

Evaluation of a LoRa-based mesh networking protocol for tactical communications

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Abstract—Tactical communication networks play a critical role in supporting the exchange of situational awareness data to enable team coordination in contexts ranging from outdoor recreation to first responders after a disaster or military operations. Recent trends tend to favor mobile mesh networks supported by radio devices equipping team units when network infrastructure may be unavailable. In this context, LoRa emerges as a suitable radio technology despite its low data rate, combining long-range connectivity, low power consumption, and low-cost transceivers. Yet, few works have published relevant data on its performance as mesh networking medium. In this paper, we evaluate the performance of Meshtastic, a popular and mature solution for LoRa-based mesh networks. Through a three-stage experimental process, we assess its suitability for tactical communications and provide performance measurements in terms of coverage, latency and reliability, intended to serve as a baseline for future work on LoRa mesh and ad hoc networking.

Index Terms—LoRa, Meshtastic, Mesh network, tactical communications, performance

I. INTRODUCTION

Tactical communications rely on networks capable of exchanging situational data: geolocation updates, text messages, and data from field sensors. Situational awareness helps the coordination of military units, but also rescue teams, fire fighters, or even outdoor recreation enthusiasts. To support such information flows, resilient mesh networks enable decentralised, flexible, and rapidly deployable connectivity in harsh environments where network infrastructures are not available (e.g., disaster area, underground facilities, battlefield, ...).

Recent trends point toward low-tech communication solutions that try to improve scalability and energy consumption by combining low-cost, off-the-shelf hardware with efficient networking protocols. LoRa radio technology offers several features that make it attractive for such tactical communication systems. Its ability to maintain long-range links at low transmission power by operating reliably at low SNR levels, enhances operation time and discreteness in military operations. Although LoRa's data rate is limited, it remains relevant for tactical situational awareness. Moreover, its broad availability on affordable devices should make LoRa a resilient and scalable foundation for tactical mesh networks.

Yet, unlike LoRaWAN which is a standardized gateway-centric protocol designed for star-topology networks, there is currently no standard for mesh networking over LoRa. In this paper, we focus on Meshtastic, a rapidly growing project

that has seen widespread adoption. Its lightweight protocol design appears particularly well suited to LoRa's constrained bandwidth with minimal protocol overhead that *should* not hinder tactical communications.

The objective of this paper is twofold. Providing a comprehensive evaluation of the Meshtastic solution not only allows us to assess the suitability of LoRa-based mesh networking for tactical communication scenarios, but it also provides a reference baseline for future research, facilitating the comparison of alternative LoRa mesh protocols and algorithms against a mature solution. The remainder of this paper is organized as follows. Section II reviews related work on LoRa-based mesh solutions for tactical networks. Section III presents the Meshtastic protocol and describes its operating principles. Section IV details our experimental methodology and setups. Section V analyzes the results of our measurements and discusses LoRa and Meshtastic performance in the context of tactical communications. Finally, Section VI concludes the paper by summarizing the experimental results and gives key insights and perspectives regarding the use of LoRa-based mesh networks for tactical communications.

II. RELATED WORK

Mesh radio devices operating in sub-GHz frequency bands have already been the subjects of several projects addressing communications in infrastructure-less areas, like Beartooth [1] or goTenna which relies on ECHO [2] and VINE [3] lightweight network protocols. Both these commercial solutions propose compact VHF/UHF radio devices designed to be paired with mobile terminals (e.g., smartphones) that can exchange short text messages and geolocation data across a mesh network spanning over long distances.

Besides these proprietary solutions, an increasing number of works have investigated LoRa physical layer as a support for mesh networking protocols. For instance, some academic works have proposed protocols based on synchronized sleep and data transfer phases to exchange sensor data on linear networks, e.g., to monitor water distribution in Sienna [4]. Centelles et al. explored mesh networking over LoRa in [5], and proposed a protocol stack based on Distance Vector Routing (DVR) protocol and a CSMA/CA approximation. Another series of works have specifically investigated LoRa mesh as a networking layer for emergency and disaster responses, or

off-grid communications in remote areas. In these studies, LoRa nodes are paired with mobile devices (smartphones) to exchange text messages and geolocation updates. LOCATE [6] uses delayed retransmissions, and has been extended in [7] with AODV routing based on RSSI. Similarly, the work presented in [8] uses RSSI and neighborhood information to form connected dominant sets acting as a backbone mesh infrastructure to enable text message exchanges between end nodes. These academic efforts have been joined by community-driven projects like the ClusterDuck protocol [9], that implements hierarchical uplinks from devices on the field to operation centers, and the Meshtastic project [10]. Meshtastic, whose protocol is thoroughly described in the next section, is an open-source mesh networking project designed to provide resilient communication over LoRa in environments where infrastructure networks might not be available.

All these protocols are nonetheless lacking extensive performance feedback, including Meshtastic. Available results are often biased due to different regional constraints that allow higher transmission power, or due to advantageous antenna elevations, which do not match the tactical communication use case considered in the present paper where nodes are mainly used as mobile, battery-powered, handheld radios. Some studies provide some Meshtastic performance evaluations, but only as side contributions supporting an emergency communication system [11] or location sharing for firefighters [12]. In this paper we propose a more extensive study including multi-hops latency measurements.

III. MESHTASTIC PROTOCOL

We decided to adopt Meshtastic as the network protocol layer to study the adequacy of LoRa mesh network for tactical communications, because of its software maturity and low hardware cost. By leveraging convenient hardware through a modular firmware, Meshtastic enables multi-hop text messaging and position sharing, among other features like telemetry. First designed as a basic mesh networking protocol, Meshtastic has now evolved into a ready-to-use solution for anyone willing to experiment mesh networking over LoRa. The different characteristics of the forwarding protocol underpinning Meshtastic are illustrated in Figure 1 and described hereafter, based on the version 2.7.15 of the firmware.

A. Physical and logical channels

In order to exchange information over the mesh, nodes have to communicate on the same physical and logical channels. Meshtastic does not provide any mechanism for scanning channels. Instead, the LoRa radio configuration of a node is static by design. Nodes must consequently be aligned on the same physical channel, which means sharing the same configuration in terms of carrier frequency, spreading factor (SF), bandwidth (BW) and coding rate (CR). Meshtastic proposes some LoRa modem presets to simplify network configuration. The default *LONG_FAST* preset operates on $SF11$, on a 250 kHz BW , with minimal correction ($4/5CR$).

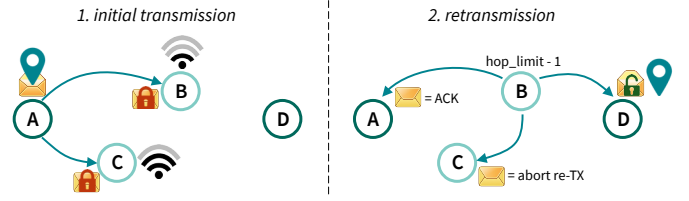


Fig. 1. Illustration of the Meshtastic forwarding protocol.

Then, each node defines one primary and up to seven secondary logical channels that consist in a channel name paired with an AES encrypted pre-shared key (PSK). Even though nodes can only decrypt and read messages sent on one of their defined channels, they still take part in the mesh by forwarding other messages that are received on their physical channel but on unknown logical channels. This behaviour is visible on Figure 1 where A's position is sent on a private channel to node D through node C which is unable to decrypt the payload.

B. Packet format and application ports

0	31	63
Destination		Sender
64	95	103
Packet ID		Flags hop count
	111	119
	Channel hash	Next hop
		Relay node
		127

Fig. 2. Meshtastic packet header.

Meshtastic packets are composed of a 16 bytes unencrypted header used for routing purposes represented on Figure 2, and a payload carrying application-specific data. Each type of payload is assigned to an application port in order to differentiate traffic, similarly to port numbers in the Internet Protocol. Core functionalities as well as mission-specific applications communicate on specific ports dedicated to routing, advertisements, text or position traffic among others.

C. Channel access

Meshtastic firmware computes expected airtime based on radio settings before each transmission in order to finely monitor channel utilization and to comply with regional duty cycle regulation. Time-on-air (ToA) computation is also used for determining the size of contention windows before any rebroadcast of a received message, or to compute random backoff durations before re-attempting a non-acknowledged transmission as explained in the following subsection.

Moreover, to minimize collisions, Meshtastic implements a form of carrier-sense multiple access with collision avoidance (CSMA/CA), by performing listen before talk (LBT) using channel activity detection (CAD).

D. Forwarding and routing protocol

Meshtastic is designed as a lightweight protocol without excessive overhead to avoid network congestion or unnecessary

packet replication. Packets are therefore broadcasted according to a *managed flooding* strategy. Figure 1 illustrates this forwarding protocol which relies on 3 principles: long hops prioritisation, implicit acknowledgement (ACK) and bounded retransmissions.

First, messages are relayed across the mesh using a priority mechanism: nodes with weaker received signal (lower SNR) are given forwarding precedence, which helps extend coverage by favoring retransmissions from more distant peers. On Figure 1, Node C forwards A's position before node B. In doing so, node B receives a second copy and therefore aborts the forwarding of the message, thereby avoiding network overload.

Then, Meshtastic does not perform end-to-end ACK, but instead implements one-hop implicit ACKs. When the more distant peer (node C) rebroadcasts, node A receives a copy of its own message and can therefore consider it as an ACK. In the event that a node does not get an implicit ACK back, it will retry to transmit its packet up to three times, after random backoffs.

Third, retransmissions are bounded in terms of hops. On Figure 1, when node C rebroadcasts A's message, it decreases its hop limit. When the hop limit of a packet reaches zero, it stops the forwarding process.

Finally, while nodes forward messages, they collect information about their retransmitting peers and continuously update their routing tables to support efficient and reliable destination-based routing. Nodes can in addition be assigned a specific role (e.g., *ROUTER*, *REPEATER*, *SENSOR*, ...). Other roles than the default *CLIENT*, which assumes that the node is paired with a terminal device, modify the node behaviour with respect to packet handling and forwarding strategies.

IV. EXPERIMENTATION SETUP AND SCENARIOS

The evaluation presented in this paper follows a three-phase experimental process aimed at assessing the performance and usability of a LoRa-based mesh network for tactical communications based on the Meshtastic implementation. During the first phase, range tests were conducted under various LoRa radio configurations to determine suitable node settings and inter-node distances for mesh deployment. In the second phase, the mesh network was deployed to evaluate its performance in terms of reliability, coverage, and multi-hop latency. Finally, the relevance and usability of the network for tactical communications were assessed through a practical scenario.

These experiment campaigns were conducted on the Saint-Cyr Coëtquidan military academy campus, either on the built area of the camp (suburban environment), or on the training area (forest environment). The experimental parameters used in the three phases are summarised in Table I.

A. Hardware and software resources

To perform these experiments, two types of hardware have been used: *Lilygo T-Beam Supreme* and *Heltec-v3* devices. Both these devices are based on an ESP32-s3 micro-controller, with Bluetooth and Wi-Fi capabilities, paired with a SX1262 LoRa radio chipset. However, only the T-Beam Supreme is

TABLE I
EXPERIMENTAL PARAMETERS.

Parameter	EXP0	EXP1	EXP2
Duration	N/A	~ 2 hours	~ 30 minutes
Area	1 km x 2 km	1 km x 5 km	1 km x 1 km
Environment	campus	indoor/outdoor	campus
Nodes	1 fixed sender 1 mobile node	1 fixed sender 1 mobile node 4 fixed relays	3 mobile nodes 1 fixed sensor 1 fixed relay
Messages	N/A	~400 per setting	232
Carrier frequency	433.375 MHz 869.525 MHz	433.375 MHz 869.525 MHz	869.525 MHz
LoRa presets	SHORT, LONG, MEDIUM <i>SF7, SF9, SF11</i>	SHORT, LONG <i>SF7, SF11</i>	LONG <i>SF11</i>
TX power (dBm)	2, 10, 14, 22	2, 10, 22	22 (CLIENT) 10 (SENSOR)
Average payload (bytes)	TEXT (20)	TEXT (20)	TEXT, POSITION, SENSOR (120)

equipped with a L76K GNSS module and a RTC clock that facilitate its use as a mobile device. The Heltec boards were mainly used as static nodes with fixed coordinates. The 2.7.15 version of the Meshtastic firmware was deployed on the devices, along with a logging module implemented to record the network traffic on the main application ports.

B. Preliminary experiment (EXP0) : range tests

Before deploying a mesh network for its evaluation, it is necessary first to find out the optimal transmission parameters and the range that can be expected in order to identify the optimal inter-node distance. To determine these parameters, several tests were carried out on the campus using different LoRa presets and different transmission powers (noted P_{TX}), on both 868 MHz and 433 MHz frequency bands, as listed in Table I. By default Meshtastic settings use the 869.5 MHz carrier frequency, whose band alleviates duty cycle constraints and allows transmission up to 27 dBm according to European regulations [13], compared to 14 dBm in the lower bands. We therefore decided to test lower power levels to better comply with energy constraints on tactical communications.

C. 1st experiment (EXP1) : mesh deployment and evaluation

The objective of this field experiment, called *EXP1* in the remainder of this paper, was to deploy a multi-hops mesh network across representative terrains (indoor and outdoor with buildings and foliage obstacles) to evaluate the performance of the Meshtastic protocol. In order to quantify end-to-end latency and packet delivery ratio under controlled traffic, various settings were implemented, namely *SF7* and *SF11* with $P_{TX}=(2,10,14,22)$ dBm for the 868 MHz band, and $P_{TX}=(2,10)$ dBm for 433 MHz due to EU regulations.



Fig. 3. EXP2 : mission deployment, paths and objective.

D. 2nd experiment (EXP2) : tactical communications

Eventually, the third and last experiment phase, called EXP2, consisted in putting the LoRa tactical mesh network to the test in a pseudo realistic scenario. The objective was to evaluate the network behaviour under potential usage conditions. In addition to the observed user experience, the traffic was analysed to measure the delivery ratio for mission-relevant data, and to estimate the overhead of the network protocol.

The implemented scenario consisted of collecting sensor data by three teams dispatched across the campus: *Fox1*, *Fox2*, and *Fox3*. Each team was equipped with a mobile *T-Beam* device and was deployed near a pond shown as the starting point on the map in Figure 3. One fixed *Heltec-v3* node was configured to run the *PaxCounter* module with reduced transmission power. This module passively scanned and counted nearby Wi-Fi beacons and Bluetooth advertisements from smartphones or smartwatches in an auditorium, marked as objective on the map, to transmit data on attendance level.

After the initial deployment, the teams followed different paths. *Fox3* was assigned the mission of moving closer to the objective and deploying a relay in a nearby building (waypoint X12 on the map) to retransmit the sensor data across the network. The primary goal of *Fox1* and *Fox2* was mostly to stretch radio links and test network coverage in a village-size area covering less than 1 km². The three teams used the Meshtastic mobile application to keep communicating orders and situation reports on a private channel, to follow each other's locations on the map, and to monitor the sensor data.

V. RESULTS

The results measurements gathered during the three experimental phases are discussed hereafter, through the analysis of key metrics such as signal quality, network latency, delivery ratio and traffic distribution analysis. In addition to quantified results, these experiments provided valuable feedback on the suitability of LoRa for tactical mesh networks.

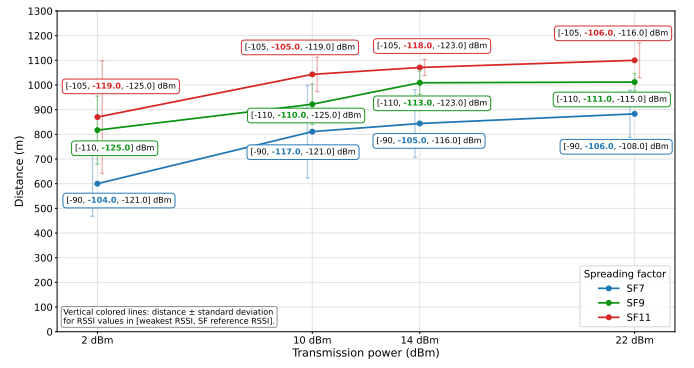


Fig. 4. Ranges recorded at 868 MHz for various SF/P_{TX} settings (EXP0).

A. Range tests and network coverage

Communication tests conducted during the first experimental phase achieved acceptable transmission ranges, even at low transmission power. The empirically observed reception threshold clustered around $RSSI \approx -125$ dBm and $SNR \approx -20$ dB depending on the spreading factors, which is consistent with the SX1262 sensitivity specifications.

Figure 4 shows the average range reached at one hop based for the lowest RSSI measurements, depending on different SF and P_{TX} values. Given the performances achieved through EXP0 and EXP1, ranges of at least 50 m to 100 m indoors, and 500 m to 1 km outdoors, can reasonably be expected in actual mesh deployments without any elevated antenna.

In a sparse forested environment, the maximum range at 433 MHz surprisingly only exceeded the 868 MHz tests by a small margin, reaching 400 m for $SF11$ and $P_{TX}=10$ dBm. Generally, we observed that 433 MHz and 868 MHz experiments yielded almost similar results in terms of range.

The highest transmission distance was eventually achieved with a particular setup between two elevated nodes located more than 5 km apart in almost line-of-sight. A good link quality was successfully maintained, slightly above -120 dBm RSSI. If we extrapolate these results, it is conceivable to cover distances of 10 to 20 km with three hops, provided that nodes are strategically positioned on elevated grounds.

B. Mesh network latency

During EXP1, transmission times were recorded over up to four hops, in order to analyse end-to-end latency and to estimate the overall mesh network latency. Figure 5 and Figure 6 present the average latency (to the nearest second) as a function of the number of traversed hops, along with the number of packets exchanged at each hop distance, recorded at $SF7$ and $SF11$.

In Meshtastic, end-to-end latency is primarily influenced by LoRa radio parameters. The spreading factor (SF), bandwidth (BW), and coding rate (CR) all directly affect transmission time. In addition, the Meshtastic protocol relies on airtime estimates to compute backoff durations and contention window sizes prior to retransmissions, for example following a failed transmission attempt.

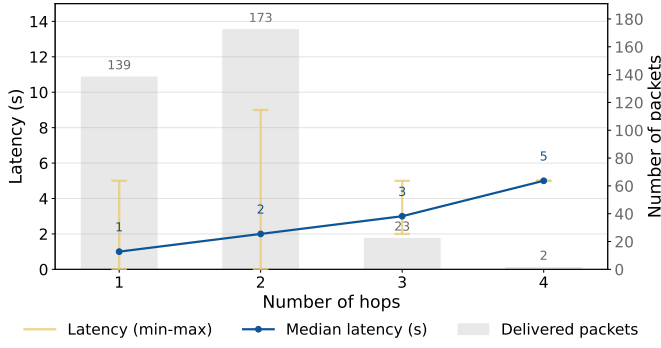


Fig. 5. Latency by number of hops (EXP1, *SF7*).

In our set of experiments, we observed an average latency of 1 s on direct (single-hop) transmissions, taking up to 5 s and 9 s for *SF7* and *SF11*. Then the average transmission time increased reasonably with each hop, up to delays of +2 s (*SF7*) and +13 s (*SF11*) between the third and the fourth hops. Although the measurements at four hops were based on a limited sample size and should therefore be interpreted with caution, they nonetheless reveal a non-linear increase in latency as the hop count grows. This behaviour helps explain why Meshtastic enforces a default limit of four hops, beyond which acceptable delivery times may no longer be guaranteed. For scenarios requiring deeper multi-hop topologies, resorting to higher *SF* and thus increasing airtime should be avoided, since it would noticeably slow the network. Even so, the observed transmission delays comply with tactical network requirements, e.g., regarding geolocation updates.

C. Mesh network reliability : packet delivery ratio (PDR)

During *EXP2*, we measured the number of recipients reached by each transmitted packet, providing an indicator of network-wide delivery performance. Figure 7 shows that undelivered messages represented 5.4% of total traffic and that 80% of messages were received by all recipients (the relay node being only up for part of the experiment). These losses did not hinder mission execution. Further analysis of the payload types associated with packet losses revealed that all mission-related *TEXT* messages were successfully delivered. The lost packets consisted exclusively of one *NODEINFO* message from *Fox1*, three *POSITION* updates from *Fox2*, and seven *PAXCOUNTER* measurements, none of which had a direct impact on team coordination.

Packet delivery was also measured during *EXP1*. On a constant mesh topology setting, the PDR naturally improved when increasing P_{TX} and *SF*, from 90% for *SF7*, P_{TX} =22 dBm to 100% for *SF11*, as shown on Table II. Overall, these results

TABLE II
PACKET DELIVERY RATIO TO ALL RECIPIENTS.

Settings	<i>SF7</i> , P_{TX} =22	<i>SF11</i> , P_{TX} =10	<i>SF11</i> , P_{TX} =22
PDR	89.2%	94.3%	100%

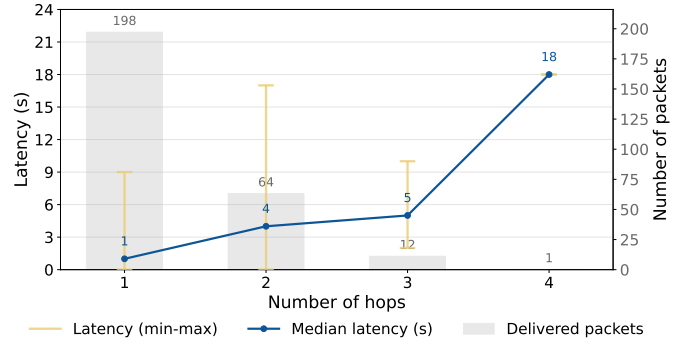


Fig. 6. Latency by number of hops (EXP1, *SF11*).

demonstrate that the LoRa-based mesh was reliable enough under dynamic conditions.

D. Protocol overhead

Protocol overhead in terms of induced latency was investigated during *EXP1* and has already been discussed in the previous subsection. Traffic overhead, represented by additional technical packets exchanged and processed by Meshtastic, was analysed during *EXP2*. Application port numbers used to dispatch received messages were recorded, enabling traffic characterisation. Figure 8 presents the distribution of packets according to their payload types (i.e., application ports). Meshtastic technical packets (*NODEINFO*, *TELEMETRY*, and *ROUTING*) accounted for only 13.4 % of the total traffic. Mission-specific packets, including *TEXT*, *POSITION*, *PAXCOUNTER*, and *WAYPOINT* messages, therefore composed the majority of the traffic, confirming the lightweight nature of the Meshtastic protocol.

E. Relevance and suitability for tactical communication

The third experimental phase enabled the evaluation of a representative tactical communication scenario leveraging Meshtastic's core capabilities, including LoRa-based mesh networking, text messaging and location sharing for situational

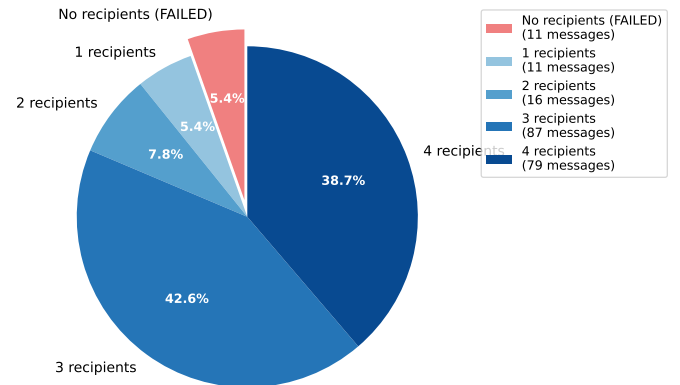


Fig. 7. Message distribution by number of recipients (EXP2).

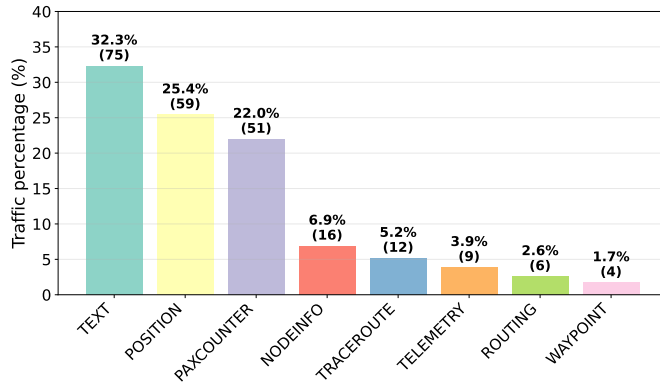


Fig. 8. Packet payload types distribution (EXP2).

awareness, sensor integration for surveillance tasks, and the use of a mobile application as a user terminal.

Overall, communications within the group proved effective, and the mission was conducted without noticeable latency or operational disruption. The mobility and communication traces have been replayed using the LEPTON emulation platform [14], and the video recording is available online ¹.

Despite these encouraging results, several limitations may prevent Meshtastic from being directly applicable to tactical communications, and particularly to military operations. First, the lack of radio agility constitutes a significant limitation. The reliance on a single physical channel, both in terms of frequency and spreading factor, makes the network particularly vulnerable to interferences with other co-located networks, or jamming in a military context. A network-wide configuration also excludes the optimisation of heterogeneous topologies combining dense mesh regions and long inter-node links, since dense areas favor lower SF (and P_{TX}) to reduce airtime and support frequent exchanges, whereas stretched links require higher SF (and P_{TX}) to ensure reliable communication, which can be a limiting factor. In addition, the use of a fixed high transmission power, without adaptation to local link conditions, increases the risk of detection and leads to unnecessary energy consumption. While battery endurance was not stressed to its limits, our observations suggest that devices being continuously listening may also accelerate energy depletion. In our tests, ESP32-s3 based modules powered by 3000 mAh batteries could operate for 5 to 10 h depending on P_{TX} and network activity.

VI. CONCLUSION

This paper presented an experimental evaluation of a LoRa-based mesh network and its practical use in a tactical communication scenario involving situational awareness and sensor data collection. Using the Meshtastic solution, we assessed both the underlying communication performance and the usability of LoRa mesh networking in representative field conditions. Overall, the results are encouraging and support

the relevance of LoRa-based mesh networks for tactical communications by demonstrating effective range, reliability, and resilience.

Several perspectives for future work arise from this study. The evaluation should be extended to larger-scale deployments, with increased node density and broader network coverage, as well as to more complex scenarios involving a greater number of participants. Additionally, hybrid topologies combining fixed elevated relay infrastructure with mobile nodes should be investigated for potential improved performance.

In conclusion, Meshtastic provides a robust baseline that paves the way for tactical communications over LoRa. Addressing the limitations of this solution through enhanced radio agility, including channel and power adaptation mechanisms, would be a key step toward making LoRa-based mesh networks suitable for tactical communications.

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¹<https://casa-irisa.univ-ubs.fr/download/videos/mesh/exp251013.mp4>