURE REVIEW

2.10.1 It is noted that each author that looked at optimisation as a tool in making the spectrum efficient agreed that it would improve the performance of LPWANs. Obviously, the cognitive radio appears with many advantages to overcome the interference problem compared with other techniques highlighted in section 2.8.6. It applies to both spectra but most especially to the unlicensed spectrum where ISM bands can be found. This band is overly crowded so the movement to a better band can easily be done using the cognitive radio. Similar to the cognitive radio is the band steering which according to the table also has some advantages of moving communication band from congested 2GHz band to a less congested 5GHz band [91]. It does alternate between these two bands simultaneously. Using the spectrum analyser is the most cumbersome of all the techniques because it requires technicians to go to the base station to adjust antenna and other parameters to make the network performance improve. Smart antenna technology equally offers some advantages when it comes to spectrum optimisation which is also different from other techniques and only one with the ability to save power which is one of the benefits of LPWANs. Adaptive Transmit Power Control has the benefit of prolonging equipment lifespan due to efficient power management schemes. With this technique, interference will be reduced for a long time which significantly improves the network quality.'

2.10.2 LPWANs/IoTs have security vulnerabilities such as: jamming attack, eavesdropping attack, worm-whole attack, insecure interfaces, insecure software/firmware [92] etc. More flexible use of the spectrum and efficient optimisation will make more bandwidth available on the spectrum to support many LPWANs/IoTs technologies which will enhance the performance of smart cities.

Replay attack has a devastating effect on LPWANs, and it is possible regardless of how the device was activated. Either by activation by personalisation (ABP) or over the air activation (OTAA).

For a standardised method of robustly securing LPWANs/IoTs deployed in smart cities, the protocols that are implemented at different layers need to interoperate by providing a conversion mechanism. Sensors and microcontrollers found in smart cities can be hacked as often as possible because they have inadequate security, encryption and privacy protocols.

Unlicensed bands LPWANs have the weakness of not offering any subscribers identity module (SIM) authentication technique [93]. Most of the LPWAN technologies deployed in smart cities use Advanced Encryption Standard for security which is specifically unsuitable for low power devices. Once session keys are compromised, security of LoRa and Sigfox would be rendered ineffective as it will be difficult to change the Advanced Encryption Standard (AES) keys.

2.10.3 The higher the temperature of LPWANs, the lower the link quality, hence less transmission power is required at lower temperature. However, weather conditions have adverse effects on LPWANs transceiver and the signal transmission. The effectiveness of LPWANs is largely influenced by local weather conditions, with temperature being the most important factor. Temperature variations have a more significant impact on LPWAN transmission compared to other weather conditions. Higher temperature can render a good LPWAN link useless, likewise droplets of water in the atmosphere due to humidity can cause LPWANs propagation delay. LPWAN network designers need to have information on how weather impacts the performance of LPWANs to aid in the design according to specifications. Temperature has more impact on LoRa than any other LPWAN due to its design architecture.

2.11 CONCLUSION

From the literature reviewed, it can be concluded that there is no literature on the issue of spectrum optimisation for smart cities at 868 MHz and 915 MHz. Though some literature mentioned one or two LPWANs and their utilisation, none made a comprehensive approach and models to spectrum optimisation of LPWANs and its usage in smart city which formed the basis for this research.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 INTRODUCTION

This chapter presents the methodology that was adopted in the research. It analyses the research methodology and the steps that were taken in ensuring that the desired result was achieved from the research. It also involves the presentation of our Optimised Frequency Hopping Model.

3.2 METHODOLOGY

The methodology adopted in this research was based on the measurement of the signal power for some time and allowing it to pass through signal analyser to observe it, and make allowance for interference and noise estimation through a particular threshold. The study was conducted in a communication scenario using MATLAB simulations to replicate a communication network, ultimately leading to the development of an optimised spectrum model. Two primary models were utilized; simulation model and network simulation model. When setting the performance parameters, literature was consulted to ensure that simulation parameters were set considering 3GPP and LPWAN network models. Different MATLAB simulation tools were used in getting the results of the experiment. Simulation parameters were set at different values for frequency, amplitude and channel bandwidth. An existing interference was used to ensure that the components of the signal contain noise. The Optimised Frequency Hopping Model was used as a combination of different Simulink Blocks such as Random Integer Generator block from Digital Signal Processing system toolbox as well as Product Block, Sine Wave Block, Multiport Switch Block among others. There was a threshold setup where there was an interference introduced to the simulink block diagram without using the Optimised Frequency Hopping Model and the output signal was observed on a spectrum analyser. When the simulation was done, the impact of interference was seen on the signal at the unlicensed spectrum at 868MHz and 915MHz. Then Optimised Frequency Hopping Model was introduced to the setup and thereafter, there was simulation of the set-up on MATLAB. Finally, the results from the Optimised

Frequency Hopping Model were compared with a benchmark which was the simulation with interference and without the Optimised Frequency Hoping Model. It was observed on the spectrum analyser that the interference has been reduced. The simulation results validated the initial results. Different results from the simulation were shown by the oscilloscope. The latency and throughput as the two major parameters showing the performance of the unlicensed spectrum were considered. There were different values for these parameters for each simulation done.

3.3 MATHEMATICAL EQUATION FOR THE MODULATED SIGNAL

Suppose $b(t) = x(t) + n(t)$ ..... (1)

$b(t)$ is the input to the filter

$x(t)$ is the signal with duration T and has a waveform *b*(t) to be detected

$n(t)$ the additive noise

The band pass filter impulse response to the signal is given as

$$m(t) = \int_{o}^{T} b(t)h(t)\,dt \quad \text{.....} \quad (2)$$

$h(t)$ is the input response of the bandpass filter

$m(t)$ is the output from the bandpass filter.

The bandpass filter is designed to allow frequencies of 868MHz and 915MHz and attenuates other frequencies above and below these frequencies.

The signal part of the output is given by the expression and given in terms of amplitude and pulse duration as

$$m_s(t) = \int_{0}^{T} b(t)h(t)\,dt \quad \text{.....} \quad (3)$$

received signal x(t)

$$x(t) = SaPd \quad \text{.......} \quad (4)$$

Where Sa = unknown signal amplitude and *Pd* is the pulse duration

The Fourier Transform of x(t) in equation (4) is

$$x(t) = SaPd(f)\, e^{-2zfto} \quad \text{........} \quad (5)$$

The peak pulse amplitude A of the received signal can be derived from the Inverse Fourier Transform (IFT) of signal part as

$$A = F^{-1} \int_o^f H(f)\, x(f)\, df \qquad \ldots.. \quad (6)$$

$$= Sa \int_o^f H(f)\, Pd(f)\, e^{j-2\bar{\Lambda}} ft \;\; df \qquad \ldots.. \quad (7)$$

The noise part of the output and its Fourier Transform are given in these equations

$$M_n(t) = \int_o^t n(t)h(t)\, dt \qquad \ldots\ldots \quad (8)$$

$$M_n(t) = \int_o^t H\,(f)Gn(f)df \qquad \ldots\ldots. \quad (9)$$

The noise variance which is part of the output can be expressed as

$$\sigma^2 \int_o^t [H(f)^2 Gn(f)df \qquad \ldots\ldots \quad (10)$$

Maximising the ratio of peak output amplitude, A to the noise

$$(\frac{A}{\sigma})^2 = \frac{S_a^2[\int_o^f H(f)Pd(f)e^{j2\bar{\Lambda}ft}]^2}{\int_o^t [F(f)]^2 Gn(f)df} \qquad \ldots\ldots \quad (11)$$

$$(\frac{A}{\sigma})^2 = S_a^2 \int_o^t \frac{[Pd(f)]^2}{Gn(f)} df \qquad \ldots\ldots. \quad (12)$$

Assuming that the Gn(f) is a white Gaussian noise with spectral density of No/2 equation 12 becomes

$$\left(\frac{A}{\sigma}\right)_{max}^{2} = \frac{2\int_a^2 Gn}{No} \int_o^t [Pd(f)]^2 df = \frac{2Ep}{No} \qquad \ldots\ldots. \quad (13)$$

Where Ep $\quad = S_a^2 \int_0^f [Pd(f)]^2\, df \qquad \ldots\ldots \quad (14)$

Signal at the output of the filter observing at instant t is given by:

$$M(t) = \frac{2Ep}{No} \qquad \ldots\ldots. \quad (15)$$

$M(t)$ can then be compared with a threshold TRE

To determine the threshold is to estimate the energy of the signal and reduce it to half so as to know that the detected signal is reliable for comparison.

If the known primary signal energy Ep, then

$$\text{TRE} = \frac{Ep}{2} \qquad \ldots\ldots \quad (16)$$

If $x(t)$ > TRE then primary signal is present

If $x(t)$ < TRE then primary signal is absent

The interference temperature T_1 can be specified as a function of bandwidth B as

$$T_1\,(f_c B) = \frac{1}{Bk} P_1\,(f_c,\ \text{B})\,\text{T}_1 \qquad \ldots\ldots \quad (17)$$

$$= \frac{1}{Bk} \left(\frac{1}{Bk} \int_{fc-\frac{B}{2}}^{tc+\frac{B}{2}} S(f) \right) df \qquad \ldots\ldots \qquad (18)$$

$$= \frac{1}{B2_k} \int_{fc-\frac{B}{2}}^{fc+\frac{B}{2}} S(f)\ df \qquad \ldots\ldots \qquad (19)$$

$$= \frac{1}{B2_k} \int_{fc-\frac{B}{2}}^{fc+\frac{B}{2}} S(f)\ df \qquad \ldots\ldots \qquad (20)$$

P1 (f_c, B) = average interference power in watts at the center frequency fc and bandwidth B.

K = Boltzmann's constant (1.38 x 10^{23}JK)

Where S(f) represents spectral power current in an RF environment. Given B, to compute valid, P, If n (number of primary users) = 0

P ≤ Pmax, the radio's maximum transit power.

Given that this research focused on unlicensed frequencies, it was assumed that these frequencies do not have primary or secondary users, as LPWANs are already occupying the 868MHz and 915MHz frequencies. The primary users can be designated as the first occupier or user of the frequencies. The secondary user here can be the secondary occupier or the network in need of the same frequency for transmission. Using the Optimised Frequency Hopping Model, many networks can coexist with this frequency and share the available spectrum which are at frequencies of 868MHz and 915MHz. This is because the signal hops in different channels found in the frequencies and avoid persistent and long exposure to interference. With this in place, the interference is reduced.

3.4 APPLYING SHANNON-HARTLEY THEOREM FOR EFFICIENT LPWAN COMMUNICATION

"Shannon-Hartley Theorem" states the channel capacity meaning the theoretical tightest upper bound on the information rate of data that can be communicated at an arbitrary low error rate using an average received signal power through an analog communication channel subject to additive white Gaussian noise.

$$C = B\log_2 (1+ {}^{S}\!/\!_{N}) \qquad \ldots\ldots\ldots\ldots \qquad (21)$$

where C the channel capacity in bits per second

- B is the bandwidth of the channel in Hertz (passband bandwidth in case of bandpass signal.
- S is the average received signal power over the bandwidth (in case of carrier-modulated passband transmission, often denoted as C) measured in watts.
- N is the average power of the noise and interference over bandwidth, measured in watts (or volts squared) and
- S/N is the signal E-noise ratio (SNR) or the carrier to noise ratio (CNR) of communication

Applying the Shanno-Hartley Theorem, it is good to take advantage of it to maximise the expansion of the bandwidth and optimise the spectrum at 816MHz and 915MHz, here, once the signal power that is coming from the shared networks or coexisting networks on the unlicensed spectrum at 816MHz and 915MHz is known, it becomes easy to minimise interference. A reduction in their signal power can bring about reduced noise and reduces interference to the barest minimum. There will be sensing by any network that wants to occupy the spectrum at 815MHz and 915MHz. This is to know when this spectrum is available or when it is not properly used or to coexist with the existing networks. Then it can share it with the initial occupier. Networks can also be installed with a device that will lower the signal power to the barest minimum so that it minimises interference and ambient noise. Another network can also share the spectrum when the two networks are idle. This is the concept behind the spectrum sharing of networks.

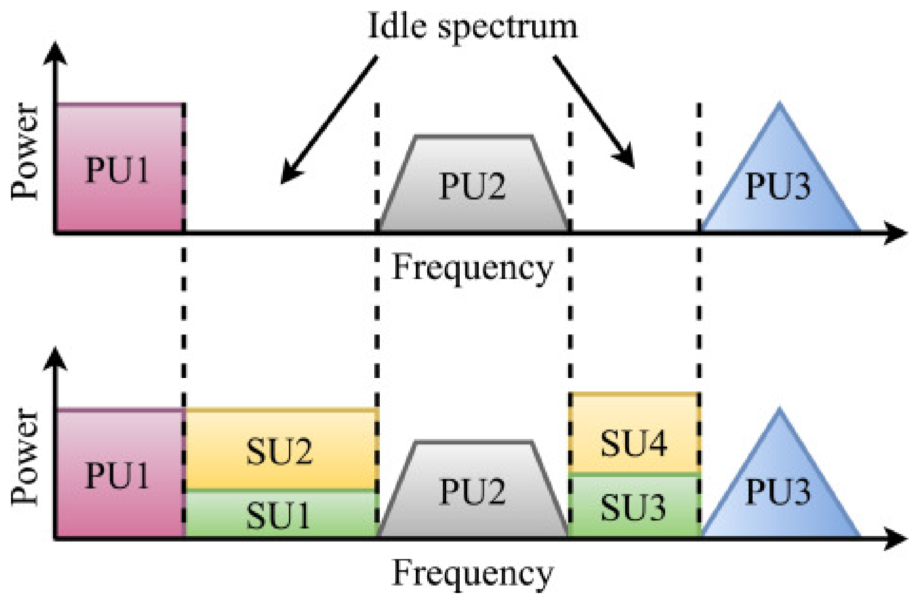

Fig. 4: Spectrum sharing with vacant or idle spectrum [95]

Figure 4 shows spectrum sharing with vacant spectrum. It can be seen that the upper diagram has a vacant or idle spectrum when it is not occupied by any network. It has three primary users namely PU1, PU2 and PU3 all occupying their positions. It immediately became vacant as shown in the upper diagram. The secondary users namely SU1, SU2, SU3 and SU4 quickly occupied the vacant position. They shared the spectrum together as each network is transmitting at the vacant position. Spectrum sharing allow this to be possible.

3.5 OPEN SHARING MODEL (OSM)

This Open Sharing Model makes use of open sharing among peers of network users. It makes provision for equal rights of the user networks to access the spectrum. Here it means both the licensed users and the unlicensed users. It can also refer to the unlicensed users or the free spectrum. However, there are no interference constraint from those networks that are available in the unlicensed spectrum [96].

3.6 HIERARCHICAL ACCESS MODEL (HAM)

The Hierarchical Access Model is built on hierarchical structure as the primary users and the secondary users. Relating it to the unlicensed spectrum, the primary users here refer to the first occupants of the unlicensed spectrum while the secondary users here are the users that are waiting to use the unlicensed spectrum while the first occupants use it. The idea behind this model is to provide openness between different users. The model has the following classifications.

3.6.1 Interweave Spectrum Sharing

In interweave paradigm, the basic idea behind it is the opportunistic communication. Here it is found that the spectrum hole where there is a temporary space-time-frequency voids that are not being used by both the licensed users and the unlicensed users. These voids or holes change with time and location. Furthermore, the interweave technique enables the activity information of the major users of the available spectrum [97]. This system continues to monitor the spectrum and intelligently detects the vacancy on any parts of the system and communicates opportunistically about the spectrum holes with low interference.

3.6.2 Overlay Spectrum Sharing

In overlay systems, the secondary user has the knowledge of the primary user codebooks and its messages. The primary user transmits at any power and the interference to the primary users can be offset by relaying the primary user's message. The characteristics of these techniques are related to the underlay spectrum sharing.

3.6.3 Underlay Spectrum Sharing

In the underlay spectrum sharing, the system has the information of the interference caused by all the users. It enables both the primary and secondary systems transmission to occur only if the interference generated by the secondary user and the primary user is well below some acceptable threshold.

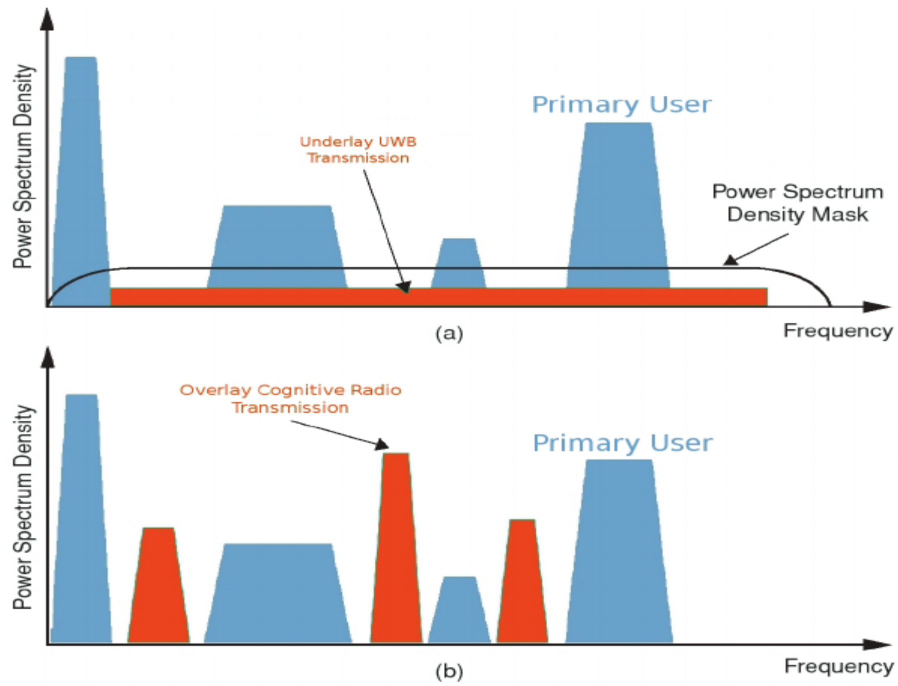

Fig. 5: Overlay spectrum and underlay spectrum sharing models [98]

Fig 5 shows the overlay and underlay spectrum sharing models where the primary users and the secondary users can share the spectrum together to achieve spectrum sharing for efficient unlicensed spectrum management and usage. One user occupies the frequency and cognitively know when there is a vacant spectrum which it can quickly use for its own transmission.

Table 5 Characteristics of interweave, overlay and underlay sharing

Interweave	**Overlay**	**Underlay**
When the primary user is not using the spectrum, the secondary user sees the spectra holes in space, time and frequency.	The secondary user knows the channel gains, codebook and the incoming messages of the primary user.	The secondary user knows the channel strength of the primary user.
The secondary user can transmit instantly with the primary user only in the case of false spectra hole detection.	The secondary user can transmit with the primary user the interference can be used by using part of the secondary user power to send messages.	If the interference is below a certain threshold secondary user can automatically transmit with the primary user.
The secondary user is limited by range of its spectra hole sensing.	The secondary user can transmit at any power the interference to the primary user can offset by relaying the primary user's message.	Secondary users transmission power is limited by interference

Table 5 shows the characteristics of different spectrum sharing. There is interweave sharing, overlay sharing, underlay sharing and the goal of these spectrum sharing is to maximise the usage of the spectrum [98]. In the interweave sharing, when the primary user is not using the spectrum, the secondary user sees the spectrum hole in space and time, the secondary user then makes use of the spectrum, in the overlay the secondary user knows the channel gains, code book and the messages of the primary user, the secondary user can then decide when to make use of the spectrum hole. In the underlay spectrum sharing, the secondary user knows the channel strength of the primary user and that allows the secondary user to decide and make use of the spectrum hole.

3.7 DYNAMIC SPECTRUM SHARING MODEL

In Dynamic Spectrum Sharing Model, the secondary users will access the spectrum to discover good paths and to transmit data. The basic components of this model include the spectrum identification, opportunity exploitation and regularity policy. The major issues that need to be addressed is the interference management. This can be managed by the allocation of frequency resources that are disjoint to those of the primary users, either through a completely different frequency band or another band that is available. Distributed dynamic spectrum protocols which have fixed topology and channel conditions can be used for dynamic spectrum accessing. The statistical estimates of the channel gain are used to set a transmit power level of SUs. This power level will be within the allowed interference of the primary users [96]. Using this power, secondary user transmitter tries to discover the route to the secondary user receiver. This route discovery is done using the network information in the discovery packets.

3.8 COOPERATIVE SPECTRUM SHARING MODEL

In the Cooperative Spectrum Sharing Models there is a communication enhancement for the performance of wireless systems by making use of spatial diversity. In using spatial diversity, the quality of the signal is improved and the risk of signal fading minimized. In this model, the cooperation comes in different forms like the secondary users helping the primary users to improve their quality of transmission or extend their coverage area in exchange for access to the spectrum. The approach can improve the efficiency of spectrum usage leading to the overall network performance and enhanced service availability for users [97].In the unlicensed spectrum, there are many networks deployed at close range, there is a chance that interference will occur in the primary network transmission. Since there is a fixed topology in the locations of the primary users, the transmission at that location does not change. The primary user locations are modelled as homogenous poisson point process in the overall spectrum sharing system. There is cell edge to communication which serves as a bottleneck to the overall quality of service simply because the interference can be more than the desired signal at the edge. To improve the QoS, a cooperation region is created between the primary users and the secondary users at the edge [98].

3.9 CONCLUSION

The Optimised Frequency Hopping Model can be used in unlicensed spectrum at frequencies of 868MHz and 915MHz. They are made available for the unlicensed spectrum user at the location where the spectrum is not being used by any user. Going by the results of the experimental set up, the unlicensed spectrum will become reliable for data communication for smart city. This OFHM helps minimise the negative effect of interference and ambient noise experienced at these frequencies.

CHAPTER FOUR

SIMULATION RESULTS AND DISCUSSION

4.1 INTRODUCTION

In carrying out the research, Optimised Frequency Hopping Model was used to improve the performance of the unlicensed spectrum where we find many LPWANs. The idea is to find ways to increase the number of users that will utilise the unlicensed spectrum more efficiently without any hindrance to their communication and optimise the spectrum for better performance. The parameters involved in the unlicensed spectrum performance include channel gain and latency. Throughput and transmission power were put into consideration. The simulation results showed an improvement in the performance of the unlicensed spectrum at frequencies of 686 MHz and 915MHz through larger throughput and lower latency. The simulation results are shown with different graphs depicting the performances of the unlicensed spectrum at frequencies under consideration. For the static channels against the time slots, there were cases of interference as seen in Figure 6. Many slots had interference depicted with the yellow blocks, but with the Optimised Frequency Hopping Model, several cases of the interference were drastically reduced making it fewer after the model was used. Also, the latency of the transmitted data of the LPWANs improved because the value became very low, signifying that more data was transmitted in shorter time. The throughput became higher, showing enough successful data transmission.

4.2 SPECTRUM SENSING

The interference power of the unlicensed spectrum user determines what happens to spectrum sensing by another user. In a situation where the interference power is high, every effort is made to minimize it. If the interference power is high, the secondary user who wants to use the unlicensed spectrum may not be able to detect the free spectrum. High interference will lead to high misdetection on the part of the secondary user and a reduction in the channel capacity.

4.3 CHANNEL BONDING

This means the secondary user can transmit over the unlicensed spectrum at the same time that the primary user is making use of the channel. The primary user here is the first occupant of the unlicensed spectrum, while the secondary is another user who also wants to use it at the same time. When this happens there can be a high interference. When there is spectrum sharing there is a significant improvement on the channel and enhancement of the channel capacity of the unlicensed spectrum.

4.4 PERFORMANCE IMPROVEMENT OF UNLICENSED SPECTRUM DUE TO OPTIMISATION

The characteristic performance of the unlicensed spectrum has been greatly improved since it has been optimised for latency, [16] transmitting power and the channel capacity. The concept of Frequency Hopping Model was adopted in the research because it is most applicable. It is the best model to achieve the desired result for spectrum optimisation at frequencies of 868 MHz and 915MHz. Though the foundation of the model is based on the principle of Cognitive Radio which can sense the environment and adjust itself for better communications [17]. Due to our work, the bandwidth of the unlicensed spectrum has also been increased making it accessible without restrictions.

4.5 OPTIMISED FREQUENCY HOPPING MODEL

Optimised Frequency Hopping Model is a model used in transmitting radio signals by rapidly switching carrier among a lot of frequency channels using a sequence called pseudorandom and allowing the channels to hop between different channels avoiding interference. The pseudorandom is known to both transmitters are receivers . The available frequency range is divided into smaller channels so there can be movement there with little exposure to interference.

In this model, instead of staying on a single frequency, the transmitter and receiver rapidly switch between different frequencies within a predefined range in the unlicensed bands. This switching happens according to a specific pattern known to both the sender and receiver.

In the unlicensed bands, there are frequency ranges where anyone can operate without needing a specific license. These bands are often crowded with various devices leading to interference issues [18].

Using the Optimised Frequency Hopping Model at frequencies of 868MHz and 915MHz, the devices can mitigate interference. When one frequency becomes crowded or experiences interference, the communication system can swiftly hop to another frequency. Here, the frequencies that communication hops to will not have been affected by interference. This hopping pattern spreads the communication across multiple frequencies, reducing the impact of interference on the overall communication quality for a smart city application.

Moreso, this model allows devices to dynamically adapt to changing interference conditions. If certain frequencies become congested or noisy due to other devices operating nearby, the system can avoid those frequencies by hopping to cleaner ones.

Assumptions

- Allowed the available system to carry out its operation over a set of *N* distinct frequencies.
- Hence, the hopping sequence is a deterministic one.

The Model:

Take $F = (f_1, f_2, \ldots, f_N)$ be the set of available frequencies. For time t, the frequency in use is given by:

$$f(t) = f\,(t \bmod N) + 1 \qquad \ldots\ldots\ldots\ldots \qquad (22)$$

This model shown above makes sure that at every time instant *t*, the system hops to the next available frequency in the set *F,* while mod is a module operator which returns the remainder when *t* is divide by N. + 1 is a constant increment applied to the functions value within one cycle.

4.5.1 Frequency Hopping with Randomness

Assumption

- It is assumed that the hopping sequences is random and not deterministic.

R(t) can be seen as a random function that returns an integer between 1 and N inclusive.

4.5.2 Frequency Hopping with Memory

(i) Assumption

- The system remembers the last M frequencies used to avoid immediate repetition.

(ii) Model

To represent this, a queue of length M is used to store the last M frequencies. At each time t, the system continues to select a frequency not in this queue. Let $Q(t)$ be the queue at time t and $R(t)$ be our random function.

$$f(t) = \text{select } f_i \text{ such that } i = \mathrm{R(t)} \text{ and } ft \notin Q(t) \qquad \ldots\ldots\ldots\ldots \qquad (23)$$

4.5.3 Frequency Hopping with Interference Avoidance

(i) Assumptions

- Considering that the system has a spectrum sensor which instantly detects interference on certain frequencies and avoids them.

4.5.4 Frequency Hopping with Randomness

(i) Assumptions

- The hopping sequences is random, not deterministic.

(ii) Model

At time t, the frequency under use can be randomly selected from the available set F. This can be represented as:

$$f(t) = f_{R(t)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \qquad (24)$$

Where $R(t)$ is a random function that returns an integer between 1 and N inclusive.

4.5.5 Frequency Hopping with Memory

(i) Assumptions

- The system remembers the last *M* frequencies used to avoid immediate repetition.

(ii) Model

To represent this, a queue of length M is used to store the last M frequencies.

Let *I(t)* be a set of interfered frequencies detected at time *t*. the system then selects a frequency which is neither in the memory queue nor in the interference set is given as;

$$f(t) = \text{select } f_t \text{ such that } i = R(t), fi \notin Q(t) \text{ and } fi \notin I(t) \ \ldots\ldots.. \quad (25)$$

4.5.6 Frequency Hopping with Priority

(i) Assumptions

- Assuming that some frequencies are preferred over others in the unlicensed bands due to better propagation characteristics or other reasons.
- Then each of the frequency found f_t has an associated priority p_i.

(ii) Model

No need to select frequencies purely based on randomness or interference; the system now also considers the priority. The frequency with the highest priority, which is neither in the memory queue nor interfered, is selected.

$$F(t) = \text{select } f_t \text{ such that } p_i = \max (p), fi\ Q(t) \text{ and } f_i \notin I(t) \ \ldots\ldots \quad (26)$$

4.6 THROUGHPUT AND LATENCY AS FUNDAMENTAL PARAMETERS FOR MEASURING PERFORMANCE OF LPWANS IN 868MHZ AND 915MHZ FREQUENCIES

4.6.1 Throughput:

Throughput refers to the rate of successful message delivery over a communication channel. It is typically measured in bits per second (bps) or packets per second.

The formular for calculating the throughput is given below,

$$\text{Throughput} = \frac{Total\ data\ successfully\ transmitted}{Total\ time\ taken}$$

For our simulation, we measure throughput as:

$$\text{Throughput} = \frac{Number\ of\ non-interfered\ slots}{Total\ number\ of\ slots} x\ size\ of\ data\ per\ slot$$

4.6.2 Latency

Latency refers to the time taken for a packet of data to move across a network connection, from sender to receiver. In the context of frequency hopping and interference, latency can be influenced by the need to retransmit data due to interference.

Formula for Latency

Latency = Transmission time + Propagation time + Processing time + Queue

For our simulation, latency is estimated by:

Latency = Time taken to find a non-interfered channel + Time taken for data

If there's interference on the chosen channel, the device will hop to another channel, which adds to the latency other reasons. Each frequency f_i has an associated priority p_i.

There is no need to select frequencies purely based on randomness or interference; the system now also considers the priority. The frequency with the highest priority, which is neither in the memory queue nor interfered, is selected.

$$f(t) – \text{select } f_i \text{ such that } p_i = \max (p), f_i \notin Q(t) \text{ and } f_i \notin I(t) \quad \ldots\ldots\ldots\ldots \quad (27)$$

4.7 ALGORITHM FOR OPTIMISED FREQUENCY HOPPING MODEL IN 868MHZ AND 915MHZ

4.71 Input:

- *F:* A list of available channels in the 868MHz and 915MHz bands.
- *M:* Memory of the last *n* used channels to avoid immediate repetition.
- *I(t):* A function to detect interfered channels at time *t*.

4.72 Output:

- f(t): Chosen frequency at time *t*.

4.73 Procedure:

1**. Initialisation:**

- Set the initial channel $f(0)$ as a random channel from *F*.
- Add $f(0)$ to *M*.

2. For each time slot *t*:

2.1 Detect interfered channels using *I(t)*

2.2 Create a list *C* of candidate channels by removing interfered channels and channel set the channel $f(0)$ as a random channel from *F*.

- Add $f(0)$ to *M*.

2. For each time slot *t*:

2.1 Detect interfered channels using *I(t)*.

2.2 Create a list C of candidate channels by removing interfered channels and channels from memory *M* from *F*.

2.3 If *C* is not empty:

2.3.1 Randomly select a channel *f(t)* from *C*.

2.3.2 Add *f(t)* to *M*.

2.3.3 If size of *M* exceeds *n*, remove the oldest channel from *M*.

2.4 Else

2.4.1 Randomly select a channel *f(t)* from *F* (since all channels have interference or are in memory).

2.4.2 Add *f(t)* to *M*.

2.4.3 If size of *M* exceeds *n*, rove the oldest channel from *M*.

2.5 End if

3. End for

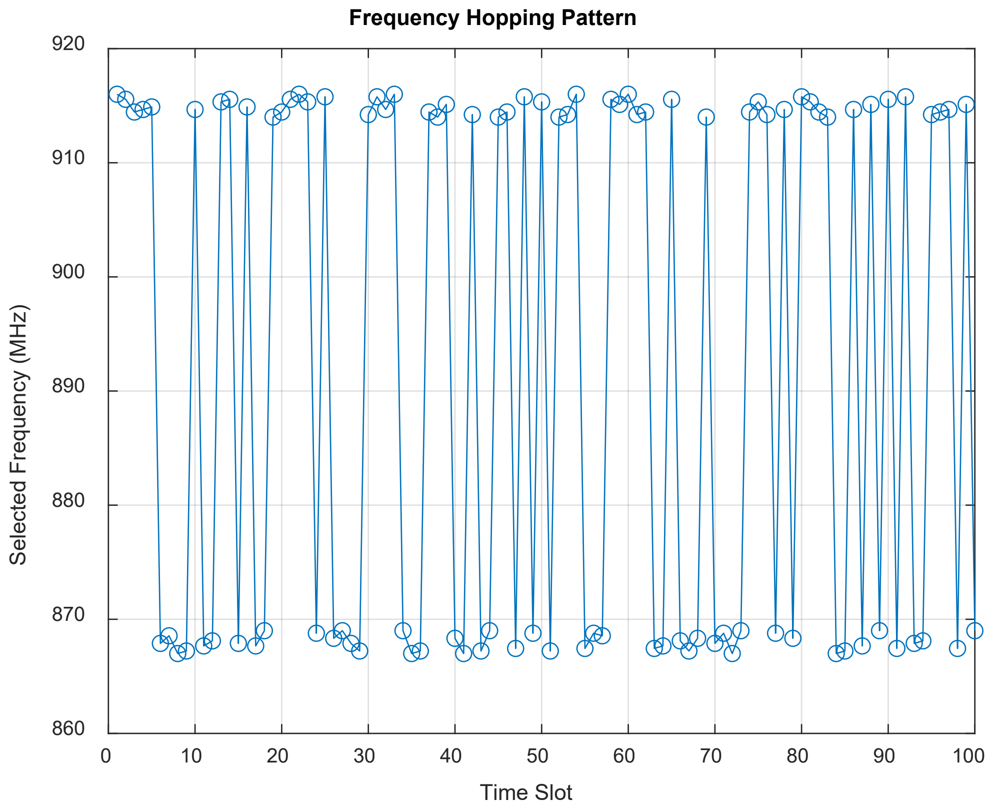

Fig. 6: Frequency Hopping Model Pattern of Unlicensed Spectrum at 868MHz and 915MHz

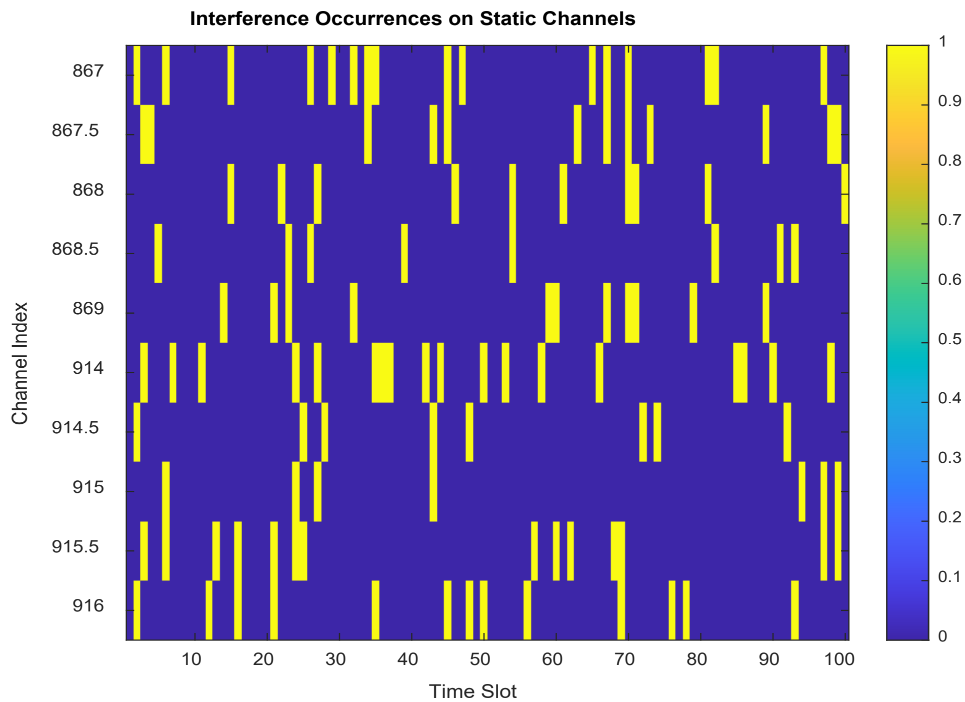

Fig. 7: Interference at 5 static channels for spectrum optimisation at 868MHz and 915MHz

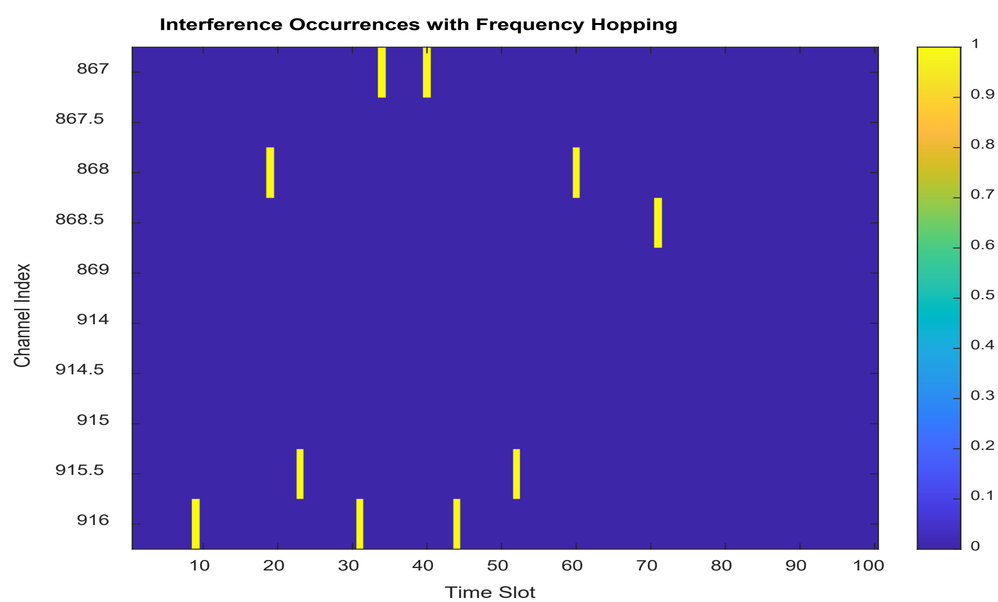

Fig. 8: Frequency Hopping at 5 static channels for spectrum optimisation at 868MHz and 915MHz

As can be seen in Figure 7, the channel index plotted against the number of slots as shown in the simulation results, interference was seen on 5 static channels. All the static channels have interference on them. But when Optimised Frequency Hopping Model was applied as showed by Figure 8, the interference was reduced drastically and there were few instances of interference on the static channels. Obviously, OFHM has helped in minimising interference of the said channels at frequencies of 868MHz and 915MHz. From the figure, the number of spots on the graph reduced showing the interference on the channel has been reduced.

4.8 ALGORITHM FOR 5 STATIC CHANNELS AT 868MHZ AND 915MHZ

1. Initialise 5 channels in the 868MHz and 915MHz bands.
2. Define the total number of time slots for simulation.
3. Define the probability of interference on any channel during a time slot.
4. Create a matrix to store interference occurrences.
5. Initialise a memory to remember the last used channels (to ensure hopping).
6. Loop through each time slot:
   - Check for interference on the current channel.
   - If interference is detected or the channel was recently used, hop to another channel.
   - Record the selected channel and any interference occurrence.
7. Display and visualise the results.

4.9 ALGORITHM OF OPTIMISED FREQUENCY HOPPING FOR 5 STATIC CHANNELS AT 868MHZ AND 915MHZ

```
% Initialisation
F_868 = linspace (867, 869, 5); % 5 channels in 868MHz band
F_915 = linspace (914, 916, 5); % 5 channels in 915MHz band
F = [F_868, F_915]; % All channels
T = 100; % Total number of time slots for simulation
% Assuming a 10% chance of interference on any channel at a given time slot
interference_probability = 0.10;
```

```
% Matrix to store interference occurrences (1 if interference, 0 otherwise)
interference_matrix = zeros(length(F), T);
% Memory to remember recently used channels
memory_size = 3;
memory = zeros(1, memory_size);
% Frequency Hopping Algorithm
current_channel = randi(length(F)); % Start with a random channel
for t = 1:T
   % Check interference on the current channel
   if rand() <= interference_probability || ismember(current_channel, memory)
      % Interference detected or channel was recently used
      possible_channels = setdiff(1:length(F), [memory, current_channel]);
      current_channel = randsample(possible_channels, 1);
   end
   interference_matrix(current_channel, t) = (rand() <= interference_probability);
   % Update memory
   memory = [current_channel, memory(1:end-1)];
end
% Displaying the results
disp("Interference Matrix:");
disp(interference_matrix);
% Plotting the interference occurrences
figure;
imagesc(interference_matrix);
colorbar;
xlabel('Time Slot');
ylabel('Channel Index');
title('Interference Occurrences with Frequency Hopping');
yticks(1:length(F));
yticklabels(arrayfun(@num2str, F, 'UniformOutput', false));
```

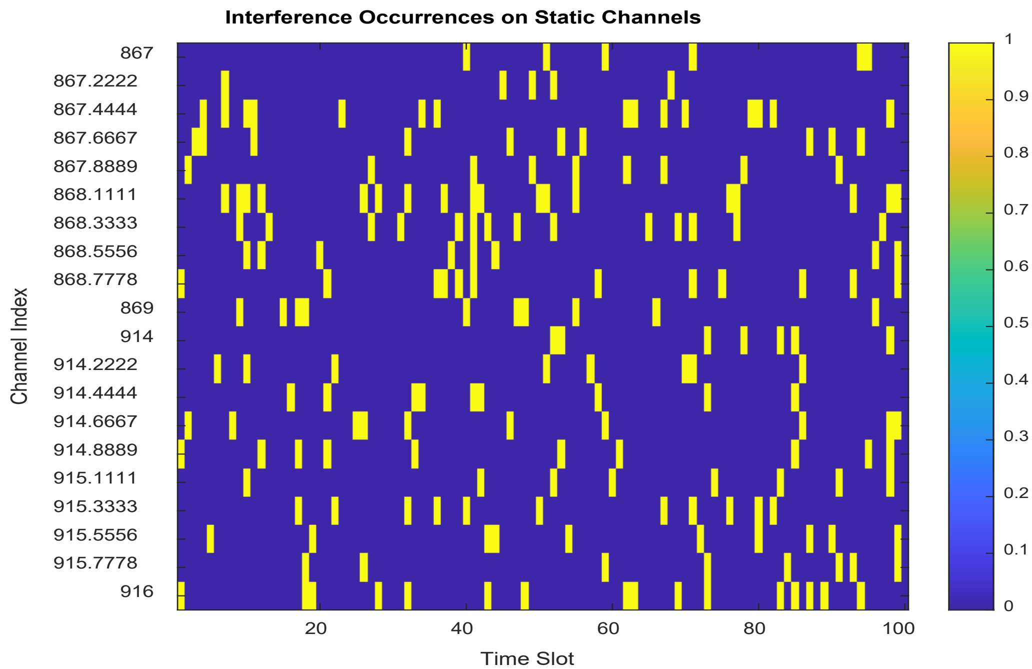

Fig. 9: Interference at 10 static channels for spectrum optimisation at 868MHz and 915MHz

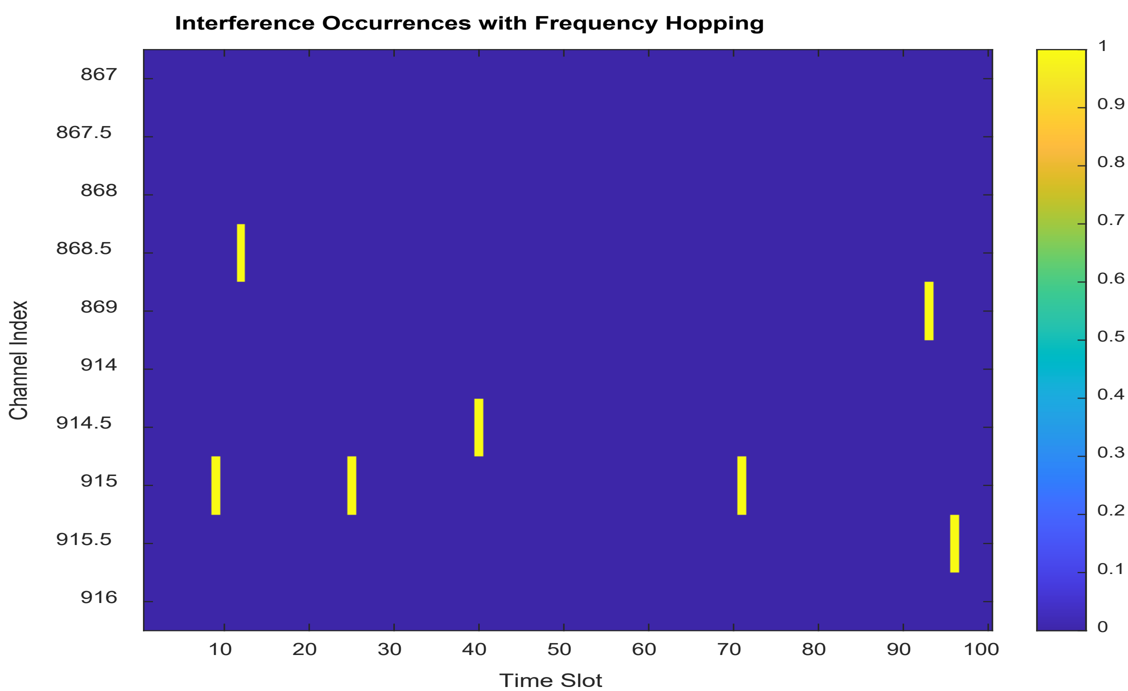

Fig. 10: Frequency Hopping at 10 Static Channels for spectrum optimisation at 868MHz and 915MHz

Looking at Figure 9, the same interference can be seen on the 10 static channels. It has a lot of interference spots as it can be seen on the graph with yellow spots. The channel index and the time slot show the performance of the Optimised Frequency Hopping Model on the unlicensed spectrum at 868MHz and 915MHz. In Figure110, the Optimised Frequency Hopping Model showed that the interference has been reduced.

4.10 ALGORITHM FOR 10 STATIC CHANNELS AT 868MHZ AND 915MHZ

1. Initialise 10 channels in the 868MHz and 915MHz bands.
2. Define the total number of time slots for simulation.
3. Define the probability of interference on any channel during a time slot.
4. Create a matrix to store interference occurrences.
5. Initialise a memory to remember the last used channels (to ensure hopping).
6. Loop through each time slot:
   - Check for interference on the current channel.
   - If interference is detected or the channel was recently used, hop to another channel.
   - Record the selected channel and any interference occurrence.
7. Display and visualise the results.

4.10.1 Algorithm of Optimised Frequency Hopping for 10 Static Channels at 868MHz and 915MHz

```
% Initialisation
F_868 = linspace(867, 869, 10); % 10 channels in 868MHz band
F_915 = linspace(914, 916, 10); % 10 channels in 915MHz band
F = [F_868, F_915]; % All channels
T = 100; % Total number of time slots for simulation
% Assuming a 10% chance of interference on any channel at a given time slot
interference_probability = 0.10;
% Matrix to store interference occurrences (1 if interference, 0 otherwise)
interference_matrix = zeros(length(F), T);
```

```
% Memory to remember recently used channels
memory_size = 5;
memory = zeros(1, memory_size);
% Frequency Hopping Algorithm
current_channel = randi(length(F)); % Start with a random channel
for t = 1:T
    % Check interference on the current channel
    if rand() <= interference_probability || ismember(current_channel, memory)
        % Interference detected or channel was recently used
        possible_channels = setdiff(1:length(F), [memory, current_channel]);
        current_channel = randsample(possible_channels, 1);
    end
    interference_matrix(current_channel, t) = (rand() <= interference_probability);
    % Update memory
    memory = [current_channel, memory(1:end-1)];
end
% Displaying the results
disp("Interference Matrix:");
disp(interference_matrix);
% Plotting the interference occurrences
figure;
imagesc(interference_matrix);
colorbar;
xlabel('Time Slot');
ylabel('Channel Index');
title('Interference Occurrences with Frequency Hopping');
yticks(1:length(F));
yticklabels(arrayfun(@num2str, F, 'UniformOutput', false));
```

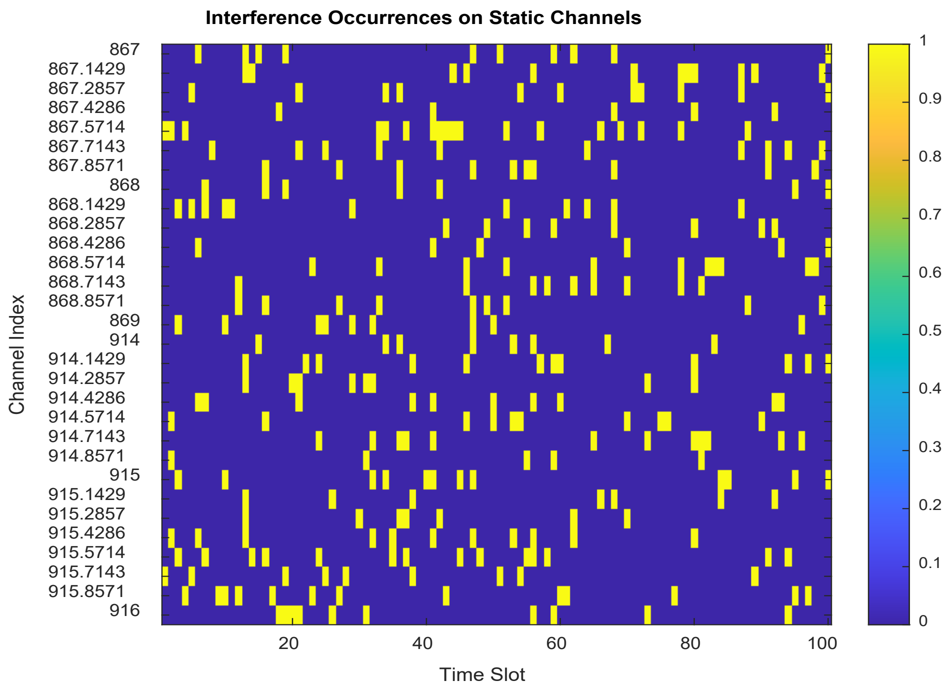

Fig. 11: Interference at 15 static channels for spectrum optimisation at 868MHz and 915MHz

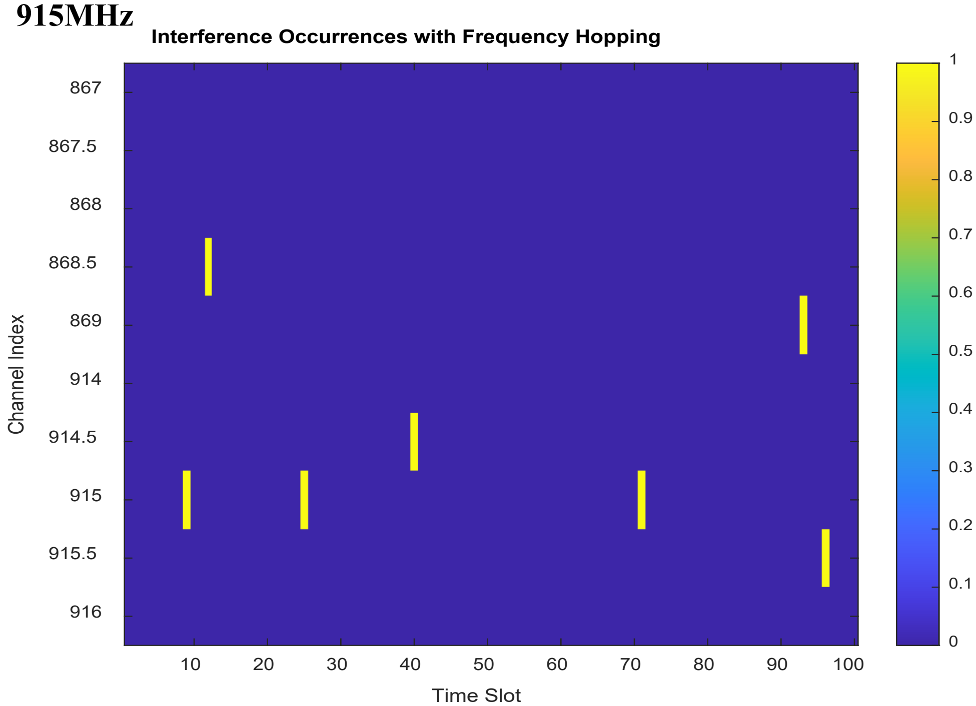

Fig. 12 Frequency Hopping at 15 Static Channels for spectrum optimisation at 868MHz and 915MHz

In Figure 11 interference can be seen on the 12 static channels. It has a lot of interference spots as shown on the graph with many yellow spots. The channel index and the time slot show the performance of interference occurrences on the unlicensed spectrum at 868MHz and 915MHz. In some of the static channels, there was no evidence of interference again after the model was used, unlike before when there were many instances of interference. The Optimised Frequency Hopping Model in Figure 12 showed that the interference has been reduced and totally removed in some instances.

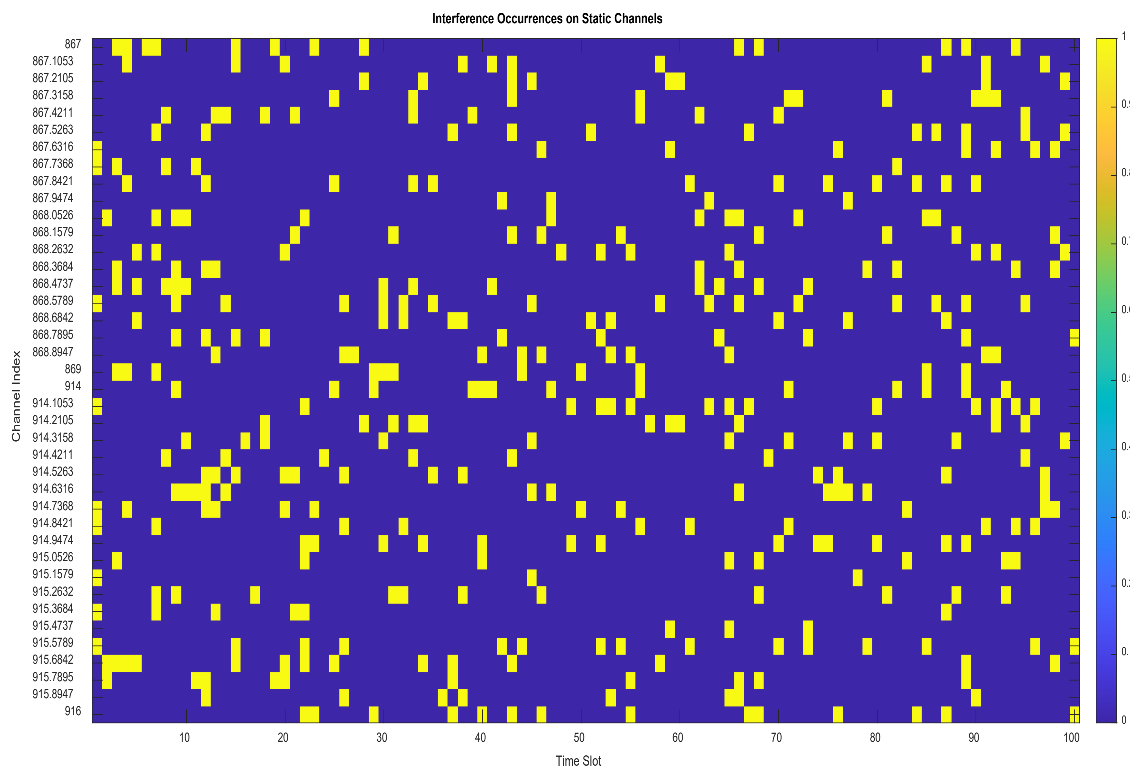

Fig. 13 Interference at 20 static channels for spectrum optimisation at 868MHz and 915MHz

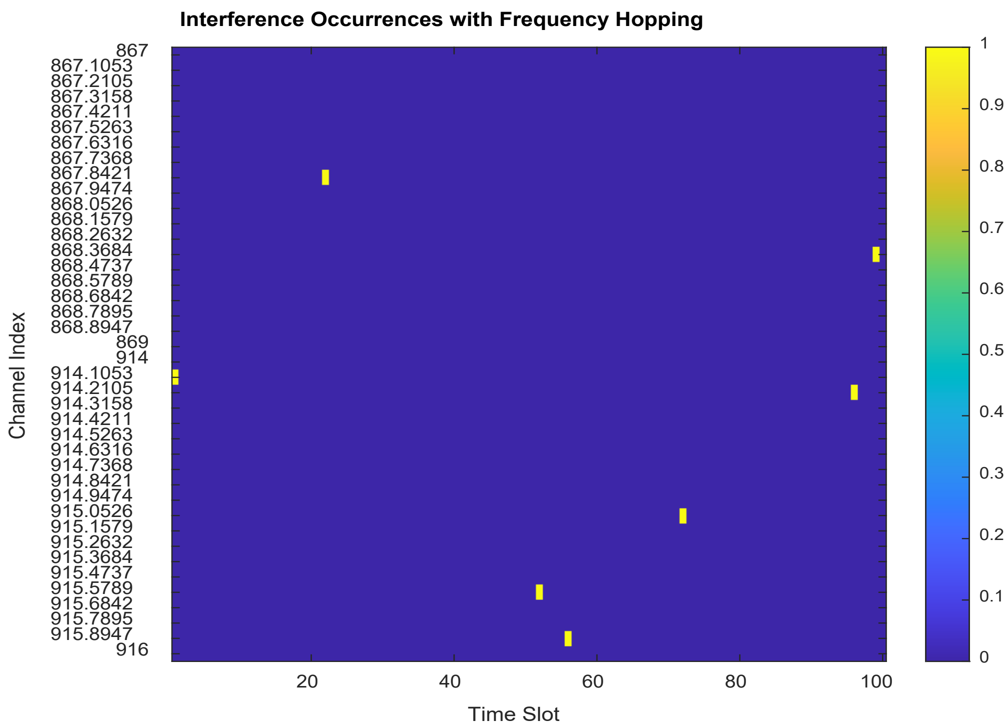

Fig. 14 Frequency Hopping at 20 Static Channels for spectrum optimisation at 868MHz and 915MHz

In Figure 13, the same interference can be seen on the 20 static channels. It has a lot of interference spots as it can be seen on the graph with yellow spots. The channel index and the time slot show the performance of interference on the unlicensed spectrum at 868MHz and 915MHz. In Figure 14, the Optimised Frequency Hopping Model showed that the interference has been reduced.

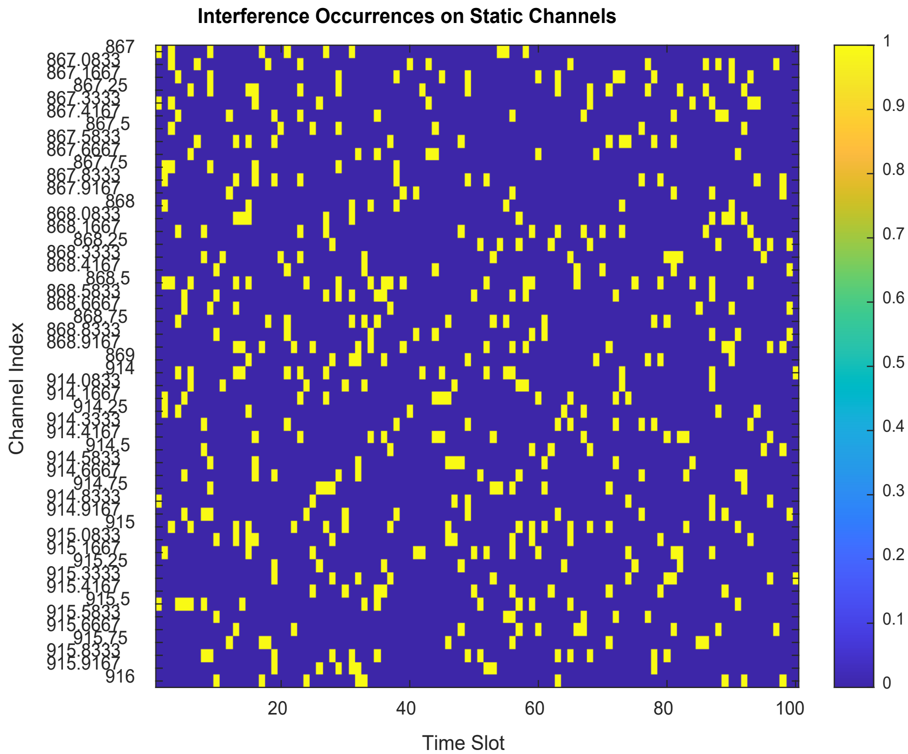

Fig.15: Interference at 25 static channels for spectrum optimization at 868MHz & 915MHz.

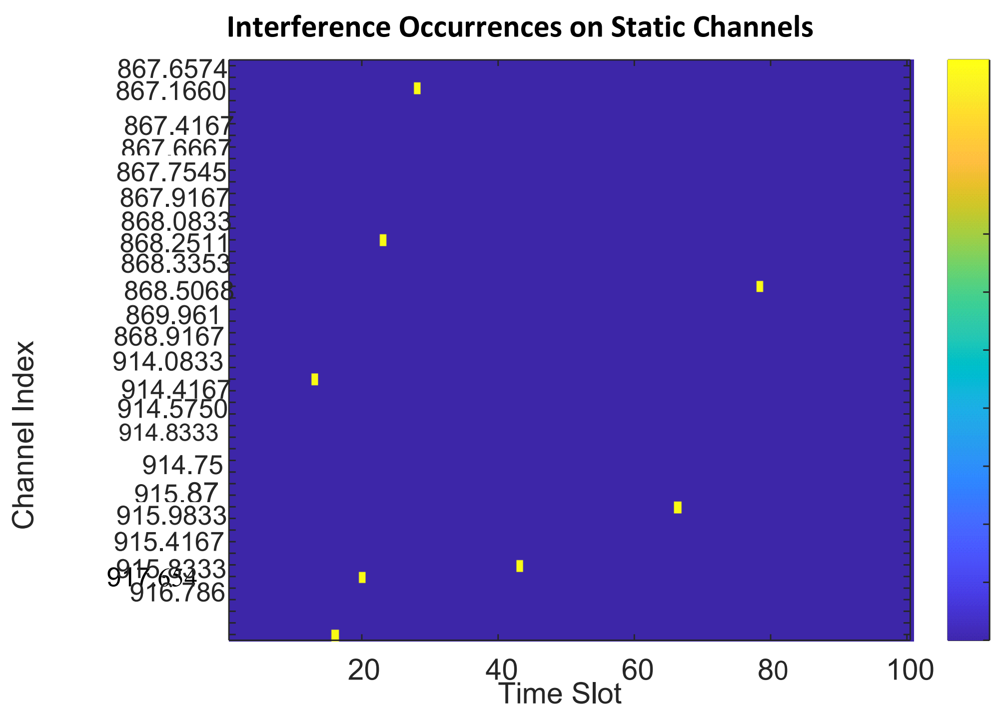

Fig.16 Frequency Hopping at 25 static channels for spectrum optimisation

Considering Figure 15 and Figure 16, the impact of Optimised Frequency Hopping Model was also shown. Interference occurred in Figure 15 with many spots depicting how the channels are subjected to high interference. It continues for a while until the model was used. The simulink results showed a deduction in the number of interference spots. They became fewer showing that interference as well as background noise has been minimised.

Table 6 Performance metrics for Optimised Frequency Hopping Model at 868MHz and 915MHz unlicensed spectrum

No of Static Channels	Latency	Throughput
5	0.0009	1002
10	0.0010	1992
15	0.0030	2993
20	0.0060	3993
25	0.0130	4987

Table 6 above shows the performance metric of Optimised Frequency Hopping Model at 868MHz and 915MHz unlicensed spectrum. It can be noted that latency becomes lower as the number of static channels reduces. It means the latency is directly proportional to the number of static channels after the Optimised Frequency Hopping Model has been used. This is a good performance metric as far unlicensed spectrum optimisation is concerned for smart city adoption. Also, throughput increases as the number of static channel increases. More LPWANs can make use of the unlicensed spectrum at these two frequencies. The Optimised Frequency Hopping Model increases the throughput.

4.11 SUMMARY

This chapter presented the simulation results carried out showing an improvement in the performance of the unlicensed spectrum at frequencies of 686 MHz and 915MHz through larger throughput and lower latency. Figure 6 to figure 16 shows the performance of the Optimised Frequency Hopping Model that was used to reduce ambient noise as well as interference to the barest minimum on the unlicensed spectrum at 868MHz and 915MHz frequencies. The number of static channels from 5 to 25 allowed the observation on each channel that was affected by ambient noise and interference. Thereafter, the model was used on each static channel and then the results were shown by noticing fewer or reduced level of interference on each static channel. The Optimized Frequency Hopping Model demonstrated enhanced performance in mitigating ambient noise and interference within the unlicensed spectrum frequencies of 868MHz and 915MHz. This model, applied to LPWANs, effectively employs dynamic frequency shifting, minimizing prolonged exposure to interference. Consequently, this leads to improved reliability in high-traffic environments, which is crucial for the effective implementation of smart city technologies. Also, the Optimised Frequency Hopping Model facilitated the achievement of reduced latency and increased throughput. Simulation results consistently indicated improvements in both parameters, demonstrating the model's efficiency in optimising the unlicensed spectrum at these specific frequencies.

An Optimised Frequency Hopping Model was developed and tailored to the unique requirements and challenges of LPWAN deployments in smart city environments. This model leveraged advanced algorithms and optimization techniques to dynamically allocate frequency channels based on real-time network conditions and traffic patterns. There was improved spectrum utilisation in the simulations attesting to the performance and effectiveness of the model in enhancing spectrum utilization, mitigating interference, and improving overall network reliability.

There is improved unlicensed spectrum utilisation at 868MHz and 916MHz because the Optimized Frequency Hopping Model effectively utilised available spectrum resources by dynamically selecting and hopping between frequency channels, reducing the likelihood of interference, and maximizing overall network capacity making the smart city run efficiently.

From this study, the Optimized Frequency Hopping Model leads to spectrum robustness by continuously adapting to changing environmental conditions and network dynamics, thereby increasing the resilience of LPWAN communication in smart city scenarios, minimizing the impact of channel impairments and external interference sources.

Through intelligent frequency hopping algorithms, the model reduced packet loss and latency, enhancing the quality of service for LPWAN applications in smart city deployments. It also demonstrates scalability and flexibility, accommodating varying numbers of LPWAN devices and applications while maintaining optimal performance and spectrum efficiency.

The algorithm of this model considers factors such as channel conditions, interference levels, and network requirements to select the most suitable frequencies for transmission at any given time.

However, the Optimised Frequency Hopping Model continuously monitors the spectral environment to identify optimal frequencies for transmission. Sometimes, the model utilises techniques such as energy detection, interference measurement, or spectrum sensing to assess the quality of available channels. Using the model for unlicensed spectrum at frequencies of 868MHz and 915MHz will make the unlicensed spectrum more utilized for smart city adoption.

This research has significant implications for the design and deployment of LPWAN systems in smart cities, providing a practical framework for optimizing spectrum utilisation and improving network performance through Optimized Frequency Hopping Model.

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CHAPTER FIVE

CONCLUSION & RECOMMENDATIONS

5.1 INTRODUCTION

The use of unlicensed spectrum has increased, leading to more networks operating within it and consequently creating coexistence issues. The use case of LPWANs occupying frequencies of 868MHz and 915MHz is considered in this study. It was noted that interference is high at these frequencies as well as the ambient noise. For smart cities making use of LPWAN networks for efficient day-to-day running, the unlicensed spectrum at these frequencies would perform better if optimised. The Optimised Spectrum Sharing Model minimises the effects of ambient noise and interference at the frequencies of 869MHz and 915MHz. In the preceding chapters the work of different researchers were reviewed, and a research gap was identified. The study showed that interference was a challenge due to proximity of many LPWANs within the unlicensed spectrum. For the use case frequencies (868MHz and 915MHz) at which these LPWANs operate, there are many other networks operating in these frequencies. This coexistence will continue to occur as communication networks constantly expand.

5.2 THE KEY FINDINGS OF THE RESEARCH

From the study the Optimised Frequency Hopping Model lowered the ambient noise at frequencies of 868MHz and 916MHz in the unlicensed spectrum and reduced the interference as seen by the simulation results. The latency, which is an important parameter in data communication, was effectively reduced by using the model. Furthermore, the throughput was improved as seen in the results. Considering the capacity of channels in the spectrum at 868MHz and 915MHz, when the proposed Optimised Frequency Hopping Model was employed, the channel capacity increased meaning that there is an improved quality of service (QoS). More LPWANs can make use of the bandwidth for their communication needs.

LPWAN technologies like LoRa and Sigfox would benefit from Optimised Frequency Hopping Model because when they dynamically change their frequencies, they are not exposed to interference for long, they can then increase their reliabilities in congested environments. Thus, the Optimised Frequency Hopping Model also increased the reliability of the LPWANs at these two frequencies under consideration.

The model reduces the performance degradation of LPWANs at frequencies of 868MHz and 915MHz unlicensed spectrum. Since there is robustness of these networks when the model was applied, interference reduced, the performance degradation of the network also reduced. Many networks can then co-exist without causing interference or disrupting the service of other networks.

5.3 CONCLUSION

In carrying out this research work and using MATLAB simulations, Optimised Frequency Hopping Model optimises the unlicensed spectrum at 868MHz and 915MHz occupied by LPWANs. The channel capacity increased, the throughput increased as well, and the latency was reduced. As other spectrum sharing models were tested in this research, it was discovered that Optimised Frequency Hopping Model performed better as shown by the simulation results. Because of this, many users can make use of the channel for their communication needs since interference has been drastically reduced, hence, high quality of service (QoS). The simulation was repeated for different values of static channels, amplitude and frequencies, different results were found for each value. It was better for both channel capacity and the latency for all the values used and whatever LPWAN that make use of these frequencies will have good communication devoid of the negative impact of interference. We can then conclude that our Optimised Frequency Hopping Model has significantly improved the performance of networks or devices operating in the unlicensed spectrum at 868MHz and 915MHz. To the best of our knowledge no research has been done in the optimisation of the unlicensed spectrum at frequencies of 868MHz and 915MHz mostly occupied by LPWANs. Our work is unique in that the optimised spectrum makes the LPWANs dependable for smart city adoption.

5.4 RECOMMENDATION FOR FUTURE WORK

In building smart cities powered by LPWANs and IoTs, the optimisation of unlicensed spectrum at certain frequencies would enhance deployment of smart technologies. But there are challenges of many devices making use of the unlicensed spectrum to interoperate and work seamlessly together. There is need for the coordination of different IoTs and sensors working together and securely so that the information by these sensors are not compromised. The integrity of the information supplied by these numerous sensors will determine how the smart cities will run. It is better that this information is secured so that the reliability of smart cities management can be guaranteed. This is one research area that needs to be pursued. Interoperability is another area where smart cities would have issues. This is because different censors powered by different LPWAN technologies need to interoperate to ensure the smart city works smoothly. Furthermore, the interoperability of devices in different domains is difficult due to lack of common standards.

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Appendix

Algorithm for 15 Static Channels at 868MHz and 915MHz

1. Initialize 15 channels in the 868MHz and 915MHz bands.
2. Define the total number of time slots for simulation.
3. Define the probability of interference on any channel during a time slot.
4. Create a matrix to store interference occurrences.
5. Initialize a memory to remember the last used channels (to ensure hopping).
6. Loop through each time slot:
   - Check for interference on the current channel.
   - If interference is detected or the channel was recently used, hop to another channel.
   - Record the selected channel and any interference occurrence.
7. Display and visualize the results.

Algorithm for Optimized Frequency Hopping at 15 Static Channels at 868MHz and 915MHz

```
% Initialization
F_868 = linspace(867, 869, 15); % 15 channels in 868MHz band
F_915 = linspace(914, 916, 15); % 15 channels in 915MHz band
F = [F_868, F_915]; % All channels
T = 100; % Total number of time slots for simulation
% Assuming a 10% chance of interference on any channel at a given time slot
interference_probability = 0.10;
% Matrix to store interference occurrences (1 if interference, 0 otherwise)
interference_matrix = zeros(length(F), T);
% Memory to remember recently used channels
memory_size = 5;
memory = zeros(1, memory_size);
% Frequency Hopping Algorithm
current_channel = randi(length(F)); % Start with a random channel
```

```
for t = 1:T
    % Check interference on the current channel
    if rand() <= interference_probability || ismember(current_channel, memory)
        % Interference detected or channel was recently used
        possible_channels = setdiff(1:length(F), [memory, current_channel]);
        current_channel = randsample (possible_channels, 1);
    end
    interference_matrix(current_channel, t) = (rand() <= interference_probability);
    % Update memory
    memory = [current_channel, memory(1:end-1)];
end
% Displaying the results
disp("Interference Matrix:");
disp(interference_matrix);
% Plotting the interference occurrences
figure;
imagesc(interference_matrix);
colorbar;
xlabel('Time Slot');
ylabel('Channel Index');
title('Interference Occurrences with Frequency Hopping');
yticks(1:length(F));
yticklabels(arrayfun(@num2str, F, 'UniformOutput', false));
```

Algorithm for 20 Static Channels at 868MHz and 915MHz

1. Initialize 20 channels in both the 868MHz and 915MHz bands.
2. Define the total number of time slots for simulation.
3. Define the probability of interference occurring on any channel during a given time slot.

4. Create a matrix to store interference occurrences.
5. Initialize a memory to keep track of recently used channels to ensure effective hopping.
6. Loop through each time slot:
   - If interference is detected on the current channel, or if the channel was recently used, hop to another channel.
   - Record the selected channel and any interference occurrence.
7. Display and visualize the results.

Algorithm for Optimized Frequency Hopping at 20 Static Channels at 868MHz &915MHz

```
% Initialization
F_868 = linspace(867, 869, 20); % 20 channels in 868MHz band
F_915 = linspace(914, 916, 20); % 20 channels in 915MHz band
F = [F_868, F_915]; % All channels combined
T = 100; % Total number of time slots for simulation
% Assuming a 10% chance of interference on any channel at a given time slot
interference_probability = 0.10;
% Matrix to store interference occurrences (1 if interference, 0 otherwise)
interference_matrix = zeros(length(F), T);
% Memory to remember recently used channels (to ensure hopping)
memory_size = 7; % You can adjust this based on your needs
memory = zeros(1, memory_size);
% Frequency Hopping Algorithm
current_channel = randi(length(F)); % Start with a random channel
for t = 1:T
   % Check for interference on the current channel
   if rand() <= interference_probability || ismember(current_channel, memory)
      % Interference detected or channel was recently used
      possible_channels = setdiff(1:length(F), [memory, current_channel]);
```

```
        current_channel = randsample(possible_channels, 1);
    end
    interference_matrix(current_channel, t) = (rand() <= interference_probability);
    % Update memory with the recent channel
    memory = [current_channel, memory(1:end-1)];
end
% Displaying the results
disp("Interference Matrix:");
disp(interference_matrix);
% Plotting the interference occurrences
figure;
imagesc(interference_matrix);
colorbar;
xlabel('Time Slot');
ylabel('Channel Index');
title('Interference Occurrences with Frequency Hopping');
yticks(1:length(F));
yticklabels(arrayfun(@num2str, F, 'UniformOutput', false));
```

Algorithm for 25 Static Channels at 868MHz and 915MHz

1. Initialize 25 channels in both the 868MHz and 915MHz bands.
2. Define the total number of time slots for simulation.
3. Define the probability of interference occurring on any channel during a given time slot
4. Create a matrix to store interference occurrences.
5. Initialize a memory to track recently used channels to facilitate effective hopping.
6. Loop through each time slot:
    - If interference is detected on the current channel or if the channel was recently used, hop to another channel.
    - Record the selected channel and any interference occurrence.

7. Display and visualize the results.

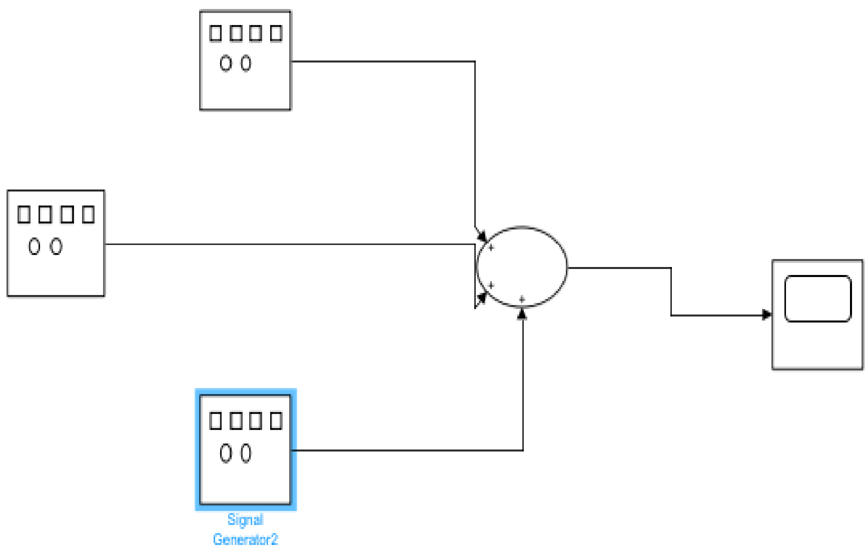
Algorithm of Optimized Frequency Hopping at 25 Static Channels

```
% Initialization
F_868 = linspace(867, 869, 25); % 25 channels in 868MHz band
F_915 = linspace(914, 916, 25); % 25 channels in 915MHz band
F = [F_868, F_915]; % All channels combined
T = 100; % Total number of time slots for simulation
% Assuming a 10% chance of interference on any channel at a given time slot
interference_probability = 0.10;
% Matrix to store interference occurrences (1 if interference, 0 otherwise)
interference_matrix = zeros(length(F), T);
% Memory to remember recently used channels (to ensure hopping)
memory_size = 8; % This can be adjusted based on your needs
memory = zeros(1, memory_size);
% Frequency Hopping Algorithm
current_channel = randi(length(F)); % Start with a random channel
for t = 1:T
    % Check for interference on the current channel
    if rand() <= interference_probability || ismember(current_channel, memory)
        % Interference detected or channel was recently used
        possible_channels = setdiff(1:length(F), [memory, current_channel]);
        current_channel = randsample(possible_channels, 1);
    end
    interference_matrix(current_channel, t) = (rand() <= interference_probability);
    % Update memory with the recent channel
    memory = [current_channel, memory(1:end-1)];
end
% Displaying the results
disp("Interference Matrix:");
```

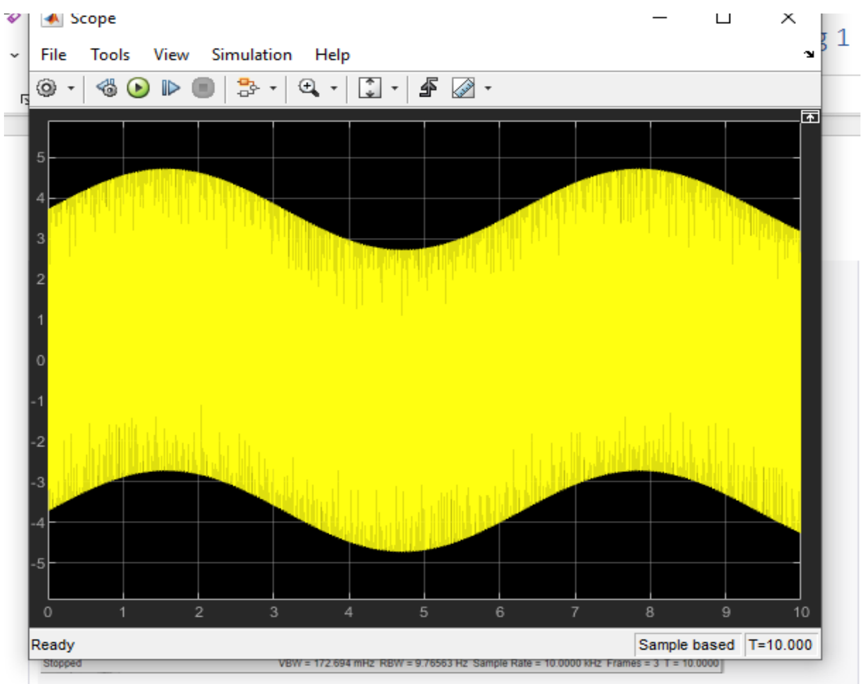
```
disp(interference_matrix);
% Plotting the interference occurrences
figure;
imagesc(interference_matrix);
colorbar;
xlabel('Time Slot');
ylabel('Channel Index');
title('Interference Occurrences with Frequency Hopping');
yticks(1:length(F));
yticklabels(arrayfun(@num2str, F, 'UniformOutput', false));
```

BLOCK DIAGRAMS OF THE SIMULATION

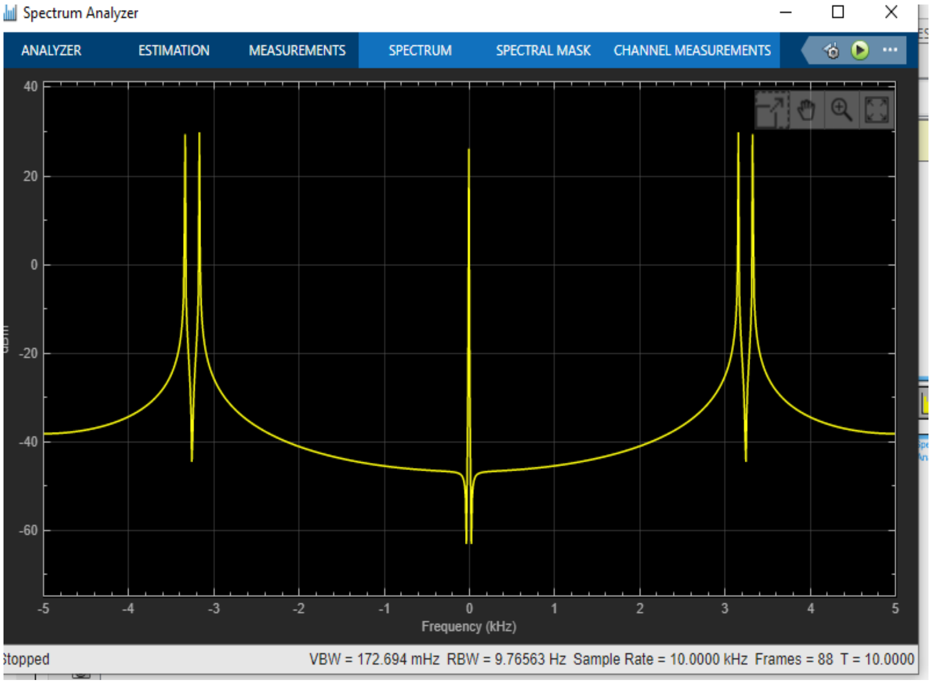
Block Diagram showing interference on the unlicensed spectrum at 868MHz and 915MHz



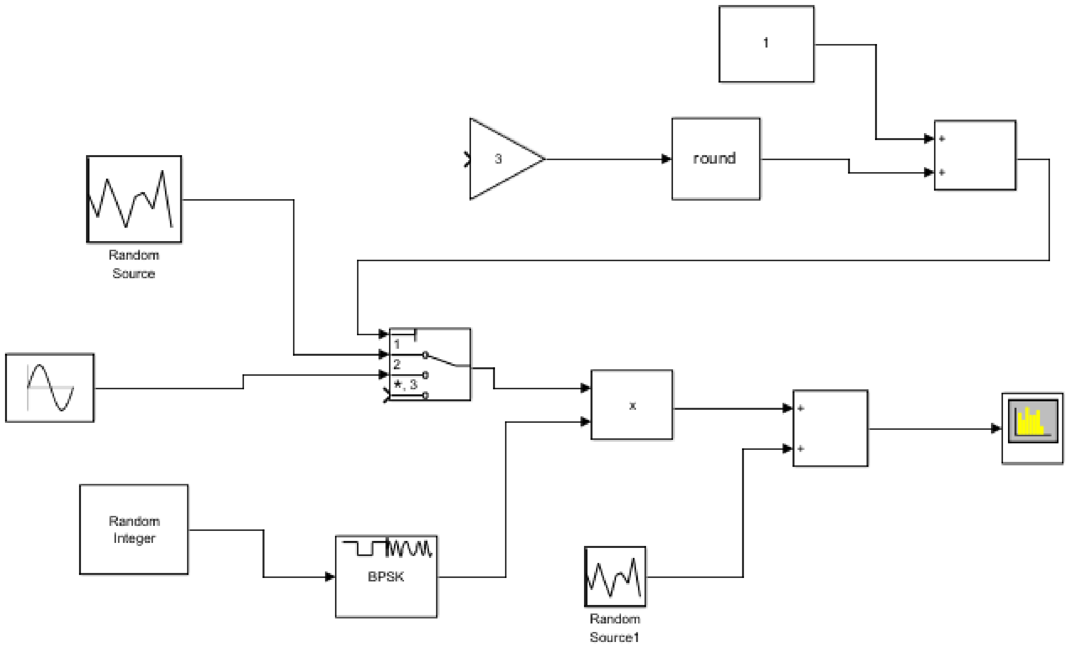
Display on the oscilloscope showing interference on the unlicensed spectrum at 868MHz and 915MHz



Display on the Spectrum Analyser showing interference on the spectrum at 868MHz and 915MHz



Block Diagram showing Optimised Frequency Hopping at 868MHz and 915MHz unlicensed bands



Display on the Spectrum Analyser showing Optimised Frequency Hopping on the Unlicensed spectrum at 868MHz and 915MHz

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16/11/2023

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RE: EDITING CERTIFICATE

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This serves to confirm that this research has been edited for clarity, language and layout.

Kind regards,

Nereshnee Govender (PhD)