A Comparative Study of Listen Before Talk Categories using Machine Learning

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Declaration

It is hereby declared that

1. The project submitted is our own original work while completing degree at Brac University.
2. The project does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.
3. The project does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution.
4. We have acknowledged all main sources of help.

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Of fall, 2020 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Engineering in Electrical and Electronic Engineering (M.Eng. in EEE) on 03 April 2023.

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Ethics Statement

This is to certify that this project titled "A Comparative Study of Listen Before Talk Categories using Machine Learning" is the result of our study for the partial fulfillment of the Master of Engineering in Electrical and Electronic Engineering (M.Eng. in EEE) degree under the supervision of Dr Saifur Rahman Sabuj, Assistant Professor, Electrical and Electronic Engineering, Brac University, and no part of this work has been summited elsewhere, partially or fully, for the award of any other degree or diploma.

Abstract

The cellular industry is seeking solutions to efficiently utilize the available spectrum band due to the rapid growth of wireless traffic and technological advancements. One potential solution that has gained attention is implementing Long Term Evolution (LTE) with unlicensed spectrum (LTE-U) using a Listen before Talk (LBT) approach, as prescribed by international regulators. To ensure fair channel access for co-located networks, it is crucial to establish a coexistence strategy that incorporates expected traffic requirements for both present and future needs. Machine learning has been recognized for its ability to automate critical wireless communication network activities, gather data from multiple sources, and employ various algorithms. Thus, this project emphasizes the significance of researching LTE and Wi-Fi coexistence in unlicensed spectrum using machine learning. It provides an overview of existing LTE-U and Wi-Fi technologies, and reviews the studies that have been conducted on their coexistence. The project also discusses LBT mechanisms and their categories as defined by the 3GPP standard, as well as previous research conducted in various categories, providing a basis for future research. The study evaluates the performance of each priority class of LBT Cat 4 using the Jains Fairness with machine learning approach to determine the best coexistence priority class of LBT Cat 4 that will enhance future network performance when coexisting with Wi-Fi. Thus in wireless communication systems, machine learning can be used to optimize the LBT protocol by learning the patterns and characteristics of the communication channel. By training the large amounts of data collected from the communication channel, the network can learn to predict when the channel will be free and when it will be busy. This can help to reduce the waiting time for devices and increase the efficiency of the communication system. Moreover it help us to understand the channel sharing fairness and signal detection probability better for each of the priority class of LBT Cat4.

Keywords: Listen Before Talk; 5G NR; LTE-LAA; Jains Fairness Index, Receiver Operating character

Dedication

To my parents, who have always encouraged me to pursue my dreams and supported me every step of the way. Your unwavering love and belief in me have been a constant source of inspiration and motivation.

To my mentor Dr Saifur Rahman Sabuj, Assistant Professor, Electrical and Electronic Engineering, Brac University, who has shared his knowledge and expertise generously and challenged me to push beyond my limits. Your guidance and encouragement have been invaluable in shaping my skills and perspective.

To my friends, who have provided unwavering support and encouragement throughout the ups and downs of this project. Your words of encouragement and unwavering belief in my abilities have kept me going, even when the going got tough.

This project is dedicated to all of you. Thank you for being a part of this journey and for making it all possible.

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I extend my heartfelt gratitude to my family for their love, encouragement, and support throughout my academic journey. Their unwavering belief in me has been a constant source of inspiration and motivation, and I am deeply grateful for their sacrifices and patience.

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Abbreviations

ABS	Almost Blank Sub-frame
ACK	Acknowledgment
AIFS	Arbitration Inter-Frame Spacing
AP	Access Points
BITR-FBE	Back off and Idle Time Reduction Frame Based Equipment
BPSK	Binary Phase Shift Keying
CA	Carrier Aggregation
Cat1 LBT	Categories 1 LBT
Cat2 LBT	Categories 2 LBT
CCA	Clear Channel Assessment
COT	Channel Occupancy Time
COTA	Channel Occupancy Time
CS	Carrier Sense
CSAT	Carrier Sense Adaptive Transmission
CSMA/CA	Carrier Sensing Multiple Access With Collision Avoidance
CTS	Clear to Send
CW	Contention Window
CWmin	Minimum Contention Window Size
CWmax	Maximum Contention Window size
DC	Direct Conversion
DCF	Distributed Coordinated Function
DECT	Digital Enhanced Cordless Telecommunications
DL	Downlinks
DFS	Dynamic Frequency Selection
DIFS	DCF Inter-Frame Spacing
DSCH	Downlink Shared Channel
DSS	Dynamic Spectrum Sharing

ECU	Effective Channel Utilization
ED	Energy Detection
EE	Energy Efficiency
EDCA	Enhanced Distributed Channel Access
E-FBE	Enhanced Frame Based Equipment
eLAA	Extended Licensed Assisted Access
eNB	Evolved NodeB
ETSI	European Telecommunications Standards Institute
FBE	Frame Based Equipment
FCC	Federal Communications Commission
FeLAA	Feature Licensed Assisted Access
FFP	Fixed Frame Period
GSM	Global System for Mobile Communication
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IP	Ideal Period
ISPs	Internet service providers
LAN	Local Area Network
LBT	Listen Before Talk or Listen Before Transmit
LTE	Long Term Evolution
LTE-LAA	LTE Licensed-Assisted Access
LTE-U	LTE in unlicensed spectrum or LTE working in unlicensed spectrum
MAC	Medium Access Control
MAN	Metropolitan Area Network
Massive-MIMO	Massive Multiple Input Multiple Output
MCOT	Maximum Channel Occupancy Time
MCWTM	Maximum CW Timer Mechanism
MPDU	MAC Protocol Data Unit

MVNOs	Mobile Virtual Network Operators
NAV	Network Allocation Vector
NR-U	New Radio Unlicensed
OFDM	Orthogonal Frequency Division Multiplexing
PDSCH	Physical Downlink Shared Channel
PHY	Physical Layer
PLCP	Physical Layer Convergence Protocol
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
ROC	Receiver Operating Characteristic
RSPP	Radio Spectrum Policy Programmed
RTS	Request to Send
SE	Spectral Efficiency
SHF	Super High Frequency
SIFS	Short Inter-Frame Space
STAs	Station
TCG	Tuneable Coexisting Gaps
TDM	Time Division Multiplexing
TXOP	Transmission Opportunities
UEs	User Equipments
UHF	Ultra-High Frequency
UNII	Unlicensed National Information Infrastructure FTD Flexible
TD	Transmission Duration
UP	Uplinks
Wi-Fi	Wireless fidelity
3GPP	Third Generation Partnership Project
5G	Fifth Generation

Chapter 1

Introduction

1.1 Definition of Listen Before Talk

LBT stands for “Listen Before Talk”, which is a protocol used in wireless communication systems to regulate access to the shared communication channel. It requires a device to listen to the communication channel before attempting to transmit data. If the channel is busy, the device must wait until the channel becomes available before it can transmit. LBT helps to avoid interference and collisions between multiple devices trying to transmit at the same time, which helps to prevent data loss and improves the overall performance of the communication system. LBT is commonly used in wireless networks such as Wi-Fi and Bluetooth, as well as in other communication systems such as cellular networks and satellite communications.

1.2 History of LBT Protocol

The concept of Listen Before Talk (LBT) in communication has its roots in the early days of wireless communication, where radio operators needed to follow strict protocols to avoid interference and collisions between transmissions. However, it wasn’t until the 1990s that LBT was standardized and incorporated into wireless communication systems.

In the 1990s, the IEEE 802.11 standard for wireless local area networks (WLANs), commonly known as Wi-Fi, was established. The protocol required devices to listen for a period of time before transmitting data. This was known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and was a form of LBT. This protocol helped reduce collisions between transmissions and improved network performance. As wireless communication technology advanced, LBT became an essential component of modern wireless communication systems. In the early 2000s, Bluetooth technology adopted LBT, which helped improve the efficiency and reliability of Bluetooth connections.

LBT has also been used in cellular networks, where it is used to manage access to the communication channel. For example, in 3G and 4G cellular networks, the Long-Term Evolution (LTE) protocol uses a form of LBT called Carrier Sense Multiple Access with Enhanced Collision Avoidance (CSMA/ECA). This protocol helps reduce collisions and ensures that devices have equal access to the communication channel. In recent years, LBT has been incorporated into emerging technologies such as Internet of Things (IoT) networks and 5G cellular networks. In IoT networks, LBT is used to manage access to the communication channel and ensure that devices do not interfere with each other. In 5G cellular networks, LBT is used to manage access to the communication channel and to prioritize different types of traffic.

In summary, the history of LBT in communication spans several decades, and it has evolved over time as wireless communication technology has advanced. LBT has become an essential component of modern wireless communication systems, helping to ensure reliable and efficient transmission of data.

1.3 Need of LBT protocol in wireless communication

The cellular community is looking for strategies to make the most use of the already available spectrum because of the rapid increase in wireless traffic and the advancement of the technology. The number of wireless devices, including laptops, smartphones, tablets, and wearable technology, has greatly increased over the past several years as a result of technological advancement. Moreover, the Internet of Things (IOT) expansion and consolidation are driving a daily increase in the quantity of wirelessly communicating electrical gadgets. The amount of wireless traffic is anticipated to increase further, reaching 17.1 billion people in 2030, up from 13.8 billion in 2020, as mention in [1]. This enormous amount of data is transmitted between devices through a number of different technologies, including IEEE 802.11(Wi-Fi), Bluetooth and Long Term Evolution (LTE). Modern innovations like LORA and SIGFOX have taken advantage of sub-gigahertz bands to make long-distance communications possible. With regard to multi-gigabit speeds, high-frequency bands like mm-Wave are also utilized with the help of IEEE 802.11ad. Thus, it is certain that the increased wireless traffic will shortly result in the wireless network's capacity to act as a bottleneck.

The licensed spectrum used by cell operators is also getting harder to find at the same time. The cell carriers are investigating alternative options that can help them achieve the criteria of reaching 17.1 billion people in 2030, up from 13.8 billion in 2020, due to the licensed spectrum's limitations and the expensive cost of a permitted band of frequencies. Some of these solutions include carrier aggregation (CA), massive multiple input multiple output (MIMO), cloud computing, and LTE operating in unlicensed spectrum. A lot of people are interested in LTE on unlicensed spectrum (LTE-U) in the wireless community, among other alternative solutions. Other well-known unlicensed technologies like Wi-Fi and LTE-U have been suggested to coexist through the use of Listen Before Talk (LBT) mechanism [2].

LTE is capable of using unlicensed spectrum by utilizing methods like Carrier Sense Adaptive Transmission (CSAT) in areas like South Korea, China, and the United

States, where it is not necessary to use the Clear Channel Assessment (CCA) method, generally known as LBT. Major cellular companies have offered the Third Generation Partnership Project (3GPP) modern LTE standard operation in unlicensed spectrum. To better prepare for 3GPP LTE-U Release 13, introduce LTE Licensed-Assisted Access (LTE LAA), which is currently in use in unlicensed spectrum. Each and every unlicensed spectrum transmission under LTE LAA must first go through the CCA process. This mechanism can be used in the places where CCA is necessary, such as in Japan and Europe. As a stand-alone wireless solution that separates LTE from networks, top wireless stakeholders advised LTE to work only with the unlicensed spectrum. They established the MulteFire Alliance to do this. The LTE is used by Internet service providers (ISPs), cable companies, building owners, and many more. The MulteFire Alliance's fundamental method for its expansion is highlighted on 3GPP LTE LAA components.

The LTE LAA standard specifies four alternative channel access priority classes in addition to the need for the CCA method to be performed earlier before, burst of transmission is done. The duration of the transmission burst that follows a successful CCA operation is one of the details provided by each channel access priority class. This period lasts for 2 to 10 milliseconds [2]. While a Wi-Fi packet transmission, on the other hand typically takes a few hundred microseconds when frame aggregation is disabled or prohibited by the IEEE 802.11 standards. Additionally, it has been determined in [3] about 50% of the packets for 802.11n with frame aggregation are sent within 30 microseconds, and 80 % of packets are sent in less than one millisecond. The ratio of LTE to Wi-Fi channel occupancy is uneven. As a result, with Wi-Fi and LTE LAA co-located, networks could cohabit in an unequal way.

Machine learning has recently been the breakthrough technology in science and technology, with researchers seeing numerous potential benefits of using machine learning approaches in communication [4]. The communication system is model-based, where extensive experimentation and measurement is done to get the good and reliable model [5]. Thus we can incorporate a machine learning approach for the automation of essential wireless communication network functions, the gathering of data and information from many sources, and the employment of various algorithms were all made possible with the help of machine learning [6]. The LBT Cat4 is the best among the categories of LBT that can coexist with Wi-Fi, as mentioned in [7]. Thus, we analyzed the performance of the Priority class of LBT Cat 4 with Wi-Fi in these studies using the Jains Fairness Index in terms of positive signal detection.

1.4 Primary Idea and Concept of LTE-U and IEEE 802.11

To know how the LTE-U and Wi-Fi coexistence the LTE-U basic concept and implementation is given below along with the Wi-Fi.

1.4.1 LTE-U

The licensed spectrum that mobile operators use has become increasingly expensive and scarce over the past few years. In order to manage the ever-increasing load on their networks, operators have been forced to look for solutions. Moreover, the cellular mobile community began looking towards solutions that could handle enormous volumes of bandwidth and enable optimal spectrum use because of the wireless traffic's unprecedented rapid growth. The performance of LTE-U in the unlicensed spectrum has drawn a lot of interest from the research groups, among the alternatives (i.e., CA, Massive-MIMO and others). Consequently, several strategies have been developed to allow LTE-U and other technologies to coexist in well-known unlicensed technologies, like Wi-Fi working in unlicensed spectrum bands.

Depending on the area legislation and the deployment situations, three primary LTE-U are functioning in unlicensed spectrum techniques. Unlicensed LTE (LTE-U), the first technique for LTE-U functioning in an unlicensed spectrum, was started in 2014. Forum for LTE-U [7] is developing LTE-U to integrate with the 3GPP Release 10/11/12. This goes after areas where it is not necessary to conduct a channel study before transmission which is well known as LBT (i.e. in USA and China). Working together with Samsung, Ericsson, Alcatel-Lucent, and Qualcomm they established the Forum for LTE-U. A forum's objective is to provide technical requirements, such as coexistence guidelines and minimum basic performance requirements for consumer electronics and LTE-U base stations running in unlicensed spectrum bands in the 5GHz frequency coverage area. A CSAT [8] developed by Qualcomm is the most popular channel access technique for LTE-U. With the use of duty-cycle times, CSAT has extended the features of 3GPP Release 12 [9] and provides the number of TXOP to the co-located networks. Consequently, ON and OFF times are separated into the temporal domain base. When LTE-U is on, it can transmit in an unlicensed channel without first checking to see if there are any other transmissions in progress, it is silent when it is off. LTE base station, often called an evolved NodeB (eNB), make a decision on how long the ON and OFF periods will lastly, based on the observed channel usage (e.g. like, the expected number of Wi-Fi Access Points (AP) or other technologies that utilize the alike unlicensed Spectrum bands).

In 3GPP Release 13 at the beginning of 2016, they allowed to include a specification that permits LTE to operate at unlicensed spectrum [10]. The LTE-LAA is the name of the 3GPP-standardized LTE operating in an unlicensed spectrum. As a channel assessment process is worldwide standard, obeying local necessary before sending data in unlicensed spectrum, LTE LAA is intended to be somehow a regulations anywhere. Simply only Downlink (DL) LTE-U traffic was allowed to transmit in unlicensed bands initially, following Release 13 LTE-LAA. Both DL and Uplink (UL) LTE-U load will be able to transmit in the unlicensed band as in Release 14 explicitly states [11]. The secondary cell that uses the unlicensed spectrum can be deployed by an operator in parallel to the licensed band owned by it, according to LTE LAA. The LTE DL data flow can be opportunistically managed in this way to offload through a Physical DL Shared Channel (PDSCH) in the unlicensed spectrum bands. As per Release 13 the licensed anchor will be used to transmit both the UL traffic and the LTE-U control signals to ensure an uninterrupted and timely transmission.

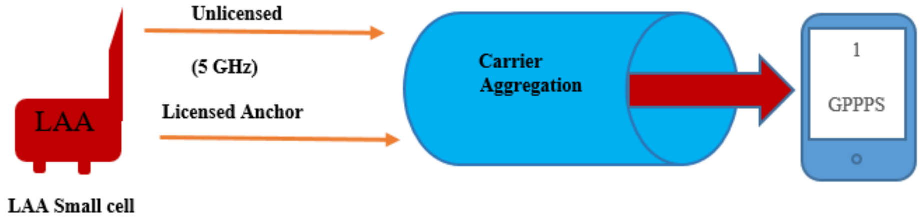


Figure 1.1: Long Term Evolution - Licensed-Assisted Access.

Both LTE LAA and LTE-U ask for a licensed spectrum owner who opportunistically offloads LTE load through a secondary cell to the unlicensed spectrum. The MulteFire Alliance was established by the top wireless stakeholders to detach LTE from the users and allow standalone LTE to operate in the unlicensed spectrum [12]. It is the ideal solution for businesses, ISPs, Mobile Virtual Network Operators (MVNOs), and building owners who have limited or no access to licensed spectrum. MulteFire LTE relies on the components of LTE LAA. Wi-Fi and LTE-U on the unlicensed spectrum were anticipated to be crucial components of the new radio 5G era. Figure: 1.1 depicts LTE-LAA operating on an unlicensed frequency. Thus, it is expected that a combination of the two technologies will coexist fairly and peacefully. Nevertheless, they weren't initially meant to peacefully coexist. The act of developing technologies that might permit equitable cohabitation or cooperation is quite difficult due to their fundamental differences.

1.4.2 IEEE 802.11

One of the most widely used wireless protocols is IEEE 802.11 for providing a fast Internet connection and network access in unlicensed spectrum bands [13]. Which is a typical set of Medium Access Control (MAC) and Physical Layer (PHY) standards guide the creation of Wireless Local Area Networks (WLAN). The IEEE 802.11 is typically utilized with the 2.4GHz Ultra High Frequency (UHF) and 5GHz Super High Frequency (SHF) frequency band. A Institute of Electrical and Electronics Engineers (IEEE) is Standardized Committee for Local Area Network (LAN)/ Metropolitan Area Network (MAN), which has the authority for developing and maintaining IEEE 802.11 standards. These regulatory authorities set regional rules which must be adhered to by every item that complies with IEEE 802.11 in a certain region to efficiently manage the spectrum. The American regulatory organization is called the Federal Communications Commission (FCC). Regulation in Europe is governed by following requirements at the national level, issued by the European Commission, as specified under the Radio Spectrum Policy Programme (RSPP). To maintain the extensive and dense IEEE 802.11 standard. Several important manufacturers established the Wi-Fi Alliance to prevent interoperability issues [14]. A nonprofit institution called the Wi-Fi Alliance will sponsor Wi-Fi technology and certifies the Wi-Fi products. Applying IEEE 802.11 specifications, according to specified test plan, the certification process is being conducted.

However, some IEEE 802.11 specifications are not required by the test plan for Wi-Fi the certification process, but some requirements are not included in the standard. As a result, the Wi-Fi Alliance outlines an extended subset of IEEE 802.11 specifications. Today, the names of the standard and the certification are used interchangeably due to term abuse and so as to market. Thus, the word Wi-Fi is used regularly throughout the remainder of the dissertation to refer to wireless networks built on the IEEE 802.11 specifications.

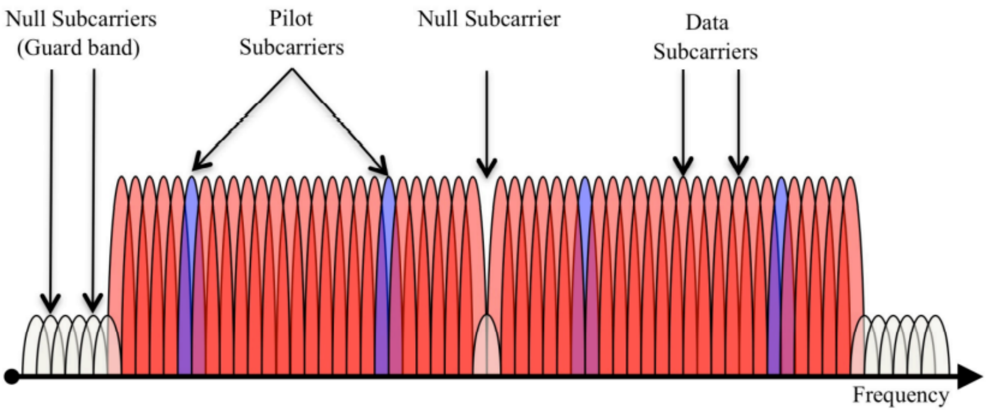


Figure 1.2: 64 Orthogonal Frequency Division Multiplexing Sub-carriers.

The digital modulation method used by Wi-Fi, known as Orthogonal Frequency Division Multiplexing (OFDM), normally divides the spectrum into 64 subcarriers with a bandwidth of 20MHz. Eleven of these subcarriers are not used and are utilized as guard bands between two adjacent channels. The Direct Conversion (DC) subcarrier is the center subcarrier, which is idle. These 52 remaining subcarriers are divided into 48 subcarriers used for data transmission and 4 subcarriers used for pilot operations. These subcarriers are separated by a 312.5 kHz frequency band. The real bandwidth that is being used is 16.6MHz [15]. The 64 OFDM subcarriers are depicted in Figure: 1.2 in the manner previously explained above. The same modulation type is used by each data subcarrier. Different modulation modes, like BPSK (Binary Phase Shift Keying), QPSK (Quadrature Phase Shift Keying), 16QAM (16 Quadrature Amplitude Modulation), 64QAM and 256QAM are supported following the chosen 802.11x standard. Pilot subcarriers are always BPSK modulated. Wider bandwidth can be used with newer versions of IEEE 802.11 specifications, like 802.11n [16] or 802.11ac [17], which can grow to up to 40MHz and 160MHz, respectively. Additionally, additional variations employ a smaller bandwidth, such as IEEE 802.11ah [18] or 802.11af [19]. (e.g. 1MHz, 2MHz, 4MHz, 8MHz, 16MHz for 802.11ah and 6MHz, 7MHz and 8MHz for 802.11af).

The decentralized and asynchronous medium is accessed via Wi-Fi using the Distributed Coordinated Function (DCF) mechanism [13]. DCF makes utilization of carrier sense multiple access with collision avoidance (CSMA/CA). This method

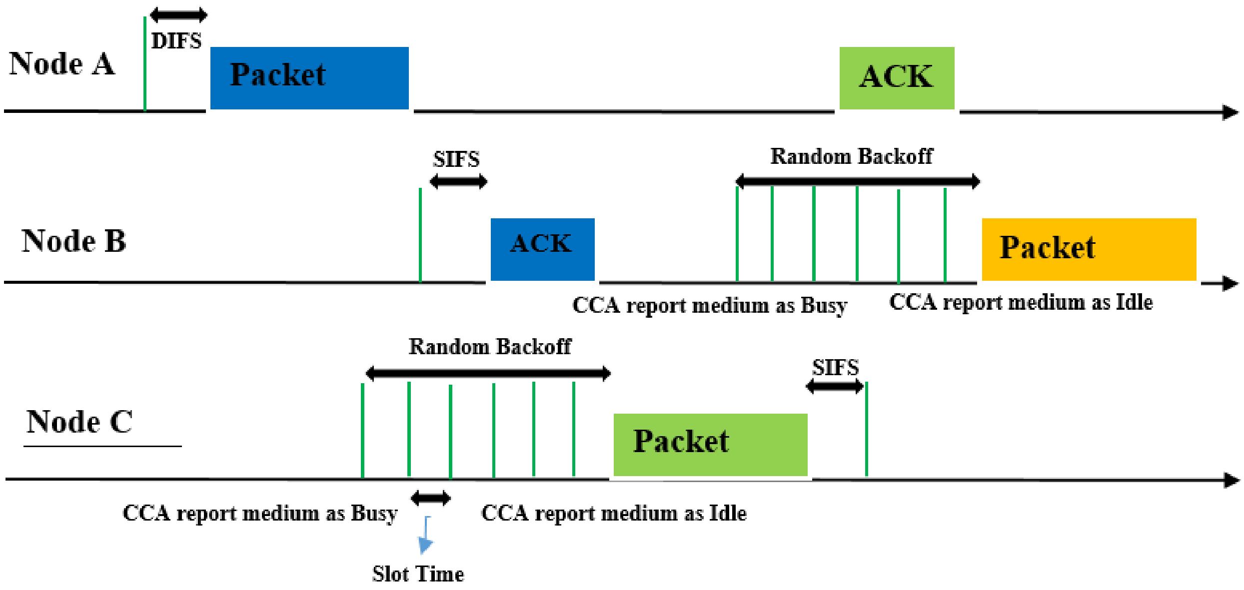


Figure 1.3: Carrier Sensing Multiple Access with Collision Avoidance for Wi-Fi.

states that before any transmission, the Wi-Fi node must assess whether the channel is free or busy, as seen in Figure: 1.3. The CCA mechanism used here is often called by the name Listen Before Talk (LBT). Thus, both the words CCA and LBT will be used interchangeably throughout the remainder of the dissertation.

Energy Detection (ED) and Carrier Sense (CS) are the two functions that makeup CCA. The CS function describes the receiver's capacity to hear the medium, recognize, and properly decode a preamble for a Wi-Fi connection. Whenever this happens and signal strength is found to be larger than or equal to -82 dBm then for the timeslot specified in the Physical Layer Convergence Protocol (PLCP) header length field of the frame and a CCA reports that the channel is fully in use for this period. The above field includes the duration of time in microseconds needed to transmit the payload of a Medium Access Control (MAC) Protocol Data Unit (MPDU) or the number of octets carried inside a frame of MPDU. It helps to calculate the duration of time needed to transmit the frame of MPDU. While in contrast, ED is used when the approaching signal information can't be decoded. An ED function describes the receiver's capacity to determine the amount of energy in the active channel depending on the presence of the same frequency band as Wi-Fi signals but not Wi-Fi signals that cause corruption or interference to Wi-Fi transmissions which are impossible to decode. The channel is reported as busy by CCA if more energy is present than -62dBm or the same as -64dBm. Since it is impossible to predict how much time duration the medium will be busy, to determine the channel's energy level, ED needs to detect it every time slot.

A Wi-Fi node must predict the state of a channel for just a DCF Inter-Frame Spacing (DIFS) period each time it needs to transmit the load. The node can send a signal if the channel is available. If not, the node must delay it to transmit and pause for a free DIFS or, when Quality of Service (QoS) was permitted, then an Arbitration Inter-Frame Spacing (AIFS) duration in addition to a random back-off time duration it waits to prevent packet collisions if a channel is detected as busy. The back-off counter shows how many slots must pass before the channel is considered idle enough to perform transmission. Within the Contention Window (CW) range, this number is consistently chosen. The node awaits to get acknowledgement (ACK), which should be received within a Short Inter-Frame Space (SIFS) duration, after a transmission. Following a fresh exponential back-off duration, the node plans retransmission if the acknowledgement is not received within this SIFS duration frame. For this situation, double the CW up to a certain point called maximum CW size (CWmax). The likelihood of additional collisions is decreased in this manner. The packet is dropped once the allotted number of retransmissions has been used. Thus after an effective transmission (the ACK have been successfully received) and the number of the CW is reset to its lowest value called minimum CW size (CWmin).

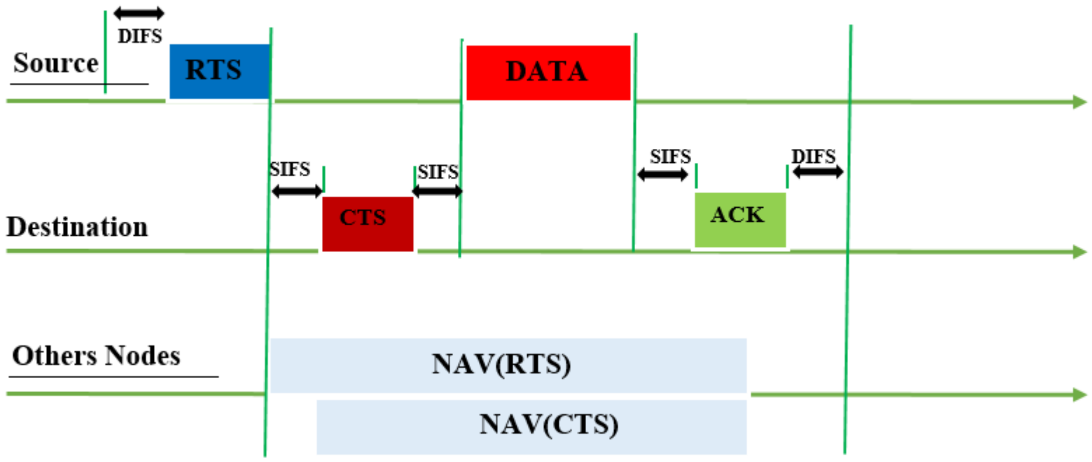


Figure 1.4: Request to Send /Clear to send Protocol for Wi-Fi.

An IEEE802.11 specification offers an optional feature known as Request to Send (RTS) and Clear to Send (CTS) procedures for decelerating any potential collisions which may result from transmissions with hidden nodes [13]. An issue of hidden nodes basically arises whenever APs and stations (STAs) are dispersed throughout a space and are unable to detect each other's transmission. The transmitted packets collide as a result, and several retransmissions take place. According to the RTS/CTS methods, a handshake is necessary before they can start communicating between two nodes. Figure: 1.4 illustrates this protocol as you can see. A node transmits an RTS frame when there is data to send. A length of time duration that the node will reserve the medium is contained in the RTS. In response to an RTS, the receiver sends a CTS frame with the reservation period in it. Every node nearby the transmitter and receiver are capable of decoding an RTS or CTS signal in such way that they are then notified to delay their transmissions for the predetermined amount of time duration. The exchange of the RTS and CTS signal adds additional network overhead and delays, which is a significant flaw in this methods. Furthermore, the RTS/CTS methods frequently unable to address the issue of the hidden terminal (like RTS/CTS message loss, node beamforming in a particular direction). Deep learning and technology recognition can be quite helpful in overcoming the covered terminal problem.

1.5 Aims and Objectives of the project

The primary goal of these projects is to learn more about the LBT coexistence mechanism, including its categories and methods of implementation, to ensure that LTE-U and Wi-Fi can coexist equally in unlicensed spectrum bands. We want to design the LBT Cat4 wireless communication system and use Jain's fairness index to analyze the LBT Cat4 priority class's performance. We also want to evaluate the total fairness of the system in percentage and see which priority class of LBT Cat4 performs best in unlicensed spectrum with Wi-Fi. We want to apply the machine learning approach in our LBT Cat4 priority class to ensure that the model that we develop is reliable and applicable in the real world. Then, we want to apply the signal detection theory and find the probability of positive signal detection and the probability of false alarm signal detection. Finally, the normalization and linearization is carried out for all the priority class of LBT Cat4.

1.6 Organization of the Project

In Chapter 1, we'll look at the current coexistence mechanisms that have been introduced to allow LTE-U and Wi-Fi to coexist fairly. Then we will likewise talk about LTE-U and Wi-Fi in unlicensed spectrum bands and how those technologies are use LBT to coexist fairly. In chapter 2, we'll briefly go over the research that has been done so far on how LTE can cohabit with other technologies in unlicensed spectrum bands. We will then examine LBT in more detail, including its categories and priority class. In chapter 3 the methods of implementation of LBT Cat4 to ensure that LTE-U and Wi-Fi may cohabit in unlicensed spectrum bands fairly have been studied. Along with the machine learning approach implementation in communication methods. In chapter 4, we will see LBT Cat 4 in detail and implement it to coexist in the LTE-U band and Wi-Fi. Then the parameter and model required to have a fairness index and a machine learning approach in wireless communication have been studied. In Chapter 5, we will analyze the coexistence performance of each priority class of LBT Cat 4 with Wi-Fi to see which priority class will have the maximum coexistence percentage with Wi-Fi using the fairness index and machine learning approach. The findings and outcomes are then presented in this section. In chapter 6 we conclude our project with brief application of LBT Cat4 and future work.

Chapter 2

Literature Review

2.1 Coexistence of LTE-U and Wi-Fi

To learn more about the limitations of the Coexistence of LTE-U and Wi-Fi operating in unlicensed spectrum bands, researchers compared the performance of LTE-U and Wi-Fi in the absence of any techniques for coexistence which can allow both technologies to access channel sharing. To coexist with Wi-Fi, LTE-U utilizes its normal schedule-based channel access mechanism. It presents and illustrates the performance estimation of each LTE-U and Wi-Fi for various simulated coexistence scenarios in [20]. The output suggests that the performance of the LTE-U is modestly hampered, but the performance of the Wi-Fi suffers greatly. Since LTE-U, doesn't employ a coexistence strategy to share its channel with Wi-Fi, LTE-U entirely controls the accessibility of channels, particularly when LTE-U is under heavy load, as demonstrated in [21], and Wi-Fi is barred from using the channel the majority of the time. The primary reason is that LTE-U uses a time-based channel access strategy that permits the use of the channel regardless of its condition, like whether it is inactive or actively transmitting Wi-Fi data. Wi-Fi, on the other hand, uses the DCF protocol, which is an LBT-based protocol that allows Wi-Fi to only use the channel when it is free from LTE-U transmissions. Thus, we can argue that LTE-U has complete control over channel access, and Wi-Fi can use the channel whenever LTE-U decides to vacate it, i.e. Wi-Fi is a slave to LTE. The same conclusion was reached in an experimental test conducted at [22], in which genuine LTE-U and Wi-Fi setup systems were placed in a typical indoor environment situation, and outdoor simulation research was conducted at [23].

Furthermore, the study revealed that Wi-Fi ability has improved in LTE-U and Wi-Fi sparse deployment circumstances. Interestingly, extending the range of Wi-Fi and LTE-U systems aids Wi-Fi in locating the idle channel within LTE-U transmission, allowing Wi-Fi to gain channel usage more frequently in dense deployment settings. Conversely, as [24] shows, raising the Wi-Fi channel access probability by expanding the separation among LTE-U and Wi-Fi networks doesn't always improve Wi-Fi ability. Moreover, for a specific range of distance among LTE-U and Wi-Fi networks, Wi-Fi may frequently discover an idle LTE-U transmission channel, but then this does not ensure that Wi-Fi transmission won't collide with the transmission of LTE-U. As a result, as shown in both [24] and [25], the Performance of Wi-Fi was not directly correlated with the separation between LTE-U and Wi-Fi networks.

Using an experimental platform, the researchers in [24] evaluate the negative impact caused by LTE-U on Wi-Fi for various LTE systems setup factors such as transmission power, LTE-U bandwidth and central frequency.

Additional testbed in [26] assesses the reciprocal effect of Wi-Fi and LTE-U in various cohabitation situations in which LTE-U and Wi-Fi coexist by overlapping completely or partially on their primary channels and secondary channels. Every one of the findings reveals that the effectiveness of both technologies was entirely dependent on the cohabitation situations, with Wi-Fi performance affected mostly in this regard. A further experimental study [27] demonstrates that LTE-U degrades Wi-Fi performance, with LTE-U downlink load interfering more as compared with LTE-U uplink load interfering with the performance of Wi-Fi. The outcome is calculated using dissimilar LTE-U time division duplex (LTE-U-TDD) configurations, Wi-Fi performance improves as the number of uplink subframes expands within an LTE-U frame [21].

The authors of [28] and [29] offer a coexistence strategy that is aware of interference owing to managing and adjusting LTE-U uplink power transfer to advance Wi-Fi ability even greater. The [30] looked at LTE-U uplink performance in diverse coexistence circumstances for various Wi-Fi traffic. Furthermore, as demonstrated in [31], LTE-U may use its beam forming capability to avoid interfering with Wi-Fi. The Wi-Fi ability in congested deployment circumstances is decreased by around 97 percent owing to LTE-U interference, an analytical approach quantifying LTE-U and Wi-Fi mutual interfering has been discussed [32]. The author in [33], developed another fresh interfering analysis method to quantitatively quantify reciprocal interfering, in which the Wi-Fi interference is lessened by increasing its cell radius of LTE-U. In [34], researchers offer an LTE-U statistics model interior planned using a model of interference for indoors, in which LTE-U eliminates interfering with Wi-Fi as much as feasible.

The findings of the latter study suggest that LTE-U must use a cohabitation strategy allowing Wi-Fi to share channel access or Wi-Fi ability will suffer significantly. The offered solutions only try Wi-Fi and LTE-U interference to maintain a minimum, while providing no guarantee of equitable channel sharing. Many researchers have proposed a solution like the Almost Blank Subframe (ABS) [35] feature of Release 10 LTE used to provide an interference avoidance strategy. The interference mitigation mechanism introduced in [36], in which the traditional LTE-U uplink (UL) power controller is adjusted to limit the transfer powers of some LTE-U User Equipment (UEs), results in the enhancement of Wi-Fi performance. Recently lots of researchers have got lots of interest in the LBT mechanism for fair cohabitation of LTE-U and Wi-Fi. Thus many studies have been carried out to highlight its coexistence scenarios. Theoretically, it has been demonstrated in [37] and [38] that the deployment of LTE-U New Radio (NR) 5G using LBT can boost the data rate and capacity of NR 5G. The LTE-U that can coexist with Wi-Fi has been found as the best solution for the deployment of 5G NR [39] and in addition, LBT was suggested to be the best coexistence mechanism for LTE-U and Wi-Fi [40]. Thus let us examine and survey a coexistence mechanism called Listen Before Talk (LBT) in depth in this article.

2.2 Listen Before Talk

Listen Before Talk (LBT), also called Listen Before Transmit or NR-CDMA/CA, is a radio communication strategy in which a radio transmitter observes its radio surroundings before transmitting. A radio device can utilize LBT to discover a network that it is allowed to operate by sensing a free radio channel, LBT is used in GSM (Global System for Mobile Communication) by the mobile device to find an ideal channel to connect to a network, and also in DECT (Digital Enhanced Cordless Telecommunications) to search for an ideal radio channel. The basic LBT algorithm, which is shown in Figure: 2.1, will be described in more detail below.

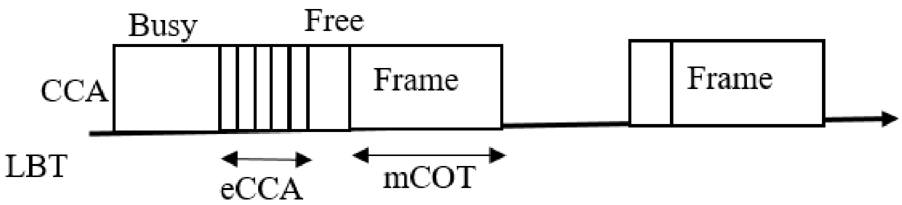


Figure 2.1: Listen Before Talk Algorithm.

An LBT is a contention technique in which the transmitter must first check the state of the channel before using it. It primarily utilizes two fundamental mechanisms: to sense the channel status during a delay time, the clear channel assessment (CCA) approach with the energy detection (ED) threshold is used and determines if any of a signal was present above a certain given power range. Once the channel was found to be idle, the maximum channel occupancy time (MCOT) that an LAA station is permitted to use for transmission began. However, enhanced CCA (eCCA) was enabled, and it must delay for a back-off amount of time set by using a Contention Window (CW), which is measured in time slots. The usage of Listen Before Talk is required in unlicensed 5 GHz bands (which include eLAA (Extended Licensed Assisted Access), FeLAA (Feature Licensed Assisted Access), and NR-U (New Radio Unlicensed)), as indicated in the definition of a shared channel downlink in a 3GPP specification [41], whereas using the licensed spectrum for signalling in the uplink is optional. For DSCH unlicensed channel access, numerous categories of the LBT method have been studied. So four categories of LBT are used to ensure that LTE-U and Wi-Fi will cohabit peacefully as defined by 3GPP standards. Figure: 2.2 demonstrates the various LBT categories' utilization of the algorithms, which will be covered in more detail later.

2.3 LBT Categories

The LBT procedure has different categories, including LBT CAT1 with no sensing, LBT CAT2 with a fixed sensing period, and LBT CAT3 and LBT CAT4 with variable sensing periods and random back-offs. If the CCA indicates that the channel is idle, the wireless device can transmit; otherwise, it must defer transmission. An illustration of LBT deployment in LTE is shown in Figure : 2.2.

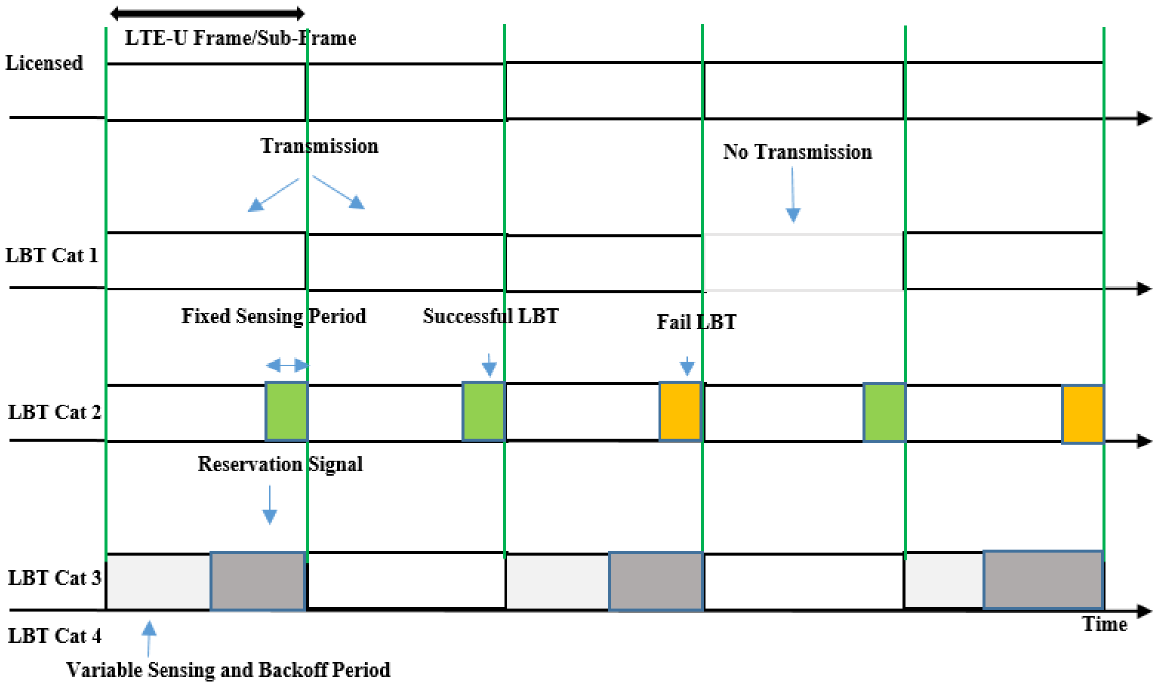


Figure 2.2: Listen Before Talk Categories Algorithm.

Here different LBT Categories is defined and we will look at their details of it in the discussion as follow

- LBT Category 1: Instantaneous transmission following a 16-μs exchanging interval with no CCA.
- LBT Category 2: Without random back-off time and a deterministic CCA period of 25-μs
- LBT Category 3: Fixed-size contention window (CW) and random back-off time
- LBT Category 4: With variable CW size and random back-off time

2.3.1 LBT Category 1

The first LTE-U proposal to cohabit with Wi-Fi using unlicensed spectrum is the Time Division Multiplexing (TDM)-based MAC layer protocol, and the same protocol was defined by the 3GPP standard as the LBT Category 1 (LBT Cat1). The words TDM-based MAC layer protocol and LBT Cat1 will now be used interchangeably throughout the remainder of the discussion. The LTE-U forum was established by several telecommunications companies, who expressed strong interest in considering the TDM-based MAC as a new LTE protocol due to its ease of adaptation to today's LTE-U systems and inclusion among major current LTE-U characteristics such as small cell deactivation and activation. As far as the 3GPP release 12, the

LTE-U rollout is faster since the mobile device does not need to wait for a new LTE-U standard to be rolled out [42]. The main aim of an LBT Cat1 was to allow for the peaceful coexistence of LTE-U and Wi-Fi with its' time division multiplexing mode, in which LTE-U is used for a predetermined period, called an on period, and then numerous LTE-U frames or subframes are assigned to Wi-Fi during the LTE-U off period. This on/off cycle will therefore produce a duty cycle phase that will be repeated throughout the LTE-U period, causing the duty cycle.

The LBT Cat1 allows for synchronous channel utilization, the first LTE-U transmitted frame begins at the beginning of subframe boundaries, and synchronous LBT is required for UEs to receive and decode signals of LTE-U. Unlike LBT Cat 3 and LBT Cat 4 LTE-U, the reservation signal is not mandatory to avoid Wi-Fi from a channel utilization up to the next LTE-U subframe boundary, at which point LTE-U starts transmitting frames. This causes a reservation signal overhead of almost one subframe, which slows down LTE-U performance. However, because the LTE-U channel does not perform CCA before sending LTE-U frames, unlike Wi-Fi, the benefits of the TDM-based protocol would harm Wi-Fi's ability. Due to this reason, several regions, such as India, Europe, and Japan, do not use the TDM-based protocol, while China, Korea, and the United States do. The TDM-based protocol is still an effective option for coexistence with other inter-radio access technologies.

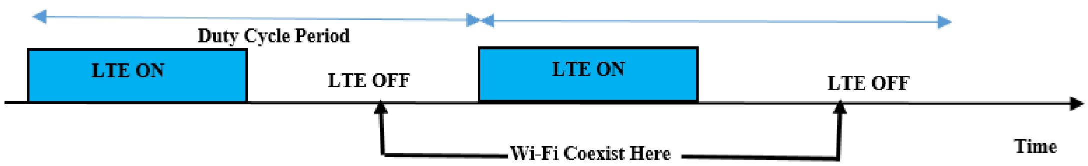


Figure 2.3: Listen Before Talk Cat1 Algorithm.

The author of [43] investigates LTE-U and Wi-Fi deployment scenarios in indoor downlink data traffic, seeing that LTE-U and Wi-Fi coexist nicely at low data traffic, but as the data traffic increases, the collision rate increases. By using a more resilient PHY layer than Wi-Fi, LTE-U discards frames in the event of collusion. The new method, which was implemented in 3GPP release 10 [44], implies temporarily muting some LTE-U sub-frames for short duty cycles to provide room for Wi-Fi transmission. However, the distribution of muted sub-frames in LTE-U frames harms Wi-Fi performance in addition to the number of muted sub-frames. Identical research has been conducted in [45], which demonstrates that for best Wi-Fi and LTE-U cohabitation performance, the LTE-U muted sub-frame duration must be carefully adjusted. On the other side, using a long enough duty cycle will have an enhanced negative effect on Wi-Fi performance at a time when LTE-U transmission interruptions with Wi-Fi are minimized. A similar finding was obtained in [46], which found that for higher Wi-Fi throughput in an outdoor setting, a long duration of the LTE-U ON period was preferable to a shorter LTE-U ON period. However, the increased Wi-Fi delay would have a significant impact on the coexistence of LTE-U and Wi-Fi. When LTE-U has a lengthy and brief duty cycle period, Wi-Fi latency and throughput are traded off. Wi-Fi performance is demonstrated to be inversely related to LTE-U at times within a set duty cycle period [47], and the effect of LTE on Wi-Fi was also investigated when LTE-U employs varied central frequency, transmission power, and bandwidth. Similar research shows that Wi-Fi incorporates a variety of given loads, modulation and coding algorithms, packet sizes, and transmit power levels [48]. Thus, it is reasonable to conclude that a variety of settings have a significant impact on how well LTE-U and Wi-Fi perform.

Qualcomm has also suggested the Carrier Sensing Adaptive Transmission (CSAT) protocol, which utilizes the TDM protocol. The LTE OFF period is maintained for a lengthy amount of time for increased Wi-Fi traffic load when the control and adoption transmissions are used, and vice versa. LTE-U and Wi-Fi performance in cohabitation was better than Wi-Fi and Wi-Fi coexistence if TDM-based protocol is adequately configured [49]. Additionally, the researchers in [50] urged the Wi-Fi access point software to be updated to WI PLUS, which will track the on and off LTE-U times and calculate the duty cycle based on the MAC layer of Wi-Fi observation. Until then, we have demonstrated that there can be no specific model that explains how LTE-U will effectively implement the protocol based on TDM to cohabit peacefully with Wi-Fi. To conduct an in-depth investigation of LTE-U and Wi-Fi cohabitation, Bianchi's model [51] was used because the behaviour of the DCF protocol for Wi-Fi, which includes a sensing phase and then a back-off time and a transmission period, wouldn't change as a result of coexistence with the protocol based on TDM.

2.3.2 LBT Category 2

Frame Based Equipment (FBE) has been designated as LBT Category 2 (LBT Cat2) in the 3GPP specification with the European Telecommunications Standards Institute (ETSI) [52]. From now on, the terms FBE and LBT Cat2 shall be used synonymously. With the use of CCA, the FBE was intended primarily to avoid Wi-Fi collision at the start of the LTE-U phase. Thus, the FBE can be described as a Protocol for TDM base with an essence of LBT base protocol using the CCA methods, which have a lower negative effect on the performance of Wi-Fi than the LBT Cat1. Here we observe a predetermined periodicity that follows a common sense/transmit structure as illustrated in figure: 2.4 below, and it's specified as follow

- Fixed Frame Period: It specifies an overall period, which comprises idle period (IP) and Channel Occupancy Time (COT). Its time is limited to 1 to 10 milliseconds. The transmission must commence at the start of a Fixed Frame Period (FFP).

- Channel Occupancy Time: It is defined as the period during which the channel will transmit without checking for channel availability. It has a 95 percent FFP duration and must come after an ideal period.

- Ideal Period: This was the time when single slot CCA was carried out. Its time should be 5 % or more of COT and no less than 100 μs.

Figure: 2.4 illustrates the usage of the LBT Cat2 Algorithm for the peaceful cohabitation of LTE-U and Wi-Fi.

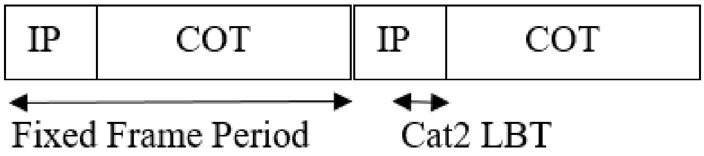


Figure 2.4: Listen Before Talk Cat2 Algorithm.

One of the main limitations of the LBT Cat2 protocol is accessing the channel by an LTE-U frame because the channel has a particular time frame in which it can broadcast. When there is Wi-Fi transmission, LTE-U must wait for the FFP, and if two LTE-U systems transmit at the same time, interference with the LTE-U frame is unavoidable [53]. The ETSI is looking for a better solution for FFP in the LBT Cat2 protocol because the LTE-U system is not synchronized [54], where one channel dominates the other in channel access. The author presented a slightly different LTE-U, MAC layer protocol in [55], which eliminates the LTE-U OFF time from the FBE protocol. An LTE-U and Wi-Fi performance made a respectable trade-off under specified cohabitation parameters, and it is an important component of LBT Cat2 to achieve equitable LTE-U and Wi-Fi cohabitation. The "Enhanced FBE (E-FBE)" and "Back Off and Idle Time Reduction FBE (BITR-FBE)" procedures [56] are two variations of the FBE protocol that use back-off operations to lessen the greediness of FBE channel access. Many LBT Cat2 protocols have CCA before LTE-U ON has been proposed, similar to TV white space [57]. These protocols do not follow the ETSI feature of a fixed frame period.

2.3.3 LBT Category 3

Load Based Equipment (LBE) is an asynchronous and demand-driven architecture of LBT that is specified by ETSI at [52], and it is called LBT Category 3 (LBT Cat3) LTE-U protocol as defined by 3GPP. From this point on, the terms LBE and LBT Cat3 will be used interchangeably. The nodes will begin executing channel utilization operations as soon as possible when the data to be transmitted becomes available. LBT Cat3 will implement the random back-off time period technique with a fixed-size contention window. FBE reduces LTE-U performance, as we saw above, however, to improve LTE-U performance the back-off time period is used ahead of any frame and is sent over a channel similar to the Wi-Fi DCF protocol since LTE is permitted to compete for channel utilization with Wi-Fi any moment of time. LTE-U has a random back-off period with a fixed size contention window (CW) ranging from 1 to q, where q is chosen by the manufacturing company, a number between 4 and 1024. Although the collision exists, LTE-U utilizes a fixed CW size, whereas Wi-Fi uses a binary exponentially rising CW. The LTE-U protocol imposes a channel occupancy time limit of less than $(13/32) \times q$ ms, which allows for the use of small CW sizes to increase LTE-U and Wi-Fi cohabitation by reducing LTE-U channel occupancy time over the channel. Figure: 2.5 depicts the use of the LBT

Cat3 Algorithm to fairly divide the channel between LTE-U and Wi-Fi.

The LBE protocol differs from the DCF protocol in two major respects. The first is the back-off time period. For most Wi-Fi networks, the LTE-U protocol has a 25-microsecond backoff period and a DCF slot duration of 9 microseconds (IEEE 802.11). Because LTE-U has a longer backoff duration than Wi-Fi, Wi-Fi performance is affected [58]. In addition, the author of [59] used a unique Markov chain technique to alleviate this difference.

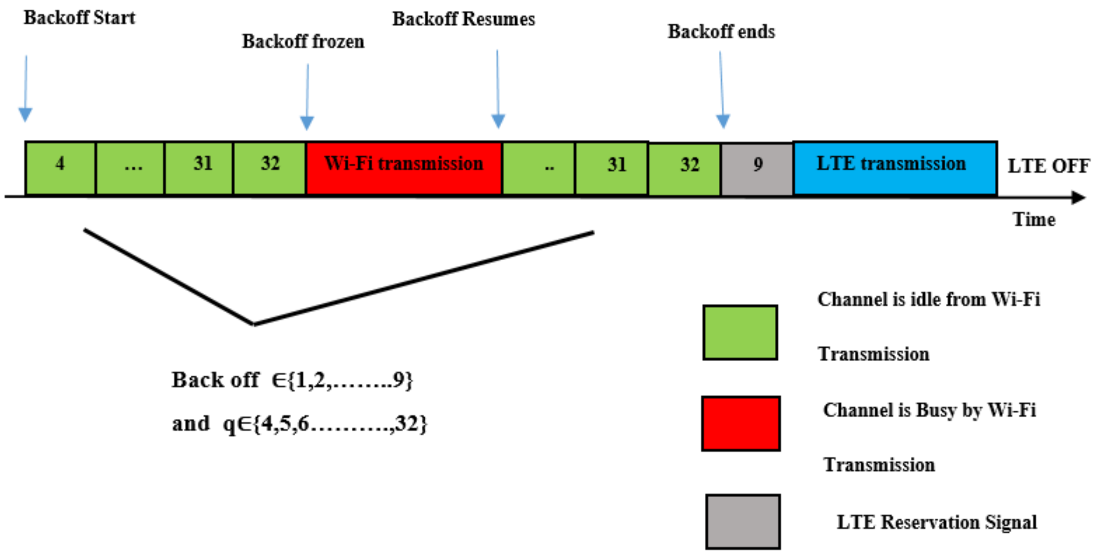


Figure 2.5: Listen Before Talk Cat3 Algorithm.

The reserved LTE-U signal is used to block Wi-Fi access until the initial LTE sub-frame boundary, at which point LTE-U begins to transmit frames; hence, LTE-U performance is slowed as a result of this reservation signal. As an example, LTE-U's Transmission Opportunity (TXOP) has three sub-frames, of which only two can be utilized for data sending, thus giving a 33 percent reduction in LTE-U performance. Whenever LTE-U use the maximum CW size, it does not affect LTE-U throughput when traffic is low, medium, or high. It is crucial to know, however, that the performance of LTE-U is better for smaller CW sizes. For a peaceful cohabitation between LBE and Wi-Fi, the author proposed the DIFS period in [60]. In this situation, the DCF protocol and the LBE protocol are identical, with the exception that LBE works with a fixed CW despite collusion. LTE-U based on Bianchi's mode has been researched in [51], which demonstrates that when the CW size is 15, there is more fairly cohabitation of Wi-Fi and LTE-U. This is due to two factors: first, the nearly identical CW for Wi-Fi and LTE-U (i.e. 16 and 15 respectively); and second, Wi-Fi uses three back-off stages instead of the IEEE standard's requirement of seven back-off stages. As a result, the employment of back-off stages by Wi-Fi has increased LTE-U and Wi-Fi coexistence while taking into consideration the use of fixed-size CW.

2.3.4 LBT Category 4

To make the LTE-U protocol like the DCF protocol, 3GPP has introduced the proposed LBT Category 4 (LBT Cat4) protocol [61]. LBT cat4 is similar to DCF because both possess a sensing time period before the back-off time period called CCA for LBT Cat4 and DIFS for DCF. Moreover, the LBT Cat4 and DCF protocol have the same back of time period drawn evenly with binary exponentially increasing CW size when the collusion happens across the channel, and both have the same slot duration of 9 μs. Conversely, LBT Cat4 has four priority classes as standardized by 3GPP; in this case, the traffic priority determines the CW size and COT [62]. In contrast, the DCF protocol of Wi-Fi has its own traffic priority class known as the access categories [63], which are different from LBT Cat4 priority classes. The difference in the protocol of LBT Cat4 and DCF makes one protocol better than the other. Like in [64] the author has found the LBT cat4 with higher COT will not guarantee fair air time between Wi-Fi and LTE-U cat4. Thus for this reason authors have adopted the COT adoption (COTA) algorithm for fair coexistence. The outline given by LTE-U release 13 is that adopt LBT cat4 protocol using LTE-U in [65], in which simulation for the cohabitation between Wi-Fi and LTE-U given by many spectrum companies confirmed that LTE-U is a friendly neighbor to Wi-Fi as compared to Wi-Fi to Wi-Fi itself with any traffic load type, including both the real-time traffic and the non-real-time traffic.

As the protocol of LBT Cat4 and DCF is similar, researchers have implemented Bianchi's model for modelling LBT Cat4 which does not require a change in the Markov chain model [62]. However, this adaptation is to calculate the LTE-U throughput over the LTE-U frame transmission, thus showing the reasonable cohabitation of LTE-U and Wi-Fi. On the other side, in [66], the author defines Bianchi's model for the LBT Cat4 analytical model, who said LTE-U Cat4 is different from the DCF protocol. Contrast is observed in the CW size of Wi-Fi; when CW reaches its maximum value, it will remain the same and does not initialize until a successful transmission happens, like in LBT Cat4. Research has been done to mitigate this drawback of Wi-Fi and let it function like the LTE-U protocol as far as the IEEE 802.11 standard, Wi-Fi will reset its CW when its maximum CW size is reached [67]. The dynamic size of the CW range adjustment algorithm depending on a load of traffic is studied in [68] and another algorithm for LBT Cat4 protocol CW size is based on slot utilization over a certain period in [69]. Similarly, in [70], authors have proposed a mechanism to control the size of CW by introducing the Maximum CW Timer Mechanism (MCWTM) which reproduces the Wi-Fi Retry Limit protocol. Lastly, the researchers in [71] suggested using the DCF protocol rather than the LBT Cat4 protocol with LTE-U and modifying the DCF size of CW for better fair cohabitation with Wi-Fi to entirely remove all MAC layer protocol diversity between Wi-Fi and LTE-U.

2.4 Priority class for LBT

An ETSI standard for LBT specifies four priority classes, where the lowest priority class is one and the highest priority class is four. Every priority class has a prioritization period (P), a random back-off time, contention window sizes ranging from CW_{min} to CW_{max} and a transmission time, which is also known as COT. The COT is indeed the maximum time the node can access the channel. The priority class determines the prioritization time, which is utilized to distinguish between various frame kinds and identify the channel state if it's idle or busy. Longer prioritization time intervals are required for low-priority classes and vice versa. Regarding the number of observational slots, prioritization time, CW_{min}, and CW_{max} were provided below. These channels use parameters to control how the congestion behaves and how long it lasts. Despite having a lower chance of success, packets with the greatest priority class will have the shortest duration, which is shown in table 2.1 below.

Class	**Po**	**C**W_{min}	**C**W_{max}	**COT[ms]**
4	1	4	8	2
3	1	8	16	4
2	3	16	64	6 to 8
1	7	16	1024	6 to 8

Table 2.1: Listen Before Talk Priority Class.

The impact of priority classes on effective channel use, probability of collusion, and channel access delays are studied in [39]. Effective Channel Utilization (ECU) was the proportion of the total time duration that a channel was used by all coexisting nodes to do successful Packets transmission or we can also say it demonstrates how effectively a channel has been used without causing collisions [72]. Intended for a hypothetical dense utilization of the upcoming 5G LTE NR-U network in each dense deployment scenario, it is demonstrated in [72] that ECU dramatically decreases even as the number of competing nodes rises. When compared with the two lesser priority types, the Performance of priority Classes third and fourth perform worse. Collisions upon this channel are thought to be the cause of the reduction in ECU. More particular, priority class 3 and class 4 seem to be more prone to collisions as compared with the other remaining two priority class types because their contention window sizes are smaller.

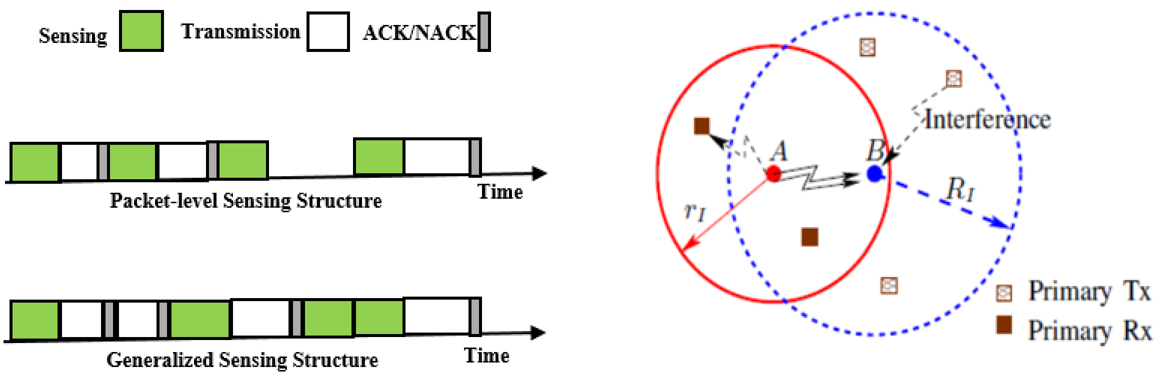
Moreover, it is demonstrated in [72] that during a multi-class compact application situation, specifically for just a two-class situation with priority class differing in one level, the overall ECU among both classes priorities decreases significantly with a rise in nodes owing to rise in channel collisions. For instance, due to negative impact of collisions for both greater priority classes 3 and 4, overall ECU of priority classes 3 and 4 lowers more quickly than it does in priority classes 1 and 2. In short we can say in multiple-class circumstances, greater priority classes here on channel are mostly linked to overall ECU degradation. Additionally, nodes in lower priority classes can endure greater mean access delays as compared with nodes in high priority classes [72]. This is due to greater priority classes have small size of contention window, which increases their probability of accessing the channel. This cause, lesser priority classes to have greater difficulties in getting access to the channel, which causes greater delays for them than for greater priority classes [72].

Chapter 3

Methodology

3.1 LBT Enabling Techniques

Some past research studies towards medium sensing has examined LBT techniques. Research in [73] and [74] emphasize the significance of LBT techniques for secondary users detecting primary signals possibilities, that is secondary users determine if they have get chance to access a channel before broadcast; which was in accordance with interference prevention. In other words, the channel is deemed to have been found opportunistically in accordance with [74] if secondary users are able to successfully interact without breaking interference limitations. When noise and fading are present during the study of such a primary detecting by secondary users, this was found that even with flawless detecting also the spectrum potential was still prone to distortion [74].



(a) Packet level sensing. (b) Primary and secondary user.

Figure 3.1: Channel sensing techniques for mitigating interference.

Whenever secondary users have many packets to broadcast following a single channel identification, the researchers of a work done in the paper [74] attempted towards enhance this technique by enabling secondary users so that opportunistically plus wisely have connection to the under used primary spectrum. Inside this paper, the threshold notion is presented and contrasted with input signals. The authors demonstrate that now in order to obtain the needed detection performance, overall sensing time must be lengthy sufficiently. As a result, weaker signals want a really lengthy sensing time that may also reduce opportunities of secondary propagation [75]. As shown in Figure:3.1(b) how secondary users (A and B) might sense the existence of primary users and start a conversation as a result. In other words, users A and B could only interact if A's transmit has no effect on any primary users inside the red cycle while B's receipt has no effect on any primary users inside the blue cycle [74].

Related to this, the research in [76] explores dynamic spectrum sharing (DSS), in which multiple accessing systems can control interferences among themselves and attempt to broadcast when they have sufficient knowledge of a channel's state using sensing mechanisms. The interfering limitation is indeed a critical concern throughout this research because ineffective interference control could prevent the system from operating at its capacity [76]. The researchers take into account heterogeneous networks, wherein two interfering management techniques can be employed. One is the handling of interference like noise, in which every nearby transmitter can only transmit a fixed amount of data depending upon channel conditions. Nevertheless, as illustrated by Figure 3.1(a) lot of recent research takes into account opportunistic spectrum usage based on packet-level detection [75]. The LBT that is based upon perfect channel detecting is yet another technique. Despite the possibility of traffic activities, it exhibited improved performance than the first method due to the utilization of CW, especially when more nodes are using the channel [76].

Wireless access innovation networks presently utilize LBT-based mechanisms due to the widespread utilization of CW and also the cooperation of a large user community. For instance, numerous LTE as well as Wi-Fi users would utilize and share the frequency band at 5 GHz fairly within the shared unlicensed band through the LBT backoff technique, even though LTE was intended to work inside the licensed spectrum band as studied in [77] and [78] indicated by 3GPP specification. Through determining the energy levels of many other users prior to every transmission, the existing LBT-based system may readily implement CSMA techniques. Since it enables interference prevention among Wi-Fi as well as LAA within the common band, which provides the benefit of efficiently resolving access technology coexistence difficulties inside this shared spectrum. Additionally, research in [78] suggests how both non-coordinated and coordinated settings could lead to peaceful cohabitation. The researchers here recommend a Tunable Coexisting Gaps (TCG)-based Adaptive LBT (ALBT) backoff mechanism that evaluates this same channels and leaves there behind the predetermined numeral gaps recognized as Tunable Coexisting Gaps (TCG). That might also make it possible for ALBT to cope well with aggregated LTE-U band channels with ease [78]. In Figure:3.2, both TCGs and LBT techniques are shown.

In this, a LAA-based protocol rotates between the predetermined numbers of readily accessible channels to prevent them from continuously monopolizing them out of greed. To put it another way, LAA-based equipment continually senses its channel by determining whether any other users are utilizing the common channel. When indeed a channel was determined to be empty, LAA-based user equipment communicates. However later, following transmitting, it checks the channel once again.

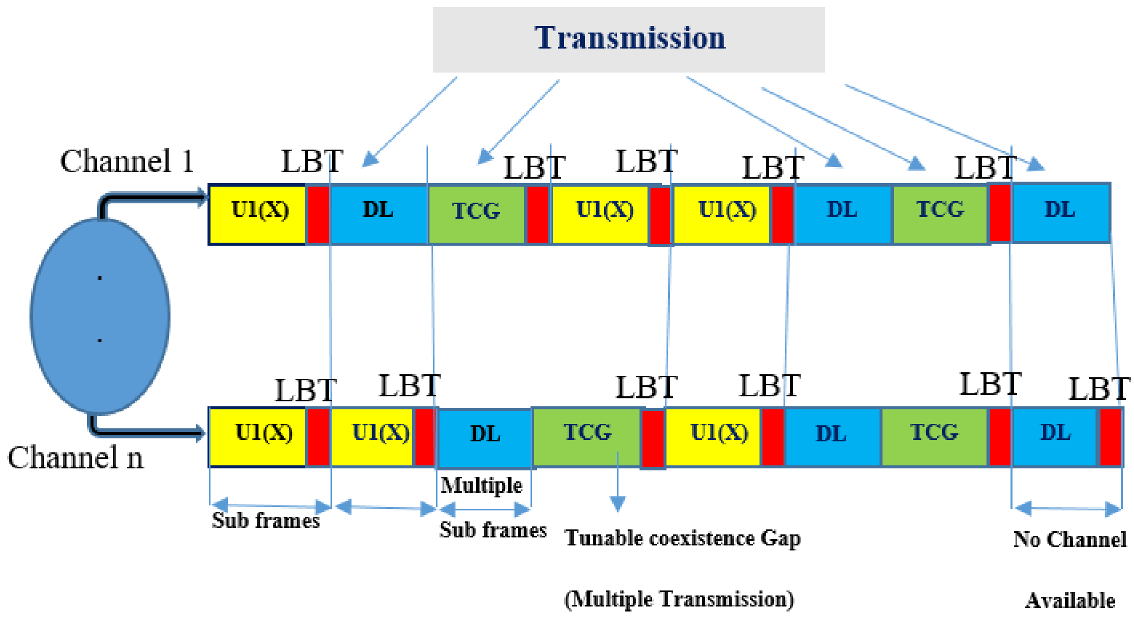


Figure 3.2: LTE-U system's adaptive Listen Before Talk operation mode.

Whenever the new channel was found to be vacant, LAA-based equipment switches to it, leaving a coexistence space open for alternative access technologies like Wi-Fi to peacefully utilize that left out channel [78]. This was crucial to remember that if gaps were left aside, LTE protocol won't start any transmission including data, control, or reference signals. Instead, they would remain down. Instead, it keeps using brand-new channels, which gives Wi-Fi systems a better chance of catching the channel. In the event that Wi-Fi needs to transmit several frames, LTE-U permits TCG lengthy enough for accommodate the multi-frame Wi-Fi broadcasts.

3.2 LAA-based LBT Cat 4 Access Mechanisms Implementation

Throughout wireless access technologies, backoff mechanisms were extremely important during channel allocation processes when users want to achieve equitable service & resource management. So to facilitate better cohabitation between LAA-based LBT Cat 4 & Wi-Fi-based access techniques, LBT Cat 4 MAC mechanism must be implemented effectively since it is one of algorithms for backoff utilized under LAA-based LBT Cat4 equipment inside the shared 5 GHz spectrum. As previously noted, we implemented this process using Matlab software to show that it was feasible. In order to ensure the greatest fairness among them when they are used in the common band, we present full descriptions of a LBT-Cat4 mechanisms in this section and demonstrate in what way the deployment is conducted for the 3GPP and recently developed LAA-based LBT Cat 4 MAC methods.

In terms of allocating channel resources, the LBT Cat 4 technique is the method under which eNodeBs or UEs could use CCA to determine whether a channel was filled or vacant by utilizing energy detection. So in order to implement this CCA within the unlicensed spectrum, we have employed the parameters mentioned in [79] and [80] under this research which is shown in table 4.1 below. The criterion states that the CCA employed in LBT Cat4 including for LAA-based LBT methods must be at least 20 milliseconds. In other words, when the channel has been watched for the length of a CCA, the device's power level was evaluated and its value was contrasted with the threshold. The threshold power on [79] has been set at -75 dBm. The channel was assumed to be empty throughout channel detection process when CCA $\geq$ 20 microseconds and threshold power surpasses the power within channel, else the channel is believed to be busy. When they employed Matlab simulation, they just took into account the fact that the channel was regarded to be empty if it is monitored for CCA $\geq$ 20 microseconds or else full. When one LAA-based LBT Cat 4 technique competes with another LAA-based LBT Cat4 technique or a Wi-Fi access technique, this technique mention above is utilized to determine whether the channel is empty. Depending on what type of equipment being used, CCA can perceive a channel in a variety of ways, which will be described in the sections that follow. Wi-Fi, in contrast hand, competes with other devices employing LAA-based techniques through use of CSMA/CA processes. For both techniques, we used various strategies, and we assessed their effectiveness by taking into account various pairings with LBT cat4 priority class.

The backoff technique being studied uses both LBT cat4 and Wi-Fi based equipment, as was already mentioned. Based on the studies in [80] and [81], we developed these techniques in Matlab. Whose implementation complies with 3GPP [82] standards for an effective and equitable cohabitation of all systems within common spectrum band. In this design, we allow LAA-based as well as Wi-Fi techniques to participate for the channel, then we assess how frequently each scheme has been given opportunities to use the channel. We break down each scheme separately in the sections that follow. We also go into detail about the implementation and the variables that were taken into account for the simulation.

3.3 Method of Training and Testing Data

To provide precise and efficient decision-making, ML-based networks of communication require training and testing data. ML models are developed using training data, and its accuracy and adaptability are evaluated using testing data. It is essential to use representative and high-quality data while building accurate models. Data testing enables the detection of potential problems, shortcomings, and constraints in ML models, and leads to an iterative optimization of the [83]. For ML-based networks of communication to be more dependable, secure, and effective, training and testing data must be carefully chosen. Here we will use NNCs and linearization method to do the tasting and training of data for the LBT Cat4 model developed in Matlab to make this model reliable and applicable [84].

3.3.1 Neural Networks and communications (NNCs)

Neural network and communications (NNCs) testing and training typically involves a number of steps. When it comes to various communication-related tasks, such as sentiment analysis, speech recognition, or recognition of images, neural networks are a sort of algorithm for machine learning which can be applied [83].

1. Data Preparation: Gathering and preparing data is the initial stage in training a NNCs. This can involves compiling and preparing a sizable dataset of communication-related data, such as text, audio, or image. Data cleaning, standardization, encoding, and extraction of features are a few examples of tasks that can be included in data preprocessing. For instance, in text-based communication the data may first be cleaned by eliminating unnecessary letters or symbols, followed by encoding into specific words or phrases. Typically, training, validation, and testing sets are created from the data.

2. Model Training: The NNCs model will be trained using the training set after the data has been prepared. Throughout training, the NNCs learns from the labeled data to find patterns or correlations between input data and output labels. Using an iterative procedure called backpropagation, which includes minimizing the error between the anticipated output and the actual output, the NNCs modifies its internal parameters, also known as weights and biases. Iterations or epochs of the training process are repeated until the model's performance is at a suitable level.

3. Model Evaluation: Following training, the validation set is used to assess the NNCs. The performance of the model on unknown data is evaluated using the validation set, and its hyper-parameters, including learning rate, batch size, and architecture, are adjusted accordingly. The model's performance can be assessed using a variety of metrics, including accuracy, precision, recall, F1 score, or loss. The model can move on to the testing stage if its performance is suitable.

4. Model Testing: The trained NNCs must be put to the test using the testing set, containing information that it hadn't encountered during training or validation. The performance and reliability of the model are evaluated independently throughout this testing phase. The model's effectiveness and suitability for the given communication task is determined using the performance indicators collected during testing. The model can be implemented for real-world applications, such as communication systems, recommendation engines, or sentiment analysis tools, if it satisfies the needed performance criteria.

The diagram give in Figure: 3.3 gives show the NNCs use in matlab to do data testing and training. In a nutshell data preparation, model training, model evaluation, and model testing are all necessary for the training and testing of data in communication utilizing NNCs. The NNC can learn from the data and gradually enhance its performance thanks to this iterative approach. To guarantee the correctness and dependability of the NNCs model in communication-related tasks, proper data preparation, model training, and accurate assessment are essential [85].

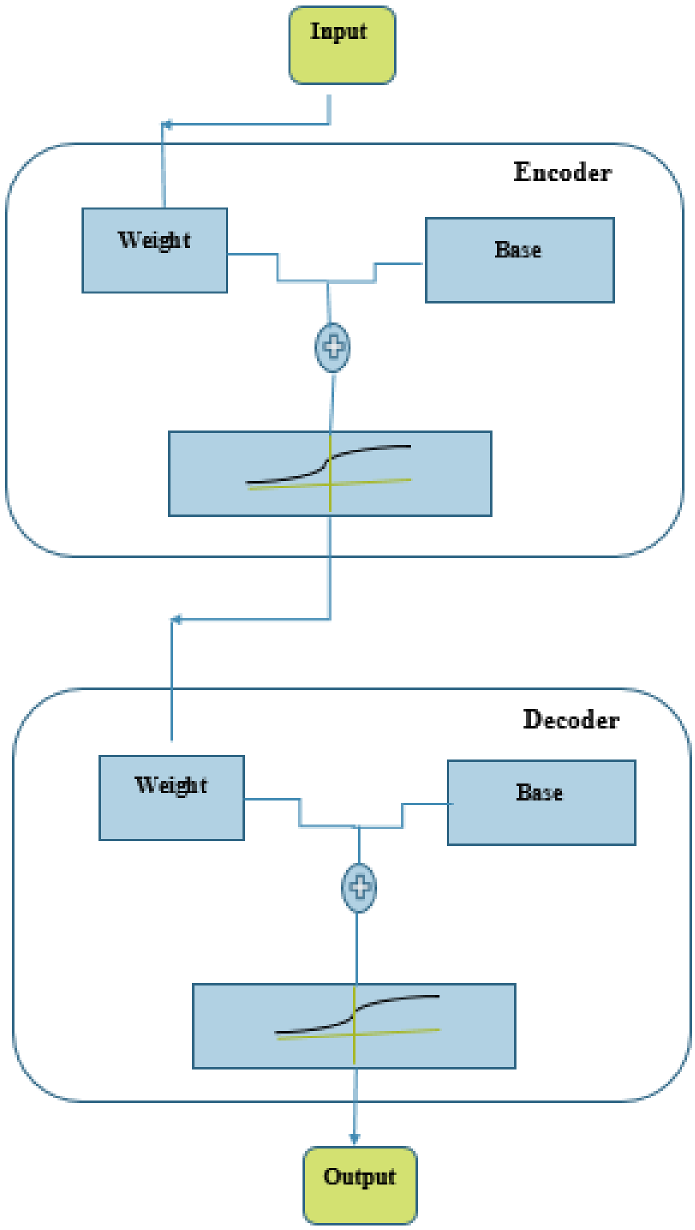


Figure 3.3: Block Diagram for Neural Networks

3.3.2 Linearize Model

As a purposes of analysis and design, the approach of linearization is used in communication systems for approximating non-linear systems with linear models [83]. In communication, testing and training data via linearization typically involves the steps as follows:

1. Data Collection: Data collection from the non-linear communication system is the initial phase. Input signals, output signals, or any other relevant parameters might be included in this data. The data, which depicts how the nonlinear system behaves under various operating settings or situations, is often obtained by measurements, simulations and experiments.

2. Linearization: Following collecting of the data, the non-linear system is linearized using mathematical approaches. This includes employing a linear model to approximate the non-linear behavior at a particular operational point. The transfer function or state-space model, which has a linear relationship between the input and output signals, is often used to depict the linear model. The linear model is typically obtained using linearization techniques, such as Taylor series expansion and small-signal analysis.

3. Model Identification and Testing: The linear model is then determined using the gathered data. Typically, this includes employing methods like least squares or maximum likelihood estimation for fitting the linear model to the data. An alternative dataset, which is not utilized for model identification, is used to evaluate the observed linear model. During this testing phase, the linear model's performance and correctness in simulating the behavior of the non-linear system are assessed. The correctness of the model can be evaluated using a variety of performance indicators, such as mean squared error or root mean squared error.

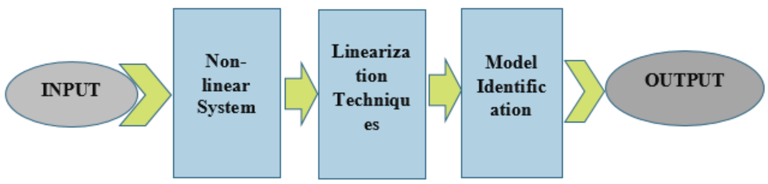


Figure 3.4: Block Diagram for Linear model

The block diagram in Figure:3.4 depicts the three basic stages of data training and testing utilizing communication-related linearization. To create a linear model, linearization methods are applied to the input signals, which reflect the data gathered from the non-linear system. The linear model is then determined or estimated using the data gathered, and tested using a different dataset to assess its precision and performance in simulating the behavior of the non-linear system [85]. The output of the linear model is represented by the estimated output according to the input signals.

Chapter 4

Simulation Model

4.1 Principle of the LBT Cat4 access mechanism

Utilizing the CCA program, user equipment through using LBT Cat4 protocol adopts the contention technique. Since the frame structure was not fixed with LBT Cat4s systems, the channel was filled for an adaptive transaction period for LBT Cat4s known as "Channel Occupancy Time (CoT)," which also defines the magnitude of a frame which is being transferred. For $COT = (13 \times q)/32$, in which N would be a random backoff counter chosen between 1 to q, was used to determine CoT. In another sense, N $\in$ [1, q] here q would be a fixed backoff scaler set between 4 and 1024 for LTE-U cellular network and also was fixed for every given piece of equipment of LTE-U [86]. A random number N affects the CW for LBT Cat4s. That's because the time slot was fixed at 20 μs, and CW was established by $20 \times N$. A uniform distribution was utilized to calculate the random backoff number (N) for the given simulations.

An illustration of how N values and q values will affect the frame size and LBT Cat4 contention window size as shown in Figure: 4.1. A sample, as illustrated in Figure: 4.1, assumes that perhaps the UE has been utilizing the channel about 1.625 milliseconds (ms), as determined by $COT = (13 \times q)/32$, for just a fixed value of q = 4. Although q was fixed for every particular UE, the newly chosen random counter N = 3 right after the transmission was from a range of q values whose ranges are 1 to 4. Where we suppose that perhaps a UE chooses a random number whenever it starts the subsequent transmission cycle and have a packet to deliver. As a result, this fluctuation in COT plus random counter (N) suggests that the frame magnitude as well as CW also depend mostly on the q values. To enable optimal cohabitation between Wi-Fi and LBT Cat4-based systems, we used the concepts in [80], in which the initial CCA test is instantly followed by an Extended CCA (ECCA) test before any data transmission.

Figure: 4.1 illustrates the process for putting the backoff mechanism for LBT Cat4 into action. As was already noted above, we used the technique in [80], in which the LBT Cat4 operation always starts with the random backoff counter N chosen at random from intervals 1 to q, and then we follow the uniform distribution. For such simulations of this technique, we perform an initial CCA test (T=0) before allowing equipment utilizes the LBT Cat4 algorithm for scanning the channel. When this

CCA fails, it indicates that now the channel is full. When it succeeds, however, it shows that now the channel is empty for additional users to participate in the channel access competition [80]. After the successful initial CCA, an ECCA check follows with a T=1 period which uses a contention window process that is chosen from backoff counter N. Calculation of the CW for LBT Cat4 yields CW = 20× N. A backoff counter N is decreased by one when the channel is deemed empty during ECCA; otherwise, it's indeed frozen.

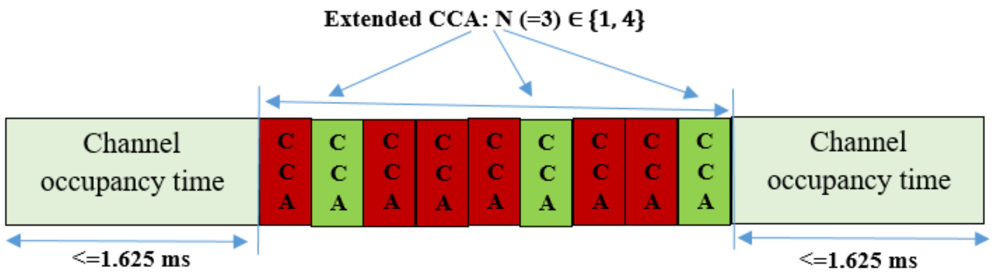


Figure 4.1: Frame size and backoff for q=4 and N=3.

The equipment thereafter performs continuous detection in accordance with the above mentioned protocol. Whereas if backoff counter approaches 0 (N = 0), then data is transfer instantly, otherwise, the new value of random number was generated before some other new value of initial CCA was once more applied in the begin of next transmission of a data.

If we thoroughly look into the condition throughout this instance, it indicates that perhaps a successful data transmission could occur after an N+1 times periods, along with the initialization CCA of LBT Cat4. Due to the identical length (20 μs) of each slot in the LBT Cat 4 contention window, 2 successive slots (T0 + T1 = 2T0) were seen as empty before any transmission of signal. As a result, this guarantees a lengthy window of opportunity for competitors. For instance, 2T0 = 40 μs can be thought of as sufficient to create space for Wi-Fi in the unlicensed shared spectrum, for whom the DIFS was 34 μs and time slot is 9 μs, or (34 + 9) μs. As a result, this lengthy CW would enable users of Wi-Fi to interact among other LBT Cat4 users in common spectrum band more effectively [80]. Additionally, it should be noted that now the LBT Cat 4 operation restarts with a fresh random counter N following the above mention described steps for implementing initial CCA as well as ECCA.

We constructed the LBT Cat 4 based access control protocol with the flowchart shown at Figure: 4.2, that depicts the process and all phases employed during this development, by adhering to the above-mentioned principle. Depending at the uniformly chosen backoff counter N, the above mechanism uses linear CW to implement CSMA. The development of the LBT cat4-based technique is outlined in the below explaining the flow chat in figure:4.2 as follow.

A random backoff counter N needs to be an integer number because the procedure begins by choosing it from a range of 1 to q, whereby q value is the positive integer within 4 to 1024 for LBT Cat 4. An initial CCA test is conducted to channel with

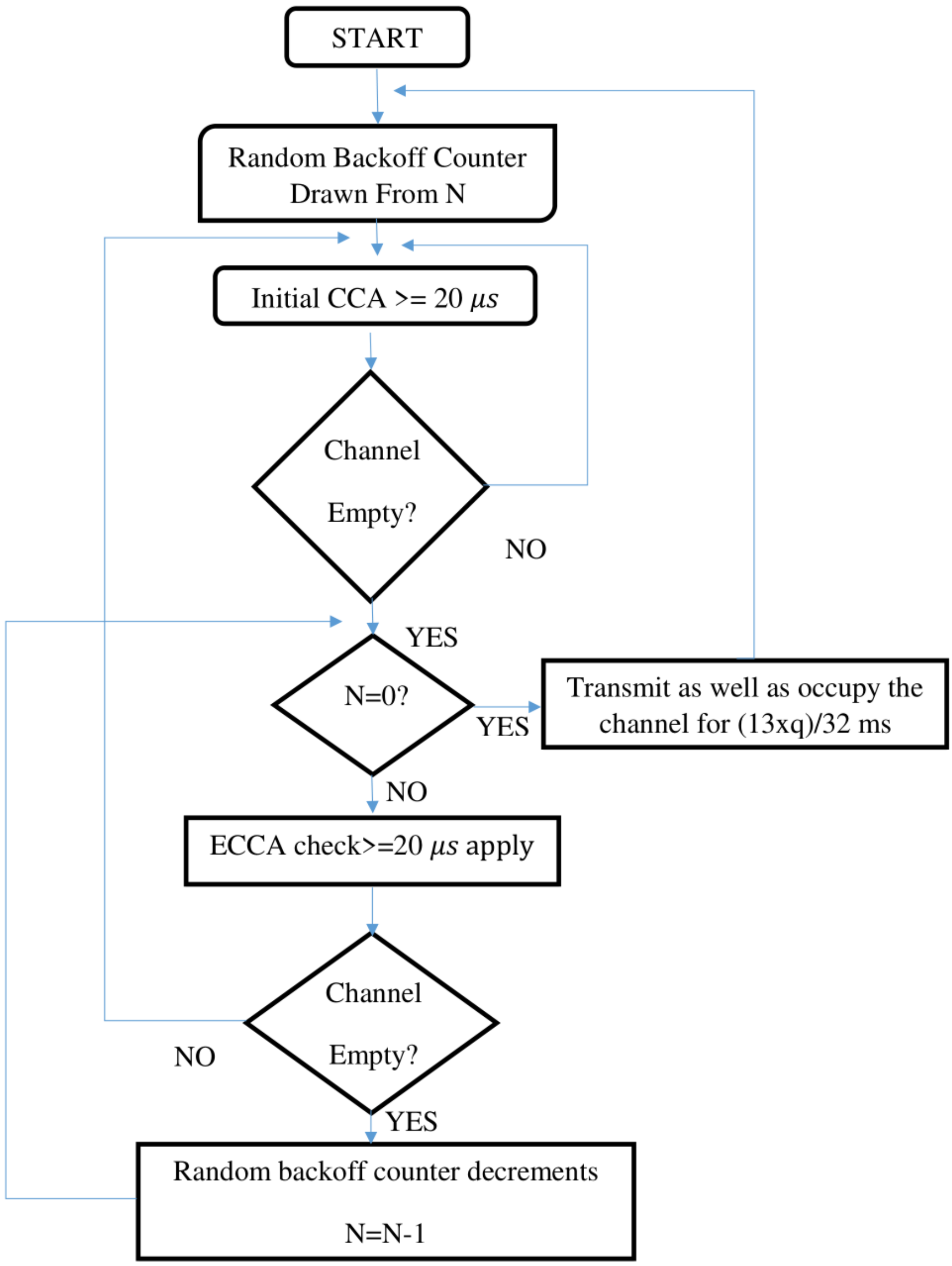


Figure 4.2: The Cat 4-based LBT with ECCA procedure's guiding principles.

CCA $\geq$ 20 microseconds following the choosing a random backoff counter to determine whether the channel was idle. When it isn't idle, CCA is once more performed; else, the method goes to the following step. The procedure reverses and begins with a new counter N after sensing the channel & determining that it has been idle for CCA $\geq$ 20 μs. If indeed the counter N had dropped to zero, this LBT Cat4 based equipment broadcasts right away and utilizes the channel for such an amount of time calculated as $COT = (13 \times q)/32$. It moves on to the subsequent stages of the other instance when (N$\neq$0). A channel is subjected to ECCA (20 μs). Till the data has been successfully sent, the processes are repeated.

4.2 Principle of the CSMA/CA access mechanism

Wi-Fi is indeed a different wireless network that is only intended to function within unlicensed spectrum bands through the use of carrier detecting for cohabit using alternative media access technologies or to use the common spectrum band throughout the competitions. It has also been applied in this research. As described earlier, this approach makes use of the CSMA/CA technique to determine the energy level by channel-detecting operations before any packets of data are transmitted through a common spectrum band [87]. Similarly to LBT Cat4-based procedures, APs as well as STAs usually check and measured energy levels toward a threshold energy level before reporting whether the channel is empty or in full use by other users. In this simulation, we applied the original CCA for DIFS duration and considered that the channel had remained idle. However, in actual, practical settings, 4 microseconds of CCA must be employed. Following the fruitful DIFS, a Wi-Fi transmitter uses a backoff technique to lessen collisions that can unintentionally occur during co-channel competitions. If indeed the equipment detects that nobody is utilizing the channel following backoff (random counter N=0), a transferring of the signal is instantly allowed [87]. In contrast, the procedure restarts once the broadcast is delayed until the channel is deemed to be empty. The procedure adopted during the Simulation analysis is shown in Figure: 4.3.

In order to determine a random backoff value for Wi-Fi, we employed uniform distribution. Additionally, we discovered even during competition how backoff plus DIFS numbers directly affect other Wi-Fi as well as LBT Cat4 systems within a common spectrum band. As they might influence the overall effectiveness of these above mention access mechanisms within the common spectrum band, DCF parameters should be cleverly engineered. While Wi-Fi users are employing the common 5 GHz band during our simulation modelling, we use CCA for just a DIFS amount of time corresponding toward 34 µs whereas the backoff was evaluated in the time slots including 1-time slot corresponding to 9 µs [87]. Those actions were taken to establish the Wi-Fi protocol in accordance with the algorithm shown in Figure: 4.3.

CCA is used for identifying the idleness of a DIFS period equal to 34 µs under the presumption that now the channel has indeed been empty. When DIFS is not in use on the channel, a randomly generated backoff counter number is chosen. When a channel was detected as being full, CCA was reused to check it again. In order to determine whether it is empty or not, the device puts a stop for 9 µs during scanning

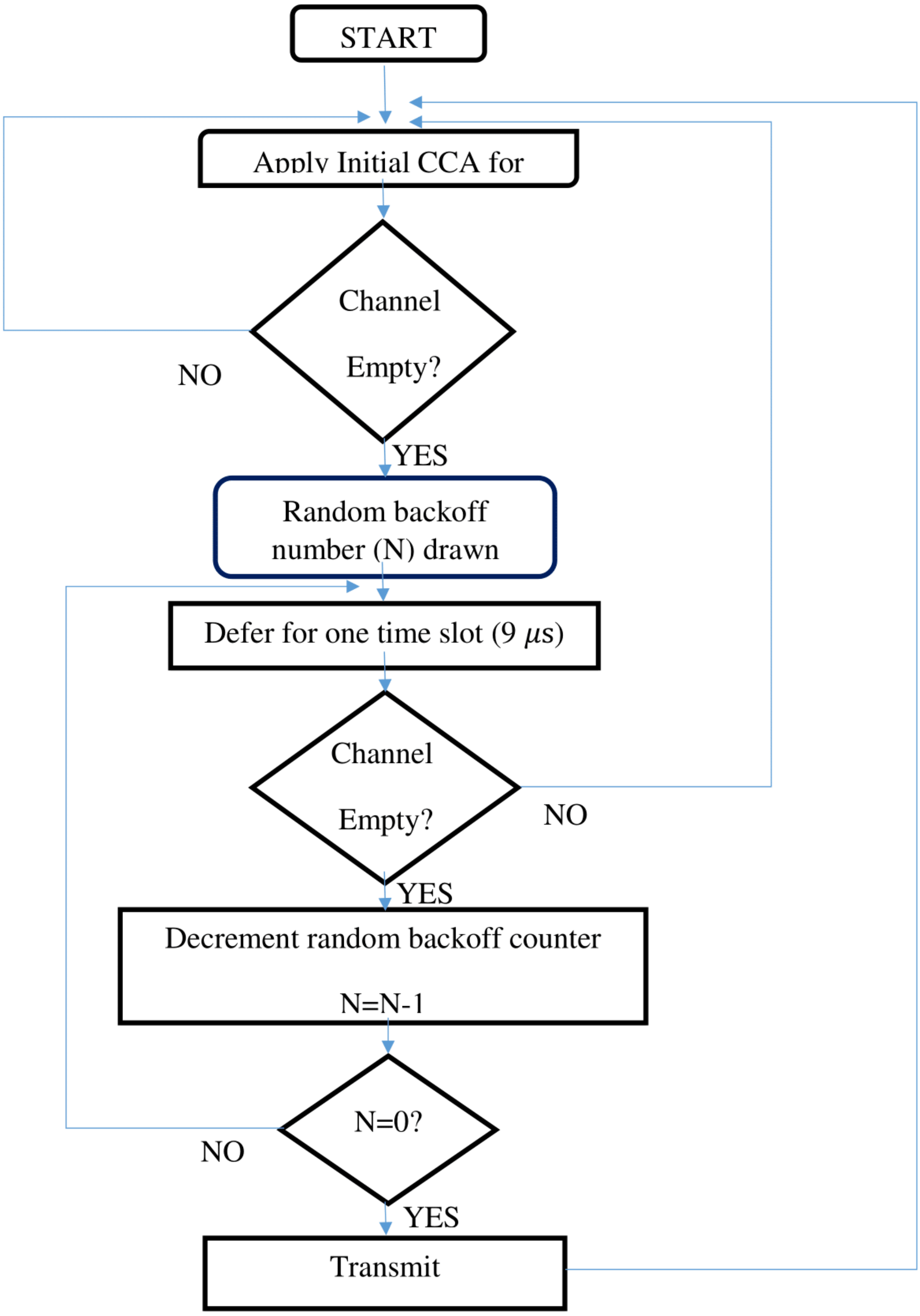


Figure 4.3: Overview of the Wi-Fi medium sensing process.

the channel. A system enables CCA for using once more for the duration of the DIFS time period when it is determined to be used; otherwise, it moves to the next process.

The number N was decreased with a time slot as (N = N-1) whereas if Channel was empty for a period of about 1-time slot (i.e. 9 µs). If this falls to zero, the frame will be sent data right away. Reactivating a contention window with CWmin (i.e 15-time slots) and using CCA once again will restart the procedure. Once the device had an opportunity to connect to the channel, we automatically presume that the data transmission for all of the methods discussed above was completed. We also presume that any transferred data is successfully acknowledged.

4.3 Jain's Fairness Index

While all users were supposed to be given an equal chance of channel allocation via MAC procedures, sharing resources and features is crucial in wireless communication systems. Fairness is a key criteria used to evaluate how well a user received an equitable share of resources delivered by MAC procedures with different LBT categories in particular LBT Cat 4 Priority class. This would be determined by taking into account Jain's F [88] in the calculation of channel allocation fair treatment and performance maximization. F isn't just utilized for performance calculation though; additional parameters could be predicted based here on technologies under examination and their purpose. Those consist of aspects like energy usage, allocating resources, and channel allocation probability. Its shared band channel allocation chances are compared inside this research utilizing F.

$$F = \frac{(\sum_{k=1}^{m} x_k)^2}{m \sum_{k=1}^{m} x_k^2} \tag{4.1}$$

It is reflected that in [79] Formula 4.1 can be used to calculate this F. When n represents the total number of users and let's consider Xk as normalized values, which are derived as Xk = T(k)/O(k), where T(k) and O(k) are indeed the measured and ideal values for every given factor under examination. As per [88], for every variable, F takes into account all users inside any system, even those who could have been allotted limited resources. For instance, measuring F for such an allocation of resources competing for hosts as per [88] evaluates and finds out if resources are deployed evenly or unequally among users. This one is judged for being long-term fairness when all users have been accessible to resources with a likelihood of p/m on behalf of an efficient long period. Moreover, F will similarly be continuous throughout that considerable time, independent of every scale, and bound within 0 and 1. As a result, let the number of users be n, worst-case situation is calculated to be 1/m, while the greatest index is 1 (100 percent). This formula 4.1 will use to calculate Jain's fairness Index for the number of users in the license and unlicensed spectrum band. In particular, in this, we are studying the fairness of the LBT Cat 4 and Wi-Fi with one user each competing for a common channel.

4.4 Total Performance Evaluation of LBT Cat 4 Access Mechanisms

Following the foregoing discussions, we next show the modeling output that were produced using the simulation models and specifications for both the Wi-Fi-based and 3GPP-proposed LBT Cat 4 Specification. For enhancement of fairness and peaceful cohabitation among other LAA as well as Wi-Fi management models within shared spectrum, their outcomes evaluation is conducted. We consequently give the performance outcomes in terms of the channel access possibilities that each competing scheme was able to acquire. We evaluate the proportion of total fairness index of the LBT Cat4 and Wi-Fi with one user each competing for channel access. Here we study four different priority class of LBT Cat 4 competing for channel access with Wi-Fi and see which priority class of LBT Cat 4 is best to coexist with Wi-Fi for LTE-U deployment. We demonstrate this performance by employing Jain's fairness index.

We expanded Jain's fairness equation, illustrated in Formula 4.1, which originally is based on the number of participants to be considered for multi-trial competition among various users. This newly expanded Formula 4.2 takes into account both the total number of participants as well as the total number of competitions that each user has entered. All of the mechanisms described in this project research are implemented using this equation.

$$I_{Tot} = \frac{1}{M} \sum_{j=1}^{M} F \tag{4.2}$$

whereby I_{Tot} is Jain's fairness index with all competitions taken into account within a certain limit. Formula 4.1 is used to generate F, which stands for the individualized fairness index among m users examined over M=100 (i.e. 100 trials). M denotes number of input variables (or we say number of indices) alongside with the range under consideration. Thus, we got 100 competitions with each M parameter (or each F). It also demonstrates the single F's variability when evaluated for a certain individual frame size (or transmission time period). We had to determine an average fairness with 100 competitions taken into account for a certain parameter range (M) as well as for a given situation through Matlab simulation, therefore we adapted this formula. This will help us to know the overall average performance of the each priority class of LBT Cat 4.

4.5 LBT Cat4 Model Design Validation with ML using Confident Interval

The confidence interval is the probability that the data of the experiment falls within the given range of value of the representative sample data used in the sample experiment. The user can determine the degree to which sufficient experiments have been performed using the confidence interval.

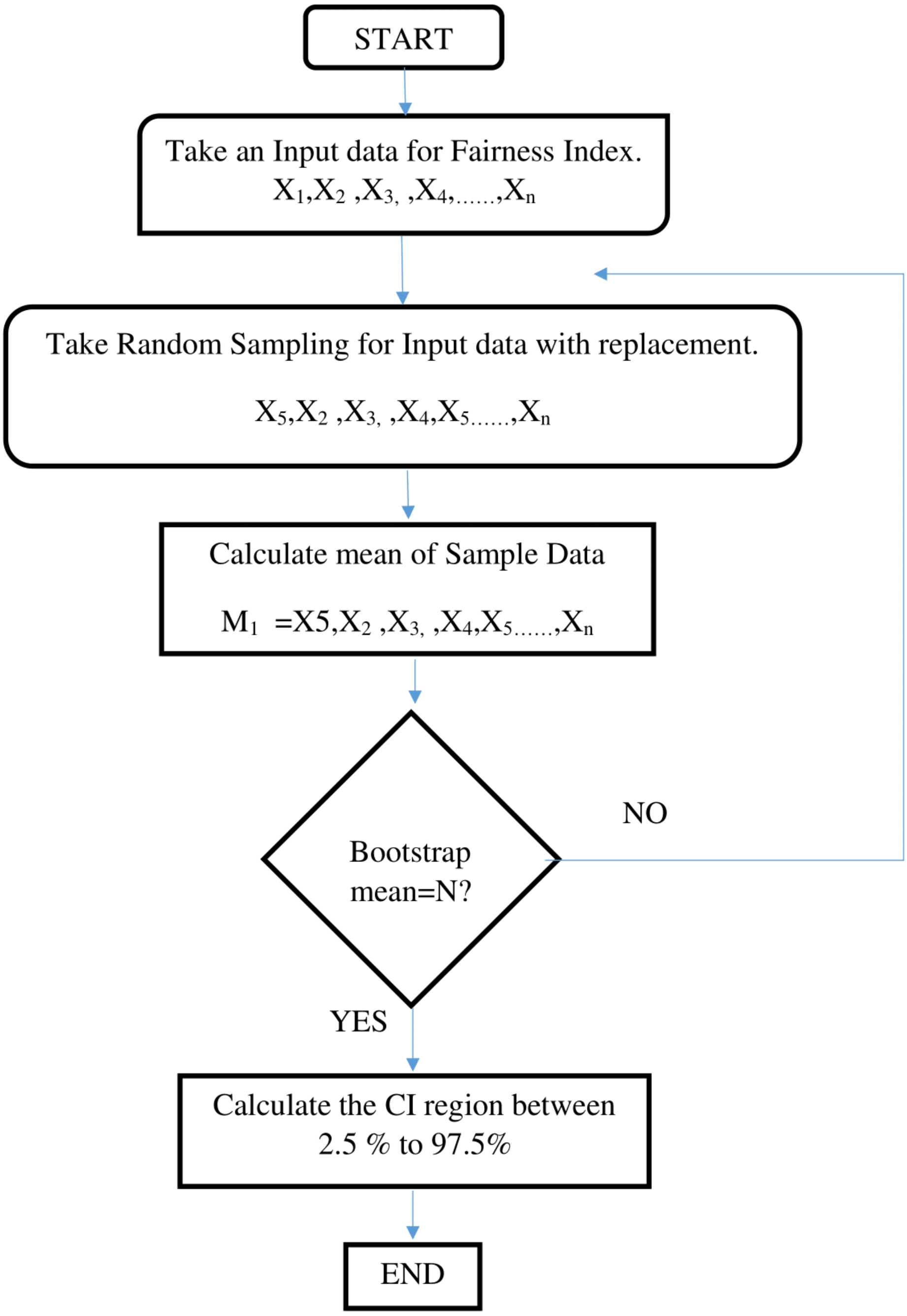


Figure 4.4: Algorithm to calculate the confident interval.

If the confidence interval is too wide for the specific application, not enough experiments have likely been performed. As the number of runs increases, the size of the confidence interval will also decrease. The client can evaluate the accuracy of the curve fit using the confidence interval. The curve fit could be good if the estimated percent out of spec values do not fall within the confidence ranges for the actual percent out of spec. It is a good indication that the differences are not substantial if the outcomes of the two simulations fall within their respective confidence ranges. Noise is a term that has been used to describe the subtle fluctuations in the data. There are two ways the confident interval is implemented using a machine learning approach, one based on applying a formula and another by empirical bootstrapping or re-sampling data [89]. Here we use empirical bootstrapping because of the limited data sample generated and it work without any assumption unlike the formula base approach [90].

Here is the flow chart to calculate the confidence interval is given below in figure: 4.4. We have loaded the data generated by the LBT Cat4 model and the mean of the data is Calculate. The same data is used and random sampling with replacement is done and the mean is calculated for this data 1000 times. Then the data within 97.5% and 2.5% is calculated as a 95% confident interval.

4.6 Machine Learning Implements for Signal Detection Theory

The receiver operating characteristic (ROC) curve was the first used by the army in World War II to detect the enemy's objects in the battle field developed by electrical and radar engineers. After World War II the signal detection theory was used by psychology for the perceptual detection of stimuli [91]. Then ROC is used in medicine, radiology, forecasting of natural hazards, data analysis and Machine learning recently. The probability of positive signal detection and Probability of false signal detection for LBT Cat4 Priority class with the help of counter to count in the algorithm of LBT Cat4. The counter counters the number of times the LBT Cat 4 assist the channel when they compete 100 times. Then the probability of LBT Cat4 detected P (H) was given by

$$P(H) = \frac{H}{N} \tag{4.3}$$

Here H number of times the LBT Cat4 assists the channel and N is the total number of times competing to assist the channel [92]. Similarly, the probability of signal miss P(FA) is given by

$$P(FA) = \frac{FA}{N} \tag{4.4}$$

Here FA number of times the LBT Cat4 could not assist the channel and N is the total number of times competing to assist the channel [89]. The probability of detected and miss have been normalized and the measure of discrimination (d') is calculated using the formula

$$d' = Z(P(H)) - Z(P(FA)) \tag{4.5}$$

Here Z(P(H)) is the normalized value of probability of signal detected and Z(P(FA)) is the normalized value of probability of signal miss [89]. This measure of discrimination (d') is call d prime also, which is used to calculate plot the receiver operating characteristic (ROC) curve from the set of d value within the probability of detection and miss (i.e. 0 to 1). The flow chart below shows how measure of discrimination can be applied to the wireless communication data for better analysis of data. Fig-

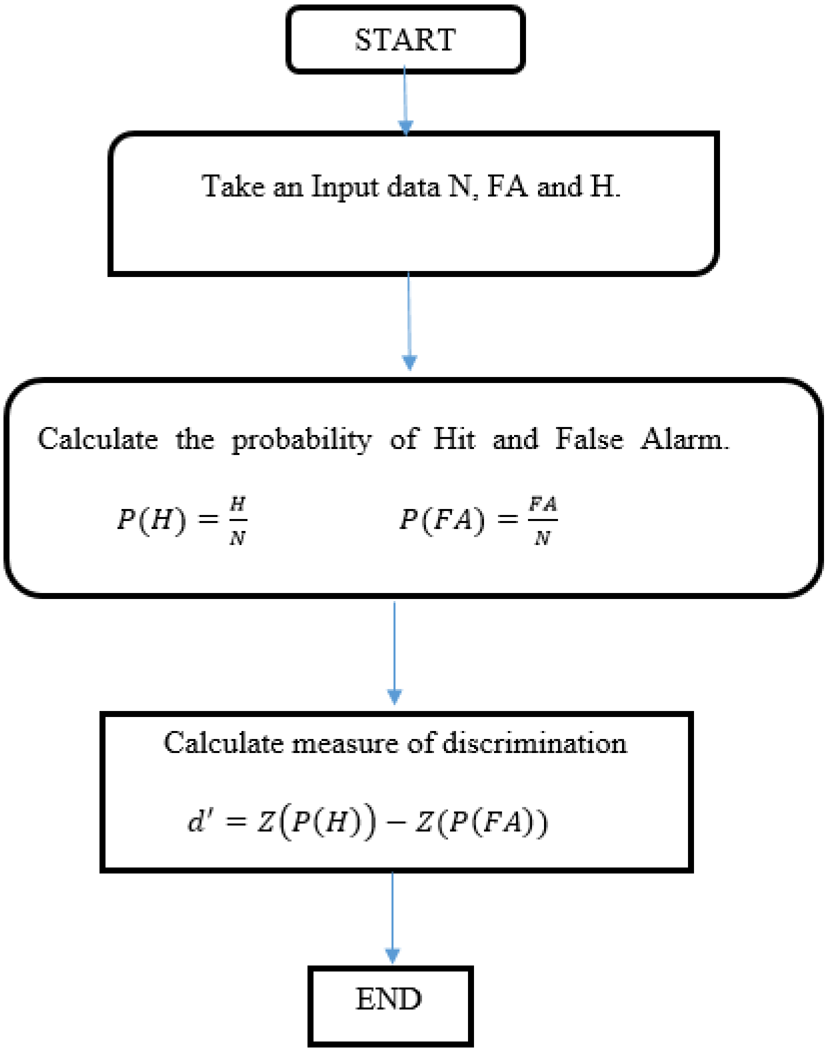


Figure 4.5: Algorithm to find the positive signal.

ure: 4.5 shows how positive detection is implemented in wireless communication. We have imported the number of times correctly received data and the number of times falsely signal detected. This data is used to calculate the probability of positive signal detection and the probability of false signal detection. Then the data is normalized and the measure of discrimination is calculated.

4.7 Testing and Training Data for Neural Networks and communications (NNCs).

The ability to make data-driven decisions, as well as their adaptability and efficiency, make neural networks and communications (NNCs) essential. NNCs are capable of processing enormous amounts of data produced by communication systems and obtaining important data for tasks like speech recognition, sentiment analysis, and image recognition. They are crucial in dynamic or developing communication systems due to their capacity to adapt to changing communication contexts, data patterns, and learning from new data. Additionally, NNCs automate labor-intensive and prone to error processes, resulting in increased accuracy and efficiency. All things considered, NNCs make communication systems more intelligent, context-aware, user-centric, resilient, efficient, and reliable [85].

The algorithm for LBT cat 4 is use to fine the total fairness of each priority class define by 3GPP. This simulated fairness data is save in Matlab for testing and training data of each priority class. The save data for each priority is run through the NNCs algorithm developed in the Matlab to evaluate the reliability and applicability of each priority class of LBT Cat4.

4.8 Testing and Training Data for Linearization.

Due to its capacity to reduce nonlinear effects in signals, channels, and feature extraction, linearization is crucial in communication applications that make use of machine learning techniques. In order to improve signal quality, equalization, and modulation recognition, linearization techniques can be used to approximate nonlinearities in communication signals, channels, or impairments. As a result, communication systems operate more effectively and consistently, improving efficiency and reliability [84].

The LBT Cat 4 algorithm is used to determine the overall fairness of each priority class specified by the 3GPP. For testing and training purposes for each priority class, this simulated fairness data is saved in Matlab. To assess the accuracy and applicability of each priority class of LBT Cat4, the save data for each priority is provided via the linearization algorithm created in Matlab.

4.9 LBT Cat4 Priority Class and Wi-Fi Simulation Parameter

Here we will simulate to see how many times channels can be accessed by LTE-U and Wi-Fi with LBT Cat 4 protocol in use. Where LTE-U and Wi-Fi has one user each when they compete 100 times to access the same channel at randomly generated CW is analysed with the use of Jain's Fairness Index formula as discussed above .

Parameters	Wi-Fi	LBT Cat 4			
		Priority class 4	Priority class 3	Priority class 2	Priority class 1
CCA (μs)	CCA as DIFS	20	20	20	20
COT (ms)	0.400 to 2.400	2	4	6 to 8	6 to 8
Off Period	Depends on CW	Depends on CW	Depends on CW	Depends on CW	Depends on CW
CW	$CW_{min} = 15$ to $CW_{max} = 1023$	$CW_{min} = 4$ to $CW_{max} = 8$	$CW_{min} = 8$ to $CW_{max} = 16$	$CW_{min} = 16$ to $CW_{max} = 64$	$CW_{min} = 16$ to $CW_{max} = 1024$
Slot Time	9 μs	20 μs	20 μs	20 μs	20 μs
DIFS	34 μs	...	...	...	...
q Range	...	4 up to 8	8 up to 16	16 up to 64	16 up to 1024

Table 4.1: Different parameter of priority class under LBT Cat 4 and Wi-Fi.

We created the simulation LBT Cat 4 model in Matlab to examine the coexistent of LTE-U and Wi-Fi fairly with each priority class of LBT Cat 4 protocol. In this simulation, the LBT Cat 4 is separated into four priority classes according to the 3GPP specified parameters as shown in table 4.1. We use the LBT Cat 4 priority class parameter given in table 4.1 to fine the coexistance of LTE-U and Wi-Fi throughout the simulation. We can see from table 2.1 that the priority class is categorized in terms of its different values of CW size and COT. Parameters like CCA, Slot time and q rang will also be given in table 2. We consider four scenarios where we use Matlab simulation model of LTB Cat 4 to look at which LBT Cat 4 priority class will give the best coexistence scenarios with Wi-Fi and LTE-U. Where under each priority class we will calculate F for 100 trials and the overall total fairness of each priority class. The four scenarios are as follows

- Scenario1- LBT Cat 4 Priority Class 4 coexistence with Wi-Fi
- 2. Scenario2- LBT Cat 4 Priority Class 3 coexistence with Wi-Fi
- 3. Scenario3- LBT Cat 4 Priority Class 2 coexistence with Wi-Fi
- 4. Scenario4- LBT Cat 4 Priority Class 1 coexistence with Wi-Fi

For all the scenarios we consider both LTE-U as well as Wi-Fi with one user each and we evaluate the F using LBT Cat 4 under different priority classes. To do this for each priority class we will plot five different q values which help to generate CW size randomly. Thus these plots will help us to generally know the best LBT Cat 4 priority class is best for the coexistence of LTE-U and Wi-Fi, although there will be some variation of F each time we simulate due to randomly generated CW.

Chapter 5

Results and Discussion

5.1 Scenario 1-LBT Cat 4 Priority Class 4 coexistence with Wi-Fi

The LBE Cat 4 Priority Class 4 as well as Wi-Fi User Equipments are competing to access the Channel with One User Each in this Scenario 1. For priority class 4 under LBT category 4, where the variable q value ranges from 4 to 8, different random backoff CW sizes are generated. For LBT Cat 4 priority class 4, we will use 2 ms of COT throughout Scenario 1.

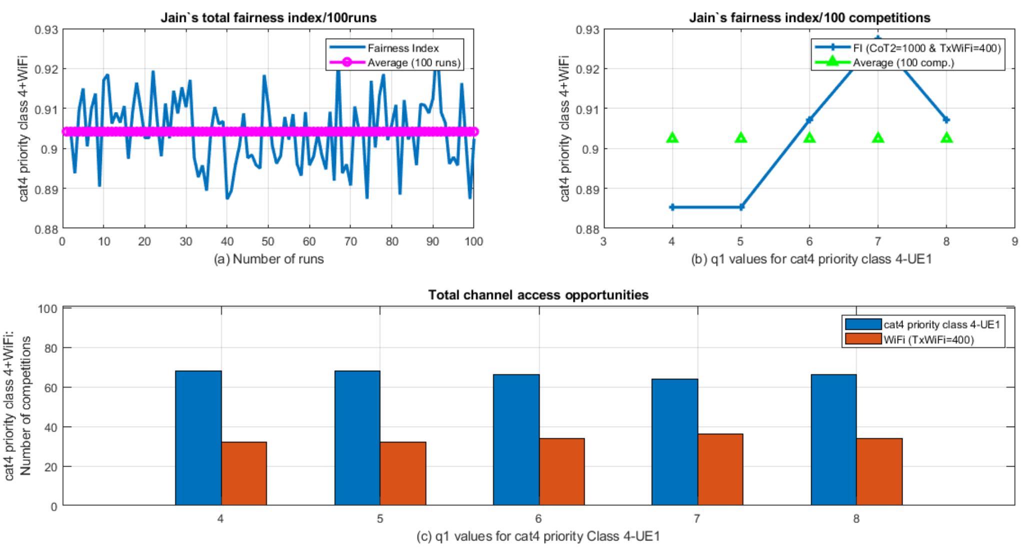


Figure 5.1: Graph showing Jain's Fairness Index priority class 4.

We have drawn three graphs, with Figure: 5.1 (a) showing the overall fairness index (F) for 100 runs and Figure: 5.1 (b) showing the fairness index for a 100 times competition involving LBT Cat 4 priority class 4 and Wi-Fi for channel access. Figure: 5.1 (c) will depict the number of times LBT Cat 4 priority class 4 and Wi-Fi could access the channel when they are competing for channel access 100 times. Figure: 5.1 shows that the fairness index for priority class 4 of LBT Cat 4 with Wi-Fi is 90.4% overall, with a fairness index for 100 runs of 90.2%. Similarly from table 5.1, we can see that the maximum fairness index is 92.7% and the minimum 88.5 %.

q Value	4	5	6	7	8
Priority Class 4	68	68	66	64	66
WiFi	32	32	34	36	34
F Index	0.885	0.885	0.907	0.927	0.907
Average Over 100 Competitions					0.902
Average Over 100 runs					0.904

Table 5.1: Listen Before Talk Priority Class.

5.2 Scenario 2-LBT Cat 4 Priority Class 3 coexistence with Wi-Fi

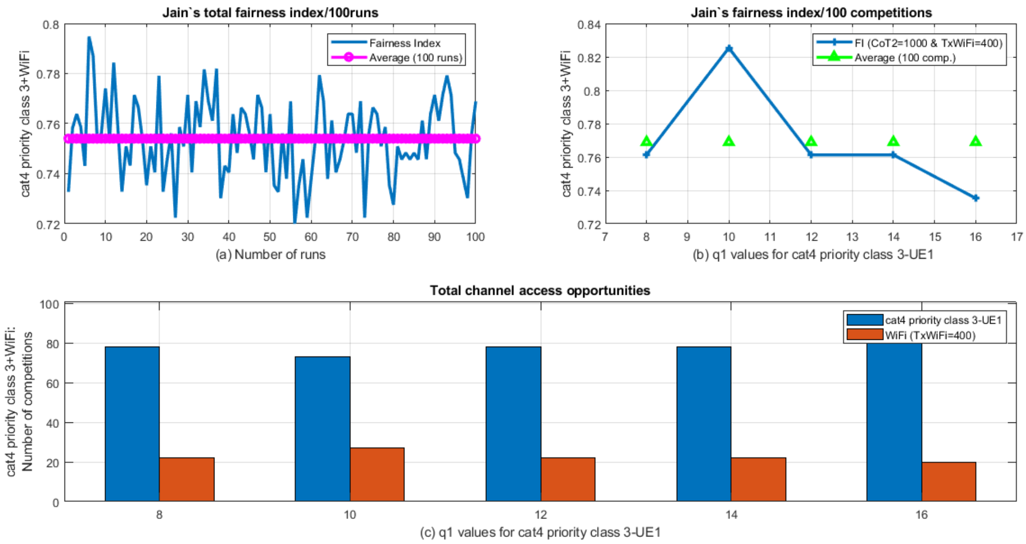


Figure 5.2: Graph showing Jain's Fairness Index priority class 3.

In this scenario 2 we will see probability that how fairly the LBE cat 4 priority class 3 as well as Wi-Fi user equipments are competing to access for channel with one user each. Where we have variable q value running from 8 to 16 which generate different random backoff CW size for priority class 3 under LBT cat4. Thought-out the Scenario 2 we will use 4 ms of COT for LBT Cat 4 priority class 3.

We have plotted three graph where overall fairness index (F) for 100 run is given by Figure: 5.2 (a) and fairness index for 100 time competition with LBT Cat 4 priority class 3 and Wi-Fi is given by Figure: 5.2 (b). Figure: 5.2 (c) will show how many times the LBT Cat 4 priority class 3 and Wi-Fi have access the channel when they are competing for 100 time to access the channel. We can see that the total fairness index of priority class 3 of LBT Cat 4 with Wi-Fi is 75.4% where it fairness index for 100 run is found to be 76.9% as shown in the Figure: 5.2. Likewise from table 5.2 we can see that maximum fairness index is 82.5% and minimum 73.5 %.

q Value	8	10	12	14	16
Priority Class 3	78	73	78	78	80
WiFi	22	27	22	22	20
F Index	0.761	0.825	0.761	0.761	0.735
Average Over 100 Competitions					0.769
Average Over 100 runs					0.754

Table 5.2: Listen Before Talk Priority Class.

5.3 Scenario 3-LBT Cat 4 Priority Class 2 coexistence with Wi-Fi

The LBE Cat 4 Priority Class 2 as well as Wi-Fi User Equipments are competing to access the Channel with One User Each in this Scenario 3. Where we have variable q value running from 16 to 64 which generate different random backoff CW size for priority class 2 under LBT cat4. Thought-out the Scenario 3 we will use 6 to 8 ms of COT for LBT Cat 4 priority class 2. We have plotted three graph where overall fairness index (F) for 100 run is given by figure: 5.3 (a) and fairness index for 100 time competition with LBT Cat 4 priority class 2 and Wi-Fi is given by figure: 5.3 (b). Figure: 5.3 (c) will show how many times the LBT Cat 4 priority class 2 and Wi-Fi have access the channel when they are competing for 100 time to access the channel.

We can see that the total fairness index of priority class 4 of LBT Cat 4 with Wi-Fi is 54.2% whereas its fairness index for 100 runs is found to be 54.6% as shown in Figure: 5.3. Similarly from table 5.3 we can see that maximum fairness index is

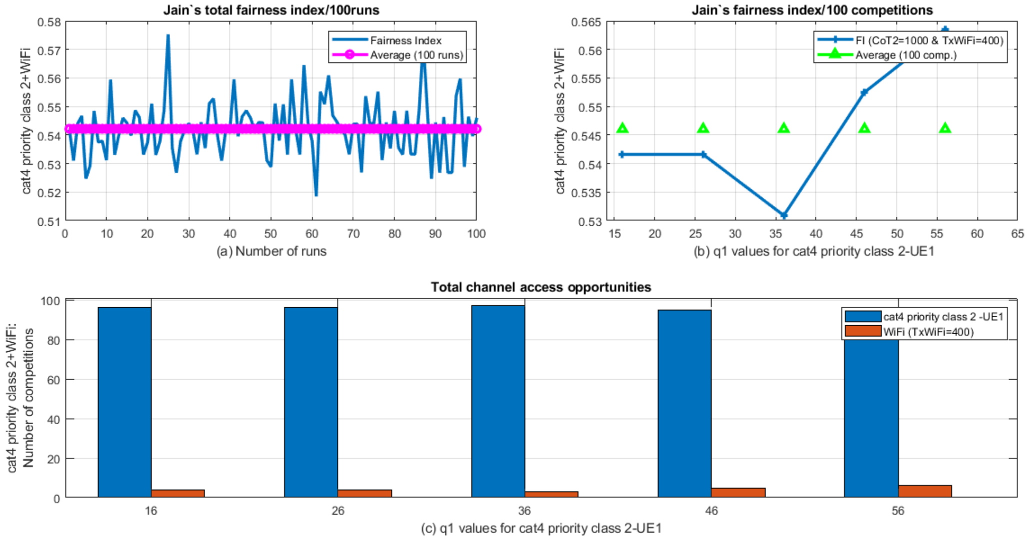


Figure 5.3: Graph showing Jain's Fairness Index priority class 2.

56.4% and minimum 53.1 %.

q Value	16	26	36	46	56
Priority Class 2	96	96	97	95	94
WiFi	4	4	3	5	6
F Index	0.542	0.542	0.531	0.552	0.564
Average Over 100 Competitions					0.546
Average Over 100 runs					0.542

Table 5.3: Simulation outcome for LBT Cat 4 priority class 2.

5.4 Scenario 4-LBT Cat 4 Priority Class 1 coexistence with Wi-Fi

In this scenario 4 we will see probability that how fairly the LBE cat 4 priority class 3 as well as Wi-Fi user equipment's are competing to access for channel with one user each. Where we have variable q value running from 16 to 1024 which generate different random backoff CW size for priority class 1 under LBT cat4.

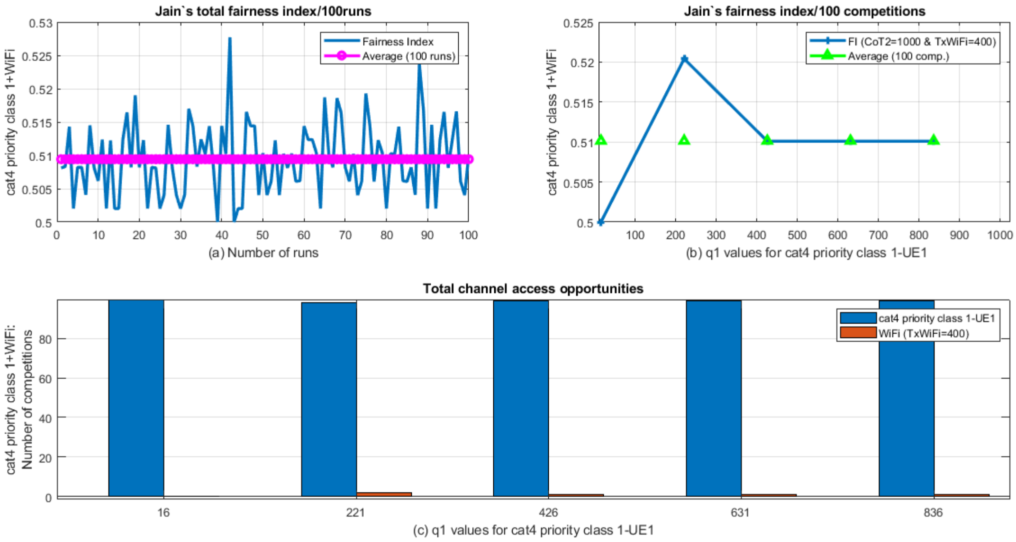


Figure 5.4: Graph showing Jain's Fairness Index priority class 1.

Thought-out Scenario 4 we will use 6 to 8 ms of COT for LBT Cat 4 priority class 1. We have plotted three graphs where the overall fairness index (F) for 100 runs is given in figure: 5.4 (a) and the fairness index for 100-time competition with LBT Cat 4 priority class 1 and Wi-Fi is given in figure: 5.4 (b). Figure: 5.4 (c) will show how many times the LBT Cat 4 priority class 1 and Wi-Fi have access to the channel when they are competing for 100 times to access the channel. We can see that the total fairness index of priority class 4 of LBT Cat 4 with Wi-Fi is 50.9% whereas its fairness index for 100 runs is found to be 51% as shown in figure: 5.4. Similarly, from table 5.4 we can see that maximum fairness index is 52% and minimum 50 %.

q Value	16	221	426	631	816
Priority Class 1	100	98	99	99	99
WiFi	0	2	1	1	1
F Index	0.5	0.52	0.51	0.51	0.51
Average Over 100 Competitions					0.51
Average Over 100 runs					0.509

Table 5.4: Simulation outcome for LBT Cat 4 priority class 1.

5.5 Validating the LBT Cat4 model using machine Learning Approach

The 95 percent confidence interval has been examined for the average fairness index over 100 runs and the fairness index for LBT Cat4 and Wi-Fi competing for a channel. This helps us to understand the probability that the same experiment carried out with each priority class will have the same value between the upper and lower bound at a 95% confidence interval. Then the measure of discrimination has been plotted to see the probability of positive and false signals being detected.

5.5.1 Confident Interval of each priority class

The average fairness index over 100 runs for each priority class is examined here closely examine with a machine approach with the set of data generated by the LBT Cat4 model developed in Matlab.

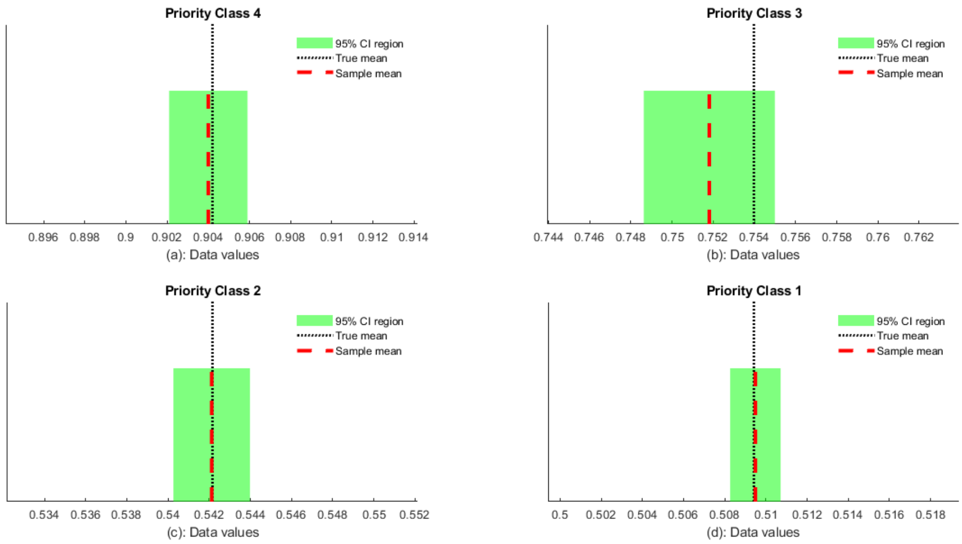


Figure 5.5: 100 Run's Confident Interval for LBT Cat4 Priority Class.

We have also calculated the mean of the data that have been generated by the LBT Cat4 model called true mean and then we have also calculated the sample mean of a set of sample data generated with replacement. Priority class 4 will have a fairness index of over 100 runs within the 90.2 % to 90.6% with a 95% confidence interval shown in figure 5.5(a). Thus this result shows that the probability of competing to access a channel for LBT Cat 4 priority class 4 users for 100 runs lies within 90.2 % to 90.6% as shown in table 5.1. We see the channels fairness in the range of 74.8% to 75.5% with a 95% confidence interval shown in figure 5.5(b) for the priority class3 over 100 runs. As a consequence, the probability of an LBT Cat4 priority class 3 user competing for access to a channel for 100 runs ranges from 74.8% to 75.5%, as shown in Table 5.2. The priority class 2 will have a fairness index over 100 runs for it's to compete with the channels within the 54% to 54.4% with a 95% confidence interval shown in figure 5.5 (c). Thus this result shows that the probability of competing to access a channel for LBT Cat4 priority class 2 users for 100 runs lies within 54% to 54.4% as shown in table 5.3. Priority class 1 will compete with channels within the range of 50.8% to 51.1%, as shown in figure 5.6(d) for a fairness score of over 100 runs. This finding demonstrates that for 100 runs, LBT Cat4 priority class1 users have a 50.8% to 51.1% chance of competing for entry to a channel, as shown in Table 5.4. We have seen for all set of data for the priority class has true mean and sample mean together and the true mean is within the confidence interval.

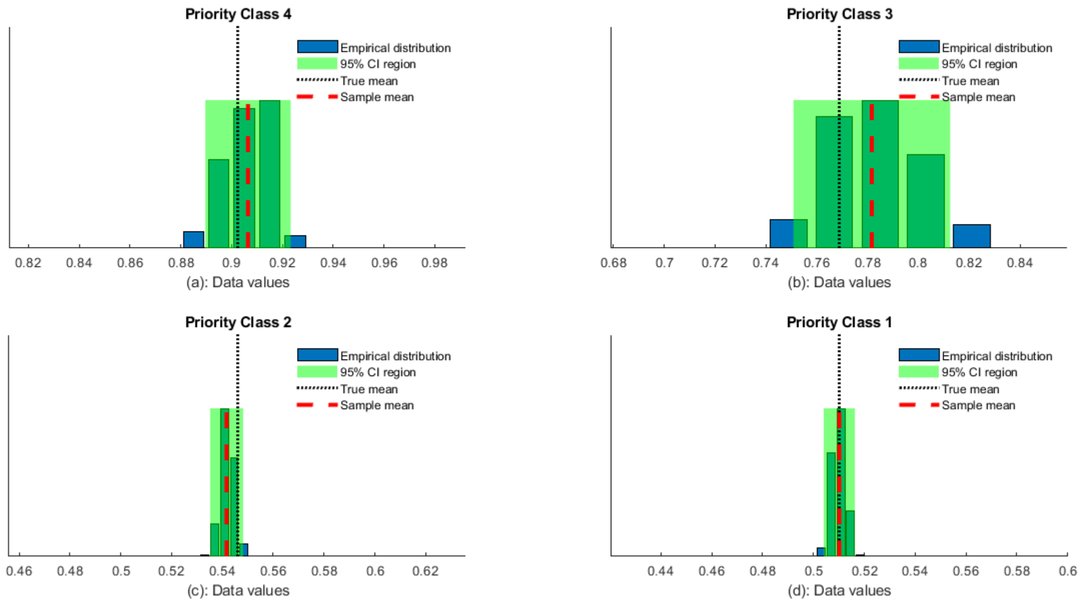


Figure 5.6: Jain's Fairness Index confident interval for priority class.

The set fairness index between LBT Cat4 and Wi-Fi has been generated using the LBT Cat4 model designed in Matlab and we want to see much validity by analyzing this data using a machine learning approach. The machine learning approach is used to calculate the 95% confidence interval for this set of fairness indices. We have shown a bar plot to indicate that the data of the sample are mostly falling within the confident interval upper and lower limit. We have also calculated the mean of the data that have been generated by the LBT Cat4 model with selected q values call true mean and then we have also calculated the sample mean of the set of sample data generated with replacement. Priority class 4 has a fair coexistent with Wi-Fi with a fairness index between 88.9% and 92.3% with a 95% confidence interval as shown in figure 5.6(a). Thus we can say that probability that the fairness index between LBT Cat4 priority class 4 and Wi-Fi will be 88.9% and 92.3% for the experiment done by using the LBT Cat4 model. As shown in figure 5.6 (b), priority class 3 has fair coexistence with Wi-Fi, with a fairness score between 75% and 81.2% with a 95% confidence interval. Thus, for the experiment carried out using the LBT Cat4 model, we can state that there is a chance that the fairness index between the LBT Cat4 priority class3 and Wi-Fi will range from 75% to 81.2%.

The priority class2 has a fair coexistent with Wi-Fi with a fairness index between

53.5% and 54.8 % with a 95% confidence interval as shown in figure 5.6 (c). Thus we can say that probability that the fairness index between LBT Cat4 priority class2 and Wi-Fi will be 53.5% to 54.8 % for the experiment done by using the LBT Cat4 model. As shown in figure 5.6 (d), priority class 1 has a fair coexistence with Wi-Fi, with a fairness score between 50.4% and 51.6% with a 95% confidence interval. Therefore, for the data measurement carried out using the LBT Cat4 model, it is probable that the fairness index between the LBT Cat4 priority class1 and Wi-Fi will be between 50.4% and 51.6%. We have seen that the bar plot is having lots of data inside a 95% confidence interval mostly around the mean. We have seen for all set of data for the priority class has true mean and sample mean together and the true mean is within the confidence interval.

5.6 Testing and Training Fairness Data using Linearization.

The set of training and testing data is created using the Total fairness data generated from each priority class of LBT Cat4's algorithm. The set of training data is shown in the Figure : 5.7, 5.8, 5.9 and 5.10 with x symbol and the set of testing data is shown with o symbol. Where red line and black line represent the line of best fit for linearization within the errors respectively. We can see that the system can be easily linearized for all priority class of LBT Cat4 easily since the line of best fit converge after few number of sample iterations.

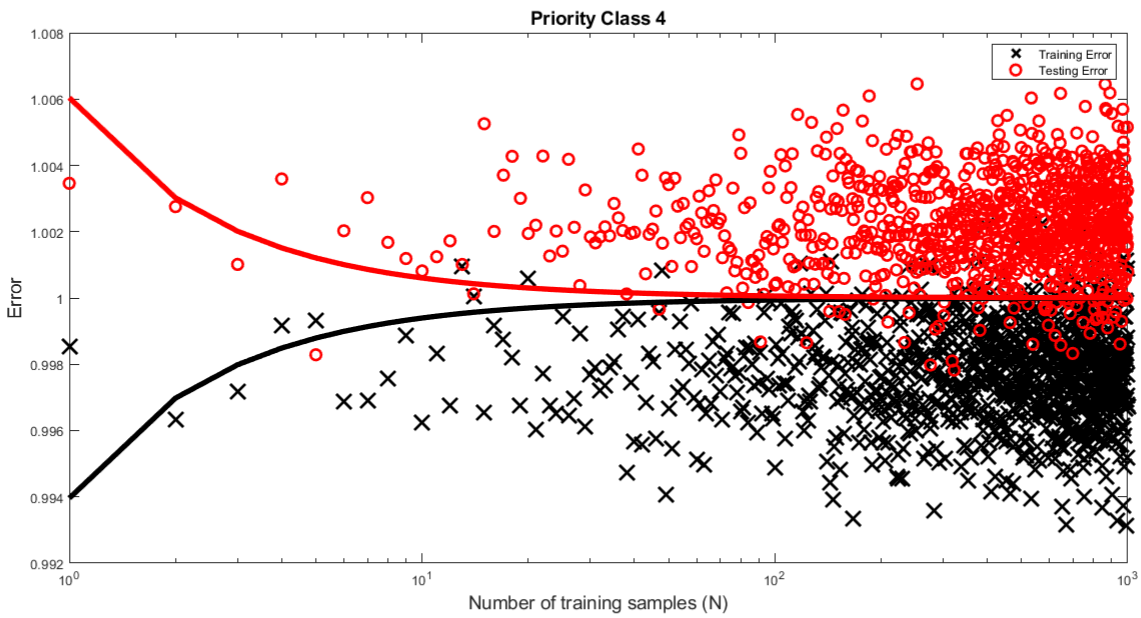


Figure 5.7: Linearization for Priority Class 4

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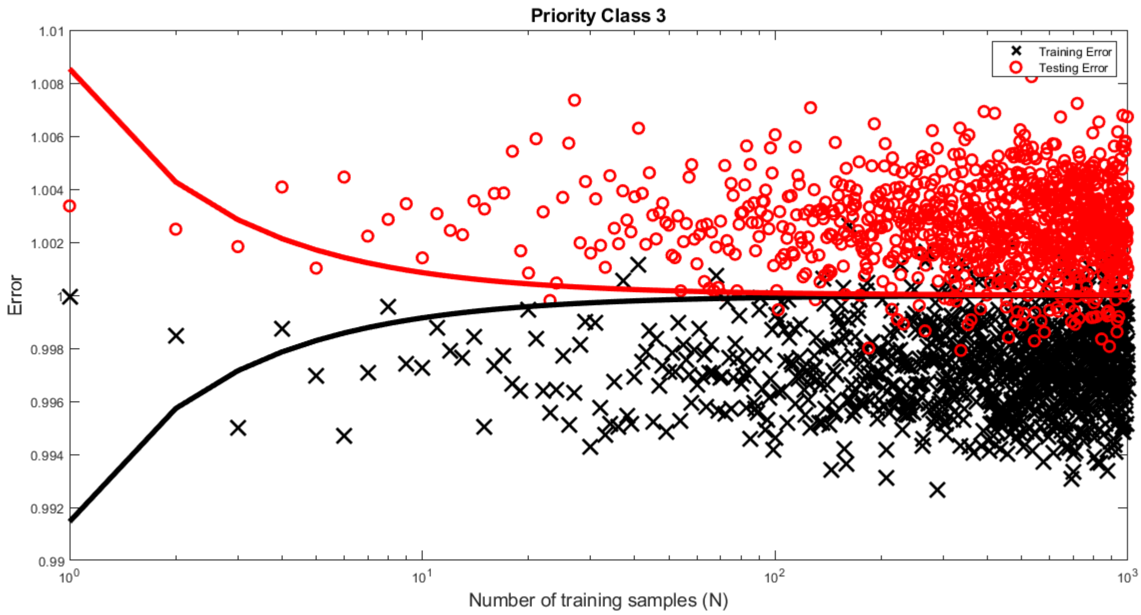

Figure 5.8: Linearization for Priority Class 3

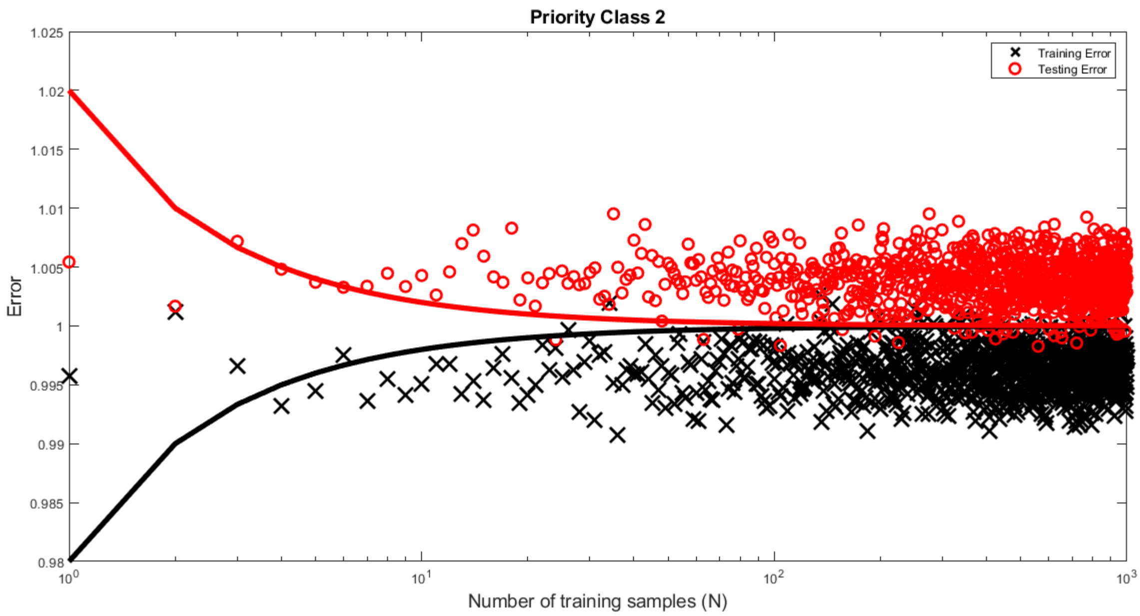

Figure 5.9: Linearization for Priority Class 2

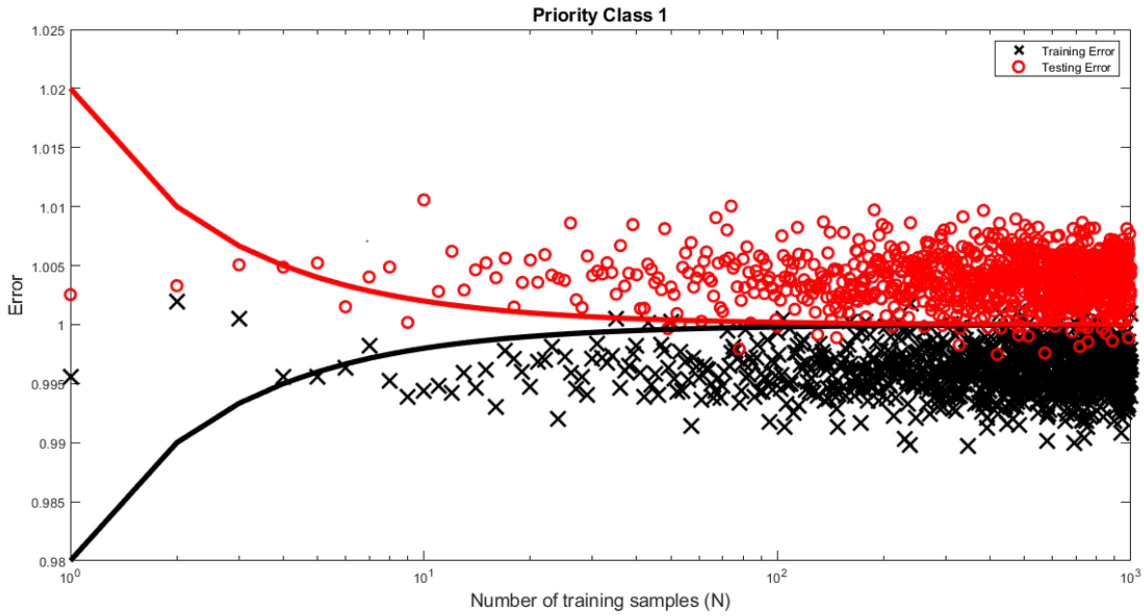

Figure 5.10: Linearization for Priority Class 1

5.7 Testing and Training Fairness Data using Neural Networks.

The total fairness data is train for each priority class of LBT Cat4 for the reliability and applicability of neural networks for communication model. The train set of data and their best line is shown in the Figure : 5.11, 5.12 , 5.13 and 5.14 in green line and dash line respectively. For each priority class of LBT cat4 the train line data and and best line data are converging easily since the system was applicable and reliable for communication. We can see that for priority class 4 the system perfectly train at 21 Epochs and for priority class 3 at 21 Epochs. Similarly for both priority class 2 and priority class 1 system train perfectly at 100 Epochs. This shows that the priority class 4 give the best performance among all the priority class of LBT cat 4.

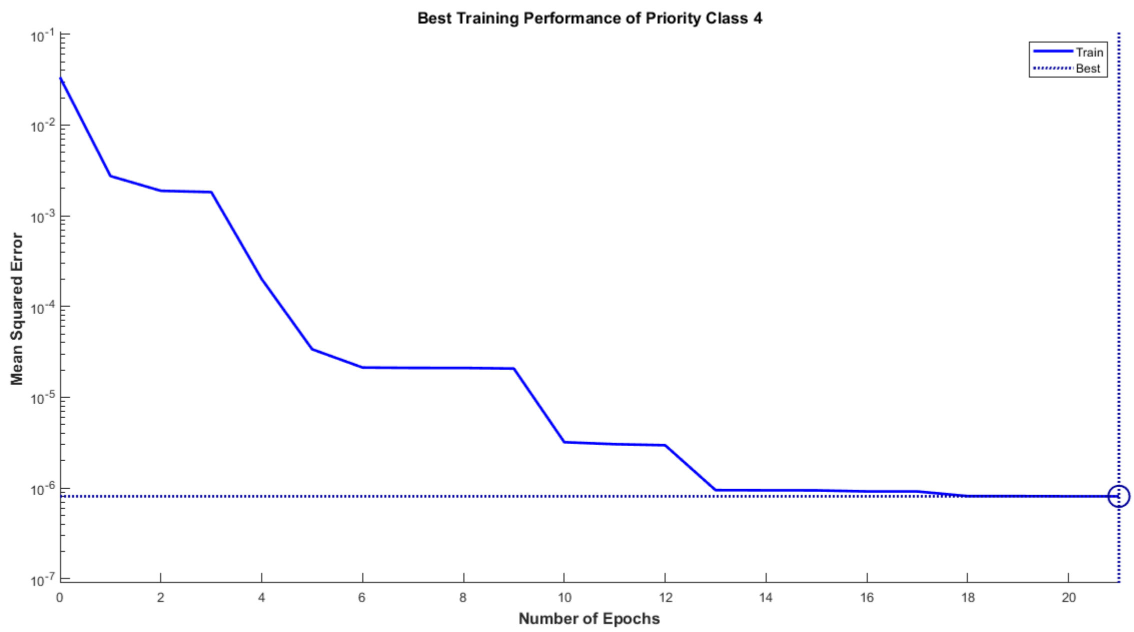

Figure 5.11: Mean Square Error for Priority Class 4

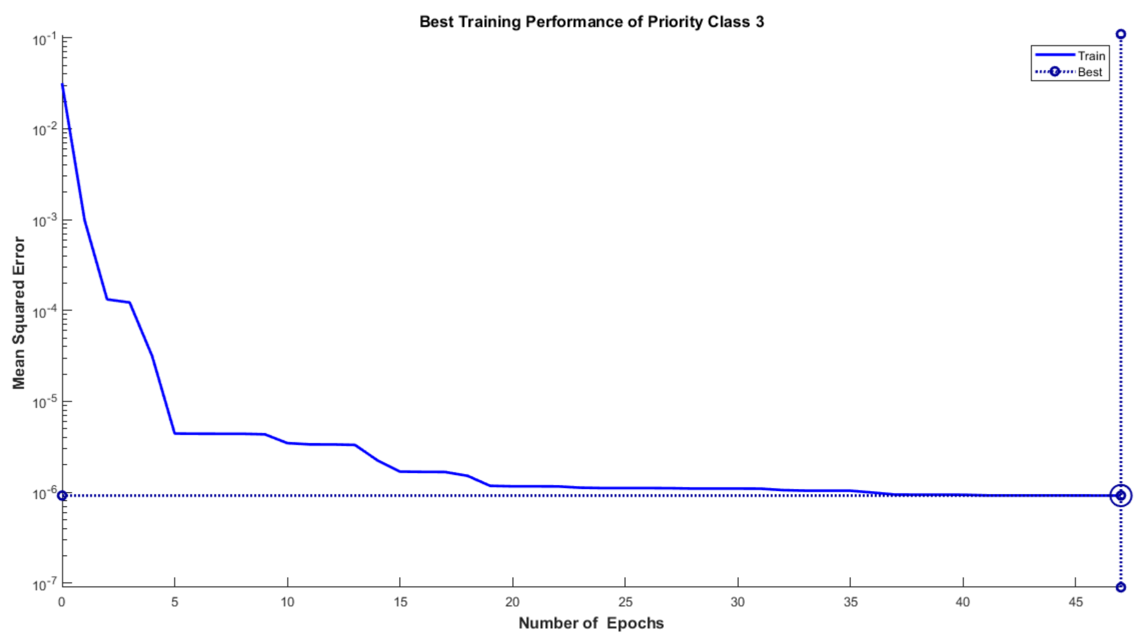

Figure 5.12: Mean Square Error for Priority Class 3

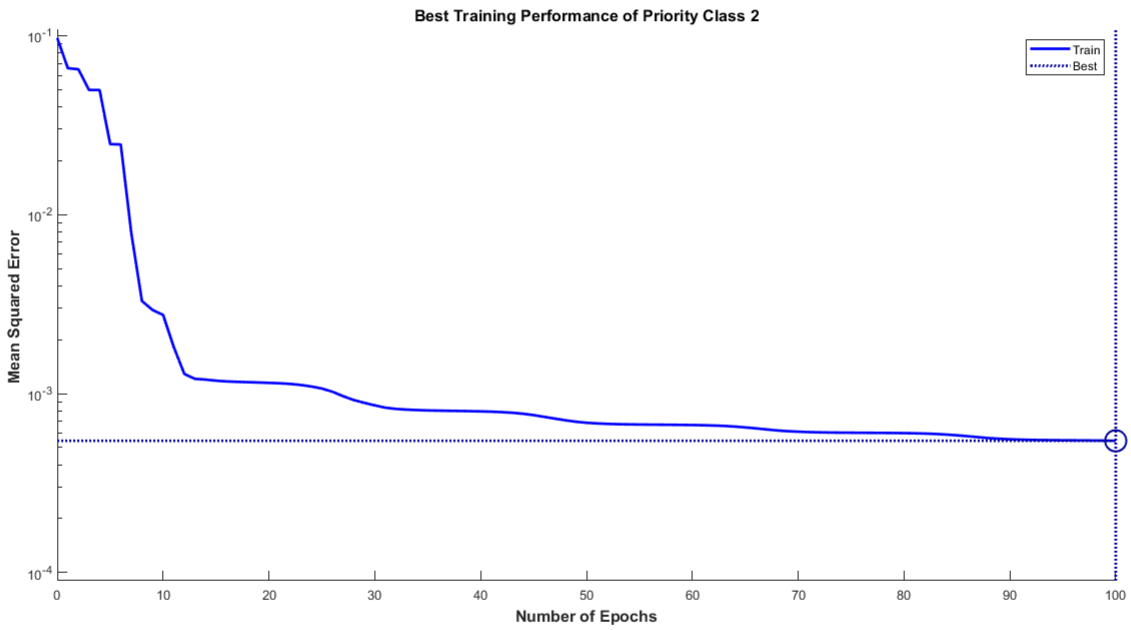

Figure 5.13: Mean Square Error for Priority Class 2

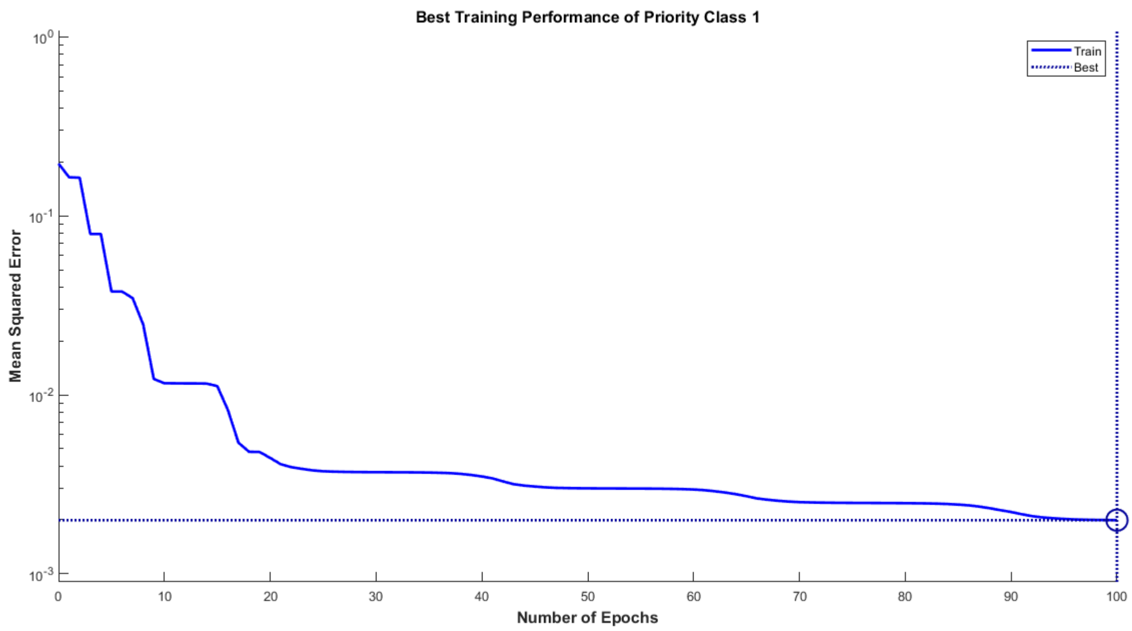

Figure 5.14: Mean Square Error for Priority Class 1

5.7.1 Receiver Operating Characteristic Curve using Machine Learning approached

The measure of discrimination have been evaluated for each priority class to know the reliability and applicability to the world of the each priority class of LBT cat 4.The curve plots the probability of detection (PD) against the number of training sample is given for all the priority class of LBT Cat4. For all the priority class we have seen that the as the number of training sample increases then the probability of detection also increased which is shown in Figure : 5.18, 5.17,5.16 and 5.15. Here we can see that the probability of detection is better for priority class 4 of LBT Cat4 as you can see in the plot.

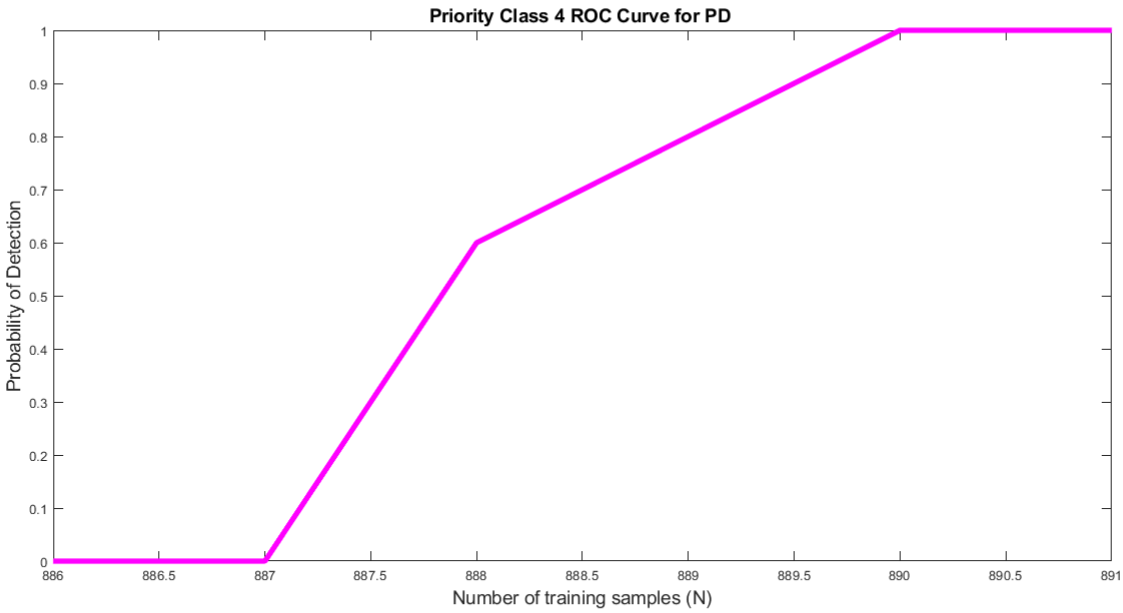

Figure 5.15: Probability of Detection for Priority Class 4

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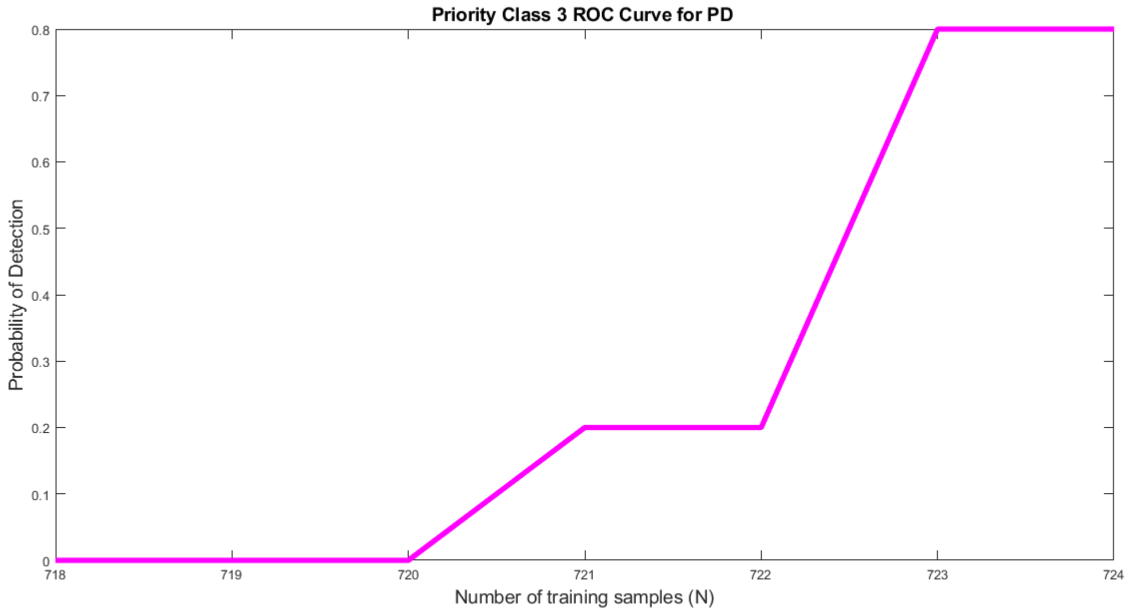

Figure 5.16: Probability of Detection for Priority Class 3

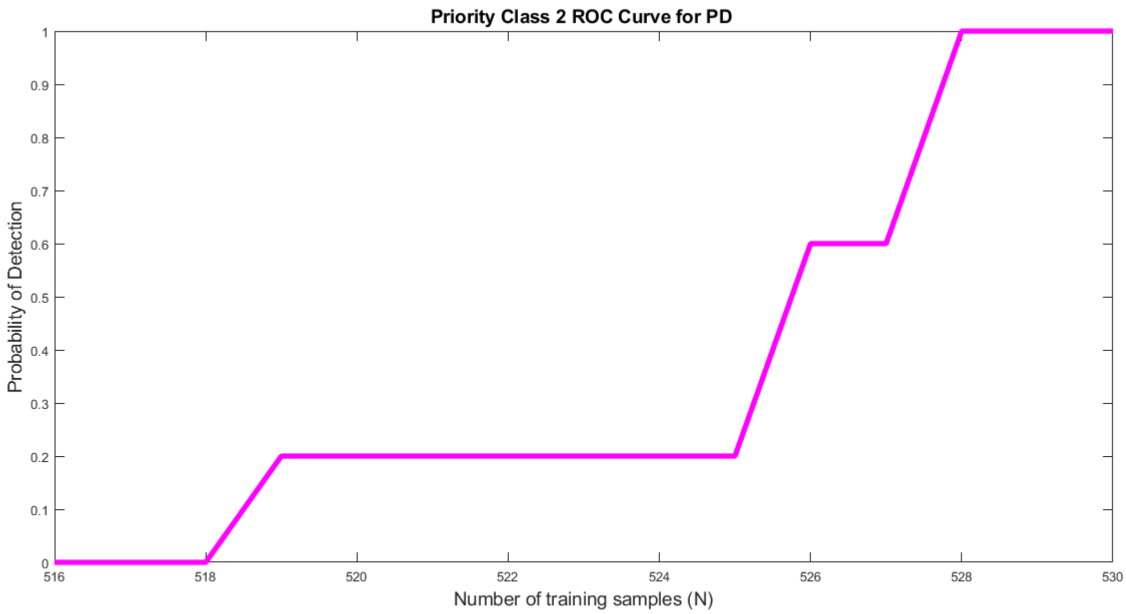

Figure 5.17: Probability of Detection for Priority Class 2

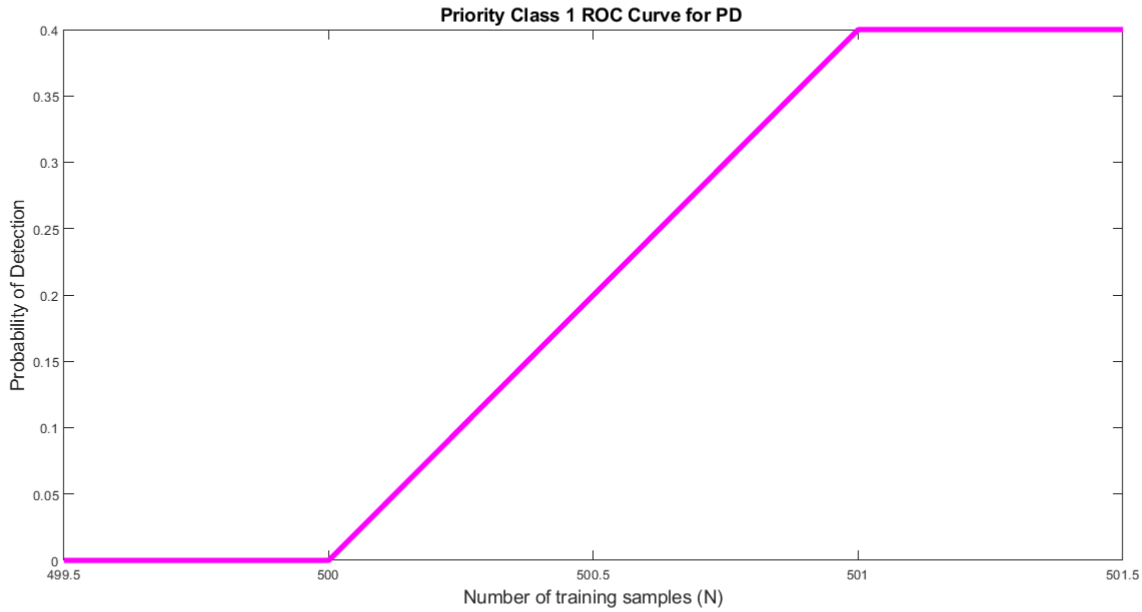

Figure 5.18: Probability of Detection for Priority Class 1

5.8 Result

As far as the 3GPP specification of the LBT Cat 4 priority classes studies theoretically we know that the LBT Cat 4 priority class 4 will have maximum coexistence with Wi-Fi. We can see the performance of the priority class in order as priority class 4 > priority class 3 > priority class 2 > priority class 1. Thus we can see that priority class 4 gives the best performance and priority class 1 gives a worse performance. From the result that we obtain, we can see that the LBT Cat 4 have a maximum coexistence performance of 90.4% whereas in the worst case, LBT Cat4 priority class 1 gives a minimum coexistence performance of 50.9%. Similarly applying machine learning approaches as far as the probability of positive signal detection also we can see that the priority class 4 > priority class 3 > priority class 2 > priority class 1. Then we also have seen that the probability of having similar data at a 95% confidence interval also verifies to us this model will have those fairness indexes for implementation of the LBT Cat4 priority class.

Chapter 6

Conclusion and Future Work

6.1 Application of LBT Cat4

Listen Before Talk (LBT) Cat4 is a mechanism designed for wireless communication networks to provide efficient and reliable communication. So LBT Cat4 protocol can be used in many different applications, ranging from consumer electronics to industrial automation and beyond, which can be seen now and in future [93]. The LBT Cat4 is a wireless communication protocol that is expected to have a wide range of applications due to its fairness and energy efficiency [94]. Here are some potential applications of LBT Cat4:

- Internet of Things (IoT): IoT is an ecosystem of connected devices that interact with each other to collect and exchange data. LBT Cat4 can be used in IoT applications to ensure reliable and efficient communication among IoT devices. The mechanism's efficient use of the wireless channel allows for increased throughput and reduced interference, which is essential for IoT devices that require low power and long battery life.

- Wireless Sensor Networks (WSNs): WSNs are used for collecting data from various environments such as industrial, agricultural, and environmental monitoring. In WSNs, LBT Cat4 can be used to ensure reliable communication and reduce interference among nodes. The mechanism's improved fairness and coexistence with other wireless networks make it ideal for WSNs.

- Industrial Automation: LBT Cat4 is also used in industrial automation applications, such as process control, monitoring and data acquisition. In these applications, wireless sensors and actuators are used to monitor and control various aspects of the production process, and LBT Cat4 helps to ensure reliable and efficient communication between these devices [95].

- Vehicle-to-Vehicle (V2V) Communication: V2V communication is a technology that allows vehicles to communicate with each other to avoid collisions and improve traffic flow. In V2V communication, LBT Cat4 can be used to ensure efficient and reliable communication among vehicles. The mechanism's improved reliability and fairness make it ideal for V2V communication, which requires fast and accurate communication among vehicles.

- Wireless Body Area Networks (WBANs): WBANs are used for collecting data from sensors attached to the human body for medical and healthcare purposes. In WBANs, LBT Cat4 can be used to ensure reliable communication among sensors and reduce interference. The mechanism's efficient use of the wireless channel and improved reliability make it ideal for WBANs.

- Telecommunications: LBT Cat4 is used in telecommunications networks to enable wireless communication between mobile devices and base stations. By using LBT Cat4, mobile devices can access the wireless channel more efficiently, which helps to improve the overall performance and reliability of the network.

- 5G Networks: As 5G networks continue to be rolled out around the world, LBT Cat4 is expected to play a key role in enabling efficient and reliable communication between devices on these networks. By using LBT Cat4, 5G devices can access the wireless channel more efficiently, which helps to improve the overall performance and reliability of the network [96], [97].

- Smart Cities: LBT Cat4 can be used in smart city applications to ensure reliable communication among various sensors and devices. Smart city applications include traffic management, environmental monitoring, and public safety. LBT Cat4 can ensure efficient communication and reduce interference among devices to improve the accuracy and effectiveness of these applications.

- Autonomous Vehicles: Autonomous vehicles are becoming increasingly common, and LBT Cat4 is expected to be used to enable communication between these vehicles and their surrounding environment. By using LBT Cat4, autonomous vehicles can communicate with other vehicles, traffic lights, and other infrastructure in a reliable and efficient way, which helps to improve safety and efficiency on the road.

- Healthcare: LBT Cat4 is expected to be used in healthcare applications to enable wireless communication between medical devices, such as wearable health monitors and remote patient monitoring systems. By using LBT Cat4, these devices can access the wireless channel fairly and efficiently, which helps to ensure reliable and timely communication between healthcare providers and their patients.

- Augmented Reality/Virtual Reality (AR/VR): AR/VR applications require high bandwidth and low latency communication to provide an immersive experience. LBT Cat4 can be used to ensure efficient and reliable communication among AR/VR devices to improve the quality of the experience.

Overall, LBT Cat4 is a versatile technology that is expected to play a key role in many future applications, ranging from wireless communication networks, including 5G networks, smart cities, Industry Automation, and AR/VR and so on as mention above [98]. Its efficient use of the wireless channel, improved fairness, coexistence with other wireless networks, and reliability make it a useful mechanism for various wireless communication applications. As wireless communication continues to become more important in our daily lives, LBT Cat4 is expected to become an increasingly important technology for enabling efficient and reliable wireless communication. As wireless communication continues to play an increasingly important role in our daily lives, LBT Cat4 is expected to become even more widespread and important in the years to come [99].

6.2 Conclusion

The research of unlicensed spectrum is currently avoidable because the use of licensed spectrum has grown so costly and exhausting. In this research, we have examined the significance of employing an unlicensed spectrum for LTE-U and Wi-Fi coexistence in the 5GHz and unlicensed spectral band in general. We have explained in brief the usage and significance of the current Wi-Fi and LTE-U in cellular communication systems. The requirement for the LBT method for the coexistence of LTE-U and Wi-Fi in the unlicensed band has been emphasized, as well as the existing study of coexistence mechanisms that have been addressed so far anyway. The LBT mechanism has been thoroughly examined with respect to its various categories, looking at how each LBT category functions.

Recently, researchers have become interested in studying the unlicensed spectrum due to the saturation of the licensed spectrum, which cannot support further increases in data rate and channel capacity. One area of interest is the coexistence of LTE-U and Wi-Fi in this spectrum, with various coexistence mechanisms proposed, including ABS, CSAT, and LBT. In this paper, we examine the LTE-U standard and existing Wi-Fi, as well as the current state of research on LTE-U-Wi-Fi coexistence in the unlicensed spectrum. We focus on the LBT mechanism, which 3GPP has designated as the coexistence mechanism for LTE-U and Wi-Fi. We specifically look at LBT Cat 4, which has been identified as the best coexistence mechanism for Wi-Fi in the unlicensed spectrum. We implemented LBT Cat 4 and Wi-Fi with each priority class in Matlab and estimated the Jains Fairness Index (F) for each priority class of LBT Cat 4. Our results show that priority class 4 of LBT Cat 4 is the optimal coexistence mechanism for Wi-Fi in the unlicensed frequency band, with the highest Jains Fairness Index. We also used a machine learning approach to determine that the probability of signal detection is highest for priority class 4. This study provides insights into the implementation of LBT mechanisms with different categories of LBT and offers researchers a clear understanding of LBT for further research.

6.3 Future Work

Unlicensed spectrum research is now crucial for the implementation of cellular networks with increased capacity and data rates. In this paper, we examined the particular coexistence research done thus far for LTE-U and Wi-Fi coexistence, which provides us with a general understanding of what are the coexistence mechanisms and how they are implemented, enabling us to further explore coexistence mechanisms in the future. We now have a better understanding of how LBT and its categories are used in modern cellular communication networks, as well as what areas of research we can be addressed in LBT in the future.

The deep learning can be used to analyze these factors and make more accurate predictions about the availability of the channel [100], [101]. For example, a deep learning model can be trained on data from sensors that monitor the wireless channel and predict the probability of a collision based on various environmental factors. The model can then adjust the LBT protocol accordingly, such as increasing the listening time when the probability of a collision is high. Moreover deep learning can also be used to optimize the performance of LBT by dynamically adjusting its parameters based on the network conditions. For example, a deep reinforcement learning algorithm can be used to learn the optimal listening time and transmit power based on the current network conditions, such as the number of devices and the amount of traffic.

This study will assist us in exploring in greater detail the method that has been employed to enable LTE-U and Wi-Fi coexistence utilizing LBT, specifically for LBT Cat 4, as well as investigating which priority class of LBT Cat 4 will be used most frequently in the future. We can further study cognitive radio for LBT as in [102] and [103]. We have implemented one user for Wi-Fi and LBT Cat4 priority class each, thus in the feature, we can implement multiple uses to calculate the Jain fairness index (F) and total fairness of the system. We can use more machine learning approaches to make our model more reliable and feasible for implementation.

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