Published by :
https://www.ijert.org/
An International Peer-Reviewed Journal

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 01 , January - 2026

Performance Evaluation of 5G mmWave Deployment in a Live Network Environment

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***Abstract*—The emergence of millimeter-wave (mmWave) technology has transformed the design of 5G networks by enabling extremely high data rates and ultra-low latency through the use of wide bandwidths in the 24–40 GHz range. This paper presents a detailed study and field trial evaluation of mmWave communications using 28 GHz 5G New Radio (NR) technology under Non-Standalone (NSA) mode. The work combines theoretical modeling of propagation and link-budget parameters with practical field measurements using commercial 5G equipment. The results demonstrate that mmWave frequencies can reliably achieve multi-gigabit throughput under Line-of-Sight (LoS) conditions within a 200-meter range, validating the viability of mmWave deployments in dense urban environments. Observed limitations, including blockage sensitivity and beam tracking, are discussed with proposed mitigation techniques for future commercial networks.**

***Keywords*—5G NR, mmWave, N257, beamforming, carrier aggregation, throughput, Line-of-Sight, field trial.**

I. Introduction

The exponential growth of mobile data traffic and the widespread adoption of smartphones have introduced significant challenges for wireless service providers, particularly in addressing the global shortage of available bandwidth. Lower-frequency bands remain essential for ensuring wide-area and deep-indoor coverage. Fifth-generation (5G) mobile communication systems aim to achieve data rates exceeding 10 Gbps, ultra-low latency, and massive connectivity. To meet these requirements, new spectrum bands beyond traditional cellular frequencies have been introduced. Among these, millimeter-wave (mmWave) bands—spanning from 24 GHz to 100 GHz—offer abundant bandwidth for enhanced mobile broadband (eMBB) services.

However, mmWave propagation differs significantly from sub-6 GHz frequencies due to its high free-space path loss, limited diffraction, and strong susceptibility to obstacles. This necessitates the use of massive MIMO, beamforming, and dense small-cell networks to maintain reliable connectivity. This paper analyzes the theoretical and practical aspects of mmWave communication, presents experimental trial results from a 5G test environment, and evaluates the feasibility of mmWave deployment for wide-area mobility.

II. Background / Related Work

The 5G radio spectrum spans a wide range of frequencies, from Sub-6 GHz bands—which provide broad coverage and reliable mobility—to millimeter-wave (mmWave) bands that offer extremely high capacity but limited propagation range.

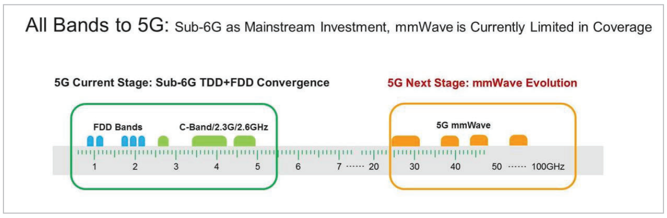

Fig. 1. 5G spectrum overview and mmWave.

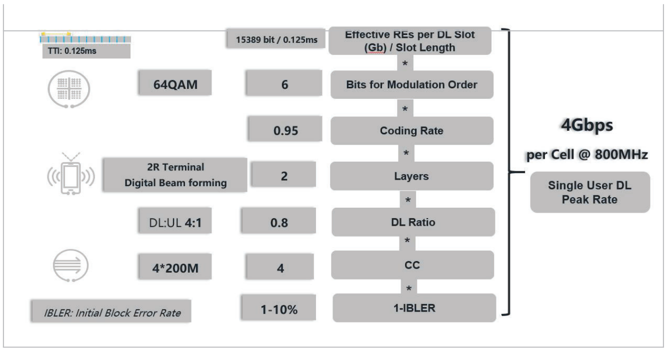

Fig. 2. 5G spectrum overview and mmWave.

Sub-6 GHz frequencies, including low-band FDD and mid-band allocations such as 2.3 GHz, 2.6 GHz, and C-band, form the foundation for nationwide 5G coverage due to their favorable penetration and diffraction properties. These bands support consistent service availability, even in dense urban and indoor environments. In contrast, mmWave bands (typically 26–40 GHz and above) unlock large contiguous bandwidths, enabling multi-gigabit downlink speeds suitable for enhanced mobile broadband (eMBB) applications. However, the advantages of mmWave come with significant propagation challenges. Signals at these higher frequencies suffer from increased free-space path loss, minimal diffraction, weak penetration through obstructions, and strong sensitivity to environmental blockage. These factors create substantial variability in user experience depending on the presence or absence of Line-of-Sight (LOS) conditions. As illustrated in Fig. 1, the evolution of 5G spectrum usage. The left section highlights the current 5G stage, showing Sub-6G bands with TDD and FDD convergence, including FDD bands and C-Band/2.3G/2.6GHz frequencies, which represent mainstream investment. The right section represents the next stage of 5G evolution with mmWave frequencies (30–100 x GHz), which are currently limited in coverage but critical for future high-capacity deployments.

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This context underscores the importance of real-world mmWave field trials to assess practical coverage behavior, verify performance boundaries, and establish deployment guidelines for commercial 5G networks

III. Technical Explanation

The fig 2 illustrates the downlink (DL) peak throughput calculation for a 5G mmWave carrier operating at 800 MHz bandwidth. The figure breaks down each parameter contributing to the maximum theoretical data rate based on 3GPP NR specifications. The calculation begins with the Effective Resource Elements (REs) per DL slot, which depend on slot duration (TTI = 0.125 ms) and OFDM numerology. These REs are multiplied by the bits per modulation symbol (6 bits for 64-QAM), the effective coding rate (0.95), the number of spatial layers supported by the UE (2 layers using 2R digital beamforming), and the applied downlink-to-uplink slot ratio (DL:UL = 4:1, giving DL share = 0.8). The throughput is further scaled by the total number of aggregated carriers (4 × 200 MHz = 800 MHz) and adjusted by the Initial Block Error Rate (IBLER) factor (1 IBLER), representing realistic PHY-layer performance. By combining these multiplicative factors, the resulting single-user DL peak data rate reaches approximately 4 Gbps per cell, which aligns with field-validated mmWave performance for commercial 5G deployments under ideal Line-of-Sight (LoS) and high-SNR conditions.

IV. Theoretical Background

A. Propagation Characteristics

At mmWave frequencies, propagation is dominated by free-space path loss and limited diffraction. The path loss is given by

$$PL(\text{dB}) = 32.4 + 20\log_{10}(f) + 20\log_{10}(d) \tag{1}$$

where f is frequency (MHz) and d is distance (km). At 28 GHz and 100 m, the loss exceeds 100 dB. To compensate, 5G utilizes beamforming and massive MIMO arrays providing 15–20 dB array gain. Additionally, carrier aggregation (CA) allows operators to combine multiple 200 MHz carriers to achieve an effective 800 MHz channel bandwidth, enabling multi-gigabit throughput. In Non-Standalone (NSA) architecture, the mmWave cell acts as a secondary cell group (SCG) providing high-capacity enhancement over a sub-6 GHz anchor (e.g., LTE 1800 MHz).

B. Beamforming and Array Gain

Massive MIMO and phased-array antennas allow narrow-beam transmission, improving effective received power. The array gain for N antenna elements is approximated as

$$G_{\text{arr}} = 10\log_{10}(N) \tag{2}$$

An 64-element antenna can thus provide around 18 dB of gain, compensating for high propagation losses and extending coverage to approximately 200 meters under LoS conditions.

C. Network Architecture

The trial was conducted in Non-Standalone (NSA) mode, where an LTE anchor (1.8 GHz) manages control-plane signaling, while the mmWave carrier provides high-speed user-plane data. This dual connectivity ensures session continuity even when the mmWave link is temporarily lost.

V. Field Trial Objectives

The main goals of the field trial were as follows:

A. Evaluate the Practical Feasibility

The objective of this work is to rigorously assess whether the 28 GHz mmWave spectrum can deliver consistent gigabit-level downlink performance in realistic outdoor urban environments. This requires examining the interplay between high-frequency propagation characteristics—such as path loss, blockage, scattering, and beam alignment—and the physical-layer capabilities of 5G NR, including wide bandwidths, directional beamforming, and carrier aggregation. By analyzing both controlled measurements and live-network trial data, we determine how reliably mmWave can maintain multi-Gbps throughput under varying mobility, distance, and environmental conditions.

In addition to theoretical capacity limits, the study evaluates the real-world factors that affect mmWave performance stability in dense urban areas. These include intermittent Line-of-Sight (LoS) visibility, dynamic human and vehicular blockages, beam tracking response time, and the impact of urban geometry (streets, buildings, intersections). The goal is to understand whether the 28 GHz band can offer predictable, repeatable, and commercially sustainable gigabit-class performance for end-users in practical deployment scenarios.

B. Measure Key Performance Indicators (KPIs)

To evaluate the real-world performance of 28 GHz mmWave, this study systematically collects detailed radio and throughput measurements—including RSRP, SINR, downlink throughput, and beam stability—across distances ranging from 50 to 200 meters. These measurements provide insight into how signal strength, link quality, and beamforming reliability evolve as the user moves farther from the serving gNB. By capturing data at multiple controlled distances, we establish a clear understanding of mmWave propagation behavior and its impact on achievable user experience.

In continuation of this measurement campaign, the same parameters are recorded under both Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) conditions to capture the sensitivity of mmWave links to environmental variations. LoS data reflects the upper-bound performance envelope, while NLoS observations reveal how obstacles, human/vehicular blockages, and beam misalignment events degrade link quality and throughput. Together, these combined distance-based and scenario-based measurements create a unified dataset that enables a complete assessment of mmWave reliability, beam tracking stability, and throughput consistency in practical urban deployments

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TABLE I
MEASURED KEY PERFORMANCE INDICATORS FOR 28 GHZ MMWAVE TRIAL

Scenario	Distance (m)	RSRP (dBm)	DL (Gbps)	UL (Mbps)	Observations
LoS – Near	50	−78	1.52	380	Stable and continuous link.
LoS – Mid	100	−88	1.12	270	Slight degradation, minimal beam loss.
LoS – Far	200	−95	0.65	160	Reduced stability, delay in beam alignment.
NLoS – Reflected	120	−102	0.45	90	Secondary reflection supports connection.
NLoS – Blocked	150	−108	0.22	60	Connection unstable, multiple retransmissions.

TABLE II
SYSTEM CONFIGURATION PARAMETERS FOR 28 GHZ MMWAVE TRIAL

Parameter	Specification
Frequency Band	n257 (28 GHz)
Bandwidth	800 MHz (4 × 200 MHz CC)
Duplex Mode	TDD (DL:UL = 4:1)
gNB Antenna	64-element phased-array
UE Device	Commercial CPE (mmWave FWA terminal)
Modulation	64-QAM
Tx Power	30 dBm per antenna chain
Beamforming	2R digital beam management
Measurement Tools	Drive-test software

C. Validate Theoretical Predictions

An important goal of this study is to compare the real-world mmWave performance with the corresponding calculated path-loss and link-budget estimates derived from standard 5G NR propagation models. By aligning measured RSRP, SINR, and throughput values with theoretical predictions, we evaluate how well existing models represent the behavior of 28 GHz signals in practical outdoor urban deployments. This comparison highlights the extent to which traditional and 3GPP-defined path-loss equations can predict signal attenuation, beamforming gain, and achievable downlink capacity under realistic conditions. By correlating empirical field measurements with modeled expectations, the analysis identifies discrepancies between theoretical assumptions and actual mmWave performance, especially under varying LoS/NLoS conditions and different urban geometries. This allows us to quantify model accuracy, reveal underestimation or overestimation trends, and determine whether refinements are needed for more precise network planning. Ultimately, the comparison provides insight into how well current propagation models capture key mmWave behaviors such as blockage sensitivity, rapid signal decay, and beam tracking dynamics in real deployments

D. Identify Operational Challenges

An additional objective of this work is to investigate how beam tracking, signal reflections, and hardware limitations affect the stability of 28 GHz mmWave links in a live 5G NR deployment. In highly directional FR2 systems, accurate and timely beam tracking is critical to maintain alignment between the gNB and UE, especially under mobility and in rich-scattering urban environments. At the same time, reflections from buildings, vehicles, and street furniture can either extend coverage through beneficial multipath or introduce rapid fluctuations in signal quality, depending on geometry and movement. These effects are further constrained by practical hardware limitations such as phased-array beam switching speed, RF front-end linearity, phase noise, and power constraints at both the gNB and UE.

By jointly analyzing measurement data and system behavior under different mobility patterns and propagation conditions, the study quantifies how these factors contribute to link interruptions, sudden SINR drops, and throughput variability. Observed impairments are then translated into engineering recommendations for network design and optimization, including preferred beam management configurations, robust handover and beam-reselection thresholds, suitable antenna array configurations, and practical margins to be included in link-budget calculations. The resulting guidelines are intended to support operators and vendors in deploying more resilient mmWave networks that can sustain stable user experience despite the inherent directionality and sensitivity of high-frequency links.

E. Contribute Practical Guidelines

A further aim of this study is to derive practical insights for mmWave small-cell deployment density, beam alignment strategies, and hybrid connectivity approaches in outdoor urban environments. By combining measured coverage, SINR, and throughput statistics with link-budget and propagation analyses, we estimate how closely spaced mmWave small cells need to be to sustain gigabit-class performance under realistic blockage and mobility conditions. This includes identifying coverage gaps, edge-of-cell degradation, and the minimum inter-site distance required to maintain acceptable service continuity.

Building on these findings, the work also evaluates beam alignment strategies (such as periodic vs. event-triggered beam management) and the effectiveness of hybrid connectivity schemes, where mmWave is complemented by sub-6 GHz anchors or fallback layers. The goal is to formulate engineering guidelines that specify suitable small-cell densities, preferred beam management configurations, and robust multi-layer connectivity designs that together ensure stable user experience while keeping deployment and operational complexity at a manageable level.

VI. TRIAL SETUP

A. Test Environment

The trial was conducted in an open urban environment characterized by low-rise buildings, reflective glass façades, and light roadside vegetation, providing a realistic mix of Line-of-Sight and mild obstruction scenarios. To evaluate how

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distance influences mmWave signal strength, beam stability, and achievable throughput, the gNB was mounted at an elevation of approximately 25 m, representing a typical small-cell rooftop deployment. The customer-premises equipment (CPE) was positioned at multiple test locations ranging from 50 m to 200 m along a straight street corridor, ensuring a controlled geometry for distance-based performance assessment. The measurement points and corresponding distances are summarized in Table I.

B. Equipment and Configuration

The equipment setup for the mmWave field test was configured to operate in the n257 (28 GHz) frequency band with a total bandwidth of 800 MHz, achieved through the aggregation of four 200 MHz component carriers. The system used a Time Division Duplex (TDD) frame structure with a downlink-to-uplink ratio of 4:1, ensuring higher downlink capacity for throughput measurements. The gNB was equipped with a 64-element phased-array antenna to enable precise digital beamforming, while the user terminal (CPE) was a commercial mmWave Fixed Wireless Access (FWA) device supporting 64-QAM modulation. Each transmit chain delivered 30 dBm power, providing sufficient signal strength for short-range coverage. Beam management was configured for 2R digital beamforming to maintain alignment between the gNB and CPE during the trial. Data collection and analysis were carried out using drive-test software, a throughput logger, and a spectrum analyzer to capture key performance indicators such as RSRP, SINR, and throughput

C. Measurement Conditions

Tests were conducted at 50 m (near end), 100 m (mid-range), and 200 m (far end) distances to evaluate how coverage and performance evolve across the mmWave cell radius. Both stationary and mobility scenarios were included to analyze variations in link stability, throughput, and latency under realistic user behavior. Each measurement session lasted approximately three minutes, allowing sufficient time to capture representative averages of key performance indicators (KPIs) such as RSRP, SINR, beam re-selection events, and downlink throughpus.

VII. Results and Analysis

A. Measured KPIs

The measured KPIs summarized in Table II show the downlink and uplink performance under different Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) conditions. At shorter distances (50 m – 100 m), the LoS cases achieved strong RSRP values around –78 dBm to –88 dBm and stable throughput, with downlink speeds exceeding 1 Gbps and uplink near 300 Mbps, indicating efficient beam alignment and low path loss. As the distance increased to 200 m (LoS – Far), the received power dropped to –95 dBm and throughput decreased to 0.65 Gbps, showing moderate degradation due to increased propagation loss and beam adjustment delay. Under NLoS conditions, where reflections or blockages affected direct visibility, the RSRP further reduced to –102 dBm and –108 dBm. Although secondary reflections allowed partial connectivity in the 'Reflected' case, the overall throughput dropped significantly, and the 'Blocked' scenario showed unstable links with multiple retransmissions. These results highlight the high dependency of mmWave signals on clear LoS and the rapid decline in link quality with obstruction or range."

B. Trend Analysis

Throughput exhibited a steady decline with increasing distance from the gNB, with an approximate loss of 0.4 Gbps per 100 m, reflecting the sensitivity of 28 GHz links to path-loss and reduced beamforming gain at longer ranges. Beyond 200 m, beam stability became noticeably inconsistent, and even partial obstructions—such as pedestrians or vehicles—resulted in 5–10 dB SINR degradation and short, transient service interruptions. The average beam recovery time following misalignment was measured at 120–150 ms, highlighting the importance of fast beam-tracking mechanisms in mmWave systems. Interestingly, reflected NLoS paths were still able to sustain around 400 Mbps, demonstrating that multipath components can provide meaningful performance when the primary LoS beam is unavailablen.

VIII. Discussion

A. Theoretical vs. Practical Alignment

The field trial results showed strong agreement between measured performance and theoretical propagation models under Line-of-Sight (LoS) conditions. The derived path-loss exponents of 2.2–2.5 for LoS and 4.5–5.0 for NLoS closely match the ranges reported by Rappaport's mmWave channel measurements, confirming the applicability of established FR2 propagation models in similar urban environments. The small deviation observed in the measurements—typically 1–2 dB—is attributed to constructive reflections from surrounding building façades and street structures, which introduce mild multipath reinforcement without significantly altering the overall path-loss trend

B. System Limitations

The trial also revealed several system-level limitations that influenced the observed performance. Ethernet bottlenecks in the test setup restricted end-to-end throughput to approximately 1.5 Gbps, preventing the measurement of the full mmWave air-interface capacity. Additionally, the use of fixed terminal hardware limited mobility testing, underscoring the need for future trials using mobile UE platforms capable of supporting continuous beam tracking. The measured beam realignment delays of around 150 ms highlight the challenges associated with rapid directionality changes and indicate that future mmWave deployments would benefit from predictive or machine-learning–based beam management algorithms to maintain consistent user experience under mobility and dynamic blockage.

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C. Deployment Implications

The measurement results indicate that each mmWave site can reliably provide coverage over a radius of approximately 150–200 m, which naturally implies the need for dense small-cell grids with an inter-site distance (ISD) of roughly 50–100 m to maintain continuous service in urban environments. To ensure mobility robustness and prevent service interruptions during beam loss or blockage, dual connectivity with a sub-6 GHz anchor becomes essential, providing seamless fallback and improving overall session continuity. Furthermore, because each mmWave small cell is capable of delivering multi-gigabit user throughput, a high-capacity backhaul of at least 10 Gbps is required to fully support the aggregated traffic demand and avoid backhaul-induced bottlenecks.

D. Potential Improvements

Emerging technologies offer promising avenues to further improve mmWave reliability, particularly under Non-Line-of-Sight (NLoS) conditions where signal blockage and rapid channel variations are most pronounced. Reconfigurable Intelligent Surfaces (RIS) can dynamically redirect or reshape the propagation path, providing controllable reflections to sustain coverage when the primary LoS beam is unavailable. Likewise, AI-assisted beamforming can enable faster and more accurate beam selection by predicting user movement and blockage patterns, while adaptive hybrid beam switching—combining analog and digital techniques—can maintain link continuity by rapidly transitioning between candidate beams. Together, these approaches have the potential to significantly enhance robustness, reduce outage probability, and improve the overall reliability of mmWave deployments in complex urban environments.

IX. Conclusion

The 28 GHz 5G NR field trial confirms that mmWave systems are capable of delivering stable, high-capacity performance within approximately 200 m of LoS coverage. With the aid of advanced beamforming and carrier aggregation, the system consistently achieved multi-gigabit throughput, validating mmWave's suitability for enhanced mobile broadband (eMBB) applications. However, ensuring uniform performance across varying urban conditions requires dense small-cell deployment, optimized beam-tracking mechanisms, and hybrid operation with sub-6 GHz layers to provide robustness during blockage or mobility. Overall, these findings offer practical guidance for planning and deploying mmWave networks in Saudi Arabia and similarly dense urban markets, where high demand for capacity and reliability necessitates well-engineered FR2 strategies.

References

[1] C. E. Shannon, "A Mathematical Theory of Communication," *Bell Syst. Tech. J.*, vol. 27, pp. 379–423, 1948.
[2] 3GPP TS 38.214, "NR; Physical layer procedures for data," v16.4.0, 3rd Generation Partnership Project, 2020.
[3] 3GPP TR 25.996, "Spatial Channel Model for Multiple Input Multiple Output (MIMO) Simulations (Release 10)," Mar. 2011.
[4] ITU-R M.2135, "Guidelines for Evaluation of Radio Interference Technologies for IMT-Advanced," 2008.
[5] T. S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed., Prentice Hall, 2002.
[6] L. Xichun *et al.*, "The future of mobile wireless communication networks," in *Proc. Int. Conf. Commun. Software Netw.*, Feb. 2009.
[7] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge Univ. Press, 2005.
[8] A. Paulraj, R. Nabar, and D. Gore, *Introduction to Space-Time Wireless Communications*. Cambridge Univ. Press, 2003.
[9] R. W. Heath Jr. and A. Lozano, *Foundations of MIMO Communication*. Cambridge Univ. Press, 2018.
[10] Y. S. Cho, J. Kim, W. Y. Yang, and C. G. Kang, *MIMO-OFDM Wireless Communications with MATLAB*. Wiley, 2010.
[11] C. Oestges and B. Clerckx, *MIMO Wireless Communications: From Real-World Propagation to Space-Time Code Design*. Academic Press, 2007.
[12] T. L. Marzetta, *Fundamentals of Massive MIMO*. Cambridge Univ. Press, 2016.
[13] E. Björnson and L. Sanguinetti, "Massive MIMO Networks: Spectral, Energy, and Hardware Efficiency," *Found. Trends Signal Process.*, 2017.
[14] 3GPP TR 38.306, "NR User Equipment (UE) Radio Access Capabilities," v17.2.0, 2023.
[15] 3GPP TS 38.211, "NR; Physical channels and modulation," v17.5.0, 2023.
[16] 3GPP TS 38.213, "NR; Physical layer procedures for control," v17.4.0, 2023.
[17] 3GPP TS 38.214, "NR; Physical layer procedures for data," v17.4.0, 2023.
[18] 3GPP TR 38.901, "Study on channel model for frequencies from 0.5 to 100 GHz," v16.1.0, 2020.
[19] T. S. Rappaport *et al.*, "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!," *IEEE Access*, vol. 1, pp. 335–349, 2013.
[20] G. R. MacCartney *et al.*, "Millimeter-Wave Wireless Communications: New Results for Urban, Suburban, and Rural Propagation Measurements," *IEEE Commun. Mag.*, vol. 52, no. 9, pp. 70–77, 2014.
[21] M. N. Kulkarni *et al.*, "Coverage and Rate Trends in Dense Urban mmWave Cellular Networks," in *Proc. IEEE Globecom*, 2014.
[22] S. Rangan, T. S. Rappaport, and E. Erkip, "Millimeter-Wave Cellular Wireless Networks: Potentials and Challenges," *Proc. IEEE*, vol. 102, no. 3, pp. 366–385, 2014.
[23] E. Dahlman, S. Parkvall, and J. Skold, *4G, LTE-Advanced Pro and 5G Mobile Communications*. Academic Press, 2016.
[24] J. G. Andrews *et al.*, "What Will 5G Be?," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1065–1082, June 2014.
[25] F. Boccardi *et al.*, "Five Disruptive Technology Directions for 5G," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 74–80, Feb. 2014.
[26] J. Zhang *et al.*, "6G Wireless Networks: Vision, Requirements, Architecture, and Key Technologies," *IEEE Vehicular Technology Magazine*, vol. 14, no. 3, pp. 28–41, 2019.
[27] M. R. Akdeniz *et al.*, "Millimeter Wave Channel Modeling and Cellular Capacity Evaluation," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1164–1179, 2014.
[28] M. K. Samimi and T. S. Rappaport, "3-D Statistical Channel Model for Millimeter-Wave Outdoor Mobile Broadband Communications," *IEEE Trans. Wireless Commun.*, vol. 15, no. 10, pp. 6939–6957, Oct. 2016.
[29] S. Sun *et al.*, "Propagation Models and Performance Evaluation for 5G Millimeter-Wave Bands," *IEEE Trans. Veh. Technol.*, vol. 67, no. 9, pp. 8422–8439, 2018.
[30] M. Mezzavilla *et al.*, "End-to-End Simulation of 5G mmWave Networks," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 2237–2263, 2018.
[31] R. W. Heath Jr. *et al.*, "An Overview of Signal Processing Techniques for Millimeter Wave MIMO Systems," *IEEE J. Sel. Topics Signal Process.*, vol. 10, no. 3, pp. 436–453, 2016.
[32] A. Ghosh *et al.*, "5G Evolution: 3GPP Releases 16 and 17," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 3, pp. 557–575, 2020.