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Directional spectrum sensing in 6 GHz

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Contents

List of acronyms

AWGN:	Additive white Gaussian noise
CCA:	Clear Channel Assesment
CSMA/CA:	Carrier Sense Multiple Access with Collision Avoidance
COT:	Channel Occupancy Time
Dir-LBT:	Directional listen before talk
DOA :	Direction of Arrival
ED:	Energy Detection
gNB:	Generation Node B
HARQ:	Hybrid Automatic Repeat Request-Acknowledgment
LBR:	Listen-Before-Receive
LBT:	Listen Before Talk
LTE:	Long Term Evolution
mm-Wave:	Millimeter Wave
NACK:	Negative Acknowledgment
NR:	New Radio
NR-U:	New Radio Unlicensed
Omni-LBT:	Omnidirectional listen before talk
QoS:	Quality of Service
RAT:	Radio Access Technology
SNR :	Signal to Noise ratio
STA:	Station
UE:	User Equipment
ULA:	Uniform Linear Array
Wi-Fi :	Wireless Fidelity

List of symbols

T :	Duration of a time frame
T_s :	Total time taken to sense beams in multiple directions
τ :	Constant sensing period along a particular direction
T_p :	Time taken to send pilot symbols in directions found to be idle
T_d :	Time taken for data transmission towards the best user
ϕ :	Beamwidth
θ :	The angle of misalignment
$G_{ml}(\theta^g)$:	Main lobe gain of gNB
$G_{ml}(\theta^u)$:	Main lobe gain of UE
P_{AP}:	Power of AP
P_g:	Power of gNB
$\hat{Q}$:	Set of beams required to be sensed in our proposed algorithm
$\hat{Q}_b$:	Set of beams required to be sensed under Baseline algorithm
σ_u^2 :	AWGN noise squared
P_{rx} :	Received power of WiFi-AP at gNB
P_r :	Received power of UE at gNB
$\hat{P}_r$:	Received power of WiFi-AP at gNB after beamwidth adaptation
count_{clk} :	number of users sensed before beam adaptation in clockwise
count_{anti} :	number of users after beam adaptation in anticlockwise
L :	Path loss
α:	Path loss exponent
$P_f(\tau)$:	False alarm probability
$P_d(\tau)$:	True detection probability
P_{rcvd} :	Received power of the pilot symbols during beam training
S_{UE} :	SNR at the intended receiver
P_p :	Interference at UE due to WiFi-AP
δ_0 :	Channel capacity when WiFi-AP is found to be idle
δ_1 :	Channel capacity when WiFi-AP is found to be busy
$P\bar{d}$:	target detection probability
ξ :	Decision threshold
β :	Spectrum sensing result
μ :	Is_in_Range result

Preface

First of all, I would like to thank my daily supervisor, Suzan Bayhan, for guiding me in finishing the thesis project and understanding me during difficult times. Your comments throughout this project were insightful and helped me see the project from angles I had yet to consider. Without her, this thesis would have not been possible.
I would also like to express my heartfelt thanks to Geert Heijenk and Alessandro Chiumento for their extended support and motivation during the thesis and their input and constructive criticism, both of which have improved my work drastically.
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Abstract

The growing demand for unlicensed spectrum has prompted policymakers to allow unlicensed access in the 6 GHz bands. Various Radio Access Technologies (RATs) such as WiFi and rapidly emerging 5G networks can operate in the unlicensed spectrum. To coexist harmoniously with each other, RATs must implement coexistence mechanisms such as Listen Before Talk (LBT). Omnidirectional-LBT (Omni-LBT) and Directional-LBT (Dir-LBT) are two LBT sensing techniques. Omni-LBT might fall short of identifying spectrum holes when the transmission is directional, while spatial reuse of the spectrum can be exploited using Dir-LBT. To find these spatial spectrum holes, more time is spent which leaves behind less time for data transmission. On the other hand, if less time is spent on sensing, sensing accuracy is affected. Therefore, using Dir-LBT might lead to a sensing-capacity trade-off. This thesis extensively investigates the trade-off between Omni-LBT/Dir-LBT. The sensing accuracy is calculated by formulating closed-form equations for the detection probability and false alarm probability. On plotting the closed-form equations, we conclude that Omni-LBT has a higher false alarm probability than Dir-LBT. As a result, the possibility to reuse the spectrum decreases, resulting in lower throughput and sensing accuracy than Dir-LBT. However, using Dir-LBT might lead to high sensing overhead. Therefore, it is essential to spend less time on sensing without hampering sensing accuracy. Towards this, we design a heuristic algorithm to reduce the sensing time of Generation Node-B (gNB). Finally, for the proposed heuristic algorithm, throughput of gNB and Wireless Fidelity (WiFi-AP) were calculated and compared with Omni-LBT and our baseline algorithm. Our simulations show that Dir-LBT outperforms Omni-LBT in terms of throughput.

Chapter 1

Introduction

The enormous increase of wireless data traffic in recent decades has resulted in spectrum scarcity. The unlicensed bandwidth in the 6 GHz bands appears promising for meeting this increase in demand. Therefore, research and development of methods that make use of the spectrum available in the 6 GHz bands are encouraged.

In general, fixed spectrum resources are allocated to specific licensed wireless users under the rigorous spectrum regulation policy, and unlicensed users are prohibited from accessing these licensed frequency bands. There are, however, numerous underused spectral resources in frequency, time, and space, which are referred to as spectrum holes. Therefore, if we can find these spectrum holes, unlicensed users will be able to utilize them. As a result, by allowing unlicensed users to utilize a spectrum hole that is unoccupied by licensed users at the correct location and at the right time, spectrum utilization can be significantly improved. This is referred to as opportunistic spectrum approach [1].

As 6 GHz (5925 MHz - 6425 MHz in Europe) is an unlicensed band, there are no licensed users present. Unlicensed users can utilize the spectrum with other unlicensed users available and have opportunities to transmit towards their users without any interference. The unoccupied spectrum is discovered using the spectrum sensing approach, which is a critical function in determining whether the spectrum is idle or not. Unlicensed users are subsequently assigned to the detected white spaces. Spectrum sensing should be performed in order to efficiently detect the activity of other user systems without producing significant interference. This is the scenario being investigated in this thesis.

Now, let us consider the coexistence of Wireless-Fidelity (WiFi-AP) and Generation Node-B (gNB) in the unlicensed band. The coexistence of WiFi-AP and gNB is depicted in Fig.1.1. Interference is caused in the direction of the jth User Equipment represented as UE$_j$ as WiFi-AP transmits along the same direction towards its user (Station) STA$_0$. This is undesirable and does affect the overall efficiency of the system. However when sensing along the direction of kth UE represented as UE$_k$, no interference is observed as WiFi-AP transmits in an alternate direction. Therefore sensing towards UE$_k$ is more favorable. Using spectrum sensing, the undesirable inter-

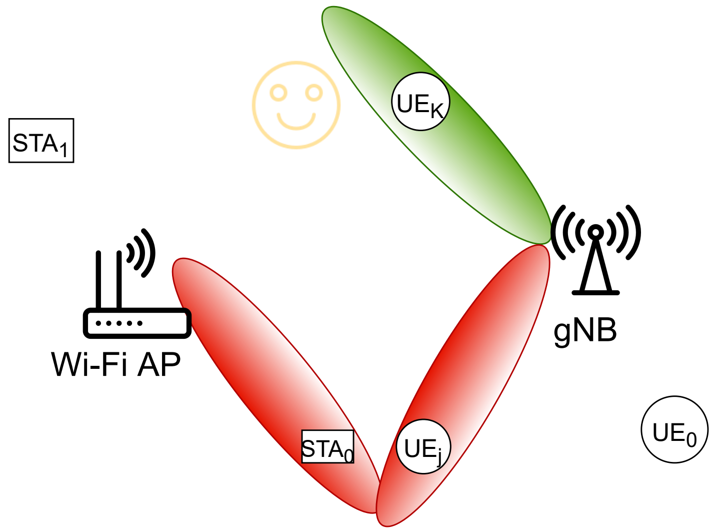

Figure 1.1: Coexistence of WiFi-AP and gNB. Interference occurs at the receivers, when both WiFi-AP and gNB transmit data along the same direction towards their respective users.

ference can be determined and a decision to transmit is examined.

If along any of the directions an interference is identified, the sensing node will either modify its antenna configuration to reduce interference and account for channel effects, or it will move to a new unoccupied channel. However, the gNB does not always provide perfect sensing results; for example, the gNB may decide that the direction is occupied by a WiFi-AP when it is free (false alarm), or that the spectrum is free when a WiFi-AP is present in the detected channel (misdetection). Many factors, such as fading and the receiver uncertainty problem, may play a significant role in the aforementioned issues [2]. Spectrum sensing should be performed in every spectral dimension to detect an unused portion of the spectrum. A frequency may be occupied for some time, but it may be idle at a later time; hence, the temporal and frequency are important dimensions to consider. The idle periods between busy wireless signal transmissions are used for opportunistic throughput.

Sensing time and throughput are two important parameters in spectrum sensing. As sensing time increases, the detection probability is improved but might lead to lower achievable throughput due to less remaining time for data transmission. On the other hand, when less time is spent on sensing, the expected achievable throughput will be high as more time is left behind for data transmission [3]. We are interested in maximizing gNB's throughput while adequately protecting WiFi users.

The existing works mostly consider the 60 GHz band (mm-Wave) for spectrum sensing. The downside of spectrum sensing in mm-Wave frequencies includes high propagation losses and sensitivity to blockage [4]. However, the devices operating on the 6 GHz range can attain peak data rates while avoiding the difficulties experienced in mm-Wave frequencies [4]. Dir-LBT is a spectrum sensing technique where sensing is performed directionally towards the target receiver [2]. Moreover, the use of beamforming and Dir-LBT in 6 GHz presents us with an opportunity to share the spectrum efficiently. In addition, prior works such as consider omnidirectional antennas for spectrum sensing [5]. These cannot determine the orientation (or direction) of the WiFi-AP resulting in harmful interference. However, our research uses a spectrum sensing approach on directional antennas. Directional antennas offer several advantages, including a greater sensing range with the same amount of energy, lower energy consumption with the same detecting range, and fine-grained sensing. Also, the beam index of the detected WiFi-AP is computed allowing for fine-grained detection. Beam index indicates at which beam the detected WiFi-AP is found. Therefore, it would be plausible to avoid undesirable interference in avoiding the beam. The gNB detects the location of WiFi-AP, thereby using the spectrum's geographic information efficiently. Furthermore, the goal of a directional antenna is to detect fine-grained spectrum holes in order to increase spatial reuse. Due to the benefits of directional sensing, we use a directional antenna to detect the spectrum in this study. In addition, this research focuses on maximizing the throughput towards its users by reducing the time taken for sensing. Towards achieving the goal, we investigate the parameters affecting spectrum sensing.
The following are the research questions that will be addressed in this thesis:

- What are the direction(s) in which spectrum sensing should be performed to find spectrum holes? (RQ1)
- To what extent can Dir-LBT be advantageous over Omni-LBT in terms of achieved throughput at gNB and WiFi-AP? (RQ2)
- What are the direction(s) that need to be selected for data transmission after finding out the spectrum holes ? (RQ3)

This thesis takes the following approach to answer the coined research questions. (RQ1) will be answered by formulating a heuristic algorithm that outputs the set of directions on performing energy detection. Next, the benefit of using Dir-LBT over Omni-LBT was analyzed by estimating the achievable throughput under various sensing approaches (RQ2). To find out the directions along which data transmission should take place (RQ3), we perform beam training using pilot symbols to understand the quality of the channel. Signal to Noise Ratio (SNR) is computed along the directions found to be idle and the user with the best channel quality is found. Along the direction of the best user, data transmission takes place after receiving feedback from the intended receiver.

This research contributes to a better understanding of the trade-offs in beam-based transmissions like sensing-throughput and Omni-LBT/Dir-LBT. Moreover, we aim to depict the higher sensing accuracy and throughput achieved on using Dir-LBT. A sub-optimal heuristic algorithm is devised to decrease the time required to sense and, as a result, increasing throughput. A case will be made for beam adaptation used in directional spectrum sensing as a potential approach for reducing the number of beams necessary to sense.

The rest of this thesis is organized as follows. Chapter II introduces the background to the research. In Chapter III, the system model is presented. Chapter IV describes the trade-offs in spectrum sensing. An algorithm to find the directions to sense and antenna configurations required to reduce the time taken for spectrum sensing is studied in Chapter V. Computer simulations are provided in Chapter VI to show the performance of the proposed algorithm in comparison to the proposed baseline and optimal approach. Finally, we draw our conclusions in Chapter VII.

Chapter 2

Background and Related Work

This chapter provides background knowledge that will assist readers comprehend the technical content in the following chapters. An introduction of spectrum sensing techniques is presented, which introduces the thesis's primary research topic. Furthermore, we will give a brief overview of the trade-offs in spectrum sensing, as well as an analysis of several forms of sensing approaches.

In 6 GHz, beamforming is used to send data towards the users. Beamforming is the process of aligning the antenna of the transmitter and receiver towards each other using narrow beams. Using beamforming, the signals are more concentrated towards a certain area, instead of spreading out in all directions as in the case of omni-directional antennas. However, in order to perform beamforming a procedure to detect if the sensed direction is idle or busy needs to be performed. The various kinds of spectrum sensing techniques used are discussed in detail next.

2.1 Listen before talk (LBT)

A spectrum sharing technique in which a device does a Clear Channel Assessment (CCA) check to detect the channel before accessing it is known as LBT [6]. LBT is utilized by LAA, MulteFire, WiFi-AP, and WiGig to adhere to the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. LBT also suffers from hidden node and exposed node problems associated with sensing, transmission, and reception range differences for omnidirectional communications. LBT reduces interference and the possibility of collision with other devices on the same channel. In addition to the advantages of high beamforming gain, the narrower beam benefits from interference avoidance as compared to omnidirectional transmission [7]. However, the high directed beam makes hearing transmissions from other terminals more difficult, making it impossible to avoid collisions.

2.2 LBT for beam-based transmissions

The prior studies such as [4] and [6] have investigated two LBT sensing techniques for gNB: Omni-LBT and Dir-LBT. The Omni-LBT detects omnidirectionally, whereas the Dir-LBT senses directionally within the transmission beam towards the intended receiver. Omni-LBT is overpro-

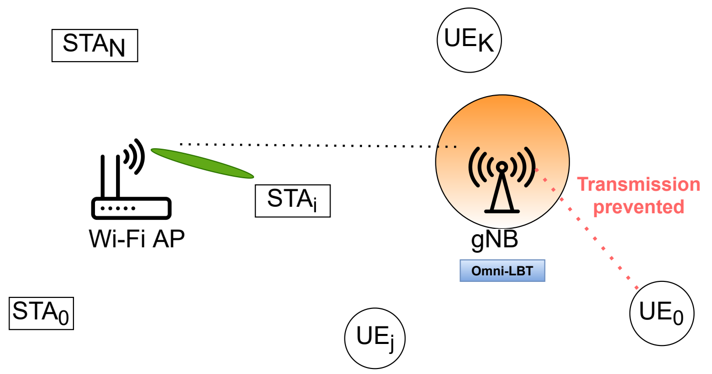

Figure 2.1: Over protection caused by Omni-LBT

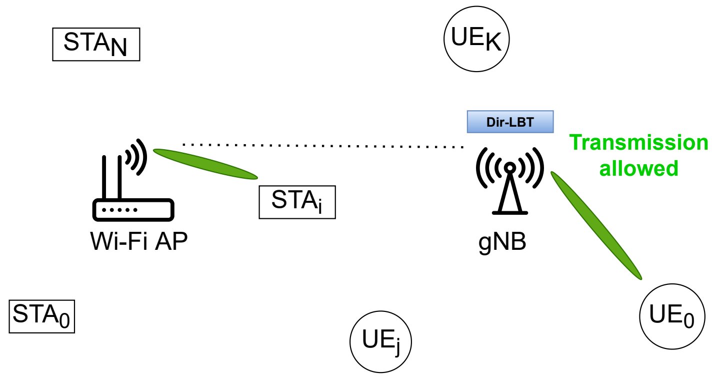

Figure 2.2: Dir-LBT senses along the transmission beam

tective and therefore spectrum reuse opportunities might be decreased. The spectrum should have been utilized but was blocked by Omni-LBT at gNB as depicted in Fig.2.1. Omni-LBT works well when transmissions are spatially aligned [6]. Dir-LBT, on the other hand, only detects the direction in which transmission will take place [4] as seen in Fig.2.2. However, if the transmission of AP is within the UE's antenna boresight, ongoing adjacent transmissions may not be detected in Dir-LBT, and directional hidden node issues may create interference [6]. When a transmitting node is oblivious of the presence of a (hidden node) while interacting with a neighboring node that is within both nodes' range is known as the hidden node problem. Since the node is unaware of the hidden node's transmissions, their signals frequently collide at the neighboring node. Hidden nodes reduce channel utilization and degrade network performance. Distance, obstructions that obstruct radio signals, unequal transmission powers, and other considerations can all lead to hidden nodes. Numerous studies such as [8], [9] have researched solving the hidden node problems. Therefore, in this research, we do not aim to solve the hidden node issue. As a result of the above, we have an Omni-LBT that is overprotective and prohibits spatial reuse, and a Dir-LBT that enables spatial reuse with hidden node problems. This presents us with an Omni-LBT/Dir-LBT trade-off. Several approaches have been proposed to solve the trade-off. We will now overview the approaches coined to solve the trade-off. The approaches include:

- Pair-LBT: Pair-LBT is directional sensing in paired directions i.e. in transmitting and opposing direction(s) [10]. Depending on whether the carrier sensing beams are reconfigurable or preset, the opposite directions can indicate a single direction or a collection of directions

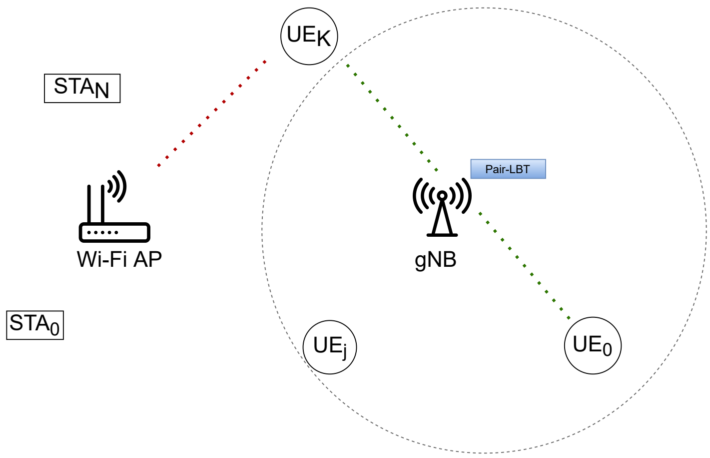

Figure 2.3: Pair-LBT does not detect all the hidden nodes present

[10]. Overall, Pair-LBT is a technique for ensuring fair coexistence of multiple RATs in unlicensed spectrum, and it can be appropriately adjusted to network density and beamwidth configurations by adjusting the LBT parameters. However, even if the gNBs are detecting in both directions, hidden nodes can remain unnoticed if the users are far distant from the gNBs' sensing range as demonstrated in Fig.2.3. Furthermore, the sensing result would be insignificant without the use of listen before receive (LBR) at the target receiver. This is because, some interference circumstances might not be observable with carrier sense at the emitting node, and performing LBT at the transmitter may fail to identify activity near the receivers. As receivers can spot potential interference, assistance from the intended user to the gNB can help to better control interference.

- LBT-Switching: Studies such as [4] show that Dir-LBT outperforms Omni-LBT at low network densities, whereas Omni-LBT is a superior approach at high network densities. Furthermore, Dir-LBT works well for narrow beamwidths, whereas Omni-LBT suffices for large beamwidths. To avoid the inappropriate behavior of conventional LBT in gNB with beam-based transmissions, the kind of physical carrier sensing should be carefully chosen depending on the beamwidth configuration and density of neighboring nodes. To identify hidden node issues, a dynamic switching technique is used, in which switching from Dir-LBT to Omni-LBT is based on indicators such as Hybrid Automatic Repeat Request-Acknowledgment (HARQ) feedback, UE measurements, and so on [11]. However, plenty of drawbacks are present. First, HARQ does not always refer to collisions; Negative Acknowledgment (NACK) can occur as a result of a sudden signal blockage. Second, it is influenced by scheduler policies that prevent collisions between various UEs may have a different impact on the switching actions of LBT, because they will be determined by the number and type of users concurrently assigned. Also in the case of multiple users, UE sends indicators such as NACK and HARQ towards the gNB that would result in higher signaling overhead as demonstrated in Fig.2.4. Therefore, LBT-switching is not considered in this research.

- RTS/CTS communication: The sender broadcasts an RTS packet including both the in-

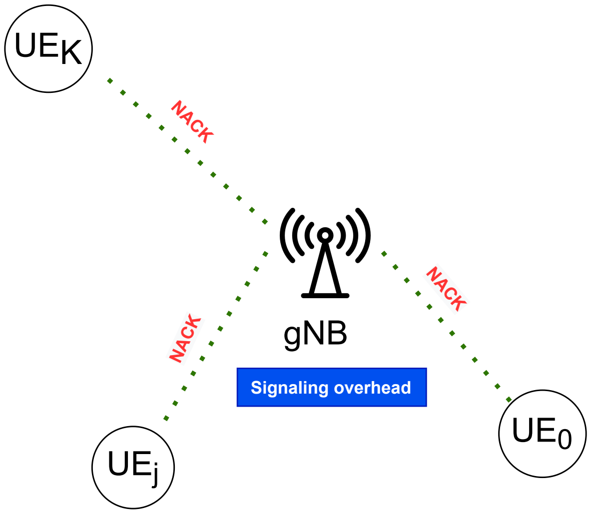

Figure 2.4: LBT switching produces a huge signaling overhead

tended destination of the subsequent data packet and the amount of channel time necessary for its delivery under RTS/CTS [12]. If the intended receiver successfully receives the RTS packet, the latter broadcasts a CTS packet with the channel time required for the new packet, informing the sender of the RTS of the transmission's acceptance and prohibiting neighboring stations from interfering during that period. This method has two disadvantages. Transmissions in a situation where the user has not been interfered with any ongoing transmission and desires to receive a data packet from gNB are blocked from sending a CTS [12]. This is because it previously heard a CTS transmitted by a user who was out of range with their targeted transmitter during the time of the desired data-packet reception, as illustrated in Fig.2.5. The RTS-CTS protocols solve the hidden-station problem in certain circumstances, but not all because hidden stations can still interfere with adjacent transmissions and cause data packet collisions under RTS-CTS [12]. The rationale for these collisions is that a station's CTS will not always be heard by all of its neighbors, since the latter may be interrupted by an ongoing transmission in their vicinity, leading to a hidden-node scenario. RTS-CTS communication does not improve the system considerably and therefore is not considered for our research.

- Listen before receive: Listen-Before-Receive (LBR) is another potential solution that is only dependent on the physical carrier sense [2]. According to this approach, the gNB prompts the UE to perform carrier sense, and the gNB can only commence transmission if the UE responds. Before sending the trigger and feedback messages over the unlicensed carrier, carrier sense is utilized. The efficiency of receiver-assisted LBT is achieved at the expense of additional message exchange between the gNB and the UE before each channel access. However, studies such as [2], [4] show that the efficiency is massively improved with the aid of this protocol. We consider LBR in this research to increase the efficiency of data transmission between gNB and UE.

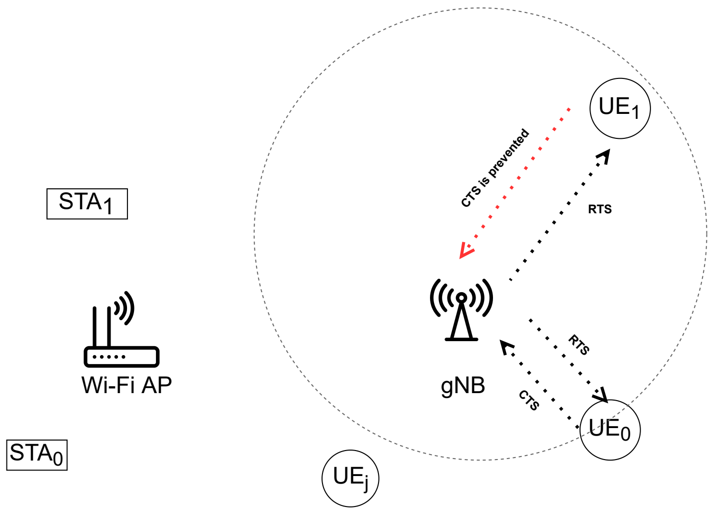

Figure 2.5: CTS is prevented due to the fact that it previously heard a CTS transmitted by a user who was out of range with their targeted transmitter during the time period of the desired data-packet reception

2.3 Types of spectrum sensing

During the LBT method, a CCA check is performed before using the channel, and certain constraints are imposed if the channel is determined to be busy. CCA detects the presence (i.e, the channel is busy) or absence (i.e, the channel is idle) of other signals on the channel using spectrum sensing methods. If the observed energy during the first CCA period is less than a specific threshold (the decision threshold), the device can access the channel for a time known as Channel Occupancy Time (COT) [6]. Otherwise, an extended CCA time begins, during which the observed energy is compared to the decision threshold again and again until channel access is granted.

Many strategies have been developed in order to conduct spectrum sensing. These include energy detection, matched filter detection, and cyclo-stationary feature detection [1]. Cyclo-stationary detection requires knowledge about the source signal's cyclic frequency, which may not be available to secondary users in practice. It has high computational complexity. The detection of signals using matched filters is thought to be the best way. It does, however, necessitate prior knowledge of the user such as (modulation type, synchronization of timing, and carrier). Furthermore, for matched filter detection, the gNB will require a dedicated receiver for each user, making practical implementation problematic. In contrast, energy detection requires no knowledge of the underlying signal and is robust to unknown channels.

As a result, in wireless networks, the most commonly used solution for spectrum sensing is an energy detector, because it is commonly assumed that there is no coordination or signaling between the WiFi-AP and gNB. Also, low computational complexity and low application cost strikes as a significant advantage over other sensing methods [1]. When the noise variance is known, an energy detector (ED) is a simple and common detector for spectrum sensing. ED requires precise knowledge of the noise variance to accurately set the decision threshold to meet a preset false-alarm likelihood. In practice, the noise variance must be estimated using an estimation procedure that is subject to a variety of errors. As a result, these estimate procedures generate noise uncertainty. The ED is fairly sensitive to the accuracy of the predicted noise variance [1].

2.4 Spectrum sensing challenges

Several factors that contribute to the challenges in spectrum sensing are listed as follows:

- The level of noise/interference varies over time, and the noise could be non-Gaussian. In practice, obtaining an accurate noise power is quite challenging due to noise variability.
- The problem is exacerbated by multipath propagation and fading in wireless signals [1]. As a result of fading, the signal power changes dramatically. In addition, channel uncertainty complicates spectrum sensing since gNB must be more sensitive to identify a faded or shadowed signal from white space.
- Sensing in all directions increases the time required for sensing and is also not cost effective. Therefore, gNB must identify the directions to sense and the the total time required for sensing in the desired directions.

To circumvent these challenges, we have assumed the noise to be Additive White Gaussian noise (AWGN). It is a fundamental noise model used in information theory to replicate the effect of various random processes seen in nature. To understand the effect of fading in the channel, we perform beam training by sending pilot symbols to understand the channel quality. Therefore, the channels with higher fading can be avoided. Our model strives to find out the directions to sense on performing energy detection along the sensed direction and the time needed to sense a direction is found.

2.5 Related work

There is a substantial amount of literature on the coexistence of WiFi and NR-U. In recent years, researchers have focused their efforts on the topic of spectrum sharing between heterogeneous wireless systems. Spectrum sharing based on beamforming has been studied in [13] and [14]. In [13], an upper and lower bound on the optimal threshold is computed. Further, a heuristic algorithm is presented for the analysis of the optimal threshold found. For cellular/WiFi coexistence, Geraci et al. describe a MIMO-based interference rejection transmission method in [14]. In addition, prior works such as [5] consider omnidirectional antennas for spectrum sensing and minimize sensing overhead at gNB. In [15], influence of various NR-U channel access strategies on WiGig nodes has been investigated using various performance measures. Furthermore, the impact of modifying the ED threshold at NR-U devices was investigated, revealing that a lower ED threshold would be a cautious approach benefiting WiGig nodes. In [16], a cognitive radio system is considered for which optimal transmit power is obtained to maximize the throughput. Our work is similar as we also consider directional spectrum sensing. In [17], the optimal decision threshold (ξ) for a cognitive radio system is computed with the aid of directional spectrum sensing as used in our research.

The aforementioned research is more concerned with examining the performance of existing protocols and optimizing parameters that affect coexistence, which is crucial when unlicensed RATs start operating in a new band. Finally, the most notable distinction between relevant literature and this research would be to use beamforming using directional antennas to detect the spectrum and to find out the directions to sense on performing energy detection along the sensed direction. Furthermore, our research aims to understand the impact of various user distributions on sensing time and the influence of sensing beamwidth on sensing accuracy and capacity.

Chapter 3

System model overview

In this chapter, we will introduce the symbols and the parameters that will be used in the rest of the thesis. Furthermore, the assumptions considered will also be discussed in detail. Moreover, the working of the gNB will be explained briefly. In addition, we give an outline to the antenna model used followed by the sensing model of the gNB which forms the basis to our research.

3.1 Description and Assumptions

We consider an indoor setting consisting of a WiFi-AP and gNB as shown in Fig.3.1. In this network, there are N WiFi stations and M cellular users.

- WiFi-AP
  - We assume that the WiFi-AP is equipped with a steerable Uniform Linear Array (ULA) having a single antenna. There are multiple sensor elements to aid beamforming.
  - The WiFi-AP performs omni-LBT and can transmit in the determined direction with power P_{AP} dBm.
  - We assume that WiFi-AP knows the location of its N users denoted by STA$_j$ where $j = [1, \cdots, N]$.
  - The distance between WiFi-AP and gNB is assumed to be D.
  - $d_i^{w,u}$ represents the distance between WiFi-AP and UE$_i$ and $d_j^{w,s}$ is the distance between WiFi-AP and STA$_j$.
- gNB
  - We assume that gNB is also equipped with a steerable ULA having a single antenna. It performs dir-LBT and directional transmissions towards the intended receiver.
  - We also assume that gNB knows the location of its M users denoted by UE_i where $i = [1, \cdots, M]$.
  - gNB operates in a time slotted system as depicted in Fig.3.2. The time slot is divided into three stages.

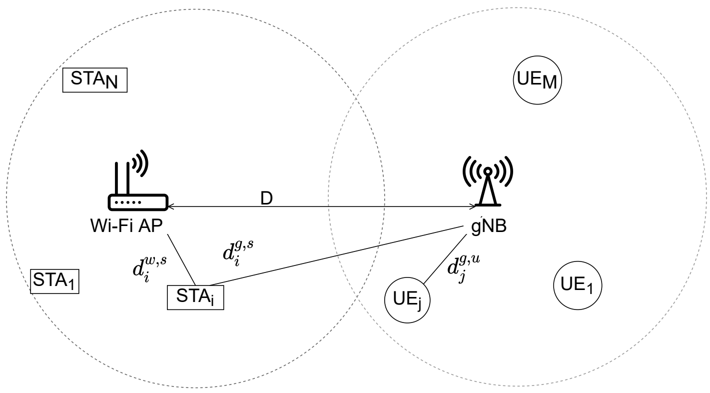

Figure 3.1: System model depicting coexistence of WiFi-AP and gNB with N WiFi stations and M cellular users. The transmitters are separated with a distance of D within the interference range of each other.

- gNB performs directional sensing with a constant beamwidth of ϕ degrees.
- The antenna can receive and transmit in any particular direction due to its steerability.
- The distance between gNB and its respective users is denoted by $d_i^{g,u}$ where $i = [1, \cdots, M]$ and $d_j^{g,s}$ is the distance between gNB and STA where $j = [1, \cdots, N]$ stations.

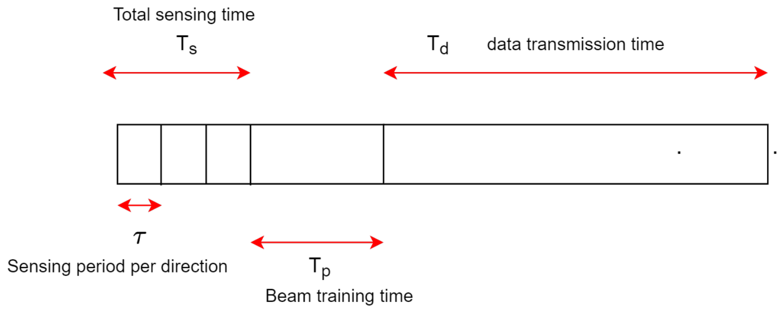

Figure 3.2: Time slotted system of gNB where T represents the total time slot duration in milliseconds. T_s is the total time taken for sensing along multiple directions with each having a constant sensing period of τ, T_p is the time taken to beam training along the directions which were found idle and T_d is the time taken to perform data transmission.

3.2 Time slotted system

As mentioned above, gNB follows a time slotted system wherein the following operations are executed:

- Sensing phase (T$_s$): During the sensing period, gNB performs energy detection along multiple directions and measures the signal energy level on the spectrum. The measured signal energy level along a particular direction is sensed for a constant time of τ milliseconds. The total time required for sensing (T$_s$) can be determined by multiplying the number of directions sensed with the time required to sense one of them (τ). If the sensed energy level is higher than the decision threshold denoted by ξ, the spectrum is considered to be busy.

If all the directions were found to be busy, the gNB needs to wait until the next time slot to sense along multiple directions again. If the direction is found to be idle, beam training is performed. Our goal is to reduce the time taken for sensing to obtain maximum throughput towards the intended user.

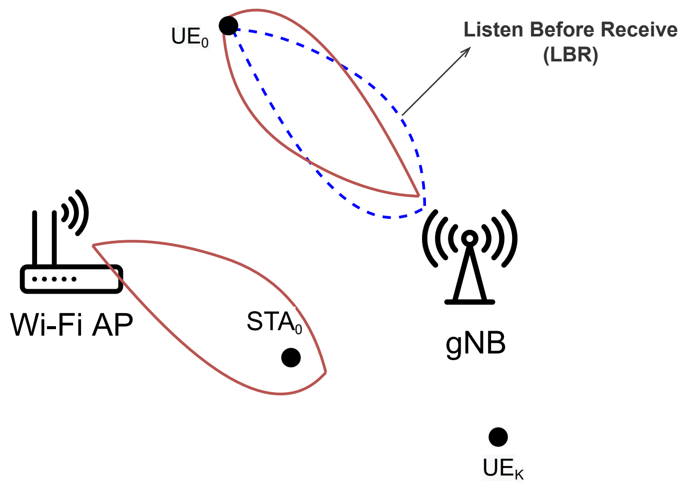

Figure 3.3: The receiver beam does not have any interference with the transmission of WiFi-AP along STA$_0$ on performing LBR.

- Beam Training phase (T$_p$): Our model considers directional transmission and directional reception to increase the benefit of directional antennas. During the beam training phase, gNB sends pilot symbols towards the users along the idle direction found during the sensing time (T$_s$). Before receiving, the users perform Listen before receive (LBR) towards the gNB as shown in Fig.3.3. The transmission is successful if no transmitters within the range of the UEs reception beam will cause interference. The goal is to understand the channel quality of the users. Performance metrics such as SNR are computed to comprehend the quality of the channel. The users report their channel quality to gNB. The gNB after collecting the feedback selects the user with the highest channel quality for the data transmission phase. However, this is achieved by compromising fairness towards the users.

- Data transmission phase (T$_d$): gNB transmits data towards the user with the highest channel quality selected in the preceding phase. We aim to compute the maximum achievable throughput towards this user.

A decision should be made on the direction(s) to sense before sensing is carried out. Sensing in every possible direction would result in high sensing overhead. However, our goal is to reduce the sensing time in order to maximize the throughput towards the intended user. Next, an overview of the antenna model implemented is discussed, from which how to calculate the gain of the transmitter and receiver is discussed in detail.

3.3 Antenna model

A detailed mathematical model of an antenna is required to study the impact of spectrum sensing on various factors such as sensing beamwidth and misalignment. In general, it is difficult to capture all of the fundamental features of real-world antennas in a simple analytical expression/model. In this section we devise the antenna model implemented in our system and the gain of the directional antenna is computed.

One of the factors that affects the performance of beamforming include beam misalignment [18]. For effective transmissions towards the intended users, the main lobe of the gNB should be completely in the direction of the user. Conservation of energy dictates that for higher gains, the beamwidth of the lobe should be small and larger for lower gains. Although narrow beams produce a strong received signal, they are susceptible to beam misalignment [18]. Due to the impact of beam misalignments, effective transmitter and reception antenna gains are less than expected for given transmitter and receiver beamwidths, resulting in transmission errors. During sensing, detecting occupancy in all dimensions of the spectrum space should be evaluated. Therefore beam misalignment towards a particular direction is essential as the received power varies with beam alignment.
Constant gains for both the main and side lobes are assumed in the most commonly used cone-plus-circle antenna model [19]. However, due to its assumption of constant gain for the main lobe the impact of beam misalignment would be hard to examine. Because any alignment error smaller than the beamwidth of main lobe would be unnoticed.

In order to understand the impact of beam misalignment, here we adapt the antenna model

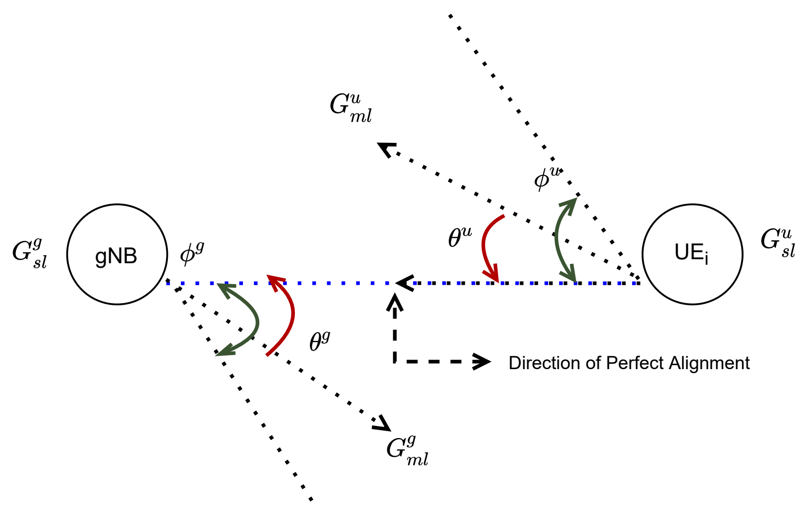

Figure 3.4: Antenna Model adapted from [18]. The figure depicts the alignment of gNB towards one of its users UE$_i$. The misalignment of gNB towards its user is given by θ and the gain of the main lobe is given by $G^{\phi^g}_{ml}$.

from [18] as depicted in Fig.3.4. We denote the main lobes of transmitter and receiver for the given misalignment angle (θ) and half power beamwidth (ϕ) by $G^{\phi^g}_{ml}(\theta^g)$ and $G^{\phi^u}_{ml}(\theta^u)$ respectively where, ϕ^u and ϕ^g represents the main lobe beamwidth of UE and gNB respectively and

G_{ml} denotes that main lobe gain. The direction of perfect alignment is where the main lobes of transmitter and receiver coincide. The angle of misalignment (θ) is measured from the direction of perfect alignment to the axis of antenna's main lobe (gNB). Let G_{sl}^{u} and G_{sl}^{g} denote the constant gain of side lobes of UE and gNB respectively. For a range of misalignment∈ [0°, 180°] and beamwidth ∈ [0°, 360°], the gain of the directional antenna (G) is given by [18]:

$$G^{\phi}(\theta) = \begin{cases} G^{\phi}_{ml}(\theta) = \left(\frac{1.6162}{sin(\phi/2)}\right)^2 e^{-K\left(\frac{\theta}{\phi}\right)^2}, & |\theta| \leq 1.3\phi \\ G^{\phi}_{sl}(\theta) = e^{-2.437}\ \phi^{-0.094}, & |\theta| > 1.3\phi \end{cases} \tag{3.1}$$

where K is $4\log_e 2$. The alignment of Tx-Rx antenna depends on θ. The direction of perfect alignment is shown in Fig.3.4. The main lobe beamwidth (ϕ^{ml}) can be evaluated from the main lobe peaks levels around -20 dB [18]. Next, a brief introduction of the spectrum sensing model is presented.

3.4 Spectrum sensing model

In this section, the general model for spectrum sensing is presented first, followed by an analysis of the energy detection system and the relationship between the probability of detection and the probability of false alarm. Moreover, the SNR calculation based on the received power during sensing is formulated.

Assume we are interested in a frequency band with a carrier frequency of f$_c$ and a bandwidth of W, and the received signal is sampled at f$_s$. The signal of the WiFi-AP is represented by s(n) and the u(n) is the noise present. The received signal at the gNB when WiFi is active can be represented as [20]:

$$y(n) = s(n) + u(n), \tag{3.2}$$

when WiFi is inactive, the received signal is given by:

$$y(n) = u(n). \tag{3.3}$$

It is assumed that the signal s(n) is independent of the noise u(n). Also we assume the signal is independent and identically distributed random process with zero mean and variance σ_s^2. The noise is also assumed to be independent and identically distributed random variable with zero mean and variance σ_u^2. This is done to nullify the effect of noise and fading as mentioned in spectrum sensing challenges. Two probabilities are essential for spectrum sensing: probability of detection, which corresponds to the probability of the technique successfully detecting the presence of WiFi, and probability of false alarm, which refers to the probability of the technique incorrectly reporting the presence of WiFi [20]. False detection at gNB can be given by P$_f$ and true detection at gNB can be given by P$_d$. Both depend on the decision threshold and sensing time. The feasible scenarios for detection are as follows [20]:

- Correct detection of WiFi signal's absence
- Correct detection of WiFi signal's presence
- Incorrect detection of WiFi signal's absence
- Busy state of WiFi signal is falsely detected

Next, we will discuss the channel model in which we derive the received power at gNB during spectrum sensing.

3.4.1 Channel Model

To understand if the sensed direction is idle or busy, the received power at gNB needs to be calculated for the time it senses the spectrum across every direction possible. The received power at gNB can be found by using Friis's free-space pathloss. Let the transmit power of AP be P_{AP}. $G^{\phi^w}(\theta^w)$ be the gain of the transmitter and $G^{\phi^g}(\theta^g)$ be the gain of the receiver and L be the path loss between WiFi-gNB. The received signal power of WiFi-AP at gNB is calculated as follows:

$$P_{rx} = P_{AP} + G^{\phi^w}(\theta^w) + G^{\phi^g}(\theta^g) - L. \tag{3.4}$$

The path loss in dB can be mathematically formulated as:

$$L = 20 \log_{10}(\frac{4\pi df}{c}) \tag{3.5}$$

where f is the frequency of the signal, d is the distance between the transmitter and the receiver and c is the speed of light.

Let β denote the result of sensing. Depending on the orientation of the users of the gNB present, either side lobe or main lobe gain is considered. Formally, the outcome of spectrum sensing denoted by π is defined as follows:

$$\beta = \begin{cases} Idle & \text{if } P_{rx} \leq \epsilon \\ Busy & \text{if } P_{rx} > \epsilon. \end{cases} \tag{3.6}$$

The SNR (γ) of WiFi measured at the gNB can be calculated as [17]:

$$\gamma = P_{AP} + G^{\phi^w}(\theta^w) + G^{\phi^g}(\theta^g) - 20 \log_{10}(\frac{4\pi df}{c}) - \sigma_u^2. \tag{3.7}$$

where P$_{AP}$ denotes the transmission power of WiFi-AP at gNB and σ_u^2 denotes the noise. Next, we derive the true and false detection probability during spectrum sensing.

3.4.2 True and False Detection

Most spectrum sensing techniques including, energy detection does not differentiate between noise and signal. Therefore, true detection and false alarm probability are two essential parameters to understand the sensing accuracy of the system. We calculate these based on the probability density function of busy and vacant channels. The probability of detection can be approximated as follows [21]:

$$P_d(\tau, \xi) = \mathcal{Q}\left(\left(\frac{\epsilon}{\sigma_u^2} - \gamma - 1\right)\sqrt{\frac{\tau f_s}{2\gamma + 1}}\right), \tag{3.8}$$

where τ is the time required for sensing, γ is the SNR of WiFi signal measured at gNB and Q(.) is the complementary distribution function of the standard Gaussian. It can be calculated as follows [21]:

$$\mathcal{Q}(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} \exp\left(-\frac{t^2}{2}\right) dt. \tag{3.9}$$

The orientation of gNB's antenna with respect to the WiFi-AP affects spectrum sensing accuracy. During sensing, to increase the true detection probability, gNB should be facing towards the WiFi-AP. However, to increase the channel capacity, gNB should be facing in the direction of UE. Thus, there exists a trade-off in terms of gNB's orientation.

In addition, greater the detection probability, the better the WiFi-AP protection [22]. However, from the perspective of the gNBs, the lower the false alarm rate, the more likely the channel can be reused when it is available, and hence the higher the possible throughput for UEs. As a result, the gNB would suffer a fundamental trade-off between sensing capability and achievable throughput [1]. The lower value of sensing time results in a lower probability of detection and higher probability of false alarm [23]. However, the desirable value would be for a given sensing time, the probability of detection is higher and the probability of false alarm is low. Now that the sensing procedure is completed, data transmission takes place. The formulation of throughput using Shannon's capacity theorem is explained in detail below.

3.5 Channel capacity

During the sensing time, gNB senses along multiple directions over its respective sensing periods τ. Only some of the directions are sensed idle due to factors such as misalignment, beamwidth and distance. These idle directions are used for beam training. During beam training, gNB can understand the channel quality of the users before deciding on the direction to transmit. Let γ_{ue} represent the SNR at UE. A table is made to store the values of SNR. The values of SNR are sorted in decreasing order. The one with the highest SNR is chosen. Now, let us assume that now that UE_j is found to be the best user at which data transmission should take place. Our proposal aims at maximizing the throughput at the UE_j where $j = [1, \cdots, M]$, M is the number of users present. Throughput is defined as the rate at which information is sent efficiently over a communication channel. The calculation of SINR gives a theoretical insight into the throughput along a communication channel. SINR, in our model, is defined as the power of the pilot symbol sent by gNB divided by background noise at UE plus the interference caused by WiFi-AP. If there is no interference at UE from WiFi-AP, SINR becomes SNR (Signal to noise ratio). The interference at the user (UE_j) due to the presence of WiFi-AP can be calculated as:

$$P_{p_j} = P_{AP} + G^{\phi u_j}(\theta^{u_j}) + G^{\phi w}(\theta^{w}) - L_{u_j,w}. \tag{3.10}$$

where $\mathrm{G}^{\phi u_j}$ and $\mathrm{G}^{\phi w}(\theta)$ denotes the antenna gain of the respective UE_j and WiFi AP respectively. P_{AP} denotes the transmit power of WiFi-AP and $\mathrm{L}_{u_j,w}$ denotes the path loss. The mathematical formulation of SINR under these cases are formulated below:

$$S_{UEj} = \frac{Received\, Power\ of\ the\, pilot\ symbol(P_{rcvd})}{Noise(N_0) + Interference\ (P_{p_j})}. \tag{3.11}$$

The received power of the pilot symbols transmitted from gNB towards the intended user is formally calculated as:

$$P_{rcvd} = P_g + G^{\phi u_j}(\theta_{u_j}) + G^{\phi g}(\theta_g) - L_{u_j,g}. \tag{3.12}$$

where the received power at the UE is denoted by P_{rcvd}. The gain of the gNB towards UE_j and the gain of UE_j towards gNB is denoted by $\mathrm{G}^{\phi g}(\theta)$ and $\mathrm{G}^{\phi u_j}(\theta)$ respectively. The transmit power of gNB is represented by P_g and the path loss between the gNB and UE_j is denoted by $\mathrm{L}_{u_j,g}$. In the preceding chapter, we calculated the received of gNB during the process of spectrum sensing. Similarly, we calculate the received power at the intended user to understand the channel capacity towards the particular user.

Therefore, the achievable bit data according to Shannon's capacity theorem becomes:

$$R_{UEj} = \log_2{(1 + S_{UEj})}. \tag{3.13}$$

The relationship between the probability of detection and the probability of false alarm was established in the preceding section. In this part, we look at the fundamental trade off between gNB sensing capabilities and attainable throughput. Let us denote δ_0 as the throughput of gNB when it operates in the absence of WiFi-AP along UE_j and δ_1 as the throughput when it operates in the presence of WiFi-AP along UE_j. Because the gNB cannot distinguish between true detection and false alarm, the transmitter will consume the same amount of power regardless of whether a true detection occurs under H_0 or a false alarm occurs under H_1.The achievable throughput can be calculated as follows:

$$\delta_0 = log_2\,(1 + \frac{P_{rcvd}}{N_0}). \tag{3.14}$$

$$\delta_1 = log_2\,(1 + \frac{P_{rcvd}}{N_0 + P_{p_j}}). \tag{3.15}$$

There are two considerations in which gNB can use the WiFi frequency spectrum. These include:

1. Case 1: When WiFi-AP is not present and no false alarm is generated by gNB (R_0)
2. Case 2: When WiFi-AP is active but it is not detected by gNB (R_1)

The achievable throughput under both cases can be formulated as follows[1]:

$$R_0(\phi, T_s, \theta) = \frac{T - (T_s + T_p)}{T} log_2\,(1 + \frac{P_{rcvd}}{N_0}). \tag{3.16}$$

$$R_1(\phi, T_s, \theta) = \frac{T - (T_s + T_p)}{T} log_2\,(1 + \frac{P_{rcvd}}{N_0 + P_{p_j}}). \tag{3.17}$$

When WiFi is active ($R_1(\phi, T_s, \theta)$), the spectrum should be considered busy and data transmission should not take place. However, this depends on orientation of WiFi AP with respect to the gNB. Since Dir-LBT is used at gNB, the spectrum could be still sensed idle when with the presence of WiFi-AP, if the interference is limited. The objective is to maximize the throughput at the intended user, for the data transmitted in that particular time frame (T_d). Multiple directions are sensed in T_s milliseconds for a particular beamwidth ϕ and misalignment θ of gNB.

3.6 WiFi-AP model

In order to evaluate the throughput at a WiFi station (STA), we define a model for WiFi-AP. We assume WiFi-AP performs Omni-LBT and can transmit in a determined direction with a power of P_{AP} dBm. WiFi-AP uses Carrier sense multiple access with collision avoidance (CSMA-CA) algorithm. The time taken for sensing towards a direction is assumed to be constant (τ_w). Using this algorithm WiFi transmits data only when the channel is idle. We assume the location of its users is known to WiFi-AP. Now, in order to transmit data towards its users, it follows round robin scheduling. This is due to fairness concerns existing in WiFi. Therefore, along the directions found to be idle, the data transmitted in round robin fashion.

To understand if the sensed direction is idle/busy, the received power at WiFi needs to calculated. Assuming the transmission power of gNB to be P_g and the gain of the gNB is $G^{\phi^g}(\theta^g)$. The gain of the WiFi-AP towards gNB is $G^{\phi^w}(\theta^w)$ and L is the pathloss between WiFi-gNB. The received power at WiFi-AP is calculated as follows:

$$P_w = P_g + G^{\phi^w}(\theta^w) + G^{\phi^g}(\theta^g) - L_{g,w}. \tag{3.18}$$

Now, we estimate the interference at the STA due to gNB. The interference of gNB on STA_k is given by:

$$P_{p_{sk}} = P_g + G^{\phi sk}(\theta^{sk,g}) + G^{\phi g}(\theta^g) - L_{sk,g}. \tag{3.19}$$

where $G^{\phi^s k}(\theta^{sk,g})$ and $G^{\phi^g}(\theta^g)$ denotes the antenna gain of the respective station (STA_k) and gNB respectively. P_g denotes the transmit power of gNB and $L_{sk,g}$ denotes the path loss.

Now that we know the interference from gNB, we can calculate the throughput at the sta-

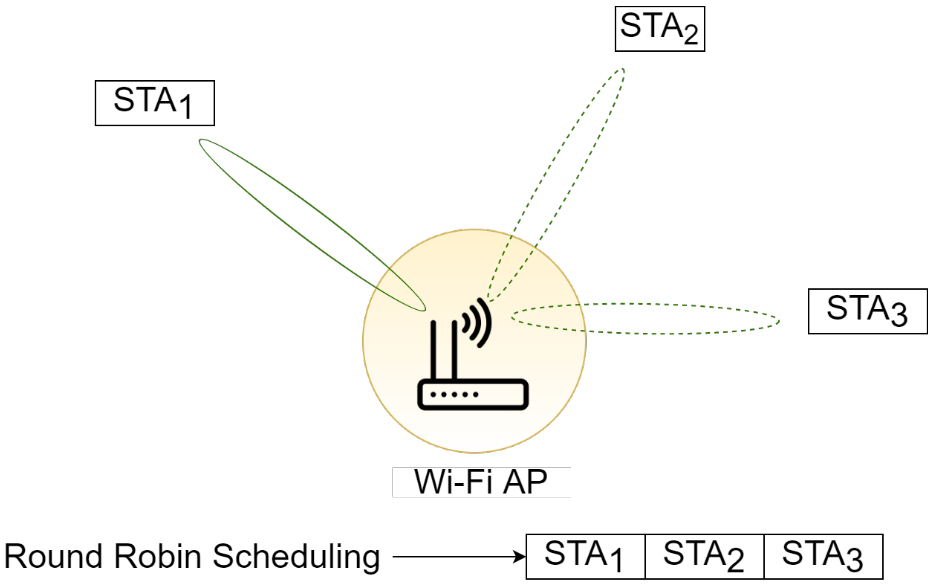

Figure 3.5: The representation of round robin scheduling used in WiFi-AP to transmit data towards its users.

tion on formulating the received signal of WiFi-AP on STA. The received signal transmitted from WiFi towards its intended user is formally calculated as:

$$P_{STA} = P_{AP} + G^{\phi sk}(\theta^{sk,w}) + G^{\phi w}(\theta_w) - L_{sk,w}. \tag{3.20}$$

where the received power at the station is denoted by P_{STA}. The gain of the WiFi towards STA_k and the gain of STA_k towards WiFi-AP is denoted by $G^{\phi w}(\theta^w)$ and $G^{\phi sk}(\theta^{sk,w})$ respectively. The path loss between the WiFi-AP and UE_j is denoted by $L_{sk,w}$. The achievable throughput can be calculated as follows:

$$\delta_{w0} = log_2\,(1 + \frac{P_{STA}}{N_0}). \tag{3.21}$$

$$\delta_{w1} = log_2\,(1 + \frac{P_{STA}}{N_0 + P_{p_{sk}}}). \tag{3.22}$$

where δ_{w0} and δ_{w1} represents the achievable throughput when the WiFi-AP operates in the absence and presence of gNB respectively.

The system as a whole has now been detailed. Next, we want to determine the directions to sense and the sensing beamwidth for all plausible scenarios so that the sensing time is reduced. Prior to designing a heuristic algorithm, a brief motivation followed by a high level description is given.

Chapter 4

Proposed Directional spectrum sensing algorithm

This chapter aims to introduce the proposed heuristic directional sensing algorithm coined towards the gNB and discusses the motivation of our proposed algorithm. In addition, the essential components of the algorithm are derived and defined. Prior to this, a high level description of the proposed algorithm along with its pseudo code is presented in detail.

4.1 Motivation

The motivation of the spectrum sensing algorithm is to reduce the time taken for spectrum sensing at gNB and leave more time for data transmission to increase the achievable throughput. To reduce the sensing time, one can do the following:

- select only certain directions to sense rather than all directions,
- sense with lower number of beams by adapting the sensing beamwidth.

Beamwidth adaptation here refers to the ability of gNB to accommodate the users that were left out previously while sensing. Hence, beamwidth adaptation is looked upon in our heuristic algorithm and the possibility of saving in sensing time is explored. We assume in our heuristic directional spectrum sensing algorithm the location of UEs are known to the gNB. Along the directions where no UEs are present, sensing is skipped. Hence, we reduce the number of beams required to sense. To understand the process of beamforming, consider a beamwidth of 30° senses m users. On performing adaptation, we end up having a beamwidth of 60° which might sense more users than the 30° beamwidth. Nevertheless, there exists a trade-off. Narrow beams have higher vertical coverage than wider beams, although they cover less area.

Therefore, the goal is to understand when beam adaptation would be viable on performing Dir-LBT and reducing the number of beams required to sense. One of the major challenges of this spectrum sensing algorithm is to determine the sensing range of gNB for an arbitrary beamwidth. Before that, the impact of sensing beamwidth on beam coverage is discussed in the next section.

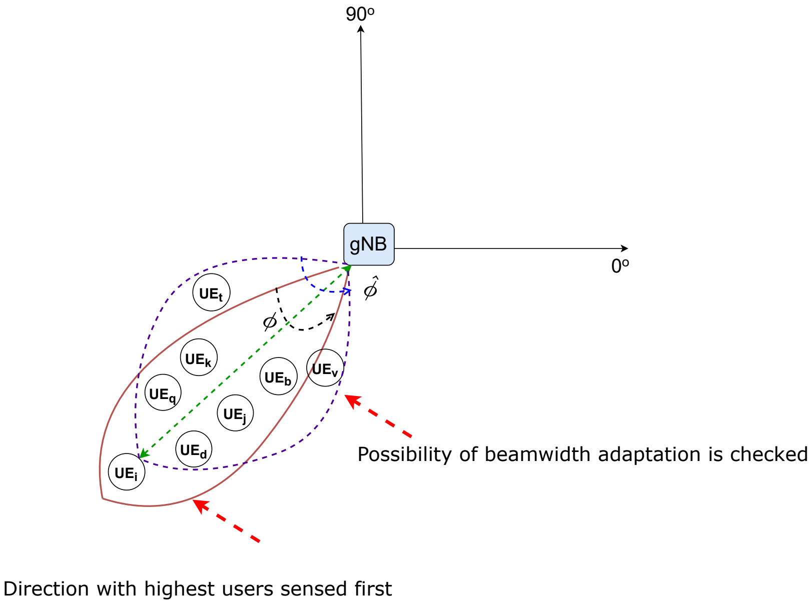

Figure 4.1: The representation of the directional spectrum sensing performed on gNB based on our heuristic algorithm. The direction with the highest number of users is sensed first followed by the possibility of beamwidth adaptation.

Table 4.1: Simulation parameters used for studying the impact of sensing beamwidth on beam coverage

Notation	Values assumed
ϕ (Sensing beamwidth of gNB)	15°, 30° and 360°
θ (Misalignment of gNB)	0°, 180°

4.2 Impact of sensing beamwidth on beam coverage

In this section, the impact of sensing beamwidth on beam coverage will be studied. The area under which a transmitter of a particular beamwidth can broadcast is known as beam coverage. In general, wider beamwidth results in a bigger area at the expense of vertical coverage (direction of transmission). On the other hand, narrow beamwidth results in larger vertical coverage at the expense of the area covered as depicted in Fig.4.2. A plot showing the beam pattern of 3 different scenarios has been depicted in Fig.4.2. The gain of the sensing beamwidths of gNB is plotted against misalignment of gNB (0° and 180°) towards the transmitter. As expected, narrow beamwidths have larger vertical coverage when compared to wider beamwidths. We calculate the gain of the gNB using the formulae in (4.1).

$$G_{ml}^{15}(0) = \left(\frac{1.6162}{sin(15/2)}\right)^2 e^{-K\left(\frac{\theta}{\phi}\right)^2}, |\theta| \leq 1.3\phi \tag{4.1}$$

The parametric values are provided in Table 4.1. On plugging the values of beamwidth and misalignment, we calculate the gain under each scenario. As we decrease the beamwidth, the gain increases along 0° misalignment.

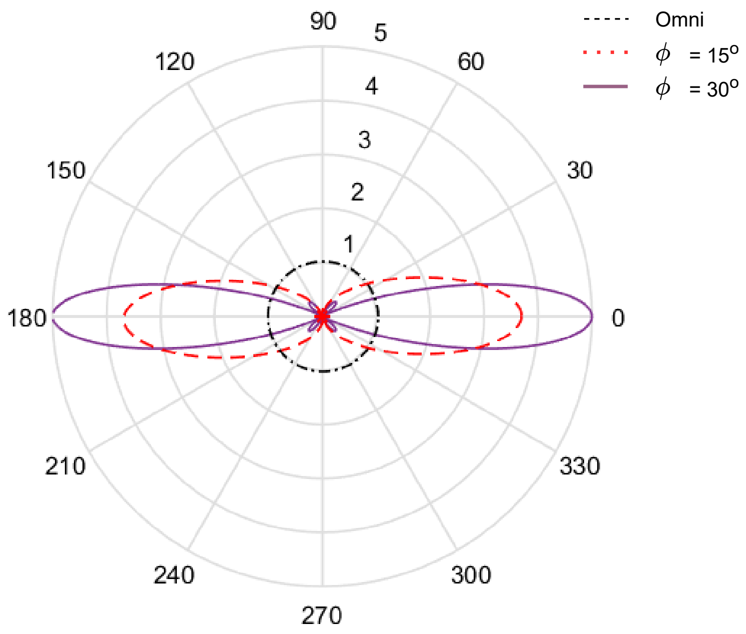

Figure 4.2: A plot showing the beam pattern for sensing beamwidths of ϕ = 15°, 30° and 360°

4.3 Sensing range of gNB

The gNB performs spectrum sensing in order to understand the location of WiFi-AP. This is done in order to understand if the WiFi-AP lies in the vicinity of the intended user as there exists a possibility for interference. In Fig.4.3, gNB uses a 15 degree beamwidth to sense along 3 particular directions. Although UE_5 lies within the sensing range, the possibility of interference is high as WiFi-AP lies in its vicinity. Therefore, gNB will defer this particular direction on calculating the received power. Hence, understanding the location of WiFi-AP is essential to spectrum sensing.

The effective range is proportional to the transmission power. The higher the transmit power, the further a signal can travel. In general, a stronger signal gives rise to a greater signal to noise ratio. Therefore depending on the transmit power, the maximum sensing range varies for a given beamwidth. In addition, not considering the transmission power might lead to spectrum inaccuracies. This is because of the range mismatch between the user and the transmitter.

We define a function (Is_in_Range) in algorithm 2 to compute the number of users under direction. The inputs such as distance of the users, location of the users, the starting angle, and the beamwidth of the gNB are given. The received power at gNB due to UE_j is given by:

$$P_r = P_{u_j} + G^{\phi u_j}(\theta_{u_j}) + G^{\phi g}(\theta_g) - L_{u_j,g}. \tag{4.2}$$

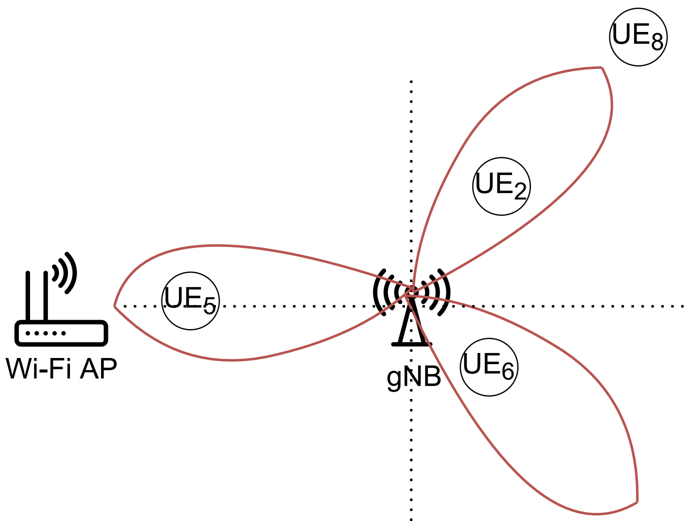

Figure 4.3: gNB uses a 15 degree beamwidth to sense along 3 particular directions to understand the location of WiFi-AP with respect to the UEs in that particular direction.

Algorithm 1: Is_in_Range function

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1 **Input:** ζ: Direction of arrival of the users, d: Distance of the user from gNB, ϕ: The beamwidth of gNB, $\hat{Q}$: Start Angle of the compartments, ξ: Decision threshold, P_{UE_j}: Transmit power of UE_j, L : Path loss between UE_j and gNB
Output: To check if an user is the range of gNB
Calculate Received Power (P_r) using Eq.4.2
if *($P_r \leq \xi$)* **then**
2   return True
3 **else**
4   return False

The path loss in dB can be mathematically formulated as:

$$L = 20\log_{10}(\frac{4\pi df}{c}) \tag{4.3}$$

where d is the distance between the gNB and the UE_j. We can calculate the pathloss assuming gNB knows the distance between the user and gNB.

Now, we ought to calculate the gain of gNB with respect to UE_j and the gain of UE_j with respect to gNB. Since the location of UE_j with respect to gNB is given as input, we know the misalignment of gNB with respect to the UE_j and the misalignment of UE_j with respect to the gNB. For a given beamwidth of gNB and UE_j, we can compute the gain of gNB and UE_j towards each other. Depending on the location of the users, the main lobe gain or side lobe gain is calculated as follows:

$$G^{\phi}_{ml}(\theta) = \left(\frac{1.6162}{sin(\phi/2)}\right)^2 e^{-K\left(\frac{\theta}{\phi}\right)^2}, |\theta| \leq 1.3\phi \tag{4.4}$$

$$G^{\phi}_{sl}(\theta) = e^{-2.437}\,\phi^{-0.094}, |\theta| > 1.3\phi \tag{4.5}$$

We assume gNB knows the transmission power of UE$_j$. The compartment along which gNB should sense is determined by the start angle ($\hat{Q}$). Therefore, for a beamwidth (ϕ) and start angle ($\hat{Q}$), gNB computes the received power due to UE$_j$. Depending on the value of the received power, the output of the function (Is_in_Range) can be defined as follows:

$$\mu = \begin{cases} True & \text{if } P_r \leq \epsilon \\ False & \text{if } P_r > \epsilon. \end{cases} \tag{4.6}$$

If the function returns true, we count the users present within each compartment. The pseudo code of the function in use is depicted in algorithm 1. This is stored for later purposes. We define a variable (U_E_C), to store the number of users in each compartment. Therefore, for a particular start angle, we calculate the number of users in the given direction.

When beamwidth adaptation is performed, the vertical coverage of the beam decreases in the expense of larger area. In order to compute the number of users after beam adaptation, the signal of the UEs present within the altered range will be received at the gNB. On performing beamwidth adaptation, the received power is changed as the gain of the antenna depends on the beamwidth and misalignment of the gNB towards the UE. Hence, the existing values of beamwidth and misalignment are replaced. We represent the new received power as $\hat{P}_r$, which can be formulated as follows:

$$P_r = P_{u_j} + G^{\phi u_j}(\theta_{u_j}) + G^{\hat{\phi}^g}(\hat{\theta}^g) - L_{u_j,g}.. \tag{4.7}$$

where P$_{u_j}$ is the transmission power of UE$_j$ and the gain of UE$_j$ towards the gNB is given by G$^{\phi u_j}(\theta_{u_j})$ and the gain of gNB towards UE$_j$ is given by G$^{\hat{\phi}^g}(\hat{\theta}^g)$.

Therefore, for a given beamwidth of gNB, we can find out if the user lies inside the beam coverage. Now we discuss the impact of sensing beamwidth on sensing accuracy in terms of true detection probability.

4.4 Impact of sensing beamwidth on spectrum sensing accuracy

A spectrum sensing technique needs to be accurate to avoid undesirable collisions that affect the efficiency of the system. For a system to be accurate, the probability of true detection should be high while the false alarm probability must remain low.

To simulate the impact of sensing accuracy on beamwidth, we consider the values provided in Table [4.2]. To compute the impact of sensing beamwidth on sensing accuracy, a closed form formulae in equation (4.9) is used to compute the true detection probability. Before calculating the values of true detection probability, we need to obtain SNR. In order to calculate the various

Table 4.2: Simulation parameters used for studying the impact of sensing beamwidth on sensing accuracy

Notation	Values assumed
ϕ (Sensing beamwidth of gNB)	0°- 180°
ϕ^w (Sensing beamwidth of WiFi-AP)	360°
τ	4 sec
P_{AP}	20dBm
f_s	20 KHz
σ_u^2	1
L	1
θ^g (Misalignment of gNB towards WiFi-AP)	50°
θ^w (Misalignment of WiFi-AP towards gNB)	130°

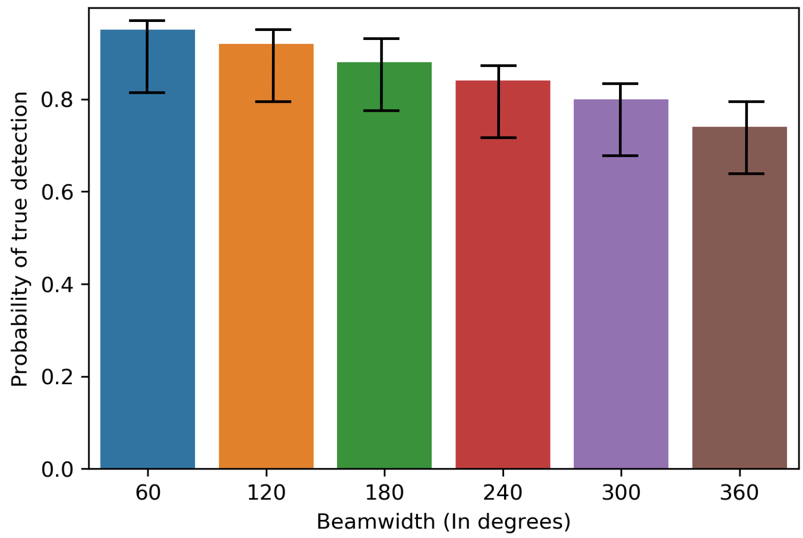

Figure 4.4: Impact of sensing accuracy over sensing beamwidth.

SNR values for each particular beamwidth, we use equation (4.8). The SINR of WiFi-AP on gNB is computed for a specific sensing beamwidth of gNB and a constant misalignment of WiFi-AP with the gNB. The transmit power of WiFi-AP is assumed to be 20 dBm.

$$\gamma = 20dBm + G^{\phi^w}(130) + G^{\phi^g}(50) - (\frac{\lambda}{4\pi\, d})^2 - 1. \tag{4.8}$$

$$P_d(\tau, \xi) = \mathcal{Q}\left(\left(\frac{\epsilon}{1} - \gamma - 1\right)\sqrt{\frac{4ms * 20kHz}{2\gamma + 1}}\right). \tag{4.9}$$

Depending on the beamwidth of gNB, the gain is calculated. For a path loss exponent (α=2), the path loss is calculated to be 1. Now that we have obtained the SNR value for a particular beamwidth, we find the true detection probability. The same procedure is repeated identically for other beamwidths.

Therefore, several values of beamwidth are plugged in to depict the impact of sensing beamwidth

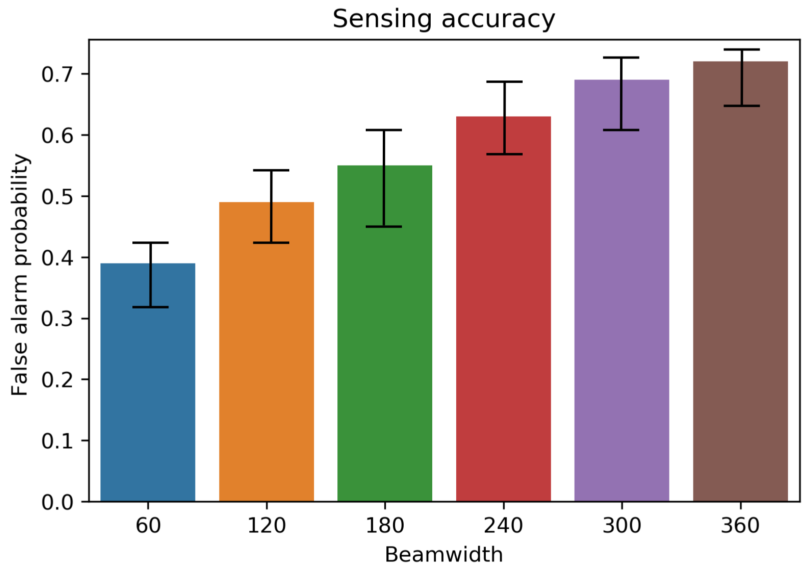

Figure 4.5: False alarm probability under increasing beamwidth. In terms of sensing, a smaller beamwidth of gNB results in lesser false alarms resulting in higher throughput. As beamwidth increases, the false alarm probability increases leading to few opportunities to transmit towards the users.

versus true detection. It can be seen from Fig.4.4 that as sensing beamwidth increases, the possibility of true detection decreases. In addition, the false alarm probability is much higher in wider beamwidths due to the overprotective nature of omnidirectional sensing as seen in Fig.4.5. Therefore the number of opportunities to transmit data towards its users is lesser than Dir-LBT resulting in lower capacity.

4.5 Basic idea

In this section, we discuss the high level description of the proposed algorithm. The challenges faced by directional sensing is explained after which how our heuristic algorithm circumvents these challenges are briefed about.

This spectrum sensing algorithm aims to sense in the direction of highest number of users as depicted in Fig.4.1. The rationale behind doing so is that the diversity is high and therefore the probability of one of the users attaining maximum capacity is high. Existing algorithms such as history assisted [24] spectrum sensing has a signaling overhead, as it would require the previous history of true detection and false detection probability values.

In order to sense in the direction of high number of users, it is essential to calculate the number of users sensed along each direction for a given beamwidth. The location of the user in space can be represented by the direction of arrival and the distance of a user.

Therefore, we can compute the number of users along each candidate direction. The direction with the highest number of users is sensed first. If the UEs are far away from each other or lie just outside the beamwidth of gNB, the number of beams to cover these UEs would increase. There is a need to increase the number of beams required to sense these leftover UEs. To circumvent this, we have included the possibility of beam adaptation of gNB to accommodate users. If the resulting beamwidth adaptation has aided in covering more users, beam merging is used. Otherwise, beamwidth adaptation is avoided. The more we reduce the number of beams required to sense, more time would be available to maximize the achievable throughput.

In order to reduce the number of beams, Omni-LBT could be used to cover the entire users using a single beam. However, there exists a trade-off. Omni-LBT affects the spectrum accuracy due to its overprotective nature. A graph is plotted Fig.4.4 to show the impact of spectrum sensing accuracy on using Dir-LBT and Omni-LBT. The probability of true detection reduces as the sensing beamwidth increases. In addition, the probability of false detection would be high resulting in lower capacity as the spectrum is assumed to be busy most of the time. Therefore spectrum reuse is not possible. This indicates that the spectrum should have been utilized under certain directions but was blocked by Omni-LBT at gNB. This is referred as the overprotective nature of Omni-LBT. Therefore, Dir-LBT is preferred over Omni-LBT for our spectrum sensing algorithm.

4.6 Spectrum sensing algorithm

This section introduces the variables and the assumptions used in the proposed sensing algorithm. Furthermore, a pseudo code is introduced along with its overview.

Let ζ denote the array of DOAs estimated from all the users. If the algorithm aids in reducing the number of directions required to sense, the sensing time (T_s) reduces. The sorting algorithm is coined to devise the order of sensing at gNB, to achieve our goal of reducing the sensing time. The pseudo code is depicted in Algorithm (2).

The inputs given to the sorting algorithm include number of users, DOA, beamwidth of gNB and distance of the user from gNB. Our goal is to the find out the directions to sense ($\hat{Q}$) for a particular beamwidth. Moreover, the parameters that affect spectrum sensing are also studied upon. The algorithm is run by varying the total number of users present ($\mathcal{N}$) and computing the number of directions required to be sensed for a particular beamwidth. In order to compute the set of directions needed to be sensed, we need to define Q for an arbitrary value of beamwidth (ϕ):

$$Q = 360 \,/\, \phi. \tag{4.10}$$

For a value of $\phi = 45°$, maximum number of directions (Q) is found to be 8. This implies that there are 8 different directions available for a beamwidth of 45°. The interval range of these individual directions are represented by an array given by:

$$\hat{Q} \;=\; [Q_0, Q_1, Q_2, \ldots, Q_i]\,, \tag{4.11}$$

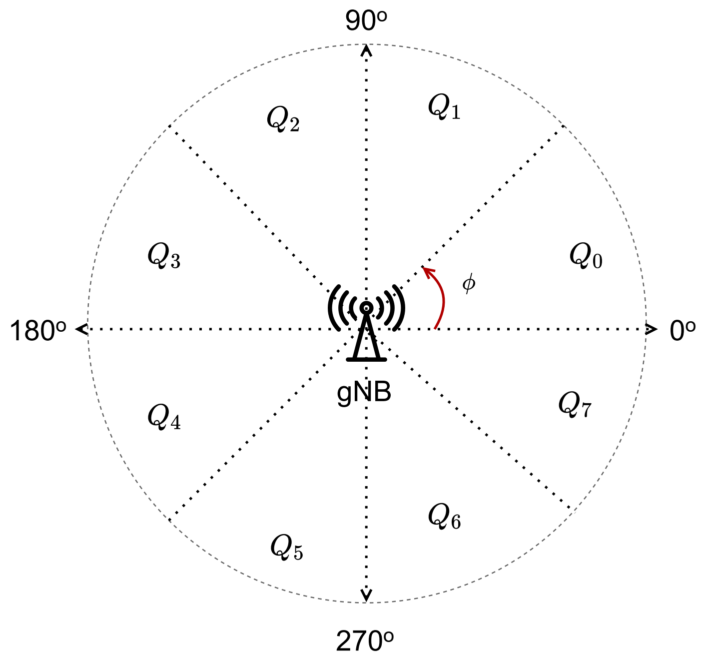

Figure 4.6: A representation of the available directions (Q) when gNB has a beamwidth of 45°.

where Q_0, Q_1, Q_2 would be 0° , 45° , 90° respectively.

For an arbitrary beamwidth of ϕ, the interval range of the individual directions can be represented as

$$\hat{Q} = [0, \phi, 2\phi, 3\phi, \ldots, Q\phi], \tag{4.12}$$

Therefore, now it would be easy for us to design the directions to be sensed for any particular beamwidth. Since we assume the locations of the users are known to the gNB, using our heuristic algorithm we avoid the directions unoccupied by users and only choosing the direction to sense in which users are present. The DOA outputs the (x,y) coordinates of the user along with the distance (d) of the user from gNB. The DOA is defined as:

$$\zeta = [(x_0, y_0), (x_1, y_1), (x_2, y_2), \ldots, (x_i, y_i)], \tag{4.13}$$

A user is said to be in a given direction, if the DOA lies within the interval range of the individual direction and the distance of the user should be within the sensing range of gNB. Let us take an example to understand this. Assume we need to find the number of users within the second compartment, for a beamwidth of gNB as 45°. For a user to be in the second compartment, the DOA of the users must be within the interval [45°, 90°]. Therefore, for a user to be within the ith compartment, the DOA must lie within the interval [Q[i], Q[i+1]]. This can be iterated to calculate the number of users across every candidate direction.

A counter is used to compute the total number of users across each direction. The direction along which the maximum number of users were found is checked for beamwidth adaptation.

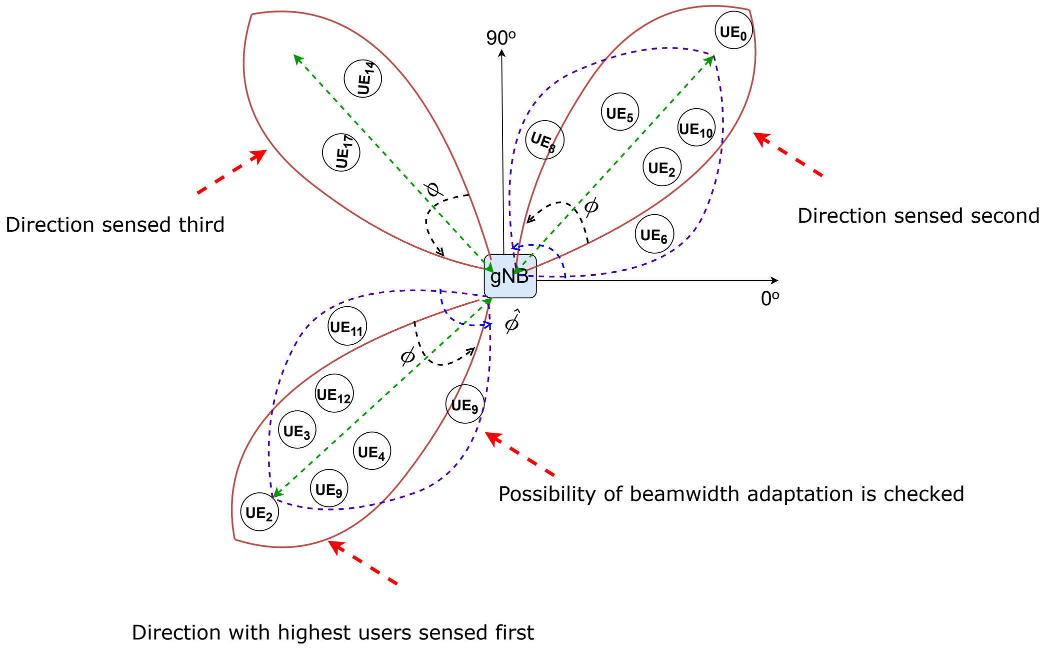

Figure 4.7: The representation of the directional spectrum sensing performed on gNB based on our heuristic algorithm. The direction with the highest number of users is sensed first followed by the possibility of beamwidth adaptation. Next, the direction with the second highest number of users is sensed according to the sorted order.

The possibility of beamwidth adaptation is checked on comparing the number of users within the coverage of gNB with and without beamwidth adaptation. Beamwidth adaptation is assumed to take place with twice the initial beamwidth of gNB ($\hat{\phi} = 2\phi$). This is done to quantify the reduction in the number of compartments needed to sense. Along the selected direction with maximum users, beamwidth adaptation is possible with the compartment in clockwise and anticlockwise direction. Say, across the second compartment maximum users are found. Now, beamwidth adaptation possibility is checked across the compartment in clockwise direction (third compartment) and anticlockwise direction (first compartment). Let us assume that count$_{clk}$ be the number of users on performing beam adaptation in the clockwise direction and count$_{anti}$ be the number of users on performing beam adaptation in the anticlockwise direction. We decide whether to execute beamwidth adaptation in the clockwise or anticlockwise direction based on the number of users. Each direction is assigned a flag (Is_BW_adaptation). If a particular direction is merged, the flag of the adapted direction is updated. Therefore, the compartment is no longer checked for beamwidth adaptation again. As a result, the number of compartments to sense can be significantly lowered.

The sensing procedure of the proposed algorithm is given in Algorithm (3). We represent the direction with maximum users as [r] as seen in Algorithm 2. We calculate the received power at the gNB, when the spectrum is sensed. We have calculated receiver power in the previous section. This is compared to the decision threshold to find if the direction is busy or idle. However if the sensed direction was busy, sensing is performed along the next direction i.e the one with the second highest number of users as sorted. The condition for a particular direction to be sensed idle is discussed in equation (3.6).

In order to select the direction to transmit, pilot symbols are sent towards the users within the compartment that consisted of the maximum number of users. The algorithm is represented in Algorithm (4). The SNR values of all users within the particular compartment are calculated. On sorting the values, we obtain the best user to which data transmission takes place.

The time complexity of the given algorithm is O($\mathcal{N}\mathcal{Q}$), where $\mathcal{N}$ is the number of users present and Q is the number of compartments. In order to calculate the number of users sensed in the candidate directions, a for loop is coined. The loop is iterated N times to calculate the number of users found under each compartment for a given beamwidth. It is undesirable to sense in multiple directions as the time required for sensing increases. Inside the inner loop, an if statement with time complexity O(1) is used. Therefore the overall complexity does not get affected. The number of beams required to sense decreases, considering that we combine the users in a given range of the beamwidth or merge the users of different beamwidths depending on the location of the users.

Using this algorithm gNB understands the direction to sense in order to attain maximum channel capacity at UE. On adapting this algorithm, the sensing overhead can be decreased and fewer directions are sensed to increase the possibility of attaining maximum throughput with minimal sensing inaccuracies. In the next chapter, we briefly analyze the performance of our adopted antenna model to understand the parameters affecting the performance of our system, Furthermore, we inspect the performance of our heuristic directional spectrum sensing algorithm on comparing it to a baseline algorithm.

Algorithm 2: Order of sensing

Input: $\mathcal{N}$: Total number of users, ζ: Direction of arrival of the users
d: Distance of the user from gNB , ϕ: The beamwidth of gNB
Output: Directions to sense = $\hat{Q}$, Beamwidth = Updated_BW, Number of users inside each beam = U_E_C.
//Initialization Q = 360 / ϕ
Updated_BW, Is_BW_adaptation, count, U_E_C = create 4 arrays of zeros with Q;
for *(i=0 upto Q-1:)* **do**
  Compute Start Angle of each compartment
  for *(k=1 upto N:)* **do**
    if *(Is_in_Range (d$_k$,ϕ,ζ_k,$\hat{Q}$) == True)* **then**
      The user$_k$ is inside the range of the beam ($\hat{Q}[i]$)
      count[i]+=1 `// Number of users under compartment is counted`
  U_E_C[i] = count[i] `// Compartment number is given by i`
count.sort() = $\hat{Q}$, r = array containing index of (count[i])
`// Beamwidth adaptation along max users direction is performed`
for *(j=1 upto len(r-1))* **do**
  count$_{clk}$[j] = 0, count$_{anti}$[j] = 0
  if *(Is_in_Range (d$_k$,2ϕ,ζ_k,$\hat{Q}$[r[j]-1]) == True)* **then**
    `// Starting angle and beamwidth are changed for clockwise beamwidth adaptation`
    The user$_k$ are inside the range of the beam ($\hat{Q}$[r[j]] to $\hat{Q}$[r[j]+ 1])
    count$_{clk}$[j]+=1, `// Clockwise beamwidth adaptation`
  if *(Is_in_Range (d$_k$,2ϕ,ζ_k,$\hat{Q}$[r[j]]) == True)* **then**
    `// Starting angle and beamwidth are changed for anticlockwise beamwidth adaptation`
    The user$_k$ are inside the range of the beam ($\hat{Q}$[r[j]] to $\hat{Q}$[r[j] - 1])
    count$_{anti}$[j]+=1 `// Anti-Clockwise beamwidth adaptation`
  if *(count$_{clk}$[j] => count$_{anti}$[j] & count[j])* **then**
    Right Merge, Is_BW_adaptation[r[j]-1] = 1, Updated_BW = 2ϕ
  else if *(count$_{anti}$[j] => count$_{clk}$[j] & count[j])* **then**
    Left Merge, Is_BW_adaptation[r[j]+1] = 2, Updated_BW = 2ϕ
  else
    Beamwidth adaptation discarded, Is_BW_adaptation[r] = 3, Updated_BW = ϕ
for *(s=1 upto Q:)* **do**
  if *(Is_BW_adaptation[s] = 1) & (Is_BW_adaptation[s] = 2)* **then**
    Beamwidth adaptation is not checked again
The directions to sense ($\hat{Q}$), Beamwidth for each directions (Updated_BW), U_E_C[i] = count[i]
return $\hat{Q}$, Updated_BW , U_E_C

Algorithm 3: Sensing procedure

Input: The directions to sense ($\hat{Q}$),
Beamwidth for each directions (Updated_BW)
distance of the user (d)
Path loss (L)
Decision Threshold (ξ)
Output: If a direction is busy or idle
//Initialization : Calculate Received Power along the candidate directions
if *Received_Power* $\leq \xi$ *at* $\hat{Q}_0$ **then**
    `// Direction with highest users`
    The direction is considered idle
else
    The direction is considered busy
    Received_Power is checked at index $\hat{Q}_1$
return Received_Power

Algorithm 4: Direction to transmit

Input: U_E_C = Number of Users along each direction
Beamwidth for each directions (Updated_BW)
Output: Direction to transmit
//Initialization : Create an array to store the SNR = Values[]
Calculate SNR towards the users within the range of gNB
for *(i=1 upto U_E_C[r_0]):* **do**
    `// Direction with highest users`
    SNR is calculated at every user$_i$ within the direction
    Values$[i]$ = Storing the values of SNR at every user
    Values.sort()
    The user with the highest SNR is selected for transmission
return Values

Chapter 5

Performance assessment

This chapter examines the performance of the implemented antenna model with various parameters. In addition, how they may be utilized to achieve high performance and increased efficiency, as well as the issues that may arise during the sensing and transmission times are studied. Further, the performance of the proposed algorithm for spectrum sensing is evaluated with a baseline algorithm and the impact of the algorithm under various use cases is discussed.

5.1 Performance assessment of the antenna model

In general, it is essential to examine the various parameters affecting the antenna model to have an understanding of the system model. Performance metrics such as distance, misalignment and beamwidth have a considerable effect on the performance of the antenna. The relationship between them and how their negative effects are nullified will be studied. Although the antenna model has been adapted from [18], we examine the performance of the antenna model to have a better understanding of our system model.

5.1.1 Gain vs Misalignment

In this subsection, we analyze the impact of gain of the antenna over misalignment for varying values of beamwidth. The goal is to examine the performance of narrow beams over wider beams under increasing values of misalignment. The impact of misalignment on beamwidth during spectrum sensing and data transmission will be estimated. As mentioned before, misalignment is the angle measured from the direction of perfect alignment to the axis of the antenna's main lobe.

A graph from [18] is used to depict the various gains of the gNB $(G_{ml}^{\phi}(\theta))$ over increasing values of beam misalignment (θ) is shown in Fig.5.1. The beamwidth of the gNB (ϕ) is varied between 5°, 15°, 30° and 60°. The gain can be calculated in dB, from the formulae in (3.1).

From Fig.5.1, let us compare the gain of 5° and 15° beamwidth versus misalignment. As expected

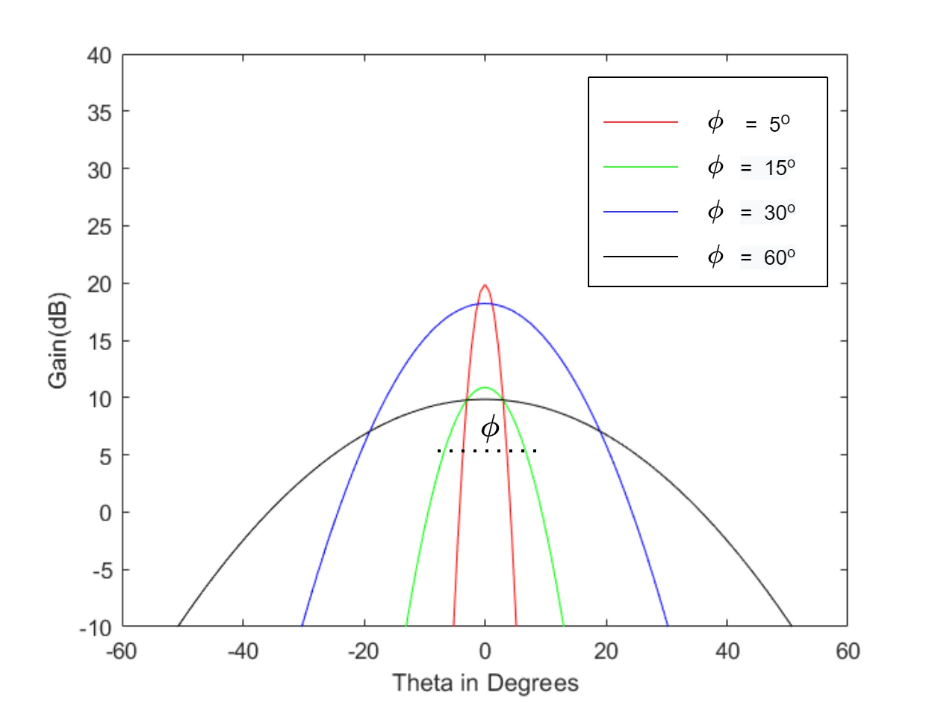

Figure 5.1: The impact of gNBs gain versus increasing values of misalignment, The goal is the examine the impact of narrow beams and wider beams on misalignment.

we find that when there is prefect alignment (misalignment equal to 0°), both beamwidths have the maximum gain. Also, we find that the gains of the 5° beamwidth decreases faster than that of the 15° beamwidth. The same holds true for all the other cases in the graph. The decrease of gain is comparatively slow when the beamwidth is the largest (in this case 60°).

Here we discuss the impact of misalignment on beamwidth during data transmission. From the graphs, we understand the gains of narrow beamwidth antennas deteriorate rapidly than those of wider beamwidth antennas. As a result, high gain narrow beam antennas are particularly vulnerable to misalignment problems. Effective transmitter and receiver antenna gains would be smaller than predicted antenna gains for a given transmitter and receiver beamwidths due to beam misalignments, resulting in transmission errors. Mobility, channel estimate inaccuracy, orientation errors owing to user device holding patterns, and flaws in the antenna array construction process, all contribute to beam misalignment.

Now, the impact of beam misalignment on beamwidth during spectrum sensing is evaluated. Spectrum sensing depends on the orientation of the WiFi-AP towards the gNB. Let us assume gNB adopts a wider beamwidth (60°) for spectrum sensing with increasing misalignment. Wider beamwidths are prone to interference from WiFi-AP, leading to fewer sensing opportunities. On the other hand, for a narrow beamwidth (15°) the probability of interference is less, giving rise to more sensing opportunities. Therefore, it is paramount to decide on the sensing beamwidth used to improve the overall performance of the system.

Table 5.1: Simulation parameters

Notation	Values assumed
P_{AP}	20 dBm
α (Path-loss exponent)	2
Beamwidth of WiFi-AP	30°,90°,360°
Beamwidth of gNB	30°,60°,90°,360°
ϵ	-74 dBm

5.1.2 Distance

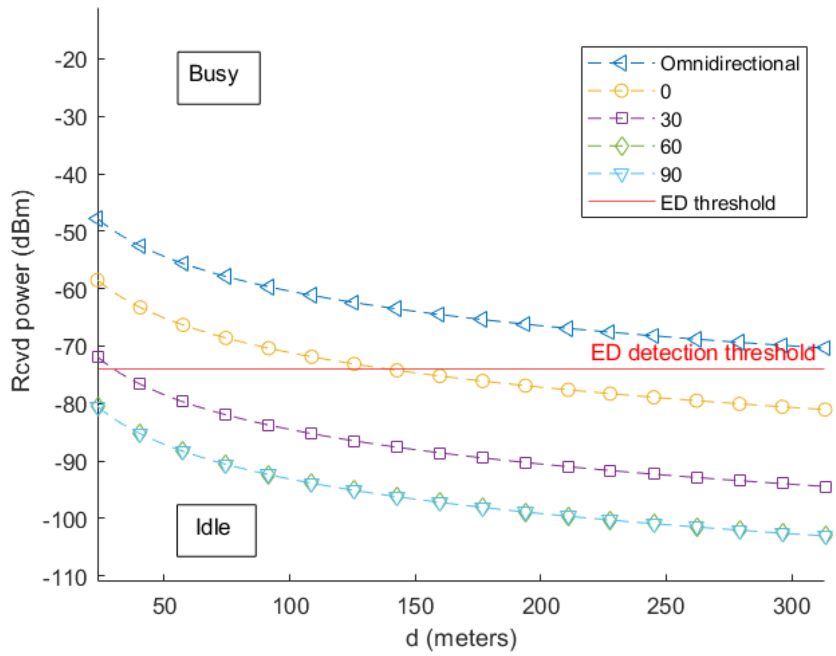

Figure 5.2: Received Power vs distance under 2 scenarios including Dir-LBT at gNB with beamwidth of (60°), while WiFi-AP with a beamwidth of (360°) and Omni-LBT at gNB and WiFi-AP

In this subsection, we aim to understand the impact of received power for two different scenarios as depicted in Fig.5.3. The distance between the WiFi-AP and gNB is varied against increasing values of misalignment for a constant value of P_{AP} and pathloss exponent (α). In addition, the influence on misalignment(θ^g) for increasing values of distances are computed. Table [5.1] displays the values of the simulation parameters. The goal of this simulation is to understand the following:

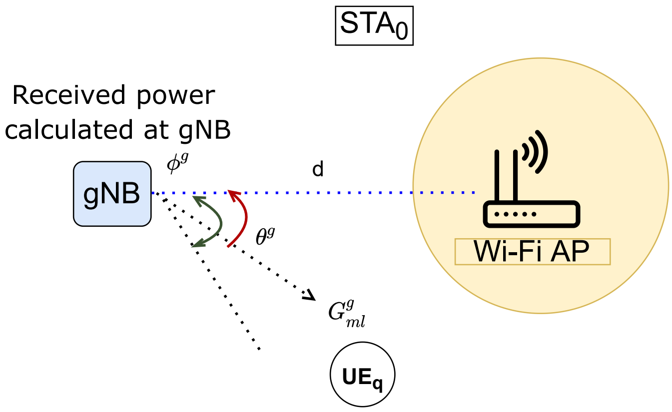

Figure 5.3: A representation of the scenarios considered to evaluate the impact of received power of gNB with increasing distance between them. WiFi-AP uses Omni-LBT, while gNB uses Dir-LBT towards its users.

- What are the distances at which a particular direction is sensed idle ?
  - The received power of gNB declines as the distance between the transmitter and receiver increases, as seen Fig.5.2. A line at the decision threshold is drawn to demarcate if the directions sensed along are busy or idle. From the graphs, we see that for larger misalignments the spectrum would be sensed idle for a beamwidth of 60°. It is important to note that as misalignment increases the boresight antenna of the transmitter, therefore the receiver would be facing in opposite directions. For a smaller misalignment though, the sensed direction will be busy for smaller values of distance. As depicted under this set-up, at the distance of 138 meters, the sensed direction is found idle for a misalignment of 0°. In addition for a misalignment of 30°, the direction is sensed to be idle at a distance of 26 meters.

- Why is Dir-LBT preferable over Omni-LBT?
  - In Fig.5.2 we consider 2 cases such as Dir-LBT at gNB with a beamwidth of 60° and Omni-LBT in WiFi-AP and Omni-LBT at both WiFi-AP and gNB. Each line on the graph, represents an increase in misalignment between the transmitter and the receiver. We also observe that as misalignment increases, the received power overlaps. From equation 3.1, we find a condition for which the gains of the WiFi-AP and gNB could lie in the main lobe or the side lobe. When $|\theta| > 1.3\phi$, side lobe gain is considered and therefore the overlap in the received power for increasing misalignment. The received power falls dramatically as the misalignment between the transmitter and receiver increases. When using Dir-LBT, we observe that the sensed direction becomes idle for certain misalignment and distance values. On the other hand, when gNB is equipped with Omni-LBT with a beamwidth of 360°, results in gNB sensing the spectrum busy most of the time, as seen in Fig.5.2. This explains the overprotective nature of Omni-LBT and the lack of sensing opportunities to maximize capacity.

5.1.3 Misalignment

In this subsection, the misalignment of gNB is varied against increasing values of distance. For a constant value of P_{AP} and pathloss exponent (α). The goal of this simulation is to understand the following:

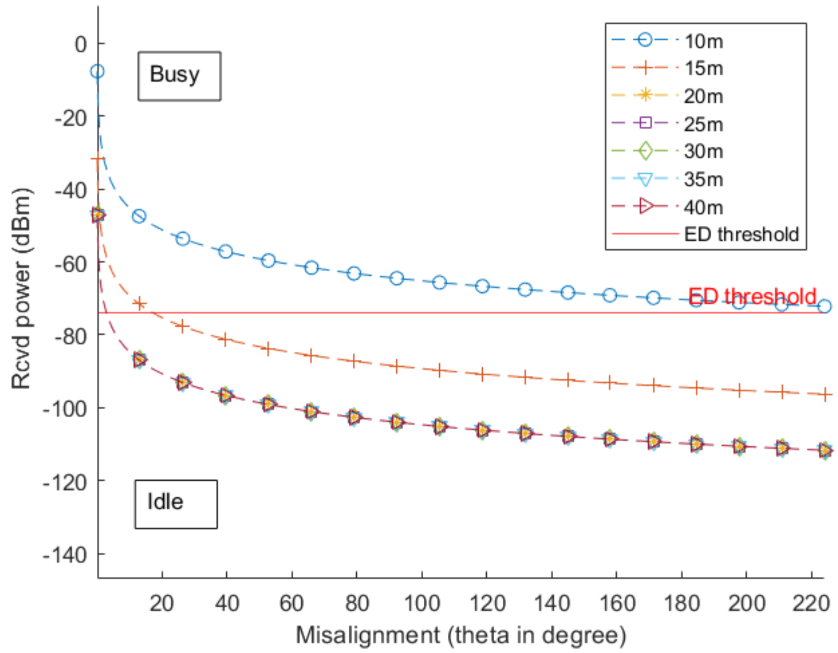

Figure 5.4: Received power vs increasing Misalignment, for gNBs' beamwidth of 30°under increasing distances between WiFi-AP and gNB

- How does received power depend on misalignment at gNB for a particular beamwidth?
  - On increasing the distance (meters) between the transmitter and the receiver, the effect of misalignment on received power is assessed. The beamwidths of gNB and WiFi AP are equal. In the first case a beamwidth of 30° is considered, followed by 90° in the second case. The points on the graph denote the distance between WiFi-AP and gNB. As expected, for the least possible distance between them, received power is maximum. As distance increases, the received power decreases as expected. However, there exists a trade-off. Received power depends on the misalignment between the transmitter and receiver antenna. Take the example of the curve when d is assumed to be 15m in Fig.5.4 and Fig.5.5, as misalignment increases, the direction becomes idle faster when the beamwidth was assumed to be 30°. Although when the beamwidth is set at 90°, the effect of misalignment is minimal. Thus, the rate of decline in received power observed at the former Fig.5.4 case is faster than the later Fig.5.5 instance. This is because, narrow beams are more susceptible to misalignment. On the other hand, misalignment has a negligible influence on larger beamwidth.

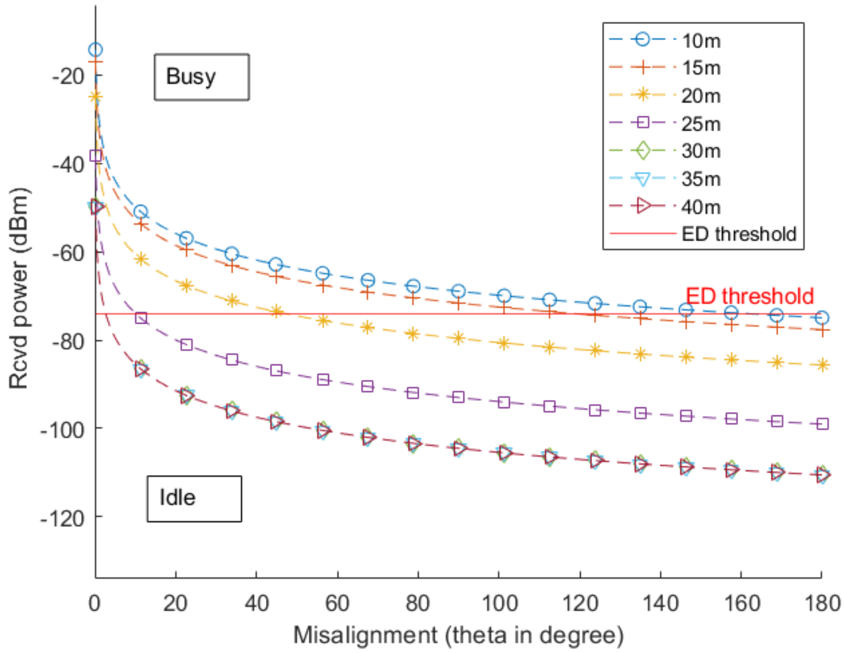

Figure 5.5: Received power vs increasing misalignment, for gNBs' beamwidth of 90° under increasing distances between WiFi-AP and gNB

5.1.4 Key takeaways

The performance of the antenna has been studied in detail and the insights obtained are as follows:

- Narrow beamwidths were found to be sensitive to misalignment when compared to wider beamwidths. The impact of misalignment on beamwidth during data transmission was discussed. As high gain narrow beams are particularly vulnerable to misalignment, effective gains during data transmission would be less resulting in transmission errors.

  Under the impact of received power on distance, we understand the overprotective nature of Omni-LBT. The direction sensed would be considered busy since gNB senses omnidirectionally. While under Dir-LBT, for a particular beamwidth the distances at which the sensed direction was found idle as studied above.

  The effect of beamwidth on misalignment during spectrum sensing is considered essential and opting for the right one is pivotal for better performance. Maximum misalignment is desirable while spectrum sensing. On increasing the misalignment, the direction would have less WiFi signal level. Hence, more opportunity to access the spectrum thereby increase in throughput towards the user. However, minimum misalignment is desirable during data transmission. This is because, the gain of transmitter and the receiver is high during minimum misalignment leading to higher throughput.

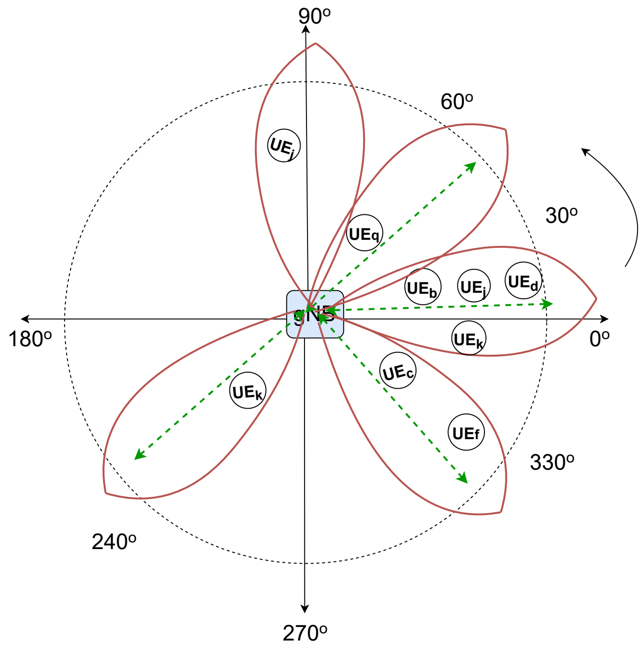

Figure 5.6: The representation of the directional spectrum sensing performed on gNB for a beamwidth of 30° (12 sectors) based on our baseline algorithm. The possibility of beamwidth adaptation is checked followed by sensing towards the particular direction. Certain directions are skipped if no UEs are present.

5.2 Performance of the spectrum sensing algorithm

In this section, we aim to discuss the performance of our proposed heuristic algorithm. In order to understand its performance, we coin a baseline algorithm. The baseline algorithm is a simple but effective method for determining the minimum performance level of an algorithm. The goals of performing the sensing algorithm is studied followed by the results. The various types of user distributions used in our research will be discussed.

5.2.1 Baseline algorithm

A baseline algorithm is devised to compare the efficiency of our sensing algorithm. A circle is divided into k sectors ranging from $[1, \cdots, k]$. The beamwidth is calculated as $360/k$. Accordingly, the number of users sensed under each compartment is calculated. Algorithm 5 summarizes the approach. The received power for each direction sensed is calculated, if the received power is greater than the decision threshold it is considered busy. Once found idle, sensing is stopped. If not, the sensing continued sequentially across the compartments starting with the first compartment as depicted in Fig.5.6. Also, it does skip sensing a direction if no UEs reside in that direction.

We compute order of sensing $(\hat{Q})$ to compare the set of directions required using our heuristic algorithm and the baseline algorithm.

In the next section, we use Omni-LBT and Dir-LBT to determine the throughput of our system model. When comparing throughput, we aim to understand how Dir-LBT outperforms Omni-LBT

Algorithm 5: Baseline Algorithm

Input: $\mathcal{N}$: Total number of users
ζ: Direction of arrival of the users
d: Distance of the user from gNB
Output: Set of directions to be sensed = $\hat{Q}$.
//Initialization Compartments = n, , Calculate Received Power across directions;
for *each,* $i \in range[1, n]$: **do**
  $\phi =$ 360/i `// Beamwidth of gNB is calculated`
  for *(k=1 upto n-1:)* **do**
    if *Received_Power* $\leq \xi$ *at* $\hat{Q}_0$ **then**
      The direction is considered idle
      break;
    else
      The direction is considered busy
      Received_Power is checked at index $\hat{Q}_1$
return ($\hat{Q}$)

in terms of throughput.

5.3 Performance evaluation of Omni-LBT/Dir-LBT in terms of throughput

5.3.1 Simulation Setup

In this section, we describe the simulation setup to depict the throughput at gNB and WiFi-AP when various sensing approaches are assumed. The goal is to study the impact of using Dir-LBT over Omni-LBT in terms of throughput. Furthermore, we analyze the throughput using our proposed baseline, directional spectrum sensing algorithm and optimal approach.

We assume WiFi uses Omni-LBT and directional transmissions towards its users. For gNB, various sensing approaches i.e, Omni-LBT, Dir-LBT using our proposed baseline, Dir-LBT using our proposed directional spectrum sensing algorithm and the optimal solution are considered. Therefore the various scenarios include:

- Omni-LBT at WiFi and gNB
- Omni-LBT at WiFi and Dir-LBT using baseline algorithm at gNB
- Omni-LBT at WiFi and Dir-LBT using our proposed directional spectrum sensing algorithm at gNB
- Omni-LBT at WiFi and Dir-LBT using optimal approach at gNB

Table 5.2: Simulation parameters used for studying the impact of throughput on number of users.

Notation	Values assumed
ϕ^w (Sensing beamwidth of WiFi)	360°
ϕ^g (Sensing beamwidth of gNB)	30°
ϕ (Transmission beamwidth)	30°
P_g	25 dBm
P_{AP}	25 dBm
τ	4 sec
N_o	1
L	1
Bandwidth	20 MHz
Path loss exponent	2

The various factors that affect throughput include the number of users present, beamwidth granularity at the transmitter, and the distance between the two networks. The goal is to understand the impact of Omni-LBT/Dir-LBT on the factors influencing throughput. We assume WiFi-AP and gNB know the location of their users. The time taken for WiFi-AP to sense a particular direction is assumed to be constant at (τ_w) seconds. For gNB, the time taken for sensing is also assumed to be constant at (τ) seconds. We assume that the users are randomly distributed. In order to compute the total sensing time required for our baseline and proposed directional sensing algorithm we find the number of directions needed to sense. Therefore the total sensing time would be the number of directions to sense multiplied by the constant time taken for sensing along a particular direction.

For the optimal approach, a simple search algorithm (Linear search) is used. A sequential search is performed across all directions one by one in this type of search. Throughput is evaluated in each direction, and if the maximum throughput is determined, that direction is returned; otherwise, the search continues until all possible directions are exhausted. Under this algorithm, gNB senses in all directions with a worst case time complexity of O(Q), where Q denotes the number of sensing directions. Data transmission takes place in the particular direction to obtain maximum throughput. Therefore the total sensing time would be equal to the time taken for sensing a particular direction. This is because, the optimal approach senses only along the particular direction determined with maximum throughput.

The simulations are run 1000 times, and the averages are reported along with the 95% confidence interval.

5.3.2 Evaluation of throughput in terms of number of users

Under this section, we observe the impact of number of users on throughput when Omni-LBT is used at WiFi-AP and various sensing approaches are opted at gNB.

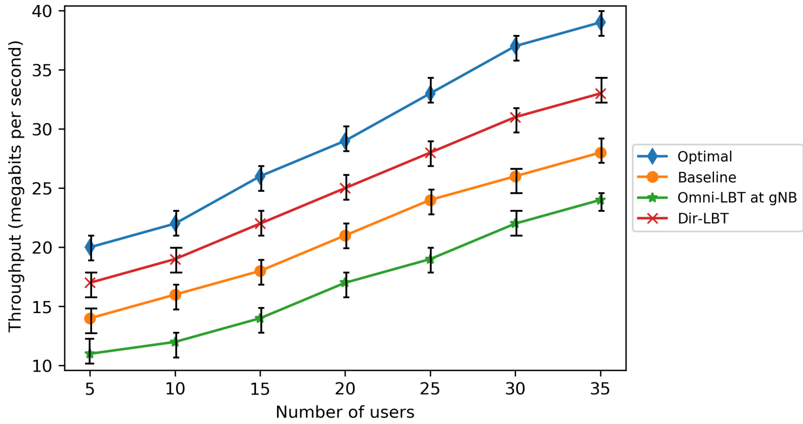

Figure 5.7: Impact of number of users on throughput. As number of users increases, the throughput increases. The optimal approach results in the maximum throughput.

Under the first scenario, we assume Omni-LBT at WiFi-AP and gNB. We assume the distance between gNB and WiFi-AP is fixed at 10m. We see that gNB finds the spectrum to be busy most of the time. Hence, data transmission does not take place. This explains the overprotective nature of Omni-LBT. On performing Omni-LBT at gNB, the transmissions that do not cause a collision with gNB are also avoided resulting in the lowest possible throughput at UE. To understand the number of users that access that channel, we simulate the scenarios. The graph in Fig.5.8 depicts the number of users that access the channel over various sensing approaches such as Omni-LBT and Dir-LBT used at gNB and only Omni-LBT at WiFi. We can infer that when both are equipped with Omni-LBT, the number of successful attempts to access the channel are equal and low in number. However, when Dir-LBT is opted at gNB, the number of successful attempts to access the channel is considerably higher at gNB compared to Omni-LBT equipped at WiFi-AP. This depicts the overprotective nature of Omni-LBT. A graph in Fig.5.9 depicts the false alarm probability when equipped with Omni-LBT and Dir-LBT. It can be seen the Omni-LBT has a higher false alarm probability leading to overprotective nature and lesser throughput. The number of users is increased in a cell and throughput is evaluated under each scenario. As depicted in Fig.5.7, as the number of users increases the achievable throughput increases.

We assume Omni-LBT at WiFi-AP and Dir-LBT using our proposed baseline algorithm at gNB in our second scenario. To find out the number of directions required to sense, we run our baseline algorithm. The number of directions to sense was found to be 5 for a beamwidth of 30° at gNB and the number of users is equal to 15. Since we assume constant sensing time, the total sensing time is computed as $5(\tau)$. This implies that along the 5 directions, spectrum sensing is performed when the number of users is equal to 15. Similarly, we increase the number of users and correspondingly find out the number of beams required under each case. A graph shown in Fig.5.10 depicts the number of beams required under each case. If the spectrum is found to be idle along any of these directions, sensing is stopped. Therefore, the throughput is computed towards the direction found to be idle. The effect of the number of users on throughput is plotted

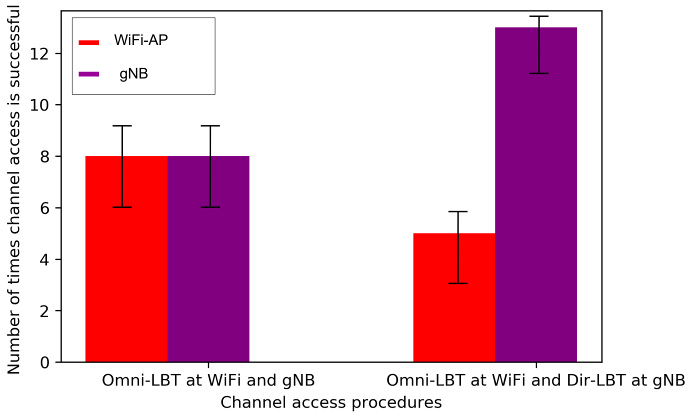

Figure 5.8: The number of successful attempts to access the channel when Omni-LBT and Dir-LBT is equipped at gNB. The overprotective nature of Omni-LBT is seen as the number of successful attempts to access the channel is lower.

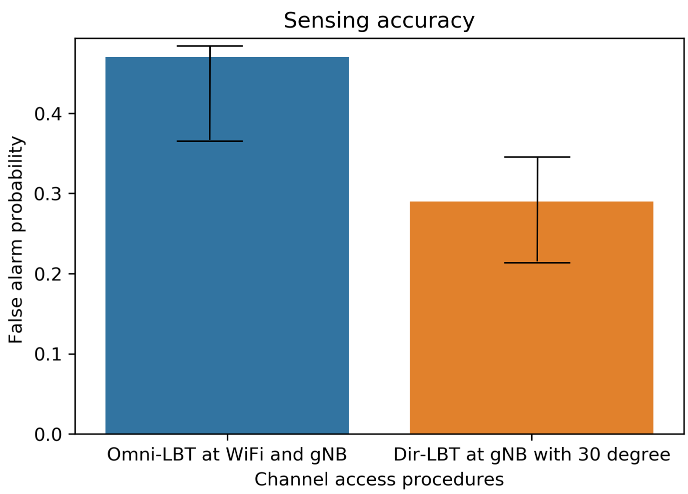

Figure 5.9: False alarm probability when equipped with Omni-LBT and Dir-LBT. It can be seen the Omni-LBT has a higher false alarm probability leading to overprotective nature and lesser throughput.

as shown in Fig.5.7. It is clear that with increase in number of users, the throughput increases. For 20 users present, we obtain a throughput of 18 megabits/second.

During the third scenario, we aim to find the impact of number of users on throughput when Omni-LBT is opted at WiFi-AP and Dir-LBT using our proposed directional sensing algorithm at gNB. Using our proposed directional sensing algorithm, the directions to sense are computed ($\hat{Q}$). The number of directions to sense was found to be 3. Therefore, the total sensing time is computed as $3(\tau)$. Spectrum sensing is performed along the direction with the maximum number of users. Consequently, if found to be idle, pilot symbols are sent to compute the SNR at the users. Along the best user, data transmission takes place. We determine the throughput for a given transmission beamwidth. As mentioned before, the goal of the proposed directional spectrum sensing algorithm is to reduce the sensing time in order to leave more time for data transmission. This is achieved with the aid of beamwidth adaptation and only sensing in certain directions. Therefore, more time is left for data transmission resulting in higher throughput than our baseline

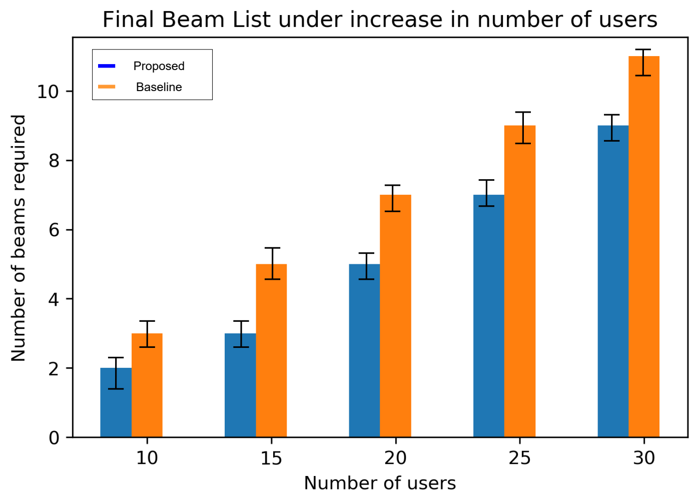

Figure 5.10: Number of beams needed to sense over increasing number of users in our baseline and proposed directional sensing algorithm.

algorithm. In addition, Fig.5.9 depicts the sensing accuracy of Dir-LBT when performed with a beamwidth of 30°. The lower false alarm enables more opportunities to transmit towards the users. Similarly, for 20 users, we obtain a throughput of 24 megabits/second which is higher than our baseline algorithm.

Under the optimal approach, gNB computes the direction to sense using a linear search algorithm. The total time needed to sense is τ milliseconds. Now, we evaluate the performance of throughput with the number of users present. As expected, Omni-LBT at gNB and WiFi results in the lowest throughput. Our proposed directional sensing algorithm results in higher throughput than our baseline. The time needed for data transmission is higher due to sensing along fewer directions and performing beamwidth adaptation. However, the optimal approach achieves the highest throughput as only the direction with the maximum throughput is used.

5.3.3 Impact of beamwidth granularity on throughput

In this section, we examine the impact of beamwidth granularity on throughput when WiFi-AP is equipped with Omni-LBT and various sensing approaches are used in gNB.

In general, beamwidth granularity is the realizable increment in beamwidth between adjacent beam positions of gNB and WiFi-AP. In terms of sensing, a smaller beamwidth of gNB results in more directions to sense. A graph in Fig.5.11 depicts the variation of the number of beams required under increasing beamwidth. Hence, more time is spent on sensing for a narrow beamwidth. However, during transmission smaller beamwidths are preferred as they prevent the undesirable interference of the neighboring network. Therefore, it is important to understand the performance of throughput in terms of beamwidth. In this case, we assume that the number of users present is constant at 20. In addition, we assume the distance between gNB and WiFi-AP is fixed at 30m.

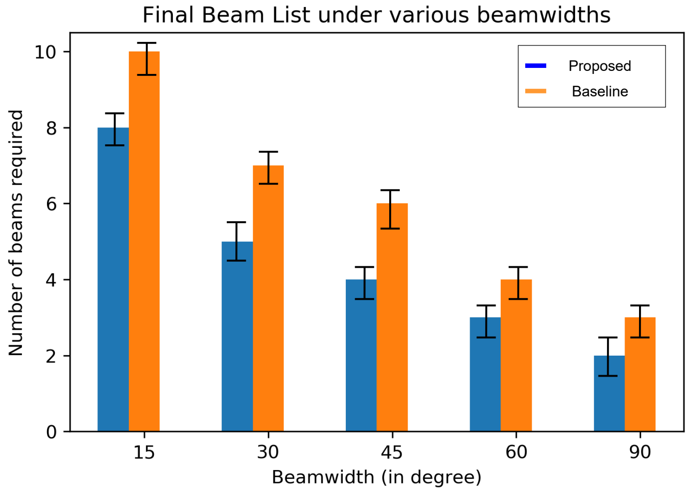

Figure 5.11: Number of beams required under increasing beamwidth

Under the first scenario, less time is required for sensing as gNB and WiFi are equipped with Omni-LBT. Each user can be covered with one single beam with no granularity. Hence, the sensing overhead is minimal. However, spectrum sensing results in the spectrum being busy. Therefore gNB does not access the spectrum assuming the spectrum to be busy most times. Although the sensing overhead is high on using Dir-LBT, it results in higher throughput as opportunities are available for data transmission.

Now to evaluate the second scenario, we find the number of directions needed to sense with increasing beamwidth granularity. For a beamwidth of 15°, the number of directions to sense in our baseline algorithm was found to be 10. However, as we increase the beamwidth of gNB to 30°, the number of directions required to sense is reduced to 7. Therefore the total sensing time might be less for a wider beamwidth. Similarly, the beamwidth is increased and the number of directions needed to sense is computed for each case. To understand the impact of sensing beamwidth, we assume constant transmission beamwidth (30°). Therefore for a constant transmission beamwidth, the throughput is computed. As depicted in Fig.5.13, as sensing beamwidth increases, throughput increases. However, the throughput decreases after a point due to minimal sensing opportunities available on opting for a wider beamwidth. This is because of the impact of sensing accuracy on sensing beamwidth. As the beamwidth increases, the sensing accuracy decreases leading to a higher false alarm probability.

Under our proposed directional spectrum sensing algorithm, the number of directions to sense is computed for increasing sensing beamwidth. It was found that the number of directions needed to sense was 8 and 5 for a sensing beamwidth of 15° and 30° respectively. Similarly, we compute the number directions to sense for increasing sensing beamwidth. The fraction of saving in sensing time is higher as fewer directions are required to sense. Therefore for a given transmission beamwidth (30°), it results in higher throughput than our proposed baseline. Although the number of directions needed to sense reduces while using a wider beamwidth, so does the sensing

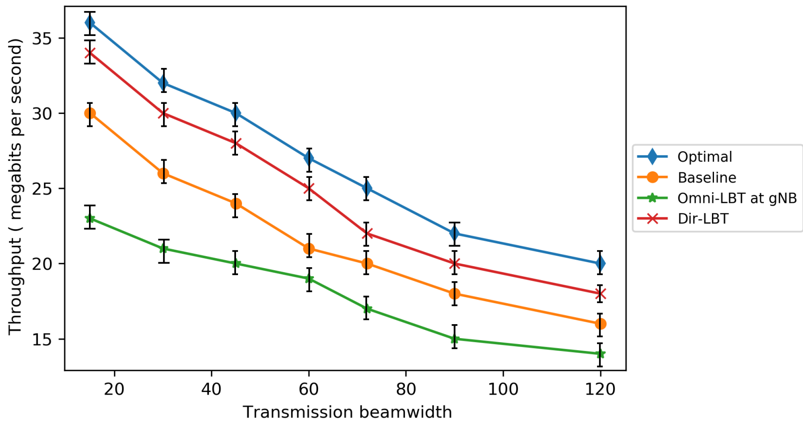

Figure 5.12: Impact of transmission beamwidth on throughput. As transmission beamwidth increases, the throughput decreases as the level of interference of increases when wider beamwidth is employed. Therefore in order to maximize throughput, narrow beamwidth should be preferred.

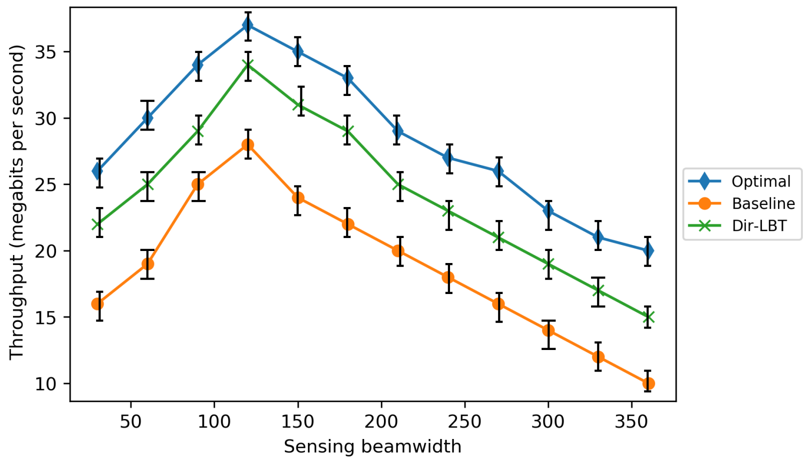

Figure 5.13: Impact of sensing beamwidth on throughput. As sensing beamwidth increases, the throughput increases for a while and decreases further during omnidirectional sensing. Most of the time the spectrum is sensed to be busy.

opportunities for gNB to transmit towards its users. Therefore Dir-LBT is beneficial inspite of having high sensing overhead.

On using our optimal approach, irrespective of the sensing beamwidth granularity only one direction is selected based on maximum throughput. Along this candidate direction, the throughput is calculated for a given transmission beamwidth (30°). For a sensing beamwidth of 60°, we obtain a throughput of 29 megabits/second as depicted in Fig.5.13. Now, we inspect the impact of transmission beamwidth on throughput. In the previous section, we computed the number of directions needed to sense for our baseline and proposed directional spectrum sensing algorithm. We find that throughput is decreased as beamwidth increases as depicted in Fig.5.12. As beamwidth increases, the possibility of interference with the neighboring network is high. Hence the SINR decreases as transmission beamwidth is increased as seen in Fig.5.14. In our optimal

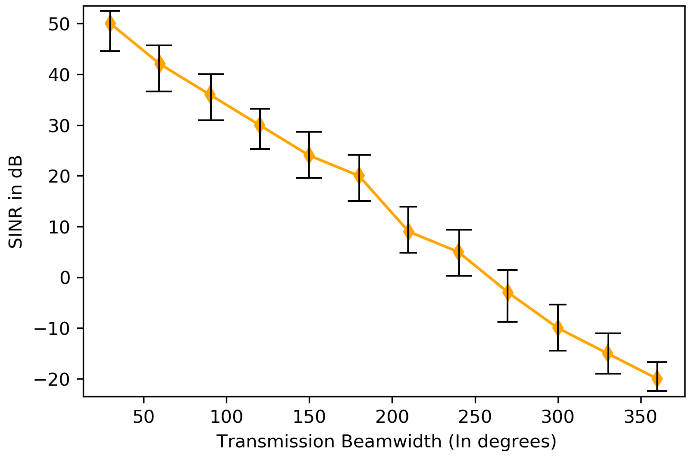

Figure 5.14: Impact of transmission beamwidth on SINR. As transmission beamwidth increases, the SINR decreases as wider beamwidths are more prone to interference.

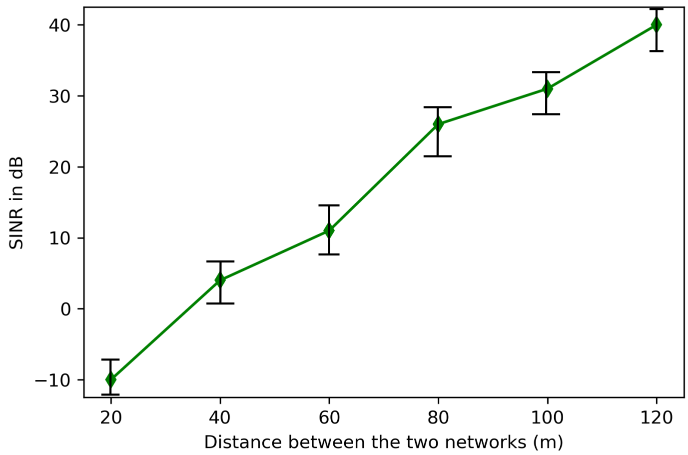

Figure 5.15: Impact of the distance between the two networks on SINR. As distance between the two networks increase, the SINR increases as the interference decreases.

approach, for a transmission beamwidth of 30°, we obtain a throughput of 32 megabits/second as seen in Fig.5.12. Therefore, it is imperative to use a narrow transmission beamwidth to maximize throughput.

5.3.4 Impact of distance between the WiFi-AP and gNB on throughput

In this section, we examine the impact of distance between the WiFi-AP and gNB on throughput when WiFi-AP is equipped with Omni-LBT and various sensing approaches are used in gNB.

When the distance between the WiFi-AP and gNB is increased, few directions are found to be idle in the first scenario. Therefore, under these directions, the throughput is evaluated since data transmission is possible. Hence as the distance is increased, data transmission takes place without any undesirable interference from the neighboring network. However, certain directions are still found to be busy due to the overprotective nature of Omni-LBT resulting in lower throughput.

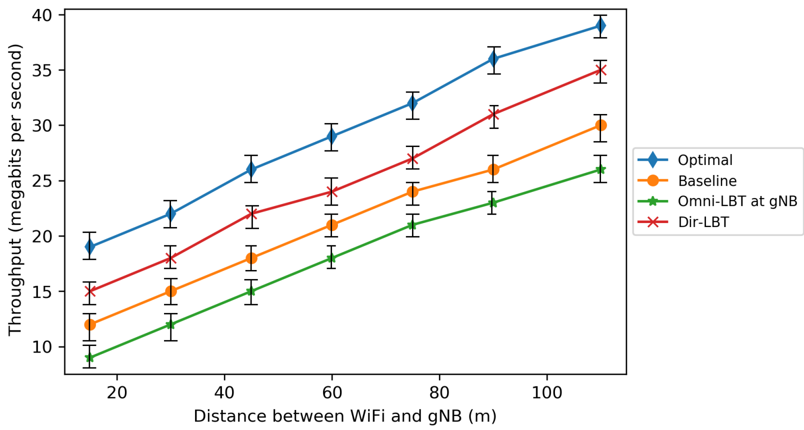

Figure 5.16: Impact of the distance between the two networks on throughput. As distance increases, the level of interference on the neighbouring network decreases resulting in a higher throughput.

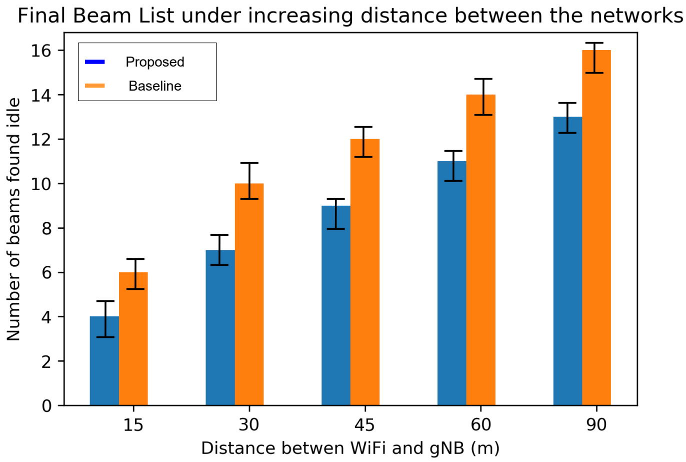

Figure 5.17: Number of beams found idle when distance between the two networks is increased, The number of beams found idle increases with distance between the two networks.

Similarly, under the second scenario and the third scenario, the distance between the WiFi-AP and gNB is increased. As the distance increases, more directions were found to be idle as depicted in Fig.5.17. For a sensing beamwidth of 15°, we compute the number of directions to sense under baseline and proposed directional sensing algorithm. For a constant transmission beamwidth (30°), the throughput increases as the distance between the WiFi-AP and gNB increases. The interference of WiFi-AP on UE is reduced as the distance between them increases. Therefore, the SINR also increases as distance between the two networks increases as seen in Fig.5.15. As depicted in Fig.5.16, we obtain a throughput of 21 megabits/second at a distance of 50m in our proposed algorithm, However, as distance increases to 110m, we obtain a throughput of 33 megabits/second.

In the optimal approach, the maximum throughput is reached at a distance of 110m. Therefore, we understand as the distance between the two networks increases, the throughput increases as lower interference is obtained.

To sum up, Dir-LBT results in higher throughput than Omni-LBT. Hence, the use of Dir-LBT is recommended over Omni-LBT to provide higher spectral accuracy and throughput.

5.4 Evaluation of the proposed directional sensing algorithm

To understand the impact of spectrum sensing under several scenarios, we aim to realize the following:

- To determine the impact of spectrum sensing under various user distributions in terms of resulting performance under the number of sensing beams.

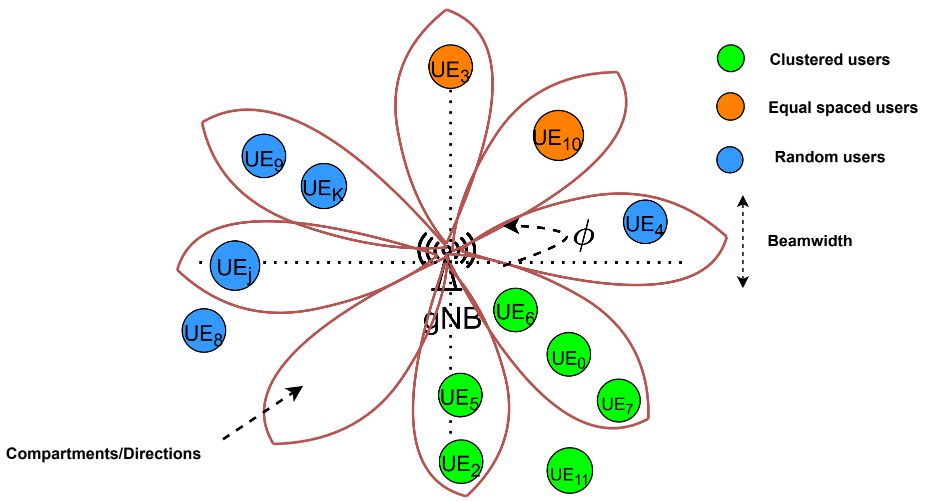

Figure 5.18: Various user distributions are depicted such as clustered users, random user distribution and equally spaced users. Clustered user distribution are depicted as group of users lying under the certain beams. Under random user distribution, the users are randomly distributed and users are spread out equally in all directions for fixed user distribution. The goal is to understand the impact of user distribution on spectrum sensing

5.4.1 Impact of user distribution on spectrum sensing

In the previous section, we devised the throughput of our proposed directional spectrum sensing algorithm under random user distribution. We have coined several use cases to show its performance under various user distributions such as:

- Random user distribution: Under this distribution, UEs are randomly distributed as depicted in Fig.5.18.

- Equal user distribution: Under this user distribution, the users are spread out equally in all directions as shown in Fig.5.18. This means that under each beam there exists equal number of users present when spectrum sensing is performed. The goal is the understand the impact of users distribution when users are spread equally on the fraction of saving in sensing time.

- Clustered users: Under this user distribution, we assume that the users are spread out as clusters. This means that few users are present under certain beams as groups whereas no users in other beams as represented in Fig.5.18.

Table 5.3: Set of values used in the proposed directional sensing algorithm to evaluate the performance of the algorithm

Notation	Values
Number of users	10, 15, 20, 25, 30
ϕ	15°and 30°

This section details the performance of the heuristic and baseline algorithm in terms of number of beams required. We find that the number of beams required to sense depends on the user distribution and the total number of users present. The results of the simulations are listed below. The simulations are run 1000 times, and the averages are reported along with the 95% confidence interval.

5.4.2 Number of beams required under various user distribution

The number of beams required to sense the users in the spectrum primarily depends on two major parameters. The number of users present in the cell and the spacing of the users. The number of beams required to sense the spectrum reduces if the number of users increases, however, if they are placed far apart from each other, the possibility of beam adaptation is decreased. Therefore in this section, we examine the impact of the number of users on the final number of beams required for directional spectrum sensing under various user distributions. The number of users is increased periodically from 10 to 30 considering the cell size of gNB as given in Table [5.3]. For various user distributions such as random, clustered and fixed, we find out the number of beams required. $\hat{Q}$ outputs the set of directions required for our proposed directional sensing algorithm. The heuristic directional sensing algorithm is run 1000 times and the averages are reported along with the 95% confidence interval. It can be inferred that when under clustered users, less number of beams are required for sensing. Only certain beams are occupied with users while other beams are completely left empty. Using beam adaptation, the number of beams can be reduced further as depicted in Fig.5.19 and Fig.5.20. The number of beams required was found to be maximum under fixed user distribution. Therefore, this approach has higher potential for clustered users.

5.5 Key Takeaways

The impact of various parameters such as number of users, beamwidth granularity and distance between the networks on throughput were studied upon using various spectrum sensing approaches. The goal was to understand the impact of Dir-LBT and Omni-LBT in terms of throughput.

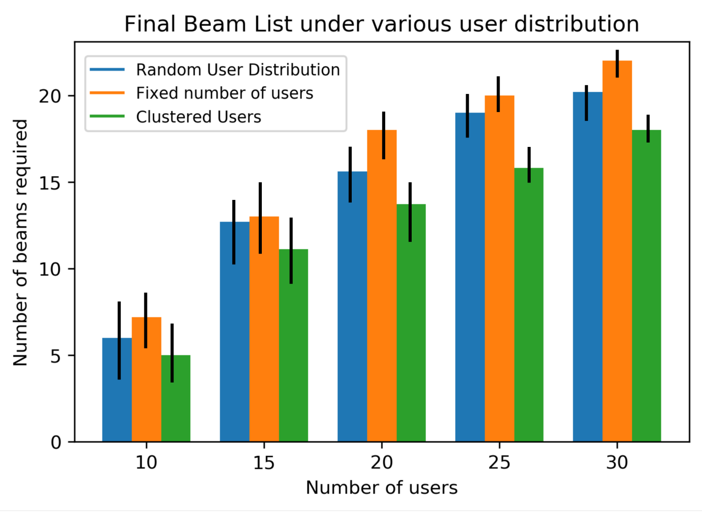

Figure 5.19: The number of beams required for spectrum sensing with increasing number of beams required for a beamwidth of 15°

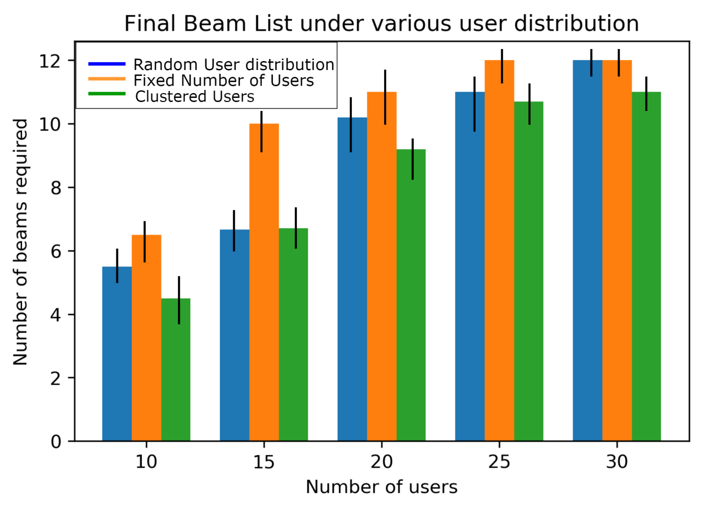

Figure 5.20: The number of beams required for spectrum sensing with increasing number of users for a beamwidth of 30°

Moreover, The impact of user distribution on spectrum sensing was discussed. Various user distributions such as random, fixed, clustered user distributions were inspected. The drawn results were as follows:

- As the sensing beamwidth is increased, the throughput increases. However, with an increase in sensing beamwidth, the probability of spectrum sensing being busy is higher. Therefore, after a certain beamwidth, throughput decreases. The optimal method results in the highest throughput followed by our proposed algorithm.
- As transmission beamwidth is increased, the throughput decreases. The rationale is that larger transmission beamwidth results in a higher possibility of interference with neighboring networks. However, narrow beamwidths have less possibility of interference. Hence, it yields a higher throughput. In addition, larger beamwidths have lower gain resulting in lower

throughput when compared to narrow beamwidths.

- As the distance between the two networks increases, the throughput increases. The interference between the network reduces as the distance is increased. Hence, throughput increases as the distance between the two networks increase.

- For any user distribution, the final beam list is dependent on the spacing of the users.

Chapter 6

Conclusions and future work

This work has attempted to find a way to determine the maximum achievable throughput on reducing the sensing time and leave more time for data transmission. Many fundamental trade-offs were studied upon towards this research. The research questions were addressed in overall. The directions in which spectrum sensing should be performed is found using our heuristic directional spectrum sensing algorithm. Our algorithm returns the set of directions to sense for a particular beamwidth. Therefore, sensing time can be reduced resulting in higher throughput on using Dir-LBT on gNB. The Omni-LBT/Dir-LBT trade-off has been introduced and studied. Computer simulations are presented to depict the advantages of using Dir-LBT over Omni-LBT.

As we have seen in Chapter 2, a lot of work has already been done in many areas of spectrum sensing including Dir-LBT, Omni-LBT, Pair-LBT and various forms on spectrum sensing strategies. However, this research, strives to address the Omni-LBT/Dir-LBT trade-off.

In Chapter 3, we define our system model including an overview of the antenna model and the assumptions considered while undergoing this research. The spectrum sensing model is also introduced and the expressions for true detection and false detection are formulated.

Chapter 4 concerns the implementation of the proposed spectrum sensing algorithm. It describes the motivation including a high level description of the proposed algorithm. The maximum range of a directional beam for a given beamwidth is computed. A pseudo code of the algorithm is then presented.

Our experiment results, discussed in Chapter 5, show us the performance of the antenna model and the impact of distance and misalignment over received power. Further, a baseline algorithm is proposed to evaluate the efficiency of the proposed spectrum sensing algorithm. The goals of the spectrum sensing algorithm are discussed and simulations are plotted to derive conclusions under the goals mentioned earlier. The performance of our proposed algorithm in terms of throughput is compared with an optimal method. As expected the optimal solution results in the maximum throughput.

The research gives us a deep insight into the trade-offs present under beam based transmissions such as sensing-throughput and Omni-LBT/Dir-LBT, and how Dir-LBT improves the efficiency of the spectrum sensing and the throughput of the users. In addition, the overprotective nature of Omni-LBT has been studied, which results in less opportunities to transmit data towards the users. Moreover, the sensing accuracy of Dir-LBT is higher as the probability of false alarm is low resulting in higher throughput. Although Omni-LBT reduces the sensing overhead, Dir-LBT is better in terms in throughput. Therefore the advantage of using Dir-LBT over Omni-LBT has been studied and benefits of using Dir-LBT are reflected.

In addition, during transmission, the use of narrow beamwidths is preferred since the undesirable interference from neighbouring networks can be avoided. It is essential to chose the right sensing beamwidth to maximize throughput. This is because, narrow beamwidths have smaller beamwidth granularity. Hence, more directions would be sensed since the number of directions increases. However, using a wider beamwidth leads to less sensing accuracy resulting in lower throughput.

A sub-optimal heuristic algorithm is coined to find the directions required to sense for the gNB. Further, the impact of user distribution on set of beams required to sense under each case has been studied. A case for beam adaptation has been touched upon as a viable solution to reduce the number of beams required to sense.

We have presented an algorithm to transmit data towards the best user by calculating the SNR at each user present within the range of gNB. On calculation of SNR, we find the user with the highest SNR and transmit data towards it resulting in maximum throughput. The limitation of the presented research is the compromise on fairness. The directions sensed are based on the highest number of users along the sensed beam. Therefore, only certain users receive data.

The prospective future based on the underlying research can be as follows:

- This study only focuses on linear array antennas, which only permit two dimensional (2D) beamforming by steering the beam into elevation or azimuthal angle, depending on the antenna orientation. Future work could include three-dimensional (3D) beamforming. Beam-searching algorithms in 3D beamforming can also be discussed further to identify the best one.

- Sensing efficiency and accuracy cannot be optimized at the same time. Sensing duration and sensing period are two of the most essential factors in spectrum sensing. The goal would be to address the trade-off between the two factors to maximize overall available spectrum opportunity.

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