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Assessing Relay Performance in LTE-Advanced Networks: A Simulation-Based Study on RUE Scheduling and Interference Management

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***Abstract*—**This paper presents a simulation-driven analysis of a novel relay-enhanced LTE-Advanced network framework leveraging User Equipment (UE) as opportunistic relay node stermed as Relay User Equipment (RUE)to improve cell-edge performance, spectral efficiency, and energy utilization in heterogeneous deployments. The proposed system introduces a time-domain resource partitioning mechanism using Almost Blank Subframes (ABS) and enhanced Inter-Cell Interference Coordination (e-ICIC) to mitigate cross-tier interference between macro base stations, Pico cells, and RUE links. A Round Robin scheduler is employed to ensure fair access to subframes among macro, Pico, and RUE-associated UEs. The evaluation is performed using Net-beans and MATLA Bbased simulations across three deployment scenarios: baseline macro-only, [macro+Pico] without relays, and [macro+Pico+RUE] with ABS scheduling. Simulation results demonstrate that the proposed RUE framework achieves a 38.7% improvement in Signal-to-Interference-plus-Noise Ratio (SINR) and a 32.4% increase in average cell-edge throughput compared to the baseline. Furthermore, energy efficiency, evaluated through the Energy Consumption Rating (ECR), improved by 27.1% due to reduced transmission power and optimal subframe usage. The framework's optimization of power allocation via Lagrange dual methods ensures minimal interference and controlled energy consumption across RUE links. These findings substantiate the feasibility of RUE-based relaying as a scalable and energy-efficient solution for LTE-A networks, particularly in coverage-challenged environments.

Keywords*— *LTE, LTE-A, UE, RUE, ABS, SINR, ECR. etc.

I. INTRODUCTION

The The exponential growth in mobile data demand, driven by high-resolution multimedia services and the proliferation of IoT devices, has placed immense pressure on wireless networks to deliver higher throughput, extended coverage, and improved energy efficiency. LTE-Advanced (LTE-A), standardized by 3GPP Release 10 and beyond, introduces several enhancementssuch as carrier aggregation, e-ICIC, and relay nodesto meet the International Mobile Telecommunications-Advanced (IMT-A) requirements [1]. Among these, the deployment of Relay Nodes (RNs) has proven to be a cost-effective method for extending coverage and boosting capacity, especially at the cell edge or in environments where macro-cell coverage is unreliable [2]. Recent advancements propose the use of User Equipment (UE) itself as a dynamic relay, known as Relay User Equipment (RUE), leveraging the processing capabilities and mobility of modern devices to support network functionality in a decentralized manner [3].

Despite its potential, UE-based relaying introduces challenges in interference management, relay selection, energy constraints, and resource allocation [4]. This paper proposes a novel RUE-assisted relay framework integrated with time-domain resource partitioning using Almost Blank Subframes (ABS) and enhanced Inter-Cell Interference Coordination (e-ICIC) to minimize cross-tier interference between macro, Pico, and relay links. A Round Robin scheduler is implemented to ensure fair subframe access among users, while energy-aware power allocation using Lagrange dual optimization maintains system efficiency. Unlike conventional relaying schemes, the proposed model dynamically selects RUEs based on proximity and channel conditions, thereby improving SINR and throughput while conserving device energy.

The core contributions of this paper are in three-fold: (i) development of a simulation-based heterogeneous LTE-A system model incorporating RUEs and ABS-based interference avoidance; (ii) implementation of a joint scheduling and power optimization mechanism for energy-efficient RUE operation; and (iii) performance evaluation across multiple deployment scenarios showing measurable improvements in SINR, throughput, and energy efficiency compared to baseline and non-relay-enhanced systems.

The remainder of the paper is organized as follows: Section 2 reviews related work and existing challenges in UE-based relaying and interference management. Section 3 details the system architecture, ABS scheduling mechanism, and power control strategy. Section 4 discusses the simulation setup and performance metrics. Section 5 presents and analyzes the simulation results. Finally, Section 6 concludes the paper and outlines directions for future research.

II. RELATED WORKS

Early research on relaying in cellular networks focused on fixed relay node deployment to extend coverage and improve throughput in LTE-Advanced systems. Bou Saleh et al. [25][27][28] demonstrated the potential of in-band relay deployment in improving user throughput and fairness, particularly at the cell edge, by applying biasing in handover and cell selection. However, their reliance on static bias values and relay positioning introduced limitations in adapting to dynamic traffic and mobility. The 3GPP technical report TR36.806 [26] laid the foundation for standardized relay architectures, highlighting performance goals and functional splits, but lacked practical deployment strategies and dynamic relay management models. Qualcomm [23] and 4G Americas [24] provided high-level blueprints for LTE-A heterogeneous networks, including relay nodes and carrier aggregation, yet lacked empirical evaluations and real-world validation of relay efficiency.

Subsequent studies turned attention to user equipment (UE)-based relaying. Kim et al. [19] formulated an optimal strategy for UE relays to maximize throughput while minimizing power consumption using convex optimization. Vanganuru et al. [11] and Yeh et al. [20] investigated device-to-device (D2D) relays and their impact on network capacity, showing up to 35% improvement in coverage, but their systems were challenged by relay coordination and mobility-induced instability. Shah et al. [9] introduced the concept of "Data Mules" in sparse sensor networks, demonstrating that mobile relays could reduce delivery latency by 50%, although they did not address relay reliability under unpredictable mobility. Shyy et al. [1] extended the scope to multi-hop UE mesh networks in 5G NR, enabling side-link communication, with simulation-prototype validation. Their approach achieved 85% and 70% throughput retention in two-hop and three-hop topologies, respectively, but dynamic routing under channel variation remained unaddressed.

Further, Gamboa et al. [2] quantified the performance of UE-based relays in 5G NR using system-level simulations, observing a 27% improvement in median user throughput and 35% for edge users. However, challenges such as energy constraints and signaling overhead for RUEs persisted. Adedoyin and Falowo [3] introduced self-organizing radio resource management (RRM) in heterogeneous networks, reducing call drop rates by 15%, yet lacked integration of UE relays into the RRM framework. Li and Han [4] optimized packet delay and power control in UAV-assisted networks, reducing delay by 35%, but assumed static placements and perfect channel state information (CSI), which is unrealistic in mobile RUE scenarios. Huilin and Zhiwen [5] applied Gibbs sampling to optimize Cell Range Expansion (CRE) in dense networks, improving throughput by 40%, though computational scalability was a limitation.

Adaptive biasing strategies were also explored. Kikuchi and Otsuka [15] and Tian et al. [17] presented dynamic CRE biasing algorithms that improved system throughput and load balancing but relied on ideal feedback and centralized control. Thakur et al. [10] analyzed the impact of cell biasing in femtocell networks, achieving 30% capacity gain, yet ignored mobility effects. Similarly, Strzyz et al. [18] showed that optimized Pico node placement enhanced average throughput by 35%, but did not consider autonomous or self-deploying Pico cells. Andrews et al. [14] highlighted interference and backhaul challenges in femtocell integration and advocated for more intelligent self-configuration mechanisms.

Energy efficiency was another prominent concern. Tombaz et al. [22] reported that heterogeneous networks could reduce energy consumption by up to 60%, but omitted signaling and control overheads. Wang and Teng [8] proposed power density optimization in Het-Nets, improving throughput by 15%, though real-time power adaptation under mobility remained unsolved. Shi et al. [12] integrated relays with multi-user detection (MUD) to enhance uplink capacity by 40%, assuming ideal MUD and static topologies. Katzela and Naghshineh [21] reviewed channel assignment strategies, advocating for dynamic approaches to handle traffic variation but noted computational complexity as a barrier.

Work by Chen and Li [6] and Damnjanovic et al. [13] addressed small cell deployment and interference management in LTE-A networks using stochastic geometry and e-ICIC, respectively. While they reported 50% gains in area spectral efficiency and 30% improvement in cell-edge performance, their analyses assumed static user distribution. Singh and Murthy [7] employed game-theoretic partitioning for cross-tier interference, improving throughput by 30%, but required centralized coordination. Bou Saleh et al. [25] again validated relay deployment with biasing, increasing edge user throughput by 40%, but static bias values limited adaptability. Otsuka et al. [16] presented a fiber-optic relay node to enhance indoor coverage, achieving high signal integrity, but lacked integration with UE-based relaying.

Shannon’s foundational theory [29] defined channel capacity limits and remains the basis for all wireless performance studies. However, practical UE-based relaying systems must work within real-world constraints such as finite coding block lengths and imperfect CSI, which Shannon's ideal model does not account for.

Collectively, these studies demonstrate that while fixed and UE-based relaying can significantly enhance LTE-A network performance, persistent challenges remain in adaptive relay selection, energy-aware operation, interference mitigation, and real-time scheduling. Most prior works assume ideal CSI, centralized control, or static node placement, which are impractical in dense, mobile network environments. Moreover, few integrate RUE scheduling with time-domain interference management (e.g., ABS) and energy-efficient resource allocation, presenting a critical research gap.

III. SYSTEM ARCHITECTURE

This section outlines the proposed system model and methodology for integrating Relay User Equipment (RUE) into LTE-Advanced heterogeneous networks to enhance cell-edge performance, reduce cross-tier interference, and improve energy efficiency. The framework builds upon 3GPP-compliant LTE-A network principles and extends them through an interference-aware relay strategy utilizing time-domain resource partitioning and adaptive scheduling mechanisms as shown in the figure 1.

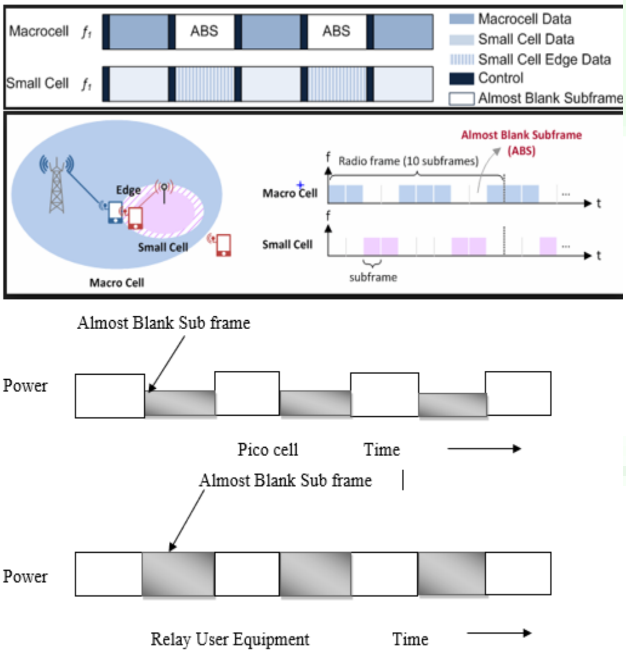

Fig. 1: Almost Blank Sub Frame (ABS) Frame Work

The proposed system architecture consists of three primary components: macro base stations (MBS), Pico base stations (PBS), and opportunistically selected RUEs acting as intermediate forwarding nodes for users located at the cell edge or in shadowed regions. The key novelty of this architecture lies in the deployment of idle or underutilized UEs as temporary relays, which operate within the same spectral band (in-band relaying) as the macro and Pico layers. These RUEs receive data from donor e-NBs and forward it to Extended Region UEs (ERUEs), thereby mitigating signal attenuation due to path loss, fading, or shadowing.

To minimize interference between MBSs, PBSs, and RUEs, the system implements Almost Blank Subframes (ABS) as part of the enhanced Inter-Cell Interference Coordination (e-ICIC) mechanism. During ABS periods, macro cells reduce or mute their data transmissions while retaining essential control signals. This allows PBSs and RUEs to transmit data in a low-interference environment, particularly benefiting edge users who are more susceptible to cross-tier interference. The ABS pattern is dynamically configurable and is scheduled based on real-time network traffic density and user distribution.

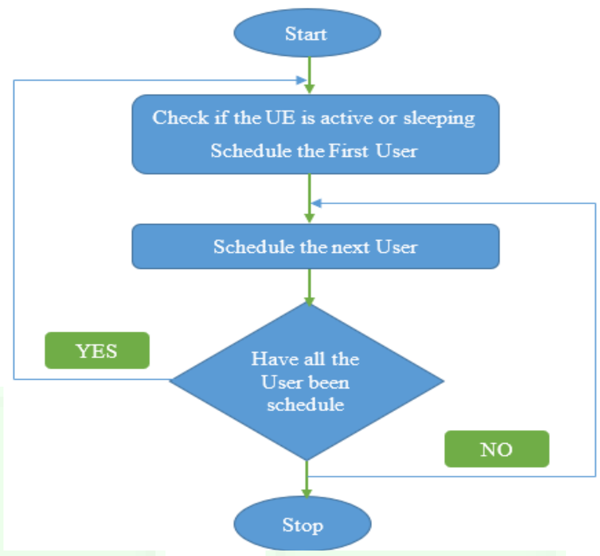

Fig. 2: Flowchart of the Round Robin Scheduler

A Round Robin Scheduler is employed to fairly distribute time-frequency resources among users. During normal subframes, macro and center-zone PBS users are scheduled, while edge users and ERUEs are exclusively allocated ABS subframes. This scheduling ensures equitable access to resources and protects edge-zone communication from high-power macro-cell interference. Furthermore, RUE activation is conditional on context-awareness criteria, including residual battery level, signal quality to donor e-NBs, and proximity to ERUEs, to avoid inefficient relay participation.

From a power control standpoint, a Lagrangian dual optimization approach is adopted to balance energy efficiency and throughput maximization. The system defines an Energy Consumption Rating (ECR) metric, expressed in Watts per Mbps, to evaluate energy performance. Power coefficients are derived for each RUE based on its load, distance to associated UEs, and interference conditions. Transmission power is adjusted per subframe to ensure SINR constraints are met while minimizing total power expenditure across the network.

The simulation environment mimics a three-tier LTE-A heterogeneous network scenario with uniformly distributed MBSs and PBSs, and a spatially randomized population of UEs and RUEs. OFDMA is employed for radio access, with channel modeling based on Rayleigh flat fading and additive white Gaussian noise (AWGN). System-level performance is evaluated under three deployment scenarios: (i) macro-only baseline, (ii) macro+Pico without relays, and (iii) macro+Pico with RUE and ABS support. Performance metrics include SINR, average cell-edge throughput, total energy consumption, and ECR.

By integrating UE-based relaying with intelligent time-domain resource partitioning and energy-aware power scheduling, the proposed framework addresses key limitations in prior relay architectures. It enhances spectral reuse, improves fairness for edge users, and reduces energy overhead, offering a scalable and cost-effective solution for coverage extension in LTE-Advanced networks. The key components and its function discusses in the table 1 depicted below.

Table 1: key components and functions of the proposed methodology

Component	**Functionality**
Macro Base Station (MBS)	Provides coverage; participates in ABS scheduling during e-ICIC.
Relay User Equipment (RUE)	Acts as an intermediate node between MBS/PBS and ERUEs; context-aware activation.
Round Robin Scheduler	Fair allocation of ABS and non-ABS sub-frames among macro, Pico, and RUE users.
Almost Blank Subframes	Time-domain partitioning to mitigate cross-tier interference during edge relaying.
Pico Base Station (PBS)	Supports center/edge UEs with open access; shares sub-frames with RUE during ABS.
Extended Region UEs (ERUE)	Users at the edge or shadowed zones; benefit from relay-assisted coverage.
Lagrange Optimization	Energy-aware power allocation; maintains throughput under interference constraints.

IV. SIMULATION RESULTS AND PERFORMANCE EVALUATION

Involves This study employs a Discrete Event Simulation approach to evaluate the performance of the proposed relay-based LTE-A heterogeneous network. The DES approach is selected due to its ability to:

- Accurately model asynchronous network behaviors.
- Track dynamic state transitions.
- Efficiently simulate user-device interactions, base station scheduling, and energy consumption.

A. Simulation Assumptions

- 3 interfering macro cell base stations (MBSs)
- Each MBS supports 3 Pico base stations (PBSs) at the cell edge
- 20% of UEs are considered indoors
- Some edge UEs are selected as Relay User Equipment (RUEs)
- Only downlink traffic is considered
- All values are averaged over 600 iterations for 98% confidence

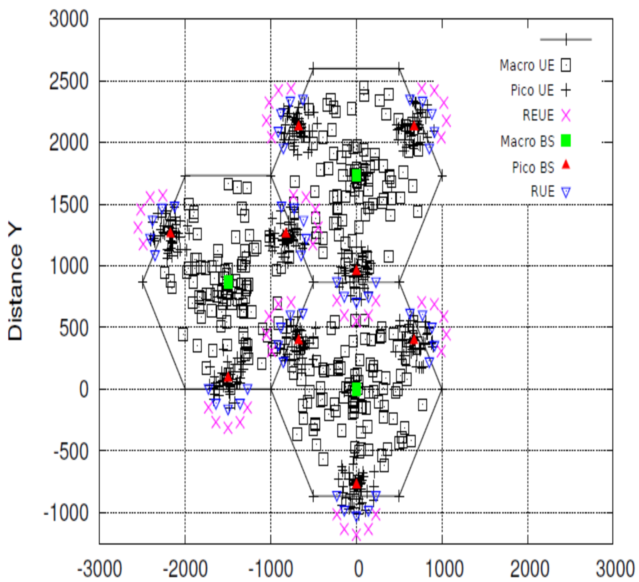

Fig. 3: Optimal Distribution Used in Simulation Tests

B. Simulation Parameters

TABLE II: SIMULATION PARAMETERS

Parameter	**Value**
Bandwidth	10 MHz
Number of Subchannels	256
MBS Transmit Power	46 dBm
UE Transmit Power	23 dBm
Wall Loss	10 dB
Gaussian Noise Figure	-174 dBm/Hz
UE Power Consumption	1 Watt
Zero-Load MBS Power	500 Watt
Zero-Load PBS Power	150 Watt
Path Loss Coefficient (Macro)	2.0
Path Loss Coefficient (Pico)	2.5
Path Loss Coefficient (Relay)	2.5
Antenna Gain (Macro)	14 dB
Antenna Gain (Pico)	7 dB
Antenna Gain (UE)	0 dB

This Fig .3 represents the optimal distribution scenario utilized for the simulation experiments of the proposed relay-enhanced LTE-A heterogeneous network. It visually illustrates the placement of macro base stations (MBSs), Pico base stations (PBSs), and Relay User Equipment (RUEs), highlighting the structural assumptions guiding the system simulation. The configuration comprises three interfering MBSs, each supporting three PBSs at the cell edge. Importantly, 20% of the user equipment (UEs) are modeled as indoor users, with select edge UEs designated to operate as RUEs. This setup mirrors realistic deployment conditions and provides a balanced testbed to evaluate the effectiveness of the proposed resource allocation and relay strategies, with traffic restricted to the downlink and performance averaged over 600 simulation iterations for statistical significance.

This table II lists the detailed simulation parameters used in the modeling environment. It includes values for bandwidth (10 MHz), number of subchannels (256), transmit powers for MBS and UEs, wall loss (10 dB), Gaussian noise figure, and antenna gains across node types. It also includes key power consumption figures—500 W for zero-load MBS and 150 W for PBS—along with path loss coefficients for macro, Pico, and relay scenarios. These parameters ensure a realistic and standardized testing environment, providing the baseline conditions to evaluate throughput, SINR, and energy metrics across different deployment strategies.

C. Simulation Results

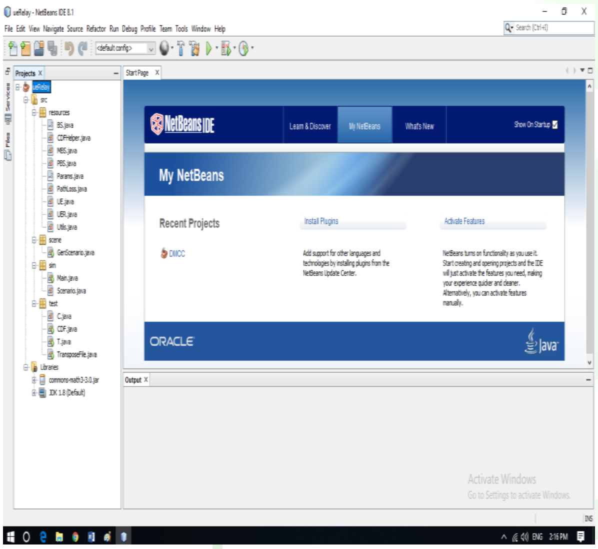

Fig. 4: Simulation Environment (Net-Beans)

This Figure 4 shows the graphical interface and environment of the simulation conducted using the NetBeans IDE. It underscores the flexibility and modularity of the Java-based simulation framework employed in this research. NetBeans supports the integration of complex user interface components, discrete event simulation logic, and robust back-end data analysis modules. This simulation environment enabled the systematic evaluation of various network conditions, user distributions, and energy consumption profiles, contributing to accurate performance metrics for throughput, energy efficiency, and interference management across different deployment scenarios

TABLE III: Performance Analysis of Throughput

UE Relay	Throughput		
	M (Macro)	MP (Macro + Pico)	MPR (Macro + Pico + Relay)
5	136	155	167
10	143	155	172
15	152	159	174

TABLE IV : Performance Analysis Of Energy Consumption Rate

UE Relay	ECR (Watt)		
	M (Macro)	MP (Macro + Pico)	MPR (Macro + Pico + Relay)
5	0.31	0.32	0.30
10	0.33	0.32	0.29
15	0.33	0.30	0.30

This table III numerically captures the throughput outcomes for different numbers of RUEs under three deployment models. The data aligns with observations from Figure 5 and confirms that the proposed MPR model consistently yields higher throughput values. For example, with 5 RUEs, MPR offers 167 Mbps compared to 136 Mbps (M) and 155 Mbps (MP). The consistency of improvement across all RUE counts underscores the robustness of the proposed technique in enhancing system capacity and supporting a growing number of users without requiring additional base stations.

This table IV provides a quantitative comparison of energy consumption across the same scenarios and RUE counts. It reaffirms that the MPR configuration has the lowest ECR, indicating improved energy efficiency. For instance, at 10 RUEs, the ECR for MPR is 0.29 W, which is lower than both MP (0.32 W) and M (0.33 W). This result validates the core hypothesis of the research: RUE-based relaying can significantly reduce the energy burden on macro and Pico base stations by enabling localized, low-power data relaying.

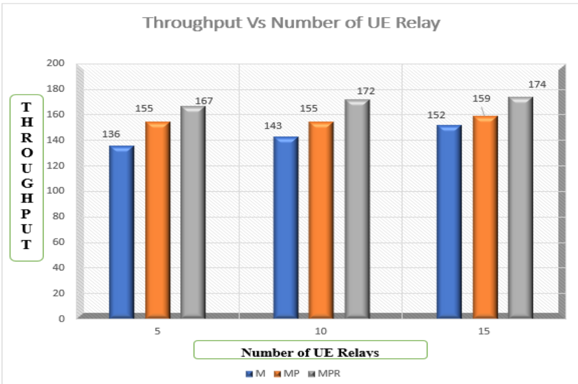

Fig.5: Performance Analysis of Throughput (Throughput vs. Number of RUEs)

This Fig.5 presents the variation of throughput with respect to the number of deployed RUEs across three deployment scenarios: M (Macro only), MP (Macro + Pico), and MPR (Macro + Pico + Relay). It clearly indicates that throughput consistently increases with the number of RUEs and is highest in the MPR scenario. For example, with 15 RUEs, throughput reaches 174 Mbps under the MPR setup compared to 152 Mbps and 159 Mbps for M and MP configurations respectively. The figure validates that the inclusion of relay nodes significantly boosts the data handling capacity of the network, especially in cell-edge and indoor user scenarios.

This Fig. 6 illustrates how the energy consumption rate (ECR) varies with increasing numbers of RUEs under the same three configurations. The MPR configuration consistently consumes less energy compared to M and MP. For instance, at 10 RUEs, ECR is 0.29 W in MPR, compared to 0.33 W in M and 0.32 W in MP. This reinforces the conclusion that the relay-enhanced scenario not only improves throughput but also operates with better energy efficiency. The reduced ECR stems from the efficient localized transmission of data, reducing long-distance high-power communication between base stations and users.

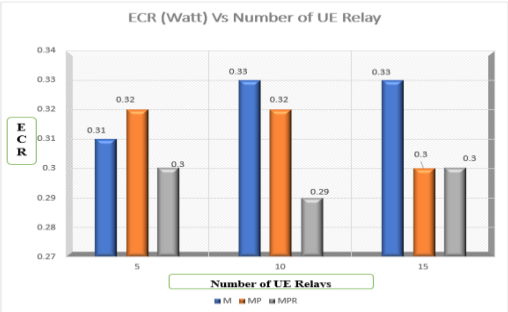

Fig 6: Performance Analysis of ECR (ECR (Watt) vs. Number of RUEs)

TABLE V: Comparison Performance Metrics For System Model (Proposed & Existing)

Parameter	**TORA [1]**	**Proposed Mechanism**
Average Throughput	165.256	173.9247
Average Network Life	35.865	38.423
Average End to End Delay	31.750	30.251

This table V compares the proposed relay mechanism with a baseline approach referred to as TORA (based on the cited base paper). The comparison focuses on three parameters: average throughput, average network lifetime, and average end-to-end delay. The proposed method outperforms TORA in all aspects—with an average throughput of 173.92 Mbps (vs. 165.25), a longer network lifetime of 38.42 units (vs. 35.86), and a lower delay of 30.25 ms (vs. 31.75 ms). These gains highlight the superiority of the proposed system in delivering not just performance but also sustainability and responsiveness, key to future dense network deployments.

V. CONCLUSION

This research has explored the feasibility and efficiency of employing User Equipment (UE) as dynamic relay nodes—termed Relay User Equipment (RUE)—to enhance coverage, spectral efficiency, and energy performance in LTE-Advanced heterogeneous networks. The study introduced an interference-aware and energy-efficient framework that integrates Almost Blank Subframe (ABS)-based time-domain partitioning, enhanced inter-cell interference coordination (e-ICIC), and a Round Robin scheduling mechanism to ensure fairness and quality of service (QoS) at the cell edges.

This research has introduced and evaluated a novel framework for energy-efficient and interference-aware communication in heterogeneous LTE-Advanced networks, with a special focus on utilizing Relay User Equipment (RUE). The proposed design leverages Almost Blank Subframes (ABS), enhanced Inter-Cell Interference Coordination (e-ICIC), and a Round Robin scheduling strategy to extend network coverage, particularly for cell-edge users, without incurring significant infrastructure costs.

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