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Analysis of Spectrum Allocation and Bandwidth Optimization in 5G-Advanced Networks

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Abstract

This paper provides a comprehensive technical investigation into the frequency spectrum utilization of 5G New Radio (NR) and 5G-Advanced systems. As the demand for multi-gigabit throughput increases, the transition from Frequency Range 1 (FR1) to Frequency Range 2 (FR2) presents unique challenges in wave propagation and signal processing. This study analyses the mathematical foundations of Path Loss, the application of the Shannon-Hartley theorem to wideband channels, and the role of Massive MIMO in mitigating high-frequency attenuation.

Introduction

The global deployment of 5G-Advanced (3GPP Release 18 and beyond) marks a pivotal shift in how electromagnetic spectrum is managed [1]. Unlike previous generations that relied on narrow slivers of sub-3 GHz spectrum, 5G utilizes a layered spectrum approach [4]. The primary objective is to balance the physical trade-off between coverage and capacity. This paper explores the three-tier hierarchy: the Coverage Layer (Low-band), the Capacity Layer (Mid-band), and the High-Throughput Layer (mmWave), providing a rigorous mathematical treatment of their performance metrics.

1. Mathematical Foundation of Frequency Propagation

As 5G shifts toward higher frequencies, the physical behaviour of the radio wave changes significantly due to diffraction loss and atmospheric absorption [2].

1.1 Free Space Path Loss (FSPL)

The reduction in power density of an electromagnetic wave as it propagates through space is governed by the Free Space Path Loss model [5]. In decibels (dB), the formula is expressed as:

$$FSPL(dB) = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right)$$

Where:

- d is the distance between the transmitter and receiver in meters.
- f is the frequency in Hertz.
- c is the speed of light ($\approx 3 \times 10^8 \frac{\text{m}}{\text{s}}$).

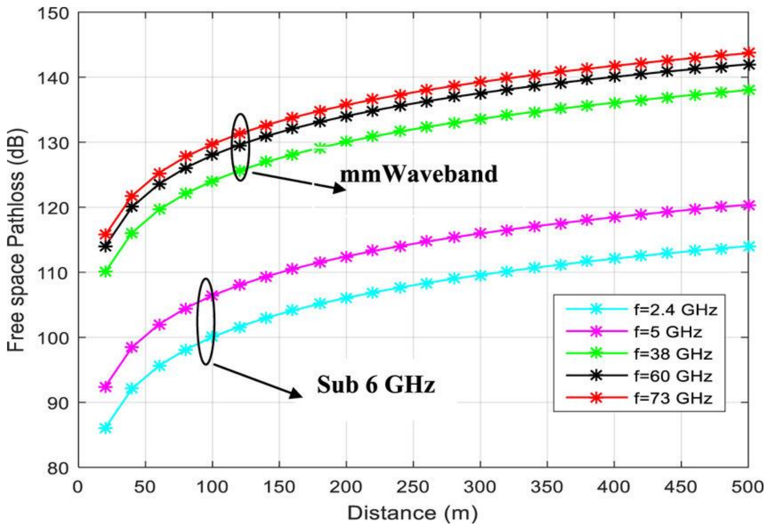


Figure 1: Free Pathloss versus distance. (Free space path loss model at both mmWave bands and sub 6 GHz).

Engineering Implication: According to this logic, a signal at 28 GHz (mmWave) experiences approximately 21.5 dB more loss than a signal at 2.4 GHz over the same distance, purely due to the physics of the frequency. This necessitates the use of high-gain directional antennas[5].

2. Bandwidth Theory and Channel Capacity

The primary driver for moving to the millimeter-wave (mmWave) spectrum is the availability of massive contiguous bandwidth [3].

2.1 The Shannon-Hartley Theorem

The maximum theoretical data rate (Capacity, C) of a 5G channel is limited by the bandwidth (B) and the signal-to-noise ratio (SNR).

$$C = B \log_2(1 + SNR)$$

In 5G-Advanced, B can reach up to 400 MHz in a single component carrier, compared to the 20 MHz limit in standard 4G LTE.

2.2 Bandwidth Efficiency and Symbol Rate

The actual bit rate is also influenced by the Modulation and Coding Scheme (MCS). For a 256-QAM system, the number of bits per symbol is 8 ($\log_2(256)$). The relationship between the symbol rate (R_s) and the bit rate (R_b) is:

$$R_b = R_s \cdot \log_2(M) \cdot \rho$$

Where:

- M is the modulation order (e.g., 256).
- ρ is the code rate (accounting for error correction overhead).

3. Frequency Range Categorization (FR1 vs. FR2)

3GPP identifies two distinct frequency ranges that define the 5G ecosystem [1].

3.1 Frequency Range 1 (FR1): Sub-7 GHz

- To overcome propagation losses, 5G utilizes Massive MIMO and beamforming gain [7].
- **Carrier Bandwidth:** 5 MHz to 100 MHz.
- **Sub-Carrier Spacing (SCS):** 15, 30, or 60 kHz.
- **Primary Advantage:** Excellent balance between signal penetration and data speed.

3.2 Frequency Range 2 (FR2): Millimeter Wave (mmWave)

FR2 covers the 24.25 GHz to 71 GHz range.

- **Carrier Bandwidth:** 50 MHz to 400 MHz.
- **Sub-Carrier Spacing (SCS):** 60, 120, or 240 kHz.
- **Primary Advantage:** Extremely low latency and multi-gigabit speeds, though limited to line-of-sight (LOS) conditions.

4. Mitigating Path Loss via Antenna Array Gain

To overcome the losses calculated in Section 2.1[FSL], 5G utilizes Massive MIMO (Multiple Input Multiple Output). By increasing the number of antenna elements (N), we create "Beamforming Gain."

The total gain (G_{array}) of a phased array antenna is calculated as:

$G_{array} = 10\log_{10} N + G\text{e}$

Where:

- N is the number of antenna elements.
- G_e is the gain of a single antenna element.

Example: A 5G base station with a 256-element array can provide a 24 dB gain, which effectively cancels out the path loss disadvantage of moving from low-band to mmWave frequencies.

Parameter	*Low-Band (Sub-1 GHz)*	*Mid-Band (3.5 - 7 GHz)*	*High-Band (24 GHz+)*
Typical Bandwidth	10 - 40 MHz	60 - 100 MHz	100 - 400 MHz
Max Throughput	~200 Mbps	~1.5 Gbps	10+ Gbps
Cell Radius	5 - 15 km	1 - 3 km	100 - 300 meters
Primary Challenge	Spectrum Scarcity	Interference Management	Atmospheric Blocking

5.SPECTRUM CATEGORIZATION

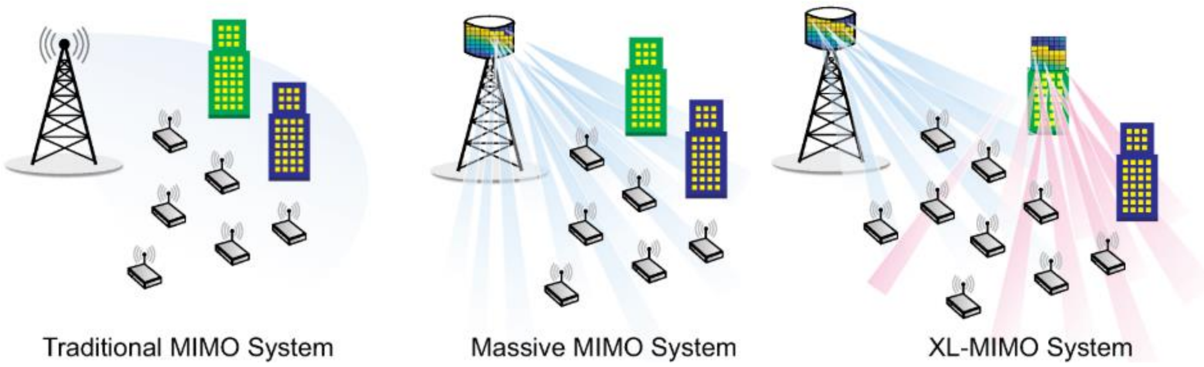
5.1. Comparative Analysis of FR1 and FR2

The **6 GHz** Debate A critical focus in 2026 is the **6 GHz** band (5.925–7.125 GHz). This "mid-band" spectrum is essential for providing the "**goldilocks**" zone—offering both the coverage of low-band and the capacity of high-band.

Feature	*FR1 (Sub-7 GHz)*	*FR2 (mmWave)*
Frequency Range	410 MHz – 7.125 GHz	24.25 GHz – 71 GHz
Max Channel Bandwidth	100 MHz	400 MHz
Sub-Carrier Spacing	15, 30, 60 kHz	60, 120, 240 kHz
Deployment Scenarios	Macro Cells (Rural/Urban)	Small Cells (Stadiums/Dense Urban)
Building Penetration	High	Extremely Low

6.ANTENNA DYNAMICS & BEAMFORMING

Massive MIMO and Beamforming Gain To counteract the path loss described in Section 2.1, 5G base stations use Massive MIMO (Multiple Input Multiple Output).



6.1 Mathematical Array Gain By using an array of N antennas, the base station can focus energy into a narrow beam, increasing the effective power at the receiver without increasing total output power.

$G_{Array} \approx 10 \log_{10} N$

For an array with 256 elements ($N = 256$):

$G_{Array} = 10 \log_{10}(256) \approx 24\ dB$

This 24 dB gain effectively nullifies the 21 dB path loss disadvantage of mmWave frequencies compared to 2.4 GHz, allowing mmWave to function over short distances (300m).

7. NR NUMEROLOGY AND ORTHOGONALITY for 5G

Scalable OFDM Numerology

A defining feature of 5G New Radio (NR) that separates it from 4G is "Scalable Numerology." In 4G, sub-carrier spacing (SCS) was fixed at 15 kHz. 5G allows the SCS to scale with the frequency to handle the physics of different bands.

7.1 The Mathematical Scaling of SCS

The sub-carrier spacing is defined by the formula:

$$\Delta f = 15 \times 2^{\mu} \quad kHz$$

Where μ is the numerology power (0, 1, 2, 3, 4).

- $\mu = 0$ **(FR1):** 15 kHz spacing. Standard coverage.
- $\mu = 3$ **(FR2):** 120 kHz spacing. Massive bandwidth.

7.2 Impact on Cyclic Prefix (CP) and Latency

As the spacing Δf increases, the symbol duration (T_s) decreases because $T_s = 1/\Delta f$.

- In FR1 (15 kHz), the symbol duration is approximately **66.7 µs**.
- In FR2 (120 kHz), the symbol duration drops to **8.33 µs**.

This mathematical reduction in symbol time is the primary reason why high-frequency 5G bandwidths achieve lower latency.

8.LATENCY ANALYSIS AND INTERFERENCE

Mathematical Modeling of Latency

The total End-to-End (E2E) latency in a 5G network $\tau_{total}$is a summation of several technical components:

$$\tau_{total} = \tau_{air} + \tau_{proc} + \tau_{queue} + \tau_{backhaul}$$

Where:

- τ_{air}: Time of flight and TTI (Transmission Time Interval).
- τ_{proc}: Base station and User Equipment (UE) processing time.

In 2026, 5G-Advanced utilizes **mini-slots**, which allow a transmission to start immediately rather than waiting for a full 14-symbol slot. This reduces $\tau_{air}$to less than **1 ms** in URLLC (Ultra-Reliable Low

9. Interference Management in Dense 5G Spectra

With the use of the 6 GHz and mmWave bands, Signal-to-Interference-plus-Noise Ratio (SINR) becomes the limiting factor. The SINR is modeled as:

$$SNIR = \frac{P \cdot G}{I + N}$$

Where:

- P: Transmit power.
- G: Channel gain (including beamforming).
- I: Interference from neighboring small cells.
- N: Thermal noise ($N = kTB$).

In the dense urban deployments, I (Interference) is the dominant variable. 5G-Advanced solves this using **Coordinated Multi-Point (CoMP)**, where multiple base stations coordinate their frequencies to "null" interference for a specific user.

CONCLUSION

The 2026 Spectrum Landscape: 5G-Advanced and Beyond

The analysis presented in this paper demonstrates that 5G bandwidth and frequency spectrum management is a delicate balance of physics and information theory. While the Shannon-Hartley theorem promises massive capacity at higher bandwidths, the Free Space Path Loss model imposes strict physical limits on range.

As of 2026, the focus has shifted toward the integration of Non-Terrestrial Networks (NTN)—using 5G bandwidth via satellites—and the opening of the Sub-THz bands (100 GHz - 300 GHz) for early 6G research[5].

The success of 5G-Advanced in 2026 relies on:

1. **Massive MIMO** to provide the necessary array gain ($24 + dB$).
2. **Flexible Numerology** to minimize latency ($< 1\ ms$).
3. **Spectrum Harmony** between the coverage of FR1 and the extreme capacity of FR2.

As we look toward the end of the decade, the mathematical frameworks established for 5G spectrum utilization will serve as the foundation for the Terahertz (THz) communications of the 6G era.

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