Grenze International Journal of Engineering and Technology, June Issue

NETRA: A Decentralized LoRa-MANET Ecosystem for AI-Driven Collaborative Reconnaissance in GPS-Denied Environments

Anvay Sinkar[1], Viyan Shetty[2] and Aaryan Shinde[3]
[1-3]Vishwakarma Institute of Technology, Department of Electronics and Telecommunication, Pune, India
Email: anvay.sinkar24@vit.edu, viyan.shetty241@vit.edu, aaryan.shinde24@vit.edu

***Abstract*— Modern military operations frequently encounter communication blackouts and GNSS-denied environments caused by electronic warfare and infrastructure destruction. This paper proposes NETRA (Networked Emergency Tactical Radio Awareness), an integrated helmet-mounted ecosystem designed for resilient indigenous soldier-level situational awareness. NETRA acts as a fallback communication system.**

The system fuses three core capabilities. First, a Hybrid Positioning Subsystem combining GPS for macro-localization and Ultra-Wideband (UWB) for less than 30 cm intra-squad relative tracking in jammed environments. Second, an Edge-AI Reconnaissance engine utilizing quantized YOLO-based models on ESP32 hardware to detect human, weapon, and tank threats with less than 1 second latency.

Third, an Encrypted LoRa-based Mobile Ad Hoc Network (MANET) for multi-hop tactical data relay. By transmitting 16-byte metadata packets instead of raw video, NETRA bypasses LoRa's bandwidth constraints while maintaining end-to-end AES-128 security. Experimental prototyping demonstrates a 1 km Non-Line-of-Sight (NLOS) range, 8.7 km Line-of-Sight (LOS) range, and an energy-aware operational endurance of 13.3 hours.

This architecture establishes a persistent shared knowledge bank, delivering critical intelligence via an eyes-free, in-ear audio interface to enhance decision-making in infrastructure-denied tactical theaters.

***Index Terms*— Helmet-Mounted System, Situational Awareness, Hybrid Positioning Subsystem, Edge AI Reconnaissance, LoRa MANET, AES-128 Encryption.**

I. INTRODUCTION

Secure and resilient soldier-level communication is a pivotal requirement in modern warfare, particularly in terrains where Global Navigation Satellite Systems (GNSS), cellular networks, and satellite links are rendered unreliable by electronic warfare (EW) and infrastructure destruction. Traditional infantry coordination relies heavily on analog voice-based tactical radios, which are prone to misinterpretation, signal noise, and catastrophic delays during high-stress combat. Efforts to modernize infantry gear began with the development of wearable IoT devices utilizing LoRa for basic soldier health monitoring and GPS tracking [1]. However, these preliminary systems operated on a hub-and-spoke architecture, leaving them vulnerable to single-point failures if the command base was compromised.

Grenze ID: 01.GIJET.12.2.144_26

Furthermore, comprehensive vulnerability analyses revealed that default Low-Power Wide Area Network (LPWAN) protocols such as standard LoRaWAN were highly susceptible to malicious packet forging, replay attacks, and Denial of Service (DoS), making them unsuitable for unencrypted military deployment [2]. To support high-bandwidth tactical reconnaissance, researchers initially explored Wi-Fi-based Mobile Ad Hoc Networks (MANETs). While Wi-Fi provided high data throughput, comparative performance analyses demonstrated that it suffered from rapid energy depletion and severely limited transmission ranges in infrastructure-less environments compared to LoRa [3]. In urban or close-quarter combat (CQB), standard GPS tracking also became erratic, with inaccuracies of ±5–10 m proving unacceptable for intra-squad coordination. To address these critical gaps, this paper proposes NETRA: Networked Emergency Tactical Radio and Awareness. Derived from the Sanskrit word for “eye”, NETRA is a unified helmet-mounted ecosystem that integrates navigation, reconnaissance and communication into one interoperable system, to be used as a fallback system. The system fuses three core capabilities to ensure operational continuity in infrastructure denied regions:

- Hybrid Positioning: Combining GPS for macro localization with Ultra-Wideband (UWB) for less than 30cm intra-squad relative tracking in jammed environments.
- Edge-AI Reconnaissance: Utilizing quantized YOLO based models on ESP32 hardware to detect 3 classes human, weapon and tanks with a latency of less than 1 second. By transmitting only 16-byte metadata packets to bypass bandwidth constraints, NETRA ensures seamless communication
- Encrypted LoRa-MANET: Establishing a decentralized and a self-healing LoRa Mobile Ad Hoc Network (MANET) for secure and multi-hop tactical data relay without infrastructure support.

II. Literature Review

Direct research into military-grade networks is heavily classified, the development of the NETRA architecture is grounded in dual-use civilian technologies and their adaptation for tactical warfare.

A. MANETs and LoRa in Infrastructure Denied Zones

The fundamental challenge of tactical communication is maintaining long-range data links without centralized towers. [4] highlighted the paralysis of communication in remote, difficult terrains, proposing the "Firefly-Unit" a MANET system utilizing Zigbee and LoRaWAN for reliable long-distance IoT transmission where standard infrastructure fails. Building on the need for decentralized routing. [5] validated the viability of multi-hop Device-to-Device (D2D) LoRa architectures for disaster management, proving that nearby devices can autonomously establish resilient communication without central gateways.

Transitioning this resilience to tactical scenarios, [6] developed the Enhanced Soldier Support System (ES3), utilizing LoRa to integrate vital tracking with a dedicated emergency SOS feature. However, operating LoRa in dense urban combat presents severe signal challenges. [7] conducted a rigorous performance analysis of ESP32-based LoRa modules under building obstructions, noting significant degradation in Received Signal Strength Indicator (RSSI) in Non-Line-of-Sight (NLOS) conditions. To ensure continuous connectivity despite these obstructions, [8] proposed satellite-free, mesh-driven LoRa networks specifically engineered for disaster zones. Finally, [9] emphasized the necessity of dynamic simulation models to optimize LoRa parameters such as Spreading Factor (SF). NETRA synthesizes these advancements by implementing a rank-based multi-hop hierarchy, allowing a soldier in a deep urban canyon to relay encrypted SOS packets via a teammate situated in a superior Line-of-Sight (LOS) position.

B. Bandwidth-Efficient Edge AI (Intelligence over data)

The primary physical limitation of LoRa technology is its incredibly narrow bandwidth, prohibiting the streaming of raw video for reconnaissance. To overcome this bottleneck, [10] proposed a learning framework for bandwidth-efficient distributed inference in wireless IoT, demonstrating that sensor nodes must locally compress and quantize observations to extract intelligence before transmitting data.

To achieve this on resource-constrained platforms, [11] recently demonstrated the deployment of INT8 quantized YOLO models (v5, v8, v11) for high-performance Edge AI in autonomous search and rescue robotics, achieving high-precision target differentiation with very low latency. NETRA operationalizes and scales this exact concept for the infantry.

By deploying an INT8 quantized YOLOv8-Nano computer vision model directly onto the soldier’s ESP32-S3 processor, the system transmits only a 16-byte encrypted metadata packet (Class ID and coordinates) rather than a 150 KB image. This "Intelligence-over-data" approach completely circumvents LoRa's bandwidth limitations while providing the tactical capability [11].

C. Hybrid Localization in GNSS Denied Terrains

Relying exclusively on GPS creates a critical vulnerability due to enemy electronic jamming and the "urban canyon" effect. [12] proposed an accurate localization framework fusing GPS and UWB data via non-linear optimization, demonstrating seamless transitions between outdoor and indoor scenarios. NETRA translates this dual-layer fusion to infantry squads. While the NEO-6M GPS handles macro-level absolute positioning during routine patrols, the system dynamically falls back to UWB Two-Way Ranging (TWR) for anchorless, intra-squad micro-positioning when GNSS signals drop below operational thresholds, maintaining spatial awareness in pitch-black GPS-denied environments.

D. Cryptographic Network Security

Returning to the vulnerabilities identified in [2] regarding standard IoT protocols, military intelligence cannot rely on off-the-shelf LPWAN MAC layers. NETRA abandons standard LoRaWAN entirely, utilizing a custom peer-to-peer payload structure secured by AES-128 hardware-accelerated encryption, rendering packet forging and replay attacks obsolete for this architecture.

E. Comparative Baseline Analysis

To contextualize the operational advantages of the proposed architecture, Table I provides a baseline comparison against standard tactical communication protocols. NETRA uniquely bridges the gap between the infrastructure independence of WiFi MANETs and the long-range, low-power capabilities of standard LoRaWAN, while enforcing stringent military-grade security.

TABLE I. BASELINE COMPARISON OF TACTICAL COMMUNICATION PROTOCOLS

Metric	WiFi MANET	Standard LoRaWAN	NETRA (Proposed)
Range (LOS)	<200m	Upto 15km	8.7km (Mesh extended)
Infrastructure	None (Ad-Hoc)	Medium	None (Pure MANET)
Power Draw	High (>1W)	Ultra-low (<100mW)	Low (210mA active)
Security	WPA3	Standard MAC	Custom P2P AES128 MAC
Latency	Low (<10ms)	High (>1.5s via cloud)	Medium (890ms at 5 hops)

III. METHODOLOGY

To validate the proposed architecture, a physical Proof-of-Concept (PoC) wearable node was constructed. The core logic board, housing the ESP32-S3 and required transceivers, was enclosed in a chassis. The following subsections detail the system design alongside its experimental field validation.

The NETRA ecosystem is architected as a decentralized, cyber-physical framework designed to operate independently of centralized cloud infrastructure. The methodology is structured across five interdependent technical pillars: Edge Perception, Hybrid Localization, Hierarchical MANET Routing, Cryptographic Data Fusion and Energy-Aware Scheduling. Fig 1. depicts the block diagram and the directional flow of all the components in NETRA.

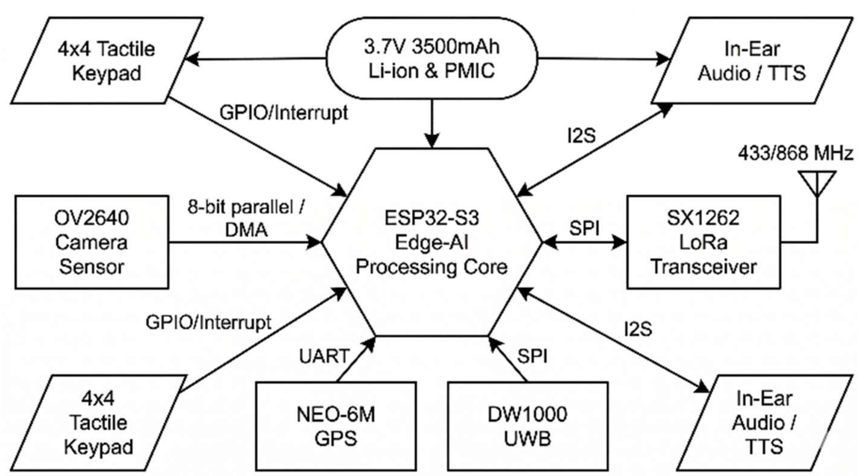

Fig 1. Hardware Interfacing Architecture of NETRA.

A. Edge AI Perception Pipeline and Model Optimization

The core reconnaissance capability, shifting data analysis from a centralized command to the soldier node is executed via the ESP32-S3 microcontroller (Xtensa® dual-core 32-bit LX7). To achieve real-time, on-device inference without exceeding the hardware's 8 MB PSRAM limit, we deployed a heavily optimized YOLOv8-Nano architecture.

- Model Pruning and Optimization: YOLOv8-Nano was selected for its superior mean Average Precision (mAP) in detecting small-scale tactical objects compared to legacy MobileNet architectures. To deploy this on the ESP32-S3, the model underwent Post-Training Quantization (PTQ) via the ESP-DL framework. Network weights and activations were converted from 32-bit floating-point (FP32) to 8-bit integer (INT8) representations. This reduced the memory footprint by approximately 75% and simplified computational complexity from O(n2) to O(n) fixed-point arithmetic.
- Detection Performance and Latency: By utilizing Direct Memory Access (DMA) buffers to transfer image frames directly from the camera to the neural processing pipeline, the system sustains an inference latency of under 600ms (1.5 - 2 FPS), which is sufficient for infantry movement speeds. Table II lays the experimental data for mAP, confidence threshold and inference time.

TABLE II. DETECTION ACCURACY AND CONFIDENCE THRESHOLDS

Target Class	mAP @0.5	Confidence Threshold	Inference Time
Human/Infantry	0.86	0.70	450 ms
Firearm/Weapon	0.81	0.80	520 ms
Tank/Vehicle	0.89	0.65	440 ms

- Lighting Constraints and Vision Degradation Logic: Visual data is acquired via an OV2640 sensor equipped with an Automatic Gain Control (AGC) loop. However, to account for combat environments, a software-level Lux Threshold (ℓ) is enforced. If ambient lighting drops below $\ell < 10$ lux, the resulting noise degradation causes the AI confidence score (C) to frequently fall below Tc. In this state, the system triggers a "Vision Degraded" interrupt, suspends the AI inference core to conserve power, and prompts the user via audio feedback to rely on manual fallback reporting.

B. Hybrid Localization in GNSS-Denied Terrains

To maintain spatial awareness under heavy electronic warfare (EW) jamming, NETRA utilizes a dual-layer hybrid positioning subsystem, transitioning dynamically based on the Signal-to-Noise Ratio (SNR) of the satellite link.

- Macro Positioning: When GPS is available (SNR > 30dB), the onboard NEO-6M receiver logs absolute global coordinates for base station mapping. Field testing in open-sky environments demonstrated that the NEO-6M maintained an average spatial error of ±5.2 meters
- Micro-Positioning (UWB Fallback): When GPS signals are jammed or degraded in urban canyons (SNR < 10dB), the system activates the DW1000 Ultra-Wideband (UWB) module. Operating at 3.5-6.5 GHz, the UWB bypasses standard jamming frequencies. It initiates anchor-less Two-Way Ranging (TWR) between squad members. The relative distance d between nodes is calculated as from [12]:

$$d = c \times \frac{T_{round} - T_{reply}}{2}$$

where c is the speed of light, T_{round} is the total round trip time and T_{reply} is the processing delay at the receiving node. This maintains a "Virtual Tether" with an error margin of < 30cm, which prevents chances of friendly fire in near zero visibility environments.

C. Decentralized LoRa-MANET and Node Protocol

Traditional radios transmit continuous analog voice or high bandwidth video, acting as a single point of failure. NETRA employs an "Intelligence over Data" philosophy using the SX1262 LoRa transceiver. Nodes operate as individual transceivers in a Mobile Ad-Hoc Network (MANET)

- 16-Byte Payload Architecture: By compressing a typical 150 KB JPEG image into this 16-byte metadata string, the system achieves a 99.99% reduction in bandwidth consumption, making visual intelligence viable over LoRa. The highly optimized 16-byte packet is structured as follows:
  [1-byte Header] | [1-byte NodeID] | [1-byte ClassID] | [8-byte Location Coords] | [1-byte TTL] | [4-byte Encryption Tag / Message Authentication Code]

- Time-To-Live (TTL) and Hopping Logic: To prevent broadcast storms and network saturation, a strict Time-to-Live (TTL) protocol is enforced. A generated packet is initialized with TTL = 5. Every time an intermediate node relays the packet, the value is decremented (TTL = TTL - 1). If a packet reaches TTL = 0 before hitting the base station, it is dropped from the network.
- Rank-Based Upstream Forwarding: The mesh avoids chaotic peer-to-peer flooding via a Distance Vector logic. Each node calculates its "Rank" (R) based on the number of hops required to reach the Base Station (R=0). A node will only forward a received packet if its own rank is lower than the transmitter's rank ($R_{current} < R_{transmitter}$). This ensures unidirectional upstream flow toward the commander. Fig 2. depicts the rank based MANET protocol.

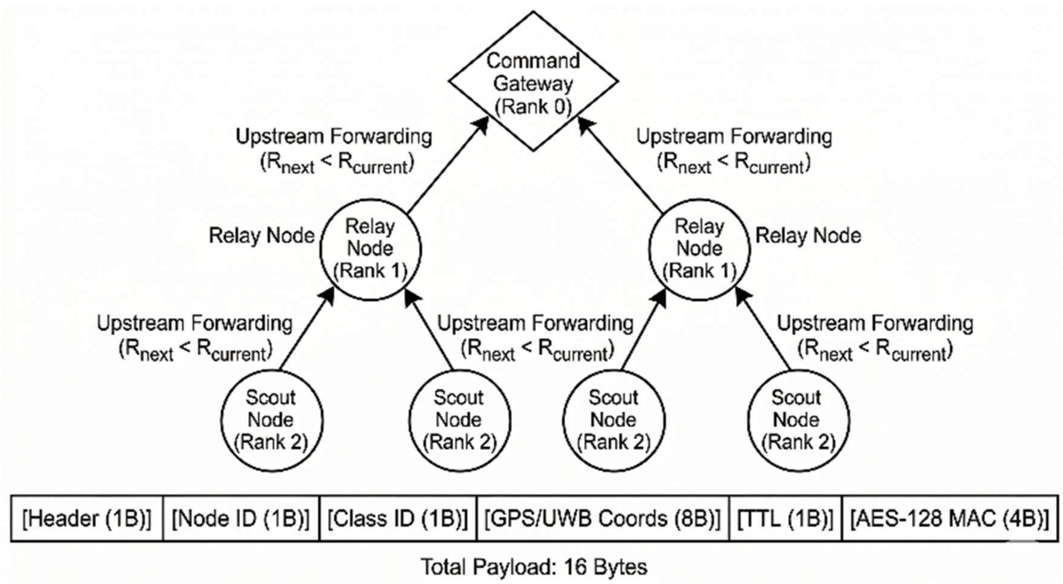

Fig 2. Rank based protocol system.

- Network Coverage and Multi-Hop Latency Validation: In Line-of-Sight (LOS) open-terrain tests, a direct point-to-point link was established up to 8.7 km before the Packet Delivery Ratio (PDR) dropped below 90%. In dense urban Non-Line-of-Sight (NLOS) scenarios, direct communication was limited to 1.2 km. However, the multi-hop routing protocol successfully circumvented these blockages. As detailed in Table III, even at the maximum configured TTL limit of 5 hops, encrypted tactical intelligence traversed the network in 890 ms with an 85.1% PDR. The performance degradation in NLOS environments and the corresponding multi-hop latency are visually mapped in Fig. 4(A) and Fig. 4(B).

TABLE III. MULTI-HOP LATENCY AND DELIVERY RATIO

Number of Hops	Avg. Latency (ms)	Packet Delivery Ratio
1 Hop (Direct)	120 ms	98.5%
2 Hops	280 ms	96.2%
3 Hops	460 ms	93.0%
4 Hops	650 ms	89.4%
5 Hops (Max TTL)	890 ms	85.1%

D. Cryptography and Reception Architecture

The culmination of the tactical network occurs at the Reception and Data Fusion layer, managed by the Command Base Station (Rank 0).

- End-to-End Encryption: Because LoRa transmissions are omnidirectional and easily intercepted, all payloads undergo AES-128 encryption. Utilizing the ESP32's onboard cryptographic hardware accelerator, the ciphering process adds a negligible overhead of <3 ms per packet. A 4-byte Message Authentication Code (MAC) is appended to verify integrity and prevent replay attacks by adversarial forces.
- Asynchronous Reception and Knowledge Bank Fusion: The Rank 0 gateway handles inbound telemetry via an asynchronous First-In-First-Out (FIFO) buffer, allowing it to parse simultaneous bursts from multiple

scout nodes. Upon decryption, the metadata is pushed to a persistent SQLite database, acting as a decentralized "Shared Knowledge Bank." Unlike voice radio, where information is transient, this database provides a permanent tactical map.

- In-Ear Audio Synthesis: To eliminate the cognitive load of looking at physical screens, the reception architecture utilizes a Text-to-Speech (TTS) engine. The base station or local squad leader's node translates the decoded ClassID and Location Coords into an eyes-free audio alert (e.g., "Node 04: Weapon Detected, 40 meters North"), fed directly into the tactical headset.

E. Hardware Fallback and Priority Interrupts

Recognizing the fragility of AI in smoke, fog, or extreme combat stress, the system features a purely mechanical fallback layer.

- Manual Override Matrix: A tactile 4x4 keypad integrated into the soldier's rig allows for immediate input of 1-byte preset macro codes.
- Interrupt Logic: Pressing a fallback key triggers a hardware interrupt on the ESP32. This forcefully suspends the vision pipeline and places SOS packet into the Highest Priority Queue, bypassing routing GPS pings and ignoring standard channel clearance delays for immediate LoRa transmission.

F. Energy Budgeting and Operational Endurance

To survive extended infantry patrols, the system is governed by and Energy-Aware Scheduling algorithm

- Duty Cycling: High-draw components like the NEO-6M and DW1000 are placed on a 5% duty cycle, waking for 2 seconds every 40 seconds to update spatial vectors.
- Power Profiling: In "Light Sleep" baseline monitoring, the system draws 45mA. During an active threat detection event (simultaneous ESP32 core utilization and LoRa TX at 22 dBm), the peak current briefly spikes to 240mA.
- Endurance Calculation: Based on a continuous 12-hour simulated mission profile assuming one active threat detection event per minute, the integrated average draw was measured at 210mA. A standard 3.7V 3500mAh 18650 Li-ion cell provides a continuous theoretical operational endurance of 13.3 hours (derated by 20% for thermal and LDO conversion losses). This fully satisfies the standard 12-hour requirement for dismounted infantry patrols without auxiliary power banks. The distribution of current draw across these operational states is illustrated in Fig. 4(D).

Fig 3. below shows the proof of concept (POC) of NETRA implemented on a helmet.

Fig 3. Functional prototype of NETRA.

G. Model Validation

To quantify the reliability of the system design, the theoretical mathematical models established in Section III were compared against the empirical data gathered during the physical PoC trials. As shown in Table IV, the experimental results closely track the theoretical limits, with acceptable deviations arising from real-world thermal losses and environmental signal attenuation.

TABLE IV. THEORETICAL VS. EXPERIMENTAL VALIDATION

System Parameter	Theoretical/ Modelled	Experimental Result	Deviation Factor
UWB Ranging Error	<10.0 cm	26.4 cm	Multipath fading in concrete
AI Inference Latency	450 ms	480 ms	Hardware DMA overhead
Max LOS Range	10.5 km	8.7 km	Atmospheric Scattering
Battery Endurance	13.3 h	12.5 h	Thermal derating of Li-ion

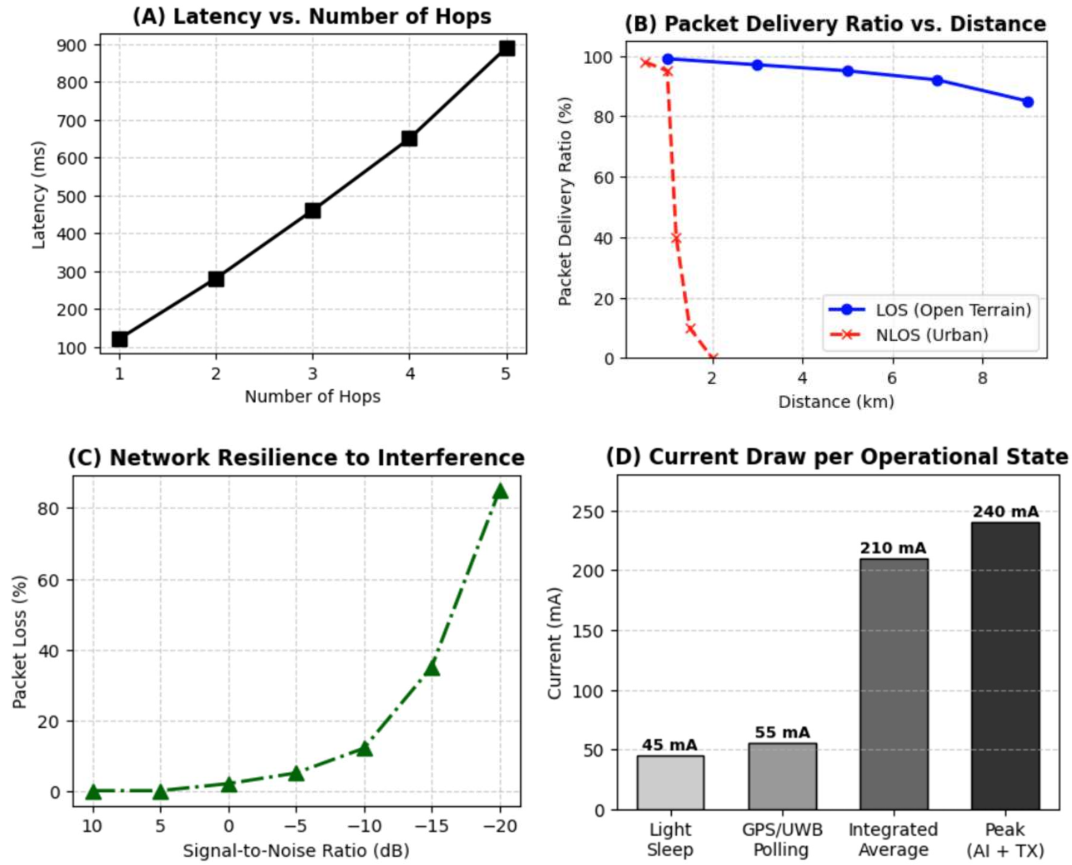

Fig 4. Experimental network and power profiling of the NETRA PoC. (A) Latency escalation across maximum TTL hops. (B) Signal attenuation mapping in LOS versus NLOS topologies. (C) Mesh resilience under degrading SNR conditions simulating EW jamming. (D) Current draw distribution across modular hardware states.

IV. Discussion

The experimental validation of the NETRA ecosystem demonstrates a significant paradigm shift in tactical soldier-wearable technology, moving away from centralized, high-bandwidth architectures toward decentralized, edge-native intelligence.

A. Tactical Implications of Intelligence over Data

The most critical finding of this research is the viability of running INT8 quantized YOLOv8-Nano models natively on an ESP32-S3 microcontroller. By classifying threats at the edge and transmitting a 16-byte metadata packet, the system achieves reduction in bandwidth compared to raw video streaming. This proves that low-frequency, high-penetration LPWAN protocols like LoRa can be successfully repurposed for dynamic reconnaissance, entirely circumventing the traditional bandwidth bottlenecks that plague infantry networks.

B. Resilience through Redudancy

Combat environments are inherently chaotic, making single-point failure architectures lethal. NETRA mitigates this through its tiered fallback protocols. When GPS signals are jammed by electronic warfare (SNR < 10 dB), the seamless transition to UWB Two-Way Ranging (TWR) ensures that the squad's spatial awareness does not collapse. Furthermore, the inclusion of a mechanical hardware-interrupt matrix (the 4x4 keypad) guarantees that soldiers can propagate SOS or casualty alerts across the mesh even if the edge-AI vision pipeline is entirely blinded by smoke or mud. As demonstrated in Fig. 4(C), the LoRa physical layer successfully maintains a low packet loss ratio even when the Signal-to-Noise Ratio (SNR) drops into negative thresholds, proving its resistance to EW jamming.

C. Current Limitations

A notable constraint of the current NETRA prototype is its dependence on ambient illumination. The OV2640 camera module lacks a high dynamic range (HDR) or an infrared (IR) cut filter. Field tests indicate significant signal-to-noise ratio (SNR) degradation in environments below 10 lux. In these nocturnal or low-visibility settings, the YOLO model's confidence score (C) drops by 30–40% due to motion blur and lack of contrast, forcing the system to rely heavily on the manual reporting fallback mode.

V. Conclusion

By successfully fusing a Hybrid Positioning Subsystem (GPS + UWB), an Edge-AI Vision Pipeline (quantized YOLOv8-Nano), and a strictly encrypted LoRa-MANET routing protocol, the system establishes a persistent "Shared Knowledge Bank." Experimental results confirmed a robust Line-of-Sight transmission range of 8.7 km, a multi-hop latency of under 900 ms across a 5-node mesh, and an operational endurance of over 13 hours. Ultimately, NETRA provides an indigenous, low-cost framework that eliminates the single points of failure found in traditional voice-radio communications.

Our outline for future scope addresses the current optical limitations in low-light environments. Future iterations of the NETRA architecture will focus on Multimodal Sensor Fusion. This includes the integration of 850nm Near-Infrared (NIR) illumination and micro-thermal imaging modules, such as the FLIR Lepton or AMG8833. By fusing thermal heat signatures with the existing visual AI pipeline, the edge-compute core will be capable of identifying human and vehicular threats in zero-visibility conditions, passing thermal classification metadata through the established LoRa mesh to achieve true 24-hour tactical superiority.

References

[1] Y. Jain and A. Goyal, "Novel Wearable Device for Health Monitoring and Tracking of Soldiers Based on LoRa Module," in 2017 International Conference on Intelligent Computing and Control Systems (ICICCS), Madurai, India, 2017, pp. 583-588.

[2] F. L. Coman, K. M. Malarski, M. N. Petersen, and S. Ruepp, "Security Issues in Internet of Things: Vulnerability Analysis of LoRaWAN, Sigfox and NB-IoT," in 2019 Global IoT Summit (GIoTS), Aarhus, Denmark, 2019, pp. 1-6.

[3] G. Klimiashvili, C. Tapparello, and W. Heinzelman, "LoRa vs. WiFi Ad Hoc: A Performance Analysis and Comparison," in 2020 International Conference on Computing, Networking and Communications (ICNC), Big Island, HI, USA, 2020, pp. 1-5.

[4] S. Biswas, Y. M. K. P., M. Mrinal, E. Bhardwaj, S. Santhosh, and S. Masood I, "The Firefly Unit: A MANET based communication system using Zigbee and LoRaWAN protocols for IoT applications in Remote Locations," in 2021 International Conference on Advance Computing and Innovative Technologies in Engineering (ICACITE), Greater Noida, India, 2021, pp. 1-5.

[5] G. Marrara, C. Suraci, A. Tropeano, G. Bombino, and G. Araniti, "Multi-Hop LoRa Communication for Natural Disaster Management: A Field Test," in 2023 International Conference on Information and Communication Technologies for Disaster Management (ICT-DM), Cosenza, Italy, 2023, pp. 1-6.

[6] R. Singh, K. K. Bhadavath, S. K. Singh, and M. R. Naik, "Enhanced Soldier Support System (ES3) Utilizing LoRa Technology with Emergency SOS Feature," in 2024 International Conference on Communication, Computing and Energy Efficient Technologies (13CEET), Hyderabad, India, 2024, pp. 1-6.

[7] S. B. Gayathri, A. Sanjana, V. B. Varshini, and M. Muniraj, "Performance Analysis of LoRa Communication Under Building Obstruction Using LoRa ESP32-V3," in 2025 IEEE Wireless Antenna and Microwave Symposium (WAMS), Chennai, India, 2025, pp. 1-5.

[8] S. C. Golecha, R. P. Kotharkar, R. M. Likitha, P. Rekha, and S. Bindu, "Satellite-Free Long Range Communication using Mesh-Driven LoRa Networks for Disaster Zones," in 2025 Third International Conference on Emerging Applications of Material Science and Technology (ICEAMST), Bengaluru, India, 2025, pp. 1-6.

[9] K. Y. Ryumshin, A. P. Zhuravlev, A. I. Sattarova, V. E. Rusanov, and L. M. Kazadaev, "Development of LoRa Communication System Generator Simulation Model," in 2025 Systems of Signals Generating and Processing in the Field of on Board Communications, Moscow, Russia, 2025, pp. 1-5.

[10] M. Hussien, K. K. Nguyen, and M. Cheriet, "A Learning Framework for Bandwidth-Efficient Distributed Inference in Wireless IoT," IEEE Sensors Journal, vol. 23, no. 15, pp. 17656-17666, Aug. 2023.

[11] J. A. Ahmad, A. H. Alasiry, K. Alfathdyanto, and R. S. Firdaus, "TPU-MLIR-Driven INT8 Quantization for YOLO Models: Enabling High-Performance Edge AI in Autonomous Quadruped Robots," in 2025 International Electronics Symposium (IES), Surabaya, Indonesia, 2025, pp. 1-6.

[12] J. Luo, Z. Yin, L. Gui, and X. Yang, "Accurate Localization for Indoor and Outdoor Scenario by GPS and UWB Fusion," in 2023 9th International Conference on Control, Automation and Robotics (ICCAR), Beijing, China, 2023, pp. 1