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Enhancing LoRa-based network architecture for military vehicle testing using LoRaWAN and local data redundancy

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ABSTRACT

Reliable communication is essential in military vehicle testing, particularly for evaluating integrated vehicular systems under dynamic and challenging conditions. This study proposes a LoRaWAN-based communication system featuring centralized network management, end-to-end encryption, and local microSD card redundancy to address the limitations of previous LoRa-only solutions. Experiments were conducted on two types of military vehicles, specifically a light open-body tactical vehicle and a light armored personnel carrier, each equipped with two sensor nodes. Testing was performed in both controlled facility and rugged hilly terrain environments. Communication performance was quantitatively evaluated by measuring packet delivery ratio (PDR), received signal strength indicator (RSSI), and signal-to-noise ratio (SNR), as well as calculating path loss and link budget. In controlled environments, open-body vehicles achieved PDR values ranging from 57.75% to 61.81% (RSSI: -40 to -41 dBm, SNR: 8.10 to 8.11 dB), while armored vehicles recorded lower PDRs of 36.65% to 38.68% (RSSI: -45.67 to -50.29 dBm, SNR: 4.67 to 6.28 dB). In hilly terrain, open body vehicles reached PDR values of 88.21% to 92.45% (RSSI: -64 to -69 dBm, SNR: 5.98 to 7.26 dB), and armored vehicles achieved PDR values of 82.56% to 98.95% (RSSI: -72 to -73 dBm, SNR: 0.15 to 3.51 dB). These results demonstrate that both vehicle design and environmental conditions substantially affect LoRaWAN communication reliability. The proposed system improves data resilience in the presence of transmission failures and supports the deployment of robust and temporary wireless networks for military vehicle testing.

Keywords: Field testing, LoRaWAN, Military communications, Path loss analysis, Vehicular networks, Wireless sensor networks.

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1. INTRODUCTION

Communication is one of the crucial aspects in military systems, functioning not only as a medium for inter-personnel communication but also as a channel for data transmission that supports information-based decision making (Russell and Abdelzaher, 2018; Kufakunesu et al., 2025). Various communication technologies have been developed for a range of purposes, however, only a select few can meet the demands of the dynamic military environment, which requires stability, security, and efficiency. One of the critical sectors that necessitate a reliable communication system is military vehicles.

Modern military vehicles serve not only as means of transportation but also as operational platforms equipped with various electronic systems and sensors. Testing military vehicles constitutes an essential stage in defense technology development, including the evaluation of their integrated communication systems (Cu and Vintr, 2021; Ochando et al., 2023). In the context of vehicle testing, an efficient, lightweight, temporary, and non-intrusive communication solution is required to ensure that it does not interfere with the vehicle's primary systems (Ab Rahman et al., 2019; Bedretchuk et al., 2023).

Various communication technologies have been applied in both military and industrial contexts, such as VHF/UHF, LTE, and 5G, which offer high bandwidth and low latency but often entail high power consumption and dependence on external infrastructure (Maghsoudnia et al., 2024). Within the realm of low power wide area networks (LPWAN), several options are available, namely LoRa, Sigfox, NB-IoT, LTE-M, and Zigbee. While Sigfox offers broad coverage and low power consumption, it is limited in data capacity and heavily dependent on operator infrastructure (Raza et al., 2017; Levchenko et al., 2022). NB-IoT and LTE-M deliver high performance but are not suitable for test environments that lack cellular network infrastructure (El Hassan et al., 2021; Islam et al., 2024; Soy, 2023). Zigbee excels in short-range communication through mesh networks but has a limited range and is more appropriate for indoor applications (Tabassum and Zen, 2015; Dash and Peng, 2022; Haque et al., 2022). Meanwhile, LoRa (long range) is a physical layer modulation technology based on chirp spread spectrum, known for its ability to cover long distances with very low power consumption. This makes it highly suitable for low power applications such as wireless sensor networks and remote monitoring systems (Kornaros et al., 2023; Olaide, 2023; Abdulmalek et al., 2024; Ahmed et al., 2024; Jabbar et al., 2024). However, LoRa alone only covers the physical layer and a basic MAC layer and therefore does not adequately support large-scale communication systems that require robust network management, enhanced security, and flexible data transmission (Jebril et al., 2018; Torres et al., 2021; Almuhaya et al., 2022). To address these limitations, LoRaWAN was developed as a higher-layer protocol built on top of LoRa modulation. LoRaWAN introduces centralized network management, device class structuring, and end-to-end encryption, enabling scalable, secure, and flexible wireless communication suitable for dynamic and constrained environments (Ertürk et al., 2019; Loukil et al., 2022; Jouhari et al., 2023).

A previous study by Fadillah et al. (2024) employed LoRa technology to monitor the cabin environment of military vehicles. However, that study did not fully utilize the LoRaWAN protocol, which offers significant advantages such as a wider communication range, enhanced reliability in data transmission through structured network management, and improved communication security via end-to-end encryption. In addition, their system lacked a local data redundancy mechanism, as it relied solely on real-time transmission without persistent storage within the node. These limitations highlight the potential advantages of adopting LoRaWAN and additional reliability measures for vehicle testing applications.

This research proposes a LoRaWAN-based system for military vehicle testing to evaluate communication performance in complex vehicular environments. In addition to implementing LoRaWAN, this study addresses limitations observed in prior LoRa-based deployments, particularly the absence of centralized network management, secure data transmission, and local data redundancy mechanisms. To overcome these challenges, the proposed system integrates a local microSD card data logging mechanism alongside LoRaWAN's advanced features, ensuring that all collected sensor data are safely recorded within the node even if transmission failures occur, thereby enhancing overall system reliability. The primary focus of this study is the measurement and analysis of key technical parameters, including received signal strength indicator (RSSI), signal-to-noise ratio (SNR), and packet delivery ratio (PDR). Based on these measurements, path loss and link budget calculations are performed to assess the feasibility and effectiveness of the LoRaWAN system in a military vehicle testing scenario (Aden and Karlsson, 2019; Ferreira et al., 2020; Di Renzone et al., 2024). This study is expected to provide a foundation for developing efficient temporary communication solutions for military vehicle testing, particularly in ensuring the integrity, reliability, and security of data transmission throughout the testing process.

The remainder of this paper is organized as follows: Section 2 reviews related works and highlights key research gaps. Section 3 details the system architecture, experimental setup, and data collection methodology. Section 4 presents and discusses the results of field testing under varying vehicular and environmental conditions. Section 5 concludes the study and outlines potential directions for future work.

2. RELATED WORK

This section reviews prior studies on communication technologies for military vehicles, with a particular focus on LoRa and LoRaWAN deployments. It also identifies key research gaps that form the foundation for the development of the proposed LoRaWAN-based communication system in this study.

Previous research on military vehicle communication systems has largely relied on conventional technologies such as VHF/UHF, LTE, and 5G networks. Maghsoudnia et al. (2024) observed that while these technologies offer high transmission speeds and low latency, their high-power consumption, configuration complexity, and dependence on external infrastructure limit their effectiveness in dynamic and remote military environments.

The emergence of LPWAN technologies such as Sigfox, NB-IoT, and LTE-M offers a promising alternative for low-power, long-range sensor data communication. Lavric and Popa (2017) and Mekki et al. (2019) highlighted that while LPWANs are widely used in IoT, their dependence on operator infrastructure and limited data capacity makes them less suitable for military contexts. Similarly, although Zigbee is effective for indoor communication or limited-scale applications, research by Shrestha and Shakya (2021) indicated that Zigbee is unsuitable for mobile and wide-area applications such as those required for military vehicles.

Bukhori et al., International Journal of Applied Science and Engineering, 22(3), 2025127

LoRa, based on chirp spread spectrum modulation, offers significant advantages in terms of range and low power consumption (Adelantado et al., 2017). However, studies like Haxhibeqiri et al. (2018) noted that LoRa's basic protocol alone is insufficient for large-scale applications that require efficient network management and high data security. This is where the LoRaWAN protocol adresses these gaps by offering additional features such as centralized network management, flexible end-device class configurations, and end-to-end encryption through AES-128 (Augustin et al., 2016).

In the context of military vehicles, the study conducted by Fadillah et al. (2024) demonstrated the feasibility of using LoRa for monitoring in-cabin within moving military vehicles. However, their approach was limited to basic LoRa and did not incorporate advanced features such as network management and data security provided by LoRaWAN. Furthermore, the system proposed by Fadillah et al. (2024) did not incorporate local data redundancy mechanisms, relying solely on successful real-time transmission without persistent onboard storage. This approach introduces potential risks of data loss if communication failures occur during testing, which is critical in military operational scenarios. Additionally, their basic LoRa implementation did not provide network-level security features such as end-to-end encryption, limiting its applicability for secure and resilient military communication systems.

Meanwhile, Di Renzone et al. (2024) conducted extensive field tests evaluating LoRaWAN performance for vehicle-to-roadside (V2R) communication under dynamic conditions. Their experiments involved vehicles moving at various speeds while transmitting to a static gateway, focusing on metrics such as packet loss and RSSI across different spreading factors. The study confirmed that LoRaWAN can sustain vehicular communication links even at higher speeds, and that the Doppler effect had only a marginal impact on transmission quality. However, their investigation primarily addressed open-road conditions without the additional signal attenuation caused by enclosed vehicle structures, leaving a gap that this current study aims to address. Table 1 compares the main advantages and disadvantages of the proposed system and key related methods, focusing on network management, data redundancy, scenario breadth, and deployment features.

Based on the reviewed literature, there is a clear gap in comprehensive evaluations of LoRaWAN performance in moving military vehicles operating under both dynamic and enclosed conditions. This study addresses this gap by analyzing key communication parameters including RSSI, SNR, and PDR. While also calculating path loss and link budget under real-world operational scenarios involving both open-body and armored vehicles in flat and rugged terrains. By integrating local data redundancy mechanisms and advanced network management, the proposed system aims to advance the reliability and resilience of wireless communication solutions for military vehicle testing.

3. METHODOLOGY

3.1 Proposed System Design

This study proposes and evaluates a LoRaWAN-based communication system specifically designed for military vehicle testing scenarios. The system consists of two LoRaWAN sensor nodes installed inside military vehicles, functioning as data acquisition and transmission units. These nodes utilize LoRa modules RFM95W and SX1276, both operating on the AS923-1 frequency band, to ensure compliance with regional spectrum regulations and compatibility with the gateway infrastructure.

The LoRaWAN nodes are integrated with several environmental and motion sensors, including temperature, humidity, pressure sensors (BME280), accelerometer and

Table 1. Comparison table: advantages and disadvantages

References	Security	Data redundancy	Network management	Vehicle types tested	Advantages	Disadvantages
Fadillah et al., 2024	No	No	No	Single (open/armored)	Simple, low power, LoRa penetration demo	No LoRaWAN, no redundancy, no encryption, limited scope
Di Renzone et al., 2024	AES-128	No	Yes	Single vehicle	Validated LoRaWAN at speed, doppler effect studied	No redundancy, no armored test, single node
This study (Proposed)	AES-128	Micro SD	Yes	Open body + armored	Full LoRaWAN, dual vehicle test, local data backup	Prototype scale, single gateway, limited environments

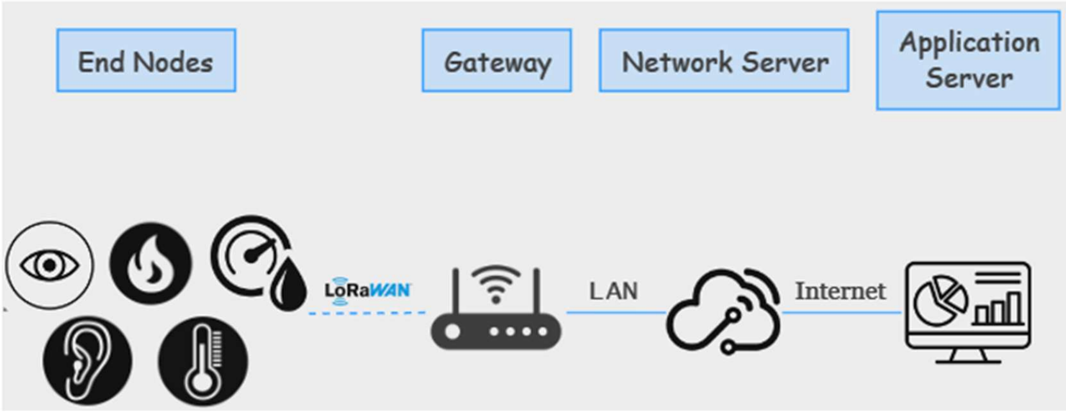


Fig. 1. Proposed LoRaWAN system architecture

gyroscope sensors (MPU6050), and sound sensors (analog sound level meter). The nodes, along with the attached sensors, are physically positioned near the passenger seats within the vehicle cabin to accurately simulate operational deployment without interfering with primary vehicle systems. Sensor data are collected periodically, packaged into binary payloads, and transmitted during vehicle motion to replicate real-world testing conditions. Each transmission carries a payload of approximately 26 bytes, containing compressed multi-sensor information.

Each node is configured with standardized communication parameters, including a Spreading Factor (SF) of 7, a Bandwidth (BW) of 125 kHz, and a Coding Rate (CR) of 4/5. These settings were selected to optimize the balance between communication reliability, transmission range, data throughput, and energy efficiency in dynamic vehicular environments.

Data packets from the nodes are transmitted wirelessly to a LoRaWAN gateway based on the SX1302 chip. The gateway is deployed at a static position within the testing environment, elevated approximately 2.5 m above ground level to enhance line-of-sight propagation and reduce reflection-induced losses. The gateway receives the data and forwards them via Ethernet to a local ChirpStack server, which serves as both the network server and application Server, managing the LoRaWAN protocol stack, decoding payloads, and visualizing the received data for analysis. A diagram depicting the proposed LoRaWAN system architecture for military vehicle testing, including sensor nodes, gateway, and web dashboard, is shown in Fig.1. In addition to wireless data transmission, the system integrates a microSD card-based local storage mechanism within each node. In addition to wireless data transmission, the system

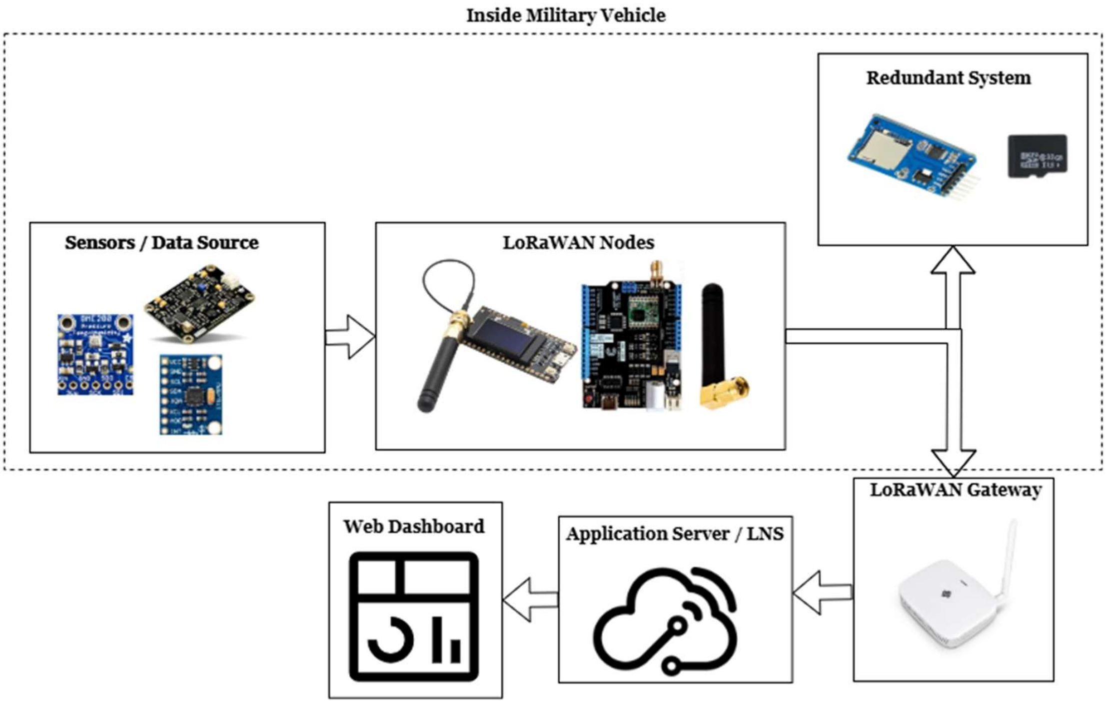


Fig. 2. Proposed system block diagram

integrates a microSD card-based local storage mechanism within each node. Sensor data are simultaneously logged onto the microSD card at the same transmission interval, ensuring redundancy in the event of packet loss or transmission failures. The local logging process operates independently of the transmission routine, preserving a complete dataset for post-test analysis without adding significant computational overhead. Fig. 2 presents a block diagram of the internal system components for each sensor node, illustrating the integration between sensors, microcontroller, LoRa communication module, and local storage subsystem.

To verify data transmission integrity, monitoring is conducted through the packet capture feature available at the gateway, allowing for confirmation of physical packet reception, and cross-validated via the ChirpStack dashboard to ensure payload content consistency.

Sensor data are encoded into binary format prior to transmission to minimize payload size, optimize data rate, and reduce airtime overhead, contributing to higher overall communication efficiency during testing. The detailed operational flow of the system, from sensor and microcontroller initialization to data transmission, storage, and verification processes, is illustrated in Fig. 3, which presents the full system workflow.

In summary, the proposed system consists of LoRaWAN-based sensor nodes integrated inside military vehicles, positioned near the passenger seats to simulate realistic operational conditions. Each node transmits compressed sensor data, with a payload size of approximately 26 bytes, to a static LoRaWAN gateway deployed at an elevated position of around 2.5 m to optimize line-of-sight propagation and minimize signal reflection losses. The nodes are configured with fixed communication parameters, including a spreading factor of 7, a bandwidth of 125 kHz, and a coding rate of 4/5, balancing transmission range, data rate, and energy efficiency for dynamic vehicular environments. In addition to wireless transmission, each node logs sensor data locally onto a microSD card as a redundancy mechanism to ensure data preservation in the event of transmission failures. This system architecture enables continuous observation and evaluation of communication performance metrics such as RSSI, SNR, and PDR, as well as the calculation of path loss and link budget across different vehicle designs and environmental conditions, offering a practical and resilient approach for temporary communication solutions in military vehicle testing scenarios.

3.2 Data Collection

Data collection in this study focuses on five key parameters: RSSI, SNR, PDR, path loss, and link budget. These parameters were selected to provide a comprehensive overview of the quality and reliability of LoRaWAN communication in military vehicle testing scenarios. Data are collected continuously during the testing sessions, with sensor nodes transmitting payloads periodically to a statically positioned gateway, while simultaneously logging sensor data locally onto microSD cards as a redundancy mechanism.

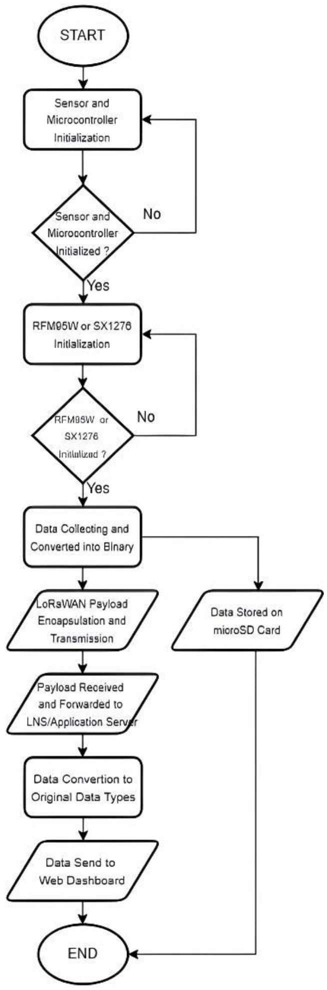


Fig. 3. Proposed system flowchart

Throughout the test sessions, each node generated approximately 500 to 2000 packets, depending on the duration of the route. To ensure consistency and minimize variability, the vehicles maintained an average speed of approximately 20 km/h during data collection. Testing for each scenario was conducted in triplicate to validate reproducibility and account for potential anomalies in the signal environment. This methodology ensures that the collected data robustly represent the communication performance under realistic dynamic conditions.

To assess the quality and performance of the wireless communication links, this study calculates key radio propagation parameters based on the collected data. The main parameters evaluated include path loss and link budget, which provide critical insights into signal attenuation and communication reliability under real-world testing conditions.

Path loss measures the decrease in signal strength as the distance between the transmitter and receiver increases. This value reflects the extent of signal attenuation caused by effectiveness (Liu et al., 2022; Oladimeji et al., 2022). It is calculated using the following equation:

$$PL(dB) = P_{tx} - RSSI \quad (1)$$

where P_{tx} represents the transmit power of the LoRaWAN nodes.

Link budget, on the other hand, represents the power balance within the communication system, i.e., the difference between the transmitted signal power and the minimum power required for effective reception. It takes into account not only the transmit power and path loss but also antenna gains and other minor system losses (Schneider et al., 2012; Singh et al., 2017). Link budget is calculated using the following equation:

$$Link\ Budget\ (dB) = P_{tx} + G_{tx} - L_{path} - L_{othe} + G_{rx} \quad (2)$$

where G_{tx} represent Transmit antenna gain (dB), L_{path} denotes the path loss (in dB), L_{other} accounts for other losses such as cables and connectors (in dB, typically minimal), and G_{rx} refers to the receive antenna gain (in dB).

This practical link budget approach is adopted instead of using the theoretical Friis transmission equation, as it better reflects field scenarios involving non-ideal environmental conditions, vehicle movement, and complex vehicle structures. This method allows for a more realistic calculation, considering actual loss factors that are often neglected in ideal formulations but have a significant impact in mobile communication systems under military field conditions (Kayode and Ezekiel, 2013; Singh et al., 2017).

To ensure data accuracy, packets are captured using the built-in packet capture tool on the LoRaWAN gateway, and the payloads are verified through the ChirpStack dashboard alongside the recorded LoRaWAN signal metrics. This dual-verification approach ensures the validation of both the physical transmission and the data integrity. Statistical analysis is then performed on the collected data to identify performance patterns and evaluate the impact of vehicle type and environmental conditions on communication outcomes.

The PDR was calculated by comparing the total number of packets stored locally on the microSD cards with the number of packets successfully recorded in the web-based database system via the ChirpStack server. This approach enabled independent cross-validation of transmission success, further ensuring the robustness of the collected data.

3.3 Testing Scenario

The testing was conducted across two types of environments to evaluate the communication performance of the proposed LoRaWAN system under varying physical conditions. The first environment was a military vehicle testing facility characterized by structured but still flat obstacles and mild vegetation, providing a controlled setting the transmission medium and surrounding environment, serving as a critical indicator of communication range to assess communication reliability under standardized conditions. The second environment featured hilly and rugged terrain, representing real-world challenges such as increased signal attenuation, reflection, scattering, and significant multipath effects that commonly occur in complex outdoor environments.

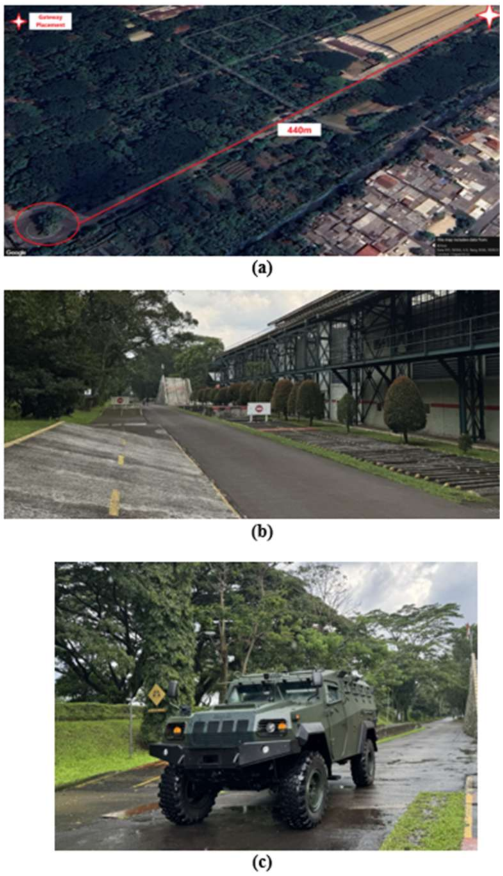


Fig. 3. (a) Testing facility map view, (b)Testing facility environment, (c) AMV on testing facility environment

Testing involved two types of military vehicles. The first type was a light tactical vehicle with an open structure, referred to in this study as the open-body military vehicle (OBMV). The open design of the OBMV minimized physical obstructions to signal propagation, supporting more optimal wireless transmission. The second type was a light armored personnel carrier, referred to as the armored military vehicle (AMV), which featured a fully enclosed metallic structure. This steel enclosure introduced substantial signal attenuation and multipath effects, presenting additional challenges for maintaining LoRaWAN connectivity.

Each vehicle was equipped with two LoRaWAN nodes (RFM95W and SX1276), installed near the passenger seat areas inside the vehicle cabin, along with integrated sensors for vehicle comfort and environmental monitoring. A Node 1 in each vehicle utilized an RFM95W LoRa modules, while

Fig. 4. (a) Hilly rugged terrain map view, (b) AMV on hilly ugged Tetrain, (c) OBMV on hilly rugged terrain

Node 2 utilized an SX1276 module, with both modules operating within the AS923-1 frequency band. During the tests, the vehicles moved along predefined routes at a controlled average speed of approximately 20 km/h, while the nodes periodically transmitted sensor payloads to a statically positioned gateway connected to a local ChirpStack server. In addition to real-time wireless transmission, all sensor data were simultaneously logged locally on microSD cards within the nodes, providing a redundancy mechanism to ensure complete data capture even in the event of transmission losses. Figs. 3(a), (b), (c) and Figs. 4(a), (b), (c) provide visual representations of the test environments used in this study.

4. RESULTS AND DISCUSSION

Following the system design, data collection procedures, and testing scenarios described in the previous section, the collected data were analyzed to evaluate the performance of the proposed LoRaWAN-based communication system under various vehicular and environmental conditions. The evaluation focuses on key communication metrics, including RSSI, SNR, PDR, path loss, and link budget, measured across two distinct vehicle types and testing environments.

Table 2 summarizes the main test parameters used throughout all experiments. The results presented in the following sections provide empirical insights into the impact of vehicle structural design and terrain characteristics on LoRaWAN communication performance in military vehicle testing scenarios. The total number of frames sent during each test scenario varied due to practical factors encountered in the field, including momentary loss of signal, test interruptions for safety or operational reasons, and varying test durations based on environmental conditions. All results are reported using the actual numbers of frames sent and received for each node, and the PDR is calculated accordingly for every scenario.

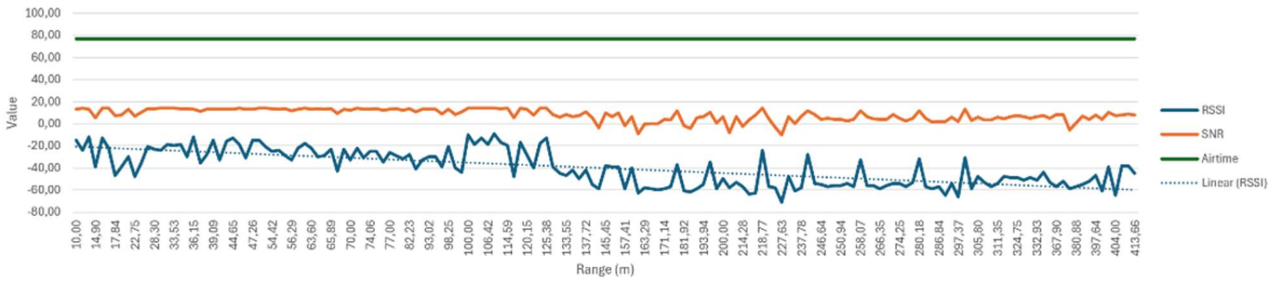
Table 2. Main test parameters

Parameter	Description
Frequency band	923 MHz (AS923-1)
Spreading factor	7
Bandwidth	125 kHz
Coding rate	4/5
Antenna gain	5dBi (Nodes and Gateway)
Transmit power	20 dBm
Node device types	RFM95W and SX1276 modules
Gateway device	WisGate edge lite 2 with SX1302 LoRaWAN concentrator
Number of nodes per vehicle	2 Nodes
Vehicle types	Armored (APC) and open body (tactical)
Node placement	In the vehicle in the assenger seat (armored and open body)
Terrain types	Flat (test facility), rugged/hilly (field site)
Gateway elevation	1 m
Packet payload size	30 ~ bytes
Data redundancy	Local microSD card in each node
Test distances	100 – 500 m
Software stack	Chirpstack LNS and RAK WisGateOS dashboard

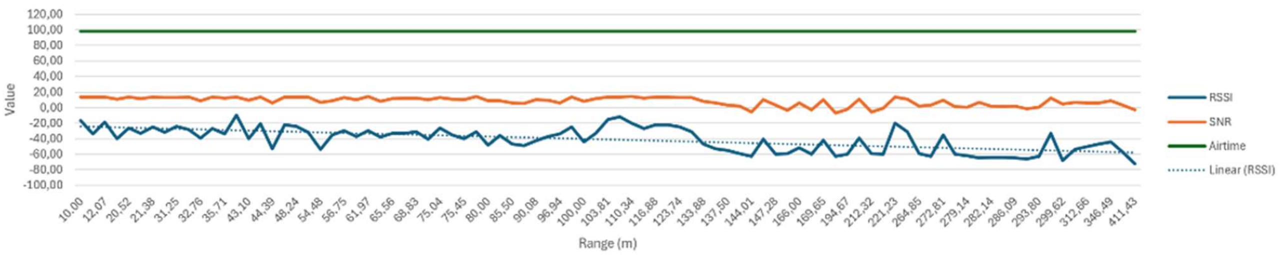
Bukhori et al., International Journal of Applied Science and Engineering, 22(3), 2025127

4.1 Testing Facility

The results obtained from the controlled facility testing demonstrate a significant difference in the communication performance of LoRaWAN between the two types of military vehicles tested, namely the OBMV and the AMV. The nodes placed inside the OBMV, as shown in Figs. 5(a) and (b), consistently exhibited better signal quality compared to the nodes installed inside the AMV. In this test, Node 1 in the OBMV recorded an average RSSI of -40 dBm with an SNR of 8.11 dB, while Node 2 in the OBMV recorded an RSSI of -41 dBm and an SNR of 8.10 dB. This superior performance is attributed to the open design of the OBMV, which allows signals to propagate freely with minimal obstruction or interference.

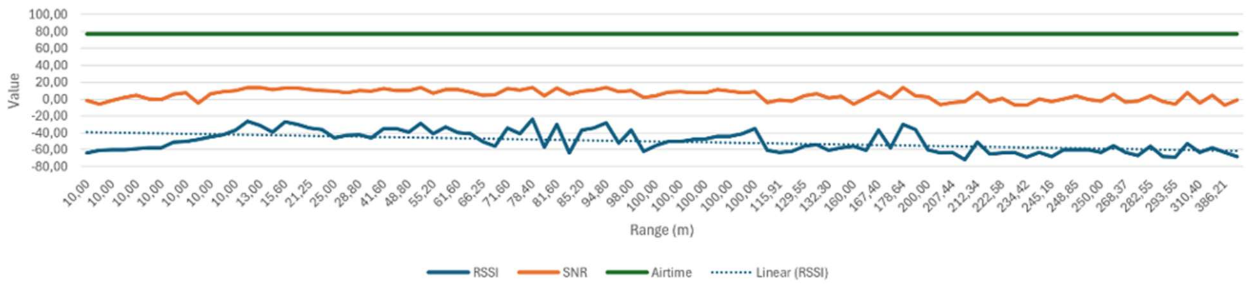


(a)

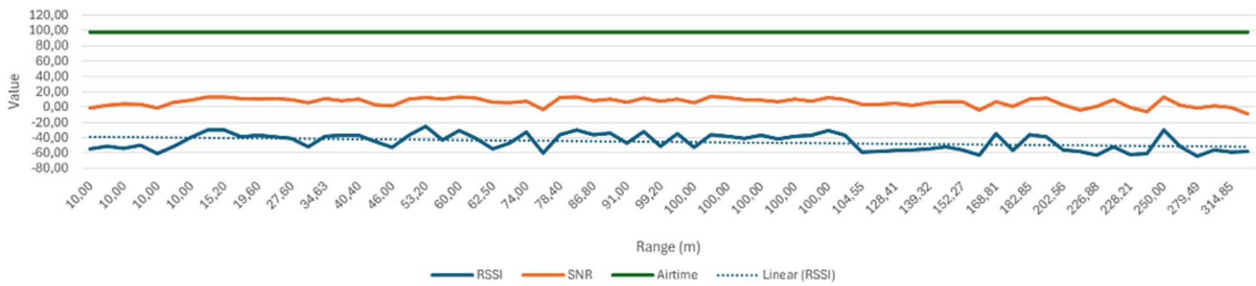


(b)

Fig. 5. (a) Signal strength node 1 OBMV. (b) Signal strength node 2 OBMV



(a)



(b)

Fig. 6. (a) Signal strength node 1 AMV, (b) Signal strength node 2 AMV

In contrast, the nodes placed inside the AMV, which features a fully enclosed steel structure, experienced a significant degradation in signal quality. This can be observed in Figs. 6 (a) and (b), where Node 1 in the AMV recorded an average RSSI of -50.29 dBm and an SNR of 4.67 dB, while Node 2 recorded an RSSI of -45.67 dBm and an SNR of 6.28 dB. The steel structure of the vehicle acts as a barrier that causes signal attenuation and induces multipath effects due to internal reflections, ultimately reducing the strength and clarity of the received signals.

The performance differences are further reflected in the PDR values, as summarized in Table 3 and 4. Node 1 in the OBMV achieved a PDR of 57.75%, while Node 2 achieved a slightly higher PDR of 61.81%. In contrast, Node 1 in the AMV recorded a PDR of 38.68%, and Node 2 recorded a PDR of 36.65%. These findings are consistent with the Fresnel zone theory, which states that physical obstructions near the signal path can significantly affect the quality of wireless communication.

Moreover, the results align with fundamental principles of electromagnetic wave propagation, which explain that enclosed metallic structures such as the AMV cause substantial signal attenuation and multipath interference due to reflection and absorption effects. The observed path loss was calculated using Eq. (1), which proved effective in quantifying attenuation across different environments. The path loss and link budget metrics obtained from the AMV nodes clearly illustrate the challenges faced. For example, Node 1 in the OBMV recorded a path loss of 60 dB and a link budget of -30 dB, whereas Node 1 in the AMV exhibited worse performance with a path loss of 70 dB and a link budget of -40 dB. The link budget calculated using Eq. (2) enables a realistic assessment of communication efficiency under varying conditions, emphasizing the impact of vehicle design on signal propagation.

4.2 Hilly Rugged Terrain

The second testing was conducted in a hilly and rugged environment, which introduced additional challenges in the form of increased signal attenuation due to environmental scattering and absorption. Node 1 in the OBMV demonstrated the strongest performance, recording an average RSSI of -64 dBm and an SNR of 7.26 dB, as shown in Fig. 7(a). Node 2 followed with an RSSI of -69 dBm and an SNR of 5.98 dB, as illustrated in Fig. 7(b). These results reflect the open-body design of the OBMV, which mitigated some of the negative effects of the extreme terrain. This finding also aligns with theoretical path loss models that predict increased signal attenuation in uneven terrains, as confirmed by the path loss calculations using Eq. (1).

In contrast, the nodes inside the AMV experienced more severe signal degradation, as shown in Figs. 8(a) and 8(b). Node 1 in the AMV recorded an RSSI of -73 dBm with an SNR close to zero, specifically 0.15 dB, while Node 2 performed slightly better with an RSSI of -72 dBm and an SNR of 3.51 dB. This significant signal degradation is consistent with the combined effects of terrain-induced attenuation and the closed metallic structure of the vehicle.

Table 3. OBMV data result on testing facility

Controlled environment (open body military vehicle)								
No	Node	Avg SNR (dB)	Avg RSSI (dBm)	Total frame sent	Total packet received	Packet delivery ratio	Path loss (dB)	Link budget (dB)
1	1	8, 11	-40	284	164	57.75%	60	-30
2	2	8, 1	-41	144	89	61.81%	61	-31

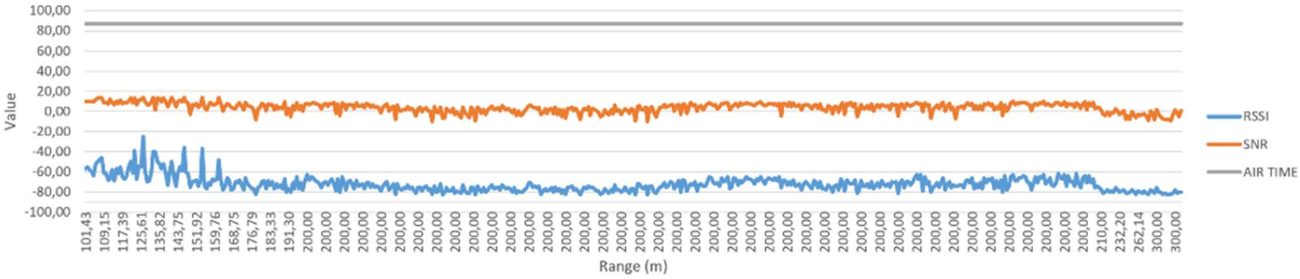
Table 4. AMV data result on testing facility

Controlled environment (armored military vehicle)								
No	Node	Avg SNR (dB)	Avg RSSI (dBm)	Total frame sent	Total packet received	Packet delivery ratio	Path loss (dB)	Link budget (dB)
1	1	4, 67	-50,29	243	94	38.68%	70	-40
2	2	6, 28	-45,67	191	70	36.65%	65	-35

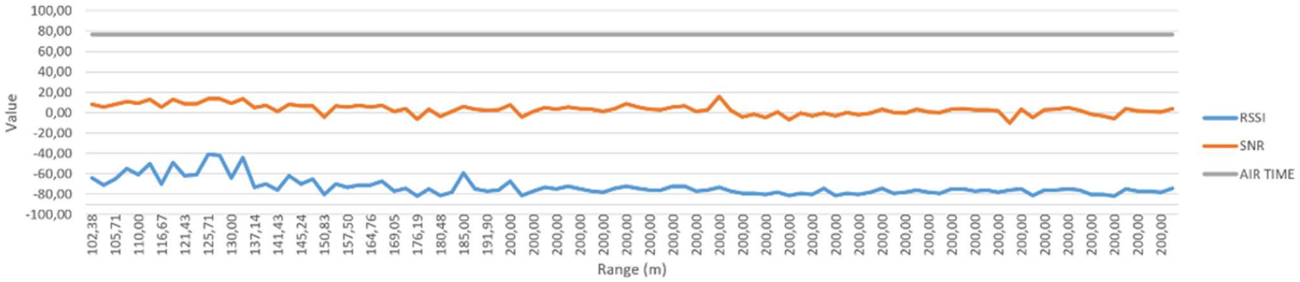
Table 5. OBMV data result on hilly rugged terrain

Hilly rugged terrain (open body military vehicle)								
No	Node	Avg SNR (dB)	Avg RSSI (dBm)	Total frame sent	Total packet received	Packet delivery ratio	Path loss (dB)	Link budget (dB)
1	1	7, 26	-64	901	833	92.45%	84	-54
2	2	5, 98	-69	1128	995	88.21%	89	-59

Bukhori et al., International Journal of Applied Science and Engineering, 22(3), 2025127

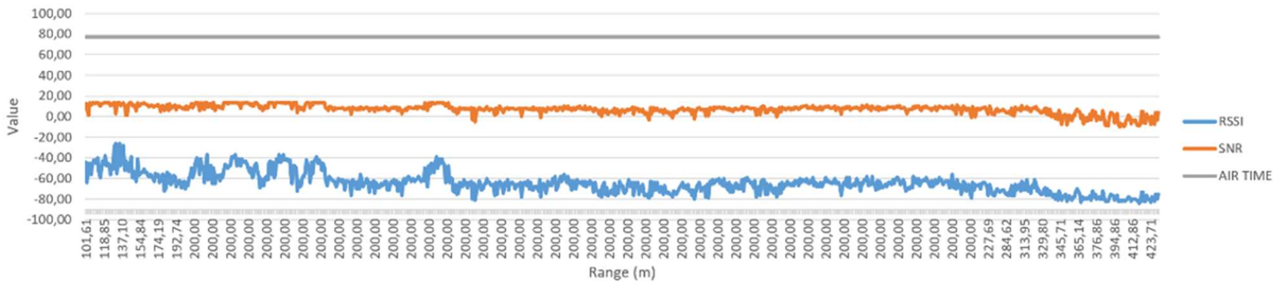


(a)

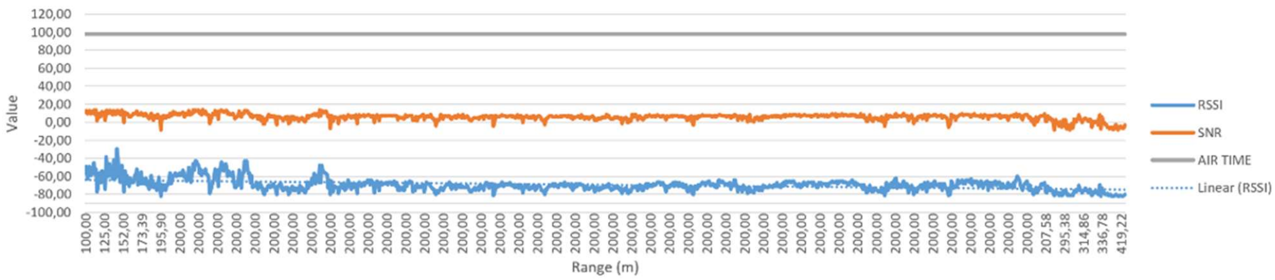


(b)

Fig. 7. (a) Signal strength node 1 OBMV, (b) Signal strength node 2 OBMV



(a)



(b)

Fig. 8. (a) Signal strength node 1 AMV, (b) Signal strength node 2 AMV

The PDR analysis for this second environment revealed some interesting results, as summarized in Table 5 and 6. Node 1 in the OBMV exhibited excellent performance, achieving a PDR of 92.45%, demonstrating high reliability even under challenging terrain conditions, while Node 2 recorded a slightly lower PDR of 88.21%. Conversely, Node 1 in the AMV surprisingly achieved the highest PDR of 98.95%, despite its poor signal quality. This unusually high PDR may be attributed to a relatively low number of transmitted packets, reducing the probability of packet collisions or network congestion. Additionally, temporary improvements in signal quality due to favorable line-of-sight conditions at higher elevation points in the terrain could have contributed to this phenomenon.

Bukhori et al., International Journal of Applied Science and Engineering, 22(3), 2025127

Table 6. AMV data result on hilly rugged terrain

Hilly rugged terrain (armored military vehicle)								
No	Node	Avg SNR (dB)	Avg RSSI (dBm)	Total frame sent	Total packet received	Packet delivery ratio	Path loss (dB)	Link budget (dB)
1	1	0, 15	-73	95	94	98.95%	93	-63
2	2	3, 51	-72	648	535	82.56%	92	-62

The path loss and link budget values in this environment showed further degradation. Node 1 in the OBMV experienced a path loss of 84 dB with a link budget of -54 dB, while Node 2 recorded a path loss of 89 dB with a link budget of -59 dB. The nodes in the AMV demonstrated worse results; Node 1 recorded a path loss of 93 dB with a link budget of -63 dB, and Node 2 recorded a path loss of 92 dB with a link budget of -62 dB. The link budget calculations based on Eq. (2) highlight the significant impact of the combined effects of rugged terrain and enclosed vehicle structures on LoRaWAN communication performance.

4.3 Discussion

The findings obtained from both testing environments clearly demonstrate that vehicle structural design and environmental conditions exert significant influence on the communication performance of LoRaWAN-based systems in military vehicle testing scenarios. Communication performance achieved within the OBMV consistently outperformed that of the AMV across all measured metrics, including RSSI, SNR, PDR, path loss, and link budget. The open structure of the OBMV allowed for freer signal propagation with minimal obstruction, resulting in stronger signal reception and more stable communication links compared to the heavily attenuated and multipath-affected environment inside the AMV.

The rugged and hilly terrain introduced additional challenges beyond those imposed by vehicle design alone. While the OBMV nodes generally maintained better performance than the AMV nodes even under extreme environmental conditions, both vehicle types exhibited notable degradation in signal quality compared to the controlled testing facility. These results align with theoretical predictions regarding increased path loss and scattering effects in non-line-of-sight environments. The findings underscore the necessity of adaptive deployment strategies such as optimizing antenna placement, adjusting transmission parameters, or deploying additional gateways to maintain reliable communication in complex terrains.

Beyond field results, the proposed system offers architectural advantages that significantly improve over previous basic LoRa-based deployments. By fully adopting the LoRaWAN protocol, this system introduces centralized network management, flexible device class configuration, and robust AES-128 end-to-end encryption, ensuring a higher level of communication security and scalability suitable for military applications. Such features were absent in earlier basic LoRa implementations, limiting their reliability and operational flexibility.

Furthermore, this study integrates a local microSD card-based data logging mechanism within each sensor node, providing redundancy that ensures all sensor data are preserved even in cases of wireless transmission failures. This redundancy is critical for military field testing, where communication disruptions are likely, and the integrity of collected data must be guaranteed. This improvement directly addresses the operational limitations of prior systems that relied exclusively on real-time transmission without persistent local storage.

Compared to the prior study by Fadillah et al. (2024), which employed basic LoRa communication for monitoring environmental parameters inside military vehicles, the system proposed here introduces multiple critical enhancements. The full implementation of LoRaWAN’s network management and security capabilities, combined with the integration of local data redundancy mechanisms, ensures greater system resilience, communication integrity, and operational reliability. Additionally, while Fadillah et al. (2024) study primarily validated static sensor readings under controlled conditions, this study extends the evaluation to dynamic vehicular testing under rugged environmental conditions, offering a more comprehensive assessment of LoRaWAN’s practical deployment challenges.

The practical implications of these findings are significant. Reliable wireless communication in military vehicles is essential for effective testing and operational monitoring. The results indicate that successful deployment of LoRaWAN-based systems must carefully account for vehicle structural design and environmental variability. Configurations such as open-body vehicle selection, strategic antenna placement, and localized data redundancy integration play vital roles in maintaining system performance under field conditions.

While the results of this study provide valuable insights into LoRaWAN communication performance in military vehicle testing scenarios, it is important to note that the findings are based on a prototype-scale deployment involving two vehicle types and two environmental settings. As such, the generalization of these results to broader operational conditions should be approached cautiously. Nonetheless, the trends observed in this study offer a strong foundation for future research involving larger deployments, multiple gateways, and more varied terrains.

Overall, the results of this study provide empirical validation of fundamental theoretical models concerning electromagnetic wave propagation, fresnel zone clearance, and multipath effects. The path loss and link budget calculations offer a realistic depiction of the communication limitations and challenges encountered during field deployment. These findings highlight the importance of holistic system design considerations including protocol choice, redundancy planning, and environmental adaptation when implementing LoRaWAN communication solutions for military vehicle testing and beyond.

5. CONCLUSION

This study developed and evaluated a LoRaWAN-based communication system for military vehicle testing, incorporating centralized network management, secure end-to-end encryption, and local microSD card-based data redundancy. Unlike previous studies that primarily focused on basic LoRa communication without network management or redundancy features, such as the work by Fadillah et al. (2024), this study implements a fully managed LoRaWAN protocol with secure transmission and local data preservation mechanisms, offering a more robust and field-resilient communication system for military vehicle testing scenarios. Field testing was conducted using two nodes per vehicle in both open-body and armored military vehicles across controlled and rugged hilly terrain environments. Quantitative analysis revealed that, in controlled conditions, open-body vehicles achieved PDR ranging from 57.75% to 61.81% with RSSI values of -40 to -41 dBm, while armored vehicles recorded lower PDRs of 36.65% to 38.68% with RSSI values of -45.67 to -50.29 dBm. In rugged terrain, open-body vehicles reached PDR values of 88.21% to 92.45%, while armored vehicles achieved PDRs from 82.56% to 98.95%, although both vehicle types experienced lower RSSI in this environment (ranging from -72 to -73 dBm).

These results demonstrate that both vehicle structural design and environmental conditions have a substantial impact on LoRaWAN communication reliability and signal quality. The integration of local data redundancy using microSD card logging was essential for ensuring complete data preservation, especially in the presence of transmission failures, thereby enhancing system robustness during field deployment.

It is important to note certain limitations of this study, such as its prototype scale, the limited range of vehicle types, the use of a single gateway, and testing restricted to two environments. These constraints may limit the generalizability of the findings to broader operational contexts.

Future research should focus on expanding testing scenarios to include urban, forested, and mountainous environments, employing multiple gateways to improve coverage and reliability, optimizing antenna configurations, and performing in-depth analysis of MAC-layer dynamics and adaptive communication strategies.

In summary, this research demonstrates that a LoRaWAN-based system, when equipped with local data redundancy and secure network management, offers a robust and practical solution for temporary communication networks in military vehicle testing scenarios under complex and challenging field conditions.

DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest.

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