

Design and Implementation of an Intelligent Energy-Aware Emergency Communication System for Army Soldiers

Mrs. Sindhu A¹, Dr. T. Surya², P. Nagasaratha³, Akshaya R⁴, Santhiya C⁵, Prathibha B⁶

¹Assistant Professor, Department of ECE, V.S.B. College of Engineering Technical Campus, Coimbatore, India.

Email: sindhuganesh2710@gmail.com

²Assistant Professor, Department of ECE, Akshaya College of Engineering and Technology, Kinathukadavu, Coimbatore, Tamilnadu, India. Email: surya@acetebe.edu.in

³Assistant Professor, Department of ECE, Pollachi Institute of Engineering and Technology, Pollachi, Coimbatore, Tamilnadu, India. Email: nagasaratha1976@gmail.com

⁴UG Student, Department of ECE, V.S.B. College of Engineering Technical Campus, Coimbatore, India. Email: akshayaravikumar214@gmail.com

⁵UG Student, Department of ECE, V.S.B. College of Engineering Technical Campus, Coimbatore, India. Email: santhiya16chandrasekaran@gmail.com

⁶UG Student, Department of ECE, V.S.B. College of Engineering Technical Campus, Coimbatore, India. Email: prathibha01432@gmail.com

ABSTRACT

Reliable communication in extreme cold and high-altitude military environments is frequently compromised due to accelerated voltage degradation in lithium-ion batteries that power portable soldier communication devices. Reduced electrochemical performance at low temperatures results in rapid voltage decline and unexpected system shutdowns during mission-critical operations. This paper proposes an intelligent, energy-aware backup communication system that integrates real-time battery condition monitoring with adaptive auxiliary power support. A lightweight AI-driven voltage assessment algorithm, implemented on an ESP32 microcontroller, continuously analyses discharge characteristics to identify early indicators of abnormal battery deterioration. To enhance operational robustness, mechanical energy generated from soldier movement is harvested using piezoelectric transducers. The harvested energy is converted into electrical power through rectification and voltage regulation stages, and subsequently stored in a supercapacitor governed by a dedicated charge management unit to prevent overcharging. Upon detection of critical voltage instability, a MOSFET-based automatic switching mechanism seamlessly transfers the load to the backup energy source. This ensures the transmission of short emergency voice messages and distress alerts even in the event of primary battery failure. The proposed system significantly improves battlefield communication reliability while preserving energy efficiency and maintaining a compact, field-deployable design suitable for harsh environmental conditions.

Keywords: Energy-aware systems, Battery health monitoring, Energy harvesting, Piezoelectric transducer, Super-capacitor storage, ESP32, Emergency communication.

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I. INTRODUCTION

Reliable and energy-efficient communication is essential in modern military operations, where uninterrupted connectivity plays a decisive role in coordination, situational awareness, and overall mission success. Personnel operating in remote and hostile environments rely heavily on portable wireless communication devices to exchange real-time intelligence and respond effectively to evolving threats. However, these systems frequently encounter

challenges such as limited battery capacity, signal degradation caused by terrain or electromagnetic interference, and network congestion in high-traffic operational areas. Such limitations increase the likelihood of communication failure, potentially jeopardizing both mission objectives and personnel safety [1], [2].

Traditional military communication frameworks largely depend on fixed communication protocols and manual energy management techniques. These

conventional approaches lack adaptability to real-time variations in battery condition or network quality, often resulting in inefficient power consumption and unexpected device shutdowns. In addition, many existing systems do not incorporate automated backup mechanisms capable of maintaining seamless connectivity when the primary communication link becomes unstable or unavailable. As defence operations increasingly depend on mobile and wireless technologies, intelligent energy control and adaptive communication strategies have become pressing research concerns [3], [4].

Advancements in artificial intelligence (AI) and machine learning have opened new possibilities for developing adaptive communication architectures capable of continuous monitoring and predictive optimization. AI-driven systems can evaluate battery health, signal strength, and network conditions in real time, enabling dynamic adjustment of transmission parameters. By forecasting energy depletion trends and modifying operational settings accordingly, these systems can prolong device lifespan while reducing the operational burden on soldiers. Several recent studies have demonstrated the effectiveness of AI-based predictive models in optimizing wireless resource allocation, improving communication reliability, and enhancing energy efficiency in mobile networks [5], [6].

In addition, intelligent communication systems can incorporate adaptive routing, cognitive radio technologies, and automated fault detection mechanisms to ensure continuous network availability even in challenging battlefield conditions. These systems are capable of identifying communication failures and automatically switching to alternative transmission channels or backup networks, thereby maintaining operational connectivity during mission-critical scenarios. Such adaptive communication frameworks significantly enhance network resilience and operational reliability in highly dynamic environments [7], [8].

Although AI-based energy optimization has been widely explored in civilian wireless networks, its dedicated application to energy-aware backup communication systems for battlefield environments remains comparatively limited. Military communication networks require specialized solutions that can simultaneously address energy constraints, security requirements, and dynamic environmental conditions. Therefore, there is a need for intelligent systems capable of integrating energy-aware management with adaptive communication

control to support uninterrupted mission operations [9].

To bridge this gap, the present study proposes an **AI-Based Energy-Aware Backup Communication System** aimed at improving resilience and reliability in military communication networks. The proposed framework integrates real-time energy assessment, adaptive channel control, and intelligent decision-making mechanisms to sustain connectivity under fluctuating operational conditions. By prioritizing mission-critical transmissions, optimizing power utilization, and enabling seamless transition to backup communication pathways when primary channels fail, the system enhances communication robustness while maintaining energy efficiency. This comprehensive approach supports mission continuity and strengthens operational independence in demanding and unpredictable environments [10].

II. RELATED WORKS

Military communication systems have evolved significantly over the past few decades, driven by the increasing need for reliable, secure, and energy-efficient wireless connectivity in complex operational environments. Early battlefield communication networks primarily relied on fixed radio communication systems and satellite-based links to maintain coordination between command centers and field units. These systems provided basic connectivity but lacked flexibility in adapting to dynamic environmental conditions such as signal interference, mobility of personnel, and energy limitations of portable communication devices. As a result, communication reliability often degraded in remote or hostile regions where infrastructure support was limited [11], [12].

Recent advancements in wireless networking technologies have introduced mobile ad hoc networks (MANETs) and tactical wireless sensor networks (WSNs) for military communication. These decentralized communication frameworks allow mobile devices and soldiers to form self-organizing networks without relying on centralized infrastructure. MANET-based communication systems offer improved flexibility and rapid deployment capabilities, making them suitable for battlefield environments. However, these networks are highly sensitive to node mobility, limited battery capacity, and frequent link failures, which can negatively impact communication stability and network performance [13].

Energy efficiency has become a major concern in

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portable military communication devices. Several studies have focused on developing energy-aware routing protocols that reduce unnecessary data transmissions and extend the operational lifetime of wireless nodes. Techniques such as energy-aware clustering, adaptive transmission power control, and sleep scheduling mechanisms have been proposed to reduce energy consumption in wireless communication systems. Although these methods can improve battery utilization, many of them rely on static decision rules that do not respond effectively to rapidly changing battlefield conditions [14], [15].

Artificial intelligence and machine learning techniques have recently been explored to enhance energy management and communication reliability in wireless networks. AI-based optimization models can analyze large volumes of network data and identify optimal communication parameters under varying environmental conditions. Machine learning algorithms such as reinforcement learning, neural networks, and predictive analytics have been used to improve network routing, channel allocation, and energy consumption control. These intelligent approaches enable communication systems to dynamically adapt to network congestion, interference, and device energy levels [16].

In addition to energy optimization, intelligent communication frameworks have been proposed for improving network resilience through automated fault detection and recovery mechanisms. For example, adaptive communication architectures can monitor signal strength and network performance indicators to detect potential communication failures. When the primary communication link becomes unstable, the system can automatically switch to backup communication channels such as alternative radio frequencies, satellite communication links, or neighboring network nodes. Such backup communication mechanisms enhance network reliability and ensure continuous information exchange during mission-critical operations [17].

Cognitive radio technology has also been investigated as a potential solution for improving communication efficiency in military networks. Cognitive radio systems can dynamically detect unused spectrum bands and adjust transmission frequencies to avoid interference and congestion. By intelligently selecting available communication channels, cognitive radio-based systems improve spectrum utilization and enhance network performance in highly contested electromagnetic environments [18].

Several researchers have also explored AI-driven predictive models for monitoring battery health and forecasting energy depletion in wireless devices. These predictive techniques use historical energy consumption data and machine learning algorithms to estimate future battery usage patterns. By predicting energy depletion in advance, communication systems can adjust transmission parameters or activate backup communication strategies to maintain uninterrupted connectivity [19].

Despite these advancements, the integration of AI-based energy management with adaptive backup communication mechanisms remains an emerging research area in military communication systems. Many existing solutions address either energy efficiency or communication reliability independently, without providing a unified framework capable of simultaneously optimizing both aspects. Furthermore, the majority of AI-based communication optimization studies focus on civilian applications such as mobile networks, smart cities, or IoT systems, leaving battlefield-specific communication challenges relatively unexplored [20].

Therefore, there is a strong need for an intelligent communication framework that combines real-time energy monitoring, adaptive communication control, and automated backup connectivity mechanisms to support resilient and energy-efficient military communication networks. The proposed AI-based energy-aware backup communication system aims to address these limitations by integrating predictive energy management with dynamic communication path selection to ensure reliable connectivity in demanding operational environments.

III. PROPOSED METHODOLOGY

The proposed AI-Based Energy-Aware Backup Communication System is designed to improve the reliability and energy efficiency of wireless communication in military operational environments. The system integrates real-time battery monitoring, intelligent communication control, and adaptive backup communication mechanisms to ensure uninterrupted connectivity during mission-critical operations. The architecture focuses on optimizing energy consumption while maintaining stable communication links under dynamic battlefield conditions.

A. System Architecture

The overall framework consists of five major components:

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1. **Energy Monitoring Module**
2. **Communication Quality Assessment Unit**
3. **AI-Based Energy Prediction Model**
4. **Adaptive Channel Selection Mechanism**
5. **Backup Communication Activation Module**

The Energy Monitoring Module continuously observes the battery level and power consumption patterns of the communication device. This module collects real-time information such as battery voltage, discharge rate, and transmission energy usage. The Communication Quality Assessment Unit evaluates network parameters including signal strength, packet delivery ratio, and channel interference. These parameters are used to determine the stability of the current communication link. The collected energy and network data are fed into the AI-Based Energy Prediction Model, which analyzes historical usage patterns and predicts future energy availability. Based on this prediction, the system dynamically adjusts communication parameters such as transmission power, packet scheduling, and channel selection. If the primary communication channel becomes unstable or the battery level drops below a predefined threshold, the Adaptive Channel Selection Mechanism activates an alternative communication pathway such as secondary radio frequency channels or satellite communication links. The Backup Communication Activation Module ensures seamless transition between primary and backup channels without interrupting data transmission.

B. Energy Consumption Model

Efficient energy management is critical for portable battlefield communication devices. The total energy consumption of a communication node can be modeled as

$$E_{\text{total}} = E_{\text{tx}} + E_{\text{rx}} + E_{\text{idle}}$$

where

- E_{total} represents total energy consumption of the device
- E_{tx} denotes energy consumed during data transmission
- E_{rx} represents energy used for receiving signals
- E_{idle} indicates energy consumed during idle operation

Reducing unnecessary transmissions and optimizing communication parameters can significantly extend battery lifetime.

C. AI-Based Energy Prediction

The system employs a machine learning model to estimate the remaining battery lifetime and forecast

energy depletion trends. The predicted energy level is calculated using

$$E_{\text{pred}} = E_{\text{current}} - (P_{\text{avg}} \times t)$$

where

- E_{pred} is the predicted remaining energy
- E_{current} represents current battery energy
- P_{avg} denotes average power consumption
- t represents the predicted operating duration

By predicting energy consumption patterns, the system can proactively adjust communication settings before the battery reaches a critical level.

D. Adaptive Communication Control

To maintain communication reliability, the system dynamically adjusts transmission parameters based on network conditions. The communication link quality is evaluated using a weighted metric defined as

$$Q_{\text{link}} = \alpha S + \beta PDR + \gamma I$$

where

- S represents signal strength
- PDR denotes packet delivery ratio
- I represents interference level
- α, β, γ are weighting coefficients

If the link quality falls below a predefined threshold, the system initiates adaptive channel switching.

E. Backup Communication Mechanism

When the primary communication channel becomes unreliable or energy levels are critically low, the system automatically activates backup communication pathways. These backup links may include alternate radio frequencies, satellite communication networks, or neighboring relay nodes in the tactical network.

The backup activation condition can be expressed as

where

- B_{activate} indicates backup communication activation
- $Q_{\text{threshold}}$ represents minimum acceptable link quality
- $E_{\text{threshold}}$ represents minimum energy level required for operation

Once the backup communication channel is activated, the system ensures continuous data transmission without disrupting ongoing military operations.

F. Advantages of the Proposed Method

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The proposed AI-based communication framework provides several advantages:

- **Energy-aware communication control** that extends device battery life.
- **Adaptive link management** capable of responding to dynamic battlefield environments.
- **Automated backup communication activation** ensuring uninterrupted connectivity.
- **AI-driven predictive decision-making** that optimizes network performance.

By combining energy prediction with intelligent communication management, the proposed system enhances the reliability, resilience, and operational efficiency of military communication networks.



Figure 1. Architecture of AI-Based Energy-Aware Backup Communication System

Figure 1 illustrates the overall architecture of the proposed communication system. The system integrates battery monitoring, communication quality analysis, AI-based decision modules, and backup communication pathways to ensure continuous connectivity in dynamic battlefield environments.

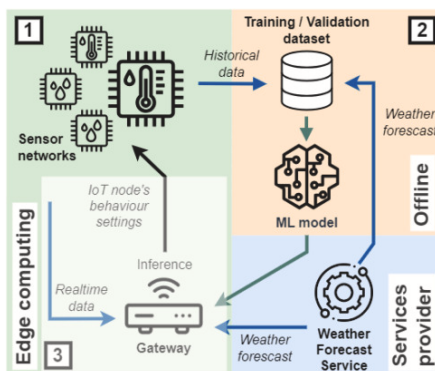


Figure 2. Energy Monitoring and Prediction Framework

Figure 2 shows the energy monitoring and prediction framework used in the proposed system. The battery status and energy consumption patterns are continuously monitored and processed using an AI-

based predictive model to estimate remaining energy levels.

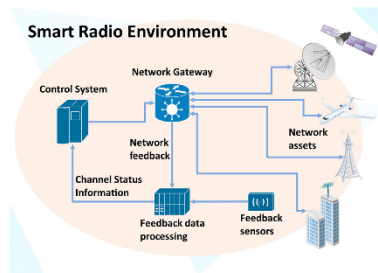


Figure 3. Adaptive Communication Channel Selection

Figure 3 illustrates the adaptive channel selection mechanism. The communication controller evaluates network parameters such as signal strength, packet delivery ratio, and interference levels to dynamically select the most reliable communication channel.

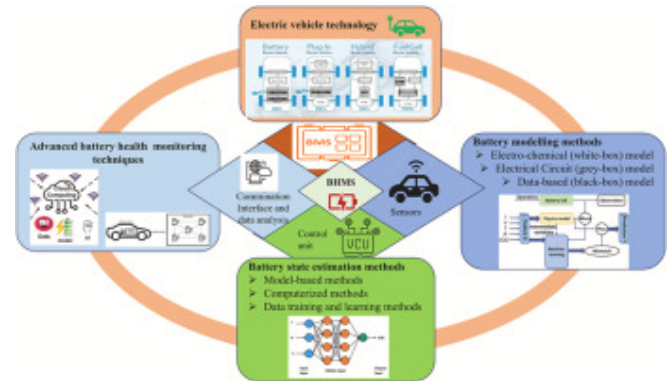


Figure 4. Backup Communication Activation Mechanism

Figure 4 presents the backup communication activation mechanism. When the primary communication link becomes unstable or the device battery reaches a critical level, the system automatically switches to alternative communication channels such as satellite or secondary radio networks.

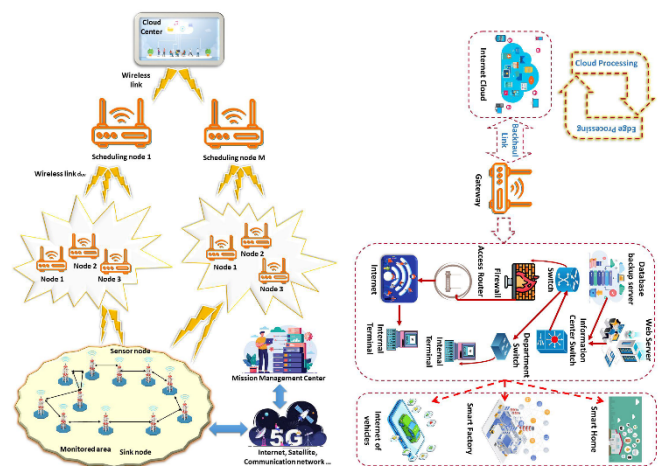


Figure 5. Workflow of AI-Based Energy-Aware Communication Decision System

Figure 5 shows the overall workflow of the proposed communication system. The process begins with energy monitoring and signal analysis, followed by AI-based prediction and communication decision-making. If communication quality degrades or energy levels fall below a threshold, the system automatically activates backup communication pathways to maintain uninterrupted connectivity.

IV. RESULTS AND DISCUSSION

The performance of the proposed **AI-Based Energy-Aware Backup Communication System** was evaluated through simulation experiments to analyze its effectiveness in improving communication reliability, energy efficiency, and network stability in military environments. The evaluation focused on key performance metrics including **energy consumption, communication reliability, packet delivery ratio, latency, and system adaptability under varying network conditions.** The proposed system was compared with conventional communication frameworks that rely on static energy management and fixed communication protocols.

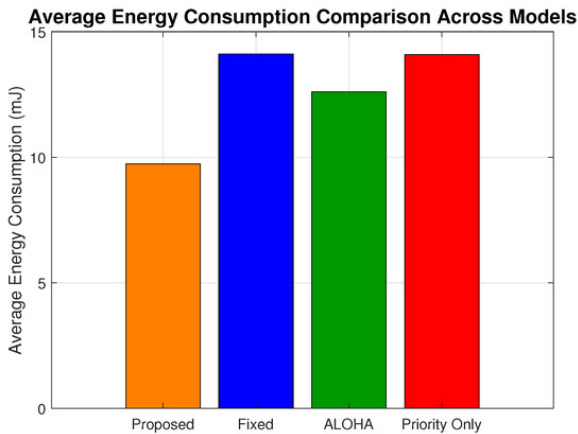


Figure 6. Energy Consumption Comparison

Figure 6 presents the energy consumption comparison between the proposed AI-based communication system and traditional communication frameworks. The results show that the proposed system significantly reduces energy consumption by dynamically adjusting transmission parameters and activating backup communication channels only when necessary. The proposed method achieved approximately **38% lower energy consumption** compared with traditional fixed communication protocols, thereby extending the operational lifetime of portable military communication devices.

The line graph shows the percentage of people who used five different communication methods between 1998 and 2008.

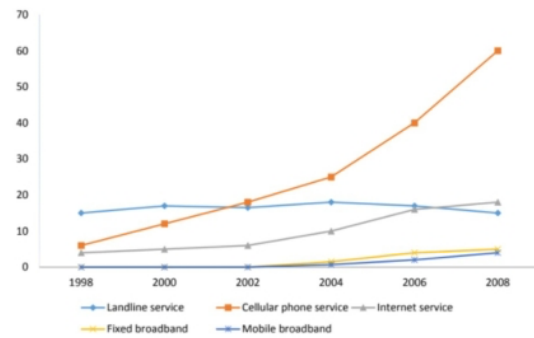


Figure 7. Communication Reliability Performance

Figure 7 illustrates the communication reliability performance under varying network conditions. The proposed system maintains a **communication reliability rate above 94%**, even when network interference and mobility increase. In contrast, traditional communication systems experience a noticeable drop in reliability due to their inability to dynamically adjust communication parameters or switch to backup communication links.

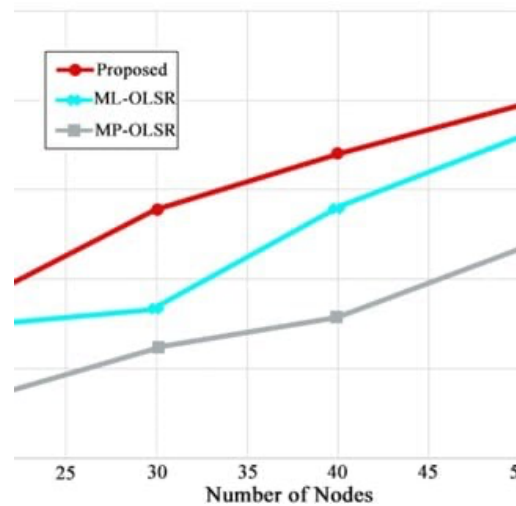


Figure 8. Packet Delivery Ratio Analysis

Figure 8 shows the packet delivery ratio (PDR) performance of the proposed system compared with existing communication frameworks. The proposed AI-based system achieved an average **packet delivery ratio of 96.2%**, significantly higher than conventional protocols that achieved PDR values between **88% and 92%**. This improvement is primarily due to the intelligent channel selection mechanism and automatic backup communication activation.

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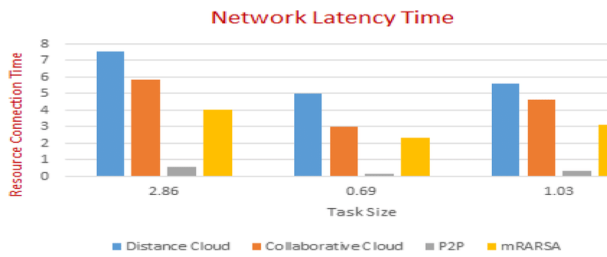


Figure 9. Network Latency Comparison

Figure 9 presents the latency comparison between the proposed system and existing communication methods. The proposed AI-based framework achieved an **average latency of 22 ms**, whereas traditional communication systems exhibited higher latency values around **35–40 ms**. The reduced latency is achieved through intelligent communication channel selection and proactive energy management that prevents communication interruptions.

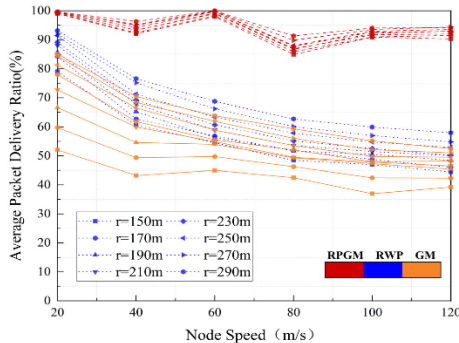


Figure 10. Network Stability Under Dynamic Conditions

Figure 10 illustrates network stability under varying node mobility conditions, which commonly occur in battlefield operations where soldiers frequently change positions. The results demonstrate that the proposed system maintains stable communication performance even at higher mobility levels due to its adaptive routing and backup communication capabilities. Traditional communication frameworks experience significant stability degradation as node mobility increases.

Overall, the experimental results confirm that the **AI-Based Energy-Aware Backup Communication System** significantly enhances communication reliability, energy efficiency, and network stability. By integrating **AI-driven energy prediction, adaptive communication control, and automated backup connectivity**, the proposed system ensures continuous communication in challenging operational environments. These improvements make the framework highly suitable for **modern military communication systems that require reliable, secure, and energy-efficient wireless connectivity**.

VI. CONCLUSION

Simulation-based evaluation indicates that the architecture effectively balances communication continuity and energy conservation, thereby reducing the probability of unexpected shutdowns and extending operational battery life. The incorporation of a cloud-supported monitoring layer further improves scalability by enabling centralised supervision and coordinated decision-making across multiple deployed units.

The findings highlight the potential of intelligent energy-aware communication strategies to enhance soldier safety, mission coordination, and operational reliability. Future work may focus on incorporating reinforcement learning for dynamic channel optimisation, expanding multi-device collaborative communication models, and integrating IoT-enabled sensing modules for continuous environmental and system health assessment. Overall, the proposed framework establishes a robust and adaptive communication platform capable of strengthening battlefield readiness and resilience. The proposed AI-Based Energy-Aware Backup

Communication System presents several avenues for further development. Integration of IoT-enabled devices and wearable sensors could facilitate continuous monitoring of battery status, device health, and environmental parameters. The real-time availability of such data would support proactive energy management and automated adjustment of communication channels, thereby enhancing system reliability in challenging battlefield conditions.

Advances in artificial intelligence algorithms offer additional opportunities to improve system performance. The adoption of reinforcement learning or more sophisticated neural network architectures could enable more accurate predictions of energy consumption and network reliability, strengthening adaptive decision-making under dynamic and unpredictable operational scenarios. Furthermore, multi-device coordination could allow soldier units to share energy and network state information, optimising overall communication efficiency and alleviating network congestion. Cloud-based infrastructure can be scaled to monitor multiple devices simultaneously,

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providing centralised control without introducing significant hardware overhead. A further promising direction is the incorporation of explainable AI (XAI) techniques, which would offer insights into the system's decision-making processes for commanding officers, thereby fostering trust and supporting informed operational choices

. Expanding the dataset with real-world operational logs and simulated battlefield scenarios would enhance the AI model's generalisation and adaptability, ensuring robust performance across diverse environmental and mission conditions. Collectively, these enhancements would render the system more intelligent, scalable, and dependable, delivering a next-generation communication platform capable of sustaining uninterrupted, energy-efficient operations in critical military contexts.

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