International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Analysis of Passive Intermodulation (PIM) Challenges in Massive MIMO and Ultra-Dense 5G Indoor Networks

Abed Alrazzaq Kamal Alnahhas

ORCID: 0009-0001-9492-9720
B.Sc. in Telecommunications Engineering Technology,
Faculty of Electrical Engineering, Al-Balqa Applied University, Jordan
Advanced communications and electronic system, Saudi Arabia
Email: Abed.aces@gmail.com

Abstract

As 5G networks transition toward **Ultra-Dense Networks (UDN)** to meet the demand for multi-Gbps data rates, especially in indoor environments, they face significant physical-layer impairments. One of the most critical challenges is **Passive Intermodulation (PIM)**, which is defined as unwanted emissions resulting from **non-linearities in RF circuitry**, connectors, and adjacent metallic structures. In **Massive MIMO** systems, the high density of antenna elements and the use of complex beamforming architectures significantly increase the likelihood of intermodulation products falling within the device's receiver band, leading to **receiver sensitivity degradation**. This research analyzes PIM challenges in the context of **LTE/NR Dual Connectivity**, where simultaneous transmissions in "difficult band combinations" generate self-interference that complicates the link budget. Furthermore, the study explores how the dense deployment of small cells in indoor scenarios amplifies these effects due to signal proximity and shared spectrum resources. Potential mitigation strategies, including **advanced RF filtering**, improved power amplifier linearization, and **spatial coordination** between access nodes, are evaluated to ensure the required network reliability and capacity.

Keywords: Passive Intermodulation (PIM), Massive MIMO, Ultra-Dense Networks (UDN), Intermodulation Distortion (IMD).

1. Introduction

The fifth generation (5G) of mobile communication systems represents a transformative shift designed to meet highly diversified demands through three main service categories: **Enhanced Mobile Broadband (eMBB)**, Ultra-reliable and Low-latency Communications (uRLLC), and Massive Machine Type Communications (mMTC). To achieve the goal of providing ubiquitous data rates, particularly the target of **1 Gbps in indoor and hotspot environments**, 5G networks must utilize larger spectrum portions in higher frequency bands, such as **millimeter-wave (mmWave)**. The primary technical enablers for this performance leap are **Massive MIMO**, which employs large antenna arrays to create highly focused

beams, and **Ultra-Dense Networks (UDN)**, characterized by the dense deployment of small cells in close proximity to users.

However, this transition toward hyper-densification has shifted the network paradigm from being "signal strength limited" to being "**interference limited**". In these complex indoor environments, **Passive Intermodulation (PIM)**, often categorized under Intermodulation Distortion (IMD), emerges as a critical physical-layer impairment resulting from **non-linearities in RF circuitry**, connectors, and surrounding metallic structures. These unwanted emissions are particularly hazardous when they fall within the device's own receiver band, leading to **receiver sensitivity degradation** and self-interference.

The challenge of PIM is further amplified in **LTE/NR Dual Connectivity (EN-DC)** scenarios, where simultaneous transmissions across "difficult band combinations" generate interference products that complicate the **link budget** and hinder the reception of weak signals. As 5G systems increasingly rely on advanced beamforming and spatial multiplexing, managing these non-linear distortions becomes essential. Consequently, research into mitigation strategies, such as **advanced RF filtering** and **power amplifier linearization**, is vital to maintain the integrity and capacity of 5G indoor solutions. This paper provides a comprehensive analysis of PIM challenges within these high-density architectures and evaluates potential solutions to ensure reliable multi-Gbps connectivity.

2. Problem Statement:

The pursuit of **ubiquitous 1 Gbps data rates** in indoor environments necessitates the deployment of **Ultra-Dense Networks (UDN)** and the utilization of **Massive MIMO** technology to overcome path loss and capacity constraints. However, this transition has shifted the network bottleneck from being "signal strength limited" to becoming fundamentally **interference-limited**. A critical yet often overlooked physical-layer impairment is **Passive Intermodulation (PIM)**, which arises from **non-linearities in RF circuitry**, connectors, and adjacent metallic structures.

In **Massive MIMO** systems, the high concentration of antenna elements and simultaneous operation of multiple power amplifiers significantly increase the probability of generating intermodulation products. The core problem occurs when these unwanted emissions fall within the device's own receiver frequency band, causing **self-interference** and a substantial **degradation of receiver sensitivity**. This issue is further exacerbated in **LTE/NR Dual Connectivity (EN-DC)** scenarios, where simultaneous transmissions in "**difficult band combinations**" produce PIM products that contaminate the receiver's noise floor, thereby compromising the **link budget** and preventing the detection of weak signals. In dense indoor settings, where 80% of data traffic originates, the proximity of reflective materials can turn the entire environment into a source of PIM, potentially negating the capacity gains intended by 5G densification.

3. Significance of the Study:

The significance of this study lies in its focus on one of the most persistent technical barriers to achieving the full potential of 5G New Radio (NR) **Passive Intermodulation (PIM)**. As the industry strives to deliver **ubiquitous 1 Gbps data rates** and supports the target of **one million devices per square kilometer**, the reliability of the physical layer becomes paramount. Since more than **80% of mobile data**

traffic originates indoors, optimizing indoor coverage solutions is not merely a technical preference but an economic necessity for the digital economy.

This research is particularly important for several reasons:

1. **Ensuring Network Reliability for Critical Applications:** 5G is designed to support life-critical services such as **remote robotic surgery** and autonomous driving, which require **ultra-reliable low-latency communication (uRLLC)**. By analyzing and mitigating PIM, this study contributes to maintaining the strict **99.999% reliability** standards required for these services, where even minor sensitivity degradation could lead to signal failure.

2. **Optimizing Massive MIMO and UDN Performance:** While **Massive MIMO** and **Ultra-Dense Networks (UDN)** are key enablers for spectral efficiency, their high concentration of antenna elements and power amplifiers creates a fertile environment for non-linear distortions. This study provides essential insights into managing these interferences to prevent them from negating the capacity gains offered by these advanced technologies.

3. **Addressing Dual-Connectivity Challenges:** Current 5G deployments often rely on **LTE/NR Dual Connectivity (EN-DC)**. The simultaneous transmission on "difficult band combinations" is a primary source of **self-interference (IMD)** that degrades receiver sensitivity. This research offers a pathway to solving these coexistence issues, ensuring a smoother transition from legacy systems to 5G Advanced.

4. **Guiding Hardware Design and Cost Efficiency:** By evaluating mitigation strategies such as **advanced RF filtering** and **power amplifier linearization**, this study aids engineers in making informed trade-offs between hardware complexity, energy consumption, and network performance.

Ultimately, this study serves as a vital reference for network operators and infrastructure vendors aiming to deploy robust, high-capacity indoor solutions that can survive in the increasingly **interference-limited** landscape of modern wireless communications.

4. Research Objectives:

The primary objective of this research is to provide a comprehensive analysis of the performance bottlenecks caused by Passive Intermodulation (PIM) in high-density 5G architectures. The specific objectives are as follows:

1. **To analyze the impact of RF non-linearities on receiver sensitivity:** Evaluate how unwanted emissions from connectors and circuitry lead to **receiver sensitivity degradation** in Massive MIMO systems.

2. **To investigate PIM challenges in Ultra-Dense Networks (UDN):** Assess how the dense deployment of small cells and the proximity of users in indoor environments amplify the level of **inter-cell and self-interference**.

3. **To evaluate "difficult band combinations" in Dual Connectivity:** Study the occurrence of PIM products when LTE and 5G NR operate simultaneously (**EN-DC**), particularly when these products fall within the device's own receiver band.

4. **To assess the trade-off between linearity and energy efficiency:** Analyze the impact of imposing **tighter linearity requirements** and power back-off on the energy consumption and cost-effectiveness of 5G indoor hardware.

5. **To propose and evaluate mitigation strategies:** Evaluate the effectiveness of **advanced RF filtering**, improved power amplifier linearization, and **BS clustering** to minimize the signaling overhead and suppress PIM in interference-limited environments.

6. **To optimize link budget reliability for 1 Gbps indoor services:** Determine the necessary adjustments in network planning to ensure that PIM does not negate the capacity gains required to reach the **1 Gbps peak data rate** target.

5. Theoretical Framework:

The analysis of **Passive Intermodulation (PIM)** within **Massive MIMO** and **Ultra-Dense Networks (UDN)** requires a multi-faceted theoretical approach that integrates radio frequency (RF) physics, advanced antenna theory, and network topology dynamics. This section establishes the fundamental principles governing these technologies and the resulting physical-layer impairments.

1. Non-Linearity and the Genesis of Passive Intermodulation (PIM)

Passive Intermodulation (PIM), also referred to as **Intermodulation Distortion (IMD)**, is defined as unwanted emissions resulting from **non-linearities in RF circuitry**, connectors, and adjacent metallic structures. Theoretically, when two or more signals at different frequencies mix in a non-linear element—such as a loose connector or a saturated power amplifier—they generate new, interfering frequencies. The most critical of these are **third- and fifth-order intermodulation products**, which frequently fall within the device's own receiver band, creating **self-interference**. This phenomenon is particularly acute in **LTE/NR Dual Connectivity (EN-DC)**, where "difficult band combinations" involve simultaneous transmissions that contaminate the receiver's noise floor.

2. Massive MIMO and Spatial Degrees of Freedom

Massive MIMO systems are theoretically defined by the utilization of a large number of individually controllable antenna elements, typically **100 or more**, at the base station (BS). The theoretical foundation of this technology lies in exploiting **spatial Degrees of Freedom (DoF)** to:

• **Spatial Multiplexing:** Transmit multiple independent data streams ("layers") over the same time-frequency resources to different users.

• **Beamforming/Precoding:** Coherently overlap signals at the target receiver to achieve **array gain** while destructively overlapping them at unintended receivers to minimize interference. However, the high concentration of power amplifiers and antenna elements in Massive MIMO increases the probability of non-linear interactions, making the system highly susceptible to **CSI (Channel State Information) errors** and PIM-induced noise.

3. Transition to Interference-Limited Ultra-Dense Networks (UDN)

The deployment of 5G moves the network paradigm from being "signal strength limited" to "**interference-limited**". **Ultra-Dense Networks (UDN)** involve the hyper-densification of small cells with inter-site distances reduced to **10 meters or less**. Theoretically, this densification maximizes spectral reuse but introduces a "sparse regime" where traditional area capacity models break down due to diminishing returns from inter-cell interference. In indoor environments, where **80% of data traffic originates**, the proximity of reflective and non-linear materials turns the physical environment itself into a potential source of **environmental PIM**.

4. Receiver Sensitivity and Link Budget Reliability

The core metric for evaluating PIM impact is **Receiver Sensitivity Degradation**. Theoretically, the **Link Budget (RLB)** serves as the tool for estimating the maximum allowed path loss between the transmitter and receiver. PIM acts as an additional noise component () that effectively raises the **noise floor**, requiring a higher received signal-to-interference-plus-noise ratio (**SINR**) to maintain the target data rate. For 5G to achieve its **1 Gbps ubiquitous indoor data rate** target, the link budget must account for these non-linear distortions to prevent coverage holes and service failures in dense urban hotspots.

6. Literature Review:

The academic and industrial consensus on 5G New Radio (NR) emphasizes a multi-phased approach to standardization and deployment, driven by the diverse requirements of the **IMT-2020** framework. Reviewing the literature reveals a significant evolution in addressing physical-layer impairments as networks transition from macro-cell coverage to **Ultra-Dense Networks (UDN)**.

1. Evolution of 3GPP Standards and Service Pillars

The literature categorizes 5G development into two primary phases. **Release 15 (Rel-15)** established the foundation for **Enhanced Mobile Broadband (eMBB)**, focusing on high data rates and the **Non-Standalone (NSA)** architecture to leverage existing LTE infrastructure. **Release 16 and 17** expanded this scope toward **Industrial IoT** and **Ultra-Reliable Low-Latency Communications (uRLLC)**, introducing features like **RedCap** (Reduced Capability) for mid-range IoT devices. While these standards addressed systemic latency and capacity, they also introduced new complexities in the radio interface, particularly in high-frequency **mmWave** bands where propagation loss is severe.

2. Massive MIMO and the "Interference-Limited" Paradigm

Massive MIMO is recognized as the key enabler for achieving the **1000x capacity increase** target. Literature indicates that by using large antenna arrays (e.g., 64x64 or 128 elements), systems can exploit **spatial multiplexing** and **3D beamforming** to focus energy directly toward users. However, as noted in the sources, the transition to **Ultra-Dense Networks (UDN)** has shifted the bottleneck from being "signal strength limited" to "**interference-limited**". In these environments, traditional Orthogonal Frequency Division Multiplexing (**OFDM**) faces challenges due to large side lobes that require tight synchronization and guard bands.

3. Passive Intermodulation (PIM) and Nonlinear Impairments

A critical physical-layer impairment identified in recent research is **Intermodulation Distortion (IMD)**, specifically **Passive Intermodulation (PIM)**. PIM arises from **non-linearities in RF circuitry**, connectors, and adjacent metallic structures, leading to a significant **degradation of receiver sensitivity**. The literature highlights a specific operational challenge in **LTE/NR Dual Connectivity (EN-DC)**: "difficult band combinations" where simultaneous transmissions generate low-order PIM products that fall into the device's own receiver band. While initial studies focused on active interference, the passive non-linear effects of PIM remain a persistent barrier to maintaining the strict **link budget** required for ubiquitous **1 Gbps indoor coverage**.

4. Mitigation Strategies and Waveform Engineering

To manage these impairments, the literature evaluates various technological components:

• **Advanced Waveforms:** Comparison between **OFDM**, **FBMC** (Filter-Bank Multi-Carrier), and **UFMC** (Universal Filtered Multi-Carrier) shows that filtered waveforms offer better **spectral containment** and reduced side lobes, which can alleviate PIM-related interference.

• **Interference Cancellation:** Techniques such as **Network-Assisted Interference Cancellation (NAIC)** and **Successive Interference Cancellation (SIC)** have been standardized to help receivers reconstruct and subtract interfering signals.

• **Linearization:** Improving **Power Amplifier (PA) linearity** and employing power back-off are noted as essential for reducing unwanted emissions, though at the cost of reduced **energy efficiency**.

5. Research Gap: PIM in Indoor High-Density Scenarios

Despite extensive research on active interference coordination (e.g., **CoMP**), there is a distinct gap in literature concerning the **long-term management of PIM in indoor UDNs**. Most current studies treat PIM as a hardware maintenance issue rather than a dynamic network variable that evolves with **3D beamforming** and **Massive MIMO** configurations. This research aims to address this gap by analyzing how dense antenna arrays and reflective indoor environments amplify PIM effects, specifically in **standalone (SA)** and **multi-connectivity** scenarios not fully resolved in Rel-17.

7. Methodology:

The research methodology follows a structured four-phase approach to analyze the impact of PIM on 5G network performance, particularly focusing on **Massive MIMO** and **Ultra-Dense Networks (UDN)**.

1. Link-Level Simulation (LLS)

The first phase involves conducting **Link-Level Simulations (LLS)** to establish the baseline performance requirements for various physical channels (e.g., PDSCH, PUSCH, and SSB). The simulation will:

• Determine the required **Signal-to-Interference-plus-Noise Ratio (SINR)** to meet specific **Block Error Rate (BLER)** targets.

• Model PIM as an additional noise component that elevates the receiver's noise floor, allowing for the quantification of **receiver sensitivity degradation**.

2. Map-based and Ray Tracing Modeling

To ensure spatial consistency in dense indoor and urban environments, a **map-based model** using **ray tracing (RT)** is employed. This deterministic approach is essential for Massive MIMO as it:

• Account for complex propagation mechanisms, including **specular reflection**, **diffraction** (using the Berg recursive model), and **diffuse scattering** from rough surfaces.

• Simulate **spatial consistency** and **dual-end mobility**, ensuring that PIM interactions from surrounding metallic structures are accurately captured as the user moves.

3. Path Loss and Link Budget Analysis

The study utilizes **linear regression fits** based on the **least-squares (LS)** method to develop environment-specific path loss models. The core evaluation metric will be the **Maximum Isotropic Loss (MIL)**, which is used to:

• Identify the "bottleneck channel" that limits coverage in high-interference scenarios.

• Calculate the **link budget** adjustments necessary to maintain the target **1 Gbps data rate** in the presence of nonlinear distortions.

4. Empirical Validation and Signal Analysis

The final phase involves validating simulation results through empirical measurements using high-performance hardware. This includes:

• Using the **High-Performance Digital Radio Testbed (HIRATE)** to collect millions of channel observations across various frequency bands (e.g., 28 GHz and 60 GHz).

• Analyzing captured waveforms to measure the **Adjacent Channel Leakage Ratio (ACLR)** and **Error Vector Magnitude (EVM)**, which are critical indicators of nonlinear impairments like PIM.

8. Results and discussions:

The synthesized results from technical evaluations, field measurements, and simulations provide critical insights into the performance limits of 5G networks in high-density environments. The following sections discuss the primary findings regarding propagation, device complexity, and physical-layer impairments.

1. Path Loss and Frequency-Dependent Propagation

Experimental data at **60 GHz** reveals that under **Line-of-Sight (LOS)** conditions, the **Path Loss (PL) exponents** are approximately **2.0**, closely aligning with **free-space propagation** models. In contrast, measurements at **10 GHz** in narrow street canyons yielded a lower exponent of **1.62**, suggesting a significant **waveguiding effect** that enhances signal strength in these corridors—an effect less pronounced at higher frequencies. Furthermore, the application of **Floating Intercept Models** was found to provide a

superior fit to empirical data, reducing **shadow factors** by several decibels compared to traditional close-in reference models.

2. Temporal Dispersion and Delay Spread Statistics

Measurements indicate that the median **Root Mean Square (RMS) Delay Spread (DS)** varies between **16 and 38 ns**, depending on the reflective nature of the environment (e.g., glass-heavy city centers vs. residential areas). While the DS generally increases with distance, it tends to **saturate at approximately 100 ns**. A comparison with simulation tools shows that **Ray Tracing (RT)** often overestimates the DS by predicting paths that are either non-existent or significantly weaker in reality, highlighting the need for empirical calibration of deterministic models.

3. Massive MIMO Performance and Device Optimization

Analytical results regarding **RedCap** (Reduced Capability) devices in **Massive MIMO** systems demonstrate the existence of an **optimal number of UE antennas ()** to maximize data rates. Increasing antennas beyond this point does not improve performance because the **spatial Degrees of Freedom (DoF)** are consumed by **multi-user interference nulling** rather than providing diversity gains. Simulations indicate that decreases as the number of **Base Station (BS) antennas** or **co-scheduled UEs** increases, allowing for the design of cost-effective, low-complexity 5G hardware without sacrificing throughput.

4. Coverage Bottlenecks and Recovery Requirements

Link budget evaluations based on the **Maximum Isotropic Loss (MIL)** identify specific "bottleneck channels" for 5G services:

• **In FR1 bands:** The **PUSCH (Uplink)** is the primary coverage limiter, requiring approximately **3 dB of coverage recovery** due to antenna inefficiency in small form-factor devices like wearables.

• **In FR2 bands:** The impact is more severe on **downlink (DL)** channels, with the **PDSCH** requiring roughly **3.4 dB of recovery**. These losses can be mitigated by adjusting data rate targets or employing repetition techniques to ensure ubiquitous service availability.

5. PIM and the Interference-Limited Paradigm

The transition to **Ultra-Dense Networks (UDN)** marks a shift from "signal-strength limited" to "**interference-limited**" environments. In these scenarios, **Passive Intermodulation (PIM)** caused by non-linearities in connectors and RF circuitry becomes a critical bottleneck, leading to **receiver sensitivity degradation**. This is especially acute in **LTE/NR Dual Connectivity (EN-DC)** scenarios involving "difficult band combinations," where intermodulation products fall directly into the receiver band, creating significant **self-interference**. Results show that further densification in UDNs is becoming less effective; for instance, doubling a user's data rate may require a 20-fold increase in BS density, whereas the same gain can be achieved by simply doubling the available **bandwidth**.

Analogy for Understanding: The results suggest that building a 5G network is like hosting a **grand orchestra** in a small, mirrored hall. **Massive MIMO** provides the numerous instruments, but the results show that past a certain point, adding more musicians () just makes it harder to coordinate. The **PIM** is like the "echo" or "microphone feedback" that occurs when instruments are placed too close together in a crowded space (**UDN**). The research highlights that the key to a better performance isn't just "playing

louder" (higher signal strength), but "tuning the hall" (interference management) and ensuring the "soloists" (weak data signals) can still be heard over the structural noise of the building.

9. Recommendations

Based on the technical findings and system evaluations, the following recommendations are proposed to optimize 5G network performance and mitigate non-linear impairments:

1. **Spectrum Policy and Harmonization:** Regulatory bodies should prioritize the allocation of **large contiguous spectrum blocks** in the 3.5 GHz and mmWave bands to maximize 5G throughput. It is highly recommended to **migrate legacy systems** (LTE/WiMax) out of these bands as soon as possible to prevent performance degradation and facilitate more efficient spectral reuse.

2. **Mitigation of Passive Intermodulation (PIM):** To address self-interference in **EN-DC (Dual Connectivity)** scenarios, operators should implement **cross-node scheduler coordination** between eNB and gNB. Specifically, for "difficult band combinations," a **single-TX operation** strategy should be enforced to prevent simultaneous transmissions that generate intermodulation products within the receiver's frequency range.

3. **Deployment of Integrated Infrastructure:** For **Ultra-Dense Networks (UDN)**, the adoption of **Cloud-RAN (C-RAN)** architectures is recommended to exploit coordination gains and reduce OPEX through centralized processing. Furthermore, **fiber-optic backhaul** should be deployed as the primary transport solution to meet the 10 Gbps peak data requirements and low-latency targets.

4. **Hardware Optimization for RedCap Devices:** Manufacturers should design **Reduced Capability (RedCap)** hardware with an **optimized number of antennas** () tailored to the network environment. The results indicate that minimizing antenna count in interference-limited scenarios can reduce device cost and power consumption without a significant loss in achievable data rates.

5. **Enhanced Reliability Frameworks:** System designs should adopt the **Reliable Service Composition (RSC)** approach, allowing services to degrade gracefully according to channel conditions rather than failing entirely. This is particularly critical for **URLLC** applications in dense indoor environments where sudden signal blockage is common.

10. Conclusion

The findings of this research emphasize that **5G New Radio (NR)** represents a fundamental shift in the philosophy of wireless communications, moving beyond simple high-speed data for smartphones to a pervasive platform for a fully connected society. Through the analysis of high-density environments and non-linear impairments, several key conclusions have been established.

First, while **Massive MIMO and Beamforming** are the primary engines for increasing spectral efficiency and achieving **IMT-2020** targets, they significantly increase the complexity of the radio interface. This complexity makes the system highly susceptible to **Passive Intermodulation (PIM)**, which has emerged as a critical physical-layer bottleneck. PIM induces **receiver sensitivity degradation** and raises the noise

floor, particularly in **LTE/NR Dual Connectivity (EN-DC)** scenarios where simultaneous transmissions on "difficult band combinations" create self-interference.

Second, the transition to **Ultra-Dense Networks (UDN)** has shifted the network paradigm from being "signal-strength limited" to "**interference-limited**". In these hyper-dense settings, simply adding more base stations yields diminishing returns. Instead, the research highlights that the only viable path to maintaining a ubiquitous **1 Gbps indoor data rate** is through advanced interference management and resource coordination enabled by **Network Softwarization** and **SDN/NFV** frameworks.

Third, for **Reduced Capability (RedCap)** devices, the research underscores a vital trade-off between cost-efficiency and coverage. The coverage loss resulting from antenna and bandwidth reduction in these devices requires specific **Link Budget recovery strategies**, such as adjusted data rate targets or repetition techniques, to ensure service continuity in challenging environments.

Ultimately, the successful evolution of 5G and the transition toward **6G** will depend on the **integration of hardware optimization and software intelligence**. Future networks must combine enhanced RF linearity to suppress PIM with **AI-driven orchestration** to dynamically manage resources in a highly variable and interference-prone landscape.

References:

1. **3GPP.** (2019). *Release 17 package for RAN: Outcome from RAN#86*. 3rd Generation Partnership Project.
2. **5G PPP Architecture Working Group.** (2016). *View on 5G Architecture* (Version 1.0). 5G Infrastructure Public Private Partnership.
3. **Dahlman, E., Parkvall, S., & Sköld, J.** (2024). *5G/5G-Advanced: The new generation wireless access technology* (3rd ed.). Academic Press/Elsevier.
4. **Ghadialy, Z.** (2020, April). *5G for absolute beginners*. 3G4G UK.
5. **GSMA.** (2019). *The 5G guide: A reference for operators*. GSM Association.
6. **Huawei Technologies Co., Ltd.** (2016). *5G network architecture: A high-level perspective*.
7. **International Telecommunication Union.** (2015). *IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond* (Recommendation ITU-R M.2083-0).
8. **International Telecommunication Union.** (2017). *Future networks: Objectives and design goals* (Recommendation ITU-T Y.3001).
9. **MacCartney, G. R., Jr., Zhang, J., Nie, S., & Rappaport, T. S.** (2013, December). Path loss models for 5G millimeter wave propagation channels in urban microcells. In *2013 IEEE Global Communications Conference (GLOBECOM)* (pp. 3948-3953). IEEE.
10. **Min, K., & Kim, T.** (2023). Performance analysis on eigenmode beamforming for reduced capability device in massive MIMO systems. *IEEE Access*, 11, 13783–13794.
11. **Moloudi, S., Mozaffari, M., Veedu, S. N. K., Kittichokechai, K., Wang, Y.-P. Eric., Bergman, J., & Höglund, A.** (2021). Coverage evaluation for 5G reduced capability new radio (NR-RedCap). *IEEE Access*, 9, 45055–45067.

12. **Osseiran, A., Monserrat, J. F., & Marsch, P. (Eds.).** (2016). *5G mobile and wireless communications technology*. Cambridge University Press.
13. **Pateromichelakis, E., Celik, H., Fantini, R., Bulakci, Ö., Campoy, L. M., Ibrahim, A. M., ... & Yang, Y.** (2016). *Interference management for 5G: A METIS-II perspective*.
14. **Penttinen, J. T. J.** (2019). *5G explained: Security and deployment of advanced mobile communications*. John Wiley & Sons Ltd.
15. **Peter, M., Weiler, R. J., Göktepe, B., Keusgen, W., & Sakaguchi, K.** (2016). Channel measurement and modeling for 5G urban microcellular scenarios. *Sensors*, 16(1330).