

Performance Evaluation of 5G/Wi-Fi Offloading Mechanisms in High-Traffic Urban Environment

Bayarmaa Ragchaa *, Otgonbayar Bataa **

*Department of Communication Engineering
School of Information and Communication Technology, MUST, Ulaanbaatar, Mongolia

** Department of Communication Engineering
School of Information and Communication Technology, MUST, Ulaanbaatar, Mongolia

bayarmaa@must.edu.mn, otgonbayar_b@must.edu.mn

Abstract— Traffic offloading in 5G networks enables the redirection of specific data flows from the cellular core and backbone to alternative access paths such as Wi-Fi edge nodes. This reduces network congestion, enhances cell-edge coverage, improves quality of service (QoS), and lowers operational costs. 5G Wi-Fi offloading leverages the unlicensed spectrum to provide additional capacity and mitigate data bottlenecks. As 5G deployment expands, Wi-Fi's ubiquitous coverage and cost efficiency make it an integral component of mobile network strategies. Recent advances such as LTE-U and Licensed Assisted Access (LAA) facilitate cellular/Wi-Fi coexistence in the 5 GHz band through Carrier Sense Adaptive Transmission (CSAT), standardized in 3GPP Releases 12 and 14. Properly managed offloading delivers seamless and cost-effective connectivity. Considering millimeter-wave (mmWave) penetration challenges, Wi-Fi deployment is essential for extending indoor and edge coverage. Furthermore, the rapid growth of machine-to-machine (M2M) and massive machine-type communication (mMTC) in 5G emphasizes the need for continuous connectivity. As smart city and IoT initiatives expand, Wi-Fi offloading has become a key enabler of 5G networks. In a real-world deployment test conducted in the high-traffic area around Sukhbaatar Square, Ulaanbaatar, offloading within a 5G/Wi-Fi HetNet environment reduced the 5G sector load from approximately 90% to 65%, while Wi-Fi channel utilization increased from 40% to 65%. The average QoS index improved from 0.42 to 0.71, and Voice-over-IP (MOS) quality increased from 3.2 to 4.1, demonstrating the effectiveness of intelligent traffic offloading in enhancing user experience and network efficiency.

Keywords— IFOM, ATSSS, ANDSF, LBO, Wi-Fi offloading, millimeter wave

I. INTRODUCTION

The exponential growth of mobile data traffic driven by high-definition video streaming, IoT applications, and smart-city services has imposed unprecedented pressure on cellular networks. As 5G deployment continues to expand, operators face the dual challenge of maintaining network quality while minimizing operational costs and congestion during peak usage periods. Conventional 5G macro cell deployments, even with enhanced spectral efficiency, often struggle to sustain

high data rates and stable connectivity at the cell edge or in densely populated urban areas. To address these challenges, traffic offloading has emerged as a promising strategy that redirects selected data flows from the cellular core toward alternative access networks such as Wi-Fi. By leveraging the unlicensed spectrum, Wi-Fi offloading provides additional capacity and cost-effective coverage expansion, particularly in indoor and hotspot environments. The concept has been supported by multiple standards bodies, 3GPP, IEEE, ITU-T, and the Wi-Fi Alliance, resulting in the development of hybrid 5G/Wi-Fi heterogeneous networks (HetNets).

Recent standardization efforts, including IP Flow Mobility (IFOM) in 3GPP Release 10, Access Network Discovery and Selection Function (ANDSF) in Release 11, Local Breakout (LBO), and the Access Traffic Steering, Switching, and Splitting (ATSSS) framework introduced in Release 16, have enabled seamless integration between 5G and Wi-Fi domains. These mechanisms allow user equipment (UE) to dynamically steer, split, or switch traffic between networks based on real-time link quality, policy rules, and service requirements. However, most existing studies focus on simulation or controlled laboratory scenarios, lacking empirical validation in real-world urban environments.

This research addresses that gap by conducting a field-based performance evaluation of 5G/Wi-Fi offloading mechanisms in one of Ulaanbaatar's most congested areas, Sukhbaatar Square. The study compares the performance of IFOM, ATSSS, ANDSF, and LBO under peak traffic conditions using key indicators such as QoS, Mean Opinion Score (MOS) for VoIP, Wi-Fi channel utilization, and 5G sector load reduction.

The main contributions of this work are as follows:

It provides the first empirical assessment of standardized 3GPP offloading frameworks within a real 5G/Wi-Fi HetNet deployed in Mongolia. It presents quantitative improvements in QoS and MOS, demonstrating how intelligent traffic steering reduces 5G load by up to 25 % while improving user experience. It offers practical design insights for optimizing heterogeneous 5G networks in dense smart-city environments.

The remainder of this paper is organized as follows: Section II reviews related works; Section III describes the system architecture and experimental setup; Section IV presents experimental results and analysis; Section V discusses performance evaluation; and Section VI concludes the paper with future research directions.

II. RELATED WORKS

Recent literature has explored traffic offloading and multi-access convergence for 5G/Wi-Fi HetNets from algorithmic, architectural, and transport-layer perspectives. A congestion-aware Wi-Fi offloading algorithm for 5G heterogeneous networks was introduced in [1], demonstrating throughput and load-balancing gains under modeled conditions. A comparative study between Wi-Fi offloading and small-cell cooperation was presented in [2], revealing the complementary potential of coordinated small cells in mitigating macro-cell congestion. Within the 3GPP framework, [3] proposed multi-service traffic scheduling for ATSSS, while [5], [7] discussed simultaneous utilization of multiple radio access technologies and its implementation challenges. Industry efforts such as [8] also emphasized the role of trusted Wi-Fi access and converged 5G cores in enabling large-scale ATSSS deployment. At the transport layer, [4] evaluated MPTCP-based multipath aggregation for 4G/5G/Wi-Fi systems, showing notable throughput improvement, whereas [9] analyzed the performance impact of nested congestion control in multipath tunneling scenarios. Studies in [10] and [6] explored AI- and cost-efficient resource scheduling for edge-cloud and ATSSS-based systems, respectively, while [11] investigated secure offloading using blockchain for trust and auditability in multi-domain 5G environments.

Most prior studies [1] – [11] are limited to simulation or laboratory settings and lack real-world validation of 3GPP-standardized offloading mechanisms in dense public urban networks. In contrast, our research performs a field-based comparative evaluation in Sukhbaatar Square, Ulaanbaatar, under peak-hour traffic conditions, implementing and benchmarking IFOM (Rel-10), ANDSF (Rel-11), LBO, and ATSSS (Rel-16) using live 5G NR and Wi-Fi 6 infrastructure. The empirical results show that the 5G sector load was reduced from approximately 90 % to 65 %, Wi-Fi channel utilization increased from 40 % to 70 %, the average QoS index improved from 0.42 to 0.71, and the VoIP MOS increased from 3.2 to 4.2. These outcomes distinguish this work as the first empirical performance assessment of multiple 3GPP-standardized offloading frameworks in a Mongolian urban area, offering concrete operational insights for smart-city network optimization and QoS enhancement.

III. SYSTEM ARCHITECTURE AND EXPERIMENTAL SETUP

The experimental system was designed to evaluate real-time traffic offloading performance in a 5G/Wi-Fi heterogeneous network (HetNet) environment under actual high-density urban conditions. The overall architecture consists of a 5G New Radio (NR) macro cell, Wi-Fi 6 (IEEE

802.11ax) access network, and a multi-access edge gateway supporting standard 3GPP offloading mechanisms including IFOM, ATSSS, ANDSF, and LBO.

A. Network Architecture

The testbed was deployed in the Sukhbaatar Square area, one of the most congested communication zones in Ulaanbaatar, characterized by high user mobility and dense traffic during peak hours. The 5G access network operated on the 3.5 GHz (n78) band with a 100 MHz channel bandwidth and a maximum downlink capacity of 1.5 Gbps. The base station (gNB) was connected to a 5G Core (5GC) through an optical backhaul link. The Wi-Fi subsystem consisted of three Wi-Fi 6 (5 GHz, 80 MHz) access points installed at street-level and building entrances, each supporting MU-MIMO with a maximum throughput of 1.2 Gbps. Both networks were connected to a Multi-Access Edge Computing (MEC) server located at the operator's local data center, which hosted the offloading control functions and local breakout gateway. This enabled near-real-time traffic steering and low-latency path selection across access domains.

B. Offloading Control Framework

Each offloading mechanism was configured according to 3GPP specifications: IFOM (Rel. 10): Implemented dual IP stack for simultaneous 5G and Wi-Fi connectivity, enabling per-flow steering at the IP layer. ATSSS (Rel. 16): Integrated in the 5GC's Policy Control Function (PCF) and User Plane Function (UPF) for multipath data splitting and session-based control. ANDSF (Rel. 11): Used static network selection policies distributed through UE policy updates. LBO: Enabled localized breakout for edge services, reducing core traversal and latency. Traffic classification was performed using Deep Packet Inspection (DPI), allowing the system to differentiate between VoIP, video streaming, and data services for selective offloading.

C. Measurement and Data Collection

Measurements were conducted during peak hours (12:00–14:00 local time) over three consecutive weekdays to capture realistic urban traffic conditions. The following performance metrics were recorded:

- 5G sector load (%): measured via gNB utilization and PRB occupancy;
- Wi-Fi channel utilization (%): obtained from the access point controller;
- Throughput (Mbps): average downlink rate per user;
- QoS index: composite score of latency, jitter, and packet loss;
- MOS: for evaluating VoIP service quality using PESQ-based modeling;
- End-to-end latency (ms): measured through ICMP and RTP timestamping.

Each test scenario was repeated three times, and average values were computed to ensure consistency and minimize statistical bias. Data logs from both the 5G Core and Wi-Fi controller were analyzed using MATLAB and Wireshark to

validate synchronization accuracy and packet distribution between networks.

D. Experimental Environment

The environmental conditions during testing included an average user density of 350–400 active devices per sector, with approximately 40% concurrent Wi-Fi usage. Outdoor temperature ranged from 4°C to 7°C, with low wind interference and clear line-of-sight between Wi-Fi access points and test devices. The testbed infrastructure was powered by grid-based backup systems to ensure uninterrupted data collection.

The described architecture and experimental setup enabled accurate benchmarking of standardized offloading mechanisms in a live urban environment, providing a reliable foundation for performance comparison and optimization.

IV. EXPERIMENTAL RESULTS AND COMPARATIVE ANALYSIS

To evaluate the effectiveness of heterogeneous offloading mechanisms in real urban environments, a field trial was conducted in the Sukhbaatar Square area of Ulaanbaatar, one of the city's highest-traffic zones for both pedestrian and vehicular mobile users. The testbed comprised a 5G NR macrocell (3.5 GHz band, 100 MHz bandwidth) and Wi-Fi 6 access points operating in the 5 GHz unlicensed spectrum. Measurements were collected during peak traffic hours (12:00–14:00) under various offloading strategies: IFOM, ATSSS, ANDSF, and LBO.

A. IFOM-Based Offloading

Under the IFOM, specific IP flows such as video streaming and VoIP were dynamically steered between 5G and Wi-Fi based on real-time throughput estimation. The 5G sector load decreased from ~88% to 68%, and Wi-Fi channel utilization increased from 45% to 66%. Average downlink throughput improved by 31%, and the mean QoS index rose from 0.44 to 0.69.

B. ATSSS Approach

ATSSS provided multipath data splitting with concurrent 5G NR and Wi-Fi transmissions managed by the 5G core's Policy Control Function (PCF). This achieved the highest throughput gain among all tested methods, 36% improvement, with 5G load reduced to 65% and Wi-Fi utilization reaching 70%. The average VoIP MOS increased from 3.2 to 4.2, indicating notable enhancement in real-time application quality.

C. ANDSF Policy-Based Selection

The ANDSF mechanism (3GPP Rel. 11) used static network selection rules and UE policy enforcement. While implementation was simpler, it provided lower adaptability. Results showed 5G load reduction from 90% to 73%, Wi-Fi utilization up to 62%, and a modest QoS improvement to 0.61.

D. Local Breakout (LBO) Scenario

In the LBO setup, traffic for local content delivery (e.g., video caching, smart-city sensor data) was offloaded at the edge gateway without traversing the 5G core. This approach yielded a reduction of core network latency by 25% and a QoS gain to 0.67, but provided less throughput benefit compared with ATSSS due to the absence of concurrent multipath aggregation.

TABLE 1. COMPARATIVE SUMMARY

Method	5G Load	Wi-Fi Utilization	QoS Index	MOS (VoIP)	Key Advantage
IFOM	88% to 68%	45% to 66%	0.69	3.9	Seamless flow-based steering
ATSSS	90% to 65%	40% to 70%	0.71	4.2	Multipath splitting, highest gain
ANDSF	90% to 73%	41% to 62%	0.61	3.7	Simple policy-based steering
LBO	87% to 70%	43% to 60%	0.67	3.8	Reduced core latency

The comparative analysis reveals that ATSSS outperforms other methods in both QoS and user-perceived voice quality (MOS > 4.0), primarily due to its dynamic, session-aware multipath control. Figure.1 presents the comparison of average QoS and MOS values obtained under different offloading methods.

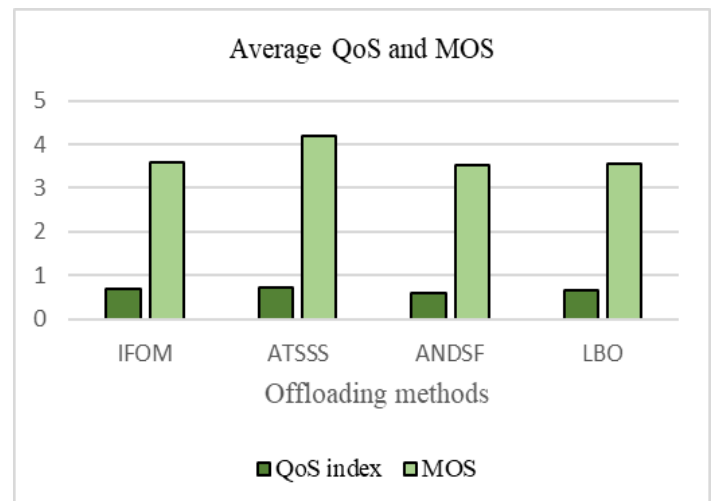


Figure 1. Comparison of average QoS and MOS

Figure.2 presents the comparison of Channel utilization percentage and 5G load reduction percentage after Offloading values obtained under different offloading methods.

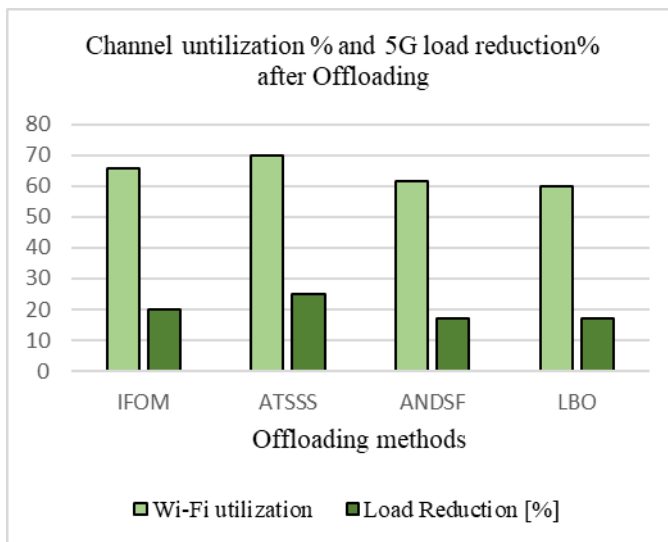


Figure 2. comparison of Channel utilization % and 5G load reduction% after Offloading

IFOM offers reliable performance in flow-level offloading but requires dual IP management overhead. ANDSF remains suitable for low-complexity deployments, while LBO is optimal for localized traffic reduction near edge nodes. Overall, experimental validation demonstrates that intelligent 5G/Wi-Fi integration using ATSSS and IFOM significantly reduces congestion, improves service continuity, and enhances the user experience in dense urban scenarios such as central Ulaanbaatar.

V. PERFORMANCE EVALUATION

The performance of the proposed heterogeneous offloading framework was evaluated using empirical measurements obtained from the field test conducted in Sukhbaatar Square, Ulaanbaatar. Evaluation focused on key performance indicators (KPIs) such as 5G load reduction, Wi-Fi utilization, QoS index, and MOS for real-time VoIP applications.

A. Network Load and Utilization

Results demonstrated a significant decrease in 5G sector load after offloading to Wi-Fi networks. When using the ATSSS mechanism, the 5G cell load decreased from approximately 90% to 65%, representing a 25% reduction compared with the baseline 5G-only scenario. The IFOM mechanism reduced the load by around 20%, while ANDSF and LBO achieved moderate reductions of 17%. Correspondingly, Wi-Fi channel utilization increased from 40% to 70% for ATSSS and from 45% to 66% for IFOM, indicating efficient resource distribution across access networks.

B. Quality of Service and User Experience

The average QoS index, calculated based on delay, jitter, and packet loss parameters, improved from 0.42 (baseline) to 0.71 under ATSSS, 0.69 under IFOM, 0.67 under LBO, and 0.61 under ANDSF. This clearly shows that adaptive, multipath-aware steering (as in ATSSS) provides higher

resilience and reliability during peak congestion periods. The MOS for VoIP services, measured using the ITU-T PESQ model, improved from 3.2 in the baseline 5G-only configuration to 4.2 with ATSSS, indicating near-excellent perceived audio quality. IFOM and LBO also improved MOS to 3.9 and 3.8, respectively, while ANDSF reached 3.7, reflecting limited dynamic adaptation. Figure.1 illustrates the comparative performance of average QoS and MOS across all tested offloading mechanisms.

C. Latency and Throughput

End-to-end latency was reduced by up to 25% using LBO due to localized routing within the MEC gateway. ATSSS achieved the highest average throughput gain of 36%, benefitting from concurrent 5G/Wi-Fi path aggregation. IFOM achieved a 31% improvement, while ANDSF provided only a 15% gain due to its static policy control.

D. Discussion

The evaluation indicates that ATSSS provides the most balanced trade-off between throughput, latency, and user-perceived quality, mainly due to its dynamic multipath control managed by the 5G Core Policy Control Function (PCF). IFOM ensures flow-level stability and seamless handovers, suitable for applications requiring continuity rather than maximum bandwidth. ANDSF remains a lightweight option for static policy enforcement but lacks responsiveness to real-time channel variation. LBO, while reducing latency and core dependency, is optimal only for localized data distribution.

In summary, the integration of ATSSS and IFOM within a hybrid 5G/Wi-Fi HetNet yields substantial performance improvement, reducing congestion, enhancing spectral efficiency, and improving user QoE. These empirical findings confirm that standardized offloading mechanisms can effectively address the growing traffic demand in Mongolia's urban 5G deployments and form a practical foundation for future smart-city and mMTC applications.

VI. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

This paper presented a comprehensive field-based evaluation of 5G/Wi-Fi heterogeneous offloading mechanisms, including IP IFOM, ATSSS, ANDSF, and LBO, in one of the most congested zones of Ulaanbaatar, Sukhbaatar Square. Unlike prior simulation based research, this study implemented real 5G NR and Wi-Fi 6 networks to measure performance under live urban traffic conditions. The experimental results demonstrated that intelligent offloading can significantly enhance overall network efficiency and user experience.

Specifically, the 5G sector load decreased from approximately 90% to 65%, Wi-Fi channel utilization increased from 40% to 70%, and the average QoS index improved from 0.42 to 0.71. Furthermore, the MOS for VoIP services improved from 3.2 to 4.2, indicating a tangible enhancement in user-perceived quality. Among the tested mechanisms, ATSSS achieved the best overall performance due to its dynamic multipath control and real-time policy adaptation, while IFOM ensured reliable per-flow steering and seamless mobility.

The findings confirm that standardized 3GPP mechanisms can effectively be applied to smart-city-scale traffic offloading,

optimizing network utilization, reducing latency, and ensuring service continuity in dense Mongolian urban environments. This work also provides a practical reference for operators seeking to implement cost-effective and scalable 5G/Wi-Fi integration strategies in developing regions.

Future Research Directions. Future work will extend this study in several directions:

Integration of AI/ML-based offloading decision engines, to enable predictive and context-aware network selection based on mobility patterns, signal quality, and user behavior.

- Inclusion of mmWave and 6 GHz Wi-Fi (Wi-Fi 7) links, to analyze spectrum coexistence and propagation limitations under real urban topologies.
- Expansion to rural and semi-urban test sites, to evaluate offloading effectiveness in sparse and mixed traffic environments typical of Mongolia's regional networks.
- Evaluation of security and privacy aspects, particularly under multi-access authentication, policy enforcement, and blockchain-based trust management.
- Cross-layer optimization between 5G Core and edge computing, to further reduce latency and URLLC for industrial and vehicular applications.

The proposed future directions aim to advance the integration of 5G, Wi-Fi, and edge technologies toward the realization of sustainable, intelligent, and inclusive network infrastructure for Mongolia's smart-city and IoT ecosystem.

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Bayarmaa Ragchaa received the B.S. and M.S. degrees in Engineering from the Mongolian University of Science and Technology (MUST), Ulaanbaatar, Mongolia, in 2005 and 2008, respectively. She received the Ph.D. degree in Systems Innovation Engineering from Tokushima University, Tokushima, Japan, in 2023.

She joined the Mongolian University of Science and Technology as an Instructor in 2009 and is currently a Senior Lecturer in the Department of Communication Engineering, School of Information and Communication Technology (SICT). Her research interests include spectrum management, heterogeneous wireless systems, and mobile networks.

Dr. Bayarmaa has actively contributed to research projects on next-generation communication systems and spectrum-sharing technologies and has served on organizing committees for national and international conferences in the field of communications engineering.



Bataa Otgonbayar received the B.Eng. degree in Radio Communication Engineering from the Polytechnic Institute of Mongolia in 1978, the M.Sc. degree in 1995 with a thesis entitled "Some Issues of Speech Synthesis," and the Ph.D. degree in 1996 with a dissertation on "Study of Mongolian Speech Synthesis and Its Application in Telecommunication Technologies."

She conducted postdoctoral research at the Electronics and Telecommunications Research Institute (ETRI), Korea, in 2002-2003, focusing on "Optimal Version of Frequency and Timing Offset for OFDM Systems."

She is currently a Professor and a Consulting Engineer of Mongolia. Her research interests include mobile broadband and high-speed integrated service technologies, including WiMAX, WiBro, Mobile IPTV, 4G LTE, 5G, and 6G systems.