FACULTY OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING
DEGREE PROGRAMME IN WIRELESS COMMUNICATIONS ENGINEERING

MASTER'S THESIS

AN INITIAL ACCESS OPTIMIZATION ALGORITHM FOR MILLIMETRE WAVE 5G NR NETWORKS

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ABSTRACT

The fifth generation (5G) of cellular technology is expected to address the ever-increasing traffic requirements of the digital society. Delivering these higher data rates, higher bandwidth is required, thus, moving to the higher frequency millimetre wave (mmWave) spectrum is needed. However, to overcome the high isotropic propagation loss experienced at these frequencies, base station (BS) and the user equipment (UE) need to have highly directional antennas. Therefore, BS and UE are required to find the correct transmission (Tx) and reception (Rx) beam pair that align with each other. Achieving these fine alignment of beams at the initial access phase is quite challenging due to the unavailability of location information about BS and UE.

In mmWave small cells, signals are blocked by obstacles. Hence, signal transmissions may not reach users. Also, some directions may have higher user density while some directions have lower or no user density. Therefore, an intelligent cell search is needed for initial access, which can steer its beams to a known populated area for UEs instead of wasting time and resources emitting towards an obstacle or unpopulated directions.

In this thesis, we provide a dynamic weight-based beam sweeping direction and synchronization signal block (SSB) allocation algorithm to optimize the cell search in the mmWave initial access. The order of beam sweeping directions and the number of SSBs transmitted in each beam sweeping direction depend on previously learned experience. Previous learning is based on the number of detected UEs per SSB for each sweeping direction.

Based on numerical simulations, the proposed algorithm is shown to be capable of detecting more users with a lower misdetection probability. Furthermore, it is possible to achieve the same performance with a smaller number of dynamic resource (i.e., SSB) allocation, compared to constant resource allocation. Therefore, this algorithm has better performance and optimum resource usage.

Keywords: mmWave, cell search, beam sweeping, SSB, UPA.

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FOREWORD

This thesis is written based on self-conducted research on new initial access algorithm for mmWave cellular communication systems as a part of the High5 and MOSSAF projects at the Center for Wireless Communications (CWC) of University of Oulu, Finland.

I would like to take this as an opportunity to express my sincere gratitude to my supervisor and mentor Prof. Nandana Rajatheva for the guidance, support and encouragement given to academic and career development throughout my master studies. I am also grateful to Academy Prof. Matti Latva-aho for the opportunity given to join this great institution and contribute to the High5 and MOSSAF projects. I would humbly like to extend my sincere gratitude and appreciation to my technical advisor, Dr. K. B. Shashika Manosha, for the enormous support and technical guidance provided to shape this research to excellence. Also, I would like to thank Dr. Pekka Pirinen, the project manager, the staff and colleagues at CWC for their support in conducting my research successfully.

At last, but not least, I would like to present my gratefulness to my parents and immediate family members for their sacrifice, support and encouragement provided to achieve this goal a success. Most importantly, my loving gratitude and appreciation toward my beloved wife for becoming truly a life partner in every situation on this challenging road of achieving Master's Degree together. Without the support of the mentioned or forgotten above, this tremendous task would not be success. Thank you!

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Indika Perera

LIST OF ABBREVIATIONS AND SYMBOLS

Acronyms

1G	First Generation
2D	Two Dimension
3GPP	3rd Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5GCN	5G Core Network
ADC	Analog to Digital Converter
BS	Base Station
DL	Downlink
eMBB	Enhanced Mobile Broadband
FDD	Frequency Division Duplex
gNB	Fifth Generation Node Base station
HPBW	Half Power Beam Width
IA	Initial Access
IoT	Internet of Things
LOS	Line of Sight
LTE	Long Term Evolution
LTE-A	Long Term Evolution - Advanced
MIMO	Multiple Input Multiple Output
mMTC	Massive Machine-Type Communications
mmWave	millimetre Wave
NB	Narrow Beam
NF	Noise Figure
NLOS	Non-Line of Sight
NR	New Radio
OFDM	Orthogonal Frequency Division Multiplexing
PBCH	Physical Broadcast Channel
PMD	Probability of Misdetection
PSS	Primary Synchronization Signal
RA	Random Access
RAT	Radio Access Technology
RF	Radio Frequency
Rx	Receive
SCS	Sub Carrier Spacing
SNR	Signal to Noise Ratio
SS	Synchronization Signals
SSB	Synchronization Signal Block
SSS	Secondary Synchronization Signal
Tx	Transmit
UE	User Equipment
ULA	Uniform Linear Array
UPA	Uniform Planner Array
URLLC	Ultra-Reliable Low-Latency Communication

WB	Wide Beam

Symbols

d_{UE}	Best UE beam direction
d_{BS}	Best BS narrow beam direction
d^*_{wb}	Best BS wide beam direction (in Iterative search)
$D_{BS,wb}$	Total number of wide beam sweeping directions in BS
$D_{BS,nb}$	Total number of narrow beam sweeping directions in BS
D_{UE}	Total number of beam sweeping directions in UE
i	Beam sweep direction
k	Beam sweep cycle
$n_{UE,i}$	Detected number of UEs in ith narrow beam direction
$n_{SSB,i,wb}$	Number of SSBs transmitted at ith direction using wide beams
$n_{SSB,i,nb}$	Number of SSBs transmitted at ith direction using narrow beams
$n_{SSB,i}$	Number of SSBs transmitted to the ith beam sweep direction
$n_{UE,total,k}$	Total number of UEs detected during kth beam sweep cycle
$n_{SSB,total}$	Total number of SSBs in a single radio frame
N_0	Thermal noise density
N_{BS}	Number of BS beam directions (in Exhaustive search)
N_{UE}	Number of UE beam directions (in Exhaustive search)
N_{wb}	Number of BS wide beam directions (in Iterative search)
N_{nb}	Number of BS narrow beam directions per wide beam (in Iterative search)
$\mathbf{n_{SSB}}$	SSBs per direction vector
$\mathbf{n^\star_{SSB}}$	Optimized SSBs per direction vector
$\mathbb{R}_+$	Positive real number set
SNR_{th}	SNR threshold
$SNR_{d_{BS}}$	SNR value at best BS narrow beam
$\overline{\mathbf{w}}$	Weight vector
$\mathbf{w}$	Normalize weight vector
$\mathbb{Z}_+$	Positive integer set
λ	Wavelength
γ	Path-loss exponent
ρ_k	Detection ratio of kth beam sweep cycle
ρ_{th}	Detection ratio threshold

Operators

$.^{\mathbf{T}}$	Matrix Transpose
$\|\cdot\|_{\mathbf{1}}$	Level 1 norm
$\sum$	Summation operation

1 INTRODUCTION

1.1 Background of the Research

Wireless communication is one of the most fascinating and amazing technologies discovered to support the development of human life. With the development of wireless communication doors to the many practical and usable applications are opened, creating a fully digital world among us. One of the major components of wireless communication that heavily impacted the society is cellular communication. With the development of cellular communication from its first generation (1G) to currently deployed fourth generation (4G), a wide variety of technology and device changes occurred. Even though now the cellular technology is at its best phases, still the new applications required a vast amount of contradictory requirements from the cellular technology. Fifth generation of cellular technology, commonly known as 5G is to address some of these new requirements.

Fifth generation (5G) new radio (NR), the mobile communication standard presented by the 3rd generation partnership project (3GPP) as the 3GPP Release 15 [1], presents major improvements to existing long term evolution-advanced (LTE-A) standard. Its main focus is on enhanced mobile broadband, ultra-reliable and low latency communications, and massive machine-type communications. To achieve these goals, 3GPP has introduced a unified network architecture, with a new physical layer design [2] that supports very high carrier frequencies (mmWaves), large frequency bandwidths, and new techniques such as massive MIMO (multiple-input and multiple-output), and beamforming.

The frequency spectrum ranging 30-300 GHz is collectively known as millimetre wave (mmWave) bands with wavelengths ranging from 1 to 10 mm. There are several motivations to utilize mmWave frequencies in future 5G. A large amount of continuous bandwidths available at mmWave frequencies has vast potential to increase the capacity of 5G cellular wireless systems which are in giga bits per seconds rates. Therefore, it can address the ever-increasing traffic demand compared to the existing sub 6 GHz radio spectrum which is fragmented and crowded [3]. Although mmWave has many benefits, it also has significant drawbacks which restrict the usage in the existing cellular systems. Due to its high frequency, it will observe severe attenuation and hence, higher path loss compared to sub 6 GHz frequency band [4]. Also, due to its short wavelength, signals highly diffract and highly penetrate by surrounding obstacles thus, highly sensitive to blockage [5].

Due to high attenuation, coverage range of the mmWave base stations (BS) will be lesser compared to the sub 6 GHz macro cells which are currently deployed. Also, to cater higher throughput, a lesser number of users are served with a single BS, and the number of BSs should increase. Therefore, mmWave small cells with low power and short-range, which covers a small geographical area are proposed to use in 5G communication.

Moreover, due to the shorter wavelength of mmWaves, physical antenna size of the antenna arrays becomes small. Therefore, it is practically feasible to integrate antenna arrays with a large number of elements to the mobile devices. Therefore, using large antenna arrays for mobile communication has become practical hence, the possibility of realizing directional communication with very narrow beams. Thus, realizing narrow beams with these antennas, accurate beamforming operations can be performed, allowing to focus the beam in very precise spatial directions [6]. Hence, highly directional transmission is inherited to mmWave communications, and with this highly directional transmissions, high isotropic pathloss of the mmWave frequencies could be mitigated.

Motivation of the Research

5G and above generations of cellular networks which planned to use mmWave communication must provide a set of mechanisms to provide the directional beam management. User equipment (UE) and mmWave next generation base station (gNB) should establish highly directional transmission links to benefit from the resulting beamforming gain. Most importantly these directional links require fine alignment of the transmitter and receiver beams. This is a new challenge that the new generation of communication systems face compared to the earlier generation of communication systems.

Initial access (IA) in a cellular communication could be defined as the establishment procedure of an initial connection between a mobile user and a base station in a cellular network. This is a critical prerequisite for any subsequent communication between the BS and UE. In mmWave communication, initial access is further challenging due to directional communication. Therefore, BS and UE required to find the correct transmission (Tx) and reception (Rx) beam pair which align with each other. Achieving these fine alignment of beams at the initial access phase is quite challenging due to the unavailability of location information about BS and UE. Hence, the motivation of this thesis is to present a suitable initial access beam searching algorithm for mmWave 5G NR communication, which can overcome the drawbacks of the mmWave communication and increase the efficiency of the mmWave base station.

Research Problem and Methodology

In mmWave communication, signals are blocked by obstacles because of their short wavelength. Therefore, transmissions towards obstacles will not reach users located behind them. Also, most of the time, users served by a small cell BS may not be distributed uniformly around the BS. Users are scattered around the BS as clusters, and due to that, some directions may have higher user density while some directions may have lower or no user density at all.

Therefore, cell search procedure at this kind of scenario requires intelligence at the BS, which can only steer its beams through a known populated area for UEs instead of wasting time and energy emitting towards an obstacle or unpopulated directions. Nevertheless, current BSs are not dynamically deciding which areas to cover or not based on user distribution.

Hence, a new dynamic weight-based beam sweeping direction and synchronization signal block (SSB) allocation algorithm is presented to optimize the cell search in the initial access procedure. In the presented algorithm, the order of beam sweeping directions and the number of SSBs allocated for each beam sweeping direction depends on previously learned experience. This previous learning is based on the number of detected UEs per SSB for each sweeping direction. Thus, by providing some learning about the UE distribution around the BS, the delay in detecting UEs during the cell search procedure will decrease, and the number of UEs found will increase during the beam scan.

This research is chosen to study the physical layer aspects of mmWave communication systems. Main focus is given to initial access procedures and mmWave beam steering. Therefore, considering the existing challenges in initial access in mmWave, a new algorithm to overcome those challenges is selected to study.

This research will not cover the contextual information based initial access or coordinated initial access concepts. Also, this algorithm is formulated considering static user distribution at the time of writing. Further, this research is currently on a single-cell environment, and multi-cell scenario is expected to study in the future.

1.2 Objectives and Structure of the Thesis

Objectives of the Thesis

A detailed description of the objectives of this Master's thesis could be listed below.

- To provide an introduction to 5G cellular technology and the new technologies introduced with it. Describe the challenges faced when using mmWave communication for 5G.
- To provide background knowledge required to understand the initial access in cellular communication and initial access in mmWave communication.
- To conduct a literature review and present existing literature on mmWave initial access algorithms and its performance.
- To propose a new mmWave initial access algorithm to overcome the drawbacks of the mmWave communication and increase the efficiency of the mmWave base station.
- To present the formulation of the proposed algorithm and explain its steps.
- To present and discuss the simulation setup and results. Compare the performance of the proposed algorithm with existing initial access algorithms.
- To propose future directions and enhancements to the research.

Structure of the Thesis

This thesis is mainly divided into five chapters. Each chapter comprises a specific area related to this research. A detailed description of the contents of the upcoming chapters of this thesis is as follows.

- **Chapter 2** - Includes the background knowledge required to understand the main concepts of this research and some literature on the existing studies on this topic.
- **Chapter 3** - In this chapter, limitations in the existing mmWave initial access techniques and the requirement for the new algorithm is explained. Then the algorithm is presented and described in details.

- **Chapter 4** - Includes the simulation setup and parameters used for simulations. Results of the numerical simulations are discussed comparing with some existing algorithms.

- **Chapter 5** - Summaries the thesis and presents the possible future works on this research.

2 BACKGROUND AND LITERATURE

This chapter describes the background knowledge required to understand the main concepts of this research and some literature on the existing researches done to pave the path to this novel algorithm. Also, this chapter will explain how the technologies differ when considering the initial access in 5G mmWave from the existing legacy technologies and systems. Moreover, this will highlight the challenges that will be faced and the aspects need to consider when moving to the initial access in mmWave.

2.1 Background

2.1.1 5G Wireless Communication

The fifth generation of cellular network technology which is commonly known as 5G is expected to address the traffic requirements of the digital society beyond 2020. It is expected to overcome current limitations, evolutionary enhance mobile broadband user experience and to support many enabling technologies to empower IoT and industries. Primarily, 5G wireless technology developed with three major use cases in mind [7]. Those use cases are described below and shown in Figure 2.1 as an overall picture for 5G [8].

- **Enhanced mobile broadband (eMBB)**

  This is mainly focused on the human centric use cases for accessing multimedia content, services and data. Thus, the broad enhancement of the data rate, spectral efficiency, coverage, capacity, latency and user density of mobile broadband access is major concerned.

- **Massive machine-type communications (mMTC)**

  This case is for a large number of connected devices which transmitting a relatively low volume of non-delay sensitive data. Typically these devices are low cost and low power consumption with very long battery life. These devices are massive in numbers and intended to support applications in logistic, industries, fields and remote sensing.

- **Ultra-reliable low-latency communications (URLLC)**

  This type of communication has very low latency, ultra-reliability and high availability requirements to satisfy. Therefore, it is used in applications such as vehicular networks and autonomous driving, industrial manufacturing process automation, remote medical surgery and public safety applications. Due to the stringent requirements in low latency and ultra-reliability, this category has many challenges in successfully achieving those.

In order to satisfy these complex and contradictory requirements in 5G, 3GPP has introduced a new radio access technology commonly referred as 5G NR (5G new radio) and new 5G core network known as 5G CN (5G core network).

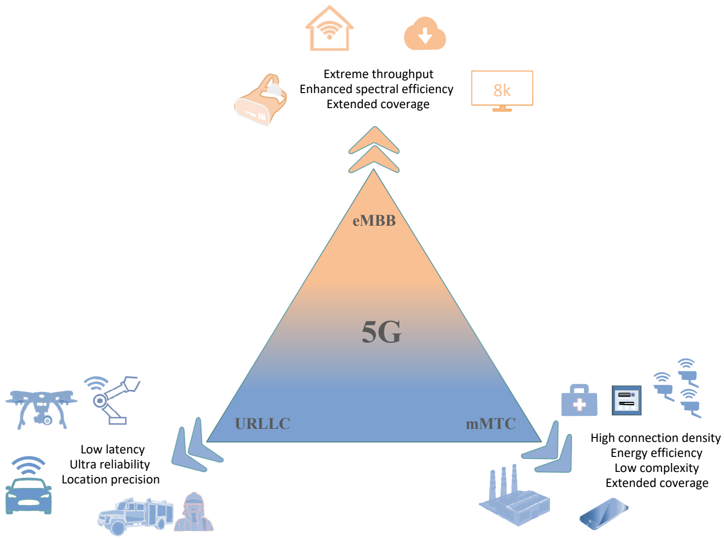

Figure 2.1. Major use cases of 5G.

2.1.2 5G NR

5G NR is the new radio access technology (RAT) developed by 3GPP for catering the diversified requirements of the 5G use cases and exploit the potential new technologies. Even though the existing LTE was not capable of catering some of those requirements, NR reuses many of the features and structures of LTE to developed as a new radio access technology.

The physical layer of the NR is designed with a flexible and scalable manner to support diverse use cases, a wide range of frequencies and different deployment options. Key technology components of the NR physical layer are modulation schemes, waveform, frame structure, reference signals, multi-antenna transmission and channel coding.

NR operating frequency bands are divided into two frequency ranges [9]:

- Frequency range 1 (FR1) includes all existing and new bands in the range 450 MHz – 6 GHz

- Frequency range 2 (FR2) includes mmWave bands in the range 24.25 -52.6 GHz.

NR Frame Structure

NR has a time-domain structure where the transmissions are organized into frames of 10 ms. Each of this frame again divided into 10 equally sized subframes of the length 1 ms. Then this subframe is again divided into slots consisting of 14 OFDM (orthogonal frequency division multiplexing) symbols each, and the duration of this slot is dependent on the numerology used.

LTE has only one numerology with 15 kHz subcarrier spacing (SCS), but NR has flexible numerology where the subcarrier spacing could take the values 15 kHz, 30 kHz, 60 kHz, 120 kHz or 240 kHz. Therefore, based on this SCS, slot duration will differ, and thus, the time-frequency resource grid would also differ from each other [1]. For the mmWave frequencies, it is proposed to use 120 kHz or higher subcarrier spacing configuration. Time-domain structure and slot duration of 5G NR FDD (frequency division duplex) frame is shown in Figure 2.2 below.

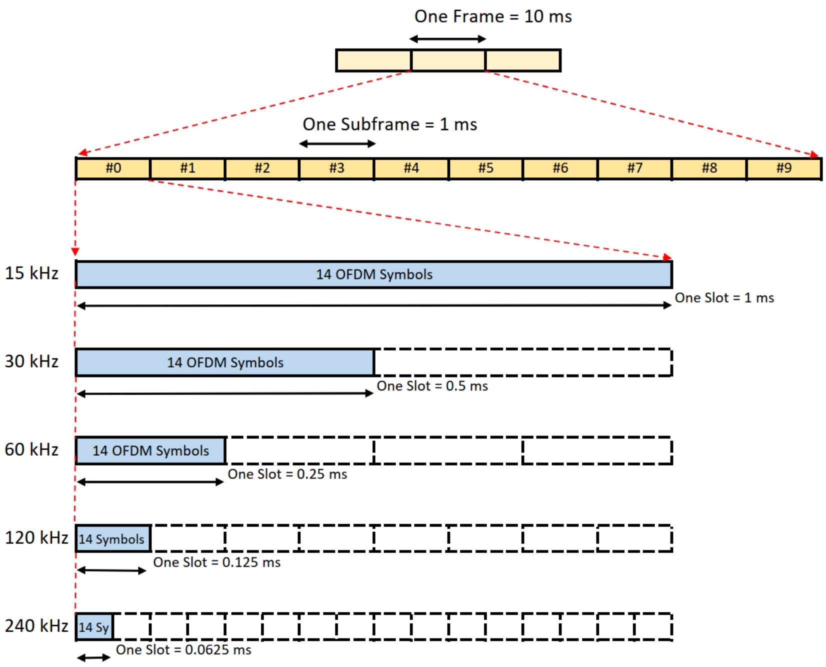

Figure 2.2. Time domain structure of NR frame.

2.1.3 mmWave Communication

5G has introduced unprecedented high data rates and low latency requirements, which is challenging to provide with the existing mobile technologies. To deliver these giga bits per second higher data rates, higher bandwidth is required, so the moving to higher frequency spectrum is needed. Currently, the sub 6 GHz spectrum is heavily congested and fragmented to cater these requirements. Consequently, the mmWave spectrum has become an enabler for the 5G performance demands.

mmWave is defined as frequency range which has 1 mm to 10 mm wave wavelengths in the electromagnetic spectrum. Therefore, 30-300 GHz frequency range is considered as mmWaves and for the 5G communication 20-60 GHz frequency range is considered [10]. Following are the key benefits of mmWave communication.

- Extreme wide bandwidth is available due to abundant, continuous spectrum resource.
- Large antenna arrays could be packed in a small area due to short wavelengths.
- More narrow formed beams could be generated since the usage of larger antenna arrays.

Moreover, due to the highly directional communication in mmWave, it could easily isolate the users and deliver a communication channel with reduced interference. Also, due to the blockage and short-range transmission, inherent security and the privacy of the communication is also improved.

However, even with all the above benefits, mmWave communication has several drawbacks when using for cellular communication. The major drawback is due to very high frequency severe attenuation will occur, hence, higher path loss and will be susceptible to shadowing. Therefore, long range ominidirectional transmission as sub 6 GHz frequencies is not possible. Hence, the base station cell coverage is limited and therefore, small cells are required for deployment. Also, the mmWave links are highly sensitive to blockage thus, obstruct by many of the surrounding buildings [5]. Apart from that, high directionality of the communication requires precise beam alignment between transmitter and receiver and due to that control overhead will increase.

2.1.4 Multi Antenna Arrays

In order to obtain versatile beams required for different requirements of 5G use cases, large antenna arrays are needed. With the introduction of antenna arrays at the BS and UE, it is possible to have highly directive steerable narrow beams with low side lobes as the communication link between BS and UE. When designing an antenna array selection of array elements, array geometry, operating frequency range and desired element excitation are needed to know for the desired beam generation.

Commonly used large antenna array types for the 5G communication are unifrom linear array (ULA) and uniform planner array (UPA). In ULA antenna elements are distributed equidistantly only in one dimension while in UPA antenna elements are distributed on a rectangular grid on a two-dimensional plane. Planar arrays provide additional variables which can be used to control and shape the pattern of the array. Hence, they are more versatile and provide more symmetrical beam patterns. Figure 2.3 below shows the antenna geometry of 64 antenna elements of the 8x8 UPA designed for 28 GHz carrier frequency.

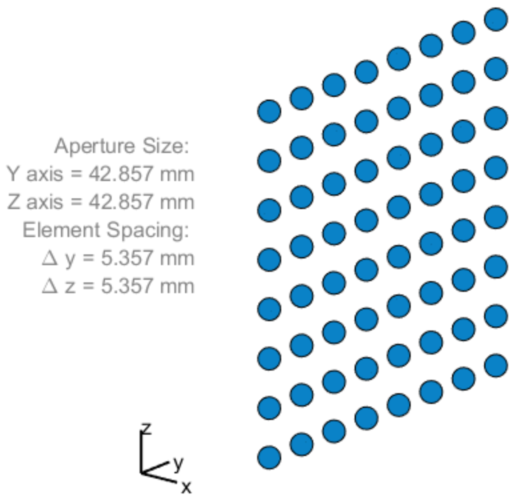

Figure 2.3. Antenna elements of a 8x8 UPA.

2.1.5 Beamforming and Beam Steering

Beamforming is defined as a signal processing technique used in multi-antenna systems to create directional signal transmission or reception. This is achieved by changing amplitude or phase of the signal such that signal at a particular angles experience constructive interference while others experience destructive interference.

Phase and amplitude of the signal applied to an antenna element in the antenna array is a complex value, and by continuously changing this complex weight value applied to each antenna element we can continuously change the direction of the beam transmitting or receiving. Thus, the continuously changing the beamforming direction or steer the beam to the desired direction, could define as beam steering.

There are three beamforming architectures proposed based on the number of radio frequency (RF) chains used, and their pros and cons are as follows.

- **Analog beamforming** uses only one RF chain for all antenna elements. Therefore, the processing is performed in the analog domain hence, less flexibility. Transmission or reception is possible only in one direction at a time. Since it is using a single analog to digital converter (ADC), less power consumption compared to the other two architectures.

- **Digital beamforming** uses separate RF chains and ADCs for all antenna elements. Therefore, the processing is in the digital domain hence, allowing to beamform at infinitely many directions. This architecture has the highest power consumption compared to the other two architectures, thus, limiting the practical usage.

- **Hybrid beamforming** is a compromise, practically usable architecture between the earlier mentions. It uses less number of RF chains and ADCs than the number of antenna elements. Therefore, the number of beamforming directions are limited but higher than analog beamforming. It has moderate power consumption compared to the other two architectures, allowing practical usage.

Using multi-antenna arrays and the beamforming, we could create different kind of beam patterns with different half power beam width (HPBW) and side lobe conditions. Figure 2.4 shows three types of beam patterns in polar and cartesian coordinates.

Figure 2.4 (a) shows a very wider beam with less beamforming power generated with 2x2 UPA, Figure 2.4 (b) shows a wide beam with moderate beamforming power generated with 4x4 UPA and Figure 2.4 (c) shows a narrow beam with high beamforming power generated with 8x8 UPA.

We can sweep this kind of beams to cover whole 360° space by beam steering these beams to the desired angle. Figure 2.5 shows beam steering a wide beam generated by 4x4 UPA to sweep the 360° coverage.

2.1.6 Initial Access

Establishment procedure of an initial connection between a mobile user and cellular network could define as initial access, and this is a critical prerequisite for any subsequent

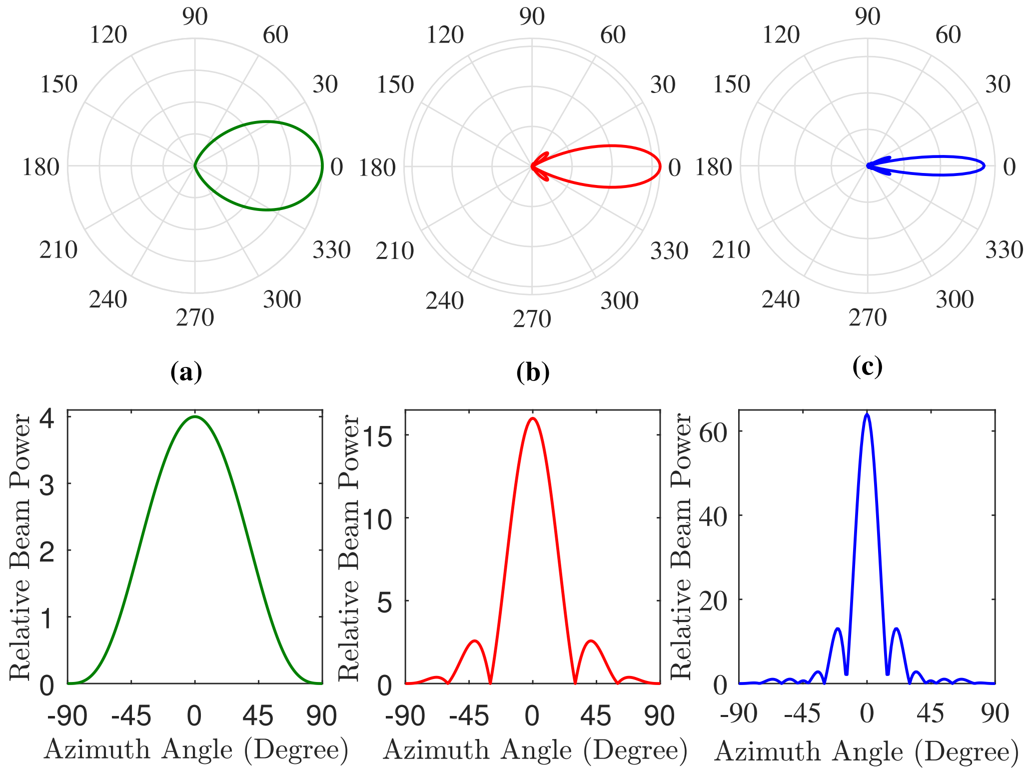

Figure 2.4. Beam patterns (a) 2x2 UPA (b) 4x4 UPA (c) 8x8 UPA.

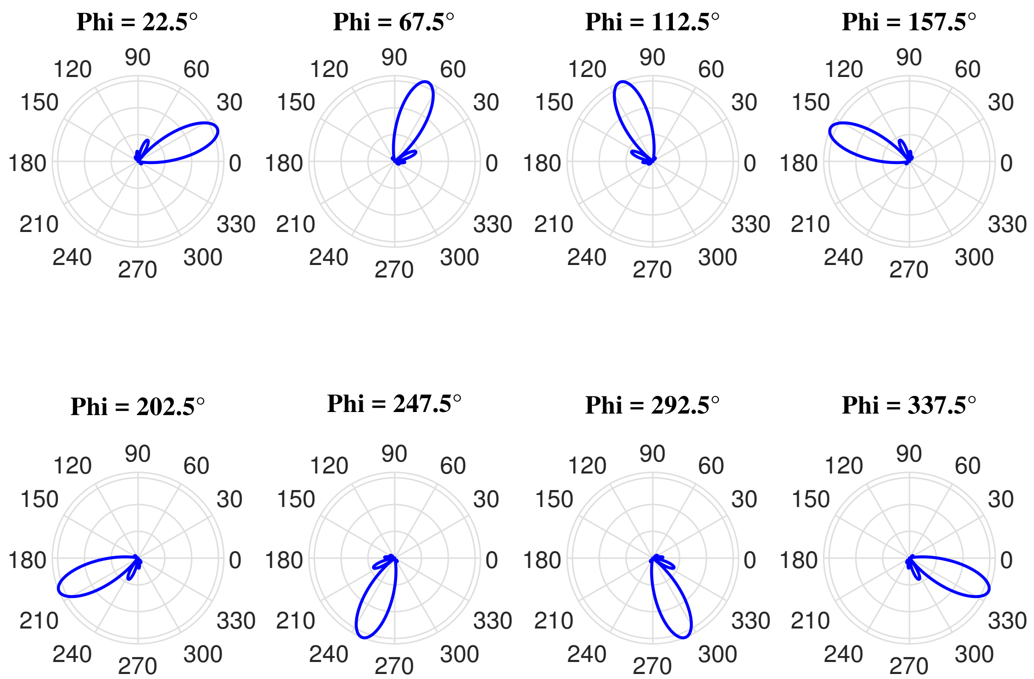

Figure 2.5. Beam steering with 4x4 UPA.

communication between that BS and UE. These procedures comprise a set of functions in multiple layers, but the main focus on this section is the physical layer aspects of the initial access.

A mobile terminal in any mobile communication system will be in IDLE mode when it is not using. When the mobile terminal wants to transit from IDLE to CONNECTED mode, it must perform the cell search and random access steps. Figure 2.6 below shows the basic steps and information transfers that happen between the BS and UE during the cell search and random access stages.

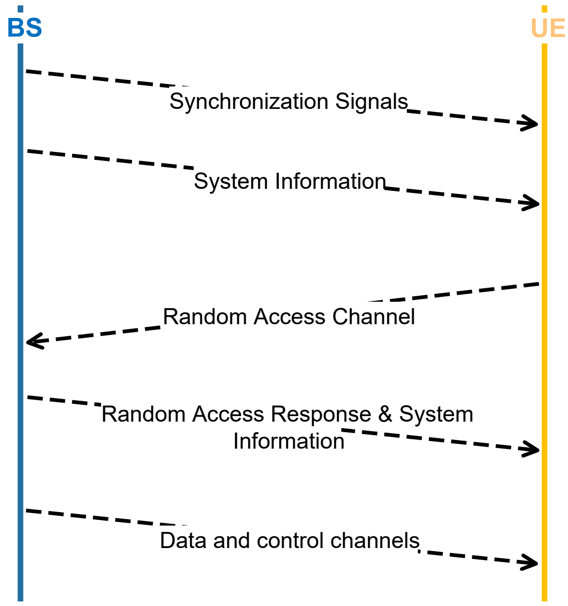

Figure 2.6. Cell search and random access procedure.

At the cell search phase, IDLE UE is permitted to find a suitable BS to connect with it. It will try to find a BS with good reception among the serving BSs around it. In the existing systems, the UE is facilitated to obtain the cell identity and time-frequency synchronization during the cell search phase. For that, the BS repeatedly transmits primary synchronization signal (PSS) and secondary synchronization signal (SSS) in the downlink. In the current cellular technologies, these synchronization signals are transmitted with an omnidirectional or weakly directive antenna in the downlink. Beamforming is also used in the existing systems, but it is only after the establishment of a physical link [11].

After the step mentioned above, UE needs to inform the BS about its desire to establish a connection. Since there is no channel available for this, the random access stage provides a means to set up this connection. Then the UE goes through the random access stage and exchanges random access messages between BS and UE. After this stage, UE is considered as connected to the network through the said BS.

2.1.7 Initial Access in mmWave 5G

Initial access in mmWave 5G is differed from the existing initial access procedures due to the directional transmission of the synchronization signals. In mmWave cells, the PSS is transmitted only in specific directions at a time by the BS, and therefore, UE's beam must scan the whole angular space to search for the BS beam and obtain the PSS to complete the access to the cell.

In the cell search stage, the BS transmits the synchronization signals (SS) in several discrete directions scanning the whole angular space that BS serves. The UE has two options to detect the synchronization signals, according to its antenna. First one is by performing beamforming, in case it is equipped with an antenna array. The second one is through an omnidirectional signal to explore the entire space.

In this second scenario, the UE suffers from high pathloss observed in mmWave since it does not exploit the beamforming gain. On the other hand, in the first case, the UE needs to scan the entire angular space for searching the synchronization signal. Due to this additional scanning of the signal, which was not in the existing technologies, mmWave initial access has to include additional procedures and change of signal structures to facilitate it. Figure 2.7 below depicts a BS and UE beam sweeps to identify the best Tx and Rx beams (circled with a dashed line) for initial access when BS is having 8x8 UPA and UE is having 2x2 UPA.

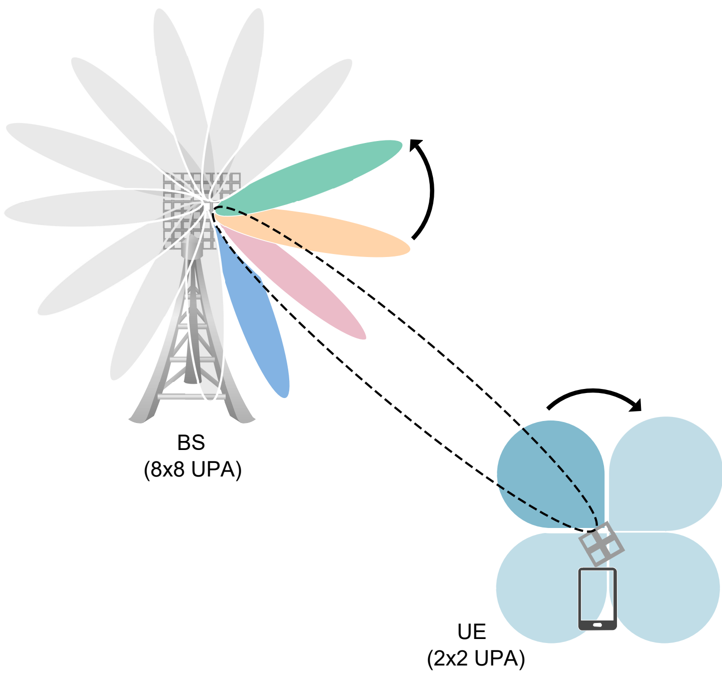

Figure 2.7. BS and UE beam sweeping to identify best Tx and Rx beams.

Synchronization in 5G NR

In 5G NR, synchronization signal (SS) consists of two main signals known as primary synchronization signal and the secondary synchronization signal. These synchronization signals, together with the physical broadcast channel (PBCH), are referred as a synchronization signal block (SSB) or SS block in 5G NR definitions. SS block is a group of 4 OFDM symbols in time and 240 subcarriers in frequency (i.e., 20 resource blocks) in NR time-frequency grid as shown in the Figure 2.8 [12].

There are several numbers of SSBs in one NR radio frame, and the number of SSBs and the time domain position of these SSBs depend on NR numerology. This is a significant

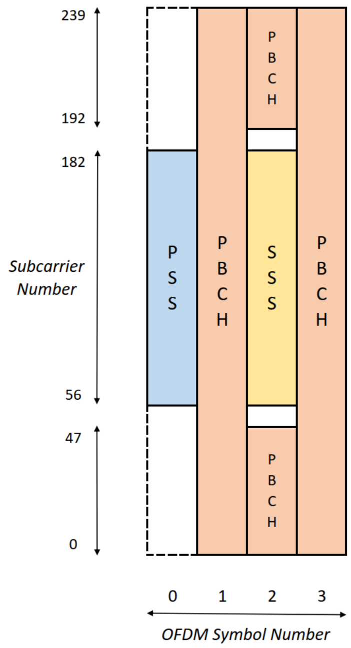

Figure 2.8. Structure of a SSB in frequency-time grid.

difference compared it to the LTE, where its number of synchronization signals and time domain positions are not changing.

One important feature introduced in NR, related to initial access beam sweeping is the possibility to apply beam-sweeping for SSB transmission, which means the possibility to transmit synchronization signal blocks in different beams in a time-multiplexed fashion [13]. Figure 2.9 depicts the above concept where each BS beam sweep direction is assigned a single SSB within the SS burst set.

The set of SSBs within a beam-sweep is referred to as **SS burst set**. One or multiple SSB(s) compose a **SS burst**, and one or multiple SS burst(s) compose a SS burst set. The periodicity of the SS burst set is flexible with a minimum period of 5 ms and a maximum period of 160 ms. However, each SS burst set is always confined to a 5 ms time interval, either in the first or second half of a 10 ms NR radio frame. Nevertheless, devices doing initial cell search, as well as devices in inactive/idle state doing cell search for mobility, can assume that the SS block is repeated at least once every 20 ms [13].

The maximum number of SSBs which can configure within an SS burst set is different and dependent on carrier frequency bands.

- For frequency bands below 3 GHz - There are up to 4 SSBs within an SS burst set, enabling beam-sweeping up to 4 beams.
- For frequency bands between 3 GHz and 6 GHz - There are up to 8 SSBs within an SS burst set, enabling beam-sweeping up to 8 beams.
- For higher-frequency bands (FR2) which is mmWave bands - There are up to 64 SSBs within an SS burst set, enabling beam-sweeping up to 64 beams.

The set of possible SSB locations in the time domain differ between different NR numerologies. The number of SSBs mentioned in the previous paragraph is not necessarily

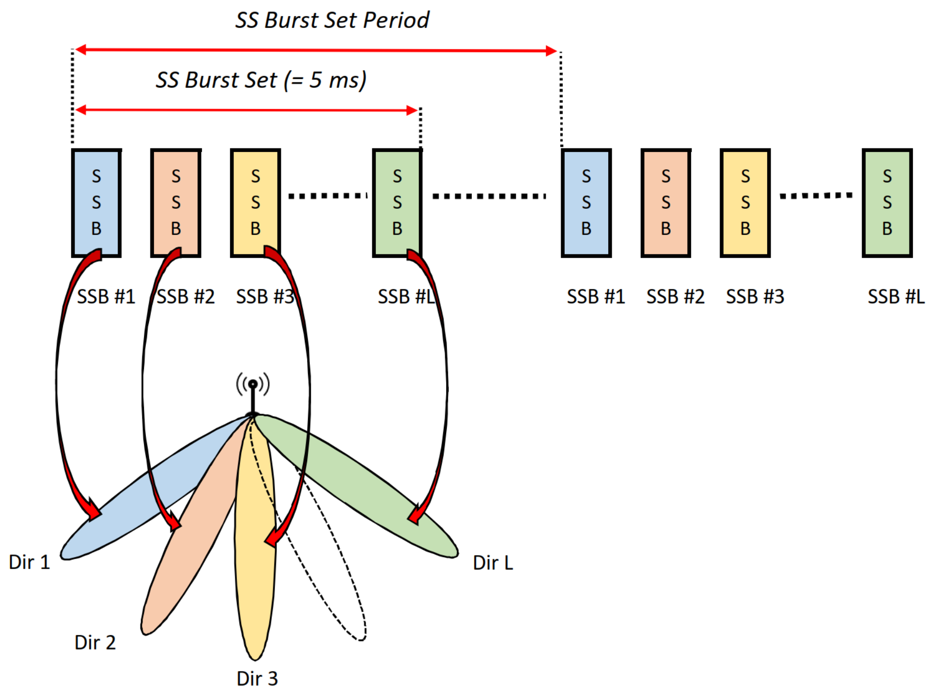

Figure 2.9. BS beam sweeping directions mapping to SSBs.

needed to transmit, and therefore, all SSB locations are not used for transmission. There is the flexibility of transmitting anything from single SSB up to the possible maximum number of SSBs within an SS burst set. Depending on the number of beams needed for the beam sweep, we can decide on the number of transmitting SSB requirement per SS burst set [13]. This is an important feature in NR that we used in developing our proposed initial access algorithm.

2.2 Literature

In this section, we present the existing studies carried out on the initial access techniques in mmWave. As explained earlier, identifying the best Tx and Rx beams at the BS side and UE side is a problem that faces when an idle UE tries to access the network. Therefore, without the knowledge of user details such as position, user orientation and user profile identifying the UE within the BS coverage is challenging task for 5G base stations.

Performing the initial access with the availability of that kind of user information is known as initial access with context information [14]. This type of initial access is possible when there is an already established control link between UE and the network. Consider a situation where there is non-standalone 5G network which coexists with LTE network. In that UE position could be informed to 5G BS by the LTE anchor cell which is already connected with the UE [15]. Context information based initial access is not considered in this research, and our primary focus is on initial access of a standalone 5G network without contextual information about the UE. Following subsections describe some of the related initial access beam search algorithms and their performance as presented in those research documents.

2.2.1 Exhaustive Search

Exhaustive search is the basic searching method available. It is a brute force sequential beam searching method which can apply to both BS and UE. BS has N_{BS} predefined beam directions that can cover the whole space the BS could provide coverage. If UE is enabled with antenna array, then UE has N_{UE} predefined beam directions that can cover the entire 360° space. These directions could also be considered as the reception directions of the UE.

As mentioned earlier, the goal is to identify the best Tx and Rx beam pair for the BS to connect with each UE in its coverage area. As the first step BS send synchronization signals in one of it N_{BS} narrow beam directions using its narrow beams. In order to match with N_{UE} UE beam directions, BS send N_{UE} synchronization signals in consecutive DL (downlink) slots per each BS narrow beam direction. UE configures its antenna array to directionally receive the transmitted N_{UE} SS signals by BS. Upon reception of the signals, UE evaluates the perceived signal to noise ratio (SNR) for each of its UE beam directions. From that, it will select the highest SNR value and identify the UE beam direction it receives. If that selected SNR is above a fixed predefined SNR threshold value, then the UE will feedback it to the BS via that identified UE direction. BS will receive the feedback message via the same directional beam as it transmits.

Then the BS moves to the next narrow beam direction and above steps are hierarchically repeated. This procedure is conducted for all the other narrow beam directions of the BS such that all the N_{BS} narrow beam directions are beam swept. After scanning the whole BS coverage area, BS can determine the best BS narrow beam direction to communicate to that UE. It will be the BS narrow beam direction with the highest received SNR value. Also, the UE could determine it's best UE beam direction base on the same criteria.

In existing literature [16], performance of these initial access algorithms is evaluated with two main evaluators. They are probability of misdetection (PMD) and discovery delay. Probability of misdetection which is defined as the probability that a UE within a cell is not detected due to the perceived SNR at the UE is below a given SNR threshold level (SNR_{th}). Discovery delay is the time required by the BS and the UE to complete their beam sweep to determine the best BS and UE directions to steer the beams.

According to the simulations carried out in [17], exhaustive search algorithm has good coverage and a higher discovery delay. Since it has to complete a brute force scan through all the directions, it is susceptible to higher discovery delay. However, simulations have shown that it is suitable for detecting edge users despite the heavy discovery delay.

2.2.2 Iterative Search

Iterative search is a two-stage beam scanning methodology where it uses two types of BS beams for beam sweep the BS coverage area. These two types of beams have two different beam widths identified as BS wide beams (WB) and BS narrow beams (NB).

There are N_{wb} wide beams and N_{nb} narrow beams per each wide beam. Therefore, BS has a total of $N_{wb} \times N_{nb}$ narrow beam directions to cover the BS serving area.

In the first stage of the scanning, BS uses only wide beams for the scanning, and it performs exhaustive beam search (as explained earlier in the previous section) with that N_{wb} wide beams. Similar as earlier in this scan also, to match with N_{UE} UE beam directions, BS send N_{UE} synchronization signals in consecutive DL slots per each BS wide beam direction it scans. After scanning the whole coverage area with wide beams, as per the same technique used in exhaustive method UE can identify its best UE beam direction to reach the BS. Also, the BS can identify the best wide beam direction (say d^*_{wb}) to reach UE based on the feedback from UE.

In the second stage of the scanning, BS refines it search only to the identified best BS wide beam direction (d^*_{wb}). Now BS transmits synchronization signals through its narrow beams in the identified best BS wide beam direction. Hence, the BS now only have to scan N_{nb} narrow beams. This is a few number of narrow beams compared to the number of narrow beams used in the earlier explained exhaustive search. Moreover, in this situation, BS will send only one synchronization signal for each narrow beam direction. Since the UE has already identified its best UE beam direction to reach the BS, UE will now receive the synchronization signals with beamforming to that best UE direction.

Therefore, after completing the second stage, BS can identify its best narrow beam direction to reach the UE. Henceforth, both the BS and UE know their best beams to communicate with each other search has competed with respect to a specific UE. Then the same search procedure is carried out from the beginning to search other UEs in the coverage area.

Simulation data from studies in [17, 18] has shown that the iterative algorithm has less discovery delay. This improvement is mainly due to the mitigation of scanning the whole 360° coverage area by refining it to wide beam direction. Even though this algorithm has a lower discovery delay, it has shown a higher misdetection probability compared to the exhaustive algorithm. Furthermore, simulations have shown that both exhaustive and iterative algorithms present an acceptable misdetection probability for users in the range 0 to 30 m. Therefore, for cells having a very small radius, iterative search is desirable to implement instead of exhaustive search which have higher discovery delay.

However, the iterative technique is not recommended when dealing with very dense networks because if multiple users are found in different wide beam directions, iterative search may need to refine all of them, one at a time causing more discovery delay. Moreover, the iterative technique shows bad performance even for edge users who are around 95 m from the BS.

2.2.3 Hybrid Search

The hybrid search algorithm is similar to the iterative search algorithm with some improvements to reduce the discovery delay. In the hybrid search algorithm also, there are two scanning stages. The first stage of the scanning is almost equal to the first stage of the iterative search. Therefore, after the first stage of the hybrid search, BS knows the best wide beam direction to communicate with UE and UE has identified its best beam direction to communicate with BS.

In the second stage of the hybrid search algorithm, BS does not transmit as earlier but only receives. Thus, the BS is now beamformed to receive with narrow beams only within the identified best wide beam direction in the first stage. Now the UE repeatedly transmit signals by beamforming in the best UE beam direction identified in the first stage. UE will transmit N_{nb} number of signals in that direction, and the BS receives sequentially with refined narrow beams. Therefore, at the end of the second stage, BS evaluates the SNR of the received narrow beams and select the BS narrow beam direction with highest received SNR. Furthermore, if that SNR is above the SNR threshold value, BS will identify that direction as the best narrow beam direction to communicate with the UE.

In [19], authors have conducted simulations to compare the hybrid search algorithm along with exhaustive and iterative algorithms. According to the results, the hybrid algorithm has performed better than the iterative algorithm in terms of discovery delay. It is mainly due to the improvement done to the iterative algorithm in developing the hybrid algorithm. Even though it has improved in discovery delay, it has the same performance as iterative search in terms of probability of misdetetction. Furthermore, they have shown that lowering the UE transmission power would not make much effect on the probability of misdetection since it is highly dominated by the first stage.

2.2.4 Historical User Location Based Search

The algorithm proposed in [20] is an improved scanning method which uses historical user location to prioritize the beam sweep direction. Therefore, the beam sweeping is same as exhaustive search mentioned earlier, but the order in which the directions are scanned is based on the previous sweeping experience. The considered scenario in this method consists of a large number of UEs all around the BS, and several obstructions such as building in some directions. The BS steers its beam in a particular direction and identifies one or more UEs. For user identification, it uses the same criteria used earlier, which is the perceived SNR greater than or equal to a given SNR threshold. If a user is detected, then it increases a counter, which is associated with that detected direction.

Authors have defined a vector for storing and updating the counters related to each direction. When a beam sweep cycle is completed, the vector is rearranged to the descending order. Then this rearranged vector is used as the order of the beam sweep directions in the next beam sweep cycle. With this improvement, they are prioritizing the sweeping directions from the most populated to the least populated direction. This happens continuously, and therefore, most populated beam direction is beam swept first in the successive beam sweep cycles.

This algorithm shows less discovery delay than the exhaustive and iterative approach mentioned previously. Moreover, in terms of misdetection, no degradation is observed. Therefore, this algorithm can detect more users with less time compared to earlier mentioned algorithms hence, increasing the efficiency of the algorithm.

3 PROPOSED ALGORITHM

In this chapter, first, we will explain the requirement for a new algorithm to improve the initial access in mmWave 5G NR networks. After that, a brief introduction of the newly proposed algorithm will be given. Finally, the algorithm will be presented and explained in details.

3.1 Requirement for the New Algorithm

As mentioned in the subsection 2.1.7, mmWave communication has several drawbacks which restrict the usage in the existing cellular systems. The major limitations are,

- mmWave signals observe severe attenuation due to high frequency. Hence, there is higher path loss compared to sub 6 GHz frequency bands [4].
- mmWave signals highly diffract and highly penetrate by surrounding obstacles due to its short wavelength. Thus, highly sensitive to blockage [5].

Therefore, to overcome the high path loss and to cater high traffic hot-spots, small cells are proposed for mmWave communication. Hence, most of these mmWave small cells will be on the urban areas [21]. Since these are in urban areas, a large number of obstacles such as buildings, vehicles and furniture will be within the coverage area of these small cells. This will severely obstruct the mmWave line of sight (LOS) communication between the BS and the UE.

Most of these small cells are targeting office environments and public places where a large number of users gather. Consequently, users are scattered around the BS as clusters, and due to that, some directions may have high user density while some directions may have lesser or no user density at all. Hence, it is quite obvious that users served by a small cell BS may not be distributed uniformly around the BS.

Therefore, cell search procedure for this kind of scenario requires some intelligence at the BS. By providing knowledge about user distribution, BS can only steer its beams through a known populated area for UEs instead of wasting time and energy transmitting towards an obstacle or less populated directions. Nevertheless, current BSs are not dynamically deciding which areas to cover or not based on user distribution. However, it is highly beneficial for BS to provide some dynamic update about the UE distribution around it.

Consequently, a new dynamic weight-based beam sweeping direction and SSB allocation algorithm is presented to optimize the cell search in the initial access procedure. The order of beam sweeping directions and the number of SSBs allocated for each beam sweeping direction are depends on previous learning about user distribution. This previous learning is based on the number of detected UEs per SSB for each sweeping direction. Thus, by providing some learning about the UE distribution around the BS, the delay in detecting UEs during the cell search procedure will decrease, and the number of UEs found during the beam scan will increase. Hence, implementing an intelligent initial access algorithm in the BS, we can overcome the said drawbacks of the mmWave communication and increase the efficiency of the mmWave BS.

3.2 Proposed Initial Access Algorithm

The flow diagram of the proposed initial access algorithm is shown in Figure 3.1. This algorithm can be mainly divided into two parts as the BS side algorithm (left-hand side) which runs in the serving BS and UE side algorithm (right-hand side) which runs in each of the UEs trying to conduct the initial access in this network. Both of these algorithms are parallel occurring in time but may start in two different time instances based on the time UE starts its initial access procedure. Further, the dashed arrows represent the actions which BS and UE interact. Procedures of these two algorithms are separately described below in algorithm 1 for BS and algorithm 2 for UE.

Algorithm 1 BS Algorithm

1: BS transmits SSBs using wide beams
2: BS transmits SSBs using narrow beams
3: BS receives UE feedback messages
4: BS calculates the detected number of UEs for each beam direction ($n_{UE,i}$, $\forall i$)
5: BS calculates detected UEs in kth sweep cycle ($n_{UE,total,k}$) and detection ratio ρ_k for $k \geq 2$: **if** $\rho_k \leq \rho_{th}$ **then** move to step 1 **else** move to next step
6: BS calculates the normalize weight vector ($\mathbf{w}$)
7: BS calculates the optimized SSBs per direction vector ($\mathbf{n}^{\star}_{\mathbf{SSB}}$)
8: Repeat step 2 onwards with new beam sweeping order and optimal SSB allocation $\mathbf{n}^{\star}_{\mathbf{SSB}}$

Algorithm 2 UE Algorithm

1: UE receives SSBs using wide beams
2: UE identifies best UE beam direction (d_{UE})
if d_{UE} found **then** move to next step **else** move to step 1
3: UE starts to receive in d_{UE} direction
4: UE determines best BS narrow beam direction (d_{BS}) **if** $SNR_{d_{BS}} \geq SNR_{th}$ **then** move to next step **else** keep on searching
5: UE feeds back the d_{BS} to BS
6: UE is detected. Proceed to RA

Since the flow diagram and algorithms contain the same steps, only the steps of the BS and UE algorithms are explained. Since these two algorithms are implemented at the same time, they are described together according to the sequential order it occurs.

There are two types of beam patterns used in BS, which are BS wide beams with low beamforming power (as shown in Figure 2.4 (a)) and BS narrow beams with higher beamforming power (as shown in Figure 2.4 (c)). Let's denote total number of wide beam sweeping directions in BS as $D_{BS,wb}$ and total number of narrow beam sweeping directions in BS as $D_{BS,nb}$. Also, the total number of beam sweeping directions in UE as D_{UE} and total Number of SSBs in a single radio frame (i.e., SS burst set size) as $n_{SSB,total}$.

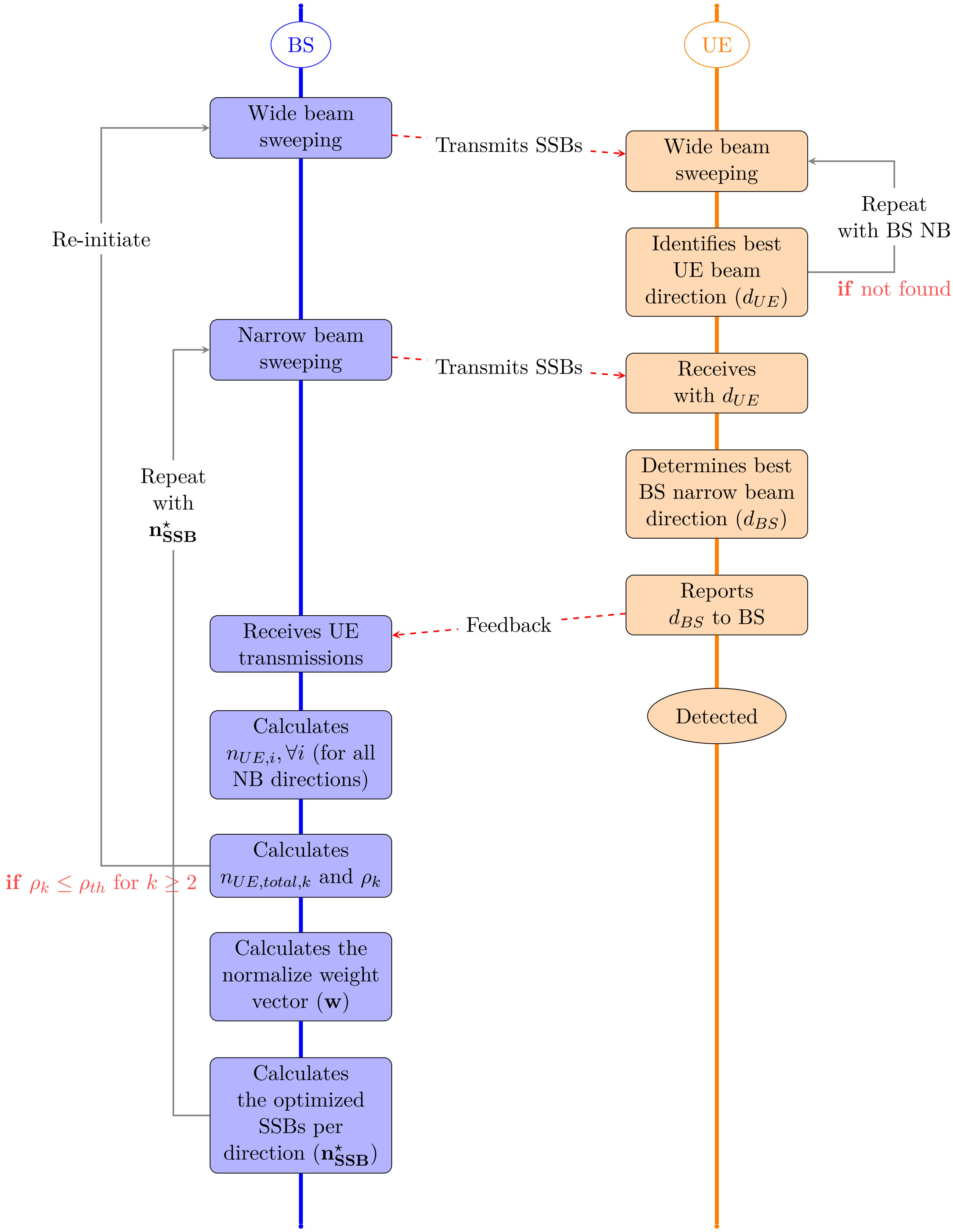

Figure 3.1. Flow diagram of the proposed IA algorithm.

3.3 Explanation of IA Algorithm

As the first step of the BS initial access algorithm, BS starts to beam sweep with its wide beams. BS transmits half of its total available SSBs in a single radio frame (i.e., $\frac{1}{2} \times n_{SSB,total}$) during this beam sweeping. Consecutive SSBs in a radio frame is transmitted in consecutive beam sweeping directions, and this process is repeated until $\frac{1}{2} \times n_{SSB,total}$ is transmitted. Hence, for a given direction i, there are

$$n_{SSB,i,wb} = \frac{n_{SSB,total}}{2D_{BS,wb}} \tag{1}$$

number of SSBs transmitted using wide beams.

The UEs around the BS who are intended to join the network starts to run the UE side initial access algorithm. They need to scan and find a suitable serving BS and correct UE beam to communicate with it. As the first step of the UE algorithm, UE starts to beam sweep 360° and receives the synchronization signals (i.e., SSBs) from nearby BSs.

As in step 2 of the UE algorithm, when UE receives enough number of synchronization signals from a specific BS to cover all UE beam directions, UE tries to identify the best UE beam direction denoted by d_{UE}. It is the UE beam direction with the highest received SNR. If UE is unable to find the best UE beam direction due to insufficient received signals or insufficient signal power, it continues to beam sweep further. This process is continued until UE have discovered its best beam direction.

Once the best UE beam direction d_{UE} is found, UE beamforms to that direction to receive further transmissions from the BS. Thus, the UE stops beam sweeping and starts receiving the transmission signals from the identified BS, as shown in step 3 of the UE algorithm.

As step 2 of the BS algorithm, BS starts to transmit the remaining SSBs of the radio frame using the BS narrow beams. When the BS finishes with wide beam sweeping (BS algorithm:step 1), then it starts the narrow beam sweeping. This sweeping is also done as earlier by transmitting consecutive SSBs in consecutive directions. Figure 2.9 illustrates this narrow beam scanning process. As the narrow beam sweep ends, for a given direction i, there are

$$n_{SSB,i,nb} = \frac{n_{SSB,total}}{2D_{BS,nb}} \tag{2}$$

number of SSBs transmitted with narrow beams in the first beam sweep cycle. When the BS narrow beam sweeping is happening, UE can be in either of the below two states.

- Receiving these BS narrow beams by beamforming to d_{UE}.
  If UE has identified the best UE beam direction, then UE is receiving these BS narrow beams by beamforming to that direction. (UE algorithm: step 3)

- Continues to beam sweep with UE beams for identifying d_{UE}.
  If UE was unable to identify the best UE beam direction with BS wide beams, then UE continues its beam sweeping with BS narrow beams. Furthermore, if that also not succeeded then tries in the next beam sweep cycle.

After the reception of synchronization signal via BS narrow beams, UE tries to determine the best BS narrow beam direction (d_{BS}) as step 4 of the UE algorithm. Thus, the UE calculates the SNR of all the received signals via narrow beams when UE beamformed to d_{UE}. UE selects the highest received SNR values denotes as $SNR_{d_{BS}}$. Then the highest received SNR value direction is identified as the best BS narrow beam direction d_{BS}, if $SNR_{d_{BS}}$ satisfies the inequality

$$SNR_{d_{BS}} \geq SNR_{th}, \tag{3}$$

where SNR_{th} is the predefined SNR threshold value required to establish a reliable communication link between BS and UE. If inequality (3) is not satisfied, then this link does not have sufficient condition for reliable communication. Therefore, the UE keep on searching a BS narrow beam direction or other possible BS that can satisfy this condition.

As the step 3 of the BS algorithm, once BS narrow beam sweeping is completed BS beam sweeps to every narrow beam direction to receive the UE messages. Thus, the BS starts to receive the UE feedback messages. At this time if there are any UEs which were able to determine the d_{BS}, transmits identified direction to the BS as shown in step 5 of the UE algorithm.

After this step, UE knows its best beam and BS knows its best narrow beam to communicate with each other. Therefore, UE is considered as a detected UE to that BS. Hence, the UE side initial access algorithm stops here, and UE proceeds to the random access procedures.

Once the BS received these UE feedback messages, as shown in the BS algorithm step 4, BS calculates the number of UEs detected for each narrow beam sweep direction $n_{UE,i}$ for all $i = 1, \ldots, D_{BS,nb}$.

Then as BS algorithm step 5, BS calculates the total number of UEs detected during the complete beam sweep cycle k, $n_{UE,total,k}$.

At this stage, we define detection ratio ρ_k for kth sweep cycle, a ratio between the total number of UEs detected within the kth sweep cycle and the $(k-1)$th sweep cycle. This ρ_k is calculated as

$$\rho_k = \frac{n_{UE,total,k}}{n_{UE,total,k-1}} \tag{4}$$

for all the $k \geq 2$ sweep cycles.

As step 5 of the BS algorithm, BS calculates the ρ_k and determines whether to proceed forward to optimization procedures or re-initiates the beam sweep process based on the inequality

$$\rho_k \leq \rho_{th}, \tag{5}$$

where ρ_{th} is predefined threshold ratio value set to satisfy the user detection capability. If the calculated ρ_k value satisfies the inequality (5) then the beam sweeping is re-initiated and algorithm returns to step 1 of BS algorithm. If the inequality (5) is not satisfied, then the BS proceeds to the optimization procedures explain below.

Optimization Procedures

The next steps of the BS algorithm are related to the procedures that the BS does when the BS decides to move forward to the optimization procedures. The basic idea behind the introduced optimization procedure is to transmit synchronization signal blocks (SSBs) according to an expected number of users in that beam sweeping direction. It is assumed when a higher number of synchronization signals are transmitted to a specific direction, a higher number of users could be detected. Due to the higher number of SSBs transmitted, UE within that area has a higher probability of receiving and decoding those

SSBs. Hence, a higher number of UEs could be detected from that direction. Also, there are situations where there are no users in a given direction may be due to blockage or geographical distribution of the users. Consequently transmitting SSBs repetitively for that direction is a waste of resources. Therefore, the optimal solution is to transmit a single SSB for that direction during a single radio frame.

An underlying problem when deciding the number of SSBs required for a given direction is, the basis we select to decide it. In the proposed algorithm number of users detected per a SSB is used as the basis for deciding it. In BS algorithm step 6, BS calculates the weight vector $\overline{\mathbf{w}} \in \mathbb{R}_{+}{}^{\mathbf{D_{BS,nb}}}$ with elements

$$\overline{w_i} = \frac{n_{UE,i}}{n_{SSB,i}}, \forall i, \tag{6}$$

where $n_{SSB,i}$ is the number of SSBs transmitted to the ith narrow beam sweep direction. Then the BS calculates the normalized weights vector $\mathbf{w} \in \mathbb{R}_{+}{}^{\mathbf{D_{BS,nb}}}$ as

$$\mathbf{w} = \frac{\overline{\mathbf{w}}}{\|\overline{\mathbf{w}}\|_{\mathbf{1}}}. \tag{7}$$

Above defined normalized weight vector provides us with information about the current detected user distribution among the transmitting narrow bream directions. We can use it to predict the number of users that will be discovered in the next beam sweep cycle.

Number of SSBs transmit per direction vector $\mathbf{n_{SSB}}$, is a vector of size $1 \times D_{BS,nb}$ defined as

$$\mathbf{n_{SSB}} = [n_{SSB,1}, \ldots, n_{SSB,D_{BS,nb}}],$$

which contains the number of SSBs need to transmit in each of the narrow beam sweep direction as elements of the vector. By using $\mathbf{n_{SSB}}$ and the calculated weights in Equation (7) above, the number of users that will discover in the next beam sweep is predicted as

$$\mathbf{w} \times \mathbf{n_{SSB}^T}. \tag{8}$$

Then as step 7 of the BS algorithm, BS calculates the optimized number of SSBs required to transmit towards each narrow beam sweep direction in the next beam sweep cycle. The optimized number of SSBs per direction $\mathbf{n^{\star}_{SSB}}$ (the optimum solution of the $\mathbf{n_{SSB}}$), for the next sweep cycle is calculated by solving the following optimization problem:

$$\begin{aligned} \text{maximize} \quad & \mathbf{w} \times \mathbf{n_{SSB}^T} \\ \text{subject to} \quad & \sum_{i=1}^{D_{BS,nb}} n_{SSB,i} \leq n_{SSB,total} && \text{(9a)} \\ & n_{SSB,i} \in \mathbb{Z}_{+}, \forall i && \text{(9b)} \end{aligned}$$

where optimization variable is $\mathbf{n_{SSB}} \in \mathbb{Z}_{+}{}^{D_{BS,nb}}$. Above integer optimization problem is formulated such that the number of users that will discover in the next beam sweep is maximized subject to below given constraints.

- Total number of SSBs that could allocate within a single radio frame should not exceed the total allowable number of SSBs in a single radio frame ($n_{SSB,total}$). Presented in Equation (9a).

- Number of SSBs transmit per direction should be a positive integer. Hence, at least one SSB is allocated to each direction. Presented in Equation (9b).

As the last step, calculated optimized vector using the integer optimization problem above is used to allocate the number of SSBs transmit per each narrow beam sweep direction in the next beam sweep cycle. Then the narrow beam sweep is conducted again using the total number of available SSBs in a single radio frame ($n_{SSB,total}$). Sweeping order is not sequential this time, and it is arranged such that the highest number of SSBs allocated direction is swept first and so on. Moreover, consecutive $n^{\star}_{SSB,i}$ number of SSBs are allocated for the ith beam sweep direction. When compared this to the earlier narrow beam sweep cycle, earlier one was conducted in a round-robin manner. This concludes the proposed dynamic weight-based optimize beam sweeping direction and SSB allocation algorithm described above.

4 RESULTS AND DISCUSSION

This chapter mainly comprises the result of the simulations and the analysis of results.

4.1 Simulation Setup and Parameters

We simulate the proposed optimized initial access technique to evaluate its performance in different aspects. In order to do so, we simulate a scenario of an urban small cell with a single 5G BS and static user deployment where no users are moving during the simulating time period. Therefore, UE handover management or UE tracking is not required. mmWave channel at 28 GHz is considered and, system parameters used for simulations are shown in Table 4.1.

Table 4.1. System specific simulation parameters

Description	**Value**
Carrier frequency	28 GHz
Channel bandwidth	1 GHz
BS Tx power	30 dBm
UE Tx power	27 dBm
Noise Figure (NF)	6 dB
Thermal noise density (N_0)	-174 dBm/Hz
Propagation model	NLOS
Path-loss exponent (γ)	2

We use 5G NR numerology 3, with 120 kHz subcarrier spacing as the radio frame structure for the simulations. For frequencies higher than 6 GHz, 120 kHz subcarrier spacing or higher is designed and therefore, we select 120 kHz subcarrier spacing for simulations. Therefore, with this frame structure maximum of 64 SSBs could be configured for a single radio frame. User distribution and other simulation parameters related to the simulations are tabulated in Table 4.2.

Table 4.2. User specific simulation parameters

Description	**Value**
Sub carrier spacing	120 kHz
Number of SSBs for radio frame	64
Number of users simulated	40
UE distance from BS	10 - 150 m
UE distribution	Uniform [0-360°]
Initial orientation of UE antenna	Random [0-360°]
UE speed	0 m/s (stationary)

5G small cell of a radius 150 m is considered and 40 users per BS is simulated. Users are distributed uniformly around the BS with different radii between 10 m and 150 m. These UEs are assumed to have random antenna orientation range from 0-360° with respect to the reference (North) direction. Ideal SNR threshold (SNR_{th}) for user detection is considered as – 5 dB but varied for obtained different simulation.

BS and UE antenna specific simulation parameters are shown in Table 4.3 below.

Table 4.3. Antenna specific simulation parameters

Description	**Value**
BS antenna configuration	8x8 UPA
Spacing between the elements	$\lambda/2$
Number of BS antenna panels	4
BS antenna panel directions	[45°, 135°, 225°, 315°]
UE antenna configuration	2x2 UPA
BS and UE antenna array elevation angle	0°
BS and UE beamforming	Analog
Number of UE beam directions	4
Number of BS wide beam directions	4
Number of BS narrow beam directions	16

At the BS side 8x8 uniform planner array (UPA) with $\lambda/2$ antenna element spacing is considered. The same type of 4 UPA panels are mounted on the BS towards the four directions mentioned in the Table 4.3 above for simulating equal beam pattern. At the UE one 2x2 UPA panel is considered for initial simulations. Both the BS and UE antenna elevation angles are considered as zero for simulating 2D beam pattern. Analog beamforming is used at both the BS and UE antenna arrays. For the given simulations, four wide beams with a half-power beamwidth of around 90° are simulated at the UE. At the BS, four wide beams same as UE wide beams, and 16 narrow beams with a half-power beamwidth of around 22.5° are simulated.

4.2 Results

4.2.1 Probability of Misdetection

Probability of misdetection is defined as the probability that a UE within a cell is not detected due to the perceived SNR at the UE is below a given SNR threshold level (SNR_{th}). This is a crucial performance indicator to measure the correctness of an initial access procedure. Therefore, misdetection probability of the proposed initial access algorithm is plotted with UE distance from the serving BS. In order to do so, at a given user range r_1 and $r_2(> r_1)$, UEs are uniformly distributed within an annulus having an outer radius of r_2 from the BS and an inner radius of r_1 from the BS. The mean distance of the inner and outer radii are considered as the distance from the UE to BS when plotting the result.

Simulations are done for BS to UE distance range of 10 m to 150 m considering the BS to UE distance of typical urban small cell scenario. Furthermore, the same simulation is conducted for the exhaustive initial access technique and iterative initial access technique and plot on the same graph to compare the misdetection probability performance of the proposed initial access technique. These two algorithms are selected since they provide the basics for initial access searching techniques and widely used for comparing the other initial access techniques. PMD at the SNR threshold of -5 dB of the proposed (optimized), exhaustive and iterative initial access techniques are shown in Figure 4.1 below.

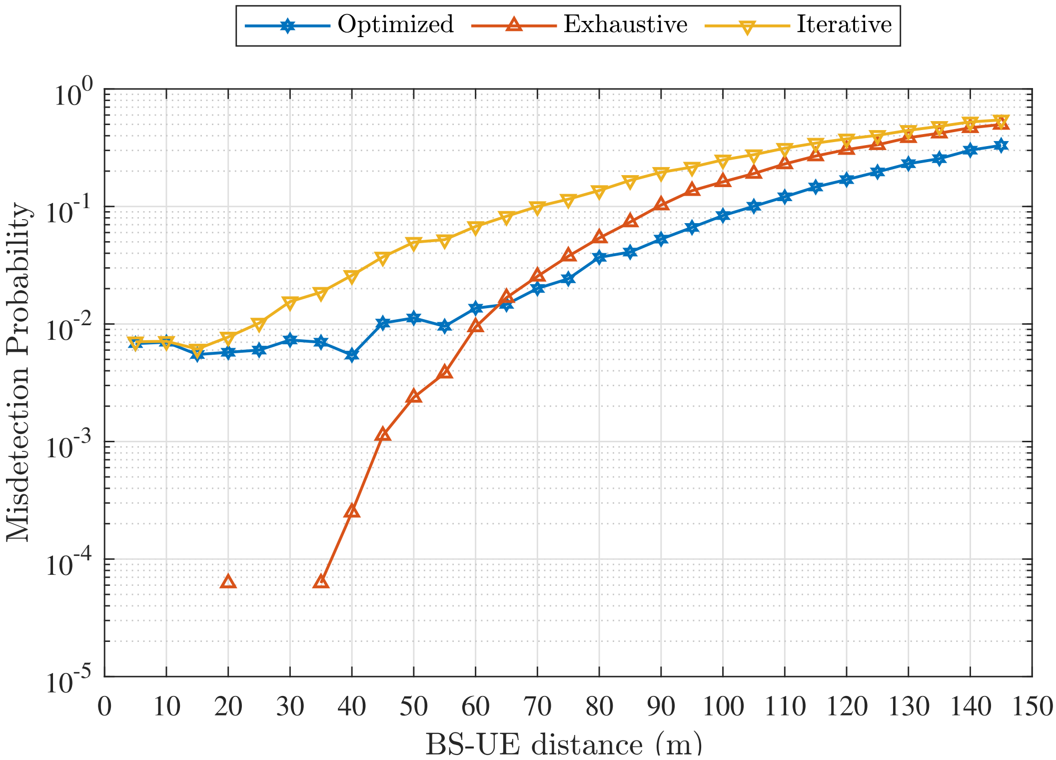

Figure 4.1. PMD at SNR threshold of -5 dB.

Results in Figure 4.1 show that all the compared initial access techniques misdetetction probability is increasing as the BS to UE distance increases. However, the proposed technique shows some improvement compared to the other two techniques, especially at the higher BS-UE distances. This is mainly due to the usage of the knowledge of the historical user location for identifying the users in a given coverage range. Therefore, that PMD gain is the advantage that achieved via optimized beam sweeping introduced in this novel algorithm.

It is worthwhile to note that at lower distances proposed algorithm shows a bit worse performance compared to the exhaustive algorithm. The crossover point of these two PMD graphs changes with SNR threshold value which is used for detecting users. This worse performance could be the result due to the usage of wide beams to beam sweep at the first stage of the algorithm. It could be easily seen that at lower distances newly proposed optimized algorithm and iterative algorithm both show, same kind of behaviour. Since both algorithms used wide beams at the first scan, there is a higher probability that some users in the range may not be detected due to the lower beamforming gain used on those wide beams. Hence, at these distances, the exhaustive search performs well compared the other two algorithms. Moreover, almost all of the time iterative search shows inferior performance compared to the other two algorithms.

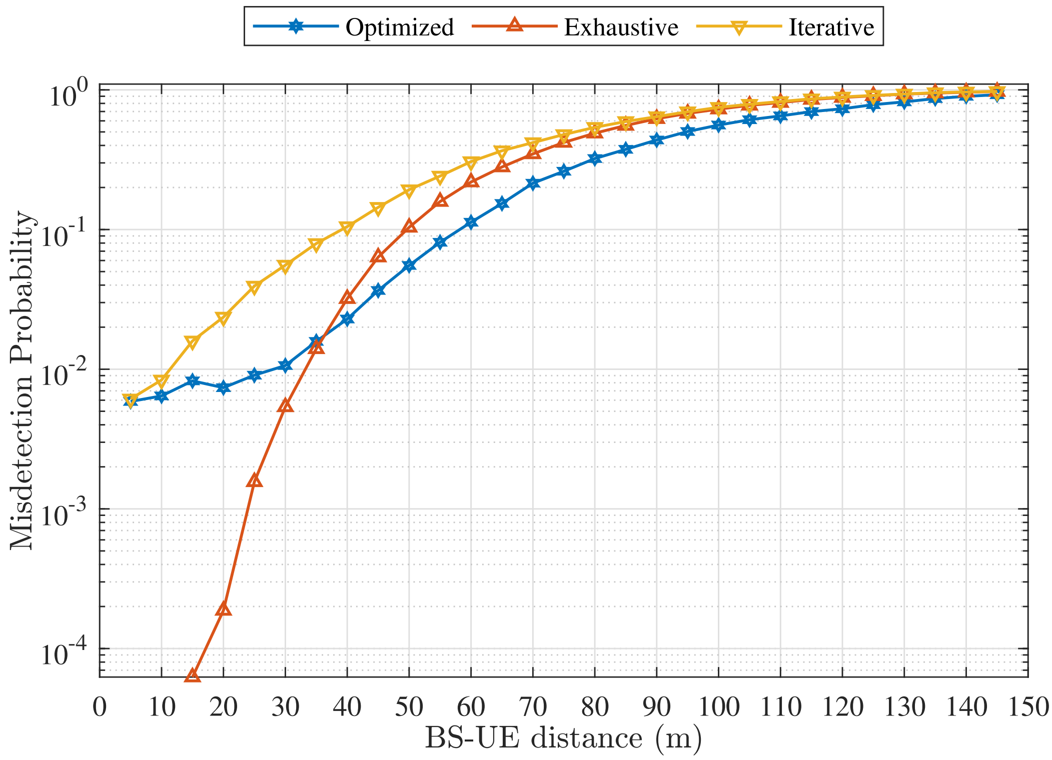

Figure 4.2. PMD at SNR threshold of 0 dB.

Same probability of misdetection simulations are conducted at 0 dB SNR threshold and plotted against the BS and UE distance. Figure 4.2 shows the PMD performance of the proposed, exhaustive and iterative algorithms at the SNR threshold of 0 dB. As mentioned earlier, it could be seen from the above graph that the crossover distance of the optimized PMD graph and exhaustive PMD graph has been lowered compared to the $SNR_{th} = -5$ dB scenario. Also, all the three algorithms show the same comparative performance as earlier curves and higher misdetection probability compared to the $SNR_{th} = -5$ dB.

4.2.2 User Detectability

According to the same method explained earlier, detection probability also plot against the BS and UE distance for a range of 10 m to 150 m. For the sake of comparisons detection probability of exhaustive and iterative method is also plotted on the same graph. Detection probability of all the three algorithms at SNR threshold of -5 dB is shown in Figure 4.3.

As can be seen from the Figure 4.3, the proposed algorithm shows a superior detection capability, especially at the higher distances from the BS compared to the other two initial access techniques. Therefore, this algorithm could provide a good detection capability for the cell-edge users who are at higher distances from BS. Even though it has a

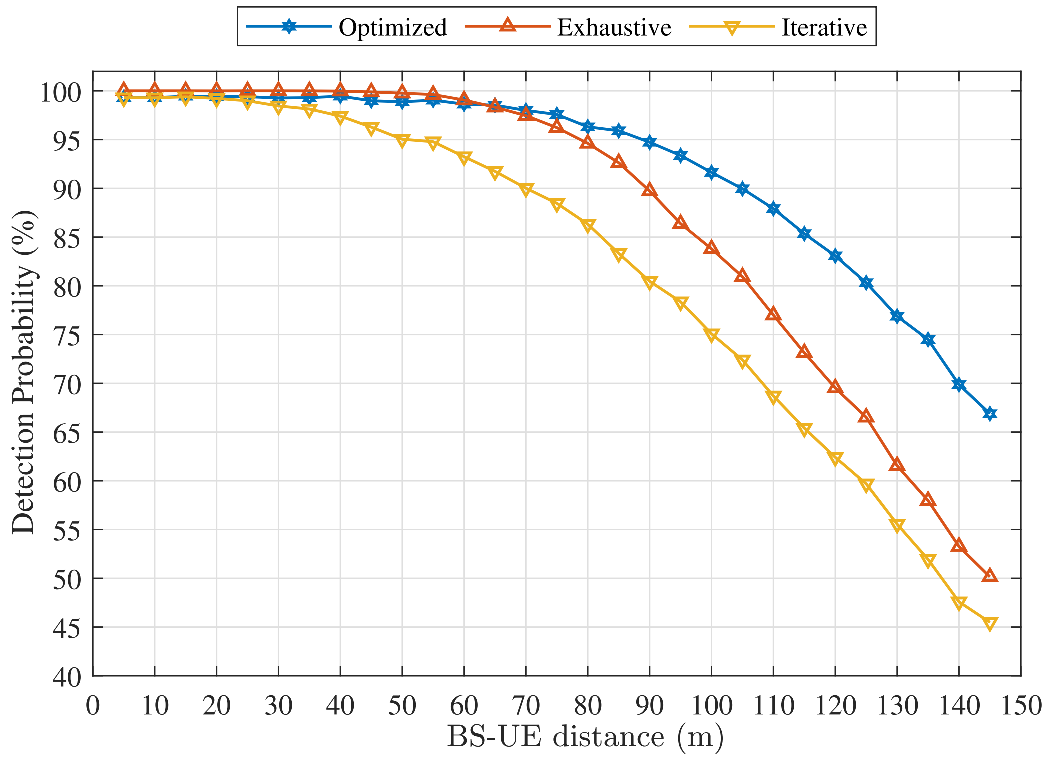

Figure 4.3. User detection percentage when SNR threshold of -5 dB.

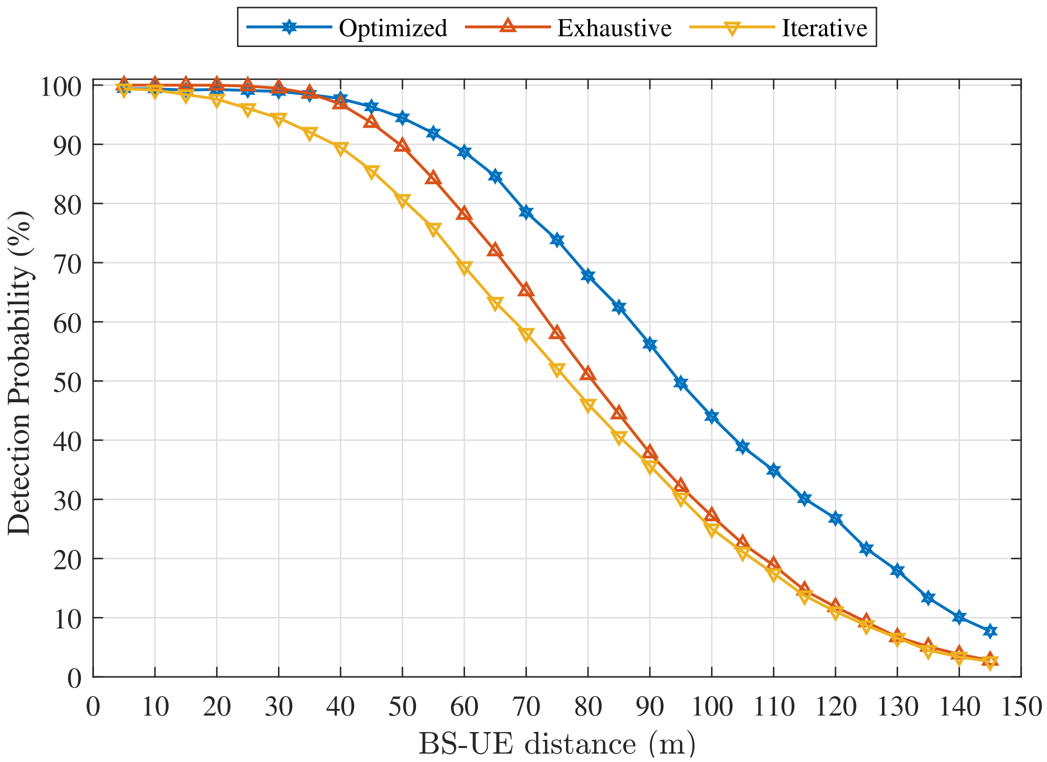

Figure 4.4. User detection percentage when SNR threshold of 0 dB.

bit lower performance compared to exhaustive method at lower distances, optimized beam sweeping capability of the proposed algorithm has overcome it and improves the detectability at the higher distances.

Detection probability of all the three algorithms at the SNR threshold of 0 dB are presented in Figure 4.4. The higher detection capability of the proposed algorithm is still visible from that result. Furthermore, it displays the strong detection capability of the optimized algorithm at the higher distances even though other two algorithms deteriorate rapidly at higher BS – UE distances.

The maximum number of users detected during a beam sweep and the percentage of times that it happened when simulated for 10,000 iterations are plotted for all the three algorithms. Histograms of the maximum number of users detected during the sweep cycle for optimized, exhaustive and iterative techniques are shown in Figure 4.5 below.

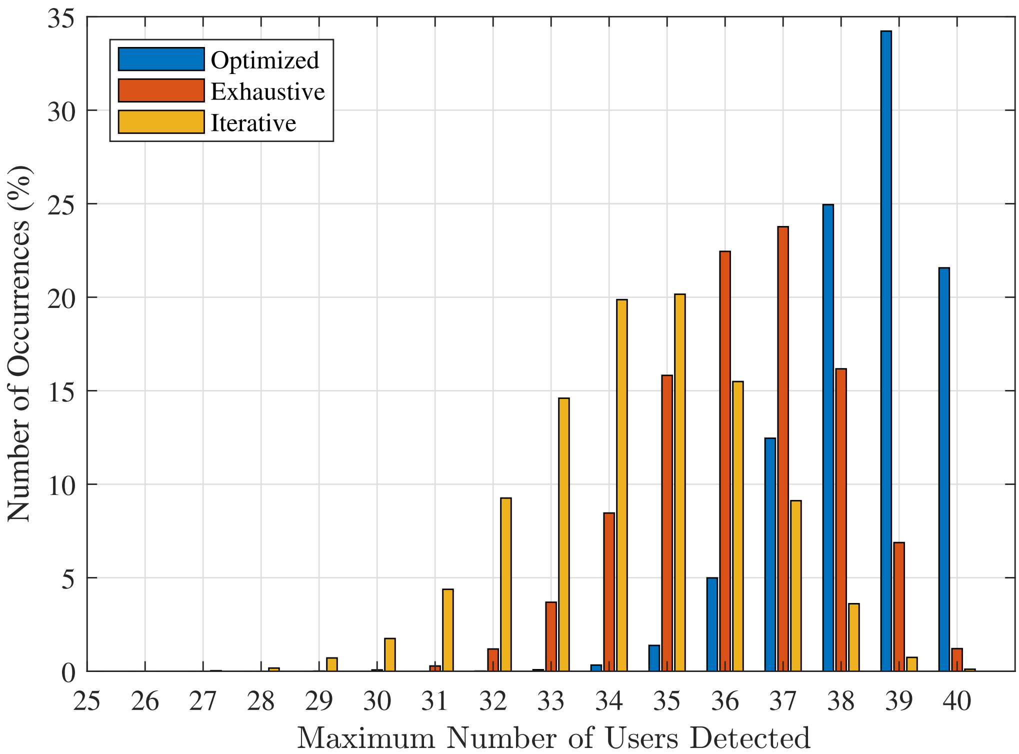

Figure 4.5. Histograms of maximum number of users detected when SNR threshold of -5 dB.

From the graph above, it could be seen that the optimized algorithm is capable of detecting all most all the users on many instances compared to the exhaustive search algorithm and iterative search algorithm. Detecting the total number of simulated users rarely happened in exhaustive algorithm while iterative algorithm was not capable of detecting the total number of simulated users within the range. Most of the time, the exhaustive algorithm is capable of detecting 37 number of users, while iterative algorithm is capable of 35 number of users out of 40 simulated users. The same simulation is carried out for SNR threshold of 0 dB, and the obtained result is shown in Figure 4.6.

According to the graph in Figure 4.6, it could be seen that the optimized algorithm is capable of detecting more users in many instances compared to the exhaustive search algorithm and the iterative search algorithm. Due to the higher SNR threshold, both algorithms are incapable of detecting all the simulated users. However, still, the optimized algorithm is capable of showing higher detection capability proving its user detection superiority over the other two legacy algorithms.

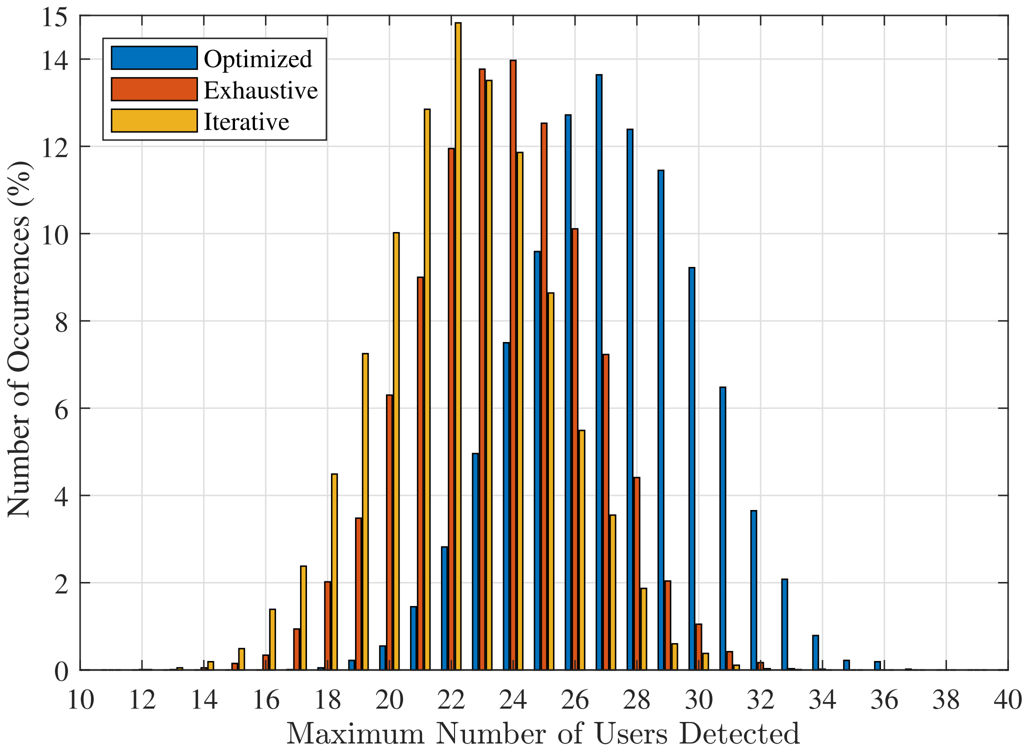

Figure 4.6. Histograms of maximum number of users detected when SNR threshold of 0 dB.

4.2.3 Resource Optimization

Several simulations are conducted to evaluate the performance impact of the optimized resource allocation and constant resource allocation for beam sweeping. In order to do so optimized number of SSBs per each beam sweep direction vs constant number of SSBs per each beam sweep direction is simulated. Constant SSB allocation implies that in one beam sweep cycle, every beam sweep direction is allocated an equal number of SSBs. For the considered 120 kHz NR subcarrier spacing configuration, we could allocate a maximum of 64 SSBs to whole 16 beam sweep directions we simulate. Therefore, we could allocate equally 1, 2, 3 or 4 SSBs per each sweep direction. Detected user percentage at each sweep cycle against the beam sweep cycle is plotted for these allowable constant allocations and the optimized SSB allocation, as shown in Figure 4.7.

The results of the same simulation when the SNR threshold is 5 dB is shown in Figure 4.8. From that graph, it could be seen that the optimized algorithm has performed better than the constant SSB allocation. Since the considered SNR threshold is a bit higher, a constant allocation is not capable of detecting more users due to limited constant

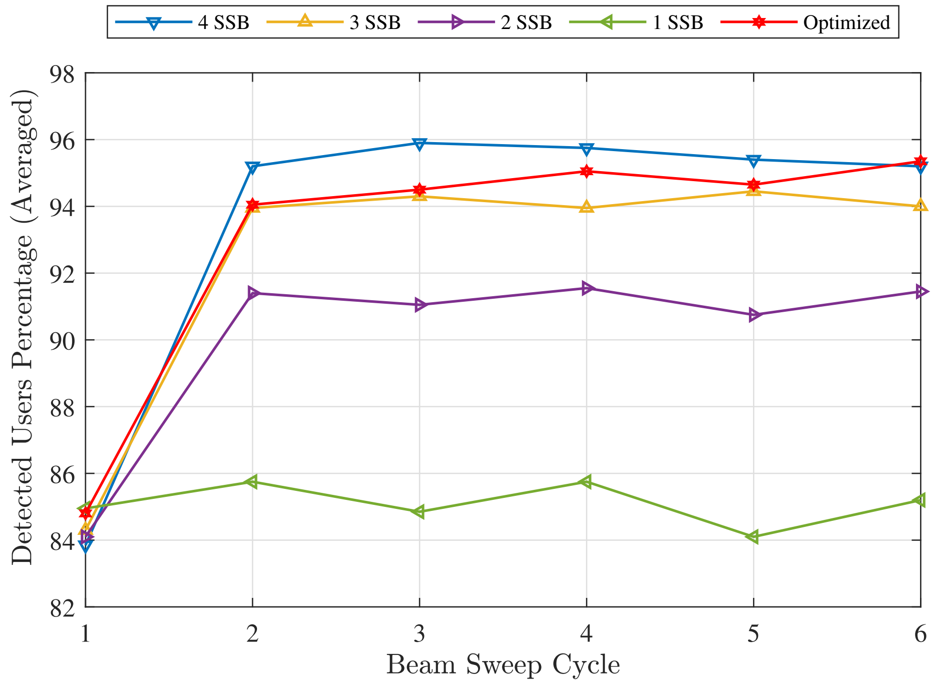

Figure 4.7. Averaged user detection percentage at each sweep cycle when SNR threshold of -5 dB.

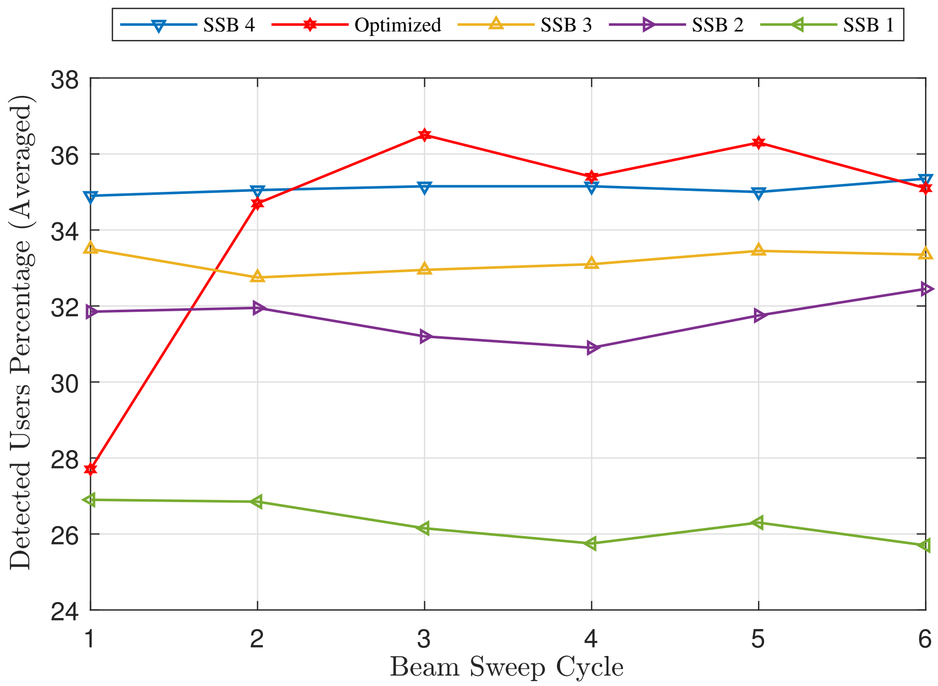

Figure 4.8. Averaged user detection percentage at each sweep cycle when SNR threshold of 5 dB.

resources allocated for each direction irrespective of user density. Although on the other hand, optimized sweeping with allocating an optimized number of SSBs based on the expected number of users or simply the user density would be benefited in detecting more users. Hence, due to optimized sweeping proposed in this new algorithm, it is capable of detecting more users, especially at lower SNR values or at higher distances.

4.2.4 Detection Errors

One of the main challenges of initial access in mmWave is identifying the correct Tx and Rx beam pair for communication. Due to the various reasons the geographically aligned Tx and Rx beam pair may not be the best Tx and Rx beam pair to communicate with each other. Therefore, some error is incurred when identifying the correct beam pair. Evaluates this erroneously detected beam pairs several simulations are carried out and erroneously detected percentage is plotted against the BS and UE distance for all the three initial access techniques. Erroneously detected percentage with BS –UE distance at SNR threshold of -5 dB for optimized, exhaustive and iterative initial access techniques are shown in Figure 4.9.

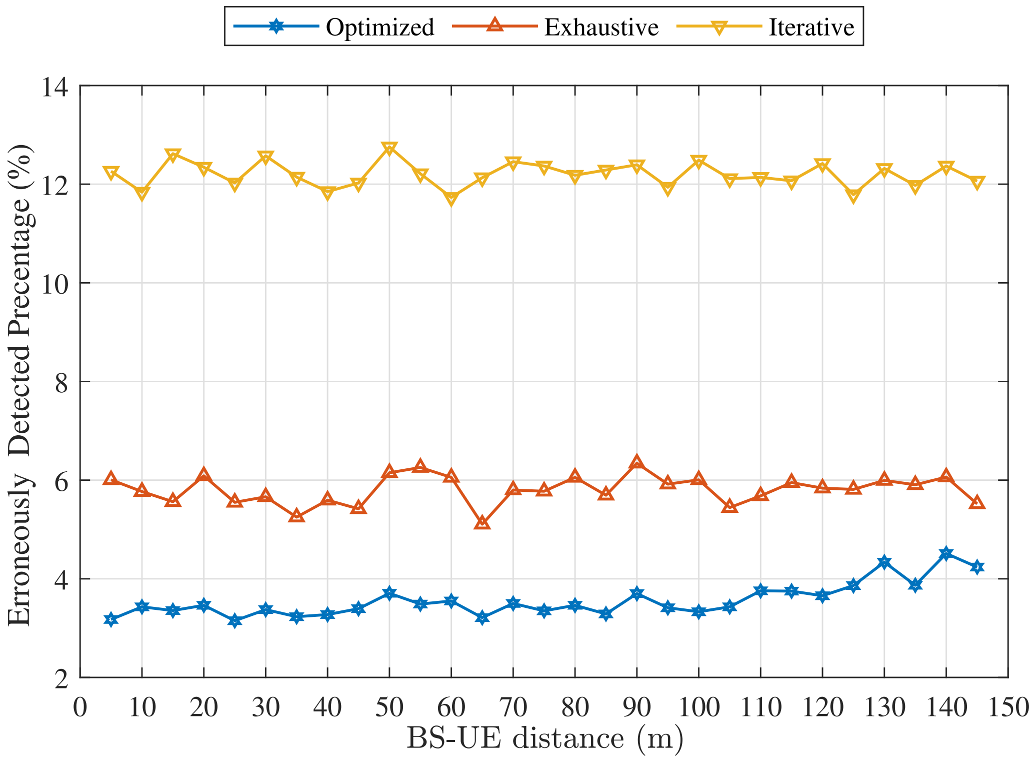

Figure 4.9. Erroneous detection percentage when SNR threshold of -5 dB.

From the above erroneous detection graph in Figure 4.9, it could be seen that the proposed optimized algorithm has the lowest erroneous detection compared to the exhaustive and iterative techniques. Almost all of the time it has low erroneous detection percentage of around 3-4% and at cell edge distances it has a bit higher value of 4%. The exhaustive algorithm has around 6% erroneous detection percentage while iterative algorithm has much higher erroneous detection percentage of around 12%. It is worthwhile to note that the erroneous detection percentage is not highly dependent on the BS – UE distance, but it is highly dependent on the initial access algorithm.

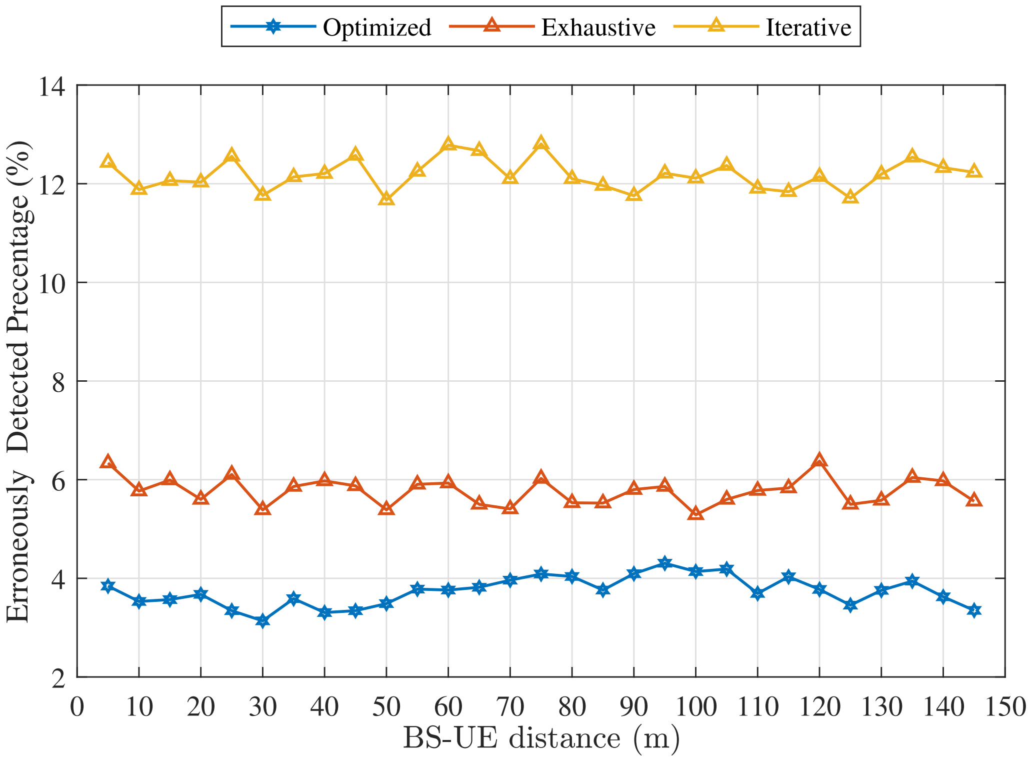

Figure 4.10. Erroneous detection percentage when SNR threshold of 0 dB.

Erroneously detected percentage with BS –UE distance at SNR threshold of 0 dB for optimized, exhaustive and iterative initial access techniques are shown in Figure 4.10. It also has the same performance as earlier. Moreover, the same erroneous probabilities could be observed despite the SNR threshold used.

5 SUMMARY

5.1 Conclusion

The research study presented in this thesis was conducted on initial access in mmWave 5G cellular networks. The main objective of this research was to study the challenges in initial access in mmWave and then develop a new initial access algorithm to overcome those challenges. Therefore, new dynamic weight-based beam sweeping direction and synchronization signal block (SSB) allocation algorithm was presented to optimize the cell search in the mmWave initial access procedure. In this algorithm, the order of beam sweeping directions and the number of SSBs allocated for each beam sweeping direction depends on previously learned experience. This learning is based on the number of detected UEs per SSB for each sweeping direction. Thus, by providing some learning about the UE distribution around the BS, the delay in detecting UEs during the cell search procedure will decrease, and the number of UEs found during the beam scan will increase.

First parts of the thesis mainly comprise of background knowledge required to understand the technical concepts presented in the thesis. In that, we have provided an introduction to 5G cellular technology and the new technologies introduced with it along with the challenges faced when using mmWave communication for 5G. In the intermediate parts, background knowledge required to understand the initial access in cellular communication and mmWave communication, existing literature on mmWave initial access algorithms and its performance is documented. Finally, proposed new mmWave initial access algorithm, formulation of the proposed algorithm and discussion on the simulation setup and results were presented.

We simulate a scenario of an urban small cell with a single 5G BS and static user deployment to check the performance of the proposed algorithm. Moreover, same scenario is simulated for exhaustive and iterative initial access techniques for comparison purposes. Based on the obtained results, the proposed algorithm has shown better probability of misdetetction compared to the other two algorithms, especially at higher BS-UE distances. In terms of detectability also, proposed algorithm has shown higher performance compared to the other two. Several simulations are conducted to evaluate the performance impact of the optimized resource allocation and constant resource allocation for beam sweeping. From the results, it could be seen that the optimized resource allocated beam sweeping algorithm is capable of delivering the same performance as maximum constant resource allocation for beam sweeping. Also, the simulation shows that the proposed optimized algorithm has the lowest erroneous detection compared to the exhaustive and iterative techniques.

The significant implication of the results is using this optimized initial access algorithm we can detect more users with lesser misdetection probability. Also, with the optimized initial access algorithm, it is possible to achieve the same performance with lesser number of dynamically allocating resources compared permanently allocating a constant number of resources. Better performance of the proposed initial access algorithm is mainly due to the usage of the knowledge of the historical user location for identifying the users in a given coverage range. Further, comparatively less resource usage of the proposed algorithm is mainly due to the optimal allocation of the SSBs to the beam sweeping directions, considering the whole user distribution around the BS. Therefore, we can conclude that the proposed algorithm has better performance along with higher resource usage efficiency.

5.2 Future Works

In the future, this research could be extended to multi BS scenario where multiple BSs are within the area to serve the users. In that case, it will become a coordinated initial access problem where each of the surrounding BS will participate in deciding the optimal SSB allocation for directions. Therefore, this algorithm needs modifications to address the optimum BS selecting among the possible serving base stations.

The currently simulated static user environment could be again simulated for moving users to check the adaptability of the same algorithm for moving user scenario. In that conditions, we may have to introduce some modifications for the existing algorithm to predict the user distribution of the next sweep cycle. Finally, we can extend this research for moving users in a multi BS scenario where several modifications for the algorithm may be required.

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