

Hierarchical Coverage and Capacity Optimization of 5G New Radio Non-Standalone in Tourism Corridors

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Abstract: A hierarchical strategy for optimizing coverage and capacity is proposed for fifth-generation (5G) New Radio networks operating in non-standalone architecture, deployed in hilly tourism corridors with transient, high-mobility users. A drive-test campaign (7,522 measurement points, collected using a mobile network testing application) was conducted on a commercial 5G non-standalone network in the Jam Gadang corridor, Bukittinggi, West Sumatra, Indonesia, and benchmarked against three radio-planning scenarios simulated using commercial radio-planning software. Three interventions were evaluated in order of increasing capital cost: antenna tilt and azimuth tuning, small-cell densification, and the addition of new macro-sites. Drive-test results show 97.55% of reference signal received power samples in the very-good band (≥ -85 dBm), confirming downlink throughput — not coverage — as the dominant constraint. Against the simulation baseline (77.30% very-good reference signal received power, 70.55% very-good signal-to-interference-plus-noise ratio), antenna tuning alone raises reference signal received power to 84.50% very-good and reduces the poor-band signal-to-interference-plus-noise ratio from 2.03% to 0.06% at zero hardware cost. Small-cell densification achieves the strongest throughput gain (99.00% very-good downlink throughput), while new macro-site addition achieves the strongest coverage gain (92.20% very-good reference signal received power, 0.00% poor). These results substantiate a cost-ordered hierarchical planning sequence transferable to similar tourism heritage corridors in emerging markets.

Keywords: 5G NR NSA; Drive test; Coverage optimization; Small cell; Atoll

INTRODUCTION

Fifth-generation (5G) cellular networks have now become the backbone of digital infrastructure worldwide, driven by the growth of mobile data traffic, which is projected to increase more than tenfold this decade (Banafaa et al., 2024) (Rafiq et al., 2025). In the tourism sector, high-quality connectivity has shifted from being merely a value-added feature to a fundamental operational necessity (H. Liu et al., 2024). Indonesia faces a dual challenge: expanding 5G network coverage to areas with complex topography while ensuring sufficient service capacity for highly mobile users. Whether users can truly benefit from the network's capabilities is largely determined by the quality of radio range planning (Demir et al., 2021), which depends on an understanding of signal propagation in real-world environments (Hernandez & Bulut, 2023)—both indoor and outdoor conditions (U. Ali et al., 2022)—and is further reinforced by empirically based models (Mercuri et al., 2021) and detailed propagation studies (Azevedo & Mendonça, 2024).

To bridge the gap in radio planning, operators rely on: massive MIMO technology (Alhaj et al., 2024), antenna design engineering (Raj et al., 2023), network planning algorithms (Gkonis, 2023), cross-spectrum coordination (Quirini et al., 2025), and densification through small cells (Ahamed & Faruque, 2021). The impact of each decision is quantified using objective KPIs (Souifi et al., 2022)—RSRP, SINR, and downlink throughput (Lazar et al., 2023)—obtained through drive tests (El-Saleh et al., 2022), comparative network analysis (Imoize et al., 2023), and real-time evaluation (Raftopoulou et al., 2025).

Nevertheless, five gaps remain unaddressed. First, the validation of radio planning in highly contoured areas remains limited (S. Ali et al., 2024) (Jaensch et al., 2026), resulting in underrepresentation of rural contexts and complex topography (Cabrera-Castellanos et al., 2021). Second, studies combining real-world drive tests with

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calibrated simulations on identical baselines remain scarce (Amanaf et al., 2020), making it difficult to isolate the comparative advantages of each intervention (Sharmin et al., 2026). Third, empirical evidence is dominated by data from developed countries (Chen et al., 2024), while research from Indonesia remains scarce (Y. Liu & Song, 2026). Fourth, operational measurement data for Non-Standalone (NSA) 5G networks remains very limited (Kousias et al., 2024) (Caso et al., 2024). Fifth, the cost-and-energy trade-offs between antenna tuning, small cells, and new sites are rarely analyzed within a sustainability framework (Ichimescu et al., 2024) (Abbas et al., 2023). Based on these five gaps, the main issue is the lack of a tiered 5G NSA network optimization framework—one that is capital-intensity-ordered, empirically validated, and applied to highly contoured tourist corridors in developing countries.

This study aims to develop and evaluate a hierarchical multi-scenario optimization strategy for improving 5G NR NSA coverage in highly contoured tourism corridors. The proposed framework consists of three optimization stages: (1) adjusting antenna tilt and azimuth, (2) densifying small cells at confirmed throughput hotspots, and (3) adding new macro sites only to address residual gaps (Sudhamani et al., 2023). This approach was validated through a 5G NR NSA drive test in the Jam Gadang corridor, Bukittinggi, with three Atoll simulation scenarios evaluated against an identical reference baseline (Megnafi et al., 2026). Each result was reported using the quality bands per category used by the operator (Vivone et al., 2021).

The novelty of this research lies in three aspects that address the gaps mentioned above. First, the empirical validation of 5G NSA radio planning in highly contoured terrain (gap 1) (Xu et al., 2025). Second, a design that combines drive tests with calibrated simulations closes the methodological gap (gap 2) (Beyraghi et al., 2025; Dubey, 2024), and generates the latest 5G NSA field data from Indonesia (gaps 3 and 4). Third, a capital-intensity-ordered optimization hierarchy provides a staged decision-making framework (gap 5) (Wulandari et al., 2026), allowing most quality improvements to be achieved before significant capital investment is justified (Hochstrasser, 1993).

This study is guided by four research questions: (RQ1) Is coverage or capacity the limiting factor? (RQ2) Do the calibrated simulation baselines reproduce the measured characteristics? (RQ3) How do antenna tuning, small cell densification, and the addition of new sites perform on identical baselines? and (RQ4) How do comparative rankings support hierarchical strategies (Martínez Abuabara et al., 2025), (Ullah et al., 2026)? Section 2 describes the research methods; Section 3 presents the results and discussion; and Section 4 summarizes the findings.

METHOD

This section presents the research procedures in chronological order, covering the research design, characterization of the study area, field measurements, radio network simulation, and classification scheme. The workflow is summarized in Figure 1, and all category thresholds are defined in Table 1.

Research Design

This study employs a quantitative empirical design that combines real-network drive-test campaigns with multi-scenario radio planning simulations (Zakeri et al., 2024), integrating two complementary sources of evidence: field measurements and controlled simulations against an identical reference baseline (Xie & Long, 2026). The study area is the city of Bukittinggi, West Sumatra, Indonesia—25.24 km² of hilly terrain at an elevation of 900–1,000 m above sea level. The Jam Gadang corridor was selected because it brings together highly mobile transient users, height restrictions on heritage buildings, and high expectations for digital services (Wang et al., 2025). The simulations followed the standard 5G radio planning workflow with identical propagation, terrain, and clutter parameters across all scenarios (Bellary et al., 2022), (Haile et al., 2020).

Study Area and Network Configuration

Measurements were conducted in the service areas of two Telkomsel gNodeBs: Site Plaza (central commercial district) and Site Toko Sehati (western residential district). Both operate in a 5G NR Non-Standalone configuration with the 5G NR n1 band (2100 MHz) carrier anchored to LTE L1/L3/L8 via E-UTRAN New Radio Dual Connectivity (EN-DC) (Parvini et al., 2023). Coordinates are referenced to WGS84 and projected to UTM Zone 48S. Terrain and clutter layers were imported from a 30-meter DEM (Fazilova, 2022) and supplemented with Google Earth Pro imagery to represent the building density around the Jam Gadang landmark (Stamou et al., 2025).

Drive-test Procedure

The drive test was conducted using G-NetTrack Pro v.30.5 on a 5G n1-band-capable smartphone, with the SIM card locked to the Telkomsel 5G network (Stroobandt et al., 2025). Measurements were taken in the Jam Gadang, Pasar Ateh, and Site Toko Sehati corridor areas. Vehicle speed was maintained at 20–30 km/h. Recorded variables included RSRP (dBm), RSRQ (dB), SINR (dB), and TPUT-DL (Mbps) in a GPS-timestamped CSV log. Of the 7,522 raw data points collected, 367 points (4.88%) were retained after a four-stage filtering process applied in Microsoft Excel. First, records were filtered by Network Mode, retaining only rows tagged "5G NR" and excluding

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LTE-only or other non-5G modes (7,155 points, 95.12%, were excluded at this stage, predominantly 4G/LTE, consistent with the intermittent 5G coverage typical of early-stage NSA deployment along the corridor). Second, rows with null values in the primary parameters (RSRP, RSRQ, SINR, TPUT-DL) were removed; nulls typically occur during inter-network handover or momentary connection loss. Third, duplicate rows sharing identical GPS coordinates and parameter values were removed to avoid statistical redundancy. Fourth, points falling outside the defined study-area boundary (the Jam Gadang corridor, verified against Google Earth Pro reference coordinates) were excluded.

Downlink throughput (TPUT-DL) was measured using the same G-NetTrack Pro application and device as the other radio parameters, configured in dedicated mode with an active Download URL data sequence (pointing to a TestMy.net test server, Dallas, TX: <https://dallas10.testmy.net/b/download>). At each logged point, the application triggered a 100 MB random-byte file download via the device browser concurrently with the drive-test log, from which the achieved downlink throughput was recorded. Measurements were taken from 10:08:28 to 10:50:30 on February 2, 2026, during peak-hour traffic conditions, reflecting the high visitor density typical of the Jam Gadang tourist area.

Baseline Simulation Validation

Rather than an iterative calibration in which propagation-model parameters are tuned until simulated and measured values converge, the Atoll baseline in this study was configured directly from the operator's as-built site configuration (Table 1) using the standard propagation models (Cost-Hata, Okumura-Hata, and 3GPP TR 38.900), without post-hoc parameter adjustment; no formal calibration procedure (e.g., mean-absolute-error minimization against drive-test samples) was performed. The two independent data sources were instead validated against each other by comparing aggregate band-share distributions at the study-area level (Table 3 versus the Atoll baseline in Fig. 4). RSRP was better in the field than in the simulation (97.55% versus 77.30% very-good), SINR was lower in the field (46.32% versus 70.55% very-good), and the largest divergence was in downlink throughput, where only 0.54% of field samples reached the very-good band compared with 93.40% in the simulation. This throughput gap is attributable to a methodological difference rather than a modeling error: the field TPUT-DL values are single-sample, real-time application-layer downloads recorded under actual peak-hour network load and contention (Section 2.3), whereas the Atoll TPUT-DL prediction is a link-budget-based estimate that does not account for live traffic contention. The absence of a formal calibration step and this throughput-measurement mismatch are acknowledged as limitations of the present study.

Multi-scenario simulation setup

Table 1 Simulation Configuration Data Detailed Atoll project configuration parameters underlying the three optimization scenarios (Scenario A, B, C)

Parameter	Simulation configuration data
Propagation model	Cost-Hata, Okumura-Hata, and 3GPP TR 38.900, applied across the baseline network and the three optimization scenarios.
Transmit power	50 (unit as recorded in the Atoll project configuration table).
Antenna gain	17 dBi for all configurations.
Antenna height	Before: Plaza Bukittinggi = 21 m, Toko Sehati = 17 m. New macro-site: 30 m. Small cell: 10 m. Final optimization: Plaza = 21–22 m, Toko Sehati = 17 m (per transmitter/site configuration data).
Tilt and azimuth (before–after)	Plaza Bukittinggi – Before: dominant azimuth 0°, 100°, 180°; mechanical tilt 2°–6°. Final: azimuth 20°, 85°, 110°, 145°, 230°, 250°, 305°; mechanical tilt 2°–6°. Toko Sehati – Before: azimuth 90°, 160°, 315°; mechanical tilt 0°–4°. Final: azimuth 15°, 90°, 130°, 145°, 180°, 235°, 275°, 320°, 345°; mechanical tilt 2°–4°.
Bandwidth	Plaza Bukittinggi: n3 = 20 MHz, n8 = 10 MHz. Toko Sehati: n40 = 20 MHz, n3 = 20 MHz. New macro-site: 20 MHz on n3, 10 MHz on n8. Small cell: 10 MHz and 5 MHz on n8.
Number and coordinates of small cells	One small cell (“Small_cell”) at 100.373335328° E, 0.310867453° S.
Number and coordinates of new macro-sites	One new macro-site (“Penambahan Site”) at 100.36811° E, 0.30618° S.

Where noted as not available, the corresponding parameter was not present in the Atoll project configuration data used for this study.

The baseline network was reconstructed in Atoll (Chandra et al., 2026) using the operator's as-built configuration with a calibrated propagation model (Mlinar et al., 2023). Three scenarios were defined: Scenario A—adjusting antenna tilt and azimuth without new hardware; Scenario B—small cell densification at high-density hotspots (Tezcan et al., 2026); Scenario C—adding new macro sites to fill residual RSRP gaps (Guijarro et al., 2024). Each scenario was simulated with identical parameters to ensure a like-for-like comparison (Natanzi et al., 2026).

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Performance Categories and Analysis

Drive test samples and simulation results were classified into four performance bands (very good, good, fair, poor) plus a "no traffic / N/A" class, with thresholds defined in Table 1 and applied uniformly across the entire dataset. The percentage in the "very good" band serves as the primary indicator of coverage, while the percentage in the "poor" band serves as the primary indicator of coverage gaps.



Fig. 1 Research workflow: drive-test acquisition, spatial filtering, Atoll baseline calibration, multi-scenario optimization, comparative ranking, and the resulting hierarchical optimization evidence.

Table 2 Category thresholds for RSRP, RSRQ, SINR, and downlink throughput

Category	RSRP (dBm)	RSRQ (dB)	SINR (dB)	TPUT-DL (Mbps)
Very good	≥ -85	≥ -10	10 to 30	14 to 20
Good	-85 to -92	-10 to -14	3 to 10	7 to 14
Fair	-92 to -102	-14 to -17	0 to 3	1 to 7
Poor	-102 to -120	-17 to -25	0 to -20	0.512 to 1

RESULT

This section presents empirical findings and simulation results. All RSRP values are reported in dBm and TPUT-DL in Mbps, consistently using the category bands from Table 1.

Drive-test Baseline (validating Section 2.3)

Of the 7,522 raw data points, 367 were retained as valid 5G NR samples after the four-stage filtering process described in the Method section (network-mode selection, null-value removal, duplicate removal, and study-area boundary verification); the remaining 7,155 points were excluded, predominantly as non-5G (4G/LTE) network-mode records. The band category distribution is summarized in Table 2. The RSRP was predominantly in the "very good" band (97.55%). RSRQ was mostly in the "good" band (95.64%). SINR was more balanced: 46.32% "very good," 11.44% "fair," and 4.90% "poor." Downlink throughput showed the weakest performance: only 0.54% in the "very good" band and 29.70% with no traffic.

Table 3 Drive-test category-band distribution (n = 367 valid 5G samples)

Category	RSRP (%)	RSRQ (%)	SINR (%)	TPUT-DL (%)
Very good	97.55	1.36	46.32	0.54
Good	2.45	95.64	37.33	38.42

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Fair	0.00	2.72	11.44	31.06
Poor	0.00	0.27	4.90	0.27
No traffic / N/A	—	—	—	29.70

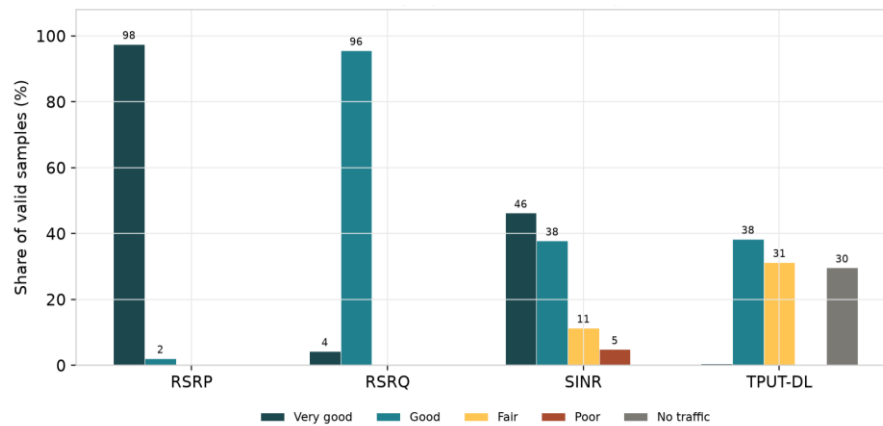


Fig 2. Drive-test baseline category-band distribution per metric (n = 367).

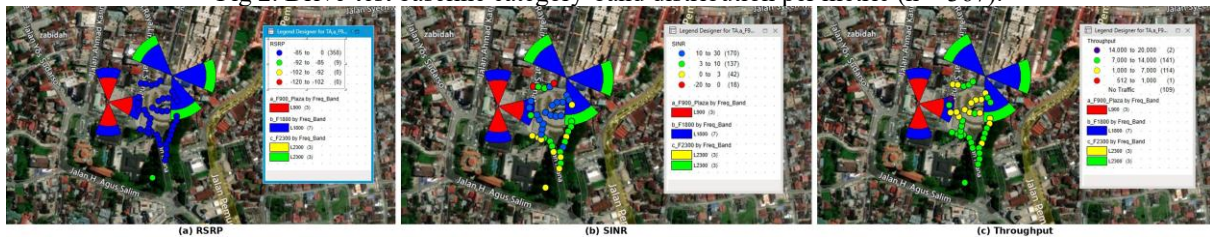


Fig 3. Geo-referenced drive-test heatmaps around Jam Gadang overlaid with the Site Plaza sector layout (F900/F1800/F2300): (a) RSRP, (b) SINR, (c) downlink throughput. Exported from the MapInfo/Atoll drive-test project.

Simulation baseline (validating Sections 2.2 and 2.4)

The baseline simulation reported 77.30% of pixels in the “very good” RSRP band, 70.55% SINR, and 93.40% TPUT-DL. The “poor” band reached 8.90% RSRP, 2.03% SINR, and 0.23% throughput.

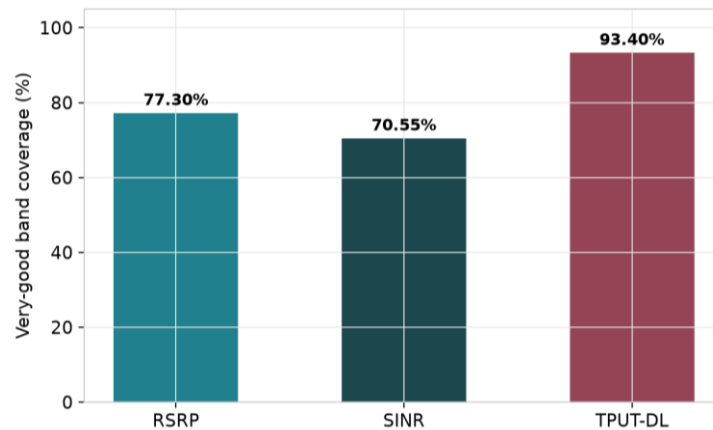


Fig 4. Atoll baseline coverage — very-good band share by metric (RSRP, SINR, TPUT-DL). Note: the actual Atoll coverage prediction maps should be inserted by the author before submission.

Optimization Scenarios (validating Section 2.4)

Each scenario was simulated using the same baseline with identical parameters. The numerical comparisons are summarized in Table 3 (very good band) and Table 4 (poor band).

Scenario A — Antenna Tilt and Azimuth Tuning

Scenario A improves the “very good” RSRP from 77.30% to 84.50% and the SINR from 70.55% to 77.85%, while the TPUT-DL increases from 93.40% to 96.30%. This scenario reduces the “poor” SINR from 2.03% to 0.06% without adding new hardware.

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Scenario B — Small-Cell Densification

Scenario B resulted in the greatest increase in throughput (TPUT-DL “very good” from 93.40% to 99.00%) and SINR from 70.55% to 85.35%, but slightly reduced the “very good” RSRP to 75.04% due to energy redistribution.

Scenario C — New-Site Addition

Scenario C resulted in the greatest improvement in coverage: the “very good” RSRP reached 92.20% and the SINR reached 85.40%, with the “poor” RSRP band completely eliminated (0.00%).

The improvements reported across scenarios are technical and practical in nature—evaluated against the fixed category thresholds in Table 2 rather than through inferential statistical testing—since each scenario represents a single deterministic Atoll simulation rather than repeated stochastic trials.

Table 4. Comparison of Atoll baseline versus three optimization scenarios (share of samples in the very-good band)

Scenario	RSRP very good (%)	SINR very good (%)	TPUT-DL very good (%)
Baseline (existing)	77.30	70.55	93.40
Scenario A (antenna tuning)	84.50	77.85	96.30
Scenario B (small cells)	75.04	85.35	99.00
Scenario C (new site)	92.20	85.40	98.40

Table 5 Share of samples in the poor band (lower is better)

Scenario	RSRP poor (%)	SINR poor (%)	TPUT-DL poor (%)
Baseline (existing)	8.90	2.03	0.23
Scenario A (antenna tuning)	8.90	0.06	0.00
Scenario B (small cells)	10.78	0.36	0.00
Scenario C (new site)	0.00	0.10	0.00

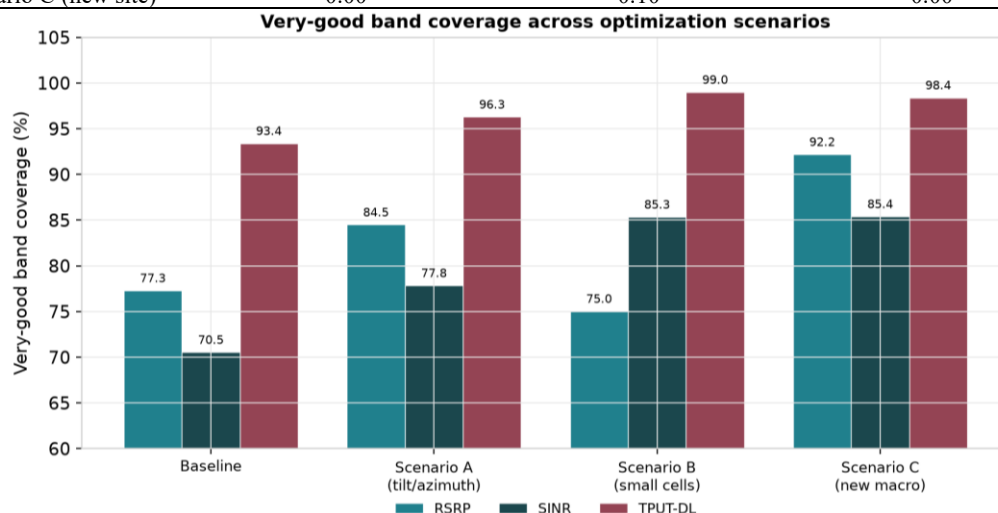


Fig. 5 Very-good band coverage (RSRP, SINR, TPUT-DL) across the baseline and the three optimization scenarios (Table 3). Representative comparison; actual per-scenario Atoll coverage maps should be inserted by the author before submission.

DISCUSSION**Interpretation of Baseline Findings (validating Sections 2.2–2.4)**

This confirms that throughput and SINR—not coverage—are the dominant constraints in this corridor.

Comparative Ranking of Optimization Strategies

Scenario C is dominant for RSRP coverage (92.20% very good, 0.00% poor). Scenario B outperforms the others for TPUT-DL (99.00% very good). Scenario A provides the lowest-cost improvement across all KPIs and nearly eliminates poor SINR (0.06%). Overall, these results reinforce the hierarchical optimization path: adjust antennas, deploy small cells at confirmed hotspots, and add macro sites only to address residual gaps. These rankings confirm the main hypothesis: the greatest benefit per cost is achieved at the lowest hierarchical level.

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The proposed sequence—antenna tuning, then small-cell densification, then new macro-site addition—follows increasing capital intensity and installation lead time. Antenna tuning requires no new hardware and can be executed using existing infrastructure, making it the appropriate first intervention for the SINR-limited condition observed at baseline. Small-cell densification is justified only where throughput gaps persist after tuning, since it requires additional site acquisition and equipment investment. New macro-site addition is reserved as the final tier because it is both the costliest intervention and the only one capable of eliminating the residual geometric shadowing responsible for the remaining poor-RSRP samples in Scenario C.

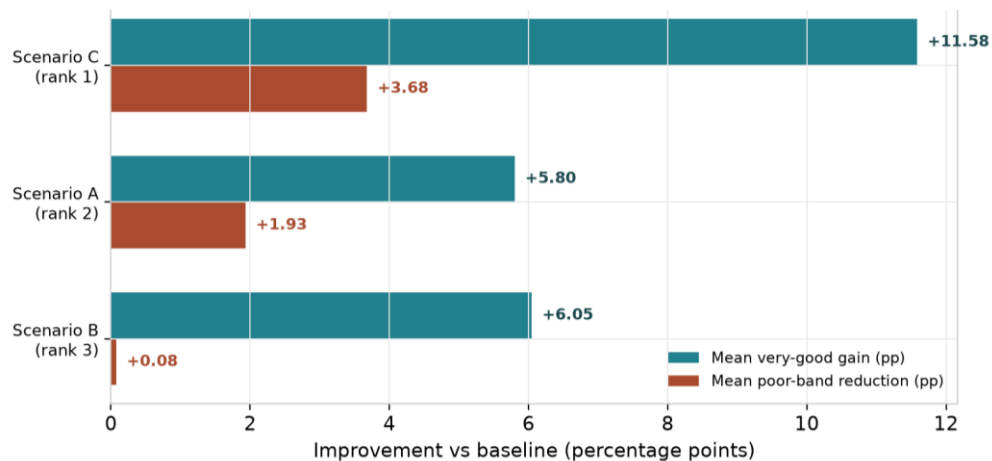


Fig. 6 Comparative ranking of the three optimization scenarios by mean very-good gain and mean poor-band reduction relative to baseline (computed from Tables 3 and 4). Scenario C ranks first overall, Scenario A second, Scenario B third.

Synthesis against the performance categories and prior work (validating Sections 2.2 and 2.5)

The band-by-band interpretation of the results using the thresholds in Table 1 reconciles the two sources of evidence. Field baseline measurements and simulations agree that the RSRP is already overwhelmingly in the “very good” band, while the SINR and throughput account for the residual gap—a hallmark of legacy corridors that are coverage-limited but capacity-constrained.

The finding that zero-cost antenna tuning improves every KPI is consistent with a previous Indonesian 5G NR NSA drive test study that reported significant tuning headroom in early commercial deployments (Putriani et al., 2023). The complete elimination of the poor RSRP band in Scenario C indicates that the residual shadowing along the southern and eastern sides of Jam Gadang is geometric in nature and can be mitigated only through additional macro coverage. A similar pattern in 5G NSA networks in urban Indonesian environments, together with throughput improvements from small-cell densification at confirmed hotspots, has likewise been reported, reinforcing the findings of Scenarios A and B. Subsections 3.1–3.4 collectively address the four research questions posed in the Introduction.

The main limitation is the scope of a single operator and two gNodeBs, assuming static traffic. The Atoll baseline was also not formally calibrated against the drive-test samples (Section 2.4), and the throughput comparison is affected by a methodological difference between the single-sample, contention-affected field TPUT-DL measurements and Atoll's unloaded link-budget prediction; both should be addressed in future work through iterative model calibration and repeated, load-matched throughput sampling. Further research is recommended for: (1) multi-operator drive tests; (2) dynamic tourism traffic models, including seasonal spikes; (3) quantitative energy consumption assessments per scenario; and (4) validation of the hierarchical framework in other heritage tourism corridors in Indonesia and developing countries with similar topography.

CONCLUSION

This study aims to determine how multi-scenario optimization strategies—adjusting antenna tilt and azimuth, small-cell densification, and the selective addition of new sites—perform in a hilly tourist corridor with highly mobile transient users, and how the resulting trade-offs align with the principles of sustainable network planning in emerging markets. These objectives were met, as evidenced by the results reported in the Results and Discussion section.

First (RQ1), 97.55% of the RSRP samples were already in the “very good” band, confirming that coverage is not the primary limiting factor. In comparison, only 0.54% of TPUT-DL samples were “very good,” making it the dominant constraint. Second (RQ2), the simulation baseline shows a different distribution from the field

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measurements, particularly for TPUT-DL, indicating that the two are not yet fully reproducible. Third (RQ3), zero-cost antenna tuning increases the “very good” RSRP to 84.50% and eliminates nearly all “poor” SINR (2.03% → 0.06%); small cell densification results in a “very good” TPUT-DL of 99.00%; and the addition of new sites results in a “very good” RSRP of 92.20% with the complete elimination of the “poor” band. Fourth (RQ4), the comparative rankings reinforce a clear hierarchical strategy.

These findings are fully consistent with expectations. Introduction: Capital-intensity-ordered and evidence-based optimization sequences align the achievement of coverage and capacity with the principle of phased investment. Practical implications: Most of the quality improvements that can be achieved in cultural heritage corridors can be realized through low-cost reconfigurations before the construction of new sites is justified.

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REFERENCES

- Abbas, W. Bin, Ahmed, Q. Z., Khan, F. A., Mian, N. S., Lazaridis, P. I., & Sureephong, P. (2023). Designing Future Wireless Networks (FWN)s With Net Zero (NZ) and Zero Touch (ZT) Perspective. *IEEE Access*, 11, 83301–83321. <https://doi.org/10.1109/ACCESS.2023.3301849>
- Ahamed, M. M., & Faruque, S. (2021). 5G Network Coverage Planning and Analysis of the Deployment Challenges. *Sensors*, 21(19), 6608. <https://doi.org/10.3390/s21196608>
- Alhaj, N. A., Jamlos, M. F., Manap, S. A., Abdelsalam, S., Bakhit, A. A., Mamat, R., Jamlos, M. A., Gismalla, M. S. M., & Hamdan, M. (2024). Integration of Hybrid Networks, AI, Ultra Massive-MIMO, THz Frequency, and FBMC Modulation Toward 6G Requirements: A Review. *IEEE Access*, 12, 483–513. <https://doi.org/10.1109/ACCESS.2023.3345453>
- Ali, S., Abu-Samah, A., Abdullah, N. F., & Mohd Kamal, N. L. (2024). Propagation Modeling of Unmanned Aerial Vehicle (UAV) 5G Wireless Networks in Rural Mountainous Regions Using Ray Tracing. *Drones*, 8(7), 334. <https://doi.org/10.3390/drones8070334>
- Ali, U., Caso, G., De Nardis, L., Kousias, K., Rajiullah, M., Alay, Ö., Neri, M., Brunstrom, A., & Di Benedetto, M.-G. (2022). Data-Driven Analysis of Outdoor-to-Indoor Propagation for 5G Mid-Band Operational Networks. *Future Internet*, 14(8), 239. <https://doi.org/10.3390/fi14080239>
- Amanaf, M. A., Hikmaturokhman, A., & Septian, A. F. (2020). Calibrating the Standard Propagation Model (SPM) for Suburban Environments Using 4G LTE Field Measurement Study Case in Indonesia. *IOP Conference Series: Materials Science and Engineering*, 982, 012029. <https://doi.org/10.1088/1757-899X/982/1/012029>
- Azevedo, J. A., & Mendonça, F. (2024). A Critical Review of the Propagation Models Employed in LoRa Systems. *Sensors*, 24(12), 3877. <https://doi.org/10.3390/s24123877>
- Banafaa, M. K., Pepeoglu, Ö., Shaya, I., Alhammadi, A., Shamsan, Z. A., Razaz, M. A., Alsagabi, M., & Al-Sowayan, S. (2024). A Comprehensive Survey on 5G-and-Beyond Networks With UAVs: Applications, Emerging Technologies, Regulatory Aspects, Research Trends and Challenges. *IEEE Access*, 12, 7786–7826. <https://doi.org/10.1109/ACCESS.2023.3349208>
- Bellary, A., Kandasamy, K., & Rao, P. H. (2022). Analysis of Wave Propagation Models With Radio Network Planning Using Dual Polarized MIMO Antenna for 5G Base Station Applications. *IEEE Access*, 10, 29183–29193. <https://doi.org/10.1109/ACCESS.2022.3158948>
- Beyraghi, S., Shabanpour, J., Geraci, G., Almasan, P., & Lozano, A. (2025). *Data-Driven Deployment of Reconfigurable Intelligent Surfaces in Cellular Networks*. <http://arxiv.org/abs/2510.10190>
- Cabrera-Castellanos, D. F., Aragón-Zavala, A., & Castañón-Ávila, G. (2021). Closing Connectivity Gap: An Overview of Mobile Coverage Solutions for Not-Spots in Rural Zones. *Sensors*, 21(23), 8037. <https://doi.org/10.3390/s21238037>
- Caso, G., Rajiullah, M., Kousias, K., Ali, U., Bouzar, N., Nardis, L. De, Brunstrom, A., Alay, O., Neri, M., & Benedetto, M.-G. Di. (2024). The Chronicles of 5G Non-Standalone: An Empirical Analysis of Performance and Service Evolution. *IEEE Open Journal of the Communications Society*, 5(October), 7380–7399. <https://doi.org/10.1109/OJCOMS.2024.3499370>
- Chandra, D., Yusnita, S., Meidelfi, D., & Anisa, S. N. (2026). Microwave Link Planning for USO/N3T Telecommunication Sites Using Atoll Radio Planning Software. *International Journal of Advanced*

- Technology and Social Sciences*, 3(12), 1603–1616. <https://doi.org/10.59890/ijatss.v3i12.150>
- Chen, Y., Li, J., & Zhang, J. (2024). Digitalisation, data-driven dynamic capabilities and responsible innovation: An empirical study of SMEs in China. *Asia Pacific Journal of Management*, 41(3), 1211–1251. <https://doi.org/10.1007/s10490-022-09845-6>
- Demir, Üzlem Tugfe, BjErnson, E., & Sanguinetti, L. (2021). Foundations of User-Centric Cell-Free Massive MIMO. *Foundations and Trends® in Signal Processing*, 14(3–4), 162–472. <https://doi.org/10.1561/20000000109>
- Dubey, V. K. (2024). A comprehensive theoretical framework for sustainable network contracts: Contracting dimensions and Contract classification. *Heliyon*, 10(1), e23622. <https://doi.org/10.1016/j.heliyon.2023.e23622>
- El-Saleh, A. A., Alhammedi, A., Shayea, I., Alsharif, N., Alzahrani, N. M., Khalaf, O. I., & Aldhyani, T. H. H. (2022). Measuring and Assessing Performance of Mobile Broadband Networks and Future 5G Trends. *Sustainability*, 14(2), 829. <https://doi.org/10.3390/su14020829>
- Fazilova, D. (2022). Uzbekistan's coordinate system transformation from CS42 to WGS84 using distortion grid model. *Geodesy and Geodynamics*, 13(1), 24–30. <https://doi.org/10.1016/j.geog.2021.10.001>
- Gkonis, P. K. (2023). A Survey on Machine Learning Techniques for Massive MIMO Configurations: Application Areas, Performance Limitations and Future Challenges. *IEEE Access*, 11, 67–88. <https://doi.org/10.1109/ACCESS.2022.3232855>
- Guijarro, V. R. F., Vega Sánchez, J. D., Paredes, M. C. P., Arévalo, F. G., & Osorio, D. P. M. (2024). Comparative Evaluation of Radio Network Planning for Different 5G-NR Channel Models on Urban Macro Environments in Quito City. *IEEE Access*, 12(January), 5708–5730. <https://doi.org/10.1109/ACCESS.2024.3350182>
- Haile, B. B., Mutafungwa, E., & Hämäläinen, J. (2020). A data-driven multiobjective optimization framework for hyperdense 5G network planning. *IEEE Access*, 8, 169423–169443. <https://doi.org/10.1109/ACCESS.2020.3023452>
- Hernandez, S. M., & Bulut, E. (2023). WiFi Sensing on the Edge: Signal Processing Techniques and Challenges for Real-World Systems. *IEEE Communications Surveys & Tutorials*, 25(1), 46–76. <https://doi.org/10.1109/COMST.2022.3209144>
- Hochstrasser, B. (1993). Quality engineering: a new framework applied to justifying and prioritising IT investments. *European Journal of Information Systems*, 2(3), 211–223. <https://doi.org/10.1057/ejis.1993.31>
- Ichimescu, A., Popescu, N., Popovici, E. C., & Toma, A. (2024). Energy Efficiency for 5G and Beyond 5G: Potential, Limitations, and Future Directions. *Sensors*, 24(22), 7402. <https://doi.org/10.3390/s24227402>
- Imoize, A. L., Udeji, F., Isabona, J., & Lee, C.-C. (2023). Optimizing the Quality of Service of Mobile Broadband Networks for a Dense Urban Environment. *Future Internet*, 15(5), 181. <https://doi.org/10.3390/fi15050181>
- Jaensch, F., Caire, G., & Demir, B. (2026). Radio Map Prediction From Aerial Images and Application to Coverage Optimization. *IEEE Transactions on Wireless Communications*, 25, 308–320. <https://doi.org/10.1109/TWC.2025.3583171>
- Kousias, K., Rajiullah, M., Caso, G., Alay, O., Brunstrom, A., Ali, U., Nardis, L. De, Neri, M., & Benedetto, M. Di. (2024). Empirical performance analysis and ML-based modeling of 5G non-standalone networks. *Computer Networks*, 241(January), 110207. <https://doi.org/10.1016/j.comnet.2024.110207>
- Lazar, R.-G., Militaru, A.-V., Caruntu, C.-F., Pascal, C., & Patachia-Sultanoiu, C. (2023). Real-time data measurement methodology to evaluate the 5G network performance indicators. *IEEE Access*, 11, 43909–43924. <https://doi.org/10.1109/access.2023.3271366>
- Liu, H., Tan, Z., & Xia, Z. (2024). The Coupling Coordination Relationship and Driving Factors of the Digital Economy and High-Quality Development of Rural Tourism: Insights from Chinese Experience Data. *Land*, 13(11), 1734. <https://doi.org/10.3390/land13111734>
- Liu, Y., & Song, W. (2026). Navigating digital colonialism: Sovereignty models and development paths in the Global South. *Social Sciences & Humanities Open*, 13, 102546. <https://doi.org/10.1016/j.ssaho.2026.102546>
- Martínez Abuabara, R., Robles, C. A., & Camargo, L. L. (2025). A multicriteria model for prioritizing 5G network deployment with Monte Carlo stability analysis: A case study in Magdalena, Colombia. *PLOS One*, 20(10), e0334781. <https://doi.org/10.1371/journal.pone.0334781>
- Megnafi, H., Karaouzene, Z., Meriah, S. M., & Merad, L. (2026). Radio Network Optimization Through

- Antenna Tilt Adjustment Using Metaheuristic Algorithms and Geographic Information Systems. *Journal of Network and Systems Management*, 34(3), 65. <https://doi.org/10.1007/s10922-026-10051-8>
- Mercuri, M., Lu, Y., Polito, S., Wieringa, F., Liu, Y.-H., van der Veen, A.-J., Van Hoof, C., & Torfs, T. (2021). Enabling Robust Radar-Based Localization and Vital Signs Monitoring in Multipath Propagation Environments. *IEEE Transactions on Biomedical Engineering*, 68(11), 3228–3240. <https://doi.org/10.1109/TBME.2021.3066876>
- Mlinar, T., Podgrajšek, U., & Batagelj, B. (2023). Comparison of Coverage-Prediction Models for Modern Mobile Radio Networks. *Electronics*, 12(22), 4554. <https://doi.org/10.3390/electronics12224554>
- Natanzi, S. B. H., Mohammadi, H., Tang, B., & Marojevic, V. (2026). AI-Driven Fuzzing for Vulnerability Assessment of 5G Traffic Steering Algorithms. *ICC 2026 - IEEE International Conference on Communications*, (Icc), 1–6. <https://doi.org/10.1109/ICC59461.2026.11587788>
- Parvini, M., Zarif, A. H., Nouruzi, A., Mokari, N., Javan, M. R., Abbasi, B., Ghasemi, A., & Yanikomeroglu, H. (2023). Spectrum Sharing Schemes From 4G to 5G and Beyond: Protocol Flow, Regulation, Ecosystem, Economic. *IEEE Open Journal of the Communications Society*, 4(October 2022), 464–517. <https://doi.org/10.1109/OJCOMS.2023.3238569>
- Putriani, O., Priyanto, S., Muthohar, I., & Amrozi, M. R. F. (2023). Millimetre Wave and Sub-6 5G Readiness of Mobile Network Big Data for Public Transport Planning. *Sustainability (Switzerland)*, 15(1). <https://doi.org/10.3390/su15010672>
- Quirini, A., Colone, F., & Lombardo, P. (2025). Outlier-Robust Three-Element Non-Uniform Linear Arrays Design Strategy for Direction of Arrival Estimation in MIMO Radar. *Sensors*, 25(16), 5062. <https://doi.org/10.3390/s25165062>
- Rafiq, G., Bose, P., & Orten, P. (2025). 5G Cellular Communication for Maritime Applications. *IEEE Access*, 13, 109451–109472. <https://doi.org/10.1109/ACCESS.2025.3581591>
- Raftopoulou, M., Awan, M. F., Ramírez-Arroyo, A., Sağlam, M. I., Jorguseski, L., Drijver, F., Maćkowiak, P., & Palattella, M. R. (2025). Deployment and Performance Evaluation of 5G Private Networks, Enabling Use Cases in Rural Remote Areas. *IEEE Access*, 13, 154581–154598. <https://doi.org/10.1109/ACCESS.2025.3603591>
- Raj, T., Mishra, R., Kumar, P., & Kapoor, A. (2023). Advances in MIMO Antenna Design for 5G: A Comprehensive Review. *Sensors*, 23(14), 6329. <https://doi.org/10.3390/s23146329>
- Sharmin, S., Ahmedy, I., Jabbaraj, B. R. P., Munir, M. U., Noor, R. M., & Ahmad, M. (2026). A comprehensive review of machine learning-driven self-organizing networks for 5G coverage and capacity. *Telecommunication Systems*, 89(1), 44. <https://doi.org/10.1007/s11235-026-01424-0>
- Souifi, A., Boulanger, Z. C., Zolghadri, M., Barkallah, M., & Haddar, M. (2022). Uncertainty of key performance indicators for Industry 4.0: A methodology based on the theory of belief functions. *Computers in Industry*, 140, 103666. <https://doi.org/10.1016/j.compind.2022.103666>
- Stamou, A., Karachaliou, E., Tavantzis, I., Bakousi, A., Dosiou, A., Tsifodimou, Z. E., & Stylianidis, E. (2025). Satellite Imagery for Comprehensive Urban Morphology and Surface Roughness Analysis: Leveraging GIS Tools and Google Earth Engine for Sustainable Urban Planning. *Urban Science*, 9(6), 1–24. <https://doi.org/10.3390/urbansci9060213>
- Stroobandt, B., Van Bladel, H., Veludo, A. F., Deprez, K., Aerts, S., Verloock, L., Thuróczy, G., Poltanski, P., Polanska, K., Tognola, G., Parazzini, M., Wiart, J., Guxens, M., Rösli, M., & Joseph, W. (2025). Auto-induced uplink 4G and 5G RF-EMF exposure assessment using a network monitoring application in different microenvironments across seven European countries. *Environmental Research*, 270(January). <https://doi.org/10.1016/j.envres.2025.121029>
- Sudhamani, C., Roslee, M., Tiang, J. J., & Rehman, A. U. (2023). A Survey on 5G Coverage Improvement Techniques: Issues and Future Challenges. *Sensors*, 23(4), 2356. <https://doi.org/10.3390/s23042356>
- Tezcan, M. G., Yazar, A., Karahan, S. N., Osmanca, M. S., & Altun, H. O. (2026). Agentic AI-Based 5G and Beyond Radio Planning Framework. *IEEE Access*, (April), 72395–72413. <https://doi.org/10.1109/ACCESS.2026.3691411>
- Ullah, I., El-Sayed, H., Dowhuszko, A., Khan, M. A., & Hämäläinen, J. (2026). Tilt-Angle Tuning in mmWave Base Stations and Non-terrestrial IAB for Mission-Critical Communications. *IEEE Open Journal of the Communications Society*, (March). <https://doi.org/10.1109/OJCOMS.2026.3681768>
- Vivone, G., Dalla Mura, M., Garzelli, A., & Pacifici, F. (2021). A Benchmarking Protocol for Pansharpening: Dataset, Preprocessing, and Quality Assessment. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 14, 6102–6118. <https://doi.org/10.1109/JSTARS.2021.3086877>
- Wang, Q., Ma, P., & Wang, Y. (2025). Sustainable Heritage Tourism in Transition: Policy, Space, and

- Authenticity in a UNESCO World Heritage Site. *Sustainability (Switzerland)*, 17(21), 1–25. <https://doi.org/10.3390/su17219619>
- Wulandari, A., Suryanegara, M., & Gunawan, D. (2026). Toward Network-Managed 5G Fixed Wireless Access: Technologies, Challenges, and Future Directions. *Informatics*, 13(4), 55. <https://doi.org/10.3390/informatics13040055>
- Xie, Z., & Long, Y. (2026). Anti interference and fault tolerant control of UAVs integrating residual based diagnosis disturbance estimation with counter drone strategies. *Scientific Reports*, 16(1), 9429. <https://doi.org/10.1038/s41598-026-37984-z>
- Xu, T., Xu, N., Gao, J., Zhou, Y., & Ma, H. (2025). Path Loss Prediction Model of 5G Signal Based on Fusing Data and XGBoost—SHAP Method. *Sensors*, 25(17), 5440. <https://doi.org/10.3390/s25175440>
- Zakeri, H., Khoddami, P., Moradi, G., Alibakhshikenari, M., Abd-Alhameed, R., Koziel, S., & Dalarsson, M. (2024). Path Loss Model Estimation at Indoor Environment by Using Deep Neural Network and CatBoost for Wireless Application. *IEEE Access*, 12(August), 159070–159085. <https://doi.org/10.1109/ACCESS.2024.3487118>