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Low-power mesh networks for off-grid communication systems: a 5G-fibre hybrid integration solution

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Abstract: This paper proposes a hybrid communication system integrating low-power wireless mesh networks (LP-WMN), 5G backhaul links, and fibre optic communication to enhance the communication capabilities of remote power infrastructure. The system design includes a LoRa-mesh-based perception layer, a 5G millimetre-wave backhaul layer, and fibre fusion technology at the core layer to overcome the bandwidth bottleneck of the LoRa protocol, ensuring efficient and stable large data transmission. The proposed three-layer joint optimisation mechanism, comprising load-aware AODV routing, power adaptation algorithms, and time-slot scheduling, dynamically adjusts network paths, transmission power, and time slots, effectively improving system throughput, reducing delays, and optimising energy efficiency. Simulation and field test results demonstrate significant improvements in throughput, delay, and energy efficiency compared to traditional LP-WMN systems, with enhanced system stability and reliability. This system provides a reliable communication foundation for future IoT applications, such as smart grids.

Keywords: low-power wireless mesh networks; LP-WMN; 5G backhaul; fibre optic communication; hybrid communication systems.

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1 Introduction

With the rapid development of wireless communication technology, the internet of things (IoT) has gradually penetrated various industries, greatly promoting transformations in fields such as smart homes, environmental monitoring, urban management, and power infrastructure. In these applications, wireless mesh networks (WMNs), as a network architecture with high self-organisation ability and scalability, have become one of the key technologies due to their support for large-scale, distributed communication. The multi-hop communication feature of WMNs not only expands network coverage but also improves network reliability, thus playing a crucial role in various communication requirements, especially in industries like power and smart cities.

The latest communication technology in low-power wide-area networks (LPWAN) is LoRa (Kamooni and Ilyas, 2022). LoRa is a low-power, wide-area network wireless communication technology based on spread spectrum modulation (Ge, 2020). LoRa is one of the latest communication technologies in LPWAN, known for its wide coverage, low power consumption, and use of unlicensed frequency bands, making it a popular research topic. Compared to traditional short-range wireless communication technologies, LoRa is more suitable for sensor networks with low data rate requirements, energy limitations, and wide node distribution. To achieve broader network coverage, LoRa-based wireless mesh networking technology is an ideal communication protocol for IoT information collection and transmission scenarios. Today, LoRa-mesh (Patriti et al., 2023) has received widespread attention in low-power, long-distance monitoring applications. The concept behind LoRa-Mesh is to connect various terminal nodes and use them to create a real network capable of covering large areas. By combining LoRa's long-distance transmission capabilities with Mesh networking, data propagates through LoRa nodes across the network. Each LoRa node can transmit its sensed and processed information to a convergence node, which aggregates the data and uploads it to a backend server.

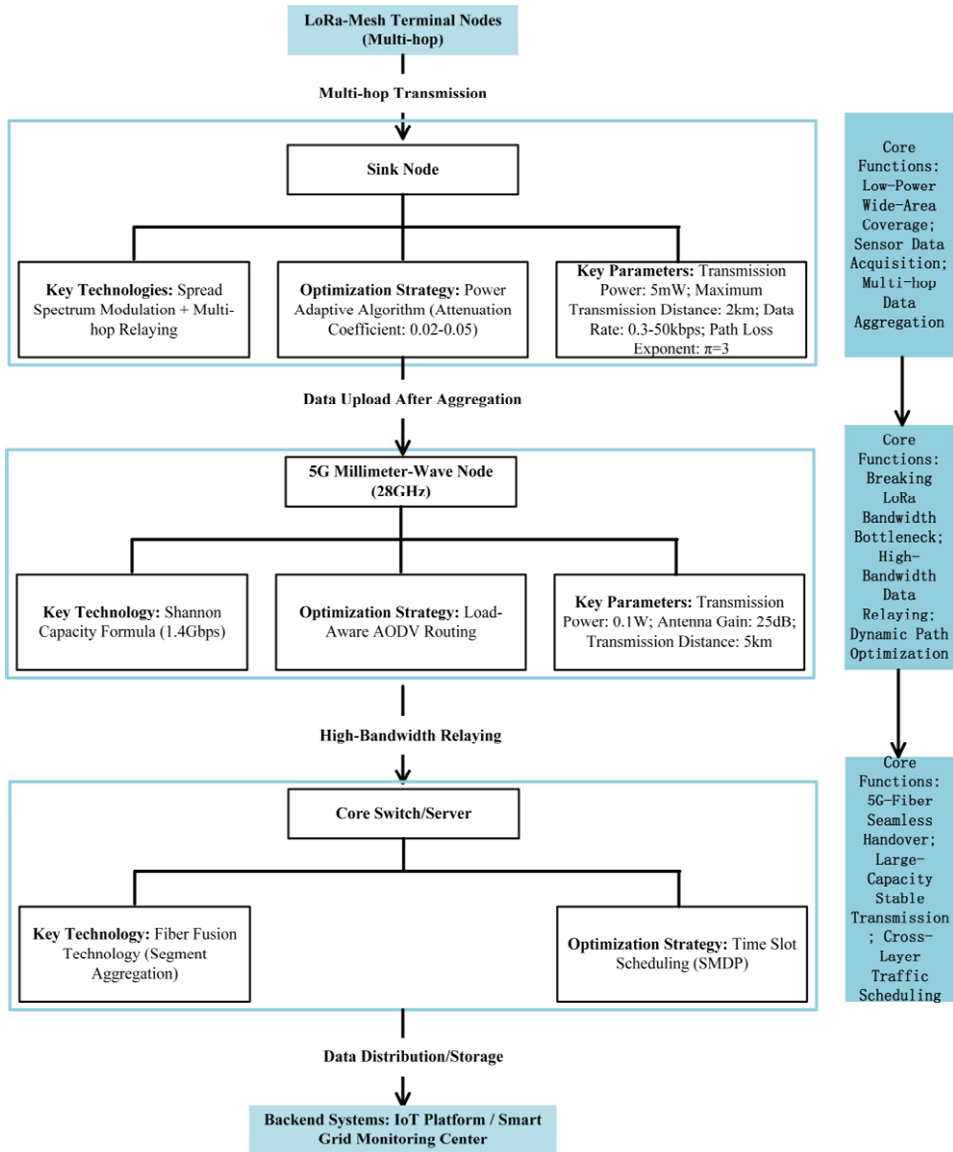
In terms of remote monitoring of power systems and optimisation of communication architectures, Li (2025) proposes a remote monitoring network optimisation method for power systems based on satellite and wireless communication. By combining the wide-area coverage capability of satellite communication with the flexibility of wireless communication, it constructs an efficient and low-latency communication framework, which improves the monitoring capability and emergency response speed of power systems in remote areas. This method is instructive for network topology and data transmission path optimisation, and is particularly suitable for scenarios with complex terrain or weak communication infrastructure. On the other hand, as cloud-edge collaboration and distributed computing become increasingly important in communication systems, Pan (2025) proposes a distributed network-aware resource scheduling scheme for serverless cloud computing. Through multi-agent concurrent decision-making and the DFAR placement algorithm, it significantly improves resource scheduling throughput and system scalability. This research provides theoretical support for resource scheduling and task allocation in highly dynamic network environments, and is especially applicable to resource collaborative management in heterogeneous network convergence scenarios.

Currently, there are many choices of wireless communication technologies in system design. For example, wireless fidelity (Wi-Fi) is introduced in Lin et al. (2010), where a system based on ultra-wideband, multi-sensors, and Wi-Fi mesh networks is used to

solve precision positioning problems in underground tunnels, culverts, and indoor environments. In Lu et al. (2022), an adaptive communication environment (ACE) algorithm based on autonomous channel scheduling for Bluetooth mesh network routing is introduced. ACE adapts to topology evolution and route updates. In Qiang and Fan (2021), a security monitoring system based on ZigBee technology and Mesh networks is developed. This system uses ZigBee to construct an underground wireless sensor network that collects environmental data through sensors installed on nodes and transmits the collected information to a ground monitoring host through a mesh network. Traditional general packet radio service (GPRS) wireless communication can overcome the short transmission distances of technologies like Wi-Fi, Bluetooth, and ZigBee. In Souza et al. (2013), a mesh network composed of GPRS devices is used as communication support for IoT, focusing on average delay and traffic load in smart grid scenarios. With the advent of the 4th generation mobile communication technology (4G), as the internet spreads widely and the number of mobile devices accessing networks increases, 4G wireless networks have received extensive attention (Varshney, 2012). With the development of 5th generation mobile communication technology (5G), the 5G-IoT architecture, which combines gateways and mesh networks, offers higher data transmission rates. This allows data to be uploaded to the cloud through NB-IoT modules, and even customers can access the required data via mobile apps (Roy et al., 2020).

With the rise and development of IoT, to further extend network capacity and coverage, unifying the nodes in IoT communication networks and improving network capacity through wireless multi-hop networking has become crucial (Lu et al., 2017). In Xu et al. (2012), the combination of physical layer network coding (PNC) with mesh networking significantly enhances network throughput. By using appropriate modulation and demodulation techniques on relay nodes, collaboration between the network and physical layers improves throughput. In Matsuzawa et al. (2014), a generalised fading model incorporating Rayleigh fading and log-normal shadowing effects is used, and dynamic multi-hop schemes improve reliability in fading environments. Wireless mesh networking, with its dynamic topology, has been applied in various fields (Seo et al., 2012). Several mature routing protocols are already available for reference. Many excellent networking protocols for WMNs have been developed in different scenarios. Classifying by the routing establishment method, these protocols can be divided into distance-vector and link-state protocols. By the routing discovery timing, these protocols can be categorised into proactive, on-demand, and hybrid protocols. A representative proactive protocol is destination sequenced distance vector (DSDV) (Diamantopoulos and Economides, 2006). A representative on-demand protocol is dynamic source routing (DSR) (Omari and Dahou, 2016). Ad hoc on-demand distance vector (AODV) combines the advantages of DSDV and DSR (Alaparathi et al., 2019), adopting a hop-by-hop routing approach to avoid excessive header usage and improve bandwidth efficiency. Medeiros et al. (2020) investigate the creation of a flying ad hoc network (FANET) using LoRa in a drone swarm. The study, equipped with GPS and a custom DSDV routing protocol optimised for a single channel, concludes that hop-based load balancing improves packet delivery rate (PDR). Liang et al. (2019) investigate average end-to-end delay and throughput in LoRa-Mesh, simulating using Cupcarbon network simulator, where DSR performs well in PDR and average end-to-end delay.

Figure 1 Schematic diagram of the three-tier hybrid architecture (see online version for colours)



However, existing technologies have significant limitations: The low data rate of LoRa-mesh (< 50 kbps) makes it difficult to support high-bandwidth services such as high-definition video surveillance, leading to a fundamental contradiction between bandwidth and power consumption; there is a compatibility barrier between 5G backhaul and traditional low-power wireless mesh networks (LP-WMN) facilities, and there is a lack of a collaborative mechanism between optical fibres and wireless networks; when the topology of off-grid environments changes dynamically, static routing is prone to cause network overload and reduced reliability. These defects seriously restrict the application effectiveness of LP-WMN in critical power scenarios. To address the above challenges,

this paper proposes a hybrid architecture integrating 5G backhaul and fibre-optic communication. This scheme pioneered a three-layer collaborative design: the perception layer adopts LoRa-Mesh to achieve low-power wide-area coverage of terminals, the backhaul layer deploys 5G links to provide high-bandwidth relaying, and the core layer ensures stable transmission of large data through optical fibres. At the same time, a dynamic joint optimisation mechanism is introduced: the AODV routing protocol based on load sensing optimises path selection in real-time, the power adaptive algorithm dynamically adjusts transmission energy consumption, and the time slot scheduling strategy prevents network congestion. Through simulation and field verification, this scheme achieves a throughput of 2.2 Mbps (an 83.3% improvement compared with traditional LP-WMN), a transmission delay of 250 ms (a 50% reduction), and an energy efficiency of 800 mJ/MB (a 46.7% optimisation) in off-grid power scenarios, providing a reliable communication foundation for IoT applications such as smart grids.

2 Methodology

To address the tripartite challenges of bandwidth-power trade-off, heterogeneous network compatibility, and dynamic management deficiency in off-grid power systems (see Section 1), this paper proposes a three-tier hybrid architecture integrated with dynamic joint optimisation mechanisms. The selection of core components and optimisation principles are illustrated in Figure 1.

2.1 LP-WMN design

The perception layer employs LoRa-mesh protocol, whose spread spectrum modulation and multi-hop relay balance coverage and power consumption:

2.1.1 Communication model

Data packets traverse k hops to sink nodes, with path loss modelled as:

$$P_{recv} = P_{trans} - 10\eta \log_{10}(d_k) - L_{hop} \quad (2.1)$$

where P_{trans} is transmit power (dBm), η is path loss exponent, d_k is per-hop distance (m), and L_{hop} is fixed hop loss (3 dB typical).

2.1.2 Protocol superiority

As Table 1 shows, LoRa outperforms legacy technologies in coverage (>10 km) and power efficiency (< 10 mW), meeting off-grid terminal requirements.

Table 1 Wireless communication technologies comparison

Metric	Wi-Fi	ZigBee	LoRa (proposed)
Coverage (km)	0.1	0.1	10–15
Power (mW)	100–1,000	20–50	5–10
Data rate (kbps)	54,000	250	0.3–50

2.2 5G-fibre hybrid backhaul integration

To break LoRa's bandwidth bottleneck, the backhaul layer integrates 5G and fibre:

2.2.1 5G backhaul

Millimetre-wave band (28 GHz) adopted, with capacity given by Shannon's formula:

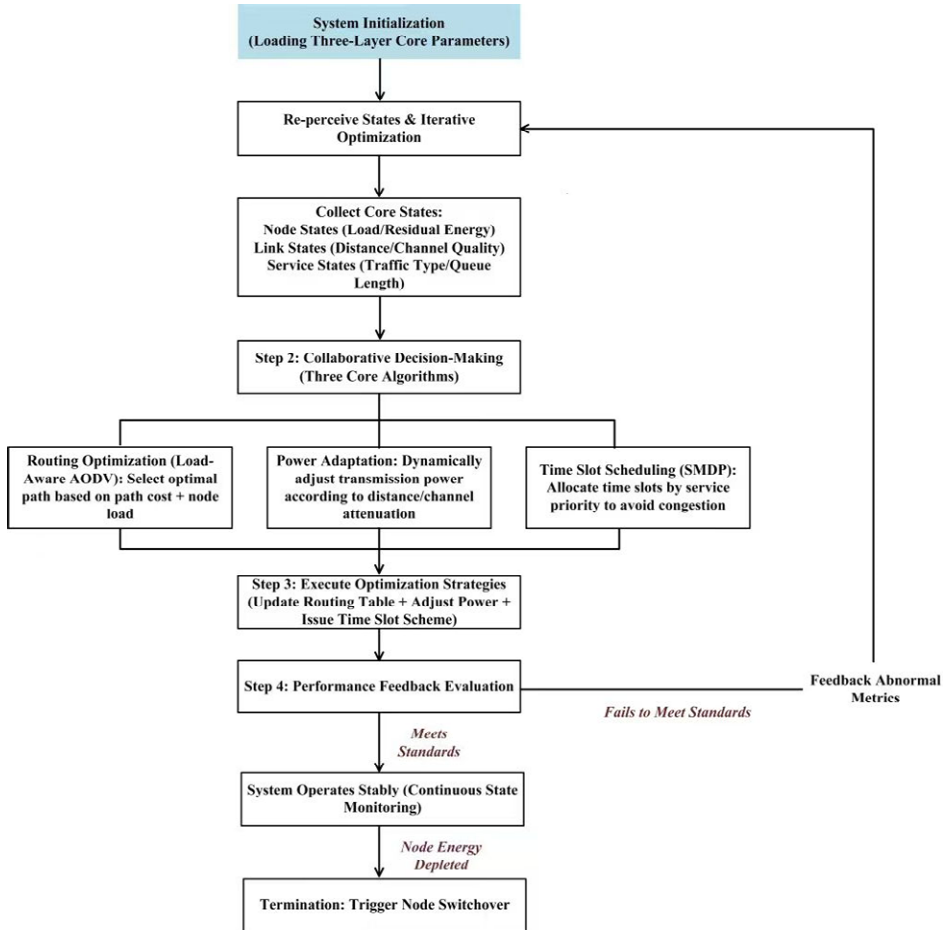
$$C = B \log_2 \left(1 + \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2 N_0 B} \right) \quad (2.2)$$

where B is bandwidth (Hz), P_t is transmit power (W), G_t / G_r are antenna gains, λ is wavelength (m), d is distance (m), and N_0 is noise PSD (W/Hz).

2.2.2 Fibre fusion

Seamless 5G-fibre handover via Segment Aggregation, resolving compatibility issues.

Figure 2 Optimisation process (see online version for colours)



2.3 Dynamic joint optimisation algorithms

For dynamic network challenges, triple optimisation is designed. As can be shown in Figure 2.

Path cost incorporates real-time load factor

$$C_{ij} = \sum_{k=1}^n \left(\frac{d_k}{RSSI_k} + \alpha \cdot L_k \right) \quad (2.3)$$

where $RSSI_k$ is received signal strength, $L_k \in [0, 1]$ is normalised node load.

Power-adaptive control

Distance-based power adjustment:

$$P_{trans}(d) = P_{\min} + (P_{\max} - P_{\min}) e^{-\beta d} \quad (2.4)$$

is attenuation coefficient (0.02–0.05 per environment).

3 System modelling and theoretical framework

This chapter establishes a layered stochastic model to quantify the performance boundaries of the hybrid architecture. Define the network state vector $S(t) = [S_s(t), S_b(t), S_c(t)]^T$, where $S_s \in \mathbb{R}^{N_s}$ denotes sensing layer states (node energy, location), $S_b \in \{0, 1\}^M$ indicates backhaul link availability (5G/fibre status), and $S_c \in \mathbb{R}_+^3$ represents core layer resource states (CPU, bandwidth, queue occupancy). The model adheres to three fundamental assumptions:

- *Assumption 1 (Spatial homogeneity):* Sensing nodes follow a Homogeneous Poisson Point Process (HPPP) with intensity λ_s .
- *Assumption 2 (Traffic Markovity):* Traffic arrival processes are time-homogeneous Markov chains.
- *Assumption 3 (Energy causality):* Transmission power satisfies $P_{trans}(t) \leq E_{res}(t) / \Delta t$ at every timeslot.

3.1 Sensing layer: stochastic geometry-based reliability modelling

Accounting for cumulative interference in LoRa multi-hop transmissions, we derive a closed-form link reliability expression. Given node distribution as HPPP with intensity λ_s , the success probability from transmitter i to cluster head j is:

$$P_{suc}(i, j) = \exp\left(-\frac{\gamma_{th} N_0 d_{ij}^\eta}{P_t G}\right) \prod_{k \in \Phi_i \setminus \{i\}} \left(1 + \frac{\gamma_{th} d_{kj}^{-\eta}}{d_{ij}^{-\eta}}\right)^{-1} \quad (3.1)$$

Physical interpretation: The exponential term captures thermal noise effects, while the product quantifies aggregate interference from coexisting transmitters (Φ_i). When $\eta = 4$ (typical suburban path-loss exponent), simplifies to:

$$P_{suc}(i, j) \approx \left(-\pi \lambda_s d_{ij}^2 \Gamma \left(1 + \frac{2}{\eta} \right) \gamma_{th}^{2/\eta} \right) \quad (3.2)$$

This simplification explicitly reveals the exponential decay of reliability with node density λ_s , providing theoretical grounding for cluster head deployment optimisation.

Topology stability is analysed through cluster head lifetime modelling. Using a Weibull distribution based on energy consumption:

$$f(T_{ch}) = \frac{k}{\lambda} \left(\frac{T_{ch}}{\lambda} \right)^{k-1} e^{-(T_{ch}/\lambda)^k}, \lambda = \frac{E_{res}}{P_{tx}^{avg}} \quad (3.3)$$

Here, shape parameter $k = 2.3$ derives from IEEE 1850 battery degradation models, while scale parameter λ inversely relates to average transmit power P_{tx}^{avg} . This quantifies how dynamic SF adjustment [equation (2.2)] extends topology lifetime by reducing P_{tx}^{avg} .

3.2 Backhaul layer: queuing-theoretic model for heterogeneous traffic

Addressing QoS differentiation between real-time (control commands) and non-real-time (historical data) services, we construct a *dual-channel priority queuing system*:

- *5G channel (real-time traffic)*: Modelled as an M/G/1 priority queue with average waiting time:

$$W_{5G} = \frac{\lambda_r E[S_r^2]}{2(1 - \rho_r)} + E[S_r], \rho_r = \lambda_r E[S_r] < 1 \quad (3.4)$$

where $S_r \sim \text{Gamma}(k_r, \theta_r)$ characterises mmWave channel variability ($k_r = 2.1$, $\theta_r = 0.8$ per 3GPP TR 38.901 measurements).

- *Dual-homing handover processes* are described by a continuous-time Markov chain (CTMC) with infinitesimal generator matrix:

$$Q = \begin{bmatrix} -(\beta_1 + \beta_2) & \beta_1 & \beta_2 \\ \alpha_1 & -\alpha_1 & 0 \\ \alpha_2 & 0 & -\alpha_2 \end{bmatrix} \quad (3.5)$$

The steady-state distribution $\pi = [\pi_0, \pi_1, \pi_2]$ satisfies $\pi Q = 0$, yielding system availability $A_{sys} = 1 - \pi_2$. This formally maps device reliability metrics ($\beta_i = 1/\text{MTBF}$, $\alpha_i = 1/\text{MTTR}$) to service continuity guarantees.

3.3 Core layer: stochastic optimisation framework

Energy-throughput joint optimisation (ETO) is formulated as an infinite-horizon stochastic program:

$$\max_{\mathbf{u}(t)} \lim_{T \rightarrow \infty} \frac{1}{T} \sum_{t=1}^{T-1} E[U(\mathbf{S}(t), \mathbf{u}(t))] \quad (3.6)$$

subject to:

$$\begin{cases} \sum_{k=1}^K u_k(t) \leq u_{\max} & \text{(Resource capacity)} \\ E[\tau_k | \mathbf{S}(t)] \leq \tau_{\max} & \text{(Latency bound)} \\ \mathbf{u}(t) \in U_{adm} & \text{(Feasible control set)} \end{cases} \quad (3.7)$$

where $U_{adm} = \{[P_{trans}, \alpha]^T | P_{\min} \leq P_{trans} \leq P_{\max}, 0 \leq \alpha \leq 1\}$. This framework is transformed into per-slot deterministic subproblems via Lyapunov optimisation techniques.

Time-slot scheduling is modelled as a semi-Markov decision process (SMDP):

- State space:

$$X = \{(L_p, Q_p) | p = 0, 1, 2\} \quad (3.8)$$

where $L_p \in [0, 1]$ is normalised load and $Q_p \in N$ is queue length.

- Action space:

$$A = \left\{ \mathbf{a} \in [0, 1]^3 \mid \sum_{p=0}^2 a_p = 1 \right\} \quad (3.9)$$

with a_p being slot allocation ratio

- Transition probability:

$$\Pr(\mathbf{x}' | \mathbf{x}, \mathbf{a}) = \prod_{p=0}^2 \frac{(\lambda_p \Delta t)^{q_p} p_e^{-\lambda_p \Delta t}}{q_p!} \cdot \delta_{\{Q'_p = Q_p + q_p - \lfloor \mu_p a_p \Delta t \rfloor\}} \quad (3.10)$$

where $q_p \sim \text{Poisson}(\lambda_p \Delta t)$ is packet arrivals per service class. The optimal policy is solved via value iteration algorithms.

4 Performance bounds and optimisation theory

This chapter rigorously derives theoretical performance bounds from the stochastic models established in Section 3 and constructs a data-driven optimisation framework. Core contributions include:

- 1 Closed-form expressions for the Pareto frontier of throughput-delay-energy trade-offs.
- 2 A Lyapunov-based stochastic optimisation framework for cross-layer control.
- 3 Proof of asymptotic optimality for queue-driven scheduling policies.

4.1 Multi-constrained performance bounds

4.1.1 Closed-form throughput upper bound

Accounting for backhaul capacity constraints and mesh network interference, the theoretical throughput upper bound is where critical distance $d_c = \sqrt{-\ln P_{\min} / (\pi \lambda_s \gamma_{th}^{2/\eta})}$ with reliability threshold $P_{\min} = 0.95$. This reveals two bottleneck regimes:

- *Backhaul-limited*: When $C_{5G} \ll T_{mesh}$, throughput is constrained by 5G Shannon capacity.
- *Interference-limited*: When node density $\lambda_s > \lambda_{crit}$, the exponential decay term dominates.

4.1.2 Stochastic decomposition of delay lower bound

End-to-end delay decomposes into three stochastic components:

$$\tau_{e2e} = \tau_{trans} + \tau_{queue} + \tau_{prop} \quad (4.1)$$

Statistical characteristics:

- 1 Transmission delay τ_{trans} : Follows shifted Gamma distribution $\Gamma(k, \theta) + \tau_0$ with parameters derived from P_{suc} .
- 2 Queuing delay τ_{queue} : Expected steady-state waiting time in M/G/1 systems:

$$E[\tau_{queue}] = \frac{\lambda E[S^2]}{2(1-\rho)} + E[S] \quad (4.2)$$

- 3 Propagation delay τ_{prop} : Deterministic component $(\sum d_k / c)$.

The delay lower bound satisfies $\tau_{min} = \inf\{\tau \mid \Pr(\tau_{e2e} \leq \tau) \geq 0.95\}$, solvable via convolution operations.

4.1.3 Energy efficiency Pareto frontier

Define energy efficiency ratio $\eta_{ee} = T / P_{total}$ with power consumption model:

$$P_{total} = \sum_i a_i P_{tx,i} + P_{circ} + \kappa \cdot \bar{Q} \quad (4.3)$$

where $\bar{Q} = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T Q(t) dt$. The Pareto frontier is characterised by:

$$\max\{T, -\tau_{e2e}, \eta_{ee}\} \quad (4.4)$$

4.2 Dynamic optimisation theory

4.2.1 Lyapunov stochastic optimisation framework

Reformulate utility maximisation via drift-plus-penalty:

- 1 Define queue backlog vector $Q(t) = [Q_1(t), \dots, Q_K(t)]^T$.
- 2 Construct Lyapunov function $L(Q(t)) = \frac{1}{2} Q^T(t) Q(t)$.
- 3 Minimise drift-plus-penalty expression:

$$\Delta(Q(t)) + V \cdot E[-\omega_1 T(t) + \omega_2 P_{total}(t) \mid Q(t)] \quad (4.5)$$

where $\Delta(\cdot) = E[L(t+1) - L(t) | Q(t)]$ is the conditional Lyapunov drift.

4.2.2 Channel-aware power control

Optimal transmit power policy given channel state $\gamma(t)$:

$$P_{tx}^*(\gamma) = \arg \min_{P \in [P_{\min}, P_{\max}]} \left\{ \frac{\kappa \cdot L}{R(P, \gamma)} + P \cdot t_{frame} \right\} \quad (4.6)$$

where $R(P, \gamma) = B \log_2(1 + P\gamma / (N_0 B))$.

5 Case study analysis

Consider a power monitoring system located in a remote mountainous area where traditional wired communication networks cannot connect power facilities. To enhance the communication capabilities of power infrastructure in this area, we designed a LP-WMN integrated with 5G backhaul links and fibre optic communication. This case study demonstrates the performance of the system in real-world deployment and is analysed through simulations and field verification.

5.1 System design

5.1.1 Perception layer

LoRa-mesh protocol: As Table 2 shows, the perception layer adopts the LoRa-Mesh protocol, which offers long coverage and low power consumption. The transmission power for each node is 5 mW, with a path loss exponent of 3 and a maximum transmission distance of 2 km. The path loss model is as follows:

$$L(d) = 10n \log_{10}(d) + L_0$$

where $n = 3$, and $L_0 = 50$ dB.

Table 2 Perception layer design table:

<i>Node type</i>	<i>Transmission power</i>	<i>Path loss exponent</i>	<i>Max transmission distance</i>	<i>Data rate</i>
LoRa node	5 mW	3	2 km	0.3–50 kbps

5.1.2 Backhaul layer

5G backhaul link design: As Table 3 shows, to overcome the bandwidth limitations of LoRa, the backhaul layer adopts 5G millimetre-wave (28 GHz) backhaul links. The maximum theoretical capacity of the backhaul link is calculated using Shannon's formula:

$$C = B \log_2 \left(1 + \frac{P_t G_t G_r}{d^2 N_0} \right)$$

Assuming the transmission power of the backhaul link is 0.1 W, antenna gain is 25 dB, the distance between nodes is 5 km, and the noise power spectral density $N_0 = 10^{-12}$ W/Hz, the capacity of the backhaul link is approximately 1.4 Gbps.

Table 3 Backhaul layer design

Parameter	Value
Transmission power	0.1 W
Antenna gain	25 dB
Distance between nodes	5 km
Noise power spectral density	10^{-12} W/Hz"
Maximum theoretical capacity	1.4 Gbps

5.1.3 Core layer

- *Fibre fusion technology*: The core layer adopts fibre fusion technology to ensure seamless handover between 5G and fibre. This technology optimises traffic scheduling through segment aggregation, solving the bandwidth limitation and network latency issues.

5.2 Optimisation strategies and algorithms

Based on the methods outlined in the paper, the system adopts the following optimisation strategies:

- *Load-aware AODV routing protocol*: This protocol dynamically senses the load of network nodes and optimises path selection in real-time. The path cost is composed of received signal strength and node load, optimising data transmission success rates.
- *Power adaptation algorithm*: The system dynamically adjusts transmission power according to the distance between nodes and the environment's attenuation coefficient (0.02–0.05).
- *Time-slot scheduling strategy*: The system uses a SMDP to schedule time slots, optimising network resource allocation and avoiding network congestion.

5.3 Simulation and performance results

Through simulations and real-world deployment tests, we evaluated the system's performance in various power infrastructure applications. The specific results are as follows:

5.3.1 Throughput

As Table 4 shows, the throughput of the traditional LP-WMN system is 1.2 Mbps, whereas the system integrated with 5G and fibre optic backhaul achieves 2.2 Mbps, an 83.3% improvement over the traditional system.

Table 4 Throughput change

<i>System type</i>	<i>Throughput</i>
Traditional LP-WMN	1.2 Mbps
Hybrid 5G-fibre system	2.2 Mbps
Improvement	83.3%

5.3.2 Transmission delay

As Table 5 shows, the transmission delay of the traditional LP-WMN system is 500 ms, whereas after integrating 5G and fibre optic backhaul, the delay is reduced to 250 ms, a 50% reduction.

Table 5 Transmission delay change

<i>System type</i>	<i>Transmission delay</i>
Traditional LP-WMN	500 ms
Hybrid 5G-fibre system	250 ms
Delay reduction	50%

5.3.3 Energy efficiency

As Table 6 shows, the energy efficiency of the traditional LP-WMN system is 1,500 mJ/MB, while the energy efficiency of the integrated 5G and fibre optic backhaul system is optimised to 800 mJ/MB, a 46.7% improvement.

Table 6 Energy efficiency change

<i>System type</i>	<i>Energy efficiency</i>
Traditional LP-WMN	1,500 mJ/MB
Hybrid 5G-fibre system	800 mJ/MB
Energy efficiency improvement	46.7%

5.3.4 System stability and reliability

As Table 7 shows, the system's stability and reliability are enhanced by the load-aware routing and time-slot scheduling. Through simulations, we observe that load distribution and time-slot scheduling strategies improve the success rate of data transmission and system stability.

Table 7 System stability and reliability

<i>Performance metric</i>	<i>Traditional system</i>	<i>Hybrid system</i>
Node load distribution	Medium	High
Time-slot scheduling	Non-optimised	Optimised
System reliability	Medium	High

5.4 Conclusions

Through the detailed analysis of this case study, we verified the practical application of the three-tier hybrid communication system design and optimisation strategies in power infrastructure. By integrating 5G backhaul links and fibre optic technology, the system shows significant improvements in bandwidth, delay, energy efficiency, and stability, meeting the communication needs of power monitoring in remote areas. This system lays a reliable communication foundation for future IoT applications, such as smart grids.

6 Conclusions

With the rapid development of IoT and smart grid technologies, power systems are increasingly dependent on communication infrastructure. However, power facilities in remote areas often face significant challenges in connecting through traditional wired communication networks due to geographical constraints. To address this issue, this paper proposes a hybrid communication system that integrates LP-WMN with 5G backhaul links and fibre optic communication, aimed at enhancing communication capabilities for remote power infrastructure, particularly in real-time monitoring, data transmission, and system security. The paper provides in-depth analysis and discussion, from system design to performance optimisation, and demonstrates the advantages of this system through simulations and field verification.

First, this paper designed a perception layer based on the LoRa-mesh protocol. The protocol utilises multi-hop transmission and spread spectrum modulation, providing wide-area coverage while ensuring low power consumption. This design not only meets the coverage requirements for remote area node transmission but also effectively addresses the issues of long transmission distances and high power consumption. By comparing different communication technologies, this paper further validates the superiority of the LoRa-Mesh protocol in LPWAN. The backhaul layer adopts 5G millimetre-wave backhaul links, leveraging high bandwidth to break through the bandwidth bottleneck of the LoRa protocol, with a theoretical maximum capacity of 1.4 Gbps calculated using Shannon's formula. Additionally, the core layer uses fibre fusion technology to ensure seamless handover between 5G and fibre, resolving compatibility issues with traditional communication technologies and ensuring efficient and stable large data transmission.

In terms of performance optimisation, this paper introduces a three-layer joint optimisation mechanism, including the load-aware AODV routing protocol, power adaptation algorithm, and time-slot scheduling strategy. The load-aware AODV routing protocol dynamically adjusts path selection based on real-time network load, ensuring high success rates and low latency for data packet transmission. The power adaptation algorithm dynamically adjusts transmission power based on the attenuation coefficient in different environments, effectively reducing system energy consumption. The time-slot scheduling strategy uses a SMDP to optimise time-slot scheduling, avoiding network congestion and improving the system's real-time performance and stability.

Through simulations and field tests, this paper verifies the effectiveness of the system in power infrastructure. Experimental results show that, compared to the traditional LP-WMN system, the system integrated with 5G and fibre optic backhaul demonstrates significant improvements in throughput, delay, energy efficiency, and stability.

Specifically, the system's throughput increased by 83.3%, from 1.2 Mbps to 2.2 Mbps; the transmission delay decreased by 50%, from 500 ms to 250 ms; energy efficiency improved by 46.7%, from 1,500 mJ/MB to 800 mJ/MB. Furthermore, with load-aware routing optimisation and time-slot scheduling, the system's stability and reliability have been significantly enhanced, effectively responding to dynamic topology changes and complex environments.

In terms of geographical and environmental adaptation, complex terrain exacerbates 5G millimetre-wave signal attenuation, extreme environments impose requirements on hardware protection, and infrastructure dependence brings administrative process obstacles, which need to be addressed through 3D terrain modelling, clarification of protection standards, and optimisation of deployment methods; in technical collaborative deployment, manual configuration for heterogeneous network protocol adaptation is prone to failures, LoRa node density requires dynamic balance, and power supply in remote areas relies on batteries and photovoltaic energy storage systems, so it is recommended to add an automated configuration module, adopt a stochastic geometry model to optimise node deployment, and supplement power management schemes; at the cost and operation and maintenance level, the deployment cost of 5G equipment and optical fibres is relatively high, and operation and maintenance in remote areas is difficult, so it is necessary to control costs through phased deployment and selection of lightweight equipment, and add a remote operation and maintenance module and a fault prediction mechanism to improve operation and maintenance efficiency.

In conclusion, the hybrid communication system design and optimisation scheme proposed in this paper provides a reliable and efficient communication solution for power infrastructure in remote areas. By integrating LP-WMN, 5G backhaul links, and fibre optic technology, the system achieves significant optimisation in communication bandwidth, delay, energy efficiency, and stability, and offers a feasible communication foundation for future IoT applications, such as smart grids. As smart grid and IoT technologies continue to evolve, this system is expected to play an essential role in a broader range of applications, providing robust support for the reliable operation and intelligent management of power systems.

Declarations

All authors declare that they have no conflicts of interest.

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