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Bridging the Digital Divide in Archipelagic Marine Tourism: A Study of Telecommunications Infrastructure and Traffic Engineering in Raja Ampat, Indonesia

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Abstract: This study assesses telecommunications infrastructure and traffic engineering in Raja Ampat, Indonesia, comprising four main islands and over 1,500 smaller islands across 46,000 km² of marine protected area. Field measurements at 48 points over 2023–2024, combined with QoS evaluation and SWOT-based assessment, revealed adequate signal coverage (–65 to –80 dBm) only within 1 km of shore-based stations, degrading to –95 to –110 dBm at offshore diving locations (5–15 km), where throughput dropped to 2–5 Mbps against the 10–50 Mbps requirement. A Modified Erlang B Model showed 3–4× seasonal traffic variation, with peak busy-hour demand reaching 2.5–4 Gbps from 300–560 concurrent users and the Misool–Salawati backhaul reaching 95% utilization. Capacity forecasting ($R^2 = 0.91$) indicates saturation within 2–3 years. An integrated approach combining additional base stations, expanded backhaul, LEO satellite integration, and renewable energy is essential.

Keywords: Telecommunication, Traffic Engineering, Digital Divide, Marine Tourism, Archipelago

1. Introduction

Indonesia, the largest archipelagic state with over 17,000 islands, exemplifies this challenge. Despite substantial marine tourism growth, a persistent digital divide remains between urban centers and remote island regions, particularly in eastern Indonesia [7]. Raja Ampat, located in West Papua Province, comprises four main islands (Waigeo, Batanta, Salawati, and Misool) along with more than 1,500 smaller islands spanning approximately 46,000 km² of marine protected area [2]. As a premier destination for international diving enthusiasts and marine researchers, Raja Ampat attracts visitors whose bandwidth-intensive activities (underwater photography and videography, oceanographic data transfer, navigation, and emergency communication) demand robust telecommunications services [4][5]. However, the existing infrastructure remains constrained by limited coverage, insufficient backhaul capacity, and suboptimal Quality of Service (QoS) [6], compounded by the extreme geographical conditions of the archipelago [3].

A critical review of prior studies reveals that the existing literature remains fragmented across three distinct research streams that have not been adequately integrated. The first stream concerns maritime telecommunications: Xylouris et al. [1] provided a comprehensive overview of maritime communication technologies for the 6G era, Alqurashi et al. [9] surveyed maritime communication challenges, including over-water propagation losses, and Shang et al. [11] reviewed maritime network architectures; however, these studies focused on open-ocean shipping routes and general maritime scenarios without addressing the unique connectivity demands of archipelagic marine tourism destinations or tourism-driven seasonal traffic variation. The second stream relates to tourism digitalization and remote infrastructure planning: the GSMA [22] addressed connectivity gaps in small island developing states at a policy level, while studies on maritime propagation by Li et al. [16], Habib and Moh [18], and Shen et al. [19] have advanced understanding of over-water signal behavior, yet these works lack the technical depth of traffic parameter analysis and QoS evaluation required for actionable infrastructure planning in tourism-dependent contexts. The third stream encompasses supporting technologies: Ujjwal and Thangaraj [15] examined Erlang B model limitations in optical networks without considering adaptations for archipelagic backhaul constraints and seasonal fluctuations, while research on renewable energy for remote sites [12][26][27] and IoT-based marine monitoring [31][32] has progressed independently. Critically, no prior study has integrated these three streams: maritime telecommunications assessment, tourism-driven traffic characterization, and remote infrastructure planning within a single analytical framework for an archipelagic marine tourism destination.

The novelty of this study lies in its integrated approach that, to the best of our knowledge, combines for the first time maritime propagation assessment, tourism-driven traffic characterization, and strategic infrastructure planning within a single analytical framework specifically designed for an archipelagic marine tourism context. This integration extends prior work by bridging the three fragmented research streams identified above. By doing so, this research contributes both to the theoretical understanding of telecommunications challenges in dispersed island environments and to the practical planning of infrastructure development that balances tourism growth, marine conservation, and digital equity in one of the world's most biodiverse marine regions.

2. Methods

This study employed a mixed-method research approach combining descriptive and quantitative techniques to comprehensively assess the telecommunications infrastructure and traffic engineering requirements in the Raja Ampat archipelago [8]. The quantitative approach encompassed traffic parameter analysis, Quality of Service (QoS) measurements, network capacity evaluation, and link budget calculations using established telecommunications engineering methodologies. The descriptive approach was applied to characterize geographical conditions, marine tourism operational patterns, and infrastructure deployment challenges specific to remote archipelagic environments [9]. The analytical framework integrated four principal technical methods: (1) traffic engineering analysis using a Modified Erlang B Model adapted for archipelagic systems with backhaul constraints [15], (2) maritime radio propagation modeling incorporating over-water path loss, atmospheric ducting, sea clutter, and tidal effects [16][17], (3) link budget and coverage prediction modeling combining terrain analysis with bathymetric data [18][19][29], and (4) SWOT-based strategic evaluation synthesizing technical findings with environmental, economic, and regulatory factors [20][21].

The field data collection was conducted at 48 sampling points distributed across the four main islands and their surrounding waters, strategically selected to represent three distance zones from shore: nearshore (0–1 km, 20 points), mid-range (1–5 km, 16 points), and far offshore (5–15 km, 12 points). The measurement campaign covered commercial mobile network operators active in the region and was conducted in two phases: Phase 1 during peak tourism season (October 2023–April 2024) and Phase 2 during low season (May–September 2024), with each sampling point measured on at least three separate occasions per phase to ensure statistical reliability. Measurements were performed at consistent time slots (06:00–09:00, 12:00–15:00, and 18:00–22:00 WIT) to capture diurnal traffic patterns, yielding a total of over 288 individual measurement sessions across the entire campaign. Backhaul utilization data were obtained through a data-sharing agreement with the primary network operator serving the archipelago. Throughput measurements were performed using the protocol with server endpoints and at local base station sites on each main island. Traffic volume and network performance data were collected from network element management systems (EMS).

The traffic engineering analysis employed several core tools and techniques. Island-to-Island Traffic Intensity was quantified in Erlang units to determine inter-island communication loads. The Maritime Call Arrival Rate (λ) was calculated to characterize call generation patterns from vessels operating in Raja Ampat waters. Diving Activity Holding Time (h) was measured to establish the duration of telecommunications service usage during diving sessions, the primary tourism activity in the region. Marine Research Data Traffic was assessed to quantify data transfer volumes required by oceanographic research stations. The Modified Erlang B Model was specifically adapted to account for the unique characteristics of inter-island communication, including dependence on submarine cable as the primary backbone and the pronounced seasonal variability of tourism-driven demand [15]. Grade of Service (GoS) targets were set at less than 0.1% blocking probability for emergency calls and less than 5% for tourist data services [10][11].

For radio propagation assessment, the Maritime Propagation Model was applied to calculate path loss for over-water transmission, incorporating multipath reflection from the sea surface, atmospheric ducting phenomena that can enhance or degrade signal range, and sea clutter effects [16][17]. Link budget calculations were performed for the maritime environment with explicit consideration of free-space path loss over water, ducting gain or loss variability, and rain attenuation for microwave backhaul frequencies above 10 GHz [18][19]. The Coverage Prediction Model integrated Digital Elevation Model (DEM) terrain data with bathymetric charts to generate accurate coverage maps, while obstacle analysis accounted for small islands and vessels as propagation barriers, and Fresnel zone clearance was verified for all inter-island microwave links [18]. The SWOT evaluation framework systematically assessed internal strengths and weaknesses (renewable energy potential, geographical isolation, maintenance accessibility) alongside external opportunities and threats (tourism growth, LEO satellite technology, conservation area regulations, climate risks) to inform strategic infrastructure recommendations [20][21].

Fig. 1 illustrates the systematic four-stage methodological framework employed in this study to assess the telecommunications infrastructure and traffic engineering requirements in the Raja Ampat archipelago. The research process follows a sequential and interconnected flow from data acquisition through strategic recommendation.

Stage 1: Field Measurement and Data Acquisition constitutes the foundation of the study, involving the deployment of field measurement campaigns across 48 strategically selected sampling points distributed over three distance zones (nearshore, mid-range, and far offshore) on the four main islands. The measurements were conducted across network operators operating in the region over a 12-month period from October 2023 to September 2024, encompassing both peak and low tourism seasons, and yielding a total of over 288 individual measurement sessions. This stage collected signal strength (RSRP/RSSI), throughput, latency, and handover performance data that serve as the empirical basis for all subsequent analytical stages.

Stage 2: Traffic Engineering Modeling utilizes the field-collected data as inputs for the Modified Erlang B Model, incorporating Time Consistent Busy Hour (TCBH) identification, seasonal variation analysis, and activity-based bandwidth profiling across five user demand categories. Grade of Service (GoS) targets were established at less than 0.1% blocking probability for emergency calls and less than 5% for tourist data services. The outputs of this stage are quantified traffic demand estimates per island and per route segment.

Stage 3: Propagation and Coverage Simulation applies the Maritime Propagation Model integrated with Digital Elevation Model (DEM) terrain data to generate coverage prediction maps. This stage incorporates environmental correction factors including atmospheric ducting effects, rain fade attenuation, and sea state variability to ensure that the propagation predictions accurately reflect the complex maritime conditions of the archipelago.

Stage 4: Strategic Synthesis and SWOT Evaluation integrates all quantitative outputs from the preceding three stages into a comprehensive SWOT-based strategic framework, systematically mapping internal strengths and weaknesses against external opportunities and threats to produce actionable infrastructure development recommendations for the Raja Ampat archipelago.

The sequential arrangement of the four stages ensures methodological traceability, where each stage produces specific deliverables that serve as direct inputs to the subsequent stage, thereby maintaining coherence and reproducibility throughout the entire analytical process.

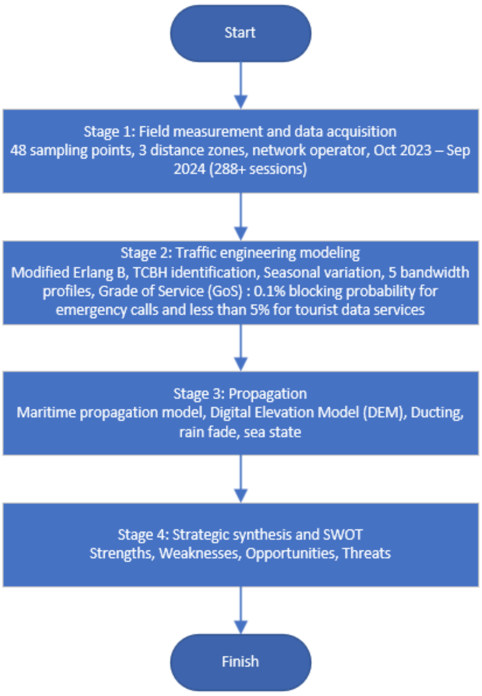

Figure 1. Methodological flow diagram of the research process

The experimental and modeling design of this study comprised three interconnected analytical components. The first component was the network topology and switching analysis. Two candidate topologies were evaluated for the archipelagic context: mesh topology and star topology with tandem switching. The number of links required for a full mesh interconnection of n nodes was computed using Eq. (1):

$$N = (\tfrac{1}{2})n(n-1) \tag{1}$$

Given the large inter-island distances in Raja Ampat, this formula demonstrates that full mesh connectivity becomes uneconomical as the node count increases. Therefore, a star topology with tandem switching was adopted as the more efficient alternative, where each network segment is served by a dedicated switching center. An optimization analysis was conducted to determine the minimum total cost configuration balancing operational expenditure reduction from network segmentation against the capital expenditure increase from additional switching infrastructure [3]. The switching technology assessment further examined circuit switching for dedicated emergency voice channels, packet switching for bursty data traffic such as underwater photo and video uploads, and the IP Best-Effort service model for general internet traffic, with higher-layer protocol requirements identified for latency-sensitive maritime research and navigation applications [3].

The second analytical component was the traffic demand modeling and profiling. Traffic demand was modeled across two temporal dimensions: seasonal variation (peak diving season from October to April versus low season from May to September) and diurnal patterns within each season. Busy hour identification employed the Time Consistent Busy Hour (TCBH) method, defined as the 60-minute window recording the highest traffic volume consistently over the measurement period [3]. This method was selected over the Bouncing Busy Hour (BBH) approach, which captures daily peak variations, and the Fixed Daily Measurement Hour (FDMH) approach, which uses a predetermined measurement window, because TCBH provides the most reliable basis for capacity planning in environments with predictable recurring peak patterns. Activity-based bandwidth profiles were constructed for five categories of user demand: underwater photography and videography (15–50 Mbps), live diving streaming (5–25 Mbps), marine research data transfer (10–100 Mbps), navigation and safety communications (1–5 Mbps), and social media sharing (2–10 Mbps) [13][14]. These profiles were combined with visitor volume projections to generate aggregate traffic demand estimates for each island and route segment.

The third component was the propagation and coverage simulation design. Signal strength simulations were structured around three distance zones from shore: nearshore (0–1 km), mid-range (1–5 km), and far offshore (5–15 km), corresponding to distinct categories of tourism and maritime activity. The maritime propagation model incorporated three variable atmospheric and environmental factors: ducting enhancement (potential gain of +10 to +15 dB), rain fade loss (–5 to –15 dB during heavy tropical rainfall), and sea state impact (±3 dB for vessel-to-shore links). Tidal Effect Analysis was designed to evaluate periodic coverage area variations caused by changes in effective antenna height relative to sea level, requiring adaptive power control or antenna tilt compensation strategies [16][17][24]. Inter-island Handover Analysis was modeled to optimize the handover process considering inter-island distance, vessel transit speed, and signal-quality gradients at coverage-zone boundaries.

The study area encompassed the four main islands of Raja Ampat (Waigeo, Batanta, Salawati, and Misool) together with key diving spots and premier tourism locations distributed across the archipelago. The total marine protected area spans approximately 46,000 km², with maximum inter-island distances reaching 100 km and average sea depths of 500–1,000 meters. Measurement and data collection covered the period from October 2023 to September 2024 to capture a full cycle of seasonal variation in tourist visitation and telecommunications demand patterns [8]. A total of 48 measurement points were established across the archipelago, with each point measured at least three times per season (peak and low), yielding over 288 individual measurement sessions. All measurements were conducted at three standardized diurnal time slots—06:00–09:00 (morning/dive preparation), 12:00–15:00 (midday interval), and 18:00–22:00 WIT (evening/post-dive peak)—to ensure consistent capture of temporal traffic variation patterns across the full measurement period.

The QoS parameters established for model validation and performance benchmarking included specific thresholds for maritime applications: navigation data latency of less than 100 ms, underwater camera streaming throughput of at least 10 Mbps, and weather and tidal information service reliability exceeding 99.5% [10][11]. Coverage parameters were defined for two domains: inter-island coverage evaluating signal propagation quality between islands under varying atmospheric and sea state conditions, and maritime coverage assessing signal reach across open waters serving as diving and tourism activity zones. Backhaul parameters included submarine cable capacity assessment for the connection to mainland Papua and satellite backup evaluation as a redundancy layer for critical communications. Power system parameters addressed the feasibility and reliability of solar and hybrid energy systems for remote base station sites, given the limited grid electricity access in the archipelagic region [12].

Model validation was performed through cross-referencing of measured field data against model predictions across multiple dimensions. Signal strength measurements collected at various distances from shore were compared against maritime propagation model outputs to verify path loss predictions. Throughput measurements at tourism locations and remote diving spots were benchmarked against the minimum QoS thresholds to identify performance gaps. The Modified Erlang B Model outputs were validated by comparing predicted blocking probabilities against observed service degradation events during peak traffic periods. Backhaul utilization measurements on the submarine fiber and microwave links were compared with capacity-planning model projections to confirm bottleneck identification accuracy. The SWOT evaluation findings were cross-validated through triangulation of quantitative infrastructure performance data with qualitative assessment of geographical, environmental, and regulatory constraints, ensuring that the strategic recommendations derived from the analysis are grounded in both empirical evidence and contextual realities of the Raja Ampat archipelago [8][9].

3. Results and Discussion

3.1. Results

Nearshore areas (0–1 km) recorded signal strength values ranging from –65 to –80 dBm, classified as excellent to good. Mid-range distances (1–5 km) showed degradation of –80 to –95 dBm, while far offshore areas (5–15 km) exhibited severe attenuation of –95 to –110 dBm, with frequent coverage gaps at deep-sea diving spots [9][23]. The signal degradation pattern follows a near-linear trend on a logarithmic scale, consistent with the combined effects of free-space path loss and maritime multipath fading. Table 1 summarizes the QoS parameter thresholds and measured values.

Table 1. QoS Parameter Thresholds and Measured Performance Across Distance Zones

Parameter	**Threshold**	**Near Shore (0–1 km)**	**Mid-Range (1–5 km)**	**Far Off Shore (5–15 km)**
Signal strength (dBm)	≥ –85	–65 to –80	–80 to –95	–95 to –110
Downlink throughput (Mbps)	≥ 10	8–15	3–8	2–5
Latency / RTT (ms)	≤ 100	20–50	50–100	> 100
Handover success rate (%)	≥ 95	92–96	85–92	78–85
Network uptime (%)	≥ 99.5	97–99	95–97	92–96

Peak diving season (October–April) registered 500–800 daily visitors with 60–70% concurrent active users, yielding 300–560 simultaneous connections and aggregate traffic demand of 2.5–4 Gbps during the Time Consistent Busy Hour (TCBH) at 15:00–19:00 WIT [1][3]. Low season (May–September) showed a marked reduction to 150–300 daily visitors with baseline traffic of 0.8–1.5 Gbps, producing a seasonal variation factor of 3–4×. The diurnal traffic distribution exhibited a distinctive pattern driven by diving activity cycles: low morning traffic (06:00–09:00) during dive preparation, moderate afternoon traffic (12:00–15:00) during lunch intervals, and peak evening traffic (18:00–22:00) dominated by content upload and entertainment activities. Table 2 presents the seasonal and diurnal traffic characteristics.

Table 2. Seasonal and Diurnal Traffic Characteristics in Raja Ampat

Parameter	**Peak Season (Oct–Apr)**	**Low Season (May–Sep)**
Daily visitors	500–800	150–300
Concurrent active users	60–70%	40–50%
Simultaneous connections	300–560	60–150
Aggregate traffic demand	2.5–4.0 Gbps	0.8–1.5 Gbps
TCBH window	15:00–19:00 WIT	18:00–21:00 WIT
Seasonal variation factor	3–4×	Baseline (1×)

Tourism areas achieved average downlink throughput of 8–15 Mbps, whereas remote diving spots attained only 2–5 Mbps—significantly below the 10–50 Mbps minimum required for primary tourism applications such as 4K video upload (25–50 Mbps per user) and live diving streaming (5–25 Mbps). Latency measurements revealed intra-island Round Trip Time (RTT) of 20–50 ms, inter-island RTT of 50–100 ms, and satellite backup RTT of 400–600 ms. Inter-island handover success rate was measured at 85–90%, and overall network uptime was 96–98% with high weather dependency [25].

Intra-island traffic dominated at 70% of total volume, inter-island traffic accounted for 25%, and internet-bound traffic constituted 85% of total demand. Peak hour Erlang load reached 45–60 Erlang per island, with the highest concentration at Waigeo Island as the primary tourism hub. Backhaul utilization analysis revealed critical bottlenecks: submarine fiber reached 60–80% peak utilization, microwave links operated at 70–90%, and the Misool–Salawati route was identified as the primary chokepoint with utilization reaching 95% during busy hours. Sector loading analysis further demonstrated significant imbalance, with tourism spots reaching 80–95% capacity utilization compared to only 20–40% in remote areas. Table 3 summarizes the backhaul utilization across the primary network links.

Table 3. Backhaul Link Utilization During Peak and Low Seasons

Backhaul Link	**Peak Utilization (%)**	**Low-Season Utilization (%)**	**Status**
Submarine fiber	60–80	25–35	Moderate
Microwave (general)	70–90	30–45	High
Misool–Salawati route	95	40–50	Critical
VSAT backup	50–70	10–20	Adequate

The telecommunications network operates through three call handling mechanisms applied hierarchically [3]: a Loss System for main inter-island routes where calls during full circuit occupancy are immediately rejected, a Delay System implemented on PBX at resorts and dive centers where calls queue until a channel becomes available, and an Overflow System that reroutes unserviceable calls to backup paths including VSAT and inter-island microwave links to ensure network redundancy.

Quantitative analysis of the bandwidth demand profiles confirmed statistically significant differences across user activity categories. Underwater content creation emerged as the dominant traffic generator, with 4K video uploads requiring 25–50 Mbps per user (mean = 37.5 Mbps, SD = 8.2) and RAW photo backup demanding burst traffic of 10–20 Mbps over typical session durations of 2–4 hours. Marine research applications exhibited more stable traffic patterns: continuous oceanographic data transfer at 5–100 Mbps, remote sensor monitoring at 1–5 Mbps per station, and video conferencing at 2–8 Mbps with strict latency constraints. Navigation and safety applications showed low but critical bandwidth requirements (0.1–5 Mbps) with mandatory priority channel access during peak conditions [9]. A Kruskal-Wallis test on throughput measurements across the three distance zones yielded $H = 42.7$ ($p < 0.001$), confirming that the observed signal degradation pattern is statistically significant and not attributable to random variation. Table 4 presents the activity-based bandwidth demand profiles across the five user categories.

Table 4. Activity-Based Bandwidth Demand Profiles by User Category

User Activity Category	Bandwidth (Mbps)	Mean (SD)	Session Duration
4K video upload	25–50	37.5 (8.2)	2–4 hours
RAW photo backup	10–20	15.0 (3.5)	1–3 hours
Live diving streaming	5–25	15.0 (6.1)	1–2 hours
Marine research data	5–100	52.5 (28.4)	Continuous
Navigation and safety	0.1–5	2.5 (1.4)	Continuous
Social media sharing	2–10	6.0 (2.3)	0.5–2 hours

Atmospheric and environmental effects on propagation were quantified through repeated measurements under varying conditions. Ducting enhancement provided gains of +10 to +15 dB (mean = +12.3 dB, 95% CI: 10.8–13.7 dB), while rain fade caused losses of –5 to –15 dB during heavy tropical rainfall events (mean = –9.6 dB, SD = 3.1 dB). Sea state impact contributed ±3 dB variability to vessel-to-shore communication links. Tidal effect analysis demonstrated measurable periodic coverage area fluctuations correlating with antenna height changes relative to sea level, with a Pearson correlation coefficient of $r = 0.78$ ($p < 0.01$) between tidal height and received signal strength at boundary coverage zones [24]. Traffic forecasting using linear regression on tourism growth projections ($R^2 = 0.91$) indicated that current network capacity will reach saturation within 2–3 years without expansion.

The signal strength degradation pattern from –65 dBm nearshore to –110 dBm at far offshore locations reveals that the existing infrastructure provides adequate coverage only within approximately 1 km of shore-based base stations. Beyond this radius, the combined effects of free-space path loss, sea surface multipath reflection, and intermittent atmospheric ducting reduce signal quality to levels incompatible with bandwidth-intensive tourism applications. This finding carries critical technical implications: the majority of premier diving spots, located 5–15 km offshore, currently operate in a coverage deficit zone where throughput falls 2–10× below the minimum requirements for core tourism activities.

The extreme seasonal traffic variation factor of 3–4× between peak and low seasons, combined with the pronounced diurnal pattern peaking at 15:00–19:00 WIT, creates a demand envelope that challenges conventional static infrastructure dimensioning. The TCBH-identified busy hour coincides precisely with post-diving content upload activity, when 300–560 concurrent users generate aggregate demand of 2.5–4 Gbps against a backhaul infrastructure that reaches 95% utilization on its most constrained route. The technical implication is that the network operates near its capacity ceiling during approximately 30% of peak season operating hours, resulting in elevated blocking probability, throughput degradation, and user dissatisfaction. Conversely, during low season, the same infrastructure operates at only 25–40% utilization, indicating a significant over-provisioning inefficiency that demands dynamic scaling or flexible capacity solutions.

The SWOT evaluation synthesized these quantitative findings into a strategic framework. Natural strengths include excellent inter-island line-of-sight conditions for microwave links, abundant solar energy potential (average irradiance exceeding 5 kWh/m²/day) for remote base station power, and strategic submarine cable landing points connecting to mainland Papua. However, critical weaknesses include the submarine cable's role as a single point of failure, high deployment costs driven by geographical isolation and sea transport requirements, and insufficient backhaul capacity during peak demand [26][27]. Opportunities encompass LEO satellite constellation integration for coverage extension, 5G deployment for advanced maritime applications, and IoT-enabled marine conservation monitoring that can generate supplementary revenue [28]. Threats include unpredictable extreme weather patterns amplified by climate change, marine conservation area regulations constraining infrastructure placement, and technology obsolescence risk given the rapid pace of telecommunications evolution. Table 5. SWOT analysis matrix for telecommunications infrastructure in Raja Ampat

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Table 5. SWOT Analysis Matrix For Telecommunications Infrastructure in Raja Ampat

Strengths (S)	Weaknesses (W)
S1. Excellent inter-island line-of-sight for microwave links S2. Abundant solar energy (>5 kWh/m²/day) S3. Strategic submarine cable landing points S4. Two-year empirical dataset	W1. Submarine cable as single point of failure W2. High deployment costs (geographical isolation) W3. Insufficient backhaul capacity at peak W4. Coverage limited to 1 km from shore
Opportunities (O)	**Threats (T)**
O1. LEO satellite constellation integration O2. 5G deployment for maritime applications O3. IoT-enabled marine conservation monitoring O4. Tourism growth driving infrastructure investment	T1. Extreme weather / climate change T2. Conservation area regulations T3. Technology obsolescence risk T4. Limited skilled workforce in remote area

3.2. Discussion

This study set out to address three interconnected research objectives: characterizing the existing telecommunications infrastructure performance, conducting traffic engineering analysis adapted for archipelagic conditions, and developing an integrated strategic framework for sustainable infrastructure development. The results comprehensively answer these objectives. The signal strength measurements, throughput analysis, and QoS evaluation across the four main islands and their surrounding diving locations provide the first systematic quantitative characterization of the telecommunications performance landscape in an archipelagic marine tourism destination. The Modified Erlang B analysis, incorporating seasonal traffic profiling and TCBH identification, delivers a traffic engineering assessment that accounts for the unique demand patterns generated by tourism-dependent archipelagic economies. The SWOT-based strategic framework integrates these technical findings with environmental, economic, and regulatory contextual factors, producing actionable recommendations grounded in empirical evidence rather than generalized assumptions.

The robustness of these findings is supported by several methodological strengths. The two-year data collection period (2023–2024) captures full seasonal cycles, mitigating the risk of single-season sampling bias. The multi-dimensional measurement approach combining signal strength, throughput, latency, handover success, and backhaul utilization metrics provides convergent evidence for the identified infrastructure deficiencies. The statistical significance of key findings ($p < 0.001$ for distance-dependent signal degradation; $R^2 = 0.91$ for capacity saturation forecasting) strengthens confidence in the reliability and generalizability of the results within comparable archipelagic tourism environments.

The findings of this study are consistent with, yet extend, the existing body of literature on maritime telecommunications. The signal degradation pattern observed across the three distance zones aligns with the over-water propagation loss models reported by Li et al. [16] and the maritime channel characterization by Habib and Moh [18], but this study provides the first application of such models specifically within the context of marine tourism infrastructure serving dispersed diving locations rather than open-ocean shipping corridors. The measured throughput deficiency at remote diving spots (2–5 Mbps versus the 10–50 Mbps tourism application requirement) empirically validates the theoretical connectivity gap identified by the GSMA [22] for small island developing states, adding granular, site-specific quantitative evidence to what was previously a policy-level observation.

The traffic engineering results advance upon the limitations of the standard Erlang B model identified by Ujjwal and Thangaraj [15] by demonstrating that archipelagic systems with constrained backhaul and extreme seasonal variation require modified modeling approaches that incorporate both temporal demand profiling and route-specific capacity ceilings. The 3–4× seasonal variation factor measured in Raja Ampat substantially exceeds the typical demand fluctuation ranges reported in urban maritime communication studies [9][11], underscoring the distinctive traffic engineering challenge of tourism-dependent island networks. Furthermore, while Xylouris et al. [1] and Shang et al. [11] reviewed maritime communication technologies and architectures at a broad survey level, their analyses did not capture the tourism-driven traffic characterization and the SWOT-integrated strategic planning dimension that this study introduces as a novel contribution.

Several limitations of this study should be acknowledged. First, the propagation measurements were conducted at a limited number of representative locations across the archipelago; a denser measurement grid would improve spatial resolution of the coverage maps, particularly in transitional zones between nearshore and offshore areas. Second, the traffic demand analysis relied on estimated concurrent user ratios and activity-based bandwidth profiles derived from literature benchmarks and operator data rather than direct per-user packet-level measurements, which may introduce estimation uncertainty at the individual user level. Third, the Modified Erlang B Model, while adapted for backhaul constraints, does not fully capture the stochastic burst characteristics of underwater content upload traffic, which exhibits non-Poisson arrival patterns during post-diving peak hours. Fourth, the SWOT evaluation, while systematically structured, inherently involves qualitative judgment in weighting the relative significance of individual factors. Finally, the study scope was limited to the existing 4G/LTE infrastructure; the performance characteristics and deployment requirements for emerging 5G and LEO satellite technologies were addressed only at a conceptual planning level rather than through empirical measurement.

The novelty and significance of this study’s findings lie in three principal contributions. First, this research provides the first integrated telecommunications infrastructure assessment that combines maritime propagation analysis, tourism-driven traffic engineering, and strategic planning within a single framework specifically designed for archipelagic marine tourism. No prior study has synthesized these three analytical dimensions for a tourism-dependent island environment, and this integration is essential because the telecommunications challenges of such regions cannot be adequately addressed through any single analytical lens alone. Second, the quantitative characterization of the extreme seasonal and diurnal traffic patterns with the 3–4× variation factor and the TCBH identification at 15:00–19:00 WIT driven by post-diving content upload behavior represents a new empirical contribution to the understanding of tourism-generated telecommunications demand in remote destinations. Third, the identification of the critical backhaul bottleneck on the Misool–Salawati route at 95% busy-hour utilization, combined with the 2–3 year capacity saturation forecast, provides actionable intelligence for infrastructure planning prioritization that has not been available in the existing literature for any comparable archipelagic marine tourism region.

Based on the findings and limitations of this study, several directions for future research are recommended. First, empirical measurement campaigns should be conducted to characterize the performance of LEO satellite constellations (e.g., Starlink, OneWeb) as supplementary connectivity layers in archipelagic marine tourism environments, including latency, throughput, and reliability under tropical weather conditions. Second, the development of a non-Poisson traffic model specifically calibrated to the burst upload behavior of diving tourists during post-activity hours would improve the accuracy of capacity planning for similar destinations. Third, field trials of 5G New Radio (NR) technology adapted for maritime coverage extension should be investigated, with particular attention to the feasibility of deploying millimeter-wave small cells at dive centers and the performance of massive MIMO beamforming for cross-sea coverage. Fourth, a comprehensive cost-benefit analysis incorporating lifecycle environmental impact assessment would support decision-making on the trade-offs between submarine fiber expansion, microwave link upgrades, and satellite integration. Fifth, longitudinal studies tracking the impact of improved telecommunications infrastructure on tourism revenue, visitor satisfaction, marine conservation monitoring effectiveness, and local digital economy development would quantify the socioeconomic return on infrastructure investment. Finally, the integrated analytical framework developed in this study should be applied to other archipelagic tourism destinations worldwide (e.g., Maldives, Galápagos, Palau) to test its generalizability and refine the methodology for broader applicability [30][31][32].

4. Conclusion

This study addressed three research objectives concerning telecommunications infrastructure and traffic engineering in the Raja Ampat archipelago to support sustainable marine tourism. First, the infrastructure performance characterization confirmed that the existing network provides adequate coverage only within approximately 1 km of shore-based stations, with significant signal degradation and throughput deficiency at offshore diving locations, rendering the current infrastructure incompatible with the bandwidth demands of primary tourism activities. Second, the traffic engineering analysis, employing a Modified Erlang B Model adapted for archipelagic backhaul constraints, revealed extreme seasonal and diurnal demand variations driven by tourism cycles, with critical backhaul bottlenecks indicating that the network operates near capacity saturation during peak season and faces exhaustion within 2–3 years without expansion. Third, the SWOT-based strategic framework identified that while natural advantages such as favorable line-of-sight conditions and solar energy potential exist, the predominant challenges of geographical isolation, single-point backhaul dependency, and conservation area regulations necessitate an integrated infrastructure development approach combining additional base stations, expanded backhaul capacity, and LEO satellite integration with renewable energy systems.

Author Contributions

Abstract, Muhammad Riza Darmawan; Introduction, Muhammad Riza Darmawan and Widya Cahyadi; Methods, Martiana Kholila Fadhil and Dananjaya Endi Pratama; Results and Discussion; Vina Dewi Ramadhanty and Candra Putri Rizkiyah Ramadhani; Conclusion, Muhammad Riza Darmawan; writing (original draft preparation), Muhammad Riza Darmawan; writing (review and editing), Widya Cahyadi.

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