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From Capacity to Connectivity: Comprehensive MATLAB-Based Evaluation of 5G NR Throughput Dynamics

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Abstract— *The deployment of 5G New Radio (5G NR) leverages diverse frequency bands, particularly sub-6 GHz and millimeter-wave (mmWave) to balance coverage and capacity. This paper presents a comprehensive comparative analysis of downlink throughput performance in 5G NR at 3.5 GHz and 28 GHz bands under realistic urban propagation conditions defined by the 3GPP TR 38.901 standard. Using MATLAB's 5G Toolbox, we implement a unified simulation framework incorporating Urban Macro (UMa) and Urban Micro (UMi) channel models, with varying user mobility, line-of-sight (LOS)/non-line-of-sight (NLOS) conditions, and MIMO configurations (4×4 and 8×8). The study quantifies the throughput–SNR–distance relationship, highlighting the trade-offs between spectral efficiency, coverage range, and link reliability. Results demonstrate that while the 28 GHz band achieves significantly higher peak throughput under LOS and high SNR, its performance degrades rapidly with distance and mobility due to severe path loss and NLOS blockage. In contrast, the 3.5 GHz band provides more consistent coverage and robustness under dynamic conditions. Furthermore, beamforming gains from 8×8 MIMO enhances SNR and throughput in aligned scenarios but increases sensitivity to misalignment and mobility. These findings underscore the necessity of hybrid multi-band deployments and adaptive beam management strategies to achieve reliable and high-capacity 5G networks. The simulation-based approach provides valuable insights for system design, resource allocation, and network planning in next-generation wireless systems.*

Keywords— *5G NR; mmWave; sub-6 GHz; downlink throughput; SNR.*

I. INTRODUCTION

5G New Radio (5G NR) serves as the fundamental air interface for next-generation mobile communication systems, designed to meet the demanding performance requirements of emerging services, devices, and deployment scenarios across both licensed and unlicensed spectrum bands. Unlike previous generations, 5G NR has been developed from the ground up to deliver substantial improvements in throughput, latency, reliability, and connection density, while ensuring backward and forward compatibility with existing mobile technologies [1].

The 3rd Generation Partnership Project (3GPP) began formal work on 5G NR through the Release 14 Study Item in 2016, which led to the first standardized specification in Release 15. The initial phase, known as Non-Standalone (NSA) 5G NR, utilized existing LTE core and radio infrastructure to accelerate early deployments, primarily targeting Enhanced Mobile Broadband (eMBB) applications. This was followed by the Standalone (SA) 5G NR specification, finalized in June 2018, which introduced a new 5G Core (5GC) network architecture, providing complete user and control plane functionality independent of LTE [2]. From a technical standpoint, 5G NR is founded on three core design principles: (1) optimized OFDM-based waveforms that enable scalable and flexible multiple access across a wide range of frequency bands; (2) a unified, adaptable framework for efficiently multiplexing diverse 5G services; and (3) advanced wireless innovations to meet stringent 5G performance goals such as ultra-low latency and high reliability. These design pillars allow 5G NR to support the three main service categories—Enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communications (URLLC), and Massive Machine-Type Communications (mMTC)—each with distinct technical and performance requirements [3]. eMBB focuses on high-data-rate services such as video streaming and immersive media, leveraging technologies like massive MIMO, millimeter-wave (mmWave) access, and advanced channel coding. URLLC is designed for mission-critical applications, including autonomous vehicles and industrial automation, demanding deterministic latency and extremely high reliability. mMTC targets large-scale Internet of Things (IoT) deployments, featuring energy-efficient, low-cost devices transmitting small data payloads [4].

Subsequent 3GPP Releases 16 and 17 further expand 5G NR's capabilities, adding support for industrial IoT, operation in unlicensed spectrum, NR-Light for mid-tier IoT devices, and broadcast/multicast features for applications such as V2X communications and public safety [5]. Central to 5G performance is the diversity of frequency bands employed, notably the sub-6 GHz range (e.g., 3.5 GHz) and the mmWave range (e.g., 28 GHz). While sub-6 GHz frequencies offer broader coverage and moderate data rates, mmWave frequencies enable significantly higher data rates but suffer from reduced coverage due to greater path loss and blockage sensitivity [6][7].

Understanding the interplay between Signal-to-Noise Ratio (SNR) and downlink throughput across these bands is essential for effective 5G deployment planning. SNR, representing signal quality, directly affects the selection of modulation and coding schemes (MCS), which in turn determine achievable throughput. Higher SNR levels allow the use of higher-order modulation, resulting in increased data rates; however, path loss, interference, and mobility can degrade SNR, thereby reducing throughput [8][9]. Simulation environments such as MATLAB, equipped with the 5G Toolbox, provide powerful platforms to model these relationships, allowing researchers to analyze performance across varying frequency bands, MIMO configurations, and channel conditions [10][11].

Although prior research has explored 5G performance in either sub-6 GHz or mmWave bands independently, few studies have performed a comprehensive comparison that jointly considers SNR dynamics, standardized 3GPP channel models, MIMO scaling, and realistic throughput estimation under consistent simulation settings. This limitation restricts operators' ability to make data-driven decisions when designing hybrid 5G networks. The present study addresses this gap by developing a unified simulation framework that evaluates the SNR–throughput relationship for both 3.5 GHz (sub-6 GHz) and 28 GHz (mmWave) bands under 3GPP TR 38.901 Urban Macro (UMa) and Urban Micro (UMi) channel models, using MATLAB's 5G Toolbox. The framework integrates realistic link budgeting, MIMO configurations (4×4 and 8×8), beamforming gain, and MCS-based throughput estimation to quantify how frequency-dependent propagation characteristics affect practical throughput across varying SNR conditions.

II. LITERATURE REVIEW

The development of 5G New Radio (NR) technology has introduced a diverse range of frequency bands, with the sub-6 GHz (e.g., 3.5 GHz) and millimeter-wave (mmWave, e.g., 28 GHz) bands emerging as particularly important. Each frequency range offers distinct strengths and trade-offs. Sub-6 GHz frequencies exhibit lower path loss and superior obstacle penetration, providing broader coverage and more reliable connectivity in non-line-of-sight (NLOS) conditions [6]. Conversely, mmWave bands offer exceptionally large bandwidths capable of supporting multi-gigabit-per-second data rates but are hindered by higher path loss, greater susceptibility to blockage, and limited coverage areas [12].

Analyzing the influence of the Signal-to-Noise Ratio (SNR) on downlink throughput across these bands is crucial for optimizing 5G network performance. SNR directly impacts the selection of modulation and coding schemes (MCS), which in turn determine spectral efficiency and achievable data rates. In high-SNR conditions, higher-order modulation schemes such as 64-QAM or 256-QAM can be utilized to maximize throughput. In contrast, lower SNR levels necessitate more robust, lower-order modulations like QPSK to maintain link reliability, albeit at the cost of reduced data rates [8].

Accurate channel modeling plays a key role in simulating realistic 5G environments. The 3GPP TR 38.901 technical report defines standardized channel models for a variety of deployment scenarios, including Urban Macro (UMa) and Urban Micro (UMi) environments. These models incorporate detailed propagation characteristics—such as path loss, shadow fading, delay spread, Doppler shift, and angular spreads in both azimuth and elevation—making them well-suited for analyzing performance across sub-6 GHz and mmWave frequencies [2].

MATLAB's 5G Toolbox provides an integrated simulation platform that conforms to 3GPP specifications. It supports comprehensive physical-layer modeling, waveform generation, link-level and system-level simulations, and performance evaluations under diverse channel conditions. Core components such as Orthogonal Frequency Division Multiplexing (OFDM), Low-Density Parity-Check (LDPC) coding, Multiple-Input Multiple-Output (MIMO) systems, and beamforming algorithms enable detailed and realistic assessments [10]. These tools make it possible to explore how variations in SNR affect throughput across different frequency bands and deployment scenarios. Simulation results consistently indicate that the 3.5 GHz band provides reliable coverage with moderate capacity, making it well-suited for dense urban environments. In contrast, the 28 GHz band despite its limited coverage resulting from higher path loss and weaker diffraction can achieve substantially higher throughput when combined with advanced techniques such as beamforming and massive MIMO [13]. These technologies help mitigate propagation losses by directing transmission energy toward intended users, thereby improving SNR [14].

To quantitatively assess the relationship between SNR and downlink throughput, simulations often employ theoretical models and formulas. A key reference is the Shannon-Hartley capacity formula, which relates the achievable channel capacity CCC to the bandwidth BBB and SNR. In 5G systems, this theoretical capacity is refined to account for practical factors such as modulation and coding efficiency, MIMO layer configuration, and realistic channel conditions [6][7]. MATLAB-based simulations typically estimate throughput by calculating the transport block size (TBS) for each transmission time interval (TTI), which depends on SNR, MCS index, and the number of spatial layers. These models form the theoretical foundation of MATLAB-based analyses, allowing researchers to evaluate how variations in SNR—driven by factors such as frequency, environment, and mobility—translate into differences in downlink throughput performance across diverse 5G deployment conditions [15].

III. MATERIALS AND METHOD

The work follows the process, Input Parameters → Path Loss Calculation to Received Power to SNR to MCS Selection to Throughput Estimation and to Plotting & Comparison. Below are relevant equations used: SNR is a fundamental parameter defined as:

$SNR(linear) = \frac{P_{rx}}{N}$ Or in dB: (1)

$$SNR(dB) = 10log_{10}\frac{P_{rx}}{N} \quad (2)$$

$$N = kTB \times NF \quad (3)$$

Where P_{rx} is Received signal power (W), N is Noise power (W), k is Boltzmann constant (1.38×10^{-23} J/K), T is Temperature (Kelvin, usually 290 K), B is Bandwidth (Hz, here 100 MHz) and NF is Noise Figure (linear). The received power is estimated from the link budget:

$$P_{rx} = P_{tx} + G_{tx} + G_{rx} - PL - L_{misc} \quad (4)$$

Where is P_{tx} is transmit power (dBm), G_{tx} and G_{rx} are transmitting and receiving antenna gains (dBi) respectively, PL is Path loss (dB) and L_{misc} is Miscellaneous losses (e.g., feeder, penetration). Urban Macro (UMa) and Urban Micro (UMi) scenarios use different models, for UMa (LOS) Path Loss and UMa (NLOS) respectively in equations (5) and (6)

$$PL_{LOS}^{UMa} = 28 + 22log_{10}(d) + 20log_{10}(f_c) \qquad (5)$$

$$PL_{NLOS}^{UMa} = 13.54 + 39.08log_{10}(d) + 20log_{10}(f_c) - 0.6(h_{BS} - 1.5) \qquad (6)$$

Where d = distance between UE and gNB (meters), f_c is Carrier frequency (GHz) and h_{BS} is base station height. At a basic level but in 5G systems, throughput also depends on modulation and coding scheme (MCS), resource allocation, and overhead:

$$C = Blog_2(1 + SNR) \qquad (7)$$

Where N_{RE} is number of Resource Elements, R_{MCS} is Code rate, M is modulation order (e.g., QPSK = 4, 16QAM=16, 64QAM=64, 256QAM=256) and T_{slot} is slot duration. You get N_{RE} based on bandwidth and slot configuration (e.g., number of subcarriers × number of symbols × number of slots per frame), the practical Throughput (using MCS and resource elements)

$$T = N_{RE} \times R_{MCS} \times log_2(M) \times \frac{1}{T_{slot}} \qquad (8)$$

Where N_{RE} is number of Resource Elements, R_{MCS} is Code rate, M is modulation order (e.g., QPSK = 4, 16QAM=16, 64QAM=64, 256QAM=256) and T_{slot} is slot duration. You get N_{RE} based on bandwidth and slot configuration (e.g., number of subcarriers × number of symbols × number of slots per frame). MIMO and beamforming provide spatial multiplexing or diversity gain:

$$G_{BF} = 10log_{10}(N_{Tx} \times N_{Rx}) \qquad (9)$$

Where N_{Tx} ,N_{Rx} = Number of transmit and receive antennas and Mobility affects channel estimation and coherence time:

$$f_D = \frac{vf_c}{c} \qquad (10)$$

$$T_c \approx \frac{0.423}{f_D} \qquad (11)$$

Where f_D is doppler shift, v is UE speed (m/s), f_c is carrier frequency (Hz) and c is Speed of light. Table 1 below shows simulation parameters.

TABLE 1: Simulation Parameters

PARAMETER	VALUE / MODEL
Frequency bands	3.5 GHz, 28 GHz
Bandwidth	100 MHz
Channel models	3GPP TR 38.901 UMa, UMi (LOS/NLOS)
MIMO configurations	4×4, 8×8
Antenna gains	15 dBi (3.5 GHz), 25 dBi (28 GHz)
Transmit power	30 dBm
Noise Figure (NF)	7 dB
Temperature (T)	290 K
Modulation schemes	QPSK to 256-QAM
Mobility	0–30 km/h (Doppler modeled)

IV. RESULT AND DISCUSSIONS

The simulation results presented in this section provide a comprehensive evaluation of downlink throughput performance in 5G New Radio (NR) systems operating at 3.5 GHz (sub-6 GHz) and 28 GHz (mmWave) frequency bands, under realistic urban propagation conditions. We analyse key performance metrics across varying link distances, user mobility levels, line-of-sight (LOS) and non-line-of-sight (NLOS) conditions, and MIMO configurations (4×4 and 8×8), with a particular focus on the relationship between Signal-to-Noise Ratio (SNR) and achievable throughput. The results highlight critical trade-offs between coverage, capacity, beamforming gain, and environmental robustness inherent in multi-band 5G deployments. Five principal simulations are discussed, together, these results offer practical insights into the design and optimization of heterogeneous 5G networks, emphasizing the complementary roles of sub-6 GHz and mmWave bands in achieving reliable, high-capacity wireless connectivity.

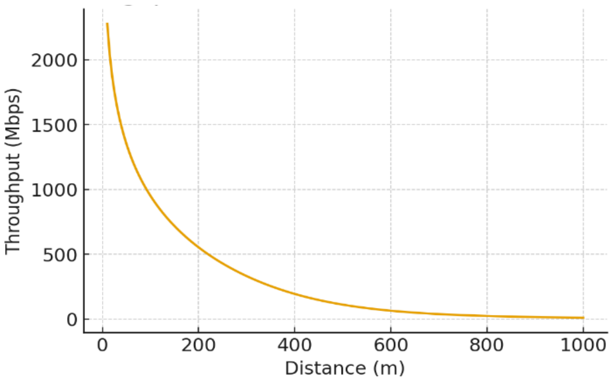

Figure 1: Throughput vs. Distance

The figure 1 shows that throughput at 28 GHz starts extremely high at short distances but drops sharply as distance increases. The reason is because mmWave signals experience severe path loss and blockage sensitivity, high bandwidth and beamforming boost peak throughput near the base station and Beyond 200–300 m, the signal degrades rapidly, reducing SNR and throughput. At this means is that 28 GHz is excellent for hotspots and dense small-cell deployment, it is not suitable as a wide-area coverage layer, confirms the coverage vs capacity trade-off in mmWave networks. The results validate that increasing frequency improves capacity but drastically shortens the coverage radius, requiring denser base-station deployment for reliable downlink performance.

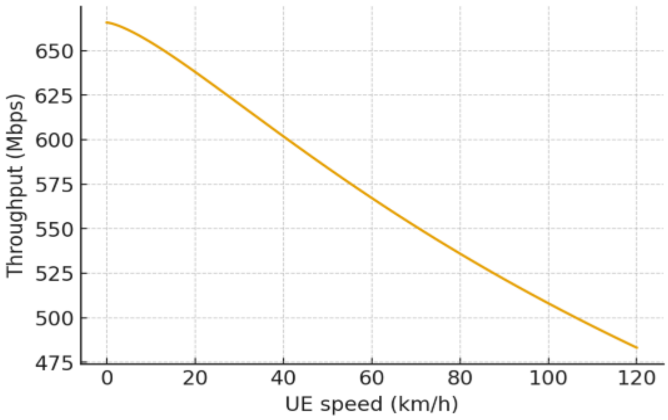

Figure 2: Mobility Impact Throughput vs UE Speed

The figure 2 shows that as UE speed rises, throughput continuously reduces because high velocity creates rapid channel variations, beam alignment and channel estimation become less accurate and packet retransmissions increase due to block errors. What this gives is that mmWave links perform best for low-mobility users like pedestrians or stationery UEs and Performance deteriorates in vehicular scenarios without sophisticated beam-tracking. Mobility introduces Doppler shift and fast channel dynamics, causing throughput degradation that must be compensated by advanced beam tracking and multi-connectivity with sub-6 GHz.

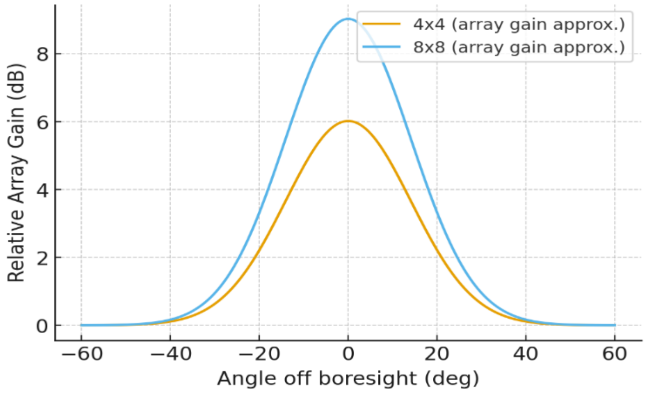

Figure 3: Beamforming Gain Comparison: 4×4 vs. 8×8 Arrays

The figure 3 shows an 8×8 beamforming has higher peak gain, The beam is narrower, meaning stronger directivity. The implications of this is that Higher gain equals better SNR and throughput in aligned conditions and narrow beams are more fragile under mobility or direction error. The trade-off between the two MIMO array is that for 4×4 MIMO Wider beam means more robust to mobility also lower peak gain and 8×8 MIMO, Narrower beam requires accurate alignment and higher SNR in ideal LOS. The results demonstrate that larger antenna arrays enhance link budget but demand precise beam management, revealing implementation complexity in real networks.

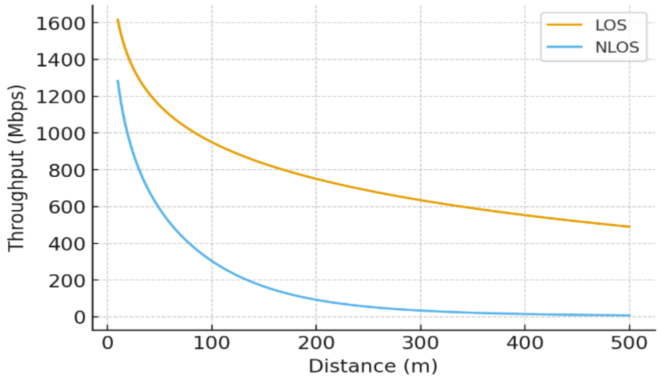

Figure 4: LOS vs NLOS Performance at 28 GHz

From figure 4 it is observed that LOS curve remains high throughput up to ~300 m while NLOS throughput collapses rapidly (almost unusable beyond ~150 m) because Buildings, trees, even the human body cause severe attenuation, NLOS causes diffuse scattering instead of direct propagation. It Implies that mmWave requires Dense small cells, reflections-aware beam searching and Fallback to sub-6 GHz. NLOS fragility confirms the need for hybrid architectures and intelligent beam steering for robust mmWave access in urban scenarios.

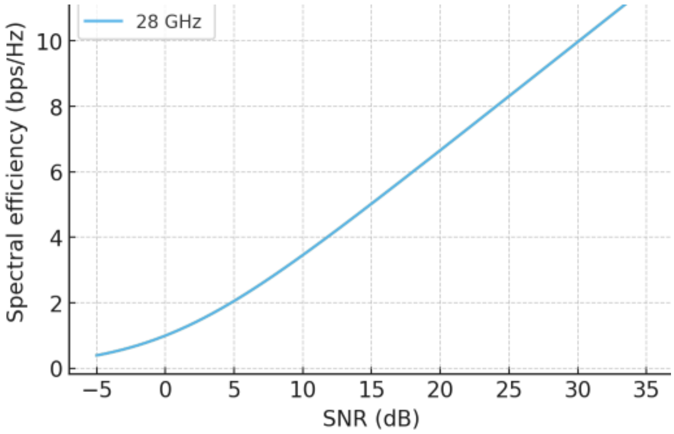

figure 5: Spectral Efficiency vs SNR

Both bands follow the same Shannon trend which is higher SNR to higher efficiency (up to modulation limits). What this in practice means is that 28 GHz achieves much higher throughput only because it supports wider bandwidth (e.g., 100 MHz–2 GHz) and it allows more MIMO layers in LOS. Frequency does not directly improve spectral efficiency. The advantage of mmWave originates from abundant bandwidth and beamformed spatial multiplexing.

The five figures collectively verify that mmWave frequencies deliver exceptional peak capacity but with short-range, direction-dependent, and mobility-sensitive performance. LOS conditions and large antenna arrays are essential for sustained operation, while NLOS and mobility reduce link reliability. This validates the necessity of advanced resource allocation techniques, water-filling optimization, and hybrid multi-band deployments to balance coverage, energy efficiency, and spectral efficiency in future green wireless networks.

V. CONCLUSION

This study presents a comparative performance evaluation of 5G New Radio (NR) downlink throughput in the sub-6 GHz (3.5 GHz) and millimeter-wave (28 GHz) frequency bands under realistic urban propagation conditions as defined by the 3GPP TR 38.901 standard. Through a MATLAB-based simulation framework incorporating Urban Macro (UMa) and Urban Micro (UMi) channel models, MIMO configurations (4×4 and 8×8), and practical link budgeting, the work quantifies the critical trade-offs between coverage, capacity, mobility robustness, and beamforming efficiency. The results clearly demonstrate that while the 28 GHz band offers significantly higher peak throughput under favorable Line-of-Sight (LOS) conditions due to wide bandwidth and high beamforming gain, its performance is severely constrained by distance, mobility, and NLOS blockages. Path loss and atmospheric absorption at mmWave frequencies lead to rapid throughput degradation beyond 200–300 meters, rendering it unsuitable for wide-area coverage. In contrast, the 3.5 GHz band provides more consistent and reliable connectivity over longer distances, with superior resilience to user mobility and non-ideal channel conditions, making it ideal for broad urban coverage.

Furthermore, the analysis reveals that 8×8 MIMO beamforming enhances SNR and throughput through higher directional gain, but at the cost of increased sensitivity to beam misalignment and rapid channel variations caused by mobility. While 4×4 MIMO offers a more robust and stable link under dynamic conditions, it sacrifices peak data rates. Additionally, spectral efficiency was shown to be fundamentally dependent on SNR rather than carrier frequency, with the capacity advantage of mmWave stemming primarily from greater bandwidth availability and spatial multiplexing gains in LOS scenarios. These findings underscore the necessity of a hybrid network architecture that strategically combines the coverage strength of sub-6 GHz with the high-capacity potential of mmWave. Effective deployment will require intelligent beam management, dynamic handover mechanisms, and multi-connectivity solutions to maintain seamless service across diverse environments.

In conclusion, this work provides valuable insights into the real-world performance dynamics of 5G NR across key frequency bands, offering a solid foundation for network planners and system designers in optimizing future 5G and beyond networks for both performance and reliability. Future work can extend this framework to include interference modeling, multi-user scenarios, and energy efficiency analysis for green 5G deployments.

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