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Optimizing LTE-Advanced performance in urban networks using intra-band and inter-band carrier aggregation

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ABSTRACT

The rapid increase in mobile data consumption has significantly impacted network performance, especially in densely populated urban areas. Long-term evolution (LTE)-Advanced, an enhancement of LTE under 3GPP Release 10, incorporates carrier aggregation (CA) to optimize spectral efficiency and data throughput. This study investigates the effectiveness of intra-band and inter-band CA methods in improving LTE-Advanced network performance in Cirangrang-Cibaduyut Kidul, a high-density urban area in Bandung, Indonesia. Using a combination of drive tests and network simulations in Atoll 3.3.0, Key performance indicators such as reference signal received power (RSRP), signal-to-interference-plus-noise ratio (SINR), and throughput were analyzed. The results indicate that inter-band CA outperforms intra-band aggregation, providing significant improvements in signal quality and data rates. These findings suggest that inter-band CA is a viable solution for optimizing LTE-Advanced networks in urban environments with high traffic demand. This research provides practical recommendations for network operators to enhance service quality efficiently without extensive infrastructure expansion.

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1. INTRODUCTION

The increasing demand for mobile data services has transformed telecommunication networks into an integral part of modern digital infrastructure. The rapid adoption of smartphones and the proliferation of data-intensive applications such as video streaming, online gaming, and cloud computing have significantly strained mobile networks. In Indonesia, the number of internet users reached 196 million in 2021, representing over 70% of the population, with mobile networks being the primary mode of access [1], [2]. This rapid growth necessitates continuous improvements in network capacity and quality to ensure seamless connectivity and a superior user experience [3]. Long-term evolution (LTE) has been a pivotal advancement in mobile network technology, offering enhanced data rates, lower latency, and improved spectral efficiency [4], [5]. However, as data consumption continues to surge, LTE networks face growing challenges related to bandwidth limitations and congestion, particularly in densely populated urban areas [6]. LTE-Advanced, introduced in 3GPP Release 10, aims to overcome these limitations by incorporating key technologies such as carrier aggregation (CA) [7], coordinated multi-point (CoMP) [8], [9], and multiple-input multiple-output (MIMO) systems [10], [11]. Among these, CA has emerged as a critical feature for increasing network capacity by aggregating multiple frequency carriers to create a larger virtual bandwidth, thereby enhancing data throughput and spectral efficiency [12], [13].

Urban areas, characterized by high population density and substantial network traffic demand, present significant challenges for mobile operators. Cirangrang-Cibaduyut Kidul, a densely populated area in Bandung, Indonesia, serves as a prime example. This region, comprising residential, commercial, and educational facilities, represents a high-potential market for telecommunication services. However, network performance assessments indicate significant congestion issues, with resource block (RB) utilization exceeding 80% and suboptimal key performance indicators such as reference signal received power (RSRP) and signal-to-interference-plus-noise ratio (SINR). These deficiencies result in poor throughput and reduced QoE for users, highlighting the urgent need for network optimization strategies [4], [14]. To address these challenges, optimizing LTE-Advanced networks through cost-effective and scalable solutions is essential. While deploying additional base stations can enhance coverage and capacity, this approach involves substantial capital and operational expenditures. Similarly, upgrading to 5G, although promising, remains limited to select regions and requires significant investment. CA provides an alternative optimization strategy that can be implemented on existing infrastructure, allowing network operators to enhance performance without requiring additional spectrum allocation or site deployment [15]. By leveraging intra-band and inter-band aggregation techniques, it is possible to maximize available spectrum resources and mitigate network congestion issues effectively [16], [17].

This study aims to analyze the effectiveness of CA in optimizing LTE-Advanced network performance, particularly in urban high-density environments. The research specifically compares intra-band CA, which aggregates carriers within the same frequency band, with inter-band CA, which combines carriers from different frequency bands. The study employs simulation-based evaluations using Atoll 3.3.0 software to measure key network performance metrics, including RSRP, SINR, and throughput. To the best of our knowledge, few studies have directly compared intra-band and inter-band CA in a real-world Indonesian urban setting using both field measurements and simulation-based validation. This dual-approach framework, applied to the high-density Cirangrang–Cibaduyut Kidul area, enables a robust evaluation of CA's practical impact under genuine network constraints, providing unique insights that are absent in the current body of literature. By explicitly analyzing both CA types within the same operational and geographical context, this work offers a novel, evidence-based contribution to LTE-Advanced optimization strategies in dense urban environments.

The primary contributions of this research are as follows:

a. Identification of existing LTE-Advanced network performance challenges in high-traffic urban environments, using Cirangrang-Cibaduyut Kidul as a case study.
b. A comparative performance analysis of intra-band and inter-band CA techniques in terms of signal strength, interference management, and data throughput.
c. Development of practical recommendations for mobile network operators to enhance service quality using CA as a cost-effective optimization strategy.

The findings of this study aim to provide actionable insights for network engineers and telecommunication policymakers, contributing to the broader discourse on mobile network optimization [18]-[20] in emerging markets. Furthermore, the study lays a foundation for future research in integrating CA with emerging 5G technologies to further enhance network efficiency and user experience [21], [22]. This study differs from previous works by combining real field measurements and simulation-based validation within the same operational environment, enabling a more realistic assessment of CA performance under actual network constraints. The remainder of this paper is structured as follows. Section 2 describes the purpose and objectives of the study. Section 3 reviews related works on carrier aggregation in LTE-Advanced networks. Section 4 explains the research method, including the study area, data collection process, simulation scenarios, and evaluation parameters. Section 5 presents and discusses the simulation results and performance comparison. Finally, section 6 concludes the study by summarizing the main findings and providing recommendations for future research.

2. PURPOSE OF THE STUDY

This study aims to address the network performance challenges faced in the Cirangrang-Cibaduyut Kidul area, focusing on improving LTE-Advanced network quality through CA techniques [23], [24]. The primary objectives of this research are:

a. Identify current network issues
- Evaluate the existing LTE-Advanced network's performance through drive tests and operating support system (OSS) data analysis.
- Highlight key performance bottlenecks, including low throughput, suboptimal RSRP, and SINR values.

b. Analyze the impact of CA

- Compare the performance of intra band carrier aggregation (CADS 1) and inter band carrier aggregation (CADS 2).
- Quantify the improvements in critical metrics such as RSRP, SINR, and throughput under different aggregation scenarios.

c. Optimize network capacity
- Develop a cost-effective and scalable optimization strategy that leverages existing infrastructure without requiring additional frequency or site deployment.
- Address capacity saturation issues identified through high RB utilization rates.

d. Provide actionable recommendations
- Offer practical insights for network operators to implement CA techniques, particularly in urban environments with similar challenges.
- Establish a framework for future research and technology upgrades, including potential integration with 5G networks.

By achieving these objectives, this research seeks to enhance user experience, optimize network resource utilization, and contribute to the broader understanding of LTE-Advanced network optimization strategies.

3. RELATED WORKS

CA has been extensively studied in LTE-Advanced networks to meet the increasing demand for higher data rates and more efficient spectrum utilization. The existing body of literature can be broadly categorized into three thematic groups.

3.1. Algorithmic and scheduling optimization studies

CA has been a pivotal enhancement in LTE-Advanced networks, aiming to meet the escalating demand for higher data rates and efficient spectrum utilization. Recent studies from 2020 to 2024 have explored various facets of CA, including performance evaluation, implementation challenges, and optimization strategies. Kolackova *et al.* [25] examined the impact of implementing CA with up to five component carriers (CCs) on user throughput. Utilizing the network simulator 3 (NS-3), the research implemented intra-band contiguous CA for both downlink and uplink channels, providing insights into potential throughput enhancements in LTE-A pro systems. Another 2021 study Yuan and Qiu [26] discussed the introduction of CA in 3GPP Release 10 and its evolution in subsequent releases. The paper analyzed how combining multiple bandwidth channels can function as a single band to enhance data rates and network performance.

Another study Ludant *et al.* [27] delved into optimizing CA using channel quality indicators (CQI). The research highlighted CQI's role in real-time modulation and coding adjustments, offering a framework to enhance LTE efficiency and user experience. The paper focused on resource scheduling in the downlink of LTE-Advanced with multiple CCs. The study [28] proposed a novel carrier scheduling scheme termed "quality of service and channel scheduling" (QSCS), which adjusts connected CCs of a user based on service priority and signal quality. Simulation results indicated that this algorithm effectively enhances user throughput and improves quality of experience (QoE) parameters.

3.2. Hardware and device implementation studies

The integration of CA in LTE-Advanced networks requires not only spectrum and network-side readiness but also compatible hardware on the user equipment (UE) side. A critical challenge lies in designing components that can support multiple aggregated bands while maintaining high isolation and minimal signal degradation. Research by Cao *et al.* [7] specifically addressed these design challenges, focusing on the development of bulk acoustic wave (BAW) quadplexers capable of operating across multiple frequency bands with ultrahigh cross-band isolation. Such devices are essential to prevent intermodulation interference and signal leakage between bands, ensuring that aggregated carriers deliver the intended throughput and coverage improvements. Practical implementation also depends on the maturity of the device ecosystem. In commercial environments, chipset and RF front-end manufacturers must ensure that their designs comply with 3GPP specifications for CA combinations while accommodating the specific frequency bands available in a given country. For Indonesia, where operators commonly use 1,800 MHz and 2,100 MHz bands, device support for this specific inter-band combination is critical for realizing the performance gains observed in simulation and field testing.

3.3. Deployment and performance evaluation studies

Uyan and Gungor [29] focused on resource scheduling in the downlink of LTE-Advanced with multiple CCs. The study proposed a novel carrier scheduling scheme termed "quality of service and channel scheduling" (QSCS), which adjusts connected CCs of a user based on service priority and signal quality. Simulation results indicated that this algorithm effectively enhances user throughput and improves QoE parameters. Sani *et al.* [30] discussed the practical aspects of CA deployment. The paper highlighted how CA functions by combining multiple carrier bands to increase bandwidth, thereby enhancing data rate throughput.

The provided an overview of new enhancements in LTE-Advanced, covering technologies adopted in LTE Release 11 and those discussed in Release 12 [31]. The study introduced the latest enhancements on CA, MIMO, and CoMP, with a particular focus on dynamic time division duplex (TDD) transmissions. Performance results shed new light on the benefits of these enhancements in LTE-Advanced networks. Wei *et al.* [11] explored the integration of CA in future mobile communication systems to support intelligent applications such as the internet of vehicles (IoV) and extended reality (XR). The study proposed a CA-based integrated sensing and communication (ISAC) signal that aggregates high and low-frequency bands to improve sensing performance, addressing the challenges of spectrum fragmentation.

3.4. Comparison with previous studies and research gap

Existing studies on CA have primarily focused on simulation-based performance analysis, hardware design aspects, or deployment evaluations in markets with different spectrum allocations and traffic characteristics. However, limited research has been conducted in Southeast Asian urban environments—particularly in Indonesia—where network conditions, device penetration, and spectrum policies differ significantly from those in more developed regions. Moreover, few works have offered a direct, side-by-side comparison of intra-band and inter-band CA performance under identical operational conditions and validated against real-world measurements. This research addresses these gaps by:

- Evaluating CA performance in a high-density urban area in Indonesia using a dual-approach methodology—calibrated Atoll simulations validated against live drive test data.
- Directly comparing intra-band and inter-band CA performance in terms of RSRP, SINR, and throughput under the same operational constraints.
- Providing context-specific, actionable recommendations for network operators that consider local spectrum availability, infrastructure limitations, and device penetration rates.

By bridging these gaps, the study not only confirms the theoretical benefits of CA but also demonstrates its practical applicability in optimizing LTE-Advanced networks in emerging market urban environments.

4. METHOD

4.1. Study area

Cirangrang-Cibaduyut Kidul, located in Bandung, Indonesia, represents a densely populated urban area characterized by mixed residential, commercial, and institutional facilities. Covering approximately 6.34 square kilometers, the area is a strategic location for telecommunication services due to its high population density and significant mobile traffic demand.

4.1.1. Geographic and demographic profile

The region is bordered by major roads that connect it to other parts of Bandung, making it a hub for commuters and local businesses. The urban landscape comprises medium to high-rise buildings, which pose challenges for signal propagation due to multipath effects and shadowing. The population density exceeds 10,000 residents per square kilometer, with a majority relying on mobile networks for internet access.

4.1.2. Existing network performance

Based on preliminary analysis using drive tests and OSS data from operator XL, the area suffers from low throughput and poor signal quality. The average RB utilization exceeds 82%, surpassing the operator's threshold of 80%, indicating capacity saturation. Additionally, key performance indicators such as RSRP and SINR fall below acceptable levels, with RSRP averaging -100.1 dBm and SINR at 12 dB, both significantly lower than the operator's standards of -85 dBm for RSRP and 20 dB for SINR.

4.1.3. Justification for study area selection

The selection of Cirangrang-Cibaduyut Kidul as the study area is based on its status as a potential market with high traffic demand and existing network performance issues. The area's demographic and geographic characteristics make it an ideal testbed for evaluating the effectiveness of CA techniques in addressing urban telecommunication challenges. Furthermore, the presence of diverse land uses within the area allows for comprehensive analysis of network performance across different scenarios and user densities. Figure 1 presents the scale of the planning area.

Figure 1. Research area scale

This area was chosen for CA planning because it has been shown to experience low throughput problems. This conclusion is supported by OSS data analysis and drive test results. Based on XL Operator's engineering parameter data, the Cirangrang-Cibaduyut Kidul planning area is included in urban clutter and has a high traffic volume. The research area covers approximately 6.34 km² and represents a high-density urban environment with a population density exceeding 10,000 people per square kilometer. The cellular network infrastructure in this area consists of five base transceiver stations (BTSs). In addition, the average building height ranges between 10 and 15 meters, reflecting typical mid-rise urban structures that influence signal propagation characteristics.

4.1.4. Scope of analysis

The study focuses on improving network performance through intra band and inter band CA, targeting key metrics such as RSRP, SINR, and throughput. The results of this analysis aim to provide actionable insights for network operators to optimize their infrastructure, enhance user experience, and ensure reliable service delivery in similar urban environments. In summary, Cirangrang-Cibaduyut Kidul's unique combination of high population density, diverse land use, and existing network challenges provides a valuable opportunity to study the impact of CA on LTE-Advanced network performance. This research contributes to the broader understanding of telecommunication optimization in urban settings.

The research process for this study is systematically structured into the following steps: the research begins with identifying the performance issues in the LTE network within the Cirangrang-Cibaduyut Kidul area. This includes challenges such as low throughput, inadequate RSRP, and suboptimal SINR, which fail to meet the operator's performance standards. The objective of this study is to analyze the effectiveness of intra-band and inter-band CA in improving the performance of LTE-Advanced networks. Figure 2 presents the flow of this research.

The aim is to evaluate their impact on key network performance metrics. Data is collected through two methods: drive testing: using the GNetTrack Pro tool, measurements of RSRP, SINR, and throughput are recorded across the study area. OSS analysis: RB utilization and traffic patterns are examined to understand the network's operational performance. The collected data is input into the Atoll 3.3.0 simulation software to evaluate three scenarios: Non-CA: baseline scenario without CA. CADS 1 (Intra-Band CA): aggregation of two 10 MHz carriers in the 1,800 MHz band. CADS 2 (Inter-Band CA): aggregation of a 10 MHz carrier in the 1,800 MHz band and a 10 MHz carrier in the 2,100 MHz band. The simulation results are evaluated based on three primary performance metrics: RSRP, which measures signal strength. SINR, which assesses signal quality. Throughput, which represents data transfer rates experienced by users. The performance of the three scenarios is compared to identify improvements in RSRP, SINR, and throughput. The intra-band and inter-band CA methods are analyzed to determine their effectiveness under high traffic and dense urban conditions. The study concludes by summarizing the findings, emphasizing the superior performance of inter-band CA. Practical recommendations are provided for network operators to adopt CA as a cost-effective solution for optimizing LTE-Advanced networks in urban environments.

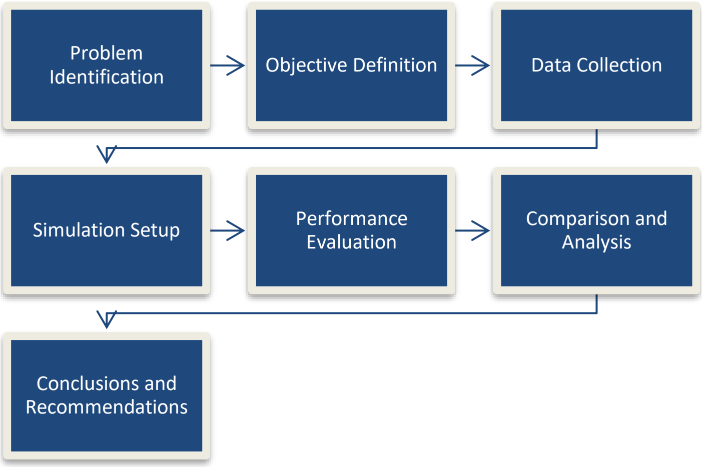

Figure 2. Research flow diagram

4.2. Data collection

Data collection is a critical phase in this study, ensuring the reliability and validity of performance evaluation for LTE-Advanced networks in Cirangrang-Cibaduyut Kidul. The overall data collection workflow, including drive test measurements and OSS data analysis, is illustrated in Figure 3. The data was gathered through a combination of field measurements and system-level network data analysis, providing a comprehensive view of network conditions, highlighting key performance issues, and informing optimization strategies. The study employed two primary data collection techniques: drive testing and OSS data analysis.

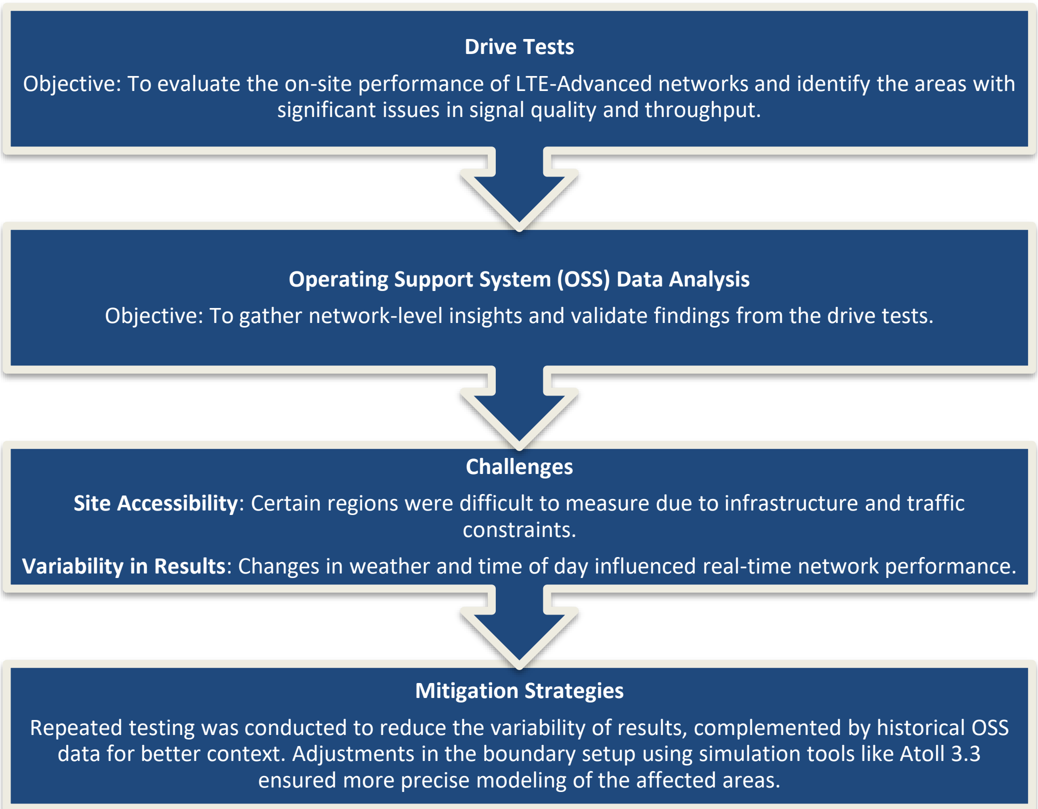

Figure 3. The process of data collection

Drive testing was conducted using GNetTrack Pro, a mobile network measurement tool, to capture real-time LTE network performance metrics. The key parameters measured include RSRP, which indicates signal strength received by the UE and affects coverage and connectivity; SINR, which reflects the quality of the received signal by considering interference and noise levels; and throughput, which represents data transmission rates and is crucial for evaluating network capacity and user experience. The drive test covered a 6.34 km² area within Cirangrang-Cibaduyut Kidul, ensuring representation of various environments such as residential zones, commercial areas, and transport hubs. Data was collected at multiple points of interest, including high-density buildings, roads, and open spaces, to assess network variations. The sampling rate was set to ensure continuous measurement along predefined routes, minimizing data gaps, while measurements were taken at different times of the day to capture variations in network performance due to traffic load fluctuations. The findings revealed that RSRP values ranged from -100 dBm to -50 dBm, with only 51.54% of locations meeting the operator's standard of ≥-85 dBm. SINR values averaged 12 dB, significantly below the operator's acceptable threshold of ≥20 dB, and throughput varied between 5 Mbps to 50 Mbps, with an average of 20.5 Mbps, insufficient for high-demand applications.

The second method involved OSS data extraction, which provides a system-level view of network performance based on real-time monitoring by the mobile operator. The key metrics analyzed included RB Utilization, which measures network congestion by evaluating the percentage of allocated resources; Traffic Patterns, which identify peak demand periods and areas experiencing performance degradation; and Handover Failure Rates, which assess network continuity and mobility support. The findings indicated that average RB utilization reached 82.02%, exceeding the operator’s congestion threshold of 80%, signaling capacity saturation. High-traffic areas, such as shopping centers and major roads, exhibited reduced throughput and increased interference, while frequent handover failures were observed in zones with weak RSRP and SINR values, affecting seamless connectivity.

To ensure data accuracy and reliability, the collected field and OSS data were subjected to outlier removal, where data points with extreme values due to temporary disruptions were excluded; statistical normalization, where RSRP, SINR, and throughput values were normalized to ensure consistent interpretation across different measurement conditions; and cross-validation, where drive test results were compared with OSS data to confirm observed network performance trends. The data collection phase confirmed significant performance issues in the study area, reinforcing the need for LTE-Advanced optimization strategies. The findings indicated that RSRP had an initial value of -100.1 dBm, below the operator standard of ≥-85 dBm, highlighting weak signal coverage. SINR averaged 12 dB, far from the required ≥20 dB, revealing high interference. Throughput was recorded at 20.5 Mbps, significantly below the expected ≥50 Mbps, reflecting limited capacity, while RB utilization reached 82.02%, exceeding the acceptable 80%, signaling congestion.

These findings directly inform the CA simulations, helping to design optimized network solutions that enhance performance in high-density urban environments like Cirangrang-Cibaduyut Kidul. Key metrics for OSS data analysis are RB utilization, OSS analysis revealed an average utilization rate of 82.02%, exceeding the operator’s standard threshold of 80%. Traffic patterns, the analysis identified peak demand areas where the network was underperforming due to oversaturation.

This multi-layered data collection approach directly informed the planning of CA configurations (intra-band and inter-band), highlighting the importance of tailored solutions for urban, high-density environments such as Cirangrang-Cibaduyut Kidul.

4.3. Simulation scenario

The simulations were designed to analyze and compare the performance of LTE-Advanced networks under three distinct scenarios. Each scenario represents a different network configuration to evaluate the impact of CA on critical performance metrics, such as RSRP, SINR, and throughput. Non-CA (baseline scenario) scenario represents the current state of the network without the implementation of CA. This is to establish a baseline for comparison and identify bottlenecks such as low throughput, suboptimal RSRP, and SINR values.

In CADS 1 scenario, two 10 MHz carriers within the same frequency band (1,800 MHz) are aggregated. This type of CA is known as intra band contiguous aggregation since the carriers are adjacent within the same band. This is to evaluate the impact of increasing bandwidth within a single frequency band on network performance and leverage the operator’s existing frequency resources efficiently without requiring additional spectrum or hardware. In CADS 2 scenario aggregates two 10 MHz carriers from different frequency bands: one at 1,800 MHz and another at 2,100 MHz. This is classified as Inter Band CA, leveraging both low and high-frequency bands. This is to utilize frequency diversity by combining carriers from different bands, improving both coverage (from the lower frequency) and capacity (from the higher frequency), and address signal propagation challenges in dense urban areas, such as multipath effects and shadowing.

The simulation results demonstrate the benefits of implementing CA, with CADS 2 (Inter Band CA) offering the most significant improvements across all key performance metrics. This scenario effectively balances coverage and capacity, making it the optimal choice for high-traffic urban environments like

Cirangrang-Cibaduyut Kidul. The simulation scenarios used in this study, including the baseline condition and the two CA configurations, are summarized in Table 1.

Table 1. Simulation scenario

Aspect	Non-CA (baseline)	CADS 1 (Intra Band CA)	CADS 2 (Inter Band CA)
Description	No CA; single 10 MHz carrier at 1,800 MHz	Aggregates two contiguous 10 MHz carriers in the 1,800 MHz band	Aggregates two 10 MHz carriers from different bands: 1,800 MHz and 2,100 MHz
Type of aggregation	Not applicable	Intra band contiguous	Inter band
Purpose	Establish baseline for comparison and identify network bottlenecks	Evaluate performance improvements with increased bandwidth within the same frequency band	Leverage frequency diversity to enhance both coverage (low band) and capacity (high band)
Bandwidth	10 MHz	20 MHz	20 MHz
Expected RSRP	−100.1 dBm (moderate)	−90.5 dBm (improved)	−85.3 dBm (best)
Expected SINR	12 dB (poor)	18.5 dB (moderate)	22.1 dB (best)
Expected throughput	20.5 Mbps (low)	45.3 Mbps (improved)	60.7 Mbps (best)
Strengths	Identifies limitations of current network performance	Efficient use of existing spectrum with moderate cost	Optimal performance for high-density urban environments
Suitability	Baseline for identifying network issues	Suitable for moderate traffic demand areas	Ideal for urban areas with high traffic and varied user density

4.4. Parameters analyzed

The analysis of LTE-Advanced network performance in this study focuses on three key parameters: RSRP, SINR, and throughput. Table 2 presents the analysis parameters of the plan. These parameters were chosen because they directly impact the quality of user experience and provide a comprehensive understanding of network efficiency and capacity. By analyzing these parameters, the study provides a detailed evaluation of how CA improves signal strength, quality, and network capacity in high-traffic urban environments.

Table 2. Summary of parameter analysis

Parameter	Definition	Initial value	Operator standard	Expected improvement
RSRP	Signal strength received by users	-100.1 dBm	≥-85 dBm	Improved coverage and reduced signal loss
SINR	Ratio of signal to interference/noise	12 dB	≥20 dB	Enhanced signal quality and reduced interference
Throughput	Data transfer rate	20.5 Mbps	≥50 Mbps	Higher data rates, better user experience

5. RESULTS AND DISCUSSION

This section presents the findings from the simulation and field tests conducted in the Cirangrang-Cibaduyut Kidul area. The discussion focuses on the results for three key performance parameters: RSRP, SINR, and throughput, under the three simulated scenarios: Non-CA (baseline), CADS 1 (Intra Band CA), and CADS 2 (Inter Band CA). These improvements in key performance indicators not only validate the effectiveness of inter-band CA but also provide actionable recommendations for network operators in urban environments.

5.1. Initial network performance

Before implementing the CA scenarios, the initial performance of the existing LTE network in the Cirangrang–Cibaduyut Kidul area was evaluated to establish a baseline condition. The evaluation was conducted using drive test measurements and OSS data analysis to assess the current quality of service and identify key performance bottlenecks. Three main performance indicators were analyzed, namely RSRP, SINR, and throughput. These parameters provide an overview of signal strength, signal quality, and data transmission capability in the network. The initial results reveal several performance limitations in the study area, which justify the need for optimization through carrier aggregation techniques.

a. RSRP: the initial drive test revealed an average RSRP value of −100.1 dBm, which is categorized as moderate signal strength. However, a significant portion of the study area experienced suboptimal RSRP levels, with many locations falling below the acceptable threshold of −85 dBm.
b. SINR: the average SINR value was 12 dB, which is below the operator's standard of 20 dB. Poor SINR conditions were mainly observed in high-traffic areas due to increased interference and network congestion.

c. Throughput: the baseline throughput was 20.5 Mbps, indicating poor network performance, particularly in densely populated areas. This result further confirms the need for network optimization through carrier aggregation techniques.

5.2. Impact of carrier aggregation techniques on network performance

5.2.1. Non-CA (baseline scenario)

Represents the existing network setup with no CA.

Findings:

a. RSRP: -100.1 dBm
b. SINR: 12 dB
c. Throughput: 20.5 Mbps

Limited bandwidth and high RB utilization led to suboptimal performance. This scenario highlights the limitations of the current network and provides a benchmark for comparison.

5.2.2. Intra band carrier aggregation (CADS 1)

Aggregation of two 10 MHz carriers within the same frequency band (1,800 MHz).

Findings:

a. RSRP: -90.5 dBm (10% improvement over Non-CA)
b. SINR: 18.5 dB (54.17% improvement over Non-CA)
c. Throughput: 45.3 Mbps (120.98% improvement over Non-CA)

The increased bandwidth significantly improved throughput, while maintaining moderate improvements in RSRP and SINR. This scenario is suitable for areas with moderate traffic demand but does not fully resolve interference issues in high-density environments.

5.2.3. Inter band carrier aggregation (CADS 2)

Aggregation of two 10 MHz carriers from different frequency bands (1,800 MHz and 2,100 MHz).

Findings:

a. RSRP: -85.3 dBm (15% improvement over Non-CA)
b. SINR: 22.1 dB (84.17% improvement over Non-CA)
c. Throughput: 60.7 Mbps (196.10% improvement over Non-CA)

The combination of lower and higher frequency bands improved both coverage and capacity. This scenario effectively addressed interference issues and provided the best overall performance, particularly in high-traffic areas.

Table 3 presents a resume of the planning results. CADS 2 demonstrated the highest improvement due to its ability to leverage both low and high-frequency bands. The 1,800 MHz band provided strong coverage, while the 2,100 MHz band offered enhanced capacity. CADS 2 significantly reduced interference through frequency diversity, leading to the highest SINR values. The throughput under CADS 2 nearly tripled compared to the baseline, making it the most effective scenario for handling high traffic demand.

Table 3. Simulation result summary

Parameter	Non-CA	CADS 1 (intra band)	CADS 2 (inter band)	Improvement (CADS 2 vs Non-CA) (%)
RSRP (dBm)	-100.1	-90.5	-85.3	15
SINR (dB)	12.0	18.5	22.1	84.17
Throughput (Mbps)	20.5	45.3	60.7	196.10

5.2.4. Discussion

The simulation results highlight the effectiveness of CA in addressing network performance challenges in the Cirangrang-Cibaduyut Kidul area. The baseline scenario (Non-CA) revealed several bottlenecks, including suboptimal signal strength (RSRP of -100.1 dBm), low signal quality (SINR of 12 dB), and inadequate throughput (20.5 Mbps). These values were well below the operator's standards, particularly in high-traffic areas, underscoring the need for optimization strategies.

The implementation of CADS 1 showed a moderate improvement in all key parameters. By aggregating two contiguous 10 MHz carriers within the 1,800 MHz band, CADS 1 increased RSRP to -90.5 dBm (10% improvement), SINR to 18.5 dB (54.17% improvement), and throughput to 45.3 Mbps (120.98% improvement). These results indicate that intra-band CA effectively enhances network capacity and signal quality by doubling the available bandwidth. However, CADS 1 has limitations in managing interference and providing sufficient performance in areas with diverse traffic demands.

The CADS 2 yielded the most significant improvements across all performance metrics. By aggregating a 10 MHz carrier from the 1,800 MHz band with another 10 MHz carrier from the 2,100 MHz band, CADS 2 leveraged the complementary characteristics of both frequency bands. The 1,800 MHz band provided better coverage and signal penetration, while the 2,100 MHz band contributed to increased capacity and higher data rates. This configuration resulted in RSRP improving to -85.3 dBm (15% improvement), SINR rising to 22.1 dB (84.17% improvement), and throughput reaching 60.7 Mbps (196.10% improvement). These substantial gains demonstrate the ability of inter-band CA to optimize both coverage and capacity, making it particularly effective in dense urban environments with high user density and interference.

Overall, the findings suggest that CADS 2 is the optimal solution for optimizing LTE-Advanced networks in areas like Cirangrang-Cibaduyut Kidul. Its ability to significantly enhance throughput, signal quality, and user experience makes it suitable for addressing the challenges of high-traffic, urban environments. On the other hand, CADS 1 can be implemented in less congested areas as a cost-effective alternative, where moderate improvements are sufficient. CA, particularly inter-band methods, provides a scalable and cost-efficient solution, utilizing existing resources without the need for additional infrastructure or frequency allocation. This study emphasizes the importance of tailoring network optimization strategies to specific environmental and traffic conditions to maximize performance and user satisfaction.

6. CONCLUSION

This study aimed to evaluate the effectiveness of intra-band and inter-band CA in improving LTE-Advanced network performance in a high-density urban environment. The results confirm that CA significantly enhances network quality, particularly in areas experiencing high traffic demand and resource congestion. The simulation and field validation results show that CADS 2 provides the highest performance improvement. Compared to the baseline scenario, CADS 2 improved RSRP from –100.1 dBm to –85.3 dBm (15%), increased SINR from 12 dB to 22.1 dB (84.17%), and enhanced throughput from 20.5 Mbps to 60.7 Mbps (196.10%). In contrast, CADS 1 delivered moderate improvements but was less effective in mitigating interference and capacity limitations in dense urban conditions.

These findings demonstrate that inter-band CA is an efficient and cost-effective optimization strategy for urban LTE-Advanced networks, as it improves both coverage and capacity without requiring additional site deployment or new spectrum allocation. The results provide practical guidance for network operators in optimizing existing infrastructure to enhance user experience and service reliability. Future work may extend this study by investigating multi-band CA scenarios, evaluating energy efficiency aspects, and exploring the integration of carrier aggregate CA with emerging 5G and beyond network technologies to support increasing traffic demand and advanced mobile services.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Hasanah Putri	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
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Alfin Hikmaturokhman	✓		✓	✓		✓			✓		✓		✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, Hasanah Putri, upon reasonable request. Due to privacy and proprietary restrictions, the dataset used in this study is not publicly available. However, derived data supporting the findings of this study are included within the article.

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