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Breaking Connectivity Barriers in Digital Mining with a Resilient LTE-WLAN Overlay Network

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ABSTRACT

Digital transformation is essential to improving productivity and sustainability in mining operations. However, complex topography—such as deep pits, high walls, and uneven terrain—creates significant challenges for wireless communication infrastructure. Standalone Wi-Fi networks suffer from unstable signals, while LTE networks experience blind spots in obstructed areas. Field assessments at a mining site in South Kalimantan, Indonesia, revealed that 21.6% of operational zones recorded LTE RSRP levels below –110 dBm, disrupting key operational connectivity. This study proposes a hybrid LTE–WLAN overlay architecture using dynamic load-balancing and failover mechanisms to ensure reliable, high-speed communication. The approach offers environmental adaptability, network flexibility, and cost-efficiency by combining LTE's wide-area coverage with WLAN's localized stability. Simulation results show FTP throughput exceeding 94%, RSRP above –100 dBm in 92.43% of areas, and SINR above 98.40%, with seamless handovers and 100% E-RAB success rates. Bandwidth analysis highlights major fluctuations in standalone Wi-Fi (0–2000 Kbps), whereas the overlay solution maintains stable 2–6 Mbps bandwidth. Connection quality in overlay networks remains above 98%, compared to frequent drops below 50% in standalone Wi-Fi. These findings demonstrate that the LTE-WLAN overlay architecture significantly enhances communication stability and performance across challenging mining environments, addressing the identified connectivity gaps through practical, field-validated implementation. Connection quality and bandwidth utilization are identified as key success parameters, confirming that the proposed solution is practical, scalable, and effective for supporting real-time monitoring, IoT integration, and industrial automation in digital mining.

KEYWORDS *LTE–WLAN Overlay, Digital Mining, Network Planning, Connectivity Stability, Bandwidth Efficiency*

INTRODUCTION

Digital transformation has become a key strategy for enhancing productivity and ensuring the sustainability of mining operations in Indonesia (International Council on Mining and Metals, 2023). The implementation of smart mining enables mining companies to optimize resource management, improve workplace safety, and support the application of Good Mining Practice (GMP) in a more measurable way (Pribadi, 2024). However, one of the main challenges in realizing digital transformation lies in the availability of reliable and stable network infrastructure that can adapt to the geographical characteristics of mining site (Pulukandang, 2024).

As a large-scale coal mining operation in South Kalimantan, Indonesia, the site requires a communication network capable of supporting real-time monitoring systems, coordinating mobile equipment, and collecting field data (Direktur Utama AMM, 2022; Kementerian Energi dan Sumber Daya Mineral, 2023). Currently, many mining areas in Indonesia still rely on Wireless Access Points (WAP) or microwave Point-to-Point (PTP) technology to build their internal networks. Unfortunately, these solutions have limitations in coverage area, signal stability, and performance, which are not optimal for supporting high mobility operations (Haeruddin, 2021; Seminar Hasil Penelitian Vokasi, 2021).

As an alternative, the adoption of LTE networks is increasingly considered due to their wider coverage, more stable signal quality, and better support for mobility in mining areas (Valdivia-Bedregal, 2021; Bhattacharya, 2023). Several pilot implementations of LTE networks in the mining industry have shown promising results. However, comprehensive studies specifically addressing LTE network design tailored to the characteristics of Indonesian coal mining operations remain limited (Ariyanti, 2019). Moreover, there is still a lack of technical frameworks that systematically outline the planning of LTE networks by considering coverage, capacity, and signal quality to support the needs of digitalized mining operations.

Amid the growing interest in smart mining research, the limited technical studies on LTE network design have created a missing link between digital transformation and the effective implementation of GMP. Therefore, this study is designed to develop an optimal LTE network design framework, focusing on technical parameters such as coverage area, signal quality, and connection stability. The results of this research are expected to serve as a practical reference for mining companies in developing digital infrastructure that supports the achievement of the national smart mining target for 2024-2030 (Kementerian Energi dan Sumber Daya Mineral, 2023) and contributes to the Sustainable Development Goals (SDG 9) (International Council on Mining and Metals, 2023).

Digital transformation is essential to improving productivity and sustainability in mining operations. However, complex topography such as deep pits, high walls, and uneven terrain creates significant challenges for wireless communication infrastructure. Standalone Wi-Fi networks suffer from unstable signals, while LTE networks experience blind spots in obstructed areas. Field assessments at a coal mining site in South Kalimantan, Indonesia revealed that LTE RSRP levels dropped below –110 dBm in 21.6% of operational zones, disrupting key connectivity for field operations. These connectivity limitations present a significant barrier to realizing fully digital mining environments.

This study presents a novel contribution by applying LTE network capacity and coverage modeling within a specific implementation scenario, including the estimation of the required number of eNodeBs and an evaluation of LTE practical use to support digital mining operations in complex environments. The research aims to assess the suitability of LTE networks in terms of capacity, coverage, and connection stability, with a particular focus on the coal mining industry in South Kalimantan. The site was selected due to its large-scale production activity, high equipment mobility, and growing demand for real-time data access all of which require a carefully planned and efficient communication network to ensure optimal signal quality.

In such dynamic and terrain diverse mining areas, LTE networks alone are often insufficient due to blind spots caused by elevation shifts and physical obstructions. While LTE provides reliable wide-area coverage and mobility support for real-time applications, it struggles in enclosed or pit areas. Conversely, standalone Wi-Fi networks offer strong localized performance but are limited in range and highly susceptible to interference and signal degradation in open-pit environments. To address these complementary limitations, this study explores the application of an LTE-WLAN overlay network that integrates LTE with existing communication infrastructures such as Wireless Access Points (WAPs) and microwave Point-to-Point (PTP) links. This overlay approach improves signal stability, extends coverage, and introduces redundancy, making it well-suited for mining operations requiring reliable communication in both mobile and hard-to-reach zones.

By adopting a resilient LTE-WLAN overlay architecture, mining companies can build a more flexible and scalable network without fully replacing existing systems. This method enables seamless data exchange, supports real-time monitoring systems, and enhances operational safety through continuous connectivity. The outcome of this research is expected to provide a strategic solution that breaks existing connectivity barriers in digital mining environments. The next stage of the study will elaborate on technical overlay mechanisms, network planning for both Wi-Fi and LTE, and performance evaluation based on simulation and early field implementation results. Ultimately, this research aims to contribute to the development of robust, cost-effective, and future-ready wireless infrastructure tailored for Indonesia's mining sector.

This research aims to: (1) design an optimal LTE-WLAN overlay network architecture that addresses connectivity challenges in topographically complex coal mining environments; (2) validate network performance through simulation and field measurements based on industry-standard KPIs; and (3) demonstrate the practical effectiveness of the overlay approach compared to standalone wireless solutions. The successful implementation of this overlay network has significant implications for operational efficiency, workplace safety, and regulatory compliance with Good Mining Practice standards. By ensuring stable, continuous connectivity, the solution enables reliable real-time monitoring, autonomous equipment coordination, predictive maintenance systems, and emergency response capabilities. This research contributes to the national smart mining target for 2024-2030 (Kementerian Energi dan Sumber Daya Mineral, 2023) and supports Sustainable Development Goal 9 on infrastructure development (International Council on Mining and Metals, 2023).

METHOD

This study employed an engineering case study design with a quantitative descriptive approach, combining simulation-based network planning with field performance evaluation. The research integrates LTE link budget calculations, WLAN capacity modeling, radio propagation simulations, and empirical drive-test measurements to validate the proposed overlay architecture. Performance is assessed through industry-standard Key Performance Indicators (KPIs) including Reference Signal Received Power (RSRP), Signal-to-Interference-plus-Noise Ratio (SINR), throughput, and connection quality metrics.

The research was conducted at a coal mining site in Tabalong Regency, South Kalimantan, Indonesia, covering approximately 45 km² of operational area divided into two primary zones: the Main Office Area (including administrative buildings, workshop, and warehouse) and the Front-Loading Area (comprising overburden removal and coal production zones). Network deployment encompasses LTE base stations (eNodeBs), Wi-Fi access points, microwave Point-to-Point (PTP) backhaul links, and end-user devices including mobile equipment (haul trucks, excavators), fixed monitoring systems (CCTV, environmental sensors), and personnel communication devices. The LTE user population was recorded at approximately 2,000 users in 2024, with projections indicating growth to 4,000 users by 2027 based on operational expansion and technology adoption plans.

Network planning and simulation were conducted using specialized software tools: Forsk Atoll version 3.4 for LTE network design including eNodeB placement, coverage prediction, and interference analysis; and Ekahau Site Survey for Wi-Fi network planning including access point positioning and channel allocation. Field performance validation utilized drive-test equipment comprising Genex Assistant software version 3.18 for LTE measurements, spectrum analyzers for Wi-Fi signal quality assessment, and GPS-enabled data logging systems. Network performance monitoring employed real-time dashboards integrated with LTE core network elements and Wi-Fi controllers to capture operational KPIs including bandwidth utilization, connection quality, handover success rates, and service accessibility metrics. Data sources included internal LTE usage logs from the operator's management system, Wi-Fi controller statistics, and field measurement databases collected over a six-month operational period.

Drive-test data were collected along predefined routes covering critical operational zones including haul roads, loading areas, dumping zones, and administrative regions. Measurements were conducted during peak operational hours (06:00-18:00 local time) over multiple sampling periods to capture variations in network loading and environmental conditions. The drive-test methodology followed standard procedures with continuous logging at 1-second intervals, recording RSRP, RSRQ, SINR, cell ID, and GPS coordinates. For Wi-Fi performance evaluation, access point monitoring data were collected continuously through network management systems, capturing bandwidth utilization, connected client counts, signal strength distributions, and connection quality metrics at 5-minute intervals. Overlay network performance was assessed through comparative analysis of standalone Wi-Fi operation versus integrated LTE-WLAN operation on identical devices and locations over equivalent time windows.

LTE network design employed standard link budget calculations incorporating transmitter power, antenna gains, cable losses, propagation models (COST-231 Hata for 1800 MHz frequency), and receiver sensitivity to determine maximum allowable path loss and cell radius. Capacity planning utilized throughput modeling based on modulation schemes (16-QAM), MIMO configuration (4×4), coding rates, and resource block allocation to estimate site capacity and required number of eNodeBs. KPI performance was classified according to industry thresholds: RSRP levels categorized as excellent (≥-85 dBm), good (-85 to -102 dBm), moderate (-102 to -110 dBm), and poor (<-110 dBm); SINR classified as excellent (≥20 dB), good (13-20 dB), moderate (0-13 dB), and poor (<0 dB); throughput targets set at ≥4 Mbps downlink and ≥2 Mbps uplink for 80% of measurements. Comparative performance analysis between standalone Wi-Fi and overlay networks employed statistical methods including mean, standard deviation, and percentage distributions across measurement samples. Connection quality was calculated as the percentage of time maintaining stable connectivity above predefined signal strength thresholds (-70 dBm for Wi-Fi, -102 dBm for LTE).

Overlay Method

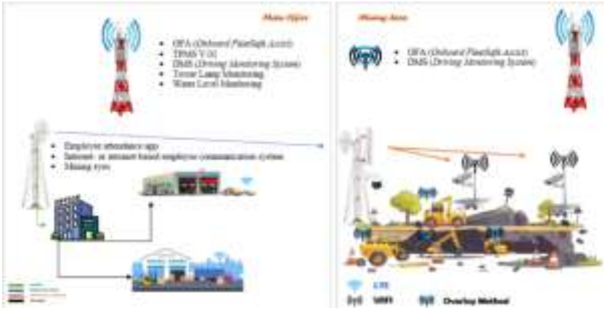


Fig. 1 Overlay Method

Overlay networks combining LTE and WLAN have been shown to significantly improve performance in industrial environments with challenging terrain. Saliba and Imad (2023) demonstrated that Wi-Fi offloading relieves congestion on LTE cells and enhances WLAN efficiency through optimized access-point planning. The 3GPP Release 13 specification also introduced LTE-WLAN Aggregation (LWA), enabling simultaneous data transmission at the PDCP layer to boost throughput. Baswade et al. (2019) confirmed that LTE-U coexistence in overlay configurations can maintain fairness and increase total throughput using techniques like duty cycling and listen before talk. Furthermore, the Situation-Aware Network (OWN) model supports seamless vertical handovers by dynamically selecting LTE or Wi-Fi based on real-time conditions (Gawande & Salunkhe, 2014). Numerous studies collectively affirm that overlay network architectures enhance communication reliability, optimize bandwidth utilization, improve mobility support, and effectively manage interference making them highly suitable for complex and demanding mining operations. The overlay approach is particularly relevant in scenarios where LTE networks experience signal degradation in obstructed or deep pit areas, and Wi-Fi alone cannot maintain stable connectivity across wide, dynamic open-pit zones. It is most effective when neither LTE nor Wi-Fi can independently provide seamless, real-time communication throughout the entire operational area, especially in zones impacted by topographical barriers and signal blind spots.

To implement overlay networks effectively, a structured and phased deployment process is required. First, Wi-Fi networks are designed to cover fixed-location areas such as control rooms, basecamps, environmental monitoring stations, and critical equipment that require stable, low-latency connections. Second, LTE networks are planned to provide wide-area coverage and support for mobile units such as haul trucks, dozers, and inspection drones that demand uninterrupted connectivity across large, rugged mining zones. Third, the overlay layer is configured to integrate both networks using technologies such as dynamic load balancing, failover switching, and seamless handover, allowing traffic to be automatically rerouted in real time based on current signal quality and coverage conditions.

To support real-time monitoring in this overlay-based architecture, integration with various digital technologies is essential. These include IoT sensors for monitoring temperature, vibration, pressure, and emissions; real-time CCTV streaming for visual supervision; GPS tracking systems for mobile equipment positioning; and edge or cloud-based analytical dashboards that visualize and process live data for operators and decision-makers. By combining resilient overlay architecture with these monitoring technologies, mining operations can achieve a flexible, scalable, and intelligent communication system transforming previously disconnected zones into a unified and adaptive digital environment capable of supporting end-to-end digital transformation.

Wireless Local Area Network (WLAN) Architecture

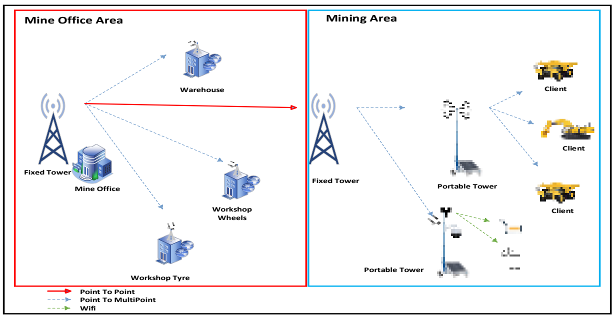


Fig. 2 Wireless Local Area Network (WLAN) Architecture

The basic architecture of a Wireless Local Area Network (WLAN) consists of several key components that operate together to enable wireless communication within a defined area. WLAN infrastructure is typically implemented using two primary methods: Point-to-Point (PTP) and Point-to-Multipoint (PTMP), both of which allow wireless data transmission without the need for physical cabling. The PTP method creates a dedicated link between two fixed nodes and is commonly used to connect remote control posts, field offices, or monitoring stations across long distances. Meanwhile, the PTMP method enables a central access point to communicate with multiple client devices simultaneously, offering localized wireless coverage across operational zones.

In open-pit mining environments, WLAN is particularly useful in areas where LTE signal strength is insufficient or unstable, such as along pit edges, static work zones, field offices, monitoring towers, or equipment requiring fixed-position connectivity. WLAN provides high-throughput, low-latency connections for fixed devices such as CCTV cameras, environmental sensors, SCADA terminals, and edge computing nodes. The use of directional or omnidirectional antennas on fixed access points enables targeted signal delivery in these specific operational areas.

WLAN plays a strategic role in LTE–WLAN overlay network architectures, complementing LTE coverage by providing stable local connectivity in signal-challenged or high-device-density areas. By deploying access points at strategic positions and integrating them with PTP microwave backhaul links, WLAN improves network redundancy and ensures reliable communication for both fixed and semi-mobile assets. Its integration in open-pit mining operations extends overall network reach, enhances safety, and supports real-time monitoring systems making it a key component in the digital transformation of surface mining environments.

LTE Architecture

Fig. 3 LTE Architecture

The LTE network deployment in the digital mining communication system is strategically divided into two primary coverage zones: the Main Office Area and the Mining

Area. This division is designed to ensure that the distinct operational requirements of each zone administrative versus field operations are effectively supported through tailored wireless infrastructure.

In the Main Office Area, the LTE network primarily serves centralized functions such as administrative operations, local server access, and integration with the Evolved Packet Core (EPC) or cloud-based management systems. The LTE tower positioned in this zone acts as the central node, managing core network activities and facilitating data exchange between the field and the enterprise backend.

Conversely, the Mining Area demands robust and stable LTE coverage due to the dynamic nature of activities, including heavy equipment operation, material transport, and real-time environmental monitoring. A dedicated LTE base station (eNodeB) is deployed specifically to provide direct coverage to mobile units such as haul trucks, excavators, autonomous vehicles, and field-deployed IoT sensors.

This dual-zone deployment architecture also establishes the foundation for implementing a hybrid LTE–WLAN overlay network. While LTE provides broad mobility support and wide-area connectivity, WLAN complements it by covering localized zones where LTE signals may degrade due to terrain variations or equipment shadowing. This approach ensures seamless communication across both high-mobility and fixed operational zones.

By segmenting the LTE deployment based on operational geography, the network can be optimized both topologically and functionally, enabling reliable, scalable, and high-performance wireless connectivity. This structure not only supports digital transformation and automation in open-pit mining but also enhances operational safety and data-driven decision-making through resilient real-time communication.

Strategic Implementation Framework for Overlay-Based Connectivity

This study employs an analytical approach grounded in the results of LTE network infrastructure implementation, aiming to accelerate digital transformation in accordance with the specific technological demands of modern mining operations. The implementation process was guided by carefully constructed research scenarios, which account for environmental constraints and operational objectives within open-pit mining environments. A hybrid network strategy was adopted through the application of an LTE-WLAN overlay method, designed to overcome connectivity challenges in areas characterized by complex terrain and diverse operational demands. The overlay architecture was implemented to align service-level requirements for each category of technological equipment deployed on-site ranging from real-time monitoring sensors and mobile heavy machinery to fixed surveillance systems. By combining LTE's wide-area mobility capabilities with WLAN's localized signal stability, the overlay method enables a flexible and scalable network model that ensures continuous connectivity even in blind-spot regions. This approach allows for service optimization based on coverage, quality, and cost-efficiency, aligned with operational priorities. To systematically guide the deployment of the proposed LTE-WLAN overlay network, a structured implementation flow was developed. The following flowchart illustrates the critical steps involved from scenario design and technical analysis to service classification and technology selection ensuring efficient and context-aware network deployment across the mining environment. The implementation strategy begins with a comprehensive assessment of operational requirements and site conditions to ensure the technical feasibility of deploying a hybrid network. Based on this assessment, a hybrid network approach is adopted, utilizing an overlay method that integrates both LTE and WLAN technologies.

Service types are then classified into critical and non-critical categories. Critical services, which demand real-time communication, wide coverage, and high reliability—such as safety monitoring, mobile unit tracking, and sensor-based alerts—are assigned to LTE networks. This selection ensures stable connectivity and supports mobility across the operational site. Conversely, non-critical services—such as local data logging, administrative access, or fixed monitoring points—are delegated to WLAN (Wi-Fi), which offers sufficient performance within localized zones and helps reduce deployment costs.

This decision-making framework aligns network resources with service demands, ensuring operational efficiency and enhancing safety outcomes. The final implementation is validated through technical reporting, which documents performance results, connectivity stability, and service responsiveness.

Simulation Scenario

This study employs two simulation scenarios: one for the design of the WiFi network and another for the design of the LTE network. The simulation scenarios utilize two software tools, namely Forsk Atoll for planning the LTE network deployment and Ekahau Site Survey for planning the WiFi network deployment. A coal mining site in South Kalimantan, Indonesia serves as the simulation environment for both LTE and WiFi network planning. A technical analysis is conducted, and the results of this analysis guide the development of implementation strategies and determine the appropriate methods to be applied during the deployment phase.

The LTE network simulation is conducted to plan the placement of eNodeB units within the designated area and to predict frequency feasibility data based on user capacity and coverage area. The final outputs of this technical analysis are Key Performance Indicators (KPIs), including Reference Signal Received Power (RSRP) and Signal to Interference plus Noise Ratio (SINR). Based on the KPI results, it can be evaluated whether the 1800 MHz frequency band is suitable for LTE operation in the mining industry context.

Subsequently, the WLAN network simulation is performed to plan the placement of access points or antenna repeaters within the planned area and to predict feasibility data based on user capacity and coverage area. The final outputs of this technical analysis include KPI values such as Signal to Noise Ratio (SNR), data rate, and throughput. Based on these KPI results, the number of devices required and the frequencies to be used for ensuring network coverage across the mining site can be determined.

Area Characteristics

The LTE and WLAN network planning in this study focuses on a coal mining area located in Tabalong Regency, South Kalimantan, Indonesia, which is classified as a suburban region with the majority of the local population working as farmers. The selection of this site is based on the growing need for reliable network infrastructure to support the integration of Industry 4.0 technologies into mining operations. Reliable communication networks are essential not only for facilitating daily operational activities but also for improving worker safety and reducing the risk of accidents in the mining area.

Aligned with the operator's commitment to digital transformation, the site's IT division continuously endeavors to ensure stable internet connectivity across the operational zones. The designated coverage area is divided into two primary zones: the Main Office Area (including administrative offices, workshop, and warehouse) and the Front Loading Area (comprising overburden and coal production zones). The total area covered in this planning spans approximately 45 km^2.

The LTE user population within the operational area of a coal mining site in South Kalimantan, Indonesia, was recorded at approximately 2,000 users in 2024, based on internal management data. Forecasting results indicate a steady annual increase in user numbers, in line with rising production activities and the growing demand for LTE-connected devices to support digital operations and real-time monitoring.

Table 1 User Total

No	User	2024	2027
1	Manpower	1778	3230
2	VHMS (Vehicle Health Management System)	60	FMS
3	Monitoring Tower Lamp	33	100
4	TPMS (Tire Pressure Monitoring System)	60	150
5	CCTV Mining Eyes	6	20
6	Monitoring Permukaan Air Gorong gorong	3	50
7	DMS (Driving monitoring system	60	150
8	FMS (Fleet Management system)	-	300
Total		2000	4000

Based on the figure above, the number of LTE users is projected to reach 4,000 users by 2027, consisting of both employees and the various technologies utilized in mining operational equipment. This indicates a growing demand for LTE network services to accommodate user needs and ensure reliable connectivity for operational activities within the mining area

Coverage Based Planning

Coverage planning is a critical aspect of LTE network design that complements capacity planning by estimating the required number of eNodeBs based on the geographical area and signal propagation characteristics. This involves calculating the link budget and selecting a suitable radio propagation model, such as Okumura-Hata or COST-231, to determine the effective cell radius. These models are chosen based on the operating frequency and terrain type, providing reliable estimations of signal loss and coverage range.

In this study, both uplink and downlink path loss values are calculated to define the maximum allowable path loss, which serves as the primary constraint for determining coverage limits. The total number of eNodeBs is then derived by dividing the target area by the computed coverage area per cell.

For WLAN access points, the planning considers both user demand and technical constraints, including required bandwidth per user, user density, network efficiency, and achievable data rates. Alternatively, AP requirements can be estimated by dividing the total target area by the effective coverage per access point.

This combined approach ensures efficient deployment of LTE and WLAN infrastructure tailored to specific service requirements and environmental conditions.

Capacity Based Planning

Capacity planning is a critical stage in LTE network design that aims to accurately forecast user demand over a multi-year period. This process involves estimating the projected number of LTE subscribers, forecasting throughput requirements, assessing site capacity, and ultimately determining the total number of LTE sites needed to support network operations.

The user estimation is based on population growth projections, adjusted for market share and LTE penetration rates. In this study, Telkomsel’s market share of 59.2% and a national LTE penetration rate of 82.36% are used to calculate the expected LTE user base within the productive age demographic.

Following user estimation, session throughput is calculated to model individual user data consumption. This involves analyzing session duration, transmission efficiency, and bearer bit rates, which are used to compute the total network throughput for both uplink and downlink directions.

Cell capacity is then derived based on system configuration parameters such as modulation scheme (e.g., 16-QAM), MIMO antenna setup (e.g., 4x4), modulation efficiency, coding rate, and the number of resource blocks. These values help define the actual cell capacity, allowing for a precise calculation of the number of sites required to meet the forecasted demand.

This comprehensive approach ensures that LTE infrastructure is designed to accommodate growing user traffic while maintaining performance and scalability in high-demand environments.

Key Performance Indicator

Key Performance Indicator (KPI) are essential parameters used to evaluate the quality and performance of a telecommunications network. In LTE networks, several key indicators commonly used include Reference Signal Received Power (RSRP), Signal-to-Interference Noise Ratio (SINR), and Throughput. RSRP measures the strength of the received reference signal (Karo Karo et al., 2019), while SINR reflects the ratio between signal power and the combined interference and noise, both of which directly impact the quality of service experienced by users (Karo Karo et al., 2019). Throughput, on the other hand, indicates the actual data transfer capacity achieved within the network.

For WiFi networks, the commonly used parameters include Signal-to-Noise Ratio (SNR), Data Rate, and Throughput. SNR assesses the ratio between the received signal strength and background noise, while Data Rate represents the theoretical speed of data transmission between devices, and Throughput reflects the actual capacity of data successfully transmitted under operational conditions (Chen et al., 2023; Price & Woodruff, 2012; Shun Kojima et al., 2022). By utilizing these parameters, network performance can be comprehensively mapped, thereby facilitating the evaluation, optimization, and planning of future network development.

RESULTS AND DISCUSSION

Coverage Based Planning Analysis

The coverage planning focused on ensuring network availability and service quality within the target area. Calculations were performed using a 20 MHz bandwidth at 1800 MHz, applying the COST-231 propagation model under rural area parameters, with a base station antenna height of 60 meters. The analysis included link budget calculations for both uplink and downlink directions, as presented in Table III

Table 2. Value of link budget

Transmitter	**UE**	**eNodeB**
Max total Tx power (dBm)	23	43
RB to distributed power	3	25
Subcarriers to distributed power	36	300
Subcarrier power (dBm)	7.432	18.229
Tx antenna gain (dBi)	0	17
Tx cable loss (dB)	0	0.5
EIRP per subcarrier (dBm)	7.437	34.729
Receiver	**ENodeB**	**UE**
SINR (dB)	-1.5	-1.68
Rx noise figure (dB)	2.9	7
Receiver sensitivity (dBm)	-129.59	-125.68
Thermal Noise (dbm)	-130.97	-130.97
Rx antenna gain (dBi)	17	0
Rx body loss (dB)	2	2
Interference margin	0.8	3.13

Min signal reception strength (dBm)	-128.039	-121.789
Penetration loss (dB)	17	17
Shadow fading margin (dB)	4.24	4.24
Max allowed path loss (dB)	130.786	137.158

Based on the calculated coverage area per cell, the results summarized in Table IV show that one site can provide sufficient coverage for both uplink and downlink across the entire mining area. However, due to geographical variations, the deployment of two sites is recommended to optimize network performance and ensure reliable LTE service delivery throughout the operational zones.

Table 3. Result of Coverage Planning

Parameter	1800 Mhz	
	Uplink	**Downlink**
Cell Coverage (km^2)	329,44	789,17
Total cell	1	1

Capacity Based Plannung Analysis

The capacity-based planning analysis was conducted as a follow-up step to ensure that the LTE network at the mining site in South Kalimantan, Indonesia, can accommodate the growing demands for traffic and network capacity. In 2024, the number of LTE users was recorded at approximately 2,000. Forecasts indicate that by 2027, this number will increase to 4,000 users, comprising both employees and LTE-connected operational devices. This growth highlights the urgent need for substantial improvements in network capacity..

The final stage of this analysis involved calculating the site capacity and the total number of sites required to meet user demand. According to Table V, the site capacity is determined to be 107.41 Mbps (uplink) and 89.51 Mbps (downlink), with each site covering approximately 11.93 km² (uplink) and 9.94 km² (downlink), equivalent to a cell radius of 3.32 km and 2.77 km, respectively.

Table 4. Result of Capacity Planning

1800 Mhz		
Parameter	**UL**	**DL**
Total LTE Users	4000	
Coverage Area (km^2)	45	
Network Throughput (Mac Layer) (Mbps)	5.010	23.349
Cell Average Throughput (Mbps)	35,80	29,84
Site Capacity (Mbps)	107,41	89,51
Number Of Site	1,25	1,50
Coverage per Site	35,80	29,83
Cell Coverage (km^2)	11,93	9,94
Cell Radius (km)	3,32	2,77

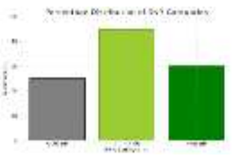
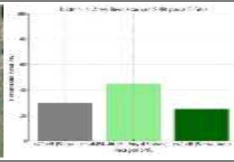
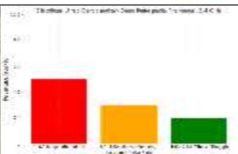
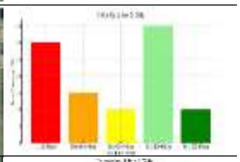
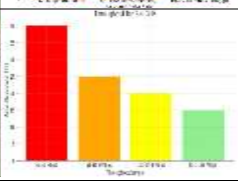
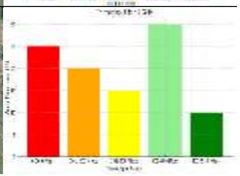
Based on these calculations, two LTE sites are required to adequately support the uplink and downlink traffic demands across the mining area, ensuring the network can accommodate approximately 4,000 LTE users by 2027 while maintaining optimal performance and service.

Network Planning Simulation

The network simulation for a coal mining site in South Kalimantan, Indonesia, was conducted to evaluate WiFi and LTE performance across key parameters including SNR, data rate, throughput, RSRP, and SINR. The simulation applied both capacity-based and coverage-based planning approaches to optimize the network design, with the goal of supporting operational efficiency and maintaining high service quality in a challenging mining environment.

For the WiFi network, SNR analysis revealed that 30% of the area had excellent signal quality, 45% moderate, and 25% poor, primarily influenced by distance from access points and physical obstructions. Data rate measurements at 2.4 GHz ranged from 1 - 240 Mbps, with only 20% of the area achieving the highest rates. At 5 GHz, data rates reached up to 555 Mbps, though coverage was more limited due to higher attenuation. Throughput analysis similarly showed better performance at 5 GHz, with top speeds between 500 -550 Mbps in areas near the main transmitters.

Table 5. WiFi Network Simulation Results

Parameter	2,4 Ghz	Clusterd Bar Chart	5 Ghz	Clustered Bar Chart
SNR				
Data Rate				
Throughput				

For the LTE 1800 MHz network, RSRP results showed that 44.8% of the area had good signal strength, 36.7% moderate, and 4.1% weak. SINR analysis indicated that 60% of the area maintained good to moderate signal quality, though 12% experienced weak or very weak conditions. Throughput measurements revealed considerable variation, with an average downlink throughput of 16,234.45 kbps and significant standard deviation, largely due to terrain and operational interferences.

Table 6. LTE Network Simulation Results

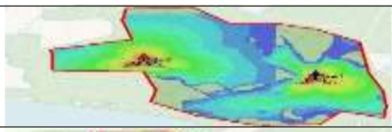
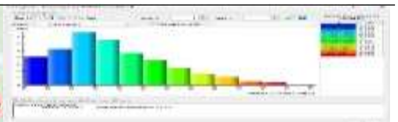
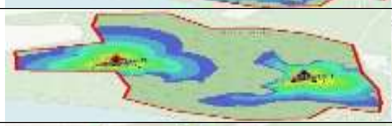
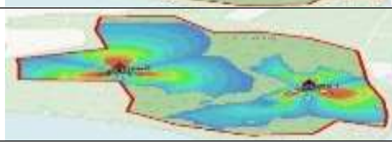
Parameter	LTE	Clustered Bar Chart
RSRP		
SINR		
Troughput		

Table 7. Statistical Drivetest TJL065

KEY PERFORMANCE INDICATOR DRIVE TEST	SERVICE	TARGET	ACHIEV	Pass /Fail
E-RAB Establishment Succes Rate	Accessibility	98.50%	100%	Pass
E-RAB Retainability Rate	Retainability	99.00%	100%	Pass
FTP DL Drive Test	Throughput	80% ≥4 Mbps	93.43%	Pass
FTP UL Drive Test	Throughput	80% ≥2 Mbps	94.43%	Pass
Handover Succes Rate (Intra-system)	Mobility	98.00%	100%	Pass
Handover Succes Rate (Inter-system)	Mobility	95.00%	100%	Pass
RSRP Distribution (Dedicated)	Coverage	90% > -102 dBm	92.67%	Pass
Signal Quality Distribution (Dedicated)	Coverage	90% >0 dB	96.98%	Pass
CSFB Session Setup Success Rate	Accessibility	98.00%	100%	Pass

Table 8. Statistical Drivetest TJL048

KEY PERFORMANCE INDICATOR DRIVE TEST	***SERVICE***	***TARGET***	***ACHIEV***	***Pass /Fail***
E-RAB Establishment Succes Rate	Accessibility	98.50%	100%	Pass
E-RAB Retainability Rate	Retainability	99.00%	100%	Pass
FTP DL Drive Test	Throughput	80% ≥4 Mbps	94.81%	Pass
FTP UL Drive Test	Throughput	80% ≥2 Mbps	94.20%	Pass
Handover Succes Rate (Intra-system)	Mobility	98.00%	100%	Pass
Handover Succes Rate (Inter-system)	Mobility	95.00%	100%	Pass
RSRP Distribution (Dedicated)	Coverage	90% > -102 dBm	92.43%	Pass
Signal Quality Distribution (Dedicated)	Coverage	90% >0 dB	98.40%	Pass
CSFB Session Setup Success Rate	Accessibility	98.00%	100%	Pass

Post-optimization, the LTE network was evaluated through drive tests at sites TJL065 and TJL048. Both sites demonstrated excellent Key Performance Indicator (KPI) results, achieving or surpassing targets for accessibility, retainability, throughput, mobility, and signal coverage. E-RAB establishment and retainability rates reached 100%, with FTP downlink and uplink tests exceeding 94%. Handover success rates were optimal, and signal quality metrics confirmed robust network performance across the mining operations.

The simulation results demonstrate that by employing combined coverage- and capacity-based planning, the WiFi and LTE networks were successfully optimized to meet the high demands of mining operations, ensuring reliable, high-quality connectivity in a challenging environment.

Technology Planning Analysis

Digitalization in the mining industry enhances economic efficiency while simultaneously improving workplace safety. Automation and real-time data analytics optimize production, reduce operational costs, and minimize equipment downtime through predictive maintenance. Additionally, the adoption of technologies such as autonomous vehicles and IoT-based monitoring systems decreases the risk of workplace accidents, ultimately lowering accident compensation costs and boosting workforce productivity.

With the right strategies, digitalization not only increases the profitability of the mining industry but also fosters a safer and more sustainable working environment. The technologies currently implemented and under development at a coal mining site in South Kalimantan, Indonesia, are presented below.

Table 9.Technology Overview in the Mining Industry

No	Technology	DepartmentAl location	Network Hierarchy	Network	Data Transfer	Total
1	VHMS (Vehicle Health Management System)	Plant , Engineering	CAN Bus → **WLAN** (WiFi 6) → Edge Server	WLAN	1.67 Kb/s (5 Minutes)	60 unit
2	Tower Lamp Monitoring System	Plant , Engineering , Production, Fa&Log	Sensor → **LTE** Gateway → Server	LTE	2 Kbps (5 Seconds)	33 Unit
3	TPMS (Tire Pressure Monitoring System)	Plant, Produksi	Sensor → **LoRaWAN** → Wlan / LTE Gateway → Server	WLAN	5 Kbps	60 unit
4	CCTV Mining Eyes	Management , HSE , Engineering, Production	Kamera → **WLAN** (802.11ax) → NVR Lokal	WLAN	4 Mbps	6 unit
5	Culvert Water Level Monitoring	HSE , Engineering, Production	Sensor → **NB-IoT (LTE-**M) → Server	LTE	2 Kbps (5 Seconds)	3 unit
6	DMS (Driver monitoring system	HSE, Production	Kamera → **4G LTE / WLAN** → Edge AI → Cloud	Overlay LTE+WLAN	5 Mbps	60 unit
7	FMS (Fleet Management System)	Plant, Engineering ,Production, HSE,	CAN Bus → **4G LTE/ WLAN** → Edge Server	Overlay LTE+WLAN	10 Kbps	200 Unit

	Management, Fa & Log

The network selection for mining monitoring systems is determined based on the specific technical requirements of each application. WLAN is considered optimal for Vehicle Health Monitoring System (VHMS) and Tire Pressure Monitoring System (TPMS) due to its bandwidth efficiency and ability to support rapid local data analysis via onsite servers. Similarly, WLAN is favored for the CCTV Mining Eyes system, which requires high bandwidth to transmit continuous video streams from fixed monitoring points. In contrast, LTE is prioritized for Tower Monitoring and Culvert Monitoring applications because of its wide coverage, stable connectivity, and capacity to support devices with high mobility. For Dispatch Management Systems (DMS), an LTE+WLAN overlay offers an effective solution to the extreme mobility demands of mining vehicles by combining LTE's reliability in open-pit areas with WLAN's high-speed data transfer in covered zones, while meeting the substantial bandwidth demands of edge computing-based video processing. Likewise, for Fleet Management Systems, the LTE+WLAN overlay is selected to ensure wide-area coverage and stable connectivity for highly mobile vehicles, enable fast local data transfer through WLAN, fulfill low-bandwidth yet real-time and low-latency communication needs, and provide scalability to accommodate a large fleet while supporting efficient edge computing operations.Comparison of WiFi and Overlay LTE+Wifi Performance

The analysis results demonstrate that the performance comparison between WiFi networks and Overlay LTE+WiFi reveals significant differences in terms of stability, speed, and reliability, particularly in supporting mining operations. Data obtained from monitoring systems across production areas indicate that the Overlay LTE+WiFi configuration provides a more stable and efficient connection compared to standalone WiFi, which tends to experience fluctuations and disruptions.

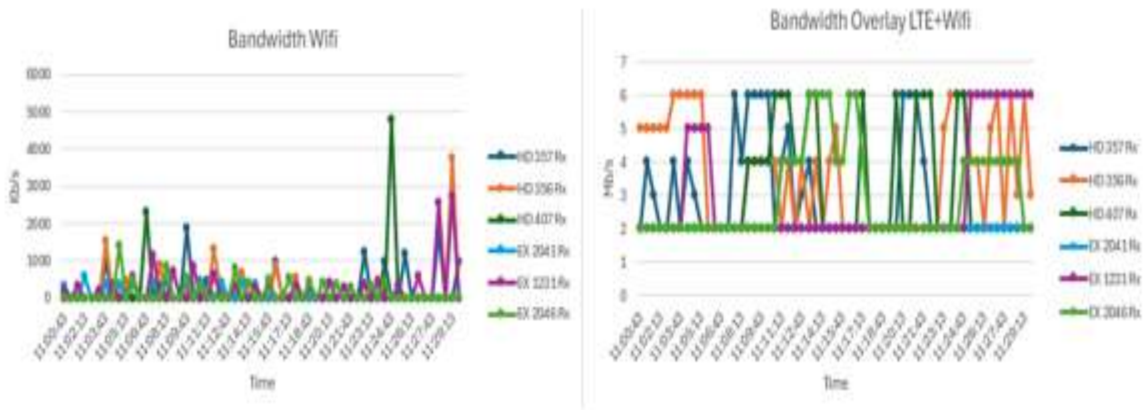


Fig. 4 Performance Comparison of WiFi Bandwidth and Overlay

Fig. 8 presents a comparison of bandwidth (BW) performance between WiFi and Overlay LTE+WiFi in terms of stability and bandwidth utilization efficiency. The graph on the left shows that WiFi bandwidth exhibits considerable fluctuations, with unstable spikes occasionally exceeding 2000 Kbps but frequently dropping close to zero. This condition reflects the instability of WiFi connections, which may be influenced by factors such as interference, limited network capacity, and environmental conditions.

In contrast, the graph on the right, representing Overlay LTE+WiFi bandwidth, shows a more stable connection, with relatively consistent values ranging between 2-6 Mbps. Although minor fluctuations are present, the variations are not as sharp as those observed in the standalone WiFi network. These findings indicate that the implementation of Overlay LTE+WiFi enhances network reliability and ensures stable data communication to support field operations.

This confirms the advantage of the overlay method as a strategic network architecture, offering dynamic load balancing and redundancy that bridges the performance gap between mobility and throughput. By integrating the broad coverage and mobility of LTE with the localized capacity of WiFi, the overlay configuration contributes to more consistent bandwidth delivery in geographically and environmentally complex mining sites. This architecture supports not only operational stability but also lays the foundation for real-time monitoring, IoT-based automation, and scalable digital transformation in the mining sector, connection quality in data transmission is also a critical factor influencing the efficiency and reliability of the network, as illustrated in Fig. 9.

Fig. 5 Performance Comparison of WiFi Data Connection Quality and Overlay

The graph on the left shows that the connection quality of the WiFi network experienced significant drops on several devices, such as units High Dump 357 and High Dump 356, at times falling below 50%. This instability is likely caused by limited WiFi coverage, high device mobility, and environmental obstructions that hinder seamless data transmission. Such degradation can lead to reduced connection reliability and the potential interruption of critical operational activities, especially in mobile or hard-to-reach zones.

Conversely, the graph on the right illustrates that the connection quality in the Overlay LTE+WiFi network is substantially more stable, with most devices maintaining levels near 100%. Although occasional signal disturbances were recorded, they did not significantly impact overall performance, with connection quality generally remaining above 98%. This consistency demonstrates the effectiveness of the overlay method in delivering enhanced resilience and data continuity, particularly in areas where either LTE or WiFi alone is insufficient.

These findings reinforce the value of hybrid network architecture in high-mobility industrial environments, where latency sensitivity and real-time data transfer are critical. By dynamically leveraging the strengths of both LTE and WiFi, the overlay network reduces data loss, increases communication reliability, and ensures uninterrupted support for digital mining applications such as IoT monitoring, autonomous equipment coordination, and remote diagnostics. The successful implementation of this architecture serves as a strong foundation for scaling smart mining initiatives and sustaining operational excellence in geographically demanding areas.

CONCLUSION

This study demonstrates that the proposed LTE-WLAN overlay network architecture effectively overcomes connectivity barriers in the topographically complex South Kalimantan coal mining site by integrating LTE's wide-area mobility with WLAN's high-throughput stability, delivering superior performance validated through field simulations and drive tests. Key results include FTP throughput exceeding 94%, RSRP above -100 dBm in over 92% of areas, SINR above 98.4%, near-100% connection quality, stable 2-6 Mbps bandwidth, and seamless handovers—far surpassing standalone Wi-Fi's fluctuations and dropouts—making it a practical, scalable foundation for real-time monitoring, IoT, and autonomous mining operations. For future research, integrating 5G New Radio (NR) with network slicing could enhance ultra-reliable low-latency communication (URLLC) and massive machine-type communication (mMTC), while exploring AI-driven systems for predictive load balancing, proactive fault detection, and adaptive resource allocation would optimize resilience in dynamic, expansive environments.

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