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RESEARCH ARTICLE

Performance Evaluation of Quality of Experience Aware Mobility Management in Heterogeneous Cellular Networks

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ABSTRACT Modern wireless communication technologies are rapidly advancing to meet the evolving needs of the upcoming generation requirements, facilitating applications and services with enhanced *Quality-of-Service* (QoS) levels, characterized by high-speed broadband connectivity, enhanced reliability, and ultra-low latency. Recent reports anticipate that Fifth-Generation (5G) technology subscriptions are expected to surpass 5.3 billion by 2029. Notably, the majority of cellular network traffic originates from densely populated urban areas, where the urban environment poses numerous challenges for wireless signal quality, stemming from its densely packed infrastructures, such as high-rise buildings, narrow-congested roads/streets, metallic structures, vehicular traffic, and more. As a result, cellular operators face challenges in ensuring improved QoS for end users, along with a defined level of *Quality-of-Experience* (QoE). With this objective in mind, this research conducts a comparative evaluation of the *User Equipment-Base Station* (UE-BS) association, aiming to comprehend the throughput experiences of UEs during mobility and to evaluate the wireless services delivered with promised QoE levels. The findings of this research highlight a significant improvement in the throughput performance of priority UEs when served by BSs, with the highest *Reference Signal Received Power* (RSRP) levels and lower UE loads. Additionally, it is demonstrated that a network characterized by low UE load at the BSs contributes to enhanced throughput performances of priority UEs, attributed to surplus bandwidth resources, thereby resulting in improved UE QoE.

INDEX TERMS 5G, mobility management, quality-of-service (QoS), quality-of-experience (QoE), throughput.

I. INTRODUCTION

A. BACKGROUND

1) CELLULAR COMMUNICATIONS GROWTH FORECAST

Theupcoming generation of wireless communication technologies is swiftly progressing to fulfil future network demands and requirements of networks, intending to provide enhanced ubiquitous wireless connectivity to the end-users. This connectivity is characterized by high-speed broadband connectivity, enhanced reliability and versatility, and ultra-low latency. Recent reports on the progress of *Fifth-generation* (5G) deployment indicate that with the implementation of 5G mid-band technology, the global population coverage is projected to reach 40% by the end of 2023 [1], [2]. At this pace, the global 5G mobile subscriptions reached 1.4 billion by the third quarter of 2023 and are expected to reach 1.6 billion by the end of 2023, with projections to surpass 5.3 billion by 2029. In addition to this, the report also predicts that the average global mobile data per smartphone will reach 56 GB per month by 2029, underscoring the extensive integration of wireless communication technologies into everyday human life.

Having said that, the Worldwide deployment of 5G technology addresses the growing demand for mobile data

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FIGURE 1. **Deployment of a heterogeneous cellular network in a densely populated urban environment.**

services. However, as global automation advances, it is clear that the existing 5G networks will not be adequate to handle the escalating data traffic [3]. This is where the *Sixth-Generation* (6G), network steps in, assured to deliver high-quality service and manage the surge in data traffic [4]. This next-gen network is a paradigm shift in mobile wireless technology, boasting ultra-fast speeds, minimal latency, and extensive connectivity. With the integration of artificial intelligence (AI) and machine learning (ML), these networks will introduce novel use cases and applications previously unattainable with 5G. Furthermore, these networks aim to lay the groundwork for smart city development, autonomous vehicles, and other bandwidth-intensive, low-latency-dependent applications [5] with capabilities such as achieving a Terabits Per Second (Tbps) data transfer rate and a sub-millisecond response time [6].

2) MOST CELLULAR TRAFFIC ORIGINATES FROM URBAN AREAS

The growth in network traffic shows that the majority of cellular network traffic originates from densely populated urban areas. According to the Ericsson Mobility Report [7], there has been an observed 80% growth in most recent years, primarily driven by the need of a large number of urban residents to access cellular networks. This concentration of population can be attributed to various factors including business/economic activities, commuting hubs, and the availability of entertainment venues such as shopping malls, restaurants, and concerts. It is worth noting that traffic growth and concentration vary between location types, including urban, suburban, and rural areas. Reports also indicate that the traffic demands in urban locations are 500-1000 times higher compared to rural areas [7].

3) URBAN CHALLENGES IN CELLULAR COMMUNICATIONS

The urban environment depicted in Figure 1, presents numerous challenges for wireless communication, due to its densely packed infrastructures. This infrastructure comprises high-rise buildings, narrow-congested roads/streets, metallic structures and machinery, vehicular traffic, various electrical/electronic equipment, and so on. Therefore, it is evident that wireless signals in such urban environments experience significant degradation as a result of the blockage, coverage holes, reflections, diffraction, and scattering phenomena. In order to meet future demands for network capacity and coverage, the potential strategies include Massive Multiple-Input-Multiple-Output (M-MIMO) [8], network densification through small cell deployment and utilizing higher bandwidth spectrum, such as millimetre-wave (mmWave), Sub-6 GHz and TeraHertz communication. Moreover, the integration of autonomous vehicles, ground vehicles, and unmanned aerial vehicles (UAV) adds complexity to cellular networks. It presents various network management challenges, e.g., guaranteed throughput speeds with reliability, dynamic radio resource allocation, interference mitigation, security/privacy, scalability and so on [9]. Therefore, in this context, researchers anticipate that Space-air-ground integrated networks(SAGIN) [10] offer the potential to deliver comprehensive communication, computation, and caching capabilities, enabling high network data rates, minimal delays, and exceptional reliability. While 5G has been shown to outperform current cellular technologies in various aspects, it might not fully meet the demanding requirements of SAGIN-based services [11]. Specifically, challenges such as integrating backhaul and front haul, managing mobility, enhancing security, achieving ultra-low latency, and ensuring extreme reliability. Therefore, 6G has the potential to address the essential needs of SAGIN-based user services by uplifting the involvement of UAVs, ground stations, and satellite communications to a higher level. 6G aims to surpass the potential of 5G by achieving peak data rates exceeding 1 Tbps, supporting extreme mobility at speeds surpassing 1200 km/h, and ensuring end-to-end reliability of 99.99999% [11].

Furthermore, this dense concentration of wireless communication infrastructures also causes co-channel interference from neighbouring cellular networks, network congestion due to a high volume of mobile users, and difficulties in managing user mobility such as ensuring seamless handovers to maintain uninterrupted connectivity. In the subsequent subsection, we delve deeper into the mobility management challenges that have arisen and their consequential impact on the Quality-of-Experience (QoE) perceived by the end-users.

4) MOBILITY MANAGEMENT CHALLENGES AND ITS IMPACT ON QOE

Having said that, a dense deployment of small cells in a heterogeneous manner in an urban environment, a cellular network is expected to be resilient during user mobility or sudden network outages. The network is expected to ensure a smooth and uninterrupted handover of mobile users between two cells. According to findings in the 3GPP report in [12], it has been revealed that the occurrence of handover failure exceeds the threshold of 60% within heterogeneous networks [13]. Furthermore, mobile users encounter co-channel interference from neighbouring cells, resulting in a reduction in the overall *Signal-to-Interference-and-Noise-Ratio* (SINR). This phenomenon occurs due to a frequency reuse factor 1, where all the cells utilize the same frequency spectrum to provide cellular services to their respective users within their coverage areas. Consequently, Communication Service Providers (CSP) implement effective interference management strategies to uphold an acceptable signal quality level during user mobility. Additionally, achieving a balance in User Equipment (UE) load across the network is crucial for efficient and optimal utilization of network resources, thereby enhancing service quality and mitigating network congestion. Hence, the challenges outlined above, underscore the crucial significance, particularly in urban mobility settings, of CSPs committing to providing services to end users with a defined level of QoE.

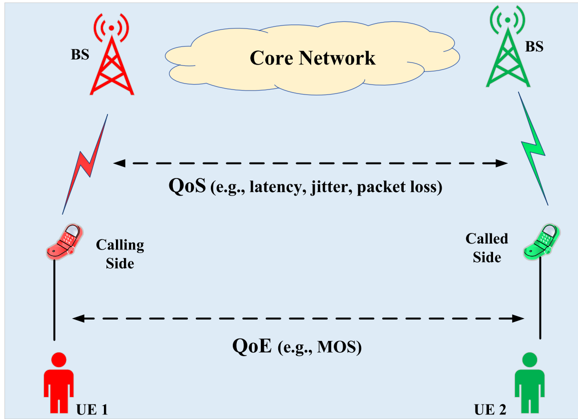

FIGURE 2. QoS and QoE in cellular communication domain.

B. QOS AND QOE IN TELECOMMUNICATION DOMAIN

1) RELATIONSHIP BETWEEN QOS AND QOE

QoS and *QoE* represent comprehensive concepts mainly employed to assess the system performance. In the realm of telecommunications, QoS evaluates the technical aspects of service provision, while QoE gauges the satisfaction level of end-users with the service they receive. According to the International Telecommunication Union Telecommunication Standardization Sector (ITU-T) [14], the terms QoS and QoE are defined as below:

- QoS— is defined as "the totality of characteristics of a telecommunications service that affect its ability to satisfy the stated and implied needs of the user of the service".
- QoE— is defined as "the degree of delight or annoyance of the user of an application or service. It results from the fulfilment of their expectations concerning the utility and/or enjoyment of the application or service in the light of the user's personality and current state".

Figure 2 illustrates a clear distinction between the QoS and QoE within the telecommunication domain. Unlike QoS, QoE encapsulates the comprehensive end-to-end performance of a service or application, incorporating not only the technical aspects but also the user's behaviour. Measuring QoE is recognized as a complex technique, involving not only technical factors, also known as objective factors, such as network devices, types of services, and environmental conditions during service usage by end-users but also taking into account the mood and tolerance level of the end-user at that particular instance, which are subjective factors.

2) READINESS OF EMPLOYING ADVANCED QOE MEASUREMENTS

Traditionally, legacy networks typically utilize generic QoE measurement, irrespective of specific services or applications. For instance, these measurements encompassed factors such as coverage area concerning the population's access to cellular technology, received signal strength on a mobile device, and speed tests conducted within a designated geographic area. However, these approaches have limitations when it comes to analyzing advanced 5G services and applications such as video streaming, mobile gaming, and augmented reality. This is because the network requirements for throughput (TP), uplink/downlink latency, jitter, and packet loss differ for each of these services and applications [15]. Therefore, it is imperative to leverage the standardization parameters to meet the increasing demands for a good user experience. In this regard, ITU-T has taken the initiative to standardize QoE measurements for video streaming [7], [16], with ongoing efforts for cloud gaming [17] and video telephony [18]. Furthermore, industrial entities like Ericsson have committed to implementing a robust service quality monitoring mechanism that involves all the stakeholders including CSPs, application developers, aggregators, and enterprise customers, responsible for delivering the services and applications to the end-users. This approach aims to facilitate the collection of real-time pertinent information on end-user experiences, aiding the stakeholders in optimizing services and applications for improved QoE management [19].

C. RELATED WORK AND MOTIVATION

Liu et al. [20], Ternera et al. [21], Wang et al. [22], Deng et al. [23], and Hiranandani et al. [24] worked on evaluating QoE for Video streaming applications. However, the proposed mechanisms emphasised applications other than the cellular mobile infrastructures. In another research, the author Gu et al. [25] modelled the mapping between QoE and QoS by conducting a statistical analysis on the real-time network conversational video streams. Xu et al. [26] conducted research on QoE-QoS mapping for services offered by satellite networks, whereas the proposed research mainly centres on QoS-QoE mapping in terrestrial communications, specifically emphasizing mobility management within cellular networks. In another study [27], the author integrated QoE investigation within mobile networks, but with a predominant emphasis on regulator and business perspectives. Wang et al. [28] introduced a model aimed at improving the QoS of applications by leveraging user mobility within indoor femtocell coverage areas along with predefined trajectory paths. In contrast, our study extends beyond QoS-QoE mapping to include interference management and UE load balancing, all geared towards enhancing the end-user experience. Reference [29] introduced a novel scheduling scheme to improve the performance of HTTP streaming services in LTE systems, with a focus on metrics aimed at reducing the jerkiness of streaming videos. Hori and Ohtsuki [30] introduced a two-step algorithm that integrated resource scheduling schemes to elevate end-user QoE by improving the TP levels. However, our approach differs as it aims to enhance SINR and TP levels for users during mobility. Reference [31] evaluated the efficacy of three distinct LTE downlink scheduling schemes across various user mobility scenarios, with an assumption of packet loss and delay. In contrast, our approach focuses on improving the SINR and TP levels for users while in motion.

D. OUR CONTRIBUTIONS

The main objective of this research is to investigate the end-user experience during mobility, particularly in the handover regions, where UEs encounter low signal levels from both serving and surrounding base stations (BSs). This study is particularly relevant as certain 5G use-case scenarios mimic similar conditions, as explained below [32].

- Implementation of novel Cooperative Connected and Automatic Mobility (CCAM) services with the use-case of Tele-operated Driving (ToD).
- Establishment of Wireless Content Production (WCP) capabilities, facilitating instantaneous real-time news coverage and live broadcasting of economic, and political rallies/events passing through dedicated urban routes.
- Provision of dedicated temporary cellular services for first responders in medical emergencies, enabling seamless connectivity between on-site medical teams and central response facilities such as control rooms and hospitals.

Hence, CSPs must have a guaranteed level of service quality to the end users. The goal of this work is to identify the shortcomings in meeting these standards and propose solutions to achieve them. To that end, the contributions of this work are as follows;

- Comparative analysis of various UE-BS association mechanisms, considering both *Reference Signal Received Power* (RSRP) levels and UE load during UE mobility within the handover region, aiming to enhance the UE throughputs levels, by connecting UEs to BSs with the highest RSRP levels/lower UE loads.

TABLE 1. Mean Opinion Score (MOS) values.

Anticipated Quality	MOS Value
Excellent	5
Good	4
Fair	3
Poor	2
Bad	1

- Incorporating a utility function with the obtained simulation results, to map the QoS to QoE. The validity of this utility function has been theoretically confirmed by one of the co-authors of this manuscript, Manzoor, in his earlier work [33].

The rest of the paper is organized as follows: Section II presents the system model and assumptions needed for the simulation campaign. Section III describes the simulation setup considered, including the parameters, followed by a discussion of the obtained simulation results. Finally, conclusions are drawn in Section IV.

II. SYSTEM MODEL

Prior to delving into the system modelling, it is pertinent to reference the research work [33] conducted by one of the co-authors, Manzoor. In this work, a utility function, a concept borrowed from economics, was theoretically validated. This utility function, also referred to as a user satisfaction function, is designed to translate the QoS to QoE, by gauging end-user satisfaction following the use of a given service and application. This research work served as a motivation for the simulation campaigns conducted in the context of this study. It is noted that various metrics are available to translate the QoS into QoE across different services and applications. For example, real-time applications often utilize the Mean Opinion Score (MOS) [34] metric to capture the end-user behaviour and usage experience. This experience is categorized as excellent, good, fair, bad, and poor, which can be numerically represented within the range of 0 to 5 as represented in Table 1. Furthermore, the non-real-time applications can be categorized via TP or goodput levels.

A. THROUGHPUT TO MOS TRANSFER FUNCTION

1) UTILITY FUNCTION

We adapt the utility function $\bar{u}_{j,o}\left(\frac{b^c_{o,k}}{n_{o,k}}\right)$ from [33] with some modifications as presented in Eq (1).

$$\bar{u}_{j,o}\left(\frac{b^c_{o,k}}{n_{o,k}}\right) := \begin{cases} 0, & if \quad \dfrac{b^c_{o,k}}{n_{o,k}} \leq \underline{b}^c_{o,k} \\ \mu_k\left(\dfrac{b^c_{o,k}}{n_{o,k}}\right) \cdot \dfrac{1 - e^{-\beta(b^c_{o,k} - \underline{b}^c_{o,k})}}{1 - e^{-\beta(\overline{b}^c_{o,k} - \underline{b}^c_{o,k})}}, & if \quad \underline{b}^c_{o,k} \leq \dfrac{b^c_{o,k}}{n_{o,k}} \leq \overline{b}^c_{o,k} \\ \mu_k\left(\dfrac{b^c_{o,k}}{n_{o,k}}\right). & if \quad \dfrac{b^c_{o,k}}{n_{o,k}} \geq \hat{b}^c_{o,k}, \end{cases} \tag{1}$$

Here, $\mu_k\left(\frac{b^c_{o,k}}{n_{o,k}}\right)$ is the maximum level of user satisfaction under ideal conditions for a user of type k with an application, real-time (RT) or non-real-time (NRT), of QoS class c from operator c. Where, n denotes the number of users and the the expression $b^c_{o,k}$ denotes the assigned bandwidth to user type k for an application QoS class c, ranging from $\underline{b}^c_{o,k}$ to $\overline{b}^c_{o,k}$ which respectively denote the minimum and maximum required bandwidth requirements for the application. It is noted that we use bandwidth and throughput requirements interchangeably here.

2) APPLICATION SENSITIVITY FACTOR (β) IN MOBILITY MANAGEMENT

In equation (1), the parameter β signifies the application's sensitivity to the bandwidth allocated to the user type k with values ranging from 0 to 1. This work specifically focuses on RT applications, which typically have a minimum bandwidth requirement for admission as illustrated in Figure 3 where this behaviour is depicted by a step function. When the application's required bandwidth is met, the user experiences maximum utility (green region). However, if the allocated bandwidth falls slightly below the minimum threshold, the utility drops to zero (yellow region). The sensitivity factor plays a crucial role in user mobility, especially when the network initiates the handover procedures for the users in the transition region. As shown in Figure 3, the light yellow region represents the transition zone between satisfied and unsatisfied user's states, adjusted by the parameter β. For instance, consider a user engaged in RT activities such as Video broadcasting with MPEG1 coding standard, which necessitates bandwidth ranging from 1.2 Mbps to 1.5 Mbps. These ranges delineate the transition region, aiding the network in determining whether to initiate the handover procedure if the service is sub-optimal. By adjusting the parameter β, the network can modulate the width of the transition region; higher values of β, narrow the region, leading to stricter bandwidth requirements to distinguish between satisfactory and unsatisfactory users as depicted in Figure 4. Moreover, Figure 5 shows the translation of achievable TP rates into MOS values for different applications of different service classes with minimal bandwidth requirements.

B. PROPOSED SIMULATION SETUP

This section details the system model employed in our simulation setup. This study facilitates a comparative assessment of two approaches aimed at establishing connectivity between the user equipment and the base stations within the handover region during user mobility as detailed in the subsequent subsections. It is noted that the proposed mobility approach will replicate the environment outlined in the motivation described in the contribution section of this study.

- *RSRP-only*— The UE establishes a connection with the BS offering the highest RSRP within the handover region. This association between UE and BS is referred to as RSRP-only throughout this paper.

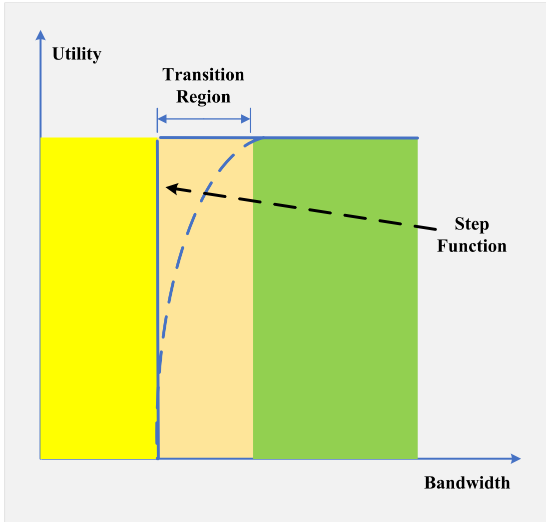

FIGURE 3. Transition region between fully-satisfied and fully-unsatisfied users.

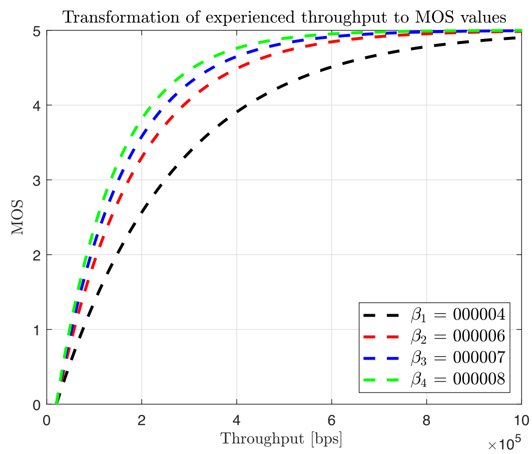

FIGURE 4. Impact of application's sensitivity factor β on the user satisfaction level as higher values of β, narrow will be the transition region between satisfactory and unsatisfactory user as also depicted by light yellow region in Figure 3.

- *RSRP + Load Balancing*— The UE establishes a connection with the BS that offers both the highest RSRP as well as serves a lower number of UEs, indicating less UE load. This method is referred to as RSRP + Load Balancing (LB) abbreviated as RSRP+LB throughout this paper.

It is noted that the RSRP+LB scheme proves to be more efficient in urban environments due to the interference-limited scenario and frequent handover between BSs. For instance, during mobility, UE often encounters significant interference from the neighbouring BSs serving other UEs within the same frequency spectrum. Additionally, the heterogeneous network environment leads to frequent handovers for UEs, as each BS operates with varying transmission power and coverage areas, increasing the likelihood of handover occurrences. Consequently, it elevates the risk

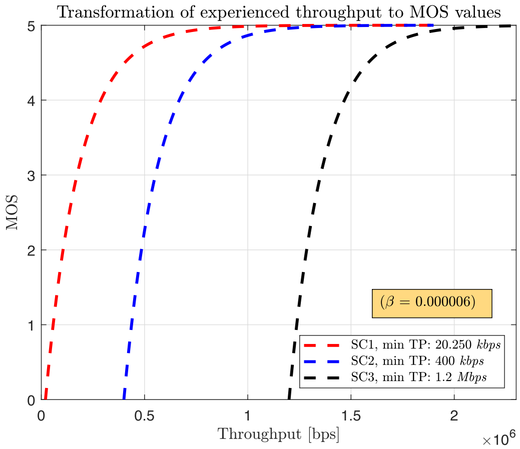

FIGURE 5. Translation of achievable throughput rates into utility-based MOS values for three different applications of different service classes (SC), $\beta = 0.000006$ and minimum bandwidth requirements.

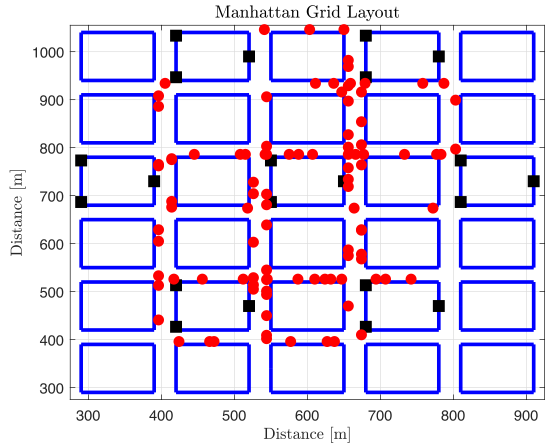

FIGURE 6. Manhattan grid layout constitutes of 30 squared-buildings (100 × 100 meter), with base station (black squares) mounted on building walls and user equipment (red circles) randomly deployed in streets with 100 meters wide on the proposed path trajectory.

of QoS degradation for the UEs, making it challenging for the CSPs to uphold the promised QoE levels for end users. Therefore, it becomes essential to facilitate the handover of UEs to the BS offering the best RSRP (resulting in an enhanced SINR level) and serving fewer UEs. This approach allows for the allocation of more bandwidth resources and ultimately leads to improved QoE for UEs.

It is also important to highlight that this work primarily emphasizes the performance assessment of UEs located within the handover region during mobility. These UEs within the handover region encounter degraded signals from their own serving BS and are subjected to high co-channel interference from the neighbouring BS, resulting in poor SINR levels and eventually, poor QoS. Throughout this paper, we refer to these UEs within the handover region as *Priority UE* (PUE).

Moreover, it is important to note that the data rate/TP achieved on the direct link between the UE and BS is contingent upon the allocated bandwidths and the received SINR levels. Hence, in the simulation flow, we first calculate the SINR on each *Physical Resource Block* (PRB) for each UE served by the corresponding BS and then map the obtained SINR into the average TP. Consequently, under Shannon's modified equation [35], [36], the attainable data rate during the transmission time interval (TTI) that corresponds to each radio frame is expressed as follows:

$$\mathrm{TP} = B_{PRB} \cdot B_{eff} \cdot \log_2\left(1 + \left(\frac{SINR}{SINR_{eff}}\right)\right) \tag{2}$$

The above Shannon's modified formula is adjusted by two parameters namely bandwidth efficiency (B_{eff}) and SINR efficiency ($SINR_{eff}$). It is noted that $B_{eff} = 1.15$, $SINR_{eff} = 0.96$, for 4 × 4 MIMO configuration along with *Round Robin* (RR) scheduler for distributing the radio resources [36]. Additionally, we have incorporated a pre-defined maximum spectral efficiency of 4.1 b/s/Hz and a minimum SINR of -7 dB for the direct link. However, it is acknowledged that the link and the achievable TP performances may deteriorate due to degradation in downlink (DL) control signalling quality. For instance, interference from cell-specific reference signals (CRS) from the neighbouring cells can degrade the cell edge TP performance of UEs [37]. In this study, the TP is considered to be zero, if the SINR level falls below the specified threshold.

III. EXPERIMENTAL RESULTS AND PERFORMANCE EVALUATION

To evaluate the performance of the proposed model, we consider a cellular network with 21 base stations in a Manhattan grid configuration as shown in Figure 6. The assumed layout covers an area of 1000 × 1000 meters. The proposed area is divided into evenly spaced (street width of 100 meters) squares measuring 30 blocks. Each square block represents a building with dimensions of 100 × 100 meters. These buildings are deployed with the outdoor base stations (depicted as black squares), mounted on the walls. Additionally, the streets are populated with user equipment and randomly distributed as depicted by red circles. It is noted that the UE establishes the connection with BS that exhibits good RSRP. We utilize the 3rd Generation Partnership Project (3GPP) channel models to compute the distance-dependent path loss encountered on the direct link [38]. The simulation parameters used to model the problem and enable Monte Carlo simulations on MATLAB tool, are presented in Table 2.

To evaluate the performance, we conduct the following simulation campaigns. In the *RSRP Only* scenario, UEs establish a connection with BS offering the highest RSRP levels. Additionally, in *RSRP+LB*, we assess the performance considering both RSRP levels and the load of UEs connected to the BS. This implies that UE will connect to the BS, providing wireless connectivity with favourable RSRP while also serving fewer UEs.

TABLE 2. Simulation parameters.

Paramters	Values
Operating Bandwidth	10 MHz
Channel Models	3GPP [38]
Number of PRBs	48 for data
Resource Scheduling Method	Round Robin (RR)
Transmission Power	33 dBm
BS Antenna Elevation	25 m
Antenna Gain	14 dBi
UE Antenna Elevation	1.5 m

TABLE 3. Impact on SINR levels experienced by priority UEs at 10^{th}%-ile, 50^{th}%-ile and 90^{th}%-ile for different use-case scenarios.

Impact on SINR levels [dB]			
1*	RSRP only	RSRP+LB for CB=2	RSRP+LB for CB=3
10^{th}%-ile	-3.5	-4	-12.4
50^{th}%-ile	-1.3	-2	-3
90^{th}%-ile	0.3	-0.12	-0.4

We further analyze the *RSRP+LB* scenario by expanding the scope to include an additional BS in the handover process. This introduces the option of a third BS with a lighter UE load compared to the two BSs initially involved in the handover process. We call these scenarios as follows below:

- *RSRP+LB/Candidate BS (CB) = 2*—This implies that the handover process of the UE involves two BSs; such that the serving BS offers the best RSRP and a neighbouring BS with both the best RSRP and lighter UE loads.
- *RSRP+LB/Candidate BS (CB) = 3*—This implies that the handover process of the UE involves three BSs; such that, the serving BS offering the best RSRP, a neighbouring BS with both the best RSRP and fewer UE loads, and an additional neighbouring BS with fewer UE loads as compared to the previous mention two BSs.

A. SIMULATION RESULTS

This section provides the simulation results for the aforementioned scenarios related to the cumulative distribution function (CDF) of the SINR per PRB along with the associated throughput (TP) experienced by the UE.

1) ACHIEVED SINR PER PRB

This subsection discusses the impact on the SINR levels per PRB for Priority UE. These types of UEs always located within the handover region encounter degraded signals from their own serving BS and are subjected to high co-channel interference from the neighbouring BS, resulting in poor SINR levels and eventually, experiencing poor QoE. Figure 7 presents the CDF of SINR per PRB in RSRP only and RSRP+LB scenarios.

As anticipated, the SINR performance of PUEs is notably lower (dashed curves) compared to the other non-priority UEs (solid curves) in the network as shown in Figure 7. This is attributed to the fact that the latter experience reduced distance-dependent path loss towards their serving

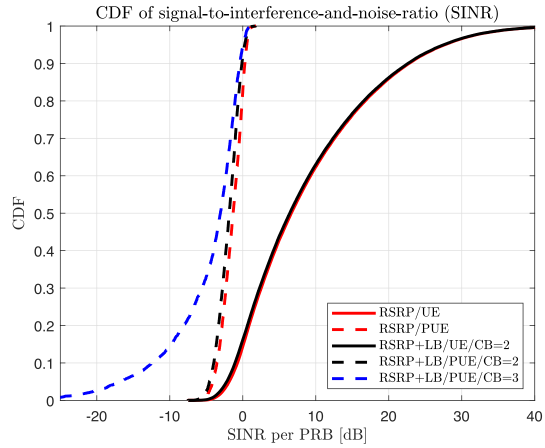

FIGURE 7. CDF of signal-to-noise-and-ratio (SINR) per PRB.

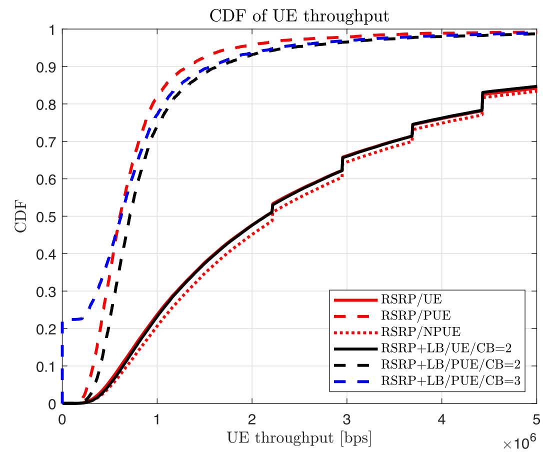

FIGURE 8. CDF of UE TPs for different use case scenarios.

BSs, resulting in improved RSRP and thus translating into improved SINR levels. Furthermore, it is noted that the SINR levels are superior in the scenario of RSRP only as compared to RSRP+LB/CB = 2. This degradation arises because, in the latter scenario, PUEs experience persistent high co-channel interference from the previous serving BS, even after handover to a potential target BS with a lower UE load. Moreover, this SINR degradation becomes more pronounced when the number of candidate BSs exceeds two, as observed in RSRP+LB/CB = 3. This is primarily attributed to the pivotal role of low UE load in initiating the UE handover process. Thus, UE benefits from abundant bandwidth resources, although experiences significant co-channel interference from other BSs as indicated by the SINR outcomes (blue dash curve) as shown in Figure 7. Table 3 summarizes the SINR per PRB levels for the aforementioned scenarios.

2) ACHIEVED UE THROUGHPUT LEVELS

Figure 8 illustrates the CDF of TP experienced by UEs. As anticipated, it is evident that the TP performance of priority UEs improves in the RSRP+LB/CB=2 scenario

TABLE 4. Impact on TP levels experienced by the priority UEs at 10^{th}%-ile, 50^{th}%-ile and 90^{th}%-ile for different use-case scenarios.

Impact on TP levels [kbps]			
1*	RSRP only	RSRP+LB for CB=2	RSRP+LB for CB=3
10^{th}%-ile	323	400	0
50^{th}%-ile	607	711	619
90^{th}%-ile	1324	1633	1560

TABLE 5. Impact on TP levels experienced by the priority UEs at 10^{th}%-ile, 50^{th}%-ile and 90^{th}%-ile for different candidate base station scenarios.

Priority UE TP levels [kbps]				
2*	CB=2		CB=3	
	RSRP only	RSRP + LB	RSRP only	RSRP + LB
10^{th}%-ile	323	400	566	676
50^{th}%-ile	607	711	1122	1303
90^{th}%-ile	1324	1632	2705	3107

as compared to the RSRP-only case. This improvement is attributed to the fact that, despite encountering high interference from the previous serving BS after handover to a potential target BS with a lower UE load, PUEs are allocated more PRBs from the BS bandwidth resource pool due to reduced UE load. Consequently, the reception of additional bandwidth resources translates into enhanced TP levels as depicted by the black-dashed curve in Figure 8.

Furthermore, it is observed that in the RSRP+LB/CB=3 scenario, PUEs have access to an ample amount of bandwidth resources, resulting in TP enhancement at 70^{th}%-ile and beyond. However, this increase in TP comes at a cost, as 23% of PUEs experiencing network outages. Such a high outage rate is deemed unacceptable for CSPs, as it jeopardizes their ability to uphold the promised QoS and QoE levels for their customers. Table 4 summarizes the TP levels for the above-explained scenarios.

Figure 9 further expands our analysis by examining the influence of the number of UE randomly deployed in the network. Here, we conduct the simulation campaigns for two scenarios, with 100 and 50 deployed UEs in the proposed path trajectory. The motivation for incorporating this scenario is to assess performance variations at different times of the day, such as peak hours, when streets are typically crowded with mobile users as compared to non-peak hours, such as late-night periods. It is evident from the results that a lower number of UEs in the network results in reduced UE load on the BSs, allowing ample amount of bandwidth resources to be available for the priority UEs. This surplus of the amount of PRBs contributes to improved TP performances. This observation underscores the importance, particularly in urban mobility scenarios, of CSPs, while considering the UE load when promising services to customers with a specified level of QoE. Table 5 summarizes the TP levels for the aforementioned scenarios.

IV. CONCLUSION

This paper conducts a comparative analysis of various User Equipment - Base Station association mechanisms, focusing on understanding UE experiences during mobility,

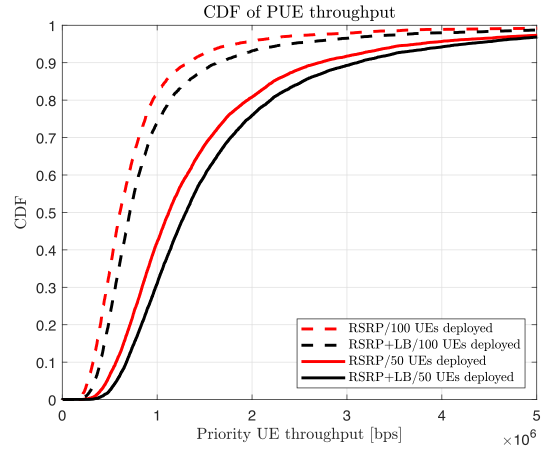

FIGURE 9. Impact on the QoE encountered by the priority UEs due to the density of UE load in the network.

particularly in the handover region, where UEs encounter low signal levels from the surrounding BSs. This investigation also includes assessing the services provided with promised QoS levels to the end users and translating these QoS levels into QoE. In this context, this study presents a comparative assessment of UE-BS connectivity based on different parameters, such as experienced RSRP and UE load at BS. The objective is to optimize end-user performance by enhancing the SINR/TP levels. This connects the priority UEs (PUE) located in the handover region to the BSs with the highest RSRP levels and lower UE loads. Additionally, the study employed a theoretical approach to map the provided QoS to QoE, translating simulation results into MOS, to capture the end-user behaviours and usage experiences. The findings demonstrated a notable enhancement in the throughput performance of priority UEs when served by BSs, with the highest RSRP levels and lower UE loads. Despite encountering low signal levels from surrounding BSs in the handover region, resulting in degraded SINR levels, this issue can be mitigated by connecting the UEs to BSs with fewer UE loads. Furthermore, the results indicate that a network with low UE load at the BSs provides an excess of bandwidth resources to priority UEs, leading to enhanced TP performances and ultimately, better QoE for end users. Therefore, it is recommended that CSPs need to adopt a dynamic approach to ensure good signal levels and sufficient bandwidth resources, guaranteeing satisfactory QoS and QoE levels.

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