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Advance Beamforming And Beam Steering For Seamless User Association From Sub-6ghz To Mmwave Tiers

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Abstract
The swift development of wireless communication technology calls for creative solutions to satisfy the growing need for dependable, fast connectivity. This research explores sophisticated beamforming and beam steering methods for smooth user association in dual-tier 5G networks that combine millimeter-wave (mmWave) and Sub-6GHz frequency bands. While mmWave bands offer noticeably better data speeds in limited, line-of-sight contexts, sub-6GHz bands offer solid connectivity and extensive coverage. Optimizing user association to balance coverage and capacity is a major difficulty in this design, especially considering mmWave signals' limited range and significant path loss. This study assesses throughput performance and user association techniques throughout the dual-tier network using MATLAB-based simulation and mathematical modeling. In order to improve signal strength and guarantee dynamic adaptation to user mobility and network circumstances, beamforming and beam steering are used. The findings show that combining these methods increases throughput and user association efficiency, with mmWave users enjoying noticeably faster data rates and Sub-6GHz users enjoying wider coverage. The results emphasize how crucial sophisticated signal processing techniques and perceptive user association mechanisms are to optimizing dual-tier 5G networks' performance. This work establishes the groundwork for advancements in beyond-5G and 6G networks by tackling the trade-offs between coverage and capacity. It also offers useful insights for developing future wireless communication systems.
Keywords: *User Association, Beamforming, Beam Steering, Throughput, Sub-6GHz and MmWave*

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I. Introduction

In order to meet the growing need for high data rates and seamless connectivity, more reliable and efficient systems are required as a result of the wireless communication technologies' explosive rise [1]. A key component of contemporary telecommunication, fifth-generation (5G) networks seek to achieve previously unheard-of performance levels with innovations including dual-tier systems that combine millimeter-wave (mmWave) and Sub-6GHz frequency bands. These technologies are made to meet the various needs of rural, suburban, and urban settings. Because of their superior propagation characteristics and reduced vulnerability to environmental impediments, sub-6GHz frequency bands—which are distinguished by their narrower frequency range—offer dependable coverage over wider distances. However, it is difficult for them to meet the increasing data demands of bandwidth-intensive applications due to their low bandwidth. On the other hand, mmWave bands have much higher bandwidth and throughput potential, which makes them appropriate for high-density urban settings and applications that need to send data extremely quickly. However, despite these benefits, mmWave signals have restricted range, increased path loss, and increased sensitivity to obstructions, which means that creative solutions are needed for successful deployment.

Beamforming and beam steering have become essential methods for improving the performance of mmWave and Sub-6GHz networks. While beam steering dynamically modifies the beam's direction to ensure optimal connectivity with mobile users, beamforming concentrates the signal in specified directions, increasing signal strength and decreasing interference. These methods allow for smooth user association throughout the Sub-6GHz and mmWave tiers and effective use of spectrum resources. In order to maximize network performance, user association—the act of matching users with the best base station or frequency tier—is essential. Networks can strike a balance between coverage and capacity by judiciously grouping users according to factors including signal strength, available bandwidth, and user needs. Furthermore, advanced algorithms for user association can dynamically adapt to changing network conditions, ensuring optimal performance in real-time.

In order to facilitate smooth user association across Sub-6GHz and mmWave tiers, this work focuses on the application and analysis of sophisticated beamforming and beam steering algorithms. The study assesses how different methods affect user association, throughput, and overall network performance by utilizing mathematical modeling and simulation. The results address the difficulties in striking a balance between coverage, capacity, and connectivity and offer insightful information for the design and optimization of next-generation wireless networks. Sub-6GHz and mmWave tiers are combined to provide a dual-tier network that can provide reliable and effective communication services. The foundation for wide coverage is provided by sub-6GHz frequencies, which guarantee dependable communication for users in non-line-of-sight (NLOS) situations or over long distances. However, in localized, line-of-sight (LOS) situations, like highly populated areas or urban hotspots, mmWave frequencies are used for high-capacity services. These frequency bands' complementing qualities highlight how crucial intelligent user association methods are.

Managing user association effectively to optimize network utility is a major difficulty in this dual-tier architecture. Choosing the right tier requires striking a balance between a number of variables, including interference levels, user mobility, available bandwidth, and signal-to-noise ratio (SNR). By strengthening signals and directing energy in the right directions, beamforming and beam steering greatly aid in overcoming these obstacles. By specifically addressing the range and reliability constraints of mmWave systems, these strategies allow for improved performance in both tiers. In contemporary networks, user association choices are intimately related to user throughput, a crucial performance indicator. Although users of sub-6GHz enjoy greater coverage, their throughput is reduced because of the constrained bandwidth. However, as long as they stay within range and have a clear line of sight to the base station, mmWave users benefit from faster data speeds. In order to guarantee optimal performance for a variety of applications, this study highlights the significance of developing adaptive systems that dynamically move users between tiers based on current conditions.

This research attempts to close the gap between theoretical developments and real-world applications in 5G networks by investigating sophisticated beamforming and user association techniques. The outcomes will pave the path for advancements in beyond-5G and 6G networks by improving the capacity, efficiency, and dependability of wireless communication systems.

II. Related Literature

A key component of contemporary 5G networks is the merging of Sub-6GHz and mmWave tiers, which provides a balance between capacity and coverage. Prior research has emphasized the function of dual-tier structures in accomplishing these goals. To satisfy the varied needs of users in different environments, [2] for example, gave a thorough overview of 5G network design, stressing the significance of combining both Sub-6GHz and mmWave frequencies. Similar to this, [3] addressed important issues including route loss and restricted range to show that mmWave communications are feasible in mobile networks. It is commonly acknowledged that beamforming and beam steering are crucial methods for maximizing the performance of wireless networks. In their discussion of sophisticated signal processing methods for millimeter-wave MIMO systems, [4] emphasized the advantages of beamforming in terms of increasing signal strength and lowering interference. Digital and hybrid analog-digital beamforming techniques were examined by [5], who showed the benefits of each in multiuser settings. These investigations highlight how beamforming and beam steering can be used to overcome the particular difficulties presented by mmWave systems.

Another crucial area of study for 5G networks is user association. By using multi-slope path loss models to evaluate user association strategies in cellular networks, [6] shed light on the variables affecting user association choices. In order to balance load and maximize throughput, [7] introduced algorithms for optimizing user association and power allocation in mmWave networks. In order to guarantee smooth connectivity and ideal network performance, these studies emphasize the necessity of clever user association techniques. Numerous studies have been conducted on user throughput in dual-tier networks in relation to resource allocation and network optimization. Tse and Viswanath (2005) and Goldsmith (2005) [8][9] offered fundamental frameworks for modeling wireless communication systems, which included estimating throughput using the Shannon capacity method. These studies constitute the foundation for assessing the coverage and data rate performance of the mmWave and Sub-6GHz tiers. In order to maximize dual-tier 5G networks, the research now in publication emphasizes the significance of combining sophisticated beamforming, beam steering, and user association techniques. By applying and evaluating these methods using mathematical modeling and simulation, this study expands on these frameworks and offers fresh perspectives on how they affect user association and throughput.

III. Mathematical Framework

We model network user association with several frequency bands (sub-6 GHz and mmWave) using a number of mathematical components in the simulation code. The main formula derivations utilized for the work are described in detail below:

Signal-to-Noise Ratio (SNR): The Signal-to-Noise Ratio is used to evaluate the quality of the received signal.

$$SNR = \frac{P_r}{N} \tag{1}$$

Where P_r is Received signal power (in watts or dBm) and N is Noise power (in watts or dBm), The received power P_r can be expressed as:

$P_r = P_t \times G_t \times G_r \times (\frac{\lambda}{4\pi d})^2$ (2)

Where P_r is transmit power, G_t *and* G_r are gains of the transmitter and receiver antennas respectively, λ is Wavelength of the signal and d is distance between the transmitter and receiver. The noise power (N) is given by:

$N = k \times T \times B$ (3)

Where k is Boltzmann constant (1.38×10−23 J/K), T is System temperature (in Kelvin) and B is the Bandwidth (in Hz) and Combining these, the SNR is:

$\text{SNR} = \frac{P_t \times G_t \times G_r \times (\frac{\lambda}{4\pi d})^2}{k \times T \times B}$ (4)

User Throughput: User throughput quantifies the data rate achievable by a user.

$\text{Throughput} = \text{B} \times log_2(1 + SNR)$ (5)

From the Shannon-Hartley theorem we have that Channel capacity (bits per second, bps)

$C = \text{B} \times log_2(1 + SNR)$ (6)

Where C is our Channel capacity (bits per second, bps), B remains Bandwidth of the channel (Hz) and SNR also is Signal-to-noise ratio, Throughput assumes perfect adaptation of modulation and coding schemes to the SNR, making the achievable rate equal to the channel capacity.

Beamforming Gain: Beamforming enhances signal strength in a particular direction.

$G_b = n \times \eta$ (7)

Where n is Number of antenna elements, and η (etaη) is Efficiency factor (typically between 0.8 and 1), Beamforming gain arises from constructive interference of signals from multiple antennas. The gain is proportional to the number of antennas, as each element contributes its share of power toward the target direction.

Path Loss: Path loss models the attenuation of the signal over distance.

$PL = 10 \times log_{10} (\frac{(4\pi df)^2}{c^2})$ (8)

Where PL is Path loss (in dB), d is distance (in meters), f is carrier frequency (in Hz), c is Speed of light (3×10^8 m/s), Path loss is derived from the Friis transmission equation. It relates the received power to the transmitted power while accounting for distance and frequency.

User Association Decision: The user association decision balances between SNR and available bandwidth.

$\text{Association Metric} = \frac{SNR \times B_{tier}}{Load_{tier}}$ (9)

Where B_{tier} is Bandwidth available in the tier (Sub-6GHz or mmWave), $Load_{tier}$ is Number of users currently associated with the tier, Better signal quality is guaranteed by higher SNR. Higher throughput is correlated with more bandwidth. Better performance results from less resource-sharing penalties brought on by lower load. The tier that optimizes this measure is the one that the user is associated with.

Composite Coverage Probability: For a dual-tier network, the composite coverage probability is given by:

$P_{coverage} = 1 - \prod_{i=1}^{2}(1 - P_{coverage,i})$ (10)

Where $P_{coverage,i}$ is Coverage probability of tier iii (Sub-6GHz or mmWave), The likelihood of not having coverage in both tiers is calculated by multiplying the likelihood of not having coverage in each tier. The likelihood of being covered by at least one tier is given by the complement of this. For assessing user association, throughput, and performance in dual-tier networks, these derivations offer a mathematical basis.

Table 1: Simulation Parameters

Parameter	Value
Sub-6GHz frequency	2.5GHz
mmWave frequency	28GHz
Sub-6GHz bandwidth	20MHz
mmWave bandwidth	100MHz
Sub-6GHz BS transmit power	30 dBm
mmWave BS transmit power	40dBm
Number of users	20
Number of base stations	2

IV. Results And Discussion

User Association: The base station with the strongest signal strength (RSSI) is linked to each user. A number of variables, including base station power, frequency, and distance, affect the connection. Because there is less route loss, users who are closer to a base station typically receive stronger signals. Higher transmit power at a base station (mmWave in this case) can help boost signal strength. Sub-6GHz signals are better suited for users who are farther away from the base stations since they have less route loss over distance than mmWave. Users connected to Sub-6GHz are displayed in blue in the scatter plot in figure 2 below, while users connected to mmWave are displayed in green. Users are visually identified by lines that connect them to the base stations they are associated with.

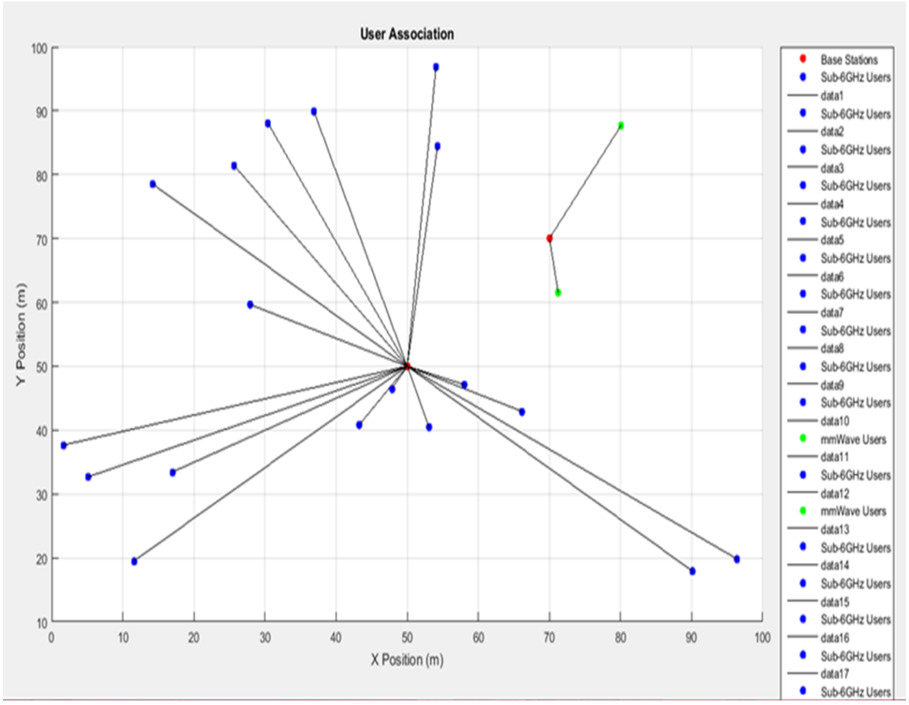

Figure 2: User Association

Throughput: The theoretical maximum throughput is determined by the Shannon capacity formula, which takes into account both the bandwidth and the signal-to-noise ratio. Compared to Sub-6GHz (20 MHz), mmWave has a larger bandwidth (100 MHz), which could allow for higher throughput. The user's distance and path loss affect signal strength (and consequently SNR). Users' throughput and the tier they belong to are displayed in Table 1 below.

Table 1: Users Throughput and Tier Association

User	Associated Tier	Throughput (Mbps)
1	Sub-6GHz	463.28
2	Sub-6GHz	470.23
3	Sub-6GHz	471.39
4	Sub-6GHz	478.15
5	Sub-6GHz	571.23
6	Sub-6GHz	561.50
7	Sub-6GHz	467.58
8	Sub-6GHz	472.62
9	Sub-6GHz	554.02
10	Sub-6GHz	490.19
11	mmWave	2656.19
12	Sub-6GHz	469.27
13	mmWave	2405.68
14	Sub-6GHz	474.31
15	Sub-6GHz	613.28
16	Sub-6GHz	482.43
17	Sub-6GHz	479.28
18	Sub-6GHz	529.20
19	Sub-6GHz	486.57
20	Sub-6GHz	511.15

The theoretical maximum throughput is determined by the Shannon capacity formula, which takes into account both the bandwidth and the signal-to-noise ratio. Compared to Sub-6GHz (20 MHz), mmWave has a larger bandwidth (100 MHz), which could allow for higher throughput. The user's distance and path loss affect signal strength (and consequently SNR). Users' throughput and the tier they belong to are displayed in Table 1 below.

The code interprets the output for each user and outputs the tier (Sub-6GHz or mmWave) to which the user belongs. It also displays the user's throughput in Mbps. All things considered, mmWave offers substantially higher throughput but is best suited for users in close proximity to the base station because to its limited range and susceptibility to route loss, whereas Sub-6GHz is best for wide coverage and supporting users far from the base station. Table 3 lists the benefits and drawbacks of the mmwave and sub-6GHz tiers.

Table 3: Trade-offs Between Sub-6GHz and mmWave Tiers

Tier	Advantages	disadvantages
Sub-6GHz	• Greater coverage due to lower frequency and better propagation characteristics. • More reliable connectivity for users at longer distances. • Suitable for non-line-of-sight (NLOS) scenarios, such as urban environments with obstacles.	• Limited bandwidth, resulting in lower potential throughput. • Congestion issues in densely populated areas due to shared spectrum usage.
mmWave	• Higher available bandwidth, enabling significantly higher throughput. • Suitable for high-data-rate applications like streaming, virtual reality, and industrial IoT.	• Limited range and higher path loss due to high frequencies. • Susceptible to obstacles (e.g., buildings, foliage) and weather conditions (e.g., rain fade). • Primarily effective in line-of-sight (LOS) scenarios.

In 5G networks, the dual-tier approach (Sub-6GHz + mmWave) is frequently employed for applications in order to balance capacity and coverage. Whereas mmWave serves urban hotspots or locations with high user activity, sub-6GHz guarantees connectivity in remote or rural locations. Furthermore, by directing energy toward users, sophisticated methods like beamforming and beam steering can be incorporated to improve mmWave coverage and get around some distance and obstacle restrictions.

V. Conclusion

Advanced beamforming and beam steering are crucial for improving dual-tier 5G networks that combine mmWave and Sub-6GHz frequency bands, as this study has shown. It has been demonstrated that combining these strategies greatly enhances throughput performance and user association efficiency. While mmWave bands allow high-capacity data transmission, albeit with limited range, sub-6GHz channels offer dependable connectivity and wide coverage. The network may efficiently balance coverage and capacity by utilizing the advantages of each frequency tier and dynamically controlling user association, guaranteeing peak performance for a variety of applications. According to the simulation results, beamforming and beam steering improve signal strength, reduce interference, and enable mobile users to connect seamlessly. While users of the mmWave tier have higher throughput in high-density locations with line-of-sight circumstances, users of the Sub-6GHz tier enjoy reliable connections over extended distances. These findings underscore the importance of sophisticated user association techniques that adapt to real-time network conditions and user mobility.

In order to forecast user behaviour and dynamically optimize user association, it is recommended that future research concentrate on creating adaptable algorithms that use machine learning approaches. To balance complexity and performance in huge MIMO systems, invest in hardware solutions that offer hybrid beamforming. Future advancements in wireless communication systems can be made possible by implementing these suggestions, which will further maximize the potential of dual-tier networks.

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