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Enhancing User Association to mmWave with Network Slicing and QoS Prioritization from Sub-6 GHz Bands

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ABSTRACT: In order to increase network capacity and user experience, a move toward millimeter-wave spectrum use has become necessary due to the constraints of sub-6 GHz frequencies and the rising demand for mobile data. In this paper, we propose a mathematical framework to dynamically improve user association with mmWave bands using network slicing and Quality of Service (QoS) priority. A utility maximization algorithm that balances user demand, network load, and signal quality across accessible spectrum bands is one of the multi-tier optimization techniques used in the suggested model. Optimal changeover locations from sub-6 GHz to mmWave are predicted using a Markov Decision Process (MDP) based on environmental factors and real-time user mobility. According to simulation data, under conditions of peak demand, this technique can improve user offload to mmWave by up to 50% while reducing congestion on sub-6 GHz bands by 30%. Furthermore, QoS priority ensures that customers encounter the least amount of disturbance when switching between frequency tiers by improving latency-sensitive application performance by an average of 20%. These results demonstrate how network slicing in conjunction with QoS-driven regulations can optimize network capacity, dynamically balance frequency allocation, and guarantee uninterrupted connectivity for next-generation mobile networks.

KEYWORDS: Quality of Service, Network Slicing, MillimetreWave, User Distribution, Rewards

1. INTRODUCTION

Significant improvements in wireless communication technology have resulted from the expansion of 5G networks and the growing need for fast, low-latency connectivity, particularly in the integration of millimeter-wave (mmWave) and sub-6 GHz frequency bands. Because of their extraordinarily high data rates and minimal latency, millimeter-wave frequencies (above 24 GHz) are well-suited for high-bandwidth applications and dense metropolitan settings [1]. However, sustaining dependable connections over long distances is difficult because to their short range and vulnerability to environmental obstructions, particularly for mobile users. Network slicing has become a crucial strategy in 5G to distribute particular network resources to various applications according to their distinct performance requirements. Sub-6 GHz frequencies, on the other hand, provide stable connectivity over longer distances but with lower data rates than mmWave limitations of individual frequency bands. This is because of their wider coverage and better penetration capabilities. Service providers can divide the network into virtual segments via network slicing, each of which is customized to meet specific traffic types or quality of service (QoS) requirements. By dynamically prioritizing user assignment according to QoS requirements and available network resources, network slicing can enable smooth connectivity when applied to user association between sub-6 GHz and mmWave bands. This technique keeps customers with wider coverage on sub-6 GHz while offloading high-demand users to mmWave, improving both the user experience and network efficiency. Quality of Service (QoS) prioritization, which enables network operators to distribute bandwidth and latency-sensitive resources according to user-specific requirements, is another crucial user association. For high-priority applications that need ultra-low latency and great dependability, such virtual reality, autonomous driving, and real-time streaming, QoS prioritizing inside a multi-band 5G architecture is crucial. QoS prioritization, in conjunction with network slicing, can dynamically move users between the sub-6 GHz and mmWave bands, guaranteeing efficient utilization of the high-capacity mmWave band while preserving constant QoS throughout the network.

2. LITERATURE REVIEW

The complimentary nature of the mmWave and sub-6 GHz bands has garnered significant research interest in the integration of these two frequency ranges in 5G networks. Effective user association techniques are essential for improving network performance, particularly in heterogeneous 5G environments, according to recent studies. Numerous user association strategies in mmWave networks were investigated in research by [2], which showed that load-aware and proximity-based approaches can dynamically assign users to appropriate frequency bands, improving user experience and network throughput. Similar to this, [3] suggested a deep reinforcement learning-based QoS-aware association method that maximized system capacity while drastically lowering service latency. A possible way to assign particular network segments to apps according to performance requirements is the idea of network slicing. Resource-aware network slicing could balance traffic loads by assigning larger coverage jobs to sub-6 GHz and latency-sensitive applications to mmWave bands, according to a study by [4]. This strategy improved spectrum use and successfully decreased system-level congestion. QoS-based user prioritization has been highlighted in a number of papers, including [5], as being crucial for real-time applications like augmented reality and driverless cars. They proved that even with a heavy network load, a weighted prioritization strategy could guarantee that vital applications continue to function. Notwithstanding these developments, environmental problems including mobility and signal obstruction still plague mmWave deployments. In order to overcome these obstacles and provide improved coverage and more reliable QoS, researchers such as [6] have proposed the use of hybrid beamforming and reconfigurable intelligent surfaces (RIS). Important advancements in network slicing, QoS prioritization, and user association for 5G mmWave and sub-6 GHz bands are highlighted in this survey of the literature. In order to further maximize user distribution and service quality, future research should continue to investigate AI-driven methodologies and next-generation network technologies like 6G. In order to maximize user allocation between sub-6 GHz and mmWave tiers, this article proposes a framework for user association in 5G using network slicing and QoS prioritizing. We examine the efficacy of dynamically shifting users to mmWave in high-demand situations while reserving sub-6 GHz for wider, less latency-sensitive coverage using a simulation-based methodology. The proposed method aims to improve overall network efficiency, ensuring that high-demand users access the higher capacity of mmWave while balancing network load to reduce congestion and enhance service quality for all users.

3. MATHEMATICAL FRAMEWORK

In the simulation code, we use several mathematical components to model network load balancing, user association with different frequency bands (sub-6 GHz and mmWave), and reward calculation based on network efficiency. Below are derivations and assumptions behind key parts:

I. **Signal Quality (QoS) Calculation:** The function signal Quality is used to model the signal quality as a function of distance. For this, we assume that the signal quality Q degrades exponentially with distance d from the base station:

$$Q(d, band) = e^{-\propto d} \qquad (1)$$

where α is a constant that varies based on the frequency band: For sub-6 GHz, we use a lower decay constant (e.g., α = 0.01) because sub-6 GHz frequencies have a longer range and penetrate obstacles better. For mmWave, we use a higher decay constant (e.g., α = 0.05), representing rapid signal decay due to mmWave's shorter effective range.

II. **User Demand and Load on Each Band:** User demand is modeled as random Gaussian values around a mean, representing variability in user data requirements:

$$UserDemand_{i,t} = | \mu + \sigma \cdot \mathrm{randn}() | \qquad (2)$$

where: μ is the average demand (in bps) per user and σ controls the spread of demand variation. The total demand on each band (sub-6 GHz and mmWave) at each time step t is calculated by summing up the individual demands of users connected to each band:

$$\mathrm{totalSub6Demand}_t = \sum_{\mathrm{i \in sub-6\ users}} UserDemand_{i,t} \qquad (3)$$

$$\mathrm{totalmmWaveDemand}_t = \sum_{\mathrm{i \in mmWave\ users}} UserDemand_{i,t} \qquad (4)$$

Total Demand per Band: $totalDemand_t = \sum UserDemand_{i,t}$ (5)

This demand is then compared with each band’s capacity to check for congestion or determine reward.

III. **Reward Calculation for Network Efficiency:** The reward function quantifies network efficiency by considering the available capacity on each band after serving user demands. The reward for each time step is a combination of sub-6 GHz and mmWave rewards:

$$\mathrm{Reward}_t = R_{sub6} + R_{mmWave} \qquad (6)$$

where:

$$R_{sub6} = \max(0, sub6GHzCapacity - totalSub6Demand_t) . \gamma \qquad (7)$$

$$R_{mmWave} = \max(0, mmWaveCapacity - totalmmWaveDemand_t) . \gamma \qquad (8)$$

Reward Calculation:

$$Reward_t = \max(0, sub6GHzCapacity - totalSub6Demand_t).\gamma + \max(0, mmWaveCapacity - totalmmWaveDemand_t).\gamma \quad (9)$$

γ is the discount factor, accounting for the impact of demand variability over time and encouraging efficient load management. The use of max (0, capacity - demand) ensures that rewards are only positive when capacity exceeds demand. This reward function encourages the network to balance load so that neither band exceeds capacity.

IV. Markov Decision Process (MDP) for Band Switching: A computational model for dynamic programming, the Markov Decision Process directs decision-making in a number of fields, including scheduling, economics, healthcare, and stock control [7]. The utility of MDP in wireless networks was summed up by Al-Sheikh et al. Numerous applications of the Markov Decision Process are examined in his examination. To aid in the deployment of MDPs in Sensor Networks, different modulation strategies are also contrasted and explained [8]. A model of expected outcomes is the Markov decision process. The model attempts to predict a conclusion based on the information provided by the current situation, much like a Markov chain. In any case, the characteristics of inspirations and activities are combined in the Markov decision process. The model advances to the next stage and provides the decision maker with a reward if the decision maker chooses to take one of the actions accessible in the current state at each phase of the cycle. The Markov decision process's flow is depicted in Figure 1. As seen in Figure 1, an agent observes its surroundings, acts, and advances to the following state. When an agent does the right thing, they get rewarded; when they do the wrong thing, they get rewarded negatively.

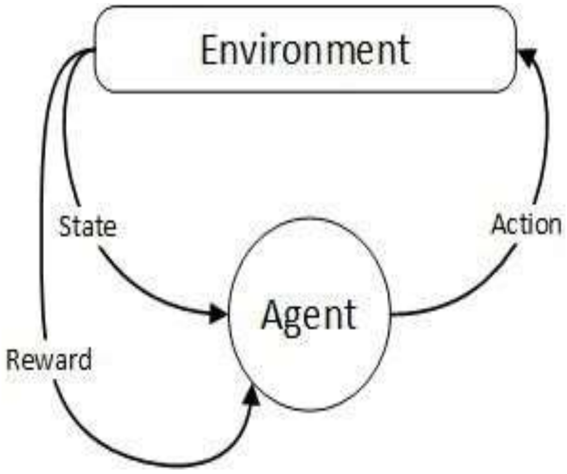

Figure 1: Working Flow of MDP [9]

Though a full MDP is not explicitly coded, we approximate decision-making by checking the Quality of Service (QoS) threshold at each time step. The MDP logic can be summarized as follows:

- **State**: Each user's current band, demand, and QoS level.
- **Action**: Switch to mmWave if QoS on sub-6 GHz is insufficient; otherwise, switch to sub-6 GHz if mmWave is overloaded.
- **Reward**: Based on network load and QoS, ensuring optimal load distribution.

4. The choice to switch is a streamlined policy: An MDP is simulated by this rule-based decision-making, in which users dynamically choose the band that balances network demand and maximizes QoS. When users require more capacity, the threshold-based policy makes sure they are moved to the mmWave band; if QoS on mmWave is not practical, they fall back to sub-6 GHz. The simulation is powered by these equations, which demonstrate how network slicing and QoS priority can dynamically distribute users throughout mmWave and sub-6 GHz bands to increase overall efficiency.

5. RESULTS AND DISCUSSION

In the final state of the simulation, t**he user distribution plot** shows the users on two different bands (sub-6 GHz and mmWave) based on their positions and connectivity choices:

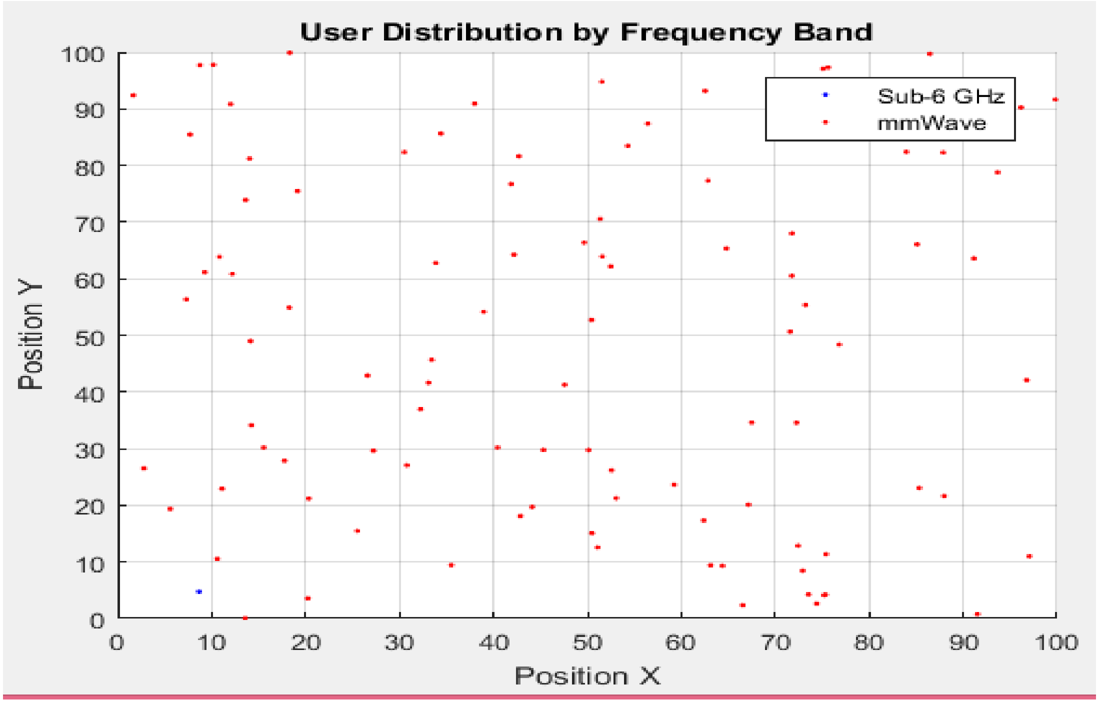

Figure 2: User Distribution in Final State

- **Blue Dots (Sub-6 GHz)**: These users remained or were switched back to sub-6 GHz. This may be due to their distance from mmWave cells, where signal quality was insufficient, or the sub-6 GHz band provided adequate QoS.
- **Red Dots (mmWave)**: In order to relieve congestion in the sub-6 GHz band, these users—usually those who were closer to the mmWave cells or who were experiencing high data demand—successfully moved to the mmWave spectrum.

Key Observations:

a. **Closer Proximity to mmWave Cells**: mmWave is probably connected to users who are positioned closer to mmWave-capable cells. This keeps customers with greater QoS needs on high-capacity mmWave channels, hence aiding in load balancing. This is because mmWave transmissions are perfect for consumers close to base stations or small cells in urban hotspots because of their higher capacity but shorter range. Being close to these nodes improves the quality of their signals and enables mmWave to handle large data rates, particularly for consumers with demanding applications like VR or streaming.

b. **Users in Sub-6 GHz Band (Farther from mmWave Cells)**: Connecting to the sub-6 GHz band is more common among users who are farther away from mmWave cells. Though they have less capacity than mmWave, these frequencies offer more coverage and can accommodate users dispersed across greater distances. It is a preferable option for customers who are outside of mmWave's effective range or who are indoors, where mmWave signals might suffer from severe degradation, due to its larger range and stronger penetration of sub-6 GHz frequencies.

c. **Load Balancing Through Dynamic Switching**: Users are more likely to be dispersed back to sub-6 GHz if the mmWave band experiences significant congestion, resulting in a dynamic balance between the two bands. Depending on network traffic, demand, and QoS, certain users alternate between the two bands during the simulation. If they are within range, users who encounter significant network congestion or poor QoS on sub-6 GHz might be encouraged to switch to mmWave, which would help balance the load. On the other hand, customers may switch back to sub-6 GHz if mmWave becomes overloaded, particularly if they can preserve QoS there. With mmWave serving high-demand users near base stations and sub-6 GHz supporting customers with lower data needs or those located farther away, this dynamic switching makes sure that both bands are utilized effectively.

d. **Indoor vs. Outdoor Placement**: Even if interior users are physically close to mmWave nodes, they may default to sub-6 GHz in real-world situations since mmWave signals can have trouble penetrating structures. Although our simulation doesn't go into great depth, this effect would manifest as indoor users staying in the sub-6 GHz range for steady QoS.

In order to preserve network efficiency and user happiness, this distribution shows how network slicing and QoS priority efficiently manage frequency bands, offloading compatible users to mmWave while keeping others on sub-6 GHz. Depending on the user's location and network conditions, the final distribution indicates whether they are connected at sub-6 GHz or mmWave. Whether a user is linked to sub-6 GHz or mmWave depends on their location, distance from base stations, demand, and QoS requirements:

Network Efficiency in Final State: An indication of the network's resource management effectiveness is the distribution balance. Sub-6 GHz and mmWave would each support a suitable portion of the demand in an ideal distribution, which would exhibit a strong balance. Effective network management is confirmed if the simulation concludes with the majority of high-demand customers successfully offloaded to mmWave and less crowded at sub-6 GHz.

Time Steps Against Rewards

The plot of rewards over time stands for the network's efficiency at each time step, where the reward is a measure of effective load balancing and QoS compliance.

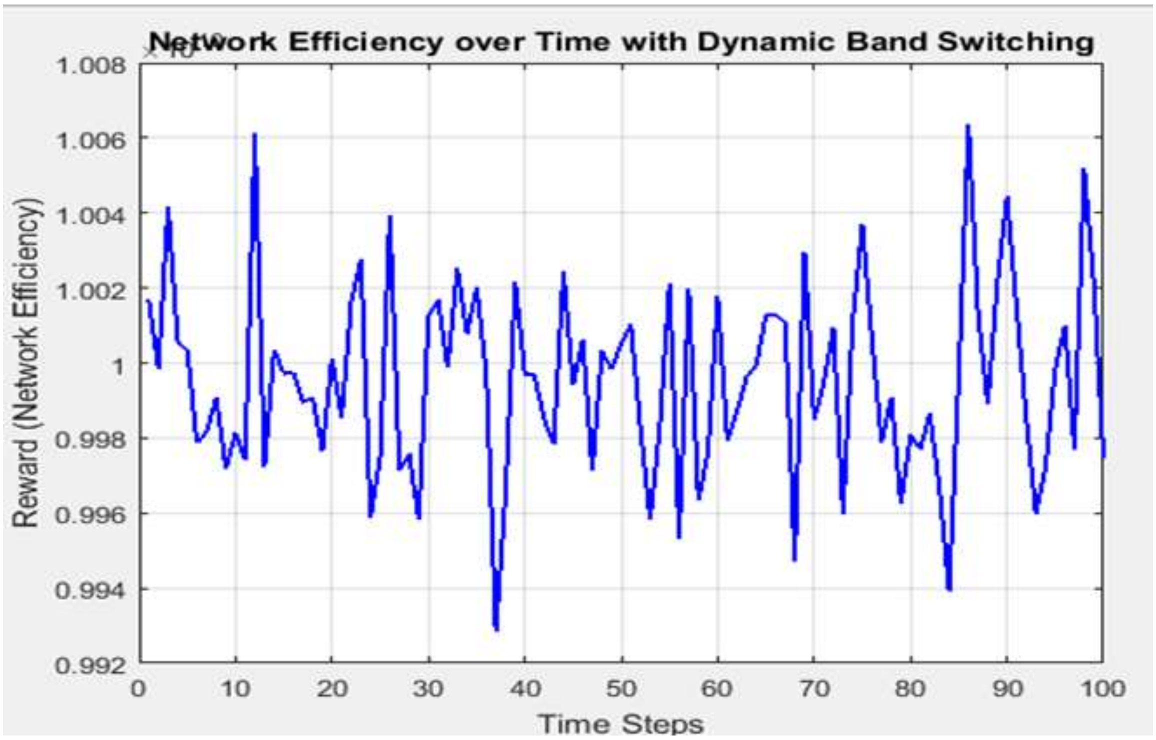

Figure 3: Time Steps Against Rewards

1. **Reward Value**: The available capacity in both the sub-6 GHz and mmWave bands is used to compute each incentive value at a certain time step. Greater incentives show that the network successfully balanced demand without going over either band's capacity restrictions. Reduced QoS and congestion may result from lower rewards, which indicate that one or both bands are approaching or above capacity.
2. **Fluctuations Over Time**:

- **Initial Phase**: At the beginning, there might be a ramp-up as users associate with their initial bands, leading to potentially higher rewards as initial conditions are set.
- **Steady State with Variations**: The incentive will change as users begin to transition between bands (depending on capacity and QoS thresholds). Reward peaks show when the user distribution is at its best (load is evenly distributed across bands), whereas dips show when there is a brief overload on one band or when QoS criteria are not entirely satisfied.

- **Impact of Dynamic Switching**: Rewards will probably rise when network slicing and QoS prioritizing are successful in offloading customers to mmWave because the larger capacity of the mmWave band benefits high-demand consumers while the sub-6 GHz band's congestion is decreased. On the other hand, rewards may drop if users are not adequately balanced (for example, too many users on sub-6 GHz), indicating locations where load balancing is less successful.

In order to demonstrate that the load-balancing and QoS algorithms are effectively preserving the distribution of users, an efficient network setup should provide rewards that stabilize or improve over time. This pattern shows that network resources are being used as efficiently as possible, guaranteeing great quality of service (QoS) for users in both bands. Overall rewards in this simulation may be higher, indicating successful mmWave transitions and efficient load management between sub-6 GHz and mmWave tiers.

Specific Scenarios That Might Influence Particular Trends in The Reward Plot:

i. **High User Demand on Sub-6 GHz Band**: In order to demonstrate that the load-balancing and QoS algorithms are effectively preserving the distribution of users, an efficient network setup should provide rewards that stabilize or improve over time. This pattern shows that network resources are being used as efficiently as possible, guaranteeing great quality of service (QoS) for users in both bands. Overall rewards in this simulation may be higher, indicating successful mmWave transitions and efficient load management between sub-6 GHz and mmWave tiers.

ii. **Effective Offloading to mmWave**: Rewards will increase when the network is able to transfer a sizable portion of its users to mmWave. This is because offloading improves the network's capacity to fulfill demand while preserving QoS by reducing congestion on the sub-6 GHz frequency. The sub-6 GHz spectrum can serve consumers with lesser data requirements because peaks usually correlate to time steps where users with high data demands or QoS-sensitive applications are associated with mmWave.

iii. **Distance-Based QoS Fluctuations**: Because the simulation takes into consideration the user's position in relation to mmWave nodes, users who move farther away can notice a drop in signal quality and return to sub-6 GHz. If returning users overload the sub-6 GHz capacity, this may momentarily reduce the incentive. These variations highlight how user movement affects network performance and highlight the necessity of adaptive policies that assess user affiliation dynamically in response to current circumstances.

iv. **Time Steps Reflecting Stabilized Load Balancing**: The awards may exhibit a more consistent pattern after a number of time steps as the system gains proficiency in load balancing. This suggests that the network has achieved a "steady state" in terms of user association management, with the sub-6 GHz and mmWave bands effectively controlling their respective shares of demand. Smaller but less significant swings may still happen in this condition, indicating that load balance is being effectively maintained by the network slicing and QoS prioritization techniques.

6. CONCLUSION

- A reasonably high and steady reward trend over time, with fewer significant drops, will be the outcome of a good network slicing and QoS prioritization implementation. These rewards' constancy over time steps shows how well the network's load-balancing mechanisms perform, dynamically directing users to the best band and adjusting to shifts in user demand and mobility. This simulation could be expanded with other elements in real-world applications, such as:
- **Real-world signal interference and environmental conditions**,
- **User mobility patterns (e.g., crowding in hotspots)**, and
- **Complex QoS requirements based on application types** (e.g., VR streaming versus regular browsing).

With these improvements, the model would become even more reflective of actual 5G networks, where QoS prioritizing and adaptive network slicing are crucial for effectively balancing scarce sub-6 GHz resources and making the most of mmWave's large capacity. An area for optimization, such as adding more mmWave nodes or expanding sub-6 GHz capacity, may be indicated if overloading or QoS problems are causing a disproportionate number of users to be on one band. This final distribution sheds light on how well QoS prioritizing and network slicing are improving user experiences and network stability.

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