Large-Scale MIMO in Sub-6 GHz and mmWave Wireless Networks: Practical Considerations and Use Cases

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Abstract

Base stations (BSs) and access points (APs) that have a large number of antennas, referred to as Massive Multiple-Input Multiple-Output (mMIMO), play a crucial role in increasing the capacity of 5G, 6G and future network generations. Although it is developed enough for sub-6 GHz frequencies, mMIMO is also very effective for millimeter wave (mmWave) frequency band. The mMIMO implementation in different frequency bands varies greatly because of the distinct propagation patterns and underlying hardware features of each band. This article provides a thorough analysis of these inequalities and both frequency band's tangible effects, while debunking common misunderstandings.

Ⅰ. Introduction

Large antenna arrays at base stations improve beamforming and spatial precision, allowing mMIMO to multiplex several users. With efficient channel state information (CSI) collection, mMIMO improves spectral efficiency over its predecessors. With 3GPP's development, LTE already has up to 64 antennas, enabling 5G's mMIMO [1]. Using mm Wave bands provides bandwidth over 30 GHz to complement sub-6 GHz frequencies. Despite increased path-loss in mmWave, the uniformity of antenna array size in mMIMO mitigates these challenges. However, the design and deployment of mMIMO varies between sub-6 GHz and mmWave owing to differences in propagation phenomena, hardware limits, and signal processing requirements. This article examines propagation variances, hand offs vs performance trade-offs, and user connectivity across the two bands to maximize their usage in developing networks.

Ⅱ. Channel propagation & Signal Processing

For mMIMO systems up to mmWave bands, understanding electromagnetic propagation reveals channel characteristics vital for network design. Path-loss, shadowing, and multi-path effects are frequent in sub-6 GHz channels, although mMIMO channels are gradually researched, highlighting the limits of i.i.d. Rayleigh fading models employed for simplicity and analytical advantages [2]. Channels include spatial correlation and line-of-sight components, which impact interference and reduce channel hardening with larger antennas. Effective beamforming may need dispersed arrays at both ends to meet these problems [3]. Blocking, diffraction reduction, and frequency-specific absorption make mmWave frequencies difficult, affecting outdoor-to-indoor coverage and link budget. Given that rapid fluctuations at higher frequencies, small-scale fading differences need more frequent channel estimates. Channel modeling and system design are crucial for mMIMO deployment and optimization in many frequency bands because to these propagation characteristics.

III. Deployment & Use Case of mmave and sub-6G Frequency Band

Channel coefficient count increases linearly with antenna number in mMIMO systems. More antennas, subcarriers, or lower coherence time increase complexity. Exploiting multi-path sub-6 GHz channels with linked coefficients for enhanced estimate is complicated. Hardware implementation and TDD mode with channel reciprocity reduce overhead. Line-of-sight and minimal reflections in mmWave channels enable more efficient parameterized estimation, concentrating on angular rather than individual coefficients. When targeting single data-streams or hybrid beamforming, this streamlines the operation, but the latter narrows the "vision" and requires beam-sweeping to maintain connections or locate users, raising overhead proportionately with antenna count. TDD suited sub-6 GHz, although frequency-division-duplex (FDD) may assist mmWave owing to the reciprocal nature of angular parameters across vast bandwidths [1]. This shows how mMIMO channel estimate trade-offs change as systems size and frequencies climb.

Despite 30-40% yearly data traffic increases, macro-cells often serve just a few users owing to network densification, particularly in congested locations with short inter-base station distances. Ultra-reliable low latency communication (URLLC) and massive machine-type communications (mMTC) for different IoT applications are predicted to significantly grow user numbers. Sensors, driverless cars, drones, and augmented reality need far more capacity from networks. This requires upgrading macro-cell base stations for many users and placing short-range base stations in high-traffic locations. Sub-6 GHz mMIMO increases macro-cell throughput, provides consistent quality service, and supports user mobility, whereas mmWave bands give high bandwidth for fixed wireless access but have limited outdoor-to-indoor propagation and blockage difficulties. Sub-6 GHz mMIMO enhances coverage and capacity in high-density hotspots, whereas mmWave offers extreme throughput owing to shorter distances and high bandwidth, making it appropriate for auditoriums and stadiums despite its rapid channel development [2]. Therefore, network infrastructure must evolve to accommodate these developments.

IV. Moblity Management & Integration of mmWave and sub-6G

The challenges of ensuring URLLC amplify with user mobility. Mobile users, especially high-speed ones like autonomous vehicles or drones, face increased handovers in small cells, raising latency and handover failures. These frequent transitions also lead to excessive power consumption for cell discovery and depleted battery life. Moreover, maintaining bounded latency in dense networks with mobile users is difficult due to congestion and queuing delays at sub-6G frequencies, leading to inefficient resource use and limited bandwidth for stationary users. Even with MAC-layer integration of mmWave and sub-6G technologies at small base stations, performance issues persist, particularly under dense user conditions. While mmWave networks struggle with reliability, sub-6G networks fail to meet latency requirements in crowded environments [1]. However, a joint traffic management strategy for mmWave and sub-6G can significantly enhance overall network reliability.

Envision a compact base station with 40 dBm of transmit power integrating mmWave and sub-6G RATs at the MAC-layer. Downlink traffic packet sizes are 20 kbits, and the TTI time is 1 ms (as per standard of LTE). The mmWave spectrum has 1 GHz of usable bandwidth, whereas the sub-6G band has 10 MHz. Both 10 ms and 20 ms delay kinds of traffic are taken into consideration. Within the cell coverage, users are spread evenly, and each user is assigned a single traffic type at random. See Fig. 1 and 2 for mmWave and Sub-6GHz network performance as users and distance increase.

V. Conclusion

This paper compares sub-6 GHz and mmWave mMIMO architecture and implementation, including propagation, hardware, and signal processing. Both bands have signal connection issues despite computational advances, offering distinct 5G and beyond prospects. The installation and future possibilities of mMIMO are unclear. The advancement of mMIMO is expected to transform user connection, cloud-RAN, and environmental sensing. mMIMO has great potential to impact future wireless networks, with many fascinating possibilities.

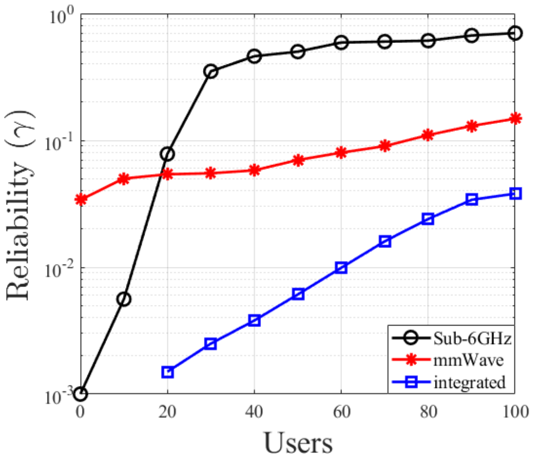

Fig. 1 Reliability comparison of Integrated mmWave and sub6GHz versus standalone mmWave and sub-6GHz.

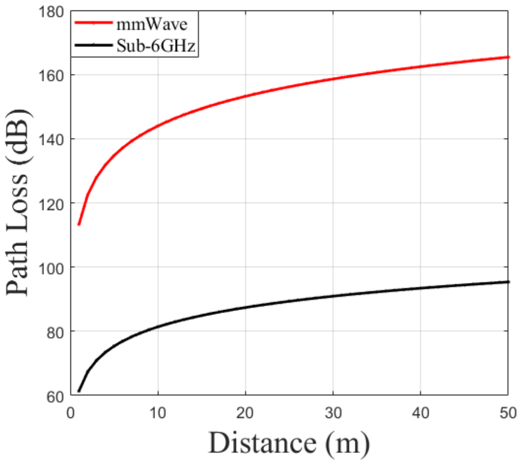

Fig. 2 Path-Loss comparison of mmWave and Sub-6GHz for dense urban area

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