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# Enhancing 5G-NR PRACH Performance Through Managing Intra/Inter-Cell Interference

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## Abstract

This study investigates the impact of User Equipment (UE) and cell configuration parameters on the performance of the Physical Random Access Channel (PRACH) in 5G New Radio (5G-NR) networks, particularly under intra-cell and inter-cell interference conditions. By leveraging simulations, we identify key factors that influence PRACH detection reliability and propose strategies to optimize these configurations. The results demonstrate that managing interference within and between cells is important for maintaining robust communication quality. The study provides insights into how optimizing these configurations can lead to significant improvements in PRACH performance by contributing to more resilient and efficient 5G-NR networks. The simulation results indicate that optimizing UE and cell configurations can enhance PRACH detection probability by up to 25% under high interference conditions.

## Keywords

Keywords: 5G-NR PRACH, Intra/Inter-Cell Interference, Quality of Service (QoS), Correct Detection Rate (CDR).

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## I INTRODUCTION

The advent of 5G NR (New Radio) technology has unlocked a new realm of possibilities in wireless communication and it promises unprecedented speeds, ultra-low latency and the capacity to connect billions of devices simultaneously. However, the robustness and reliability of 5G NR networks in real-world scenarios depend heavily on the ability to effectively manage and mitigate interference, both within cells (intra-cell interference) and between neighboring cells (inter-cell interference).

The novelty of this research lies in its focused examination of the impact of intra-cell and inter-cell interference on the performance of the Physical Random Access Channel (PRACH) in 5G-NR networks. While previous studies have addressed various aspects of 5G communication, the specific challenge of optimizing PRACH performance under such interference conditions has received limited attention. This study fills that gap by providing a comprehensive analysis of how UE (User Equipment) and cell configuration parameters influence PRACH detection reliability, particularly in the presence of these interferences.

The primary contributions of this research are twofold. First, it offers a detailed analysis of how intra-cell and inter-cell interference impact PRACH performance in 5G-NR networks. Second,

it provides evidence through rigorous simulations by highlighting the specific conditions under which PRACH detection robustness is compromised. These contributions are particularly significant as they provide valuable insights into the challenges of maintaining reliable and interference-resilient 5G NR networks which are crucial for achieving seamless connectivity and high-quality user experiences.

The motivation behind this study stems from the important role that PRACH plays in 5G-NR networks. As the gateway for UE to initiate communication with the network, PRACH's efficiency directly impacts overall network performance, latency and Quality of Service (QoS). Given the increasing density of 5G deployments and the growing demand for high-speed, low-latency services, optimizing PRACH performance in the face of interference has become a paramount concern for network operators and researchers alike.

This paper is structured as follows: Section II presents the essential aspects of Random Access (RA) in 5G-NR context as Preambles play a key role in synchronization and initial access. Section III provides an overview of related work, focusing on advancements in PRACH detection and interference management. Section IV details the research methodology, including the simulation setup and the interference modeling techniques employed. In Section V, we present the results of our simulations and discuss the impact of various interference scenarios on PRACH performance. Finally, Section VI concludes the paper by summarizing our findings and suggesting potential directions for future research.

## II PRACH PRINCIPLE AND PREAMBLE DETECTION

This section presents the essential aspects of Random Access (RA) in 5G-NR context. Preambles play a crucial role in synchronization, initial access and signal detection.

### 2.1 Preamble Structure and Procedure

RA is a basic procedure in 5G-NR technologies. It enables UEs to establish uplink synchronization and initiate uplink transmission. PRACH employs phase modulation based on Zadoff-Chu sequences [1] with distinct phase variations among different symbols within the sequences. Before sending its random access request, UEs must retrieve a set of information transmitted by the base station through the SIB2 (*System Information Block Type 2*) message [2].

With this information, the UE can transmit the PRACH preamble using the resources indicated by the Next-Generation NodeB (gNB) during the transmission of SIB2. The transmission of the PRACH is associated with the RA-RNTI (*Random Access RNTI*).

When an UE enters a new cell, it has no prior knowledge of the gNB. After identifying the optimal SSB (*Synchronization Signal Block*) through downlink synchronization, the UE transmits the PRACH containing its information based on the best time index of the SSB. Figure 1 illustrates the interactions between the UE and the gNB during the initial access procedure [3].

Random access process is described in Figure 1 where UE selects randomly a preamble from a list of parameters broadcasted through the SIB2 and transmits it in PRACH with an initial power result of a basic downlink pathloss estimation. If there is no answer from the gNB, UE makes a retry with higher power level.

The 5G-NR PRACH preamble consisted of a complex sequence (SEQ) which an OFDM symbol, built with a Cyclic Prefix (CP). This allows for an efficient frequency-domain receiver at the gNB. The preamble length is shorter than PRACH slot in order to provide room for a

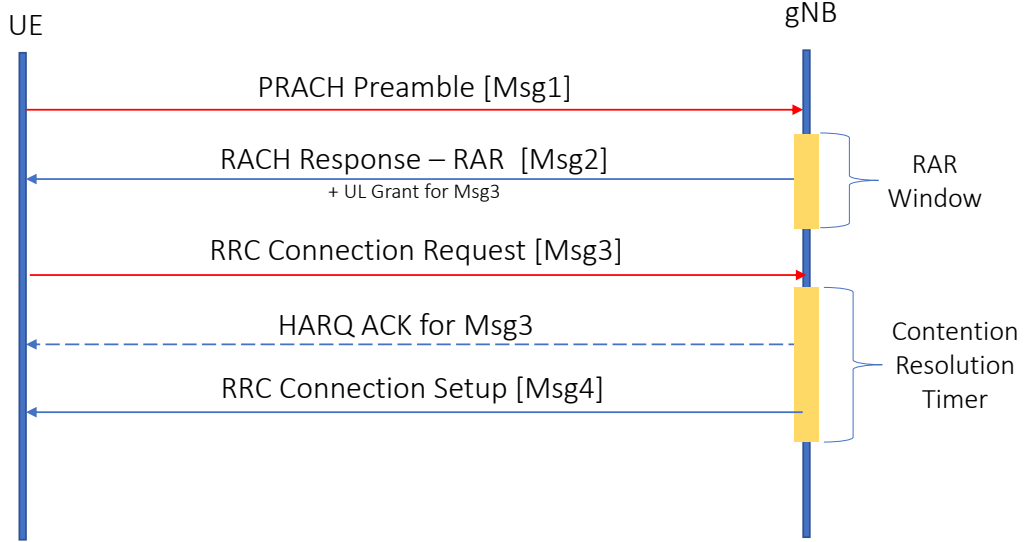


Figure 1: NR-PRACH Procedure.

Guard Period (GP) to absorb the propagation delay. The CP facilitates PRACH processing in the frequency domain. Refer to Figure 2 for the NR-PRACH structure.

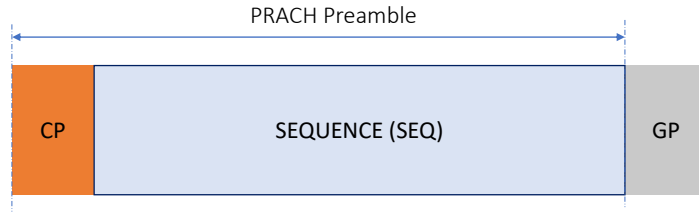


Figure 2: NR-PRACH structure.

## 2.2 Preamble Sequence Generation

The preamble sequence length is set to a prime number of 839. There are 838 sequences with optimal cross-correlation properties. The  $u^{\text{th}}$  ( $0 \leq u \leq 837$ ) root Zadoff-Chu sequence is defined by ( $N_{ZC}$  is the length of the Zadoff-Chu sequence):

$$x_u(n) = e^{-j \frac{\pi u n(n+1)}{N_{ZC}}}, 0 \leq n \leq N_{ZC} - 1 \quad (1)$$

From the  $u^{\text{th}}$  root ZC sequence, random access preambles with Zero Correlation Zones (ZCZ) of length  $N_{ZC} - 1$  are defined by Cyclic Shifts (CS) according to [4]:

$$x_{u,v}(n) = x_u((n + C_v) \bmod N_{ZC}), \quad (2)$$

where  $C_v$  is the cyclic shift and  $N_{ZC}$  is the cyclic shift offset. This paper adopts preamble format 0 in the 5G-NR, which generates from a 839 point ZC sequence which is specifically designed for contention-based access, where multiple UEs may attempt to access the network simultaneously.

## 2.3 Preamble Detection

The PRACH receiver is implemented to maximize the probability of “correct” preamble detection and minimize processing latency. The functional diagram of the conventional PRACH receiver, which shares certain operations with the Orthogonal Frequency Division Multiplexing (OFDM) demodulator, is illustrated in Figure 3. The 5G-NR PRACH receiver process [5] :

- (1) **CP-GP (Cyclic Prefix and Guard Period) Removal**: In this step, the Cyclic Prefix (CP) and Guard Period (GP), which are added to the transmitted PRACH signal for synchronization purposes, are removed to obtain the original signal.
- (2) **Frequency Shift**: The received signal is shifted in frequency to bring it to a common reference frequency, aligning it with the system’s reference.
- (3) **Decimation**: The signal is sampled at a lower rate, reducing the data rate while retaining essential information, to simplify subsequent processing.
- (4) **FFT (Fast Fourier Transform)**: An FFT is applied to the decimated signal to transform it from the time domain to the frequency domain, allowing the identification of frequency components.
- (5) **Sub-Carrier Demapping**: In this step, sub-carriers used for the PRACH signal are demapped, extracting the relevant information from the frequency domain representation.
- (6) **IFFT (Inverse Fast Fourier Transform)**: An IFFT is performed to convert the signal back from the frequency domain to the time domain, preparing it for further processing.
- (7) **Signature Detection**: Finally, signature detection technique is applied to identify and extract specific patterns or signatures in the PRACH signal, which are crucial for synchronization and channel estimation in 5G-NR communication systems. Figure 4 shows the basic functions of the signature detector.

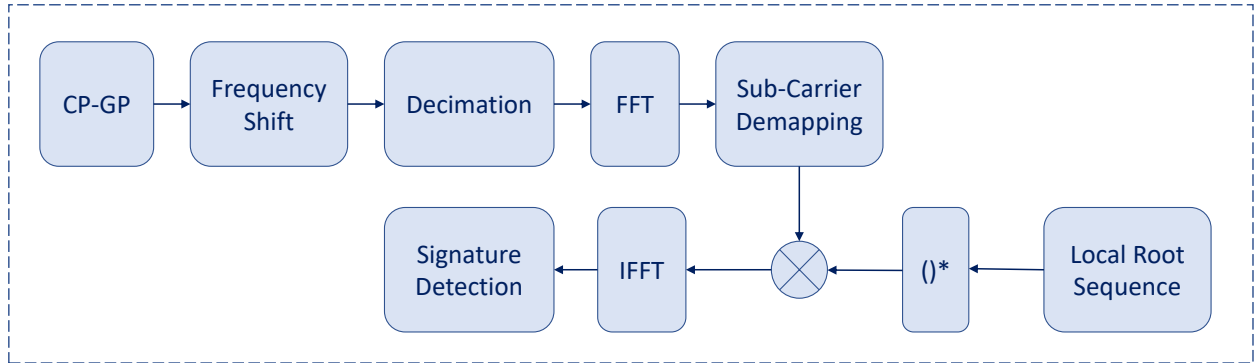


Figure 3: 5G-NR PRACH Receiver Block Diagram.

The fact that different PRACH signatures are generated from Cyclic Shifts (CS) of a common root sequence means that the frequency-domain computation of the Power Delay Profile (PDP) of a root sequence provides in one shot the concatenated PDPs of all signatures derived from the same root sequence. Therefore, the signature detection process consists of searching, within each ZCZ defined by each Cyclic Shifts (CS), the PDP peaks above a detection threshold over a search window corresponding to the cell size.

- (1) **Power Correlation Extraction**: In this step, the received signal’s power is correlated with a known “root sequence” to identify potential preamble candidates within the received signal. This process helps in locating the start of the frame.
- (2) **Detection threshold Calculation**. The target false alarm probability  $p_{fa}(T_{det})$  drives the setting of the detection threshold  $T_{det}$ . In [5], it is showed that under the assumption that the  $L$  samples in the uncertainty window are uncorrelated Gaussian noise with variance  $\sigma_n^2$

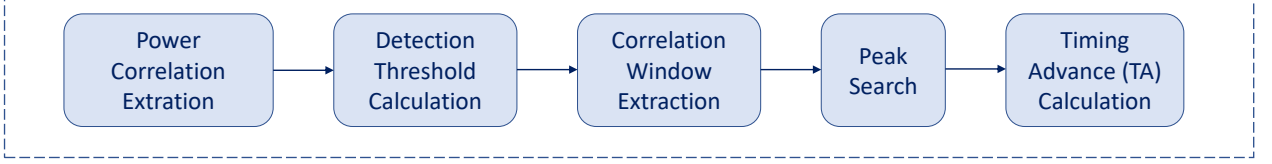


Figure 4: Preamble Detection Block Diagram

in the absence of preamble transmission, the complex sample sequence  $z_a^m(\tau)$  received from antenna  $a$  (delayed to reflect a targeted time offset  $\tau$  of the search window and despread over a coherent accumulation length (in samples)  $N_{ca}$  against the reference code sequence) is a complex Gaussian random variable with variance  $\sigma_{n,ca}^2 = N_{ca} \times \sigma_n^2$ . In practice,  $N_{ca}$  is the size of the IFFT. The non-coherent accumulation  $z_{nca}(\tau)$  is modelled as follows [5] :

$$z_{nca}(\tau) = \sum_{a=1}^{N_a} \sum_{m=0}^{N_{nca}-1} |z_a^m(\tau)|^2 \quad (3)$$

where  $N_a$  is the number of antennas and  $N_{nca}$  is the number of additional non-coherent accumulations (e.g. in case of sequence repetition).

$z_{nca}(\tau)$  follows a central chi-square distribution with  $2N = 2N_a \times N_{nca}$  degrees of freedom, with mean (defining the noise floor)  $\gamma_n = N \times \sigma_{n,ca}^2$  and Cumulative Distribution Function (CDF)  $F(T_{det}) = 1 - p_{fa}(T_{det})^L$ . It is worth noticing that instead of the absolute threshold, in [5] the authors consider the threshold  $T_r$  relative to the noise floor  $\gamma_n$  as follows:

$$T_r = \frac{T_{det}}{\gamma_n} = \frac{T_{det}}{N_a \times N_{nca} N_{ca} \sigma_n^2} \quad (4)$$

- (3) **Correlation Window Extraction:** The received signal is divided into smaller time intervals or windows to focus the correlation process on specific parts of the signal. These windows allow for more precise identification of the preamble within the signal.
- (4) **Peak Search:** Within each correlation window, the highest correlation peak is identified. This peak corresponds to the position where the preamble sequence aligns most closely with the received signal, indicating the start of the frame.
- (5) **Timing Advance (TA) Calculation:** Once the peak is found, the timing advance (TA) is calculated to determine the timing misalignment between the received signal and the expected frame timing. The TA is used to synchronize the receiver with the incoming signal for further data reception and processing.

### III RELATED WORKS

The existing literature on 5G-NR PRACH performance and interference management reveals a comprehensive array of studies focused on understanding and mitigating the challenges posed by intra-cell and inter-cell interference as summarized in Table 1.

Table 1: Summary of Literature on 5G-NR PRACH Performance and Interference Management

Category	Subcategory	Contributions	Limitations	References
Inter/Intra-Cell Interference	Intra-Cell Interference	Identifies interference within cell affecting PRACH detection.	Difficult to manage with dense UE scenarios.	[3], [6], [1], [7]
	Inter-Cell Interference	Analyzes inter-cell interference impacting PRACH performance.	Complex coordination required for mitigation.	[8], [9], [5], [7]
Interference Management Techniques	Interference Measurement	Develops methods for precise interference measurement.	Introduces additional network overhead.	[8], [6], [4]
	Interference Mitigation	Proposes techniques to reduce or cancel interference effects.	High implementation complexity.	[3], [1], [7], [6]
PRACH Detection Algorithms	Matched Filtering	Improves PRACH detection using matched filters.	Less effective in dynamic environments.	[1], [5], [6]
	Adaptive Algorithms	Adjusts detection parameters dynamically for changing interference.	Increased computational requirements.	[7], [9], [8], [6]
Optimization Strategies	UE Configuration	Optimizes UE parameters to reduce PRACH interference.	Dependent on accurate interference prediction.	[6], [7], [5]
	Cell Configuration	Adjusts cell settings to reduce interference.	Requires complex coordination across cells.	[3], [9], [1]
Advanced Approaches	Cognitive Radio	Enables dynamic spectrum access, reducing interference.	Requires complex sensing and decision-making.	[10]
	Machine Learning	Predicts interference, optimizes resource allocation dynamically.	Requires large datasets, computationally intensive.	[11], [12]

### 3.1 Intra/Inter-Cell Interference

Interference is a critical challenge in 5G-NR PRACH performance, particularly affecting the reliability of communication systems. Two primary types of interference are observed: intra-cell interference which occurs within the same cell and inter-cell interference which arises from neighboring cells.

#### 3.1.1 Intra-Cell Interference

Intra-cell interference refers to the interference that occurs within the same cell. This impacts the performance of PRACH detection. This type of interference arises when multiple UEs within the same cell contend for the same resources leading to signal degradation and reduced detection accuracy. Key studies exploring intra-cell interference include [1, 3, 6, 7]. The literature provides a comprehensive understanding of the causes and effects of intra-cell interference by enabling the development of targeted mitigation strategies.

However, current approaches often focus on static or limited dynamic scenarios, potentially lacking robustness in highly variable environments. Intra-cell interference management is critical for maintaining PRACH performance with strategies such as UE configuration optimization showing promising results.

### *3.1.2 Inter-Cell Interference*

Inter-cell interference occurs between neighboring cells. This could significantly impact PRACH performance, especially in dense network environments. This interference type is influenced by the proximity of cells and the overlapping use of frequencies. Relevant studies include [5, 7–9]. The research provides insight into the mechanisms of inter-cell interference and offers solutions such as coordinated scheduling to alleviate its effects.

The complexity of managing inter-cell interference increases with network density. This could require more sophisticated algorithms and cross-cell coordination [8]. Effective inter-cell interference management is essential for maintaining overall network performance, with approaches like interference coordination being key.

## **3.2 Interference Management Techniques**

To ensure optimal PRACH performance in 5G-NR networks, various interference management techniques have been proposed. These include both measurement and mitigation approaches that are crucial for maintaining reliable communication in the presence of interference [1, 3, 4, 6–8].

### *3.2.1 Interference Measurement*

Interference measurement techniques are crucial for quantifying interference levels and informing adaptive PRACH strategies. These methods enable accurate assessments of the interference environment, allowing for more effective mitigation measures. Key references include [4, 6, 8].

Accurate interference measurement is foundational for effective interference management as it provides the data necessary for informed decision-making. However, these measurement techniques can be resource-intensive and may introduce additional overhead, potentially affecting network efficiency. Despite these challenges, high-quality interference measurement directly supports the development and implementation of mitigation strategies by making it a critical component of PRACH performance optimization.

### *3.2.2 Interference Mitigation*

Mitigation strategies are designed to reduce or cancel the effects of interference on PRACH performance. Techniques such as adaptive filtering and interference rejection combining (IRC) are commonly used to minimize the impact of interference [1, 3, 6, 7].

Mitigation strategies often require complex hardware or software implementations which can increase the cost and complexity of network deployments. When properly implemented, these techniques can drastically reduce the impact of both intra-cell and inter-cell interference, leading to more reliable PRACH performance.

## **3.3 PRACH Detection Algorithms**

The performance of PRACH in 5G-NR networks is heavily influenced by the detection algorithms employed. Matched filtering and adaptive algorithms are two key approaches used to enhance detection accuracy in the presence of interference.

### 3.3.1 Matched Filtering

Matched filtering is a technique used to maximize the signal-to-noise ratio (SNR) of the received PRACH signal, making it easier to detect in noisy environments. This approach is particularly effective in scenarios where the interference characteristics are well-known [1, 5, 6].

Matched filtering is highly effective at enhancing the detectability of PRACH signals, particularly in low-noise environments. This technique can be less effective in highly dynamic environments where interference characteristics change rapidly, requiring frequent recalibration of the filter. Matched filtering is a robust method for managing interference in stable environments, but its effectiveness decreases in more variable settings.

### 3.3.2 Adaptive Algorithms

Adaptive algorithms dynamically adjust detection parameters based on real-time conditions, offering a flexible approach to managing interference. These algorithms are particularly useful in environments with fluctuating interference levels [6–9].

The adaptability of these algorithms allows for continuous optimization of PRACH detection performance, even under varying interference conditions. However, the complexity of adaptive algorithms can lead to increased computational requirements and potential delays in response time. Despite these challenges, these adaptive algorithms are highly effective at mitigating interference, particularly in dynamic environments where traditional static approaches may fall short.

## 3.4 Optimization Strategies

Optimizing both UE and cell configurations is essential for managing interference and enhancing PRACH performance in 5G-NR networks.

### 3.4.1 UE Configuration

Optimizing UE configuration is a critical strategy for minimizing interference during PRACH. This involves adjusting UE settings to reduce susceptibility to interference, as discussed in [5–7].

**Strengths:** Proper UE configuration can significantly improve PRACH performance by reducing the impact of both intra and inter-cell interference. However, finding the optimal configuration can be challenging, particularly in environments with highly variable interference. Optimizing UE configuration is a proactive approach to interference management, offering significant potential for enhancing PRACH reliability.

### 3.4.2 Cell Configuration

Cell parameters, such as frequency planning and cell size, play a critical role in managing inter-cell interference. Adjusting these parameters can help to reduce the overlap of frequency resources between neighboring cells, thereby mitigating interference [1, 3, 9].

Proper cell configuration can drastically reduce the likelihood of inter-cell interference, leading to more efficient network operation. However, reconfiguring cell parameters often requires coordination across multiple cells, which can be complex and time-consuming. Effective cell configuration is a cornerstone of interference management, providing a strong foundation for high-performance 5G-NR networks.

### 3.5 Advanced Approaches

As 5G networks continue to evolve, traditional interference management techniques are increasingly being supplemented and enhanced by advanced approaches such as cognitive radio and machine learning. These cutting-edge technologies offer significant potential to improve interference mitigation and resource allocation in dynamic and complex 5G environments.

#### 3.5.1 Cognitive Radio Approaches

Cognitive radio (CR) represents a significant advancement in interference management by enabling dynamic spectrum access and intelligent resource allocation. CR systems are capable of sensing the radio environment and adapting their transmission parameters in real-time to avoid interference with other users. This adaptability is particularly beneficial in 5G networks, where the demand for spectrum is high and interference can be unpredictable. The use of CR in 5G-NR allows for more efficient utilization of the available spectrum, reducing the likelihood of interference and improving overall network performance [10].

Cognitive radio systems offer significant flexibility, allowing 5G networks to dynamically adjust to changing interference patterns. This leads to more efficient spectrum use and reduces the need for static, pre-allocated frequency bands. However, the implementation of cognitive radio requires sophisticated sensing and decision-making algorithms, which can increase the complexity and cost of 5G networks. Despite these challenges, CR systems are highly effective in managing interference in environments with dynamic spectrum usage, making them well-suited for dense urban deployments where interference is common.

#### 3.5.2 Machine Learning-Based Approaches

Machine learning (ML) has emerged as a powerful tool for optimizing interference management and resource allocation in 5G networks. ML algorithms can analyze vast amounts of network data to predict interference patterns, optimize resource allocation and even automate decision-making processes in real-time. These capabilities are particularly useful in managing the complex, multi-dimensional environments typical of 5G networks.

For example, deep learning models can be trained to predict interference levels based on historical data, allowing the network to proactively adjust PRACH parameters and improve detection accuracy. Reinforcement learning (RL) is another promising approach, where the network learns optimal interference mitigation strategies through trial and error, continuously improving its performance over time [11].

ML approaches are highly adaptive and can handle the complexity of 5G networks better than traditional methods. They enable real-time optimization, which is crucial for maintaining high network performance in the presence of dynamic interference. The primary challenge with ML-based approaches is the need for large datasets and substantial computational resources for training models. Additionally, there is a risk of overfitting, where the model may perform well on training data but poorly in real-world scenarios.

ML algorithms are highly effective in managing and mitigating interference, particularly in dynamic and complex environments. They offer the potential for significant improvements in network performance, especially when combined with other advanced techniques like cognitive radio.

## IV RESEARCH METHODOLOGY

This section provides a detailed description of the technical methodology employed in this study which focused on evaluating and analyzing 5G-NR PRACH performance in the context of intra-cell and inter-cell interference. The simulation environment, data collection methods and tools used for the analysis are thoroughly explained to ensure the clarity and reproducibility of the research.

### 4.1 Technical Methodology

The primary objective of this research was to investigate the impact of various interference scenarios on the PRACH detection performance in 5G-NR networks. To achieve this, a comprehensive simulation framework was developed using Matlab [13], a widely recognized tool for simulating wireless communication systems. Matlab's integrated functionalities [13] for 5G-NR including those related to PRACH were leveraged to accurately model and analyze the performance under different conditions.

The technical methodology involved several key steps:

1. **Simulation Setup:** The simulation environment was configured to replicate real-world conditions. This included setting up user equipment (UE) configurations, PRACH parameters and propagation channel characteristics. Detailed configurations were established for both the "Target" UE and the "Interfering" UE to explore the effects of intra-cell and inter-cell interference.
2. **Interference Modeling:** Intra-cell and inter-cell interference were modeled to assess their impact on PRACH performance. For intra-cell interference, multiple UEs within the same cell were configured to contend for PRACH resources, while inter-cell interference was simulated by having UEs from neighboring cells compete for the same PRACH resources.
3. **Performance Evaluation:** The performance of PRACH was evaluated using key metrics such as the Correct Detection Rate (CDR) under varying levels of interference. The simulation results were analyzed to identify trends and assess the effectiveness of different interference management strategies.

### 4.2 Simulation Setup Parameters

The simulation setup was carefully designed to reflect the conditions under which 5G-NR networks operate. Tables 2, 3 and 4 summarize the key parameters used in the simulation.

To conduct our investigations, we utilized the Matlab tool [13], which inherently integrates functionalities of the 5G-NR transmission chain. This powerful tool enabled us to simulate various aspects of PRACH efficiently, ensuring the reliability and accuracy of the outcomes.

### 4.3 The choice of Simulation Parameters

The parameters used in the simulation were carefully chosen to reflect the real-world conditions under which 5G-NR networks operate. Each parameter was selected based on its relevance to the objectives of this study, particularly the evaluation of PRACH performance under various interference scenarios.

Table 2: User Equipment (UE) Configuration

	“Target” UE (T-UE) Configuration	“Interfering” UE (I-UE) Configuration	Description
NULRB	6	6	Number of UL Resource Blocks (RB)
DuplexMode	FDD	FDD	Frequency Division Duplexing (FDD)
CyclicPrefixUL	Normal	Normal	Normal cyclic prefix (CP)
NTxAnts	1	1	Number of transmit antennas

Table 3: PRACH Configuration

	PRACH Configuration for “Target” UE (T-UE)	PRACH Configuration for “Interfering” UE (I-UE)	Description
Format	0	0	PRACH format: TS36.104, Table 8.4.2.1-1
SeqIdx	22	[0, 1, 2, 3, 4, 22]	Root Sequence Index
CyclicShiftIdx	1	1	Cyclic shift index
HighSpeed	0	0	Normal mode, i.e., not optimized for “HighSpeed”
FreqOffset	0	0	Default frequency location
PreambleIdx	32	[0, 3, 37, 42, 63]	Preamble Index

#### 4.3.1 User Equipment (UE) Configuration

In the simulation as shown in Table 2, UE configurations were designed to reflect typical scenarios encountered in 5G-NR networks. Two types of UEs were modeled: the "Target" UE (T-UE) which represents the device of interest in terms of PRACH detection performance and the "Interfering" UE (I-UE) which is responsible for generating interference within the network.

For both the T-UE and I-UE, the number of uplink resource blocks (NULRB) was set to 6 in order to reflect a standard allocation in 5G networks [3]. The duplex mode was configured as Frequency Division Duplexing (FDD) which is commonly used in 5G deployments to separate uplink and downlink transmissions.

Each UE was configured with a normal cyclic prefix (CyclicPrefixUL) which is suitable for environments with moderate delay spread, ensuring efficient communication without unnecessary

Table 4: Propagation Channel Configuration

	Channel Configuration	Description
NRxAnts	2	Number of receiving antennas
DelayProfile	“ETU”	Extended Typical Urban (ETU) delay profile
DopplerFreq	70.0 [Hz]	Doppler frequency
MIMOCorrelation	“Low”	MIMO correlation
Seed	1	Channel seed
NTerms	16	Oscillators used in the fading pattern
ModelType	“GMEDS”	Rayleigh fading model type
InitPhase	“Random”	Random initial phases
NormalizePathGains	“On”	Normalize delay profile power
NormalizeTxAnts	“On”	Normalize for transmit antennas

overhead. Both the T-UE and I-UE were equipped with a single transmit antenna ( $NTxAnts = 1$ ), a typical setup in many mobile devices to simplify the analysis of interference effects without the complexities introduced by multiple-input multiple-output (MIMO) systems.

These UE configuration parameters were chosen to strike a balance between simulation complexity and the ability to accurately model the interference scenarios under investigation. By standardizing the UE settings across different scenarios, we could focus on the specific impact of interference on PRACH performance without introducing variability from other factors.

#### 4.3.2 PRACH Configuration

The PRACH configuration is important for evaluating the performance of the 5G-NR system under different interference scenarios. In our simulation, we carefully configured the PRACH parameters as shown in Table 3 for both the "Target" UE (T-UE) and the "Interfering" UE (I-UE) to reflect realistic operating conditions. The PRACH format was set to Format 0 which is defined in TS36.104, Table 8.4.2.1-1 and is widely used in 5G deployments. This format was selected due to its compatibility with our study's focus on initial access procedures in 5G-NR networks.

The Root Sequence Index, a critical parameter that differentiates UEs within the same cell, was set to 22 for the T-UE while the I-UEs were assigned a range of indices including 0, 1, 2, 3, 4 and 22, to simulate various interference situations. The Cyclic Shift Index was kept constant at 1 for both the T-UE and I-UEs. This ensures that the primary variable affecting interference was the Root Sequence Index rather than the timing or frequency shifts.

Additionally, the High-Speed Flag was disabled (set to 0) for all UEs, as our study was focused on normal operation modes rather than scenarios optimized for high-speed movement. The Frequency Offset was also set to 0 for both the T-UE and I-UEs, aligning the PRACH transmissions to the center frequency and eliminating any frequency domain offsets that could introduce additional variables into the interference analysis.

Finally, the Preamble Index, which is used to identify specific PRACH resources within a cell, was assigned a value of 32 for the T-UE. For the I-UEs, a diverse set of preamble indices, including 0, 3, 37, 42 and 63, were used to thoroughly investigate the impact of different PRACH resource allocations on the interference levels experienced by the T-UE.

This careful configuration of PRACH parameters ensured that our simulations accurately captured the dynamics of PRACH detection under both intra-cell and inter-cell interference conditions, providing valuable insights into the performance limitations and optimization opportunities in 5G-NR networks.

#### 4.3.3 Propagation Channel Configuration

The propagation channel configuration is a key aspect of the simulation setup, as it directly influences the accuracy and relevance of the results obtained. The configuration shown in Table 4 was carefully selected to reflect the typical conditions encountered in urban environments, where 5G networks are expected to operate.

The number of receiving antennas ( $NRxAnts$ ) was set to 2, which is a common configuration in many 5G deployments. This choice allows for the simulation of MIMO (Multiple Input Multiple Output) scenarios, which are essential for improving signal reliability and capacity in modern communication systems.

The delay profile used in the simulation was the Extended Typical Urban (ETU) profile, designated as "ETU". This profile was chosen because it accurately represents the multipath environment characteristic of urban areas, where signals are often reflected off buildings and other structures, leading to complex propagation paths.

A Doppler frequency of 70 Hz was selected to simulate the effects of mobility in the network. This value corresponds to the Doppler shift expected at a moderate vehicle speed (30 km/h), which is typical for urban scenarios. The Doppler effect is crucial in assessing the performance of PRACH under conditions where the relative movement between the transmitter and receiver causes frequency shifts, potentially impacting detection accuracy.

MIMO correlation was set to "Low" in order to reflect an environment where the antennas experience uncorrelated or minimally correlated channels. This setup allows for greater diversity gain which helps mitigate the effects of fading and improves overall network performance.

The channel seed (`Seed`) was set to 1 to ensure reproducibility of the simulation results. The fading pattern was modeled using 16 oscillators (`NTerms`) which is sufficient to capture the complex fading behaviors typical in urban environments.

The Rayleigh fading model was selected as the `ModelType` ("GMEDS"), appropriate for scenarios where there is no line-of-sight (LOS) between the transmitter and receiver, which is often the case in dense urban environments.

Random initial phases (`InitPhase`) were used to ensure that each simulation run would encounter a unique fading scenario, providing a more comprehensive analysis of the PRACH performance.

Finally, the `NormalizePathGains` and `NormalizeTxAnts` parameters were enabled to ensure that the power of the delay profiles and the transmit antennas were normalized. This normalization ensures that the simulation results reflect the impact of interference and propagation effects rather than variations in power levels.

#### 4.4 Intra-Cell and Inter-Cell Interference Considerations

In the realm of 5G-NR communication, the presence of intra-cell and inter-cell interference is a critical aspect that demands meticulous consideration. We carefully modeled these types of interference within our Matlab simulator [13] to ensure the accuracy and reliability of our simulation outcomes.

- (1) **Intra-Cell Interference:** In the Matlab simulator [13], intra-cell NR-PRACH interference is modeled using an "Interfering" UE (i.e., the UE generating the interference) with the same UE configuration (refer to Table 2) and the same PRACH configuration (refer to Table 3), except for the "Preamble Index," which differs from that of the "Target UE" (T-UE). This scenario is exemplified by "Interfering" UE<sub>1</sub> (I – UE<sub>1</sub>) in Figure 3.
- (2) **Inter-Cell Interference:** In the case of NR-PRACH inter-cell interference, it is modeled using an "Interfering" UE that shares the same UE configuration (refer to Table 2) and the same PRACH configuration (refer to Table 3) with the "Target" UE, with the exception of the "Logical sequence index" or "Root sequence index," which differs from that of the "Target" UE. This corresponds to the "Interfering" UE<sub>2</sub> and "Interfering" UE<sub>3</sub> in Figure 5. In a 5G-NR cell, all UEs within the cell share the same "Logical Sequence Index" or "Root Sequence Index," while the UEs themselves are differentiated by a "Preamble Index." The "Logical Sequence Index" or "Root Sequence Index" serves to distinguish

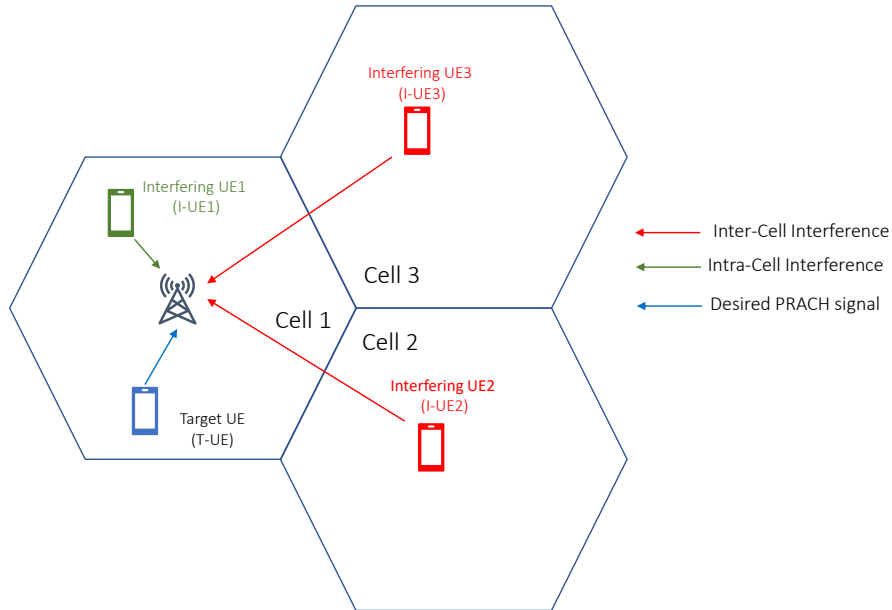


Figure 5: Inter-Cell and Intra-Cell Interference in 5G-NR PRACH Scenario.

5G-NR cells from one another. For example, “Target” UE (T-UE) and “Interfering” UE<sub>1</sub> in Figure 5 share the same “Logical Sequence Index” or “Root Sequence Index” but have different “Preamble Indexes” for Random-Access (RA).

## V RESULTS AND DISCUSSION

In this section, we present the simulation results obtained using MATLAB by modeling an up-link transmission chain corresponding to the initial access procedure, which occurs through the Physical Random Access Channel (PRACH). The simulations were conducted in two scenarios: (i) an initial access context with the presence of intra-cell interference and (ii) an initial access context with the presence of inter-cell interference, as illustrated in Figure 5.

### 5.1 NR-PRACH Performance under Intra-Cell Interference Conditions

The performance of NR-PRACH was evaluated through the Correct Detection Rate (CDR) or Preamble Detection Probability over 1000 subframes. In this scenario, intra-cell interference was modeled by introducing an “Interfering” UE (I-UE) within the same cell as the “Target” UE (T-UE). The I-UE shared the same “Logical Sequence Index” but used a different “Preamble Index” compared to the T-UE.

The results, depicted in Figure 6 and Figure 7, demonstrate the impact of varying the Preamble Index of the I-UE on NR-PRACH performance. The performance degradation observed as the interference level increases (i.e., as the SNRdB of the I-UE increases) is indicative of the challenges posed by intra-cell interference in maintaining PRACH robustness. The use of different Preamble Indexes by the I-UE consistently led to a reduction in the correct detection rate, emphasizing the sensitivity of NR-PRACH to intra-cell interference.

These results align with the expected behavior of PRACH under intra-cell interference conditions. As interference levels rise, the ability of the system to correctly detect preambles diminishes. This finding underscores the importance of carefully managing intra-cell interference to ensure reliable PRACH performance.

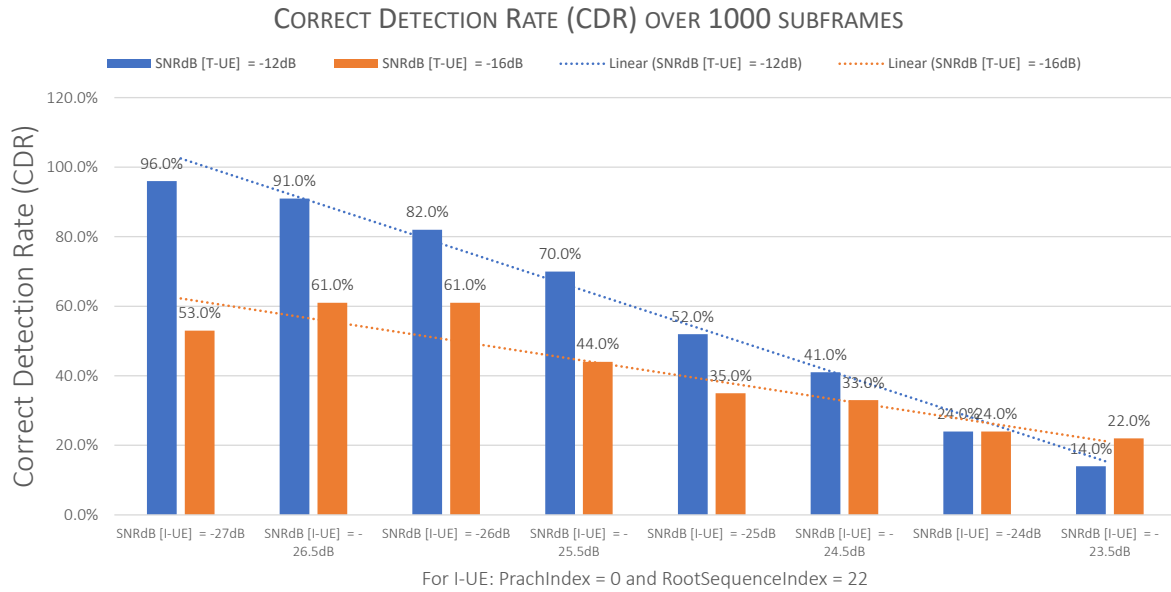


Figure 6: 5G-NR PRACH Performance in the Presence of Intra-Cell Interference with Preamble Index = 0 and Root Sequence Index = 22

Further analysis, depicted in Figure 8 and Figure 9, explored the performance of PRACH under varying Preamble Indexes for the T-UE while keeping the interference level constant. The results suggest that at lower interference levels, the PRACH performance remains relatively stable across different Preamble Indexes. However, as the interference level increases, the choice of Preamble Index becomes more critical, with certain indexes offering better resilience against interference.

## 5.2 NR-PRACH Performance under Inter-Cell Interference Conditions

The NR-PRACH performance was also evaluated under inter-cell interference conditions, where the I-UE was positioned in a neighboring cell with a different "Logical Sequence Index" but po-

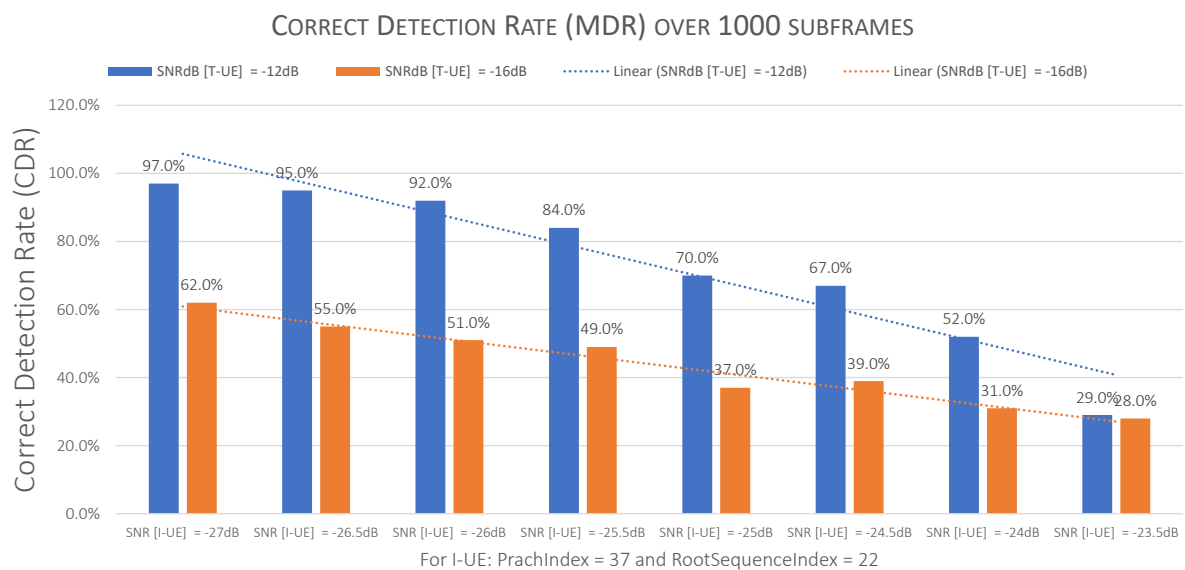


Figure 7: 5G-NR PRACH Performance in the Presence of Intra-Cell Interference with Preamble Index = 37 and Root Sequence Index = 22

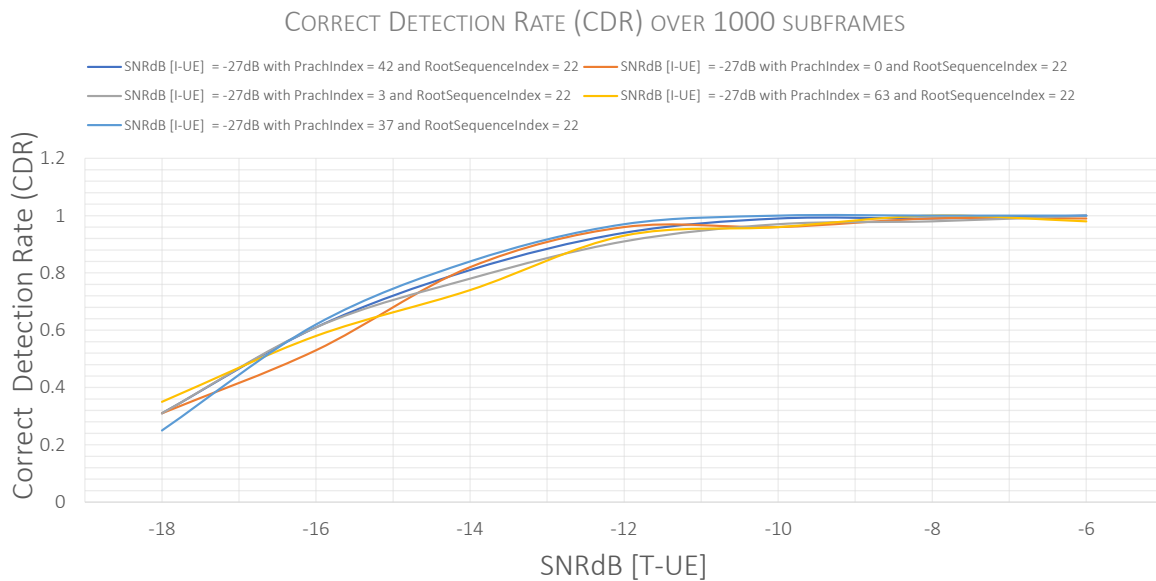


Figure 8: PRACH Performance in presence of Intra-Cell Interference with a Root Sequence Index of 22 and SNRdB [I-UE] of -27 dB for various “Preamble Index” values.

tentially the same "Preamble Index" as the T-UE.

The results depicted in Figure 10 and Figure 11 reveal that the PRACH performance deteriorates with increasing inter-cell interference, mirroring the trends observed under intra-cell interference conditions. This decline in detection probability, irrespective of the Root Sequence Index used by the I-UE, highlights the challenges of inter-cell interference management.

Additional simulations, shown in Figure 12 and Figure 13, examined the PRACH performance across different Root Sequence Indexes for the I-UE while maintaining a constant level of interference. The findings indicate that PRACH performance is relatively unaffected by Root

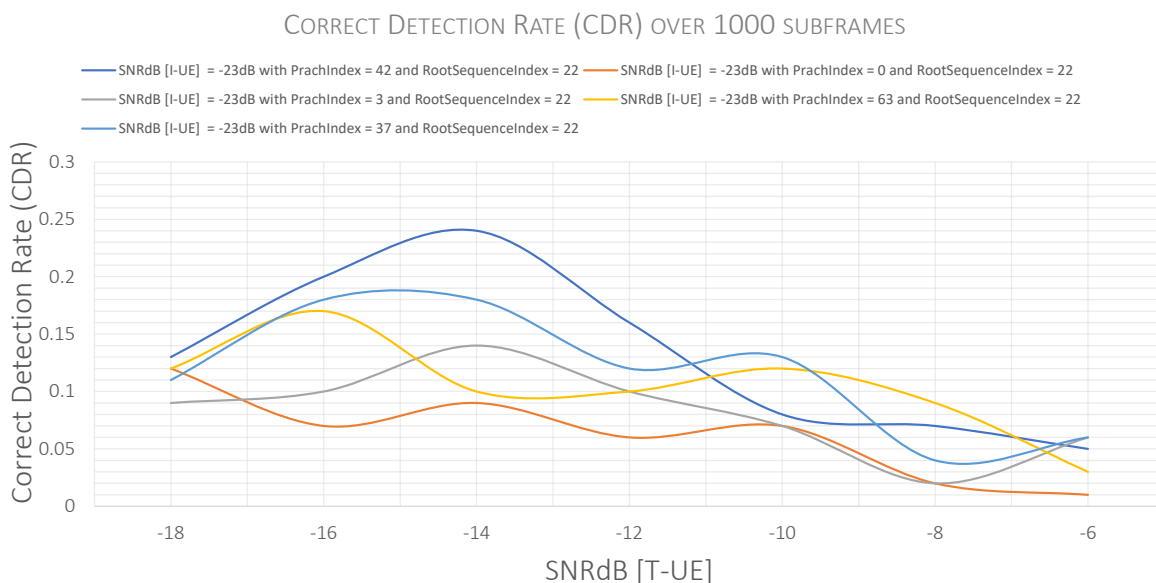


Figure 9: PRACH Performance in presence of Intra-Cell Interference with a Root Sequence Index of 22 and SNRdB [I-UE] of -23 dB for various “Preamble Index” values.

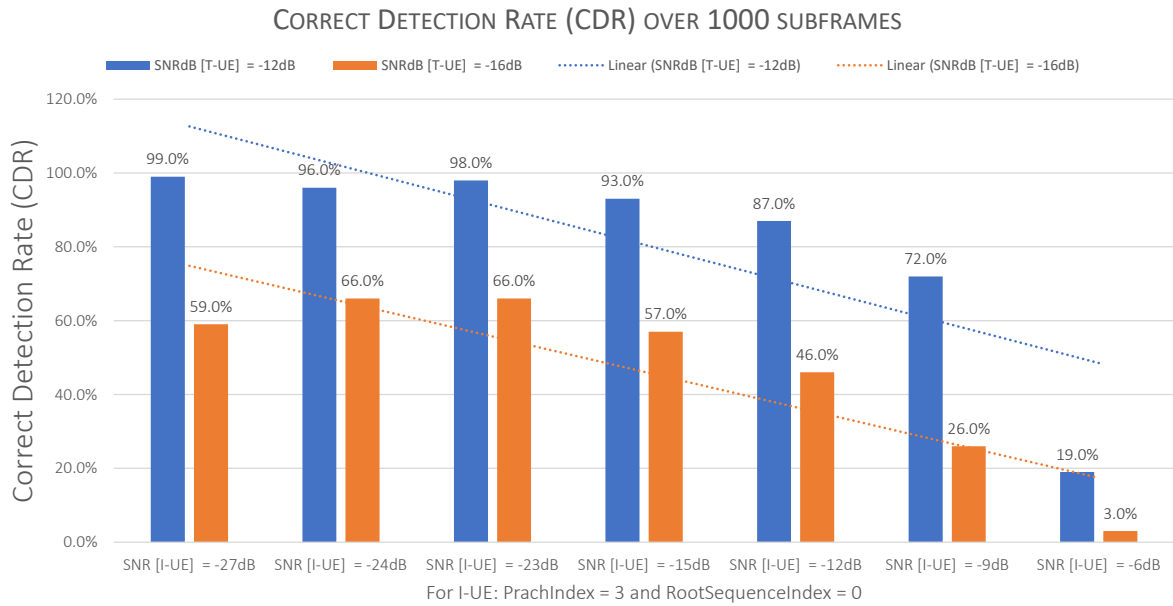


Figure 10: PRACH Performance in the Presence of Inter-Cell Interference with “Preamble Index” = 3 and Root Sequence Index = 0.

Sequence Index variations at low interference levels. However, as interference increases, certain Root Sequence Indexes result in more pronounced performance degradation.

### 5.3 Comparative Analysis: Intra-Cell versus Inter-Cell Interference

Finally, a comparative analysis between intra-cell and inter-cell interference was conducted, as depicted in Figure 14, Figure 15 and Figure 16. The analysis aimed to determine which type of interference exerts a greater impact on NR-PRACH performance. The results indicate that at lower interference levels, NR-PRACH performance remains similar for both interference

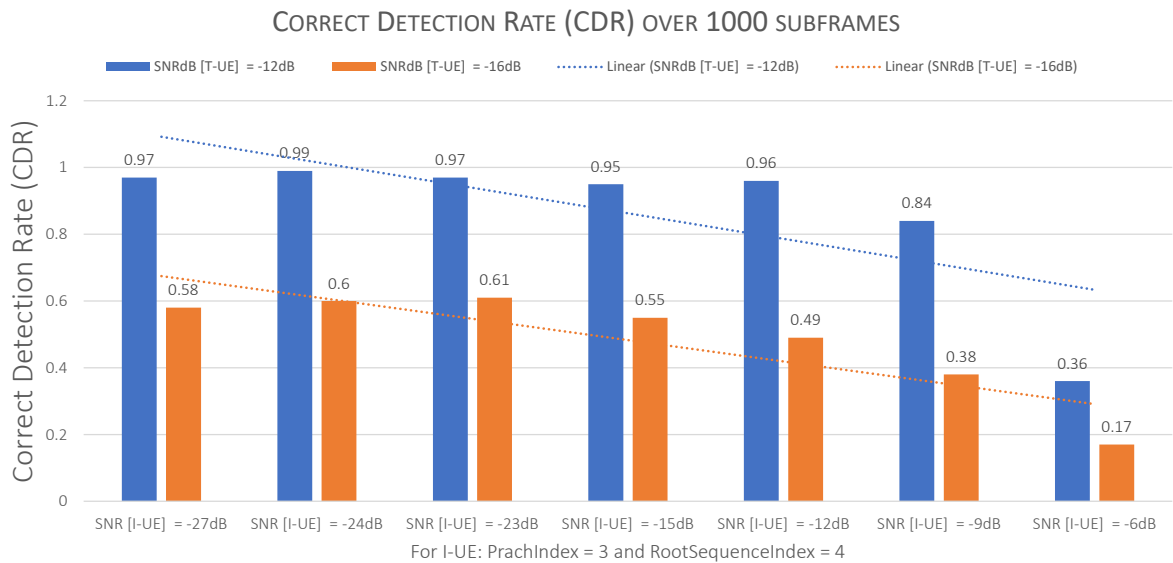


Figure 11: PRACH Performance in the Presence of Inter-Cell Interference with “Preamble Index” = 3 and Root Sequence Index = 4.

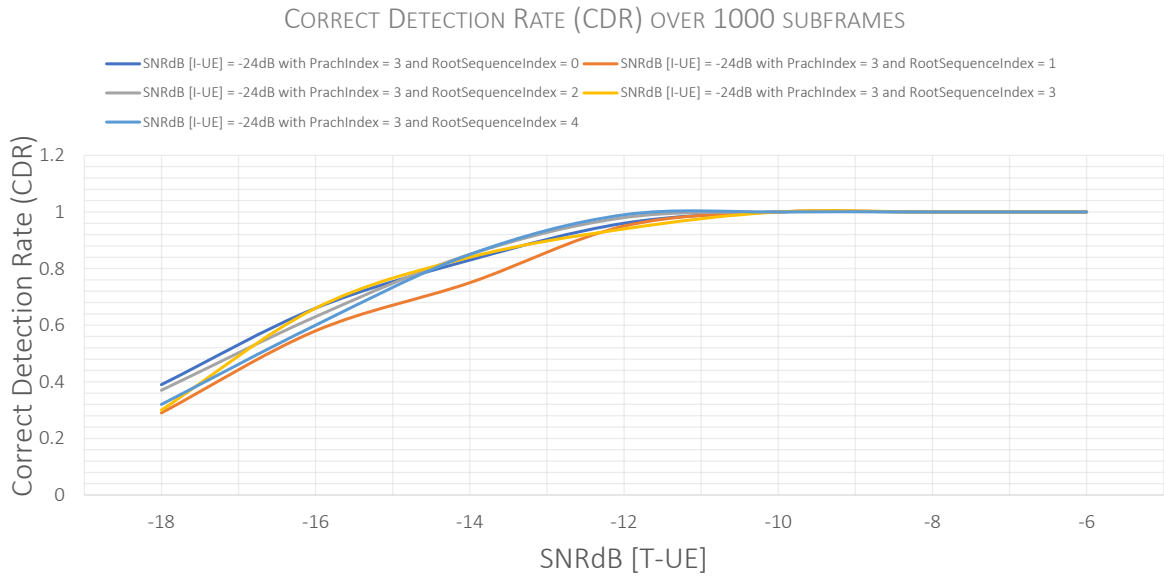


Figure 12: PRACH Performance in the Presence of Inter-Cell Interference with “Preamble Index” = 3 and SNRdB [I-UE] = -24dB for different Values of RootSequenceIndex for the Interfering Cell.

types. However, as interference levels rise, NR-PRACH exhibits greater resilience to inter-cell interference compared to intra-cell interference.

These findings underscore the importance of selecting appropriate configuration parameters, such as Preamble Index and Root Sequence Index, to mitigate interference effects in practical deployments.

#### 5.4 Outcomes and Future Directions

The results of this study highlight the significant impact that both intra-cell and inter-cell interference can have on NR-PRACH performance. Effective management of these interference

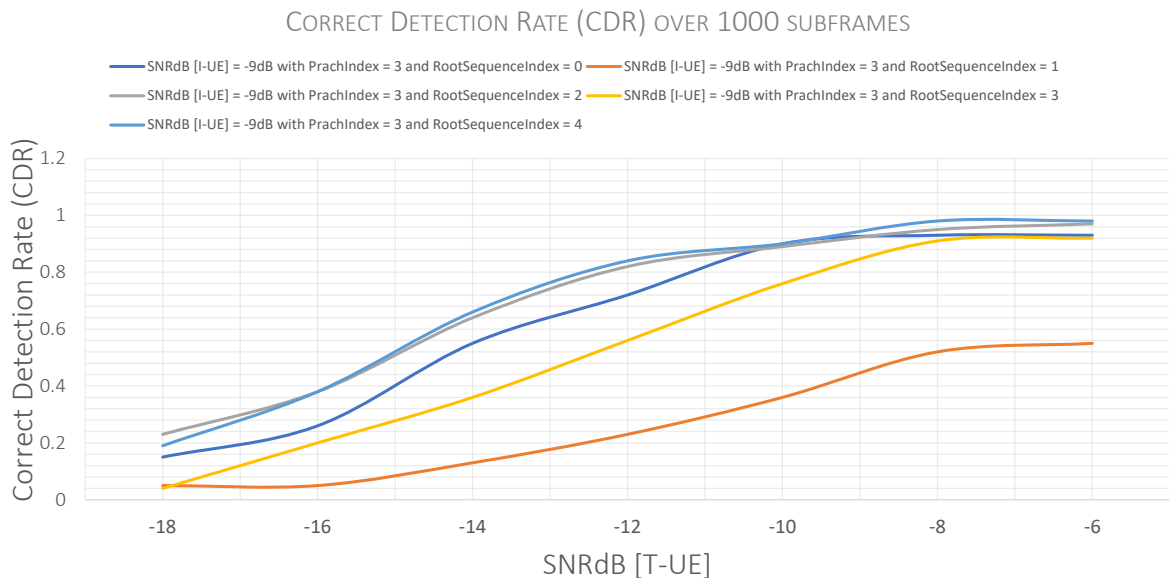


Figure 13: PRACH Performance in the Presence of Inter-Cell Interference with “Preamble Index” = 3 and SNRdB [I-UE] = -9dB for different Values of RootSequenceIndex for the Interfering Cell.

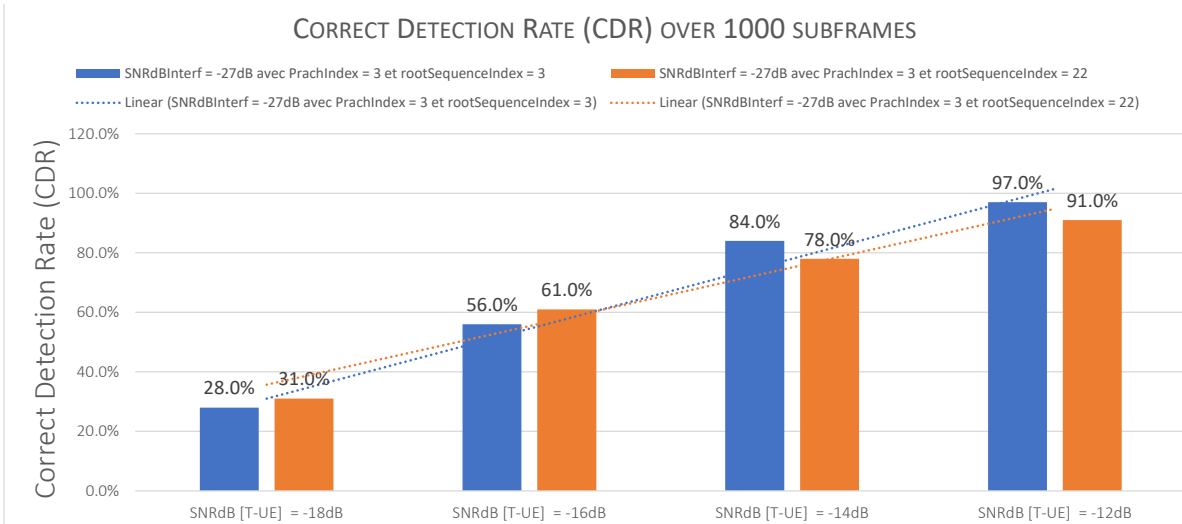


Figure 14: Comparison of PRACH performance in the presence of intra-cellular and inter-cellular interferences with “Preamble index = 3” and SNRdBInterf = -27dB.

sources, through careful selection of parameters such as Root Sequence Index and Preamble Index, is crucial for optimizing PRACH detection and overall network performance. Future research should explore advanced techniques, including Artificial Intelligence (AI) and Machine Learning (ML), to further enhance interference management and PRACH performance in increasingly complex 5G environments.

In conclusion, the insights gained from this research provide a solid foundation for improving interference management strategies in 5G NR networks. The integration of AI/ML approaches is anticipated to play a pivotal role in the future of PRACH detection, enabling more dynamic and adaptive interference management capabilities.

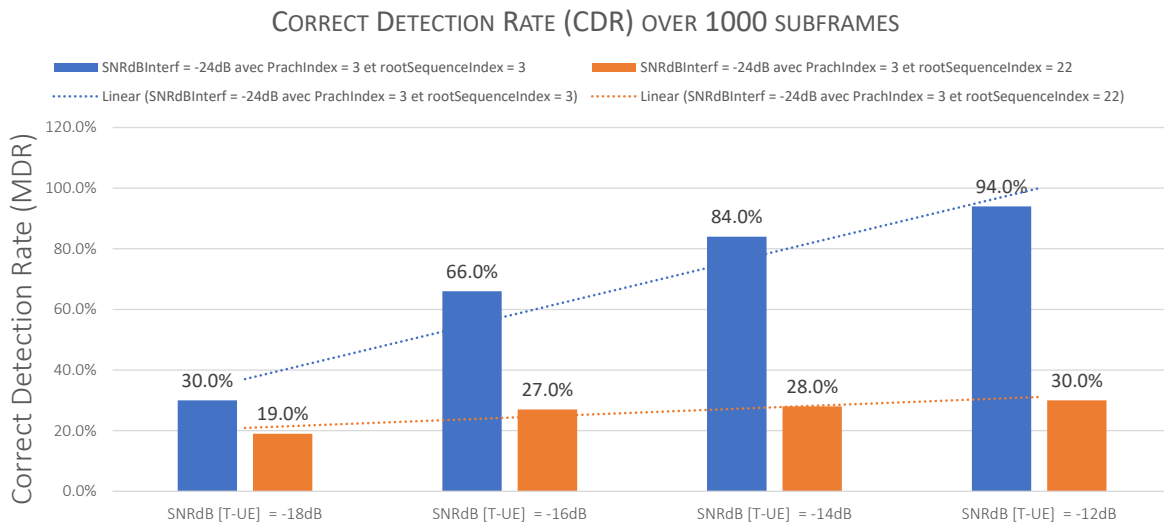


Figure 15: Comparison of PRACH performance in the presence of intra-cellular and inter-cellular interferences with “Preamble index = 3” and SNRdBInterf = -24dB.

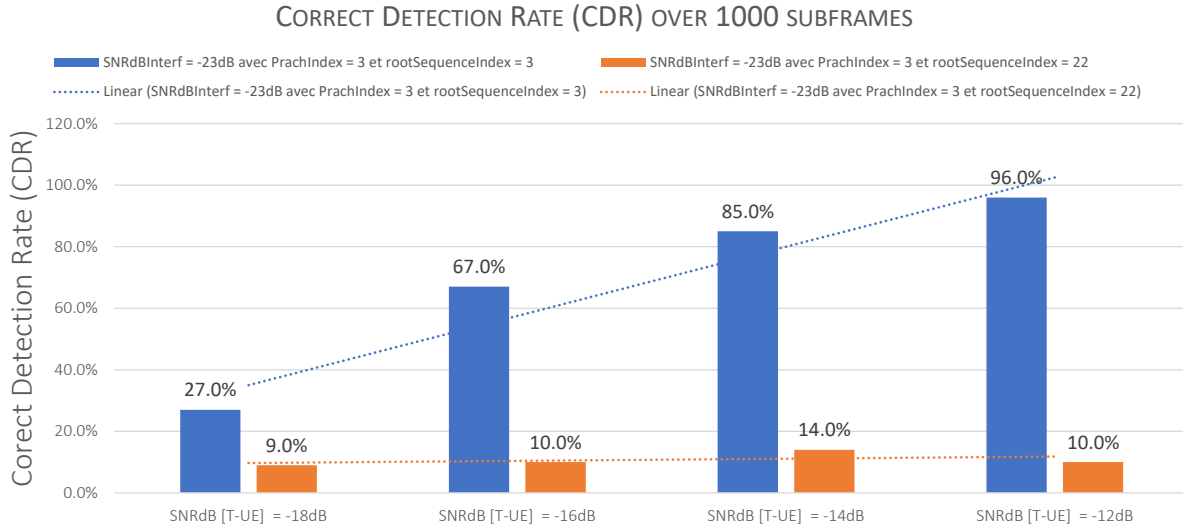


Figure 16: Comparison of PRACH performance in the presence of intra-cellular and inter-cellular interferences with “Preamble index = 3” and SNRdBInterf = -23dB.

## VI CONCLUSION

This research has provided significant insights into the performance of the 5G-NR PRACH under both intra-cell and inter-cell interference conditions. The key findings indicate that the NR-PRACH performance, particularly in terms of preamble detection probability, is highly sensitive to interference levels. As interference increases, whether within the same cell or between neighboring cells, the reliability of PRACH detection diminishes. Indeed, the results show that the preamble detection probability dropping by up to 30% as interference increases from -27 dB to -9 dB whether within the same cell or between neighboring cells. This study has demonstrated the critical importance of selecting appropriate parameters, such as Preamble Index and Root Sequence Index, to mitigate the adverse effects of interference.

The contributions of this research extend beyond the identification of interference challenges. By employing a robust simulation framework using Matlab, the study has effectively modeled real-world scenarios. It provides a detailed understanding of how different interference conditions impact PRACH performance. The findings underscore the need for careful configuration of UE and cell parameters to optimize 5G-NR network performance. Moreover, the research highlights the potential of integrating advanced techniques such as AI and ML to further enhance interference management in future networks.

However, this study also has certain limitations. The simulations were conducted under specific scenarios and parameter configurations which may not capture the full range of real-world conditions. Additionally, the study primarily focused on static configurations and the dynamic nature of 5G networks was not fully explored. Future research could address these limitations by considering a wider range of scenarios; this could include dynamic and adaptive network configurations. Moreover, exploring the application of AI/ML techniques in real-time interference management and PRACH optimization would be a valuable direction for further investigation.

In conclusion, effective interference management is paramount to ensuring the robustness and reliability of 5G-NR networks. As 5G continues to evolve, addressing the challenges posed by intra-cell and inter-cell interference will be crucial for maintaining high-quality communication

services. The findings from this research contribute to the ongoing efforts to optimize PRACH performance by paving the way for more resilient and efficient 5G networks in the future.

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