COEXISTENCE BETWEEN 5G CELLULAR AND FIXED SATELLITE SERVICES IN C-BAND BASED ON MACHINE LEARNING MODELS

By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Chair : Prof. Ir. Aduwati Binti Sali, PhD
Faculty : Engineering

This thesis addresses limitation of existing Next-generation wireless mobile networks. The spectrum resource, especially below 6 GHz. such as 5th generation mobile networks, may reduce capacity bottlenecks by using radio frequency (RF) spectrum sharing. Spectrum sharing allows several wireless systems to coexist in a single spectrum band. The research on spectrum coexistence difficulties between 5G base stations (BS) and fixed satellite services (FSS) has recently increased. In Malaysia, the 5G uses frequencies between 3.6 - 3.7 GHz, while FSS operates with 3.8 - 4.2 GHz. Although there is a gap between both of them, adjacent channel interference might occur. For this reason, the FSS downlink Earth Station (FSS-ES) interference should be investigated from the 5G-BS to the FSS-ES and the 5G-ES to the 5G User Equipment (UE). This is one of the main goals of this thesis, focusing on the Malaysian scenario. Several proposals are drawn after realizing the interference happened and affected the performance: The first part is the design of an exclusion zone on how coexistence between 5G-BS and FSS-ES can be used to avoid adjacent co-channel interference in 5G and B5G to FSS-ES. Co-channel and adjacent channel interference are investigated at various stages in 5G-BS and FSS-ES. For investigating interference in the same frequency band, measurements have been carried out and data have been analyzed with 5G-BS and FSS-ES. Then, 5G technologies addressed the optimal exclusion zone. In order to analyze and improve state of the art, Machine Learning (ML) techniques such as Radial Basis Function Neural Network (RBFNN) and General Regression Neural Network (GRNN) have been used. The results indicated that the proposed ML has its own set of characteristics that can be used to create a new exclusion zone design that is more efficient. Furthermore, the adjacent channel interference comprised the Interference-Noise Ratio (INR), where interference occurred with INR levels below -12.2 dBm (-55dBc). It has been shown that RBFNN has better accuracy, but lower MSE is obtained with GRNN.

The second part of the thesis focuses on the proposal of a filtering model denoted Filter to Remove Broadband Interference 5G (FIREBRING) based on the carrier-to-noise (C/N). It has to be designed jointly with the Guard Band (GB). The results indicate that the proposed offered a complete analysis of the 5G signal, considering the implications of out-of-band (OOB) emissions, potentially LNB define saturation into the FSS receiver, and the repercussions of deploying the 5G BS active antenna systems. With the LNB and down-converter in place, it can be found that the signal interference between 1.450GHz and 1.550GHz, is nearly 18dB. In the third part of the thesis, it is found that a lower look-up angle for the FSS-ES is needed for future field trials with various 5G Active Antenna Unit variants. The results suggest that 5G transmission operates at 3.620 GHz to protect satellite services at 3.7 GHz. A further field trial was conducted to evaluate further whether the distance and Guard Band (GB) can be reduced. It is concluded that FSS-ES can coexist with 5G-BS as close as 85m apart, with 100 MHz GB and Bandpass Filter (BPF) rejection at least more than 45 dB. Also includes a new filtering technique called 5G-Filter to Remove Interference in Major Broadband (5G-FRIMB) to improve the signal. In the last part of the thesis, an analytical model for 5G-BS and FSS-ES in C-Band based on ML for the design of the exclusion zone is developed. In order to address these challenges, this thesis examined whether it is possible to design a proper exclusion zone for small cell 5G and FSS receivers based on the tropical region's characteristics. Specific to the interference between 5G-BS and FSS-ES in the adjacent and co-channel channel. Machine learning techniques have been used to model co-channel interference. This PhD thesis shows that ML can help with some of the modelling problems in RF, even in the presence of interference.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

KEWUJUDAN SERENTAK RANGKAIAN SELULAR JALUR LEBAR GENERASI KELIMA (5G) DAN PERKHIDMATAN SATELIT TETAP PADA JALUR – C-BERDASARKAN MODEL PEMBELAJARAN MESIN

Oleh

AL-JUMAILY ABDULMAJEED HAMMADI JASIM

November 2022

Pengerusi : Prof. Ir. Aduwati Binti Sali, PhD
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Tesis ini menangani had rangkaian mudah alih tanpa wayar generasi akan datang yang sedia ada. Sumber dari spektrum, terutamanya yang berjalur bawah 6 GigaHertz (GHz), sebagai contoh rangkaian mudah alih generasi ke-5 (5G), boleh digunakan untuk mengurangkan kesesakan kapasiti dengan berkongsi spektrum berfrekuensi radio (RF). Perkongsian spektrum tersebut membolehkan beberapa sistem tanpa wayar wujud dalam satu jalur spektrum. Walaubagaimanapun, terdapat peningkatan penyelidikan berkaitan kesukaran mewujudkan kebersamaan spektrum antara stesen pangkalan jaringan 5G (5G-BS) dan perkhidmatan satelit tetap (FSS). Di Malaysia, jaringan 5G menggunakan frekuensi antara 3.6 - 3.7 GHz, manakala FSS beroperasi dengan 3.8 - 4.2 GHz. Walaupun terdapat perbezaan frekuensi antara kedua-duanya, kemungkinan terdapat gangguan pada saluran disebabkan frekuensi yang berdekatan masih boleh terjadi. Atas sebab ini, gangguan FSS pautan menurun di stesen bumi (FSS-ES) harus disiasat, iaitu daripada 5G-BS kepada FSS-BS dan 5G-BS kepada Peralatan Pengguna 5G (5G-UE). Ini adalah antara matlamat utama tesis ini, memfokuskan kepada senario Malaysia. Selepas menyedari terdapatnya gangguan yang berupaya menjejaskan prestasi, beberapa cadangan telah diutarakan untuk isu ini iaitu bahagian pertama adalah mereka-bentuk zon batasan dengan menggunakan kewujudan bersama 5G-BS dan FSS-ES untuk mengelakkan gangguan saluran frekuensi berdekatan dalam 5G dan generasi jaringan yang termaju darinya (B5G) kepada FSS-ES. Gangguan pada saluran yang sama dan yang disebabkan frekuensi berdekatan disiasat pada pelbagai peringkat dalam 5G-BS dan FSS-ES. Untuk menyiasat gangguan dalam jalur frekuensi yang sama, pengukuran telah dijalankan dan data telah dianalisis pada 5G-BS dan FSS-ES. Seterusnya, teknologi 5G menangani zon batasan secara optimum. Untuk penganalisaan dan penambah-baikan yang lebih terkini, teknik Pembelajaran Mesin (ML) seperti Rangkaian Neural Fungsi Asas Jejari (RBFNN) dan Rangkaian Neural Regresi Umum

(GRNN) telah digunakan. Keputusan dari kajian ini menunjukkan bahawa sistem ML yang dicadangkan mempunyai ciri tersendiri yang boleh digunakan untuk mencipta reka bentuk zon batasan baharu yang lebih cekap. Gangguan saluran berdekatan yang terdiri daripada Nisbah Gangguan-Bunyi (INR) berlaku pada INR di bawah -12.2 dBm (-55 dBc). RBFNN telah dibuktikan mempunyai ketepatan yang lebih baik kerana mempunyai Min Ralat Kuasa Dua (MSE) yang lebih rendah daripada GRNN. Bahagian kedua tesis memfokuskan kepada cadangan model penapisan yang dinamakan Penapis Nyah Gangguan Jalur Lebar 5G (FIREBRING) berdasarkan pembawa kepada nisbah bunyi. Ia perlu direka-bentuk bersama dengan Pita Pengaman (GB). Hasil kajian menunjukkan bahawa cadangan ini memberikan analisis yang lengkap terhadap isyarat 5G, dengan mengambil kira implikasi pancaran di luar jalur, kemungkinan ketepuan blok rendah bunyi (LNB) dalam penerima FSS, dan kesan penggunaan sistem antena aktif di 5G-BS. Dengan adanya LNB dan penukar bawah, didapati bahawa gangguan isyarat pada frekuensi antara 1.450GHz dan 1.550GHz adalah hampir 18 decibel (dB). Dalam bahagian ketiga tesis, didapati bahawa sudut pandang FSS-ES yang lebih rendah diperlukan untuk pengujian menggunakan pelbagai jenis Unit Antena Aktif 5G di masa hadapan. Hasil kajian menunjukkan bahawa penghantaran 5G beroperasi pada frekuensi 3.620 GHz bagi melindungi perkhidmatan satelit pada frekuensi 3.7 GHz. Ujian di lapangan telah dijalankan untuk menilai sama ada jarak dan GB boleh dikurangkan. Kesimpulan dari ujian tersebut adalah FSS-ES boleh wujud bersama 5G-BS sedekat 85 meter, dengan 100-MegaHertz (MHz) GB dan Penapis Laluan Jalur (BPF) dengan nilai penolakan sekurang-kurangnya lebih daripada 45 dB. Juga termasuk teknik penapisan baharu yang dipanggil Penapis 5G NyahGangguan Jalur Lebar Utama (5G-FRIMB) untuk menambah baik isyarat. Di bahagian terakhir tesis, model analisis untuk 5G-BS dan FSS-ES dalam jalur frekuensi C telah dibangunkan berdasarkan ML untuk mereka-bentuk zon batasan. Kajian ini menyiasat kemungkinan untuk mereka-bentuk zon batasan yang sesuai untuk sel kecil penerima 5G dan FSS berdasarkan ciri kawasan tropika, khusus kepada gangguan saluran bagi frekuensi berdekatan dan gangguan dalam saluran yang sama antara 5G-BS dan FSS-ES. Teknik ML telah digunakan untuk memodelkan gangguan pada saluran yang sama. Tesis PhD ini menunjukkan bahawa ML boleh membantu dengan beberapa masalah pemodelan dalam RF, walaupun dengan adanya gangguan.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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This is to confirm that:

- the research and the writing of this thesis were done under our supervision;
- supervisory responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2015-2016) are adhered to.

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LIST OF ABBREVIATIONS

UPM	Universiti Putra Malaysia
5G NR	Fifth-Generation New Radio
5G gNB	Next Generation Node B
5G-FRIMB	5G-Filter to Remove Interference in Major Broadband
4G	Fourth-Generation Wireless
AAS	Active Antenna Systems
ACIRL	Adjacent Channel Interference Ratio Level
ACLR	adjacent channel leakage ratio
ACS	Adjacent Channel Selectivity
AI	Artificial Intelligence
ANN	Artificial Neural Networks
ANN-LM	Artificial Neural Network Learning Model
AOA	Angle of Arrival
AOD	Antenna-on-Display
BER	Bit Error Rate
BEM	Block Edge Mask
B5G	Beyond 5G
BS	Base Stations
BPF	Bandpass Filters
BWA	Broadband Wireless Access
CDF	Cumulative Distribution Function
CEPT	European Conference of Postal and Telecommunications Administrations
CIRR	Co-Channel Interference Ratio Level
C/N	carrier-to-noise ratio

DL	Downlink
DSA	Dynamic Spectrum Access/Allocation
ECO	European Communications Office
EIRP	Effective Isotropic Radiated Power
eMBB	enhanced Mobile Broadband
ES	Earth Station
EU	European Union
FCC	USA Federal Communications Commission
FDD	Frequency Division Duplex
FIREBRING	Filter to Remove Broadband Interference 5G
FSS	Fixed Satellite Services
GB	Guard Band
Gmax	Antenna Maximum Gain
IMT-Advanced	International Mobile Telecommunications-Advanced
GRNN	General Regression Neural Network
ITU	International Telecommunication Union
IoT	Internet of Things
INR	Interference-to-Noise Ratio
LNAs	low Noise Amplifiers
LNB	Low-Noise Block
LTE	Long-Term Evolution
LOS	Line-of-Sight
MC	Monte Carlo
MEASAT	Malaysia East Asia Satellite
MIMO	Multiple-Input and Multiple-Output
MLR	multiple linear regression model

MLP	Multilayer Perceptron
ML	Machine Learning
mMTC	massive Machine Type Communications
M2M	Machine-to-Machine
MSE	Mean Squared Error
NLOS	Non-Line-of-Sight
OOB	Out-of-Band
RBFNN	Radial Basis Function Neural Network
RBW	Resolution Bandwidth
RF	Radio Frequency
RFI	Radio Frequency Interference
RSS	Received Signal Strength
RX	Receives Signal
SINR	Signal-to-Interference Noise Ratio
SLP	Single Layer Perceptron
SWT	Sweep Time
T-1, T-2, T-3	Test Numbers
TDD	Time Division Duplex
TOA	Time of Arrival
TX	Transmitter Signal
UE	User Equipment
UL	Uplink
UPM	Universiti Putra Malaysia
uRLLC	Reliable Low Latency Communications
VBW	Video Bandwidth
VSAT	A very small aperture terminal

Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WMO	World Meteorological Organization
WRC	World Radio communication Conferences

CHAPTER 1

INTRODUCTION

This chapter introduces an overview of the relationship between Fifth-Generation new radio (5G-NR) and fixed satellite services earth station (FSS-ES) wireless systems, followed by a discussion of related problem statements. To address the issues addressed by the study's goals, an overview of research objectives, the scope of the research module, and a brief methodology are provided. This chapter concludes with a list of the research contributions. And finally, the organisation of the thesis.

1.1 Background

In current era, implemented a wide array of applications has led to the global mobile data service becoming a fast-growth mode with diversified intelligent terminal mobile applications. The spectrum is essential for the future growth of the 5G sector as the essential resource required for wireless communication. Currently, the domestic low-band mobile bandwidth is around 600MHz. 5G communications will require approximately 1GHz bandwidth by 2024 (Kabalci, 2019). Thus, low adaptability can be compared to measured data analysis. However, the traditional channel modelling methods have weaknesses. Science and technology progress slowly. 5G wireless carriers enable applications requiring high data, reliability, and low latency (M. J. R. I. Series, 2015). World regulators are allocating new frequency bands below 6-GHz may also be suitable for a 5G wireless service. It is possible to provide a European Union (EU) comprehensive wireless broadband electronic communication service using the 3.4 - 3.8GHz frequency range for terrestrial networks. Notwithstanding that, the European Conference of Postal and Telecommunications Administrations (CEPT) has established unified technological standards to ensure daily spectrum usage (Draft, 2018).

Japan sets a 5G frequency range of 3.6 - 4.2 GHz and 4.4 - 4.9 GHz (Son & Chong, 2018d). It is proposed by the South Korean Ministry of Science and ICT (M. J. J. I. W. C. Marcus, 2015). Data traffic for terrestrial broadband internet services is expected to double by 2022 (Obile, 2016). Also, 5G-NR will be located below the 6-GHz band, providing more coverage than the mmWave band. The 3.4 ~ 4.2 GHz frequency range in Hong Kong is mainly used for FSS-ES (DATE, 2019). For IMT-Advanced, the previous researcher's Japanese study group has a 4-year spectrum-sharing study. In addition to investigating the sharing of 3 - 4 GHz radiation, the research team tested existing FSS-ES performance after installing the base station (BS) in the same band. Their first contribution was to improve the ITU-R 452 propagation model for detecting anomalous propagation probabilities.

The other purpose is to measure the effect of clutter loss in urban areas, which was unrealistic due to the building heights. As a result of their proposal, a new model version was created. Asia-Sat is a heavy C-Band satellite operator in Asia. They published numerous articles and studies on coexistence. In addition to controlling low-noise block downconverter (LNB) saturation, their latest commercial feature is a Bandpass filter (BPF) for 5G interference rejection. There need to be more measures to control saturating the LNB. Rejecting the LNB filter tradeoff causes higher insertion loss. The insertion loss causes an increase in noise temperature, a sensitive issue. An insertion loss of less than 0.4 dB was attempted to claim for one of these company front-end filters within the three-year warranty frequency ranges of 3.4 - 3.6 GHz. Their experiment used 5G base stations (BS) deploying a full-loaded beam to an ES deployed with its BPF, distant 100 m away. Their white paper stated that the earth station was regularly running and reducing interference. Adopt and promote 5G by 2022. Malaysia also released a 5G system frequency usage plan in the 3 - 5 GHz range, clearly defining 3.3 ~ 3.4 GHz as the 5G system operating band and 3.4 - 3.6 GHz as the indoor use band (W. A. Hassan, Jo, & Tharek, 2017). The frequency range 3.7 - 4.2 GHz is the standard C-Band FSS-ES, and 3.4 - 3.7 GHz is the extended C-band. Several satellite networks use the 3.4 - 3.7 GHz extended C-band. Also, several FSS-ES are authorized to operate in the 3.4 ~ 3.7 GHz band, and FSS-ES are authorized to operate in the 3.4 - 3.6 GHz band, as Malaysia reported to International Telecommunication Union (ITU). Wireless communication signals rely on electromagnetic wave propagation, and the frequency band is the most valuable resource.

That is to avoid interfering with wireless TV broadcasts, mobile communication networks, and military frequency bands. Because 6GHz or less radio waves in the airpower attenuation are small, intense penetration is regarded as a high-quality band resource. Many applications rely on radio wave propagation in this crowded band. Telecommunications and other companies are expanding as technology advances in all areas of our lives. However, mobile communication network data was demanded as science and technology advanced. The capacity of the communication network is also truly tested by "mission-critical machine communication" (Weinand, Karrenbauer, Lianghai, & Schotten, 2017), such as industrial automation and vehicle communication. A wide range of industries, including agriculture, industry, environmental protection, medical care, transportation, and more, generate many data. Data has permeated the organization's daily business in various application scenarios.

Using machine learning to process and analyze massive amounts of data faster will help organizations understand fundamental economic changes and take advantage of growth opportunities (Paul, Ahmad, Rathore, & Jabbar, 2016). The 3.5 GHz band is also used for 5G mobile services in the EU, China, Australia, the US, the UK, and Japan regulators and operators use it. Furthermore, the C-Band is allocated for fixed satellite services (FSS) and provides coverage of continental zones. In the United States, the downlink frequency ranges between 3.7 GHz to 4.2 GHz, whereas in Europe, the range is between 3.4 GHz to 4.2 GHz. The C-Band is the best option for sustaining telecommunications and broadcasting services whenever the terrestrial infrastructure is insufficient or nonexistent in rural and seaside locations. The low sensitivity to rain fade of the C-Band enables it for reliable connections in tropical climates, a further advantage. Services in the C-Band are also important for emergency cases and calamity recovery. However, combining a frequency spectrum with other users implies interference with already-running services. Interference in the downlink may cause the low-noise blocks (LNB) to become saturated. The fixed and mobile earth stations' current receiving systems do not support the use of filters. The received signal is already insufficient and would no longer be detectable after travelling up to 36 000 km from a geostationary orbit to the earth station. Whereas regulatory restrictions provide recommendations for developing a cellular network, but they cannot guarantee that waves will not propagate further than expected.

The performance limitations of interference situations at the component and system levels must be investigated to enable the seamless coexistence of 5G and satellite services in the C-band. On the regulatory side, it is necessary to establish the equivalent isotropic radiated power (EIRP) of nearby stations and to identify any out-of-band (OOB) emissions. For active antenna systems, such as those utilised in 5G, the transmitted radiated power (TRP) value will be used in place of the EIRP for legacy base stations (Carciofi, Grazioso, Petrini, & Matera, 2019; Jaedon Park et al., 2019b). This study aims to investigate the 5G and FSS-ES downlink coexistence in the 3.4 - 3.6 GHz band.

1.2 Problem Statement

The following section addresses the most significant problems introduced by this study, which are listed as follows:

1) A mobile communications network uses radio transmission to enable wireless connectivity between smartphones, tablets, machines, and fixed infrastructure. Due to increased demand for mobile communications and rapid technological advancement, successive generations of mobile networks have been deployed across the country, each with superior capabilities. This increased demand necessitates more 5G-BS and radio spectrum, especially frequencies in urban areas. The 3.4 - 3.6 GHz spectrum has been designated the perfect innovator for 5G. Commitment to extending the spectrum covers several frequency bands. We are looking for a new spectrum for a 5G generation mobile network (Juho Lee et al., 2018d). The LNB and filter properties are then tested in the lab, and the coexistence requirements are verified in the field. The measurements and field-testing results will allow 5G and FSS coexistence to reduce interference and ensure 5G and FSS coexistence based on distance.

2) The 5G-BS saturation interference is considered using the latest 5G-NR characteristics and the isolation distance between the two systems (Q. Sun

& Nan, 2012; Y. Wang & Lu, 2018). The LNB and filter properties are then tested in the lab, and the coexistence requirements are verified in the field. The measurements and field-testing results will allow 5G and FSS coexistence to reduce interference and ensure 5G and FSS coexistence based on distance. It depends on many variables, each of which must be evaluated individually. Evaluated individually different uses coexistence in the same frequency range to avoid mutually harmful interference (Bensky, 2019).

3) Notwithstanding expanding coverage and capacity, the public should be encouraged to use the 5G system (Tullberg et al., 2016). The expected operation did not meet mobile users' communication needs. A multi-operator constellation is required for successful 5G deployments, requiring many more extensive sections of the C-Band (Varrall, 2018). A better understanding of antennas and the network's ability to adapt to specific needs are offered by 5G technology. 5G high flexibility allows for more system setup options. Radio propagation is an important physical phenomenon in satellite communications. Radio propagation is possible due to radio waves' interaction with topography, structures, and the environment. Radio propagation is possible due to radio waves' interaction with topography, structures, and the environment. Less radio signal modulation means more geographical separation of potentially conflicting systems (Mazar, 2016; Nuaymi, 2007; Shahajahan, 2009).

The C-Band studies share between 5G and FSS systems. There is proof of this separation distance, but no simulation or saturation interference tests were conducted (Jo, Yoon, Lim, Park, & Yook, 2007; Su, Han, Yan, Zhang, & Feng, 2014; Q. Sun & Nan, 2012; Y. Wang & Lu, 2018). The high data rate and spectrum quality can be improved by finding more space for the spectrum. Increasing spectrum efficiency in heterogeneous wireless networks is difficult because the sub-3GHz spectrum is crowded, slipped, and inefficient. The most significant problem is the potential for co-channel and adjacent channel interference between 5G-BS and FSS-ES signals receiving on the same frequency band. Moreover, the Artificial neural networks (ANN) in machine learning (ML) techniques to develop the quality of services, that is, to plan 5G Next Generation Node Base Station (5G-gNB) deployment without interference to FSS. According to the current research results in this thesis. ML is an effective improvement and supplement to the severely impacted by co-channel and adjacent channel interference if the optimal exclusion zone is not addressed by traditional channel modelling approach.

1.3 Research Objectives

This research aims to design and develop propagation models of coexistence between 5G-BS and FSS-ES, using measurements received signals and predicting the optimal RSS and Path Loss interference mitigation technique. The models measure 5G-BS and FSS-ES interference in the same frequency range. Machine learning models are used for C-Band interference and path loss measurements. The following are the study's main objectives concerning the problems presented:

(i) To determine the optimal exclusion zone between Fixed Satellite Service (FSS) station and 5G- gNB considering the Malaysian scenario.
(ii) To conduct measurements campaign to determine optimal exclusion zone considering Malaysian scenario.
(iii) To analyze and optimize system model parameters between 5G-BS and FSS-ES, in C-Band 3.5GHz, towards finding the optimal exclusion zone base on ML.
(iv) To develop analytical models for 5G-BS and FSS-ES in C-Band based on using Machine Learning (ML) towards addressing the optimal exclusion zone.

1.4 Scope of Research and Research Module

This thesis examines the coexistence between 5G-BS and FSS-ES to identify new opportunities for green 5G and B5G wireless communication network design using satellite communications. The goal is to develop a serious perspective on how coexistence between 5G-BS and FSS-ES can be used to avoid co-channel and adjacent channel interference in 5G and B5G to FSS-ES. Co-channel and adjacent channel interference are investigated at various stages in the design of 5G-BS and FSS-ES. For investigating interference in the same frequency band, the measurements and analysis begin with 5G-BS and FSS-ES. 5G and B5G technologies address the optimal exclusion zone. ML has its own set of characteristics that can be used to create a new exclusion zone design that is more efficient. As a result, this thesis examines the current coexistence between 5G-BS and FSS-ES to avoid co-channel and adjacent channel interference, as well as the key research directions that aim to achieve coexistence via 5G-BS and FSS-ES. It should be noted that most of the existing research has focused on a specific access technology, namely IMT-Advanced. However, current research is based on real-world measurements of 5G-BS and FSS-ES, leaving some new opportunities to be discovered.

As a result, additional research problems can be identified, and new research directions for future work can be proposed. The coexistence between 5G-BS and FSS-ES is thus thought to be promising candidates for 5G to FSS-ES design, given the newly identified opportunities and research directions. Figure 1.1 on the following page depicts the scope of the current study and a summary of the approaches used to achieve the established goals. The dashed line distinguishes the emerging technologies of the proposed system model in each objective, while the colored boxes show the direction to reach the previously mentioned objectives. It is worth noting that the uncolored boxes represent other technologies and scenarios that need to be covered in this research.

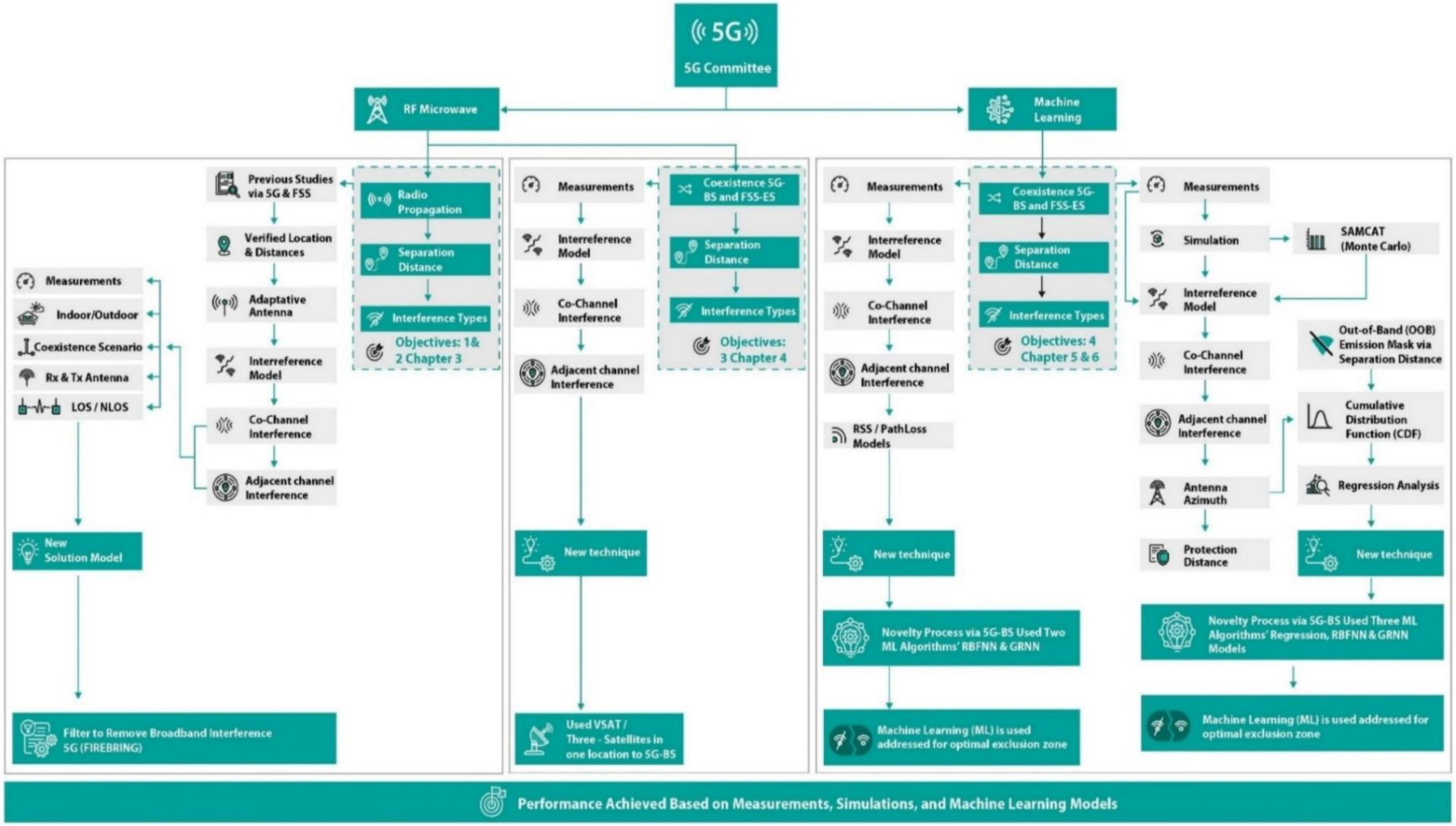

Figure 1.1: Research Scope Module

1.5 Brief Methodology

The methodology outlined how important data and information for research projects are systematically gathered. It will indicate how researchers can address some urgent problems and conduct research. Theoretical approaches are used to collect appropriate data and spots, such as by evaluating experiments or comparative investigations. The current research analysis is based on field test results; all measurement results except T1, T2, and T3 are consistent with the S21 parameter, whereas higher rejection was observed for the first carrier as opposed to the second carrier of 5G transmissions. These are due to RF leakage between band-pass filters (BPFs) and low-noise block downconverters (LNB). The VSAT experienced blocking interference when its LNB was unable to fully reject or reduce 5G signals below the satellite reception level. Based on field observations, the level of LNB blocking interference reduces exponentially at higher VSAT downlink frequencies. Furthermore, the frequency range of the LNB has no effect on the impact of blocking interference, as no interference was observed at 85 m with a gaud band (GB) of 100 MHz for all types of LNB when paired with a BPF with sufficient rejection.

At 85 metres and above, no significant impact is observed for both direct and indirect facing VSAT, as no interference with 100 MHz GB was observed. Furthermore, the directly facing VSAT at 115 m on the 3.836.27 GHz downlink frequency experienced out-of-band (OOB) emission interference from the 3rd carrier of 5G transmission from 3.600 to 3.650 GHz with 200 W transmit power. The OOB interference is fully eliminated when the power is reduced to 100W. No VSAT could coexist with 5G within 85 m and with 50 MHz GB due to OOB emission interference from the 3rd carrier of 5G transmission from 3.600 to 3.650 GHz with 100 W Tx power. Based on field testing with various distance meters, it has been determined that VSAT can coexist with 5G as close as 85 m with 100 MHz GB and BPF rejection of at least 45 dB. A minimum of 80 MHz GB (3.730–3.650 GHz) is needed to avoid OOB emission interference from 5G. Therefore, 5G carriers should stop at 3.620 GHz to protect satellite services at 3.700 GHz and above. Further field tests with different 5G Active Antenna Unit (AAU) models and VSATs with direct facing and a lower look-up angle than MEASAT VSAT are welcome to evaluate whether the distance and GB can be reduced further. Moreover, measurements, simulations, and analysis were implemented as the following points:

- Indoor and outdoor measurements of 5G-BS with FSS-ES were conducted for research and interpretation. As a result, only a few guidelines were available to ensure that the thesis' objectives were met, and the research technique was regulated correctly. Methodologies were used to assess the reliability of 5G-BS in the presence of FSS-ES.

- The RSS and Path Loss Mitigation Technique predicted the coexistence of 5G-BS and FSS-ES for the optimal signal strength. Nonetheless, the methodology flowchart goes into great detail about the information gathered.

- The current investigation is included in the scope of this study. 5G NR deployment has been considered in the overall research methodology in terms of characteristics and occurrences such as mandating necessities. On the other hand, further differences in distances, frequency ranges, propagation models, and representatives could be based on sub-6 GHz raw data. In practice, the 5G-BS is excellent for 5G NR. Figure 1.2 depicts the research methodology linked to the objectives that addressed the research problems.

- The current research has advanced significantly, with potential designs and developments contributing to high-ranking international research via 5G-NR. In wireless communications experiments, the new technique, which includes neural networking algorithms and is designed to interfere with 5G-BS and FSS-ES design modelling systems, produces significant results.

- Artificially intelligent models (AI), innovative techniques, and technologies were used to evaluate the 5G-BS and FSS-ES for advanced technologies obtained using ML algorithms. Furthermore, the artificial neural network (ANN) and machine learning (ML) for the development of novel accuracy analysis experimental models for 5G-BS and FSS-ES are based on the use of to determine the optimal exclusion zone.

- Machine models were developed based on c-Band interference and path loss measurements. Again, the models were subjected to 5G-BS and FSS-ES interference across the C-Band frequency range. Figure 1.3 shows the research methodology scheme and summarises the techniques adopted to control interference based on the proposed ML.

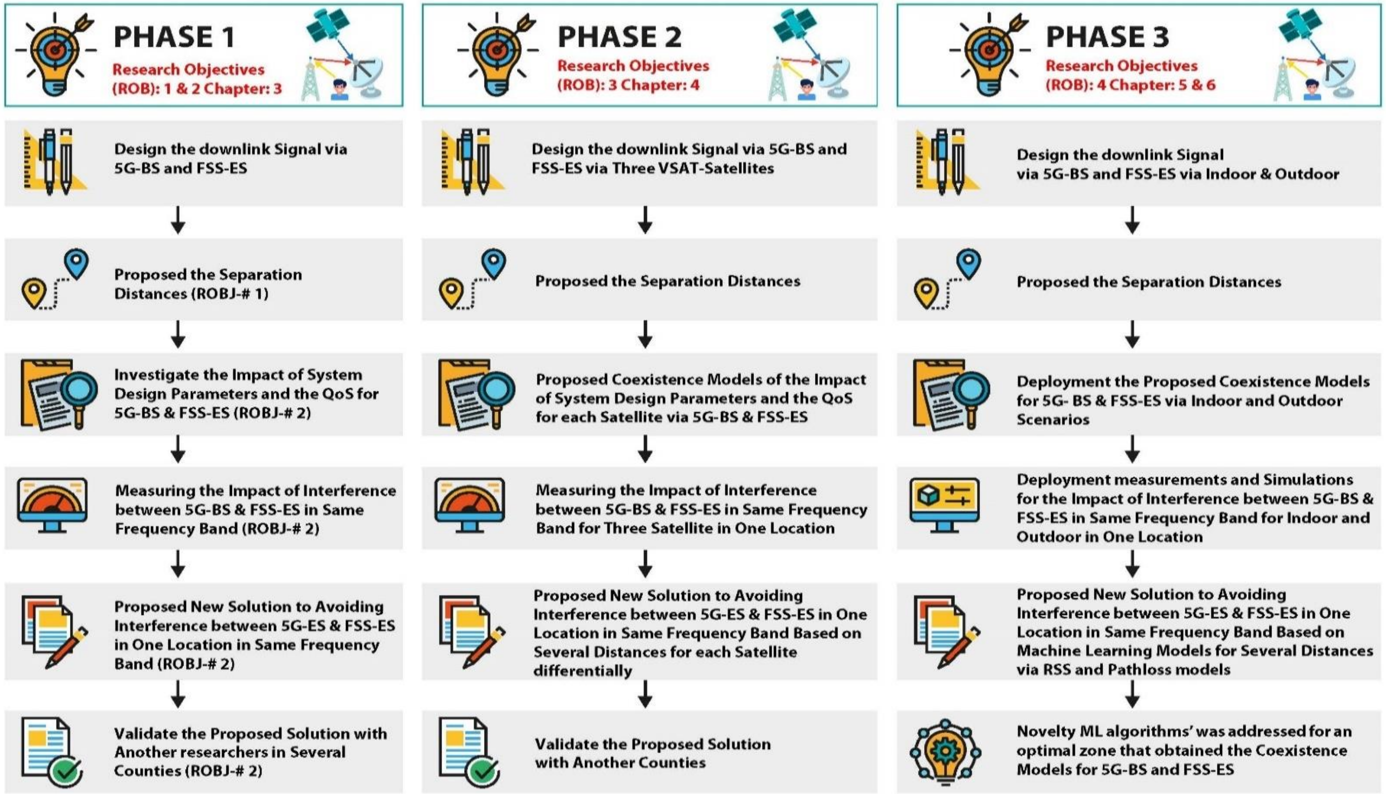

Figure 1.2: Methodology Organization

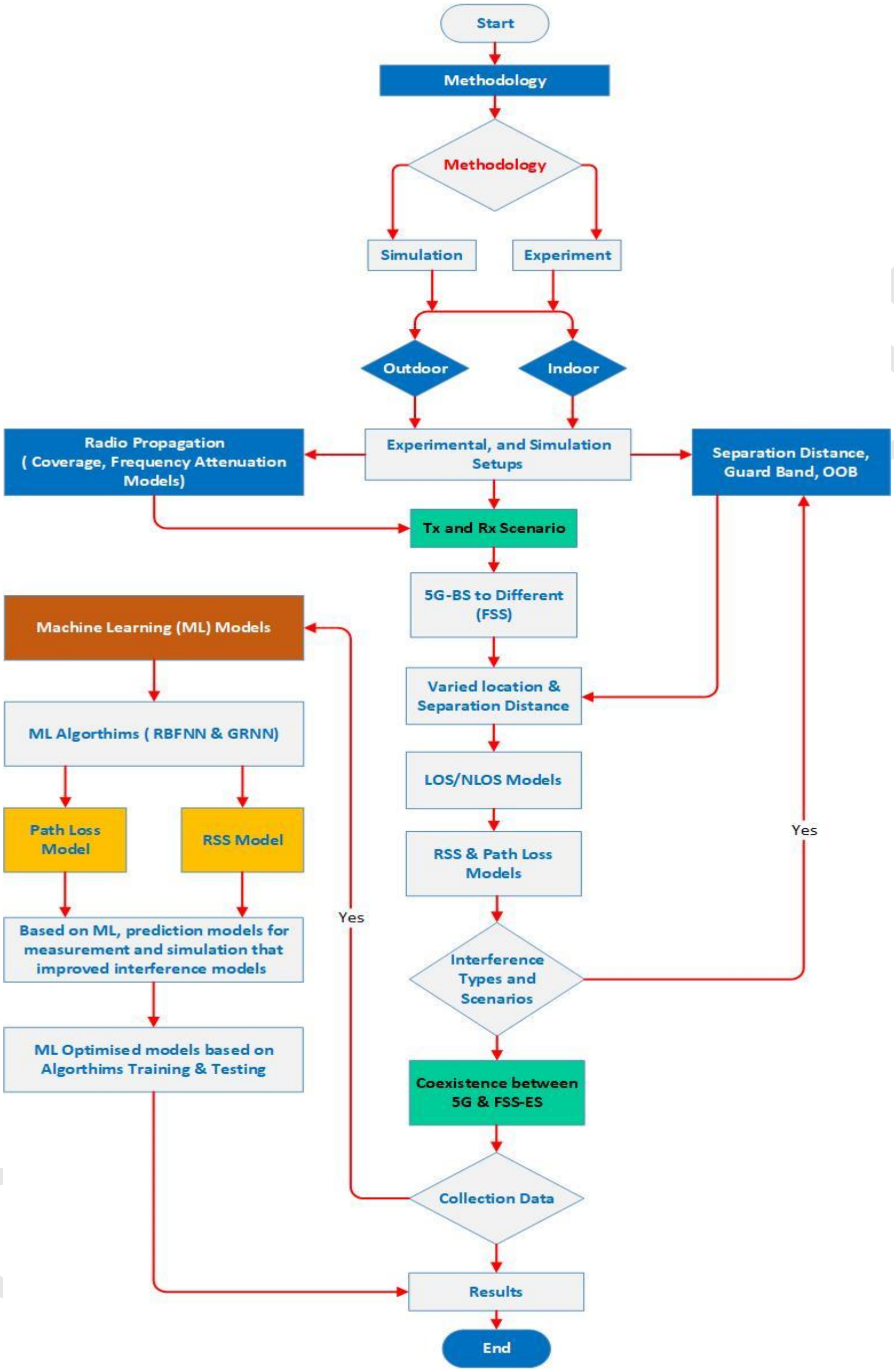

Figure 1.3: The Methodology Scheme Summarises the Techniques Adopted to Control Interference Based on the Proposed ML

1.6 Research Contributions

Satellites are becoming increasingly important in our daily lives. Satellite technology is used everywhere where cables and wireless are practically impossible once there are barriers to their use. As a result of wireless technology, information can be accessed from any location on the planet. Because of technological advances, such as 5G, it has never been easier or more convenient to share information, communicate, or have fun. Wireless technology eliminates the need for wires or cables to transmit and receive data. Electronic devices linked or networked together without using cable are wireless technology. Furthermore, these devices can transmit and receive large amounts of data over radio waves; neither communication nor navigation satellites would be possible without radio waves. Examples include wireless networks, television broadcasts, cordless phones, and other radio-based technologies. In order to keep up with rapid advancements in technology and its applications, we have been forced to adopt a trendsetting mindset. When it comes to PhD thesis research, the most significant contribution is to be presented. However, there are a total of three significant contributions are addressed in current research to serve 5G-NR technologies:

(i) 5G measurements via C-Band in several locations, such as RekaScape Cyberview, Cyberjaya, Sungai Buloh, MAEPS Serdang, UPM, and Selangor, Malaysia.
(ii) Coexistence models obtained the optimal exclusive zone in the same frequency band for 5G-BS and FSS-ES.
(iii) Interference models for RSS and Path Loss via 5G-BS and FSS-ES for optimal exclusive zone based on machine learning (ML) model results.

1.7 Thesis Organization

The chapters of this Thesis are organized as follows:

Chapter 1:

This chapter presents the introduction with the historical perspective and the background of the study, which explains the research. Moreover, it is followed by the researcher's research problems and challenges to conduct the study, objectives, research questions, study scope and motivations, research contributions, and publication. And finally, the organization of the document.

Chapter 2:

The literature review, as the title, covered the research with essential knowledge of the 5G-BS system to describe FSS. This chapter also presented the 5G spectrum new radio frequency and coexistence between 5G-BS and FSS-ES via C-Band frequency. As well as the machine learning (ML) studies for 5G new radio.

Chapter 3:

Preliminary results of the 5G coexistence and interference signal evaluation in the C-Band satellite earth station in most countries, FSS-ES was the only C-Band service. 5G (3.3-3.6GHz) is now widely available, making FSS obsolete. This research conducted a measurement campaign, and the interference was analyzed. Regional exclusion zones of maximum radiated power in 5G base stations (BS) are proposed and evaluated to reduce detrimental interference for the FSS. The filtering model Filters to Remove Broadband Interference 5G (FIREBRING) is proposed and analyzed in C/N. This research also assesses 5G interference in the FSS. Test the satellite down-conversion signal at the receiver with a Low-Noise Block (LNB) 3.7 ~ 4.2GHz. The research examined the 5G signal from all angles, including out-of-band (OOB) emissions, LNB saturation into FSS receivers, and the deployment of 5G BS active antenna systems.

Chapter 4:

This chapter addresses the results and efficiency analysis of current 5G outdoor measurements and the effectiveness of minimizing interference. However, the coexistence Evaluation of 5G Mobile Service (3400-3600 MHz) and 3 Fixed Satellites (VSAT) (3700-4200 MHz). Based on field measurements, VSAT can coexist with 5G at 85m with 100 MHz GB and BPF rejection of at least 45 Db. To avoid 5G out-of-band emission interference, the GB must be at least 80 MHz (3730-3650 MHz). As a result, 5G carriers should stop at 3620 MHz to protect satellite services. It would be great to see more field measurements using different VSAT and 5G-BS models with direct facing and lower look-up angles than MEASAT VSAT.

Chapter 5:

Machine Learning-based Co-Channel Coexistence for 5G Small Cells and Fixed Satellite Service (FSS). The C-Band frequency spectrum has been a priority band for 5G implementation in most countries, including Malaysia. However, former users of the frequency band used for Fixed Satellite Service (FSS) may be dissatisfied with its use for this 5G operation, and thus the service level agreement (SLA) may be compromised. That resulted in developing co-channel interference modelling for the C-Band channel, especially at 3.4 ~ 3.6 GHz. Hence, this research investigates the possibility of developing an optimal exclusion zone for the small cell 5G and the FSS receivers for the intended frequency spectrum, considering the tropical region's characteristics. However, the results can easily be extrapolated to other scenarios. An analysis of received signal strength from a measurement campaign has also been conducted in Malaysia. A co-channel interference model has been proposed and analyzed based on machine learning techniques. Two novel machine learning (ML) models were developed and used, which are radial basis function network (RBFNN) and general regression neural network (GRNN).

Chapter 6:

The 5G mobile communication access technology, the most advanced currently available, uses sub-6 GHz c-bands and mmWave. In high-traffic areas, parts of the 5G network are deployed alongside the 4G network. There may be greater demand for 5G bandwidth in the future. However, to minimize interference and make the most accessible frequency, research into the coexistence of 5G and existing radio systems using an adjacent or similar channel is required. This research focuses on 5G downlink radio, which will impact FSS-ES that operate in the upper 3.5 GHz band in a co-channel and adjacent channel. The machine learning model significantly accurately affects the 5G NR Downlink Signal with FSS-ES. This research also considers two cases of interference between 5G-BS and FSS-ES in the co-channel and adjacent channel, three phases of analysis simulation and 5G measurements of 5G-BS, and a predicted model based on Machine learning (ML). Nonetheless, the findings of this research may be useful for future 5G design and deployment, 5G-BS around an FSS-ES.

Chapter 7:

Concludes the Thesis by summarizing the critical theories, observations that were achieved, contributions to future works, and recommendations.

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