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Analysis of the Effect of Frequency Band Variation on 4G LTE Coverage and Capacity

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ABSTRACT

Growing demand for data services is prompting mobile network operators to provide Long Term Evolution (LTE) networks that can balance service coverage with network capacity. This study analyses the impact of frequency band variations on the performance of 4G LTE networks operating at 900, 1800 and 2100 MHz in the Padang Timur sub-district. Atoll simulation was employed to evaluate the Reference Signal Received Power (RSRP) and Signal-to-Interference-plus-Noise Ratio (SINR) parameters, as well as throughput. Meanwhile, Monte Carlo simulation was utilised to analyse network capacity based on user distribution. The simulation results show that the 900 MHz frequency provides the best coverage performance, with the entire study area falling into the 'Excellent' category based on the RSRP and SINR parameters. However, service capacity at this frequency is relatively low, with a connected user percentage of 13.6 % in the Monte Carlo simulation. In contrast, the 2100 MHz frequency provided the best capacity performance, with a connected user ratio of 73.8 % and a cumulative application throughput of 1,104.06 Mbps. The 1800 MHz frequency demonstrated performance falling between the two frequency bands. The research results indicate a trade-off between coverage and capacity due to variations in frequency bands. Monte Carlo simulations provide a more realistic representation of user distribution than deterministic capacity dimensioning when evaluating network service capabilities. Based on these results, the 900 MHz frequency is better suited to providing coverage, while the 2100 MHz frequency is better suited to providing capacity in the study area.

INTRODUCTION

Advances in mobile communications technology have increased public demand for broadband services that can provide high-speed, stable and reliable connectivity. The increasing use of digital services such as video streaming, cloud computing, online learning and the Internet of Things (IoT) has resulted in a steady rise in mobile data traffic. According to a report by the Indonesian Internet Service Providers Association (APJII), the increase in the number of internet users in Indonesia has driven the need for greater network capacity to maintain service quality (APJII, 2025). While fifth-generation (5G) technology is being rolled out, Long Term Evolution (LTE) continues to play a vital role in providing mobile broadband services thanks to its extensive coverage, mature infrastructure, and high device compatibility (Prayoga et al., 2025; Irmayani, 2023). Consequently, designing an LTE network that can meet coverage and capacity requirements remains a key part of developing mobile networks.

The performance of an LTE network can be evaluated using the following parameters: Reference Signal Received Power (RSRP), Signal-to-Interference-plus-Noise Ratio (SINR) and throughput. RSRP represents the signal strength received by the user; SINR indicates the quality of the signal relative to interference and noise; and throughput describes the network's ability to transmit data. The performance of these three parameters is influenced by propagation characteristics, antenna configuration, environmental conditions and the frequency band used (Ibrahim et al., 2025; Wenadri et al., 2024). Different frequency bands result in different propagation characteristics; lower frequencies generally have a wider propagation range, while higher frequencies tend to offer greater capacity but with more limited coverage. To predict network performance prior to implementation, Atoll simulations can analyse radio propagation, coverage, signal quality, and throughput (Agustin & Arohman, 2021; Suandi., 2024; Fakhrurozi et al, 2024; Jaramillo et al., 2024). Meanwhile, capacity analysis can be supplemented with Monte Carlo simulations modelling random user distributions to make estimates of the network's ability to handle traffic more representative (Yoo et al., 2023; Taher et al., 2024).

Several studies have examined the planning and optimisation of LTE networks, employing performance measurements and simulations. Jaramillo et al. (2024) showed that Atoll simulations can evaluate coverage, throughput, and packet scheduling strategies, thereby improving network quality. Similarly, Yuhanef et al. (2026) showed that optimising antenna parameters with Atoll can enhance RSRP, SINR, and LTE network throughput. Other studies have

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also shown that coverage planning and propagation model optimisation can improve LTE service quality (Ketut et al., 2025; Silalahi et al., 2022). Regarding capacity, Monte Carlo simulations have been employed to estimate a network's capacity to serve users by taking more realistic user and traffic distributions into account (Agustin & Arohman, 2021; Taher et al., 2024).

In light of this gap, this study uses Atoll for coverage planning, as well as Monte Carlo simulation and capacity dimensioning, to analyse the impact of variations in the 900 MHz, 1800 MHz and 2100 MHz frequency bands on the performance of the 4G LTE network in Padang Timur sub-district. The analysis was conducted based on RSRP, SINR, throughput, coverage area and the network's ability to serve users according to traffic distribution parameters. Furthermore, drive test data were used to describe the empirical conditions of the existing LTE network and to provide a benchmark against which to measure the characteristics of the simulation results. This approach was employed to identify the characteristics and trade-offs between coverage and capacity across each frequency band.

This research aims to provide an integrated evaluation of the impact of frequency band variations on LTE network coverage and capacity by combining Atoll measurements and Monte Carlo simulations within a single analytical framework. The results are expected to provide an overview of the performance characteristics of the 900 MHz, 1800 MHz and 2100 MHz bands and serve as a reference for determining frequency band usage strategies based on coverage and capacity requirements in urban areas.

LITERATURE REVIEW

Research into the performance, planning and optimisation of 4G Long Term Evolution (LTE) networks has been conducted using various approaches, including field measurements, mathematical modelling and simulations using network planning software. A review of previous research is necessary to identify research developments, the limitations of the approaches used, and the position and novelty of this study. Several studies relevant to the analysis of variations in frequency bands, coverage, and LTE network capacity are described below. Yuhanef et al. (2024) optimised 4G LTE network throughput using the drive test method to identify dead spots. Network quality issues were subsequently addressed through antenna tilt adjustment as a corrective measure to improve signal quality. That study focused on optimising physical antenna parameters to improve network performance under existing operational conditions. In contrast to this approach, this study focuses on the effect of frequency band variations on LTE network performance by comparing the 900 MHz, 1800 MHz and 2100 MHz frequencies. An evaluation was carried out on coverage and capacity to identify the characteristics and performance trade-offs of each frequency band.

Chandra et al. (2020) compared LTE network coverage using Frequency Division Duplexing (FDD) at 1800 MHz and Time Division Duplexing (TDD) at 2300 MHz in the city of Padang, employing a drive test method. While this study provides an overview of differences in coverage characteristics based on frequency bands, the analysis remains limited to signal coverage range and quality. The present study broadens this analysis by evaluating three frequency bands namely 900 MHz, 1800 MHz and 2100 MHz and considering the network's ability to handle user traffic through capacity analysis and Monte Carlo simulation. Agustin and Arohman (2021) designed an LTE network across three sub-districts in the city of Depok, taking a coverage and capacity-based approach. This study used mathematical modelling to determine the initial network dimensions based on regional conditions and demographic data. While this approach provided a theoretical basis for determining network requirements, it did not integrate dynamic user distribution via Monte Carlo simulation, nor compare the performance of multiple frequency bands within a single study area. This study builds on this approach by combining coverage planning, capacity dimensioning, and Monte Carlo simulation to evaluate network performance across the 900 MHz, 1800 MHz, and 2100 MHz bands.

Trirahmi, Aulia, and Chandra (2023) analysed the effect of cell overshooting on the coverage quality of 4G LTE networks using a drive test method with RSRP, SINR, and PCI parameters. The measurement results were then visualised using MapInfo Professional to identify areas experiencing coverage issues. This study highlights the importance of field measurements in evaluating LTE network quality. However, the focus of the research was on identifying and addressing overshooting cells, rather than analysing the impact of frequency band variations on the relationship between coverage and network capacity. This study utilised drive testing to characterise the empirical conditions of the existing network and compare them with the characteristics of simulation results. Wenadri et al. (2024) compared the performance of LTE networks at 900 MHz and 2100 MHz and demonstrated differences in propagation characteristics that affect service quality. The 900 MHz frequency provided better coverage characteristics, whilst the 2100 MHz frequency exhibited higher throughput performance under certain traffic conditions. That study demonstrated a relationship between frequency characteristics and coverage and data performance. However, the analysis was still limited to two frequency bands. This study extends the comparison to three frequency bands—namely 900 MHz, 1800 MHz and 2100 MHz—and adds a capacity analysis based on user distribution via Monte Carlo simulation.

Al-Hilfi and Abbas (2020) evaluated the influence of network planning parameters on the maximum capacity of an LTE cell, including Maximum Allowable Path Loss (MAPL), MIMO configuration, bandwidth, and the OFDMA modulation scheme. The study employed a theoretical approach to identify parameter combinations that could maximise the capacity of an LTE cell. Whilst this approach provides an important foundation for capacity dimensioning analysis,

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it does not yet account for variations in capacity performance resulting from differences in frequency bands within a service area or from dynamic user distribution. This study extends that analysis by evaluating capacity across three frequency bands simultaneously and utilising Monte Carlo simulation to model user distribution within the study area.

Based on previous research, it is evident that studies on LTE networks have covered antenna optimisation, coverage evaluation, design based on coverage and capacity, analysis of cell overshooting issues, and theoretical capacity evaluation. However, there are still limitations in research that comprehensively compares the impact of the three LTE frequency bands on coverage and capacity within a single study area. Furthermore, the integration of coverage planning simulations, capacity dimensioning, Monte Carlo-based user distribution, and drive test measurement data remains relatively limited. These circumstances highlight the need for an evaluation that considers not only signal coverage quality but also the ability of each frequency band to serve user traffic.

This study contributes to an integrated analysis of the impact of the 900 MHz, 1800 MHz and 2100 MHz frequency bands on the coverage and capacity of the 4G LTE network in Padang Timur Sub-district. Atoll simulation was used to evaluate RSRP, SINR and throughput, whilst capacity dimensioning and Monte Carlo simulation were used to analyse the network's ability to serve user distribution. Drive test data were used as a benchmark or for validating the simulation results in accordance with the research scenarios. Through this approach, the study not only produced a comparison of performance across different frequencies but also identified trade-offs between coverage and capacity, which can form the basis for selecting strategies for the use of frequency bands in urban areas.

METHOD

This study employs a quantitative approach by integrating two complementary methods: empirical field measurements (drive tests) and simulation-based network modelling using Atoll software. These approaches were used to analyse the impact of variations in the 900 MHz, 1800 MHz and 2100 MHz frequency bands on the coverage and capacity performance of the 4G LTE network in Padang Timur Sub-district, Padang City. Drive test measurements were used to obtain empirical data on network performance, whilst Atoll simulations were used to model coverage, signal quality, throughput and network capacity for each frequency band. The research flowchart is shown in Figure 1.

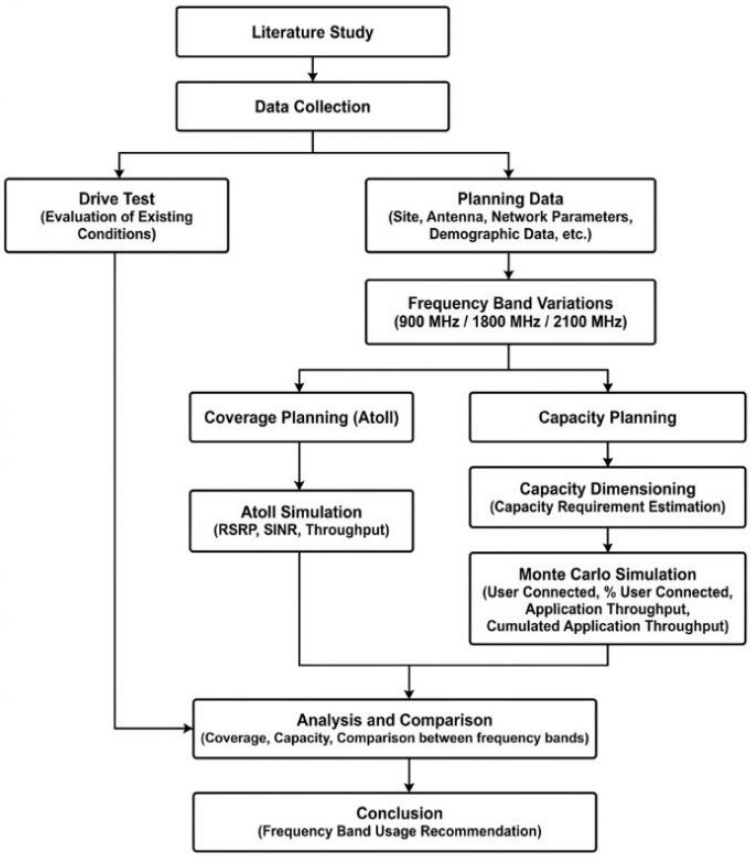


Figure 1. Research Flowchart

Figure 1 shows the overall research stages, the research process begins with a literature review. The research stages included a literature review on LTE network planning, propagation models, coverage analysis and Monte Carlo simulations. Data collection was then carried out, covering population data, administrative boundaries, coordinates of

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existing sites, radio equipment specifications, antenna configurations, technical network parameters and equipment datasheets, and scientific references. Field measurement data were obtained via drive tests using TEMS Pocket. Measurements were carried out using the RAT Lock LTE and Band Lock configurations on each of the analysed frequency bands, namely 900 MHz, 1800 MHz and 2100 MHz. The main parameters recorded included RSRP, SINR and throughput. The drive test data was then used to characterise the empirical network conditions and as a benchmark against the simulation results.

In terms of coverage planning, simulations were conducted using Atoll software to obtain coverage distributions based on Reference Signal Received Power (RSRP), Signal-to-Interference-plus-Noise Ratio (SINR) and throughput parameters. These results were then used to determine the coverage area and service quality achieved by each frequency band. For capacity planning, a dimensioning process was performed to estimate the required network capacity based on the number of users and their traffic demands. Monte Carlo simulations were then conducted to evaluate the network's ability to serve users under the specified traffic conditions. The analysed parameters included connected users, rejected users, RLC cumulative throughput and application cumulative throughput, which were used as indicators of network capacity performance.

The results of the coverage and capacity analyses were then compared for the different frequency bands. The aim of this comparison was to identify the frequency band that delivered the best performance in terms of both coverage and capacity. The results were also compared with existing network conditions, using drive test data, to assess the impact of changes to the frequency bands on network performance. The final stage involved drawing conclusions and formulating recommendations for frequency band usage based on the findings of the analysis. These recommendations were developed by balancing coverage area, signal quality, user serviceability and network traffic capacity.

The next stage is coverage planning, which involves calculating the link budget, the maximum allowable path loss (MAPL), the cell radius and coverage area, and estimating the number of eNodeBs required. The MAPL value is calculated using equation (1).

$$\text{MAPL} = \text{EIRP} - \text{S}_{\text{Rx}} - \text{Margin}_{\text{Interferensi}} + \text{Gain}_{\text{Rx}} - \text{Loss}_{total} \qquad (1)$$

Next, the cell coverage area is calculated using Equation (2).

$$L_{cell} = 2{,}6\ x\ d^2 \qquad (2)$$

L_{cell} is the cell coverage area (km²) and d is the cell radius (km). The estimated number of sites is calculated using Equation (3).

$$Number\ of\ sites = \frac{A_{region}}{A_{cell}} \qquad (3)$$

In addition to coverage planning, capacity planning is carried out to calculate traffic demand and network capacity. Traffic demand is calculated using Equation (4).

$$Traffic_{Demand} = N_{active} \times SUT \qquad (4)$$

N_{active} is the number of active users and SUT is Single User Throughput. The capacity of a single cell is calculated using Equation (5).

$$C_{cell} = \frac{TBS \times N_{MIMO}}{TTI} \qquad (5)$$

The calculation of the total network capacity is done using equation 6.

$$C_{network} = N_{site} \times 3 \times C_{cell} \qquad (6)$$

The planning parameters were implemented in the Atoll software by configuring the propagation model, antenna parameters, transmit power, bandwidth, and MIMO settings. The simulation parameters used in this study are shown in Table 1.

Table 1. LTE Network Simulation Parameters

Parameters	900 MHz	1800 MHz	2100 MHz
Bandwidth	10 MHz	20 MHz	20 MHz
Propagation Model	Okumura-Hata	COST-231 Hata	COST-231 Hata
Transmission Power eNodeB	47,78 dBm	47,78 dBm	47,78 dBm
Antenna Height	40 m	40 m	40 m
Configuration MIMO	2×2	2×2	2×2

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RESULT

The Effect of Frequency Variation on Coverage

A 4G LTE network coverage simulation was carried out using Atoll software, based on parameters derived from coverage planning. These parameters included link budget calculations, maximum allowable path loss (MAPL), cell radius, cell coverage area and estimates of site requirements. The simulation was performed across three frequency bands 900 MHz, 1800 MHz, and 2100 MHz to evaluate network coverage characteristics in the Padang Timur sub-district. The results of the calculations for the cell radius, cell coverage area, and number of sites for each frequency band are presented in Table 2.

Table 2. Calculated Cell Radius and Site Requirements for the Padang Timur District

Frequency	MAPL (dB)	Cell Radius (km)	Cell Area (km^2)	Number of Sites
900 MHz	138.67	2.5481	16.8815	1
1800 MHz	133.38	0.9326	2.2612	4
2100 MHz	133.55	0.8195	1.7461	5

Based on Table 2, the 900 MHz frequency produced the highest MAPL value of 138.67 dB, with a cell radius of 2.5481 km and a cell coverage area of 16.8815 km². These conditions resulted in an estimated requirement of 1 site to cover the study area. The 1800 MHz frequency produces a MAPL of 133.38 dB with a cell radius of 0.9326 km and a coverage area of 2.2612 km², meaning that 4 sites are required. Meanwhile, the 2100 MHz frequency yields a MAPL of 133.55 dB, a cell radius of 0.8195 km and a coverage area of 1.7461 km², meaning the requirement increases to 5 sites. The differences in cell radius across the three frequency bands result from the interaction between frequency characteristics, link budget parameters, and the propagation models used in each scenario. These results indicate that, under the planning parameters used in the scenarios, increasing the frequency band from 900 MHz to 1800 MHz and 2100 MHz leads to a reduction in cell radius and an increase in the number of sites required.

Drive tests were conducted to obtain an empirical picture of the condition of the existing 4G LTE network across each frequency band. The parameters observed included RSRP, SINR and throughput. The drive test data were used as an empirical comparison against the simulation results to assess the consistency of network performance characteristics across each frequency band. The RSRP measurement results are shown in Figure 2, whilst a comparison of the RSRP distributions between the drive test and simulation results is presented in Figure 6.

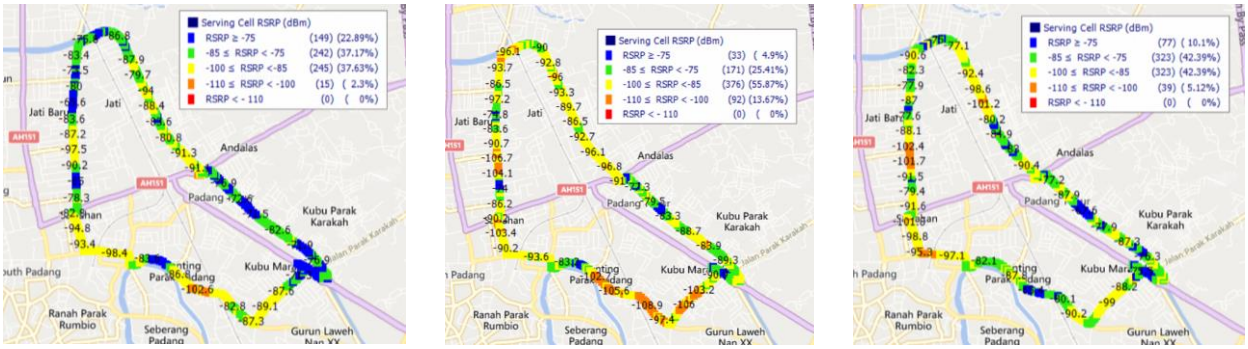


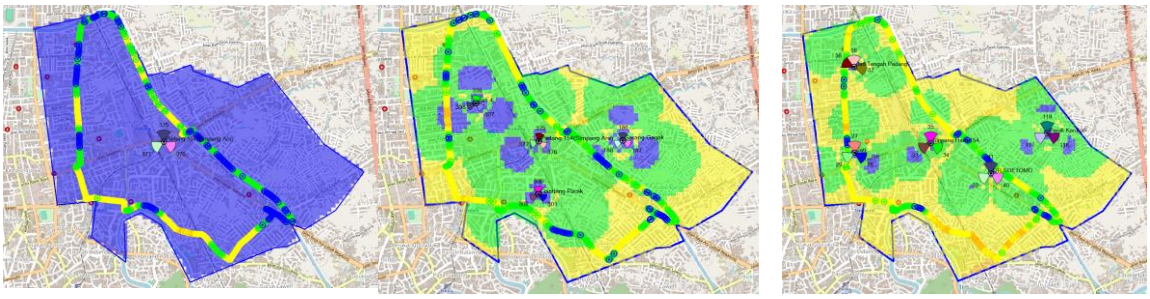
Figure 2. Plots of RSRP drive test results (a) 900 MHz, (b) 1800 MHz, (c) 2100 MHz

RSRP indicates the reference signal strength received by the user from the serving cell. Based on the drive test results in Figure 2, there are differences in the distribution of RSRP quality across the three frequency bands. The 900 MHz band showed the best coverage performance, with 22.89 % of the measured area falling into the 'Excellent' category. At 1800 MHz, the percentage of area in the 'Excellent' category fell to 10.10 %, whilst at 2100 MHz it reached only 4.90 %. An increase in frequency, whilst other parameters remain constant, tends to increase propagation losses, thereby limiting signal range. The drive test results indicate that the 900 MHz frequency offers better penetration and coverage in the study area. Figure 3 presents the coverage simulation results based on RSRP parameters at 900 MHz, 1800 MHz and 2100 MHz. The percentage distribution of each RSRP quality category from the simulation results and their comparison with the drive test results are shown in Figure 3.

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(a) (b) (c)

Figure 3. Simulation results for RSRP coverage at (a) 900 MHz, (b) 1800 MHz and (c) 2100 MHz

Table 3. Statistics on the Results of the RSRP Coverage Simulation

Range (dBm)	Legend	900 MHz(%)	1800 MHz (%)	2100 MHz (%)
RSRP ≥ −75	*Excellent*	100 %	11,2 %	2.67 %
-85 ≤ RSRP < -75	*Very Good*	0 %	56.9 %	48.77 %
-100 ≤ RSRP < -85	*Good*	0 %	32 %	47.88%
-110 ≤ RSRP < -100	*Bad*	0 %	0 %	0.67 %
RSRP < -110	*Poor*	0 %	0 %	0 %
Total		100 %	100 %	100%
RSRP ≥ -100 dBm		100%	100%	99.32%
Mean		-57.5 dBm	-81.91 dBm	-84.95 dBm
Standard Deviation		8.04 dBm	5.67 dBm	6.05 dBm

Figure 3 shows the results of coverage simulations based on RSRP parameters at frequencies of 900 MHz, 1800 MHz and 2100 MHz, whilst the percentage distribution of areas with an RSRP of ≥ −100 dBm is presented in Figure 6. The 900 MHz frequency provides the best coverage performance, with 100 per cent of the area falling into the 'Excellent' category and an average RSRP value of −57.50 dBm. At 1800 MHz, coverage is dominated by the 'Very Good' category at 56.90 per cent, with an average RSRP of −81.91 dBm. Meanwhile, the 2100 MHz frequency produced a coverage distribution still dominated by the 'Very Good' and 'Good' categories, with an average RSRP of −84.95 dBm. Although the average RSRP value decreases as the frequency increases, all frequency bands are still capable of providing service areas with an RSRP ≥ −100 dBm, thereby meeting the LTE network coverage criteria in the study area.

The SINR parameter indicates the quality of the signal received by the user relative to the signal served by a cell (eNodeB), taking into account the effects of interference and noise. The results of the SINR drive test are shown in Figure 4 and the SINR coverage simulation in Figure 5. Meanwhile, the percentage distribution of each SINR quality category from the simulation results is presented in Table 4.

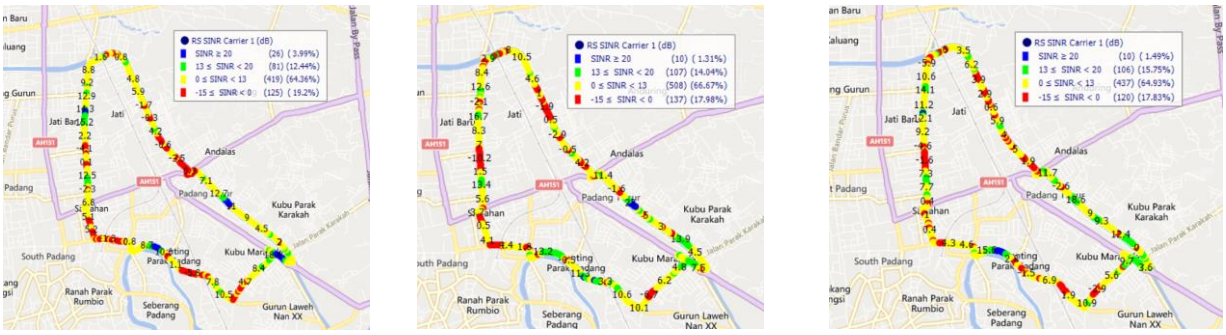


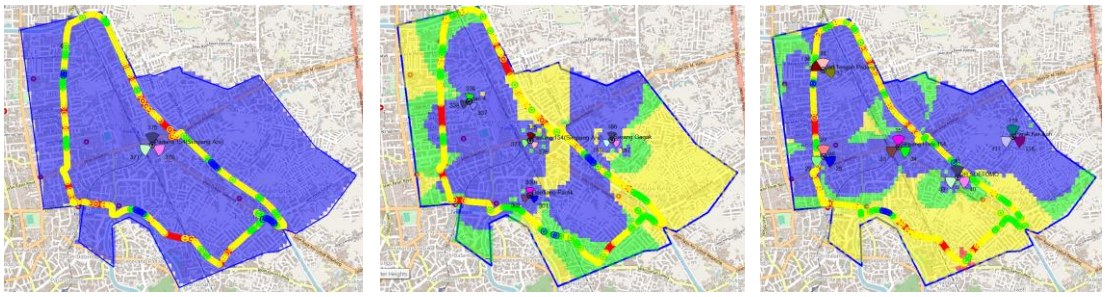
Figure 4. Plot of Drive test SINR Results: (a) 900 MHz, (b) 1800 MHz, (c) 2100 MHz

Based on Figure 4, at the 900 MHz frequency, the percentage in the 'Excellent' category was 3.99 %, whilst the 'Very Good' category stood at 12.44 %. At the 1800 MHz frequency, the 'Excellent' category fell to 1.31 %, whilst the 'Very Good' category rose to 14.04 %. The 2100 MHz frequency showed the best SINR performance amongst all the frequencies tested. The percentage in the 'Excellent' category was 1.49 % and in the 'Very Good' category 15.75 %. Based on this distribution, the 2100 MHz frequency showed a relatively higher proportion of high-quality SINR categories compared with other frequencies in the field measurement results.

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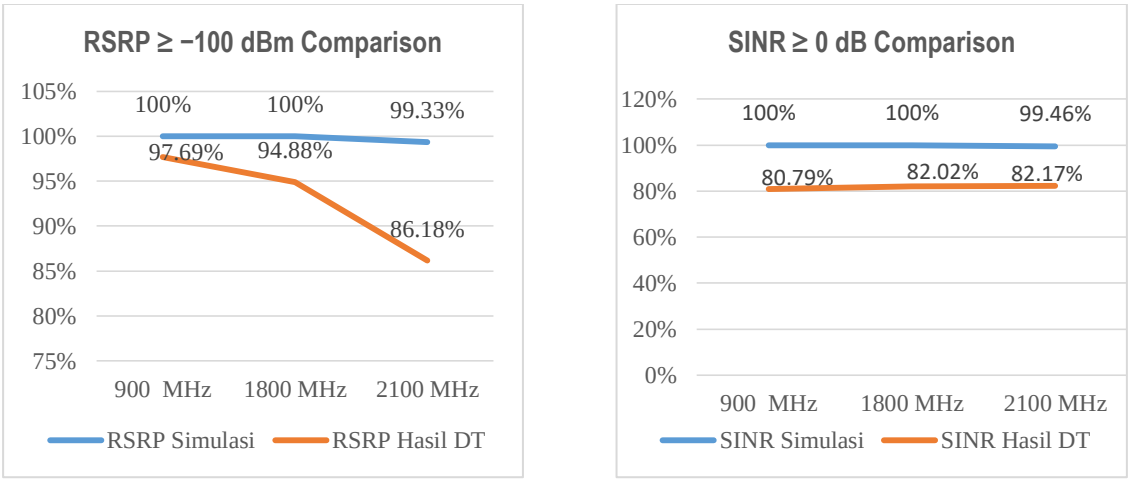
(a) (b) (c)

Figure 5. Simulation Results for SINR Coverage at (a) 900 MHz, (b) 1800 MHz and (c) 2100 MHz

Table 4. Statistics on the Results of the SINR Coverage Simulation

Range (dB)	Legend	900 MHz (%)	1800 MHz (%)	2100 MHz (%)
SINR ≥ 20	*Excellent*	100 %	46.8 %	60.49 %
13 ≤ SINR < 20	*Very Good*	0 %	21.6 %	12.55 %
0 ≤ SINR < 13	*Bad*	0 %	31.5 %	26,6 %
-15 ≤ SINR < 0	*Poor*	0 %	0 %	0.46%
Total		100 %	100 %	100 %
SINR ≥ 0 dB		100%	100 %	99.46%
Mean		42.82 dB	19.4 dB	23.61 dB
Standard Deviation		9.42 dB	11.1 dB	12.96 dB

The results of the SINR coverage simulation at 900 MHz and 1800 MHz show that 100 per cent of the area meets the KPI (SINR ≥ 10 dB). At 2100 MHz, coverage was 99.54 % thus, in general all three scenarios provided adequate signal quality for LTE services. However, analysis based on average SINR values revealed differences in channel quality. The 900 MHz frequency produced the highest average SINR of 42.82 dB, the 2100 MHz frequency 23.61 dB and the 1800 MHz frequency 19.40 dB. These results indicate that, although all frequencies met the minimum KPI, the resulting radio channel quality was not uniform; consequently, the 900 MHz frequency continues to deliver the best SINR performance.



(a) (b)

Figure 6. Graph Comparing RSRP and SINR Coverage at Various Frequencies: (a) RSRP, (b) SINR

The comparison graph was based on areas meeting the criteria for good service (RSRP ≥ -100 dBm); for the 900 MHz frequency, both sets of results showed a high degree of agreement. The simulation predicted 100 per cent coverage, whilst the drive test results indicated 97.69 % coverage, resulting in a difference of just 2.31%. At the 1800 MHz frequency, with RSRP ≥ -100 dBm, the simulation results showed 100% coverage, whilst the drive test results showed 94.88%, resulting in a difference of 5.12%. At the 2100 MHz frequency with RSRP ≥ -100 dBm, the simulation produced a coverage of 99.33 %, whilst the drive test results only reached 86.18 %, thus there was a difference of 13.15 %. These results indicate that the 900 MHz frequency is capable of providing excellent signal coverage across the majority of the measurement area. Generally, the measurement results show that the SINR values do not exhibit the same pattern of decline as the RSRP parameter. A comparison of SINR values from drive tests and simulations shows

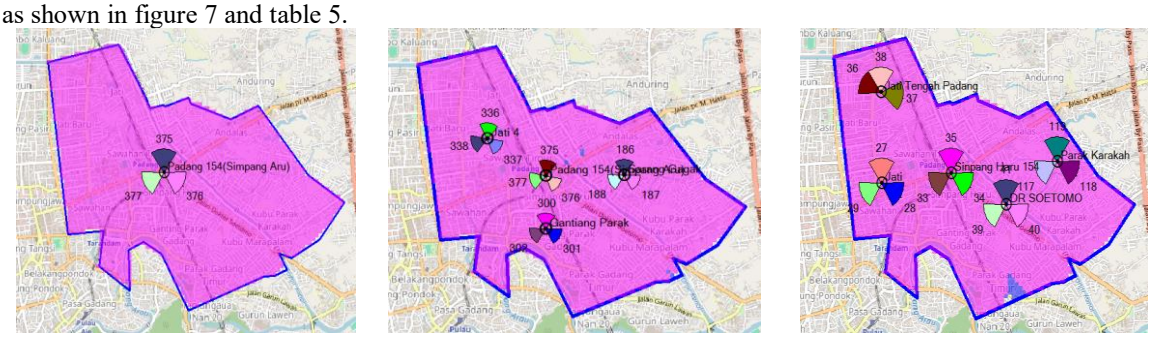
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that for SINR ≥ 0 dB, the figure reaches 80.79 %. Meanwhile, the SINR value ≥ 0 dB at the 1800 MHz frequency reached 82.02 %, slightly higher than that of the 900 MHz frequency. The 2100 MHz frequency demonstrated the best SINR performance among all the frequencies tested, with SINR ≥ 0 dB reaching 82.17 %, which is the highest value in this study. Meanwhile, in the SINR coverage planning using simulation, the 900 MHz and 1800 MHz frequency bands showed 100 % for SINR ≥ 0 dB, whilst the 2100 MHz band showed 99.46 %.

The Effect of Frequency Variation on Capacity

Capacity is related to throughput, capacity is the maximum ability of a network to handle data traffic. Throughput is a parameter that indicates the actual amount of data successfully transmitted from the network to the users device within a specific unit of time. Unlike RSRP and SINR, which focus on radio quality, throughput directly reflects the service performance experienced by users when accessing the internet. The results of the throughput coverage simulation at various frequencies are used to illustrate the LTE networks ability to provide data services in the study area, as shown in figure 7 and table 5.



(a) (b) (c)

Figure 7. Simulation results for coverage and throughput: (a) 900 MHz, (b) 1800 MHz and (c) 2100 MHz

Table 5. Statistics on Simulation Results for Coverage and Throughput

Value Range Throughput (kbps)	Color	(%) 900 MHz	(%) 1800 MHz	(%) 2100 MHz
THP ≥ 12,000	*Excellent*	100 %	99.8 %	99.4 %
7,200 ≤ THP < 12,000	*Very Good*	0 %	0.2 %	0.6 %
1,500 ≤ THP < 7,200	*Good*	0 %	0 %	0 %
324 ≤ THP < 1,500	*Bad*	0 %	0 %	0 %
0 ≤ THP < 324	*Poor*	0 %	0 %	0 %
Total		100 %	100 %	100 %
THP ≥ 7.200 kbps		100 %	100 %	100 %
Mean		96,338.6 kbps	116,953.71 kbps	116,640.03 kbps
Standard deviation		1,296.94 kbps	66,439.55 kbps	65,829.25 kbps

The throughput simulation results show that all three frequency bands are capable of delivering throughput coverage of ≥7,200 kbps across almost the entire study area. The 1800 MHz and 2100 MHz frequencies produced the highest average throughput, at 116,953.71 kbps and 116,640.03 kbps respectively, whilst the 900 MHz frequency produced an average throughput of 96,338.60 kbps. These results indicate that the increased bandwidth at the 1,800 MHz and 2100 MHz frequencies provides greater data transmission capacity compared to the 900 MHz frequency.

Based on the capacity dimensioning results, the traffic requirement for the study area is 1,582.9 Mbps. The 900 MHz frequency only provides a network capacity of 220.17 Mbps, and is therefore unable to meet the traffic demand. Conversely, the 1800 MHz and 2100 MHz frequencies yield capacities of 1,809.02 Mbps and 2,261.28 Mbps respectively, meaning that, in theory they meet the areas traffic requirements.

Table 6. Traffic Requirements and Network Capacity

Research Areas	Total *Demand* (Mbps)	Frequency Band	Number of Sites	Total Network Capacity (Mbps)
Padang Timur	1.582,9	900 MHz	1	220.17
		1800 MHz	4	1,809.02
		2100 MHz	5	2,261.28

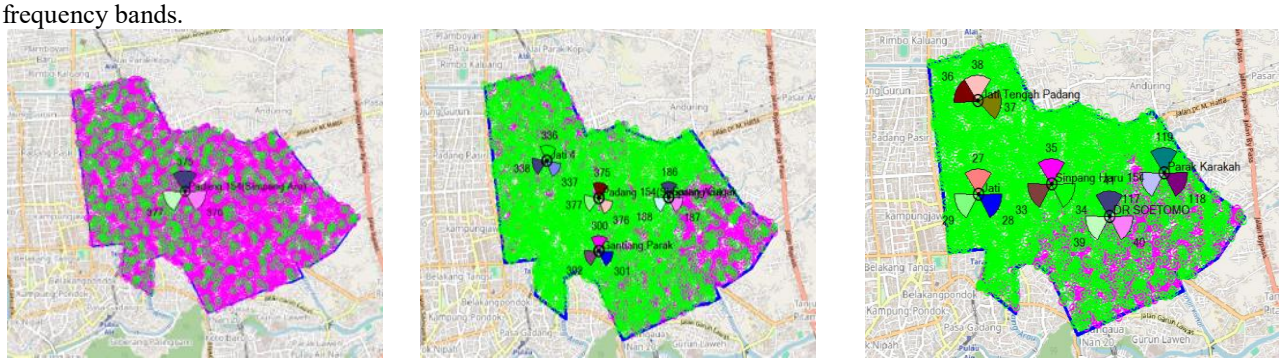
To evaluate network capacity under more realistic user distribution conditions, a Monte Carlo simulation was conducted with approximately 4,397 users randomly distributed across the study area. Figure 8 shows the simulated user distribution across each frequency band, whilst Table 7 summarises the network capacity performance indicators, which include connected users, RLC Cumulative Throughput, and Application Throughput. The simulation results show

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that the 2100 MHz frequency delivered the best performance with a connected user ratio of 73.8%, followed by the 1800 MHz frequency at 65.5%, whilst the 900 MHz frequency was only able to serve 13.6% of users due to network capacity limitations. Furthermore, the 2100 MHz frequency also produced the highest cumulative application throughput of 1,104.06 Mbps, demonstrating a greater ability to meet traffic demands compared to the other two frequency bands.



(a) (b) (c)

Figure 8. Results of LTE Network Capacity Simulations using the Monte Carlo Method
(a) 900 MHz, (b) 1800 MHz, (c) 2100MHz

Table 7. Statistical Results for Throughput Using the Monte Carlo Method Across Various LTE Frequency Bands

Frequency Band	***Connected* (%)**	**RLC *Throughput* (Mbps)**	***Application Throughput* (Mbps)**
900 MHz	13.6	216.00	205.20
1800 MHz	65.5	1,037.88	979.50
2100 MHz	73.8	1,167.48	1,104.06

The research findings indicate that the 2100 MHz frequency provides the most balanced performance in the study area. This frequency yielded the highest connected user ratio of 73.8 % and a cumulative application throughput of 1,104.06 Mbps, which was higher than in the other two scenarios. These results indicate that network performance is determined not only by theoretical capacity, but also by the balance between coverage, channel quality and the utilisation of radio resources.

The research findings indicate a discrepancy between the theoretical capacity derived from capacity dimensioning and the actual capacity obtained through Monte Carlo simulation. In capacity dimensioning, capacity is calculated on the assumption that each cell operates under ideal conditions, meaning that all radio resources can be utilised optimally. Conversely, the Monte Carlo simulation takes into account the random distribution of users, thereby providing a picture that more closely approximates actual network operating conditions. This difference is evident at the 1800 MHz and 2100 MHz frequencies. Although both frequencies met traffic requirements based on capacity dimensioning, the results of the Monte Carlo simulation showed that the 2100 MHz frequency was capable of achieving a higher ratio of connected users compared to the 1800 MHz frequency.

The difference in performance between the 1800 MHz and 2100 MHz frequencies is thought to be influenced by user distribution and radio channel quality in each simulation scenario. Although both frequency bands utilise a 20 MHz bandwidth and a 2×2 MIMO configuration, the uneven user distribution results in varying traffic loads across each cell, meaning that resource block utilisation is not optimal.

DISCUSSION

The research findings indicate that an increase in operating frequency leads to an increase in path loss, thereby reducing the Maximum Allowable Path Loss (MAPL) value and decreasing the cell radius. In this study, the 900 MHz frequency produced the highest MAPL of 138.67 dB with a cell radius of 2.5481 km, whilst the 1800 MHz and 2100 MHz frequencies had smaller cell radii, thus requiring a greater number of sites to cover the study area. These findings indicate that lower frequency bands possess better propagation characteristics and are therefore more effective at extending service coverage. This is reflected in this study, where the 900 MHz frequency delivered the best coverage performance compared to the other two frequency bands.

However, improved coverage at lower frequencies is accompanied by capacity limitations. (Silalahi et al., 2022) show that 900 MHz LTE with a 5 MHz bandwidth has a single-user capacity of only 25.2 Mbps, which is significantly lower than that of 1800 MHz LTE, which reaches 95.76 Mbps. Therefore, LTE at 900 MHz is better suited to functioning as a coverage layer to extend coverage and reduce traffic load on higher frequency bands. The same findings are evident in this study, where the 900 MHz frequency was only able to serve 13.6 % of users in the Monte Carlo simulation, despite providing the best coverage performance.

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In addition to being influenced by the choice of frequency band, coverage performance is also determined by the optimisation of network parameters. (Yuhanef et al., 2024) demonstrate that optimising the electrical tilt of the antenna and increasing the EIRP in an 1800 MHz LTE network can significantly improve RSRP and SINR quality. These findings indicate that frequency band selection and radio parameter optimisation are two complementary approaches to improving network performance. Optimising antenna parameters can significantly improve RSRP and SINR quality without the need to change the frequency band in use. Thus, the results of this study demonstrate that improvements in channel quality result from a combination of frequency characteristics and optimised network configuration.

Overall, the research findings indicate that the 2100 MHz frequency is the most balanced choice for the study area, as it offers the best compromise between coverage, signal quality and network capacity. These findings suggest that the selection of a frequency band should not be based solely on theoretical capacity, but should also take into account propagation conditions and traffic distribution in order to optimise network performance.

The research findings indicate that each frequency band has distinct characteristics; therefore, their selection must be tailored to the objectives of network planning. The 900 MHz frequency offers the best coverage performance and is therefore more suitable for use as a coverage layer, particularly for extending service coverage in areas with low traffic density. Meanwhile, the 2100 MHz frequency offers the best balance between coverage and capacity, making it more suitable for use as the primary capacity layer in the study area. The 1800 MHz frequency can be utilised as a supporting layer as it offers a compromise between service coverage and network capacity. Consequently, the selection of a frequency band is determined not only by available capacity but also by service requirements and the characteristics of the implementation area.

CONCLUSION

The results of the 4G LTE network quality measurements show that each frequency band has different performance characteristics. The 900 MHz frequency band produced the best signal coverage quality, with 97.69 per cent of measurements showing an RSRP of ≥ −100 dBm. The 2100 MHz frequency band delivers coverage quality with an 82.17 per cent of SINR ≥ 0 dB. A comparison of coverage quality based on Atoll simulation results and drive test measurements reveals a consistent trend across all frequency bands. The 900 MHz frequency band offers the best coverage capability as it provides a wider RSRP coverage area compared to higher frequencies. Meanwhile, the 2100 MHz frequency band demonstrates better SINR quality, thereby supporting more stable communication quality. Among the three frequency bands evaluated, the 2100 MHz frequency band offers the most balanced performance between coverage and capacity, with the highest connected user ratio of 73.8 per cent and a cumulative application throughput of 1,104.06 Mbps. Meanwhile, the 900 MHz frequency is more suitable for use as a coverage layer as it is capable of providing extensive service coverage, whilst the 1800 MHz frequency can act as a supporting layer that provides a balance between coverage and capacity. These findings indicate that the selection of frequency bands needs to be tailored to the characteristics of the service and traffic requirements in the implementation area.

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