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Intelligent Spectrum Management: Facilitating the Migration to mmWave Connectivity

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Abstract
As the demand for high-speed wireless connectivity continues to surge, intelligent spectrum management becomes crucial in facilitating the widespread adoption of millimetre wave (mmWave) communications. This paper explores strategies that promote user migration from sub-6 GHz bands to mmWave frequencies through adaptive, context-aware network operations. Key mechanisms include dynamic spectrum allocation, device capability detection, and real-time load balancing to ensure efficient utilization of available spectrum. Enhanced beamforming and beam-steering techniques extend mmWave coverage, while power and signal threshold adjustments help prioritize mmWave access where feasible. Furthermore, Quality of Service (QoS) prioritization and network slicing ensure that latency-sensitive, high-bandwidth applications are preferentially assigned to mmWave resources. Together, these techniques not only optimize spectrum usage and alleviate congestion on legacy bands but also improve user experience by aligning network resources with application requirements and user conditions. The proposed framework highlights a path toward seamless, intelligent integration of mmWave into future heterogeneous wireless networks.
Keywords: *mmWave Connectivity, Sub-6 GHz, User Association, Network Slicing, Beamforming and Beam Steering*

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I. Introduction

The explosive growth in mobile data demand, coupled with the proliferation of bandwidth-intensive applications such as ultra-high-definition (UHD) video streaming, augmented reality (AR), and cloud gaming, has accelerated the evolution of mobile networks toward more efficient and dynamic spectrum utilization [1]. The International Telecommunication Union (ITU) projects that global mobile traffic will triple between 2023 and 2029, driven largely by the adoption of 5G and the expanding Internet of Things (IoT) ecosystem [2]. As a result, mobile network operators (MNOs) are under increasing pressure to optimize spectrum allocation to meet user demands while maintaining service quality.

Sub-6 GHz bands, including both low-band (<1 GHz) and mid-band (1–6 GHz) frequencies, have traditionally served as the backbone of wireless communication due to their favourable propagation characteristics. These bands provide wide-area coverage, high reliability, and good penetration through obstacles. However, they are becoming increasingly congested, particularly in urban and high-density environments, due to their limited spectrum capacity and growing user base. The overuse of these bands creates performance bottlenecks, reduced throughput, and increased latency—conditions that are unsustainable for emerging use cases requiring consistent low-latency and high-throughput connections.

In contrast, millimeter-wave (mmWave) spectrum, operating in the high-frequency range (typically 24–100 GHz), offers significantly greater bandwidth and ultra-fast data rates, often exceeding 1 Gbps under optimal conditions. However, mmWave deployment faces unique technical challenges, including short-range coverage, high susceptibility to signal attenuation, and sensitivity to physical obstructions such as buildings and foliage. Despite these constraints, the successful integration of mmWave into 5G networks is a critical enabler for delivering the full spectrum of next-generation applications and services. This appraisal evaluates the technical strategies and intelligent spectrum management approaches that enable networks to effectively transition users from the sub-6 GHz tier to the mmWave tier. Techniques such as dynamic spectrum management, device capability detection, load balancing, beamforming, application-aware routing, and network slicing will be examined in detail. The objective is to highlight how these tools collectively contribute to optimizing network performance, enhancing user experience, and ensuring scalable and future-proof mobile infrastructure.

II. Dynamic Spectrum Management

Dynamic spectrum management (DSM) represents a foundational strategy for optimizing the use of available radio frequency resources across heterogeneous bands, including both sub-6 GHz and mmWave tiers. By leveraging real-time traffic data, user location, and device capability, DSM enables mobile networks to allocate spectrum adaptively shifting users to underutilized bands such as mmWave whenever environmental and technical conditions permit. This dynamic approach maximizes spectral efficiency, reduces congestion in legacy bands, and promotes more equitable distribution of bandwidth-intensive services.

At the core of DSM is the integration of advanced radio access network (RAN) intelligence and machine learning algorithms capable of predicting usage patterns and channel conditions. These algorithms assess key performance indicators (KPIs) such as signal-to-noise ratio (SNR), latency, and throughput across different frequency bands to make informed decisions about spectrum allocation. When network load in the sub-6 GHz spectrum surpasses a certain threshold, users who are within line-of-sight (LoS) or near mmWave base stations can be selectively migrated to the mmWave tier. This proactive steering reduces latency and increases available bandwidth for both migrating and remaining users.

Dynamic spectrum sharing (DSS) technologies further enhance DSM by allowing simultaneous usage of different frequency bands for 4G and 5G services. DSS enables the same spectrum block to be partitioned dynamically based on traffic demand, ensuring backward compatibility while optimizing spectral utilization for 5G mmWave-capable users [3]. While DSS is often associated with sub-6 GHz deployments, its intelligent integration with DSM policies supports mmWave offloading by freeing up capacity in lower bands.

Network operators have begun to implement policy-based DSM frameworks where predefined rules trigger spectrum reallocation based on service type and user priority. For example, during periods of high video streaming activity, users with mmWave-capable devices can be redirected to mmWave cells to ensure low latency and minimal buffering, while freeing sub-6 GHz resources for users engaged in voice calls or low-bandwidth tasks [4]. Additionally, 3GPP Release 17 supports enhancements to spectrum management that allow better coordination between different access technologies and spectrum tiers, further accelerating mmWave adoption.

However, DSM's effectiveness is contingent on widespread mmWave infrastructure and the presence of capable user equipment (UE). Without dense small cell deployment and robust beamforming, mmWave offloading may lead to degraded performance in non-optimal conditions. Consequently, DSM must be implemented in conjunction with environmental sensing, predictive mobility modeling, and robust fallback mechanisms to ensure a seamless user experience. Ultimately, dynamic spectrum management serves as a strategic enabler for efficient user migration to the mmWave tier. By intelligently balancing load across spectrum layers and adapting to real-time network dynamics, DSM contributes significantly to realizing the ultra-high capacity and low-latency potential of 5G networks.

III. Device Capability Detection

The ability of a 5G network to intelligently migrate users from sub-6 GHz to mmWave is fundamentally dependent on the network's understanding of device capabilities. Device capability detection plays a pivotal role in identifying which user equipment (UE) can operate on mmWave frequencies and under what conditions such transitions can be executed without compromising quality of service (QoS). Modern UEs routinely signal their capabilities to the network as part of the registration and attachment processes. These capability messages—defined by 3GPP standards—include information about supported frequency bands, maximum uplink/downlink throughput, antenna configurations, and beamforming support [5]. Through this process, networks can construct detailed UE profiles that inform RAN decisions about which spectrum tier is most appropriate for a given device, especially when high-band spectrum is underutilized.

This capability awareness becomes even more potent when integrated with real-time analytics within the RAN. Intelligent RAN architectures, such as Open RAN and centralized RAN (C-RAN), are increasingly leveraging device-level intelligence alongside contextual information—such as user mobility, application type, and cell congestion—to make optimized frequency allocation decisions. For instance, a stationary user with a mmWave-capable smartphone in a dense urban area may be proactively steered toward mmWave, while a fast-moving user may remain on sub-6 GHz to maintain session continuity.

Furthermore, this device-aware management facilitates the preferential use of mmWave as the default access tier for eligible devices. By modifying cell reselection and handover priorities at the RAN level, networks can nudge capable devices to establish and maintain mmWave connections when coverage and signal quality are acceptable. Recent software-defined RAN advancements have enabled dynamic policy enforcement that promotes mmWave engagement without requiring explicit user intervention or manual configuration. These dynamic preference schemes are especially effective in high-density venues such as stadiums, campuses, and airports, where mmWave small cells are strategically deployed. Moreover, device vendors are increasingly collaborating with network equipment providers to ensure that hardware and firmware configurations align with operator strategies for mmWave promotion. Some device operating systems are also being optimized to allow more aggressive scanning for high-band frequencies when large data sessions like ultra-HD video streaming or AR/VR applications—are initiated.

In summary, device capability detection allows networks to make nuanced and context-aware decisions regarding user association with mmWave tiers. By embedding UE intelligence into the broader RAN decision-making process, networks can optimize spectral efficiency, improve end-user experience, and alleviate pressure on mid-band resources.

IV. Load Balancing and Congestion Management

In high-density urban environments and during peak usage periods, sub-6 GHz frequency bands can quickly become congested, leading to degraded quality of service and user dissatisfaction. To address this challenge, 5G networks are increasingly leveraging intelligent load balancing and congestion management techniques that prioritize spectrum efficiency and user experience. These methods play a vital role in facilitating the migration of compatible users to the mmWave tier, where greater bandwidth and lower latency are available.

The adoption of AI-driven load balancing algorithms has significantly enhanced real-time congestion control capabilities. These algorithms monitor a wide array of network metrics—including traffic load, spectral efficiency, latency, and signal quality in real time to dynamically shift users across available frequency bands. AI models, particularly those utilizing reinforcement learning and deep neural networks, have demonstrated efficacy in optimizing handovers and load distribution by learning from historical patterns and current network states. When sub-6 GHz cells approach saturation, the system can identify mmWave-compatible devices within suitable proximity and automatically offload them, reducing mid-band congestion while maximizing high-band utilization.

In parallel, predictive analytics has emerged as a powerful tool in pre-empting congestion before it occurs. By analysing temporal and spatial traffic trends, machine learning models can forecast traffic spikes—such as those associated with commuter hours, sporting events, or emergencies—and preconfigure RAN behaviour to redirect compatible users toward mmWave small cells. This proactive load shifting not only preserves service quality but also flattens demand curves across spectrum tiers, resulting in more uniform network performance.

Empirical evidence supports the efficacy of these strategies. A simulation study conducted by [6] demonstrated that applying predictive load balancing with mmWave offloading in a dense metropolitan environment led to a 32% improvement in overall user throughput and a 27% reduction in latency during peak hours. Similarly, a case study in Tokyo’s Shibuya district showed that dynamic spectrum allocation combined with AI-based congestion management reduced mid-band saturation levels by 40% during high-traffic events, while sustaining high throughput on mmWave connections [7].

The ability to distribute load intelligently across spectrum bands ensures that mmWave is not treated merely as a niche resource, but rather as an integral part of the broader 5G infrastructure. Through real-time decision-making and predictive modelling, networks can balance capacity and coverage while minimizing service degradation in congested environments.

V. Enhanced Beamforming and Beam Steering

The deployment of mmWave frequencies in 5G networks presents unique challenges, including limited range, poor diffraction, and high susceptibility to physical obstructions such as buildings and foliage. To mitigate these limitations, advanced antenna technologies, particularly beamforming and beam steering have emerged as foundational enablers for extending the usability and reliability of mmWave links. These techniques, combined with massive Multiple Input Multiple Output (MIMO) architectures, are critical for expanding mmWave coverage footprints and improving the overall performance of high-frequency transmissions.

At the core of this transformation is beamforming, a signal processing technique that allows base stations to direct radio energy in focused beams rather than broadcasting uniformly in all directions. This capability is especially valuable in mmWave transmissions, where precise signal targeting helps overcome high path losses and ensures that power is efficiently delivered to users [8]. Massive MIMO enhances this capability by employing large arrays of antennas at both the transmitter and receiver ends, enabling simultaneous formation of multiple narrow beams for different users, thus increasing spatial multiplexing and spectral efficiency [9]. Dynamic beam steering, an extension of beamforming, further increases the robustness and adaptability of mmWave links. Unlike static beam patterns, dynamic beam steering uses real-time feedback and motion tracking algorithms to adjust the beam’s direction as the user moves, maintaining a consistent high-quality connection. This adaptability allows mmWave cells to serve users in motion, extending the effective coverage zone beyond line-of-sight (LOS) scenarios. Such systems are particularly effective in dense urban areas where user mobility and complex propagation environments demand agile link management.

In addition, adaptive antenna systems (AAS) have significantly enhanced signal strength and range by tailoring transmission characteristics based on environmental feedback. AAS technologies dynamically alter

beamwidth, direction, and power in response to signal degradation, obstacles, or interference. This level of responsiveness has proven especially useful in urban deployments, where reflections and blockages are prevalent. Empirical studies have demonstrated that adaptive beamforming in mmWave small cells can improve signal-to-noise ratios by over 15 dB in obstructed urban scenarios.
[10] in their work illustrated in Figure 1, users are associated with base stations based on the Received Signal Strength Indicator (RSSI), showing distinct associations for sub-6GHz and mmWave tiers.

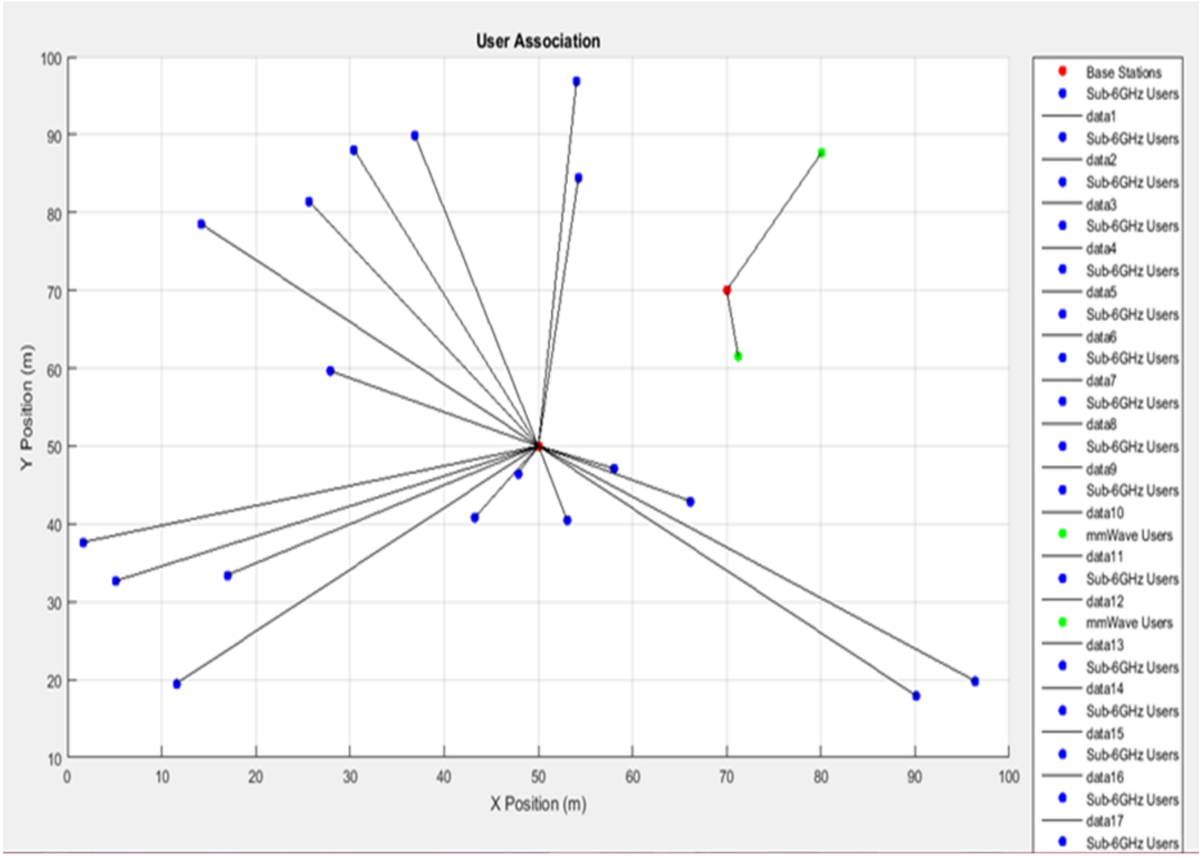

Figure 2: User Association [10]

Users located farther from base stations are more likely to associate with sub-6GHz (blue), benefiting from its superior coverage range, while users closer to the base station associate with mmWave (green), taking advantage of its high throughput potential. From the Result Obtained: Sub-6GHz users maintain connectivity over a larger radius due to better propagation characteristics. mmWave users are clustered near base stations, limited by higher path loss and blockage sensitivity. This tier-based user association enables higher network throughput in the mmWave zone and reliable baseline connectivity in the sub-6GHz zone. The visual result supports the premise that RSSI-based association can dynamically optimize resource allocation in dual-tier networks.

Overall, these beam-centric technologies not only compensate for the inherent limitations of mmWave propagation but also promote its viability as a dependable access tier. By maintaining consistent and high-quality connections even under dynamic and challenging conditions, beamforming and beam steering technologies make it feasible to nudge more users from the sub-6 GHz tier to the mmWave tier with minimal compromise in user experience.

VI. Incentivizing mmWave Use for High-Bandwidth Applications

One of the most effective strategies to shift user traffic toward mmWave frequencies is to design network policies that associate mmWave access with high-bandwidth, latency-sensitive applications. Given the immense capacity and low-latency characteristics of mmWave bands, they are particularly well-suited to support next-generation services such as ultra-high-definition (UHD) video streaming, augmented/virtual reality (AR/VR), and real-time cloud gaming. By aligning traffic engineering with application profiles, networks can maximize both user experience and spectrum efficiency.

Modern 5G networks increasingly employ application-aware traffic routing as part of their network policy framework. This approach uses deep packet inspection (DPI), traffic tagging, or service-level identifiers (SLIs) to classify flows based on their performance requirements [11]. Once categorized, the network can dynamically route these flows to the most appropriate radio access technology—favouring mmWave tiers for services that benefit from high data rates and ultra-low latency. This intelligent steering ensures that the superior characteristics of mmWave are reserved for use cases where they have the greatest impact.

Prioritization of latency-sensitive and high-throughput applications is crucial in achieving optimal network performance. For instance, AR/VR applications require end-to-end latency below 20 milliseconds and sustained data rates in the range of 100 Mbps or higher [12]. Similarly, 4K and 8K video streaming demand bandwidths exceeding what is typically available on mid-band frequencies during peak hours. By configuring network slices or radio schedulers to give these applications preferential access to mmWave resources, operators can both offload mid-band congestion and provide seamless quality to premium services [13].

Moreover, this policy-driven approach enhances the Quality of Experience (QoE) for users, which has become a primary metric in evaluating network performance. Studies have shown that application-aware mmWave steering significantly improves metrics such as start-up delay, jitter, and video buffering ratio for streaming service. Importantly, this not only satisfies user expectations but also contributes to improved spectrum efficiency by aligning usage intensity with the most capable spectrum tier. When high-demand services are isolated onto mmWave, lower-tier frequencies are freed up for broader-coverage or legacy services, enabling better overall resource utilization.

In conclusion, incentivizing mmWave usage through application-specific prioritization creates a dual advantage: it ensures an optimized user experience for bandwidth-intensive services and strategically reallocates spectrum resources to match traffic demand profiles. As network slicing, AI-driven orchestration, and service classification mature, this method will become a cornerstone of intelligent spectrum management in 5G and beyond.

VII. Signal and Power Threshold Adjustments

The reliability of mmWave connectivity is intrinsically linked to signal strength and power constraints, due to the higher path loss and susceptibility to blockage compared to sub-6 GHz frequencies. To encourage user migration to mmWave where feasible, networks can manipulate signal thresholds and handover triggers by dynamically adjusting received signal strength indicator (RSSI) and reference signal received power (RSRP) criteria. This form of calibration steers compatible user equipment (UE) toward mmWave access when channel conditions meet minimum quality thresholds, rather than defaulting to sub-6 GHz frequencies.

Specifically, by lowering the threshold for acceptable mmWave signal strength and simultaneously increasing the tolerance for path loss in handover decision algorithms, the system biases initial access and secondary cell association toward the mmWave tier. This ensures that users who are within the functional mmWave zone—especially outdoors or in open urban areas—are preferentially allocated to high-band spectrum [14]. Furthermore, cell reselection and mobility management functions in the Radio Resource Control (RRC) layer can be tailored to favour mmWave when both mmWave and sub-6 GHz signals are concurrently available [15].

To maintain session continuity and mitigate the effects of mmWave link intermittency, networks rely on dual connectivity frameworks, particularly those standardized in 3GPP Release 15. Under this architecture, UEs are simultaneously connected to a master node (typically operating in sub-6 GHz) and a secondary node (often in mmWave), allowing seamless switching and data split across bands [16]. This approach ensures that when mmWave signal degradation occurs due to obstructions or mobility, the UE can fall back to sub-6 GHz without disrupting service quality.

At the base station (gNB) level, policy-based handover control mechanisms are critical in determining when and how users transition between tiers. These mechanisms use real-time radio conditions, user mobility state, QoS requirements, and power budgets to make intelligent handover decisions. For instance, a static user engaged in 4K streaming might be locked to mmWave even with marginal signal strength, whereas a fast-moving UE may be retained on mid-band frequencies to avoid frequent handovers. Policies can also incorporate historical analytics and predictive models to anticipate link degradation and pre-emptively reroute traffic, further improving user experience and network efficiency.

[17] in figure 3 demonstrates adaptive user association based on signal strength and power thresholds between Sub-6 GHz and mmWave bands. The dominance of red dots near the central mmWave base station indicates successful association of nearby users due to stronger received power, enabling high-throughput connections (300–500 Mbps).

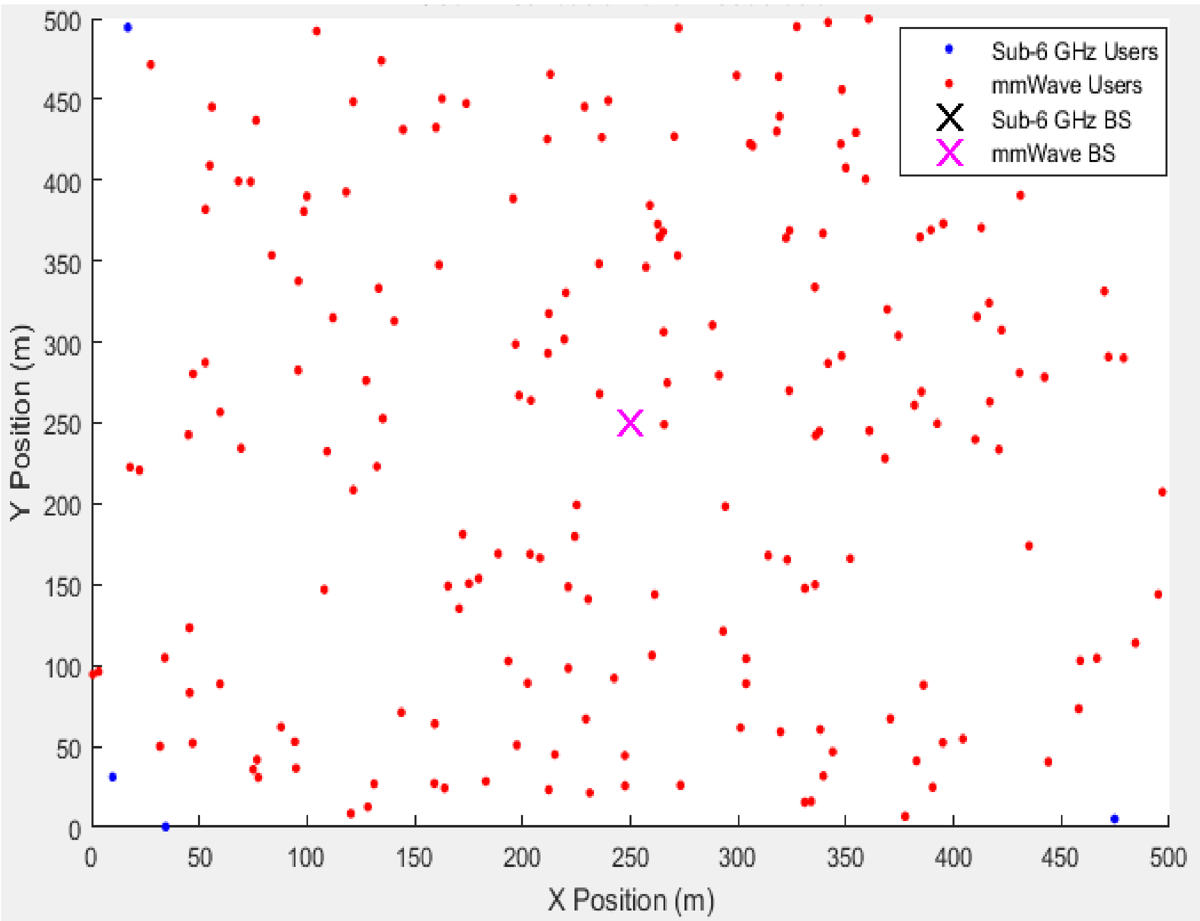

Figure 3: User Distribution [17]

Sparse blue dots at the periphery reflect fallback to Sub-6 GHz for distant users or those in non-line-of-sight (NLOS) conditions, maintaining modest throughputs (150–300 Mbps). This spatially aware strategy ensures effective load balancing across bands. The efficient distribution confirms that mmWave's high-capacity spectrum is fully utilized where feasible, while Sub-6 GHz guarantees broader coverage and penetration. Minimal user isolation indicates optimal signal threshold tuning and spatial planning. Overall, the system maintains SINR fairness and maximizes aggregate throughput by dynamically adapting user association based on proximity and channel quality.

In summary, signal and power threshold adjustments, in conjunction with dual connectivity and intelligent handover policies, form an integral strategy for expanding mmWave adoption. These mechanisms ensure that users are not only nudged toward mmWave when it is available but are also retained on it without compromising reliability, forming a seamless transition architecture for heterogeneous 5G networks.

VIII. Network Slicing and QoS Prioritization

One of the cornerstone innovations of 5G architecture is network slicing, which enables the creation of virtualized, end-to-end logical networks tailored for specific use cases or service requirements. Within this framework, dedicated slices can be provisioned over mmWave bands, reserving high-capacity and low-latency resources for services or user groups that demand them, such as autonomous vehicles, augmented reality (AR), virtual reality (VR), and ultra-high-definition (UHD) media applications [18]. This mechanism allows mobile network operators (MNOs) to dynamically allocate mmWave spectrum based on the service profile, thus effectively nudging high-performance use cases away from the congested sub-6 GHz tier.

A critical enabler of this migration strategy is the integration of Quality of Service (QoS) classifiers and Service Level Agreements (SLAs) into the radio access and core networks. 5G NR defines a sophisticated QoS framework comprising QoS Flow Identifiers (QFIs), which are mapped to specific service data flows and aligned with the corresponding slice characteristics [16]. Through this mechanism, traffic associated with premium or latency-sensitive services can be preferentially routed through mmWave-enabled slices. For example, a slice configured for Enhanced Mobile Broadband (eMBB) may leverage mmWave for high-throughput applications, while a separate slice for massive Machine Type Communications (mMTC) remains anchored in the sub-6 GHz band [19].

The control plane orchestration of these slices relies heavily on Software-Defined Networking (SDN) and Network Function Virtualization (NFV) principles, enabling centralized and programmable decision-making regarding user placement and routing. Service-aware policies, informed by traffic type, user context, and SLA parameters, guide the network to shift users onto mmWave-based slices when the service profile and radio conditions are favourable. Additionally, orchestration platforms like ETSI NFV MANO and ONAP can automate the lifecycle management of mmWave slices, ensuring that resources are scaled and allocated in real time to meet service demand [20].

Furthermore, intelligent slicing can be extended to user segmentation, offering differentiated access based on device capabilities, subscription tiers, or enterprise profiles. Enterprises requiring deterministic latency for industrial automation may be assigned dedicated mmWave slices, while general mobile broadband users share the sub-6 GHz tier. This segmentation not only ensures efficient spectrum utilization, but also improves overall Quality of Experience (QoE) by aligning service delivery with resource availability and network conditions.

[21] in Figure 3 illustrates the user association outcome from a dual-band simulation integrating mmWave and Sub-6 GHz bands with QoS-aware slicing. Most users (red dots) were successfully offloaded to mmWave, validating the strategy of prioritizing high-capacity access for high-demand or proximal users. Sub-6 GHz (blue dots) supported fewer users, primarily those either farther from mmWave cells or with lower QoS requirements.

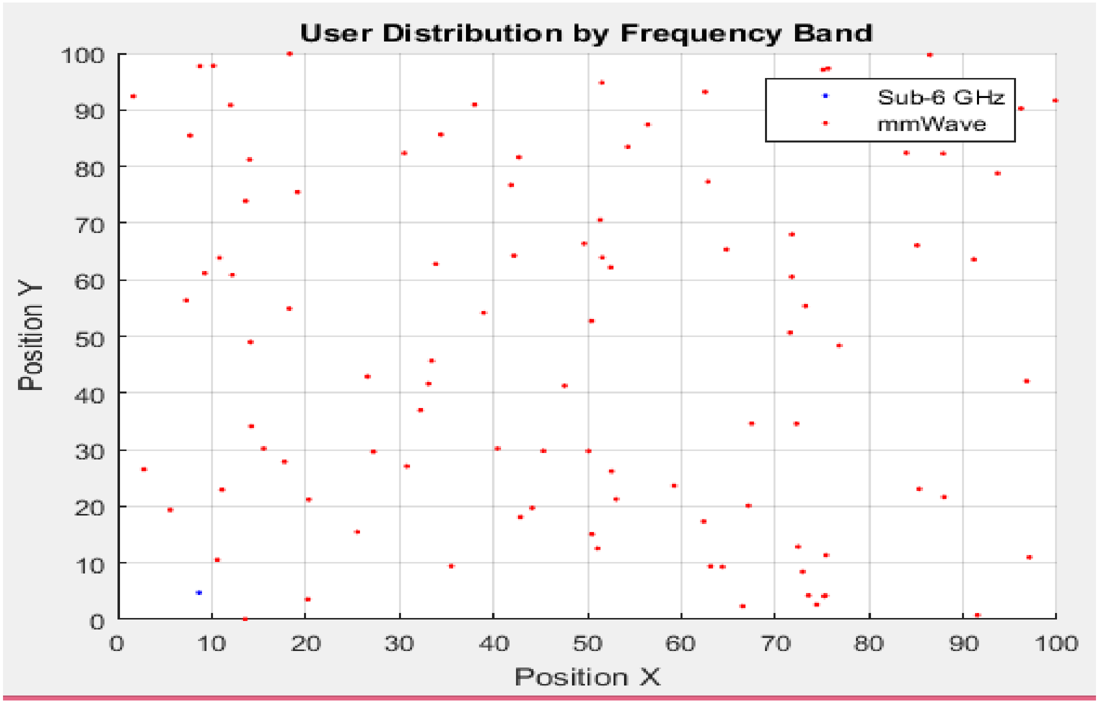

Figure 2: User Distribution in Final State [21]

The distribution reflects effective network slicing and dynamic load balancing, which adapts user association based on proximity, QoS, and traffic conditions. This strategy optimizes spectrum utilization and minimizes congestion. Although the simulation does not explicitly model indoor attenuation, practical deployment would require Sub-6 GHz support for indoor users near mmWave base stations. These findings confirm the feasibility of enhancing mmWave access via adaptive association and slicing in heterogeneous networks.

In summary, network slicing and QoS prioritization empower 5G networks with granular control over spectrum allocation and user steering. By coupling service-driven policies with real-time orchestration, networks can ensure that mmWave resources are strategically leveraged, thereby alleviating congestion in lower bands and delivering differentiated service quality across diverse applications.

IX. Conclusion

As 5G networks continue to evolve to accommodate an ecosystem of ultra-reliable, low-latency, and high-bandwidth services, the efficient utilization of the radio frequency spectrum has emerged as a foundational imperative. Traditional reliance on sub-6 GHz bands, while effective for wide-area coverage and penetration, is no longer sufficient to meet the growing demand for mobile data and real-time applications. In contrast, mmWave frequencies historically underutilized due to their limited propagation characteristics—now present a transformative opportunity for achieving unprecedented throughput and spectrum reuse.

This appraisal has examined the multi-dimensional strategies required to facilitate user migration toward mmWave tiers, focusing on intelligent spectrum management practices. Techniques such as dynamic spectrum allocation, device capability signalling, AI-based load balancing, and advanced beamforming collectively enable networks to make real-time, data-driven decisions that optimize both spectrum efficiency and user experience. Additionally, the application of network slicing, QoS-based routing, and policy-driven handovers ensures that high-value and latency-sensitive applications—such as AR/VR and UHD streaming—are preferentially routed through high-capacity mmWave links.

The integration of these technologies is not merely a technical enhancement but a necessary evolution in managing heterogeneous network resources. By embracing context-aware and adaptive frameworks, mobile network operators can proactively alleviate congestion in sub-6 GHz bands, extend the usability of mmWave deployments, and deliver the performance guarantees expected from next-generation wireless systems. This orchestrated migration strategy, underpinned by AI and software-defined infrastructure, is central to realizing the full potential of 5G—and ultimately, the broader vision of pervasive, high-performance connectivity in 6G and beyond.

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