Evaluating Use of ARQ Strategies in Communication Protocols for Search and Rescue

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Abstract: Search and Rescue (SAR) operations often occur in remote and challenging environments where conventional communication infrastructures are unavailable or unreliable. Effective communication is crucial for mission success. Low-power wide area network (LPWAN) protocols, particularly the LORA (Long Range) protocol, have gained traction due to their low power consumption and extended range. However, LORA's low reliability presents significant challenges in the time-sensitive context of SAR operations, necessitating effective communication strategies. This paper examines the reliability of communication protocols in real scenarios, focusing on Stop & Wait (S&W) and Selective Repeat (SR) Automatic Repeat reQuest (ARQ) protocols. It evaluates their suitability by addressing operational constraints such as geographic barriers, time sensitivity, and simplicity of implementation. Key contributions include investigating the current literature, a real implementation of the ARQ algorithm, and a comparative analysis of these protocols under real-world conditions. Furthermore, the study presents a real-world implementation of ARQ mechanisms and evaluates their operational trade-offs in SAR scenarios, considering both computational constraints and deployment feasibility.

1 INTRODUCTION

In Search and Rescue (SAR) operations, effective communication is the backbone of successful missions (Alsaeedy and Chong, 2020). These operations often occur in remote, hostile, or challenging environments where traditional communication infrastructures, such as cellular networks or satellite communications, are either lacking or unreliable (Calabrò and Marchetti, 2024). In these conditions, the availability of robust and streamlined communication protocols that can operate under these difficult conditions is a stringent need.

Among the various communication technologies available, low-power wide area network (LPWAN) protocols, particularly the LORA (Long Range) protocol, have gained significant traction due to their capability to facilitate communication over extensive distances while consuming minimal power. LORA protocol is especially valuable in SAR missions, where team members or equipment may spread across large areas that are difficult to access. LORA networks can support many devices with lower energy requirements, permitting extended operational periods without frequent recharging or replacement. However, despite these advantages, a notable drawback of LPWAN protocols like LORA is their inherently low reliability. Given the time-sensitive nature of SAR operations, failures in communication can have critical implications. Consequently, maintaining data integrity and ensuring timely transmissions is extremely critical. Numerous strategies have been explored in the existing literature to enhance the reliability of communications in SAR contexts (Mendelsohn et al., 2024; Mabulu et al., 2024; Akgun et al., 2023), such as multi-hop communication (Anuradha et al., 2022) and Automatic Repeat reQuest (ARQ) (Vasiliev and Abilov, 2015).

Each method possesses distinct advantages and disadvantages that are particularly relevant to the unique contexts in which SAR operations are conducted. Specifically, multi-hop communication strategies focus on relaying data through intermediate nodes to extend the transmission range and enhance connectivity. This approach can significantly bolster communication in scenarios where geographical features, such as mountains or dense forest,s hinder direct transmission. However, this method often relies

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on having a certain level of infrastructure in place, such as additional communication nodes or devices. In SAR operations, this infrastructure may not always be available, potentially limiting the effectiveness of multi-hop communication. The Automatic Repeat reQuest mechanisms provide a systematic approach to retransmitting lost or erroneous packets, thereby improving the reliability of data communication. Different ARQ protocols (YOSHIMOTO et al., 1991), such as Go-Back-N, Selective Repeat, and Stop & Wait, can be used to identify and recover transmission errors efficiently. However, ARQ can introduce additional latency into the communication process. In a SAR context, where timely updates are crucial, this latency may not be the most efficient solution, especially in simpler, single-core systems where the overhead of managing ARQ may outweigh its benefits.

This paper aims to investigate these enforcements on communication, focusing on the peculiarities of ARQ. In particular, the paper focuses on the hypothesis that the benefits of the Selective Repeat (SR) ARQ protocol are often limited, resulting in performance that may be functionally similar to Stop and Wait (S&W) in many situations. Therefore, we will evaluate its cost-effectiveness in SAR environments through several key analyses, including:

- Investigation of current literature: We provide an overview of the current methodologies in protocol reliability to classify their challenges and limitations. This will assist in identifying optimal guidelines for applying these communication strategies in SAR operations.
- Implementation of the algorithms: We will detail the design and application of various algorithms specifically tailored for simplistic systems. These algorithms aim to optimize transmission times without significantly increasing complexity or cost.
- Comparative performance analysis: we will showcase the comparative analysis of the implemented transmission improvement algorithms under real-world conditions to ascertain their effectiveness.

Therefore, the paper wants to provide a realistic investigation of the operational constraints inherent in SAR missions, providing valuable data to support informed decision-making when selecting communication strategies. In our exploration, we will provide essential components to support our findings, including a detailed description of i) the hardware configurations and technical specifications, ii) the execution environment, including actors such as geographic location, terrain characteristics, and environmental challenges that could impact possible SAR operations; iii) the data packets, including their structures and specific transmission requirements.

This will allow for possible experiment replication with different protocols and conditions. Through this extensive exploration, we aim to contribute valuable knowledge that could enhance the communication strategies employed in SAR operations. By advancing our understanding of ARQ protocols and their alternatives, we ultimately seek to improve the efficacy and safety of these critical missions, ensuring that personnel can communicate effectively and respond swiftly to emergencies.

Although Go-Back-N ARQ is widely studied, this work focuses on Stop & Wait and Selective Repeat due to their lower computational requirements and suitability for low-power devices, which are more aligned with SAR operation constraints.

Roadmap. The remainder of this article is organized as follows. The main background and related works are presented in Section 2, while the proposed architectural design and its reference behavior are described in Section 3. The Selective Repeat ARQ implementation and the system deployed for its execution are presented in Section 4. Furthermore, in Section 5, the experimental results are evaluated and discussed. Finally, in Section 7, conclusions and possible future works are highlighted.

2 BACKGROUND AND RELATED WORK

This section reports the current research activity in optimizing LoRa communications and the required background knowledge in Section 2.2 and 2.1, respectively.

2.1 State-of-the-Art

Optimization of LoRa communications has stimulated different research field solutions (Hilmani et al., 2022; Kamal et al., 2023). Most proposed solutions use intermediate nodes (end devices or gateways) to expand the network coverage (Bor et al., 2016). The intermediate nodes forward data until they reach a final gateway according to specific routing protocols (Jouhari et al., 2023; Leonardi et al., 2023; Lundell et al., 2018; Paredes et al., 2023) that can take into consideration also quality parameters such as usage, remaining battery life, and traffic rate (Anedda et al., 2018; Wong et al., 2024; Islam et al., 2023; Ebi et al., 2019; Zhao et al., 2023).

In (Zorbas et al., 2021), the authors tackle the problem of scheduling the retransmission of buffered data in LoRa networks, typical of the situations in which connectivity between gateways is not available, and propose a time-slotted transmission scheduling mechanism. It is also highlighted that synchronous communications positively affect data collection time and network performance. In (Chen et al., 2019), the authors present a cost-effective hardware architecture for a LoRa gateway that increases throughput by improving bandwidth usage. Other solutions adopt organization algorithms of the nodes to specific topology (Haubro et al., 2020; Leenders et al., 2023; Gkotsiopoulos et al., 2021) or cluster (Cotrim and Kleinschmidt, 2020; Sun et al., 2022; Almuhaya et al., 2022; Mamour and Congduc, 2019) to ensure reliable data transfer to the target gateway (Dwijaksara et al., 2019; Wong et al., 2024; Bomgni et al., 2023).

A machine learning (ML) approach is used in (Abubakar et al., 2022), proposing a scalability optimization for LoRaWAN networks based on a combination of ML algorithms. The authors identify the average distance between LoRa end-devices and gateways as a function to be minimized with the constraint of improving the received signal strength (RSSI) at each end-device, then solve this optimization problem by combining K-Means clustering (to optimize gateways' locations) and Regression Neural Networks (to maximize RSSIs). Furthermore, they perform a series of trials to form the foundation for developing an adaptive algorithm capable of dynamically allocating bandwidth autonomously.

Finally, hybrid solutions exist, which rely on message transmission and synchronization techniques to reduce energy consumption while improving coverage and dependability at the same time (Zhou et al., 2019; Tanjung et al., 2020).

2.2 LoRa Communication and ARQ

This section details the two main baseline concepts used in this paper: LoRa communication and Automatic Repeat Request (ARQ).

LoRa Communication. LoRa is a wireless communication technology designed for long-range, low-power applications conceived by Cyleo (Grenoble) in 2009 and released in January 2015 (Sornin et al., 2015). It is based on the Chirp Spread Spectrum (CSS), which allows maintaining communications over several kilometers, making it an ideal solution for scalable applications such as the Internet of Things (IoT) (Grunwald et al., 2019), smart cities, digital agriculture (Codeluppi et al., 2020), environmental monitoring (Fraga-Lamas et al., 2019), and asset tracking. One of the main advantages of LoRa is its ability to provide deep indoor penetration and connectivity in challenging environments, such as urban areas or buildings with thick walls, where traditional wireless technologies may struggle to maintain reliable communication. In addition, LoRa supports bi-directional communications, which means that devices can transmit data and receive commands or updates from a central server or gateway.

Automatic Repeat Request. Automatic Repeat Request (ARQ) (Lin et al., 1984) is an error-control strategy used in data communications to ensure reliable information delivery over unreliable or error-prone transmission channels. It includes mechanisms for checking errors on received data, such as timeouts and feedback signals (acknowledgments), to handle the re-transmission of erroneous or missing data segments. There are several ARQ protocols described in the literature (Makridis et al., 2022; Kalør et al., 2022; Choi et al., 2020), including

- Stop-and-Wait ARQ, which is based on the acknowledgment of reception for one segment of data before sending the next segment
- Go-Back-N ARQ, which allows the transition of multiple data segments without waiting for individual acknowledgments and
- Selective Repeat ARQ, which allows the individual acknowledgment of each received segment and provides for re-transmission only in the event of segments with errors.

Table 1 summarizes the main features of the three ARQ protocols according to the literature overview(Makridis et al., 2022; Kalør et al., 2022; Choi et al., 2020). The table's purpose is to highlight each protocol's strengths and weaknesses so that easy implementation decisions can be made and to assist in identifying optimal guidelines for applying these communication strategies in SAR operations.

While Go-Back-N represents a moderate trade-off between complexity and performance, its requirement for retransmission of multiple frames upon a single error is suboptimal in SAR contexts with high energy constraints. Our implementation instead prioritizes resource efficiency and simplicity, aligning with the limitations of real SAR equipment. Considering the current state of the art, a contribution of the paper is a comparative analysis of these algorithms under real-world conditions to confirm the overall analysis

Table 1: Main features of the three ARQ strategies.

	Stop and Wait	Go-Back-N	Selective Repeat
Channel Utilization	Poor	Better than SW	Best among the 3
Implementation Complexity	Simple	Moderate	Most complex
Memory Requirements	Low	Moderate	High
Bandwidth Efficiency	Low	Moderate	High
Error Handling	Retransmit current packet	Retransmit all packets from error point	Retransmit only erroneous packets
Packet Reordering	Not needed	Not needed	Required at receiver
Error Recovery Time	Fast but inefficient	Can be slow due to mass retransmission	Efficient, only retransmits needed packets

provided in Table1 and ascertain their practical limitation and effectiveness. For this, we first focused our attention on the Selective Repeat and Stop&Wait algorithm since these strategies proved to be better performing than others (such as the single-hop method used by LoRaWAN (Choi et al., 2020)) in improving reliability across LoRa networks (Choi et al., 2020; Abedina et al., 2023). Eventually, we adopted the Selective Repeat ARQ protocol, as it is the most suitable for increasing data transmission's reliability and robustness, ensuring data integrity while minimizing retransmissions and energy consumption.

3 ARCHITECTURAL DESIGN

This section describes the architecture for implementing Selective Repeat (SR) and the Stop & Wait (S&W) ARQ protocols. Figure 1 illustrates the baseline main components of the instantiated system (i.e., the *Mobile Station* and the *Base Station*) connected through a LoRa channel. The *Base Station* remains fixed in position, enhancing the signal reception and the overall spatial coverage. It is responsible for managing the activities done by the receiver of the two ARQ protocols in practical scenarios when the transmitter device moves in a natural environment.

As shown in Figure 1, both the *Base Station* and *Mobile Station* infrastructures include computational devices (Computer) for data storage and management operations. In particular, the *Base Station* includes a database, while the *Mobile Station* relies on a logger for the storage activities. *Base Station* and *Mobile Station* communicates through a LoRa channel. The *Mobile Station* and *Base Station* include a LoRa node with an *ARQ Logic* artifact for implementing the ARQ strategy (SR or S&W). Finally, the *Mobile Station* includes a *GPS* device for gathering the position of the *Mobile Station*. More details of *Mobile Station* and *Base Station* implementation are provided in the next section.

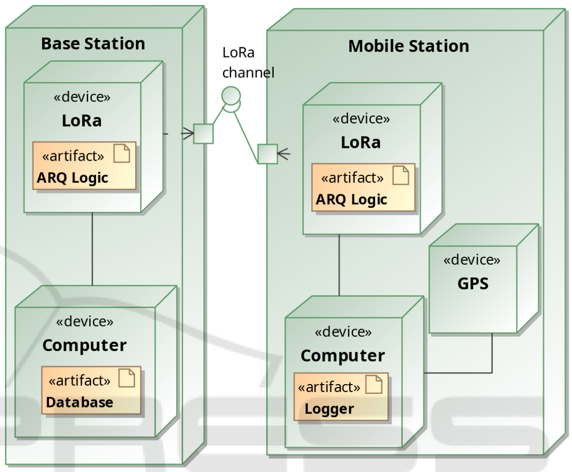

Figure 1: Architectural overview.

4 PROTOTYPE IMPLEMENTATION

This section presents an instance of the architecture depicted previously. In particular, details of the two components, *Base Station*, and *Mobile Station*, are provided in Section 4.1 and 4.2.In comparison, the details related to the implementation of the ARQ protocol are provided in Section 4.3.

4.1 Base Station

Figure 2 shows the instantiation of the *Base Station* presented in Figure 1. In realizing the *Base Station* devices, the following have been selected: A barebone computer for the *Computer* component. As in Figure 2, *Barebone* is in charge of managing the storage of the data collected during the execution. The *Barebone* device executes two artifacts: *MySQL*, which is an instance of the popular open-source DB, where the *SerialManager* stores the data gathered by the transmission received through

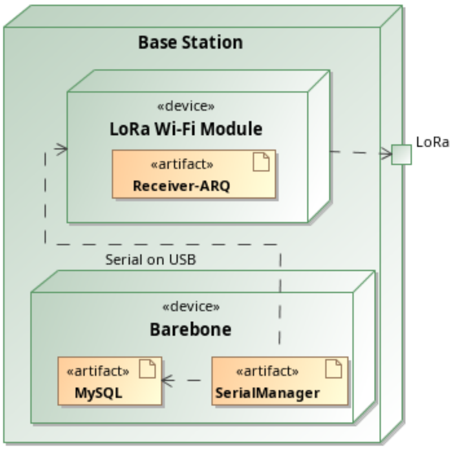

Figure 2: Base Station Architecture.

the *LoRa Wi-Fi module*. The *SerialManager* artifact has been developed using Java code. The *Barebone* device is connected to the *LoRa Wi-Fi module* through a USB port that emulates a serial port. The *LoRa Wi-Fi module* manages the transmission using the LoRa radio protocol. In particular, the *Receiver-ARQ* artifact is the component developed on top of the *LoRa Wi-Fi Module* for executing the ARQ protocol (i.e., Selective Repeat or Stop & Wait). In the proposed implementation, the *Barebone* device is realized through a Lenovo ThinkEdge SE10 running Windows 10 IoT Enterprise; the *LoRa Wi-Fi Module* is built by means of a LilyGo LoRa32 V2.1 device equipped with an ESP32 and an SX1262 LoRa node chip. The *Receiver-ARQ* software has been developed using Arduino IDE [1], and LilyGo libraries [2]. The prototype is shown in Figure 5.

4.2 Mobile Station

Figure 3 details the instantiation of the architecture of *Mobile Station*. It is composed of three different devices:

- a Raspberry PI Model 4B (*R-PI 4 Mod.B*) that represents the instantiation of the *Computer* shown in Figure 1;
- a *LoRa Wi-Fi Module*, connected using a USB port that emulates a serial port to the R-PI 4 Mod.B;
- and a *GPS* device connected using another USB port of the R-PI 4 Mod.B.

On the *R-PI 4 Mod.B* device, three artifacts have been deployed: the Java-developed *SerialManager*

[1]https://www.arduino.cc/en/software

[2]https://github.com/Xinyuan-LilyGo/TTGO-LoRa-Series

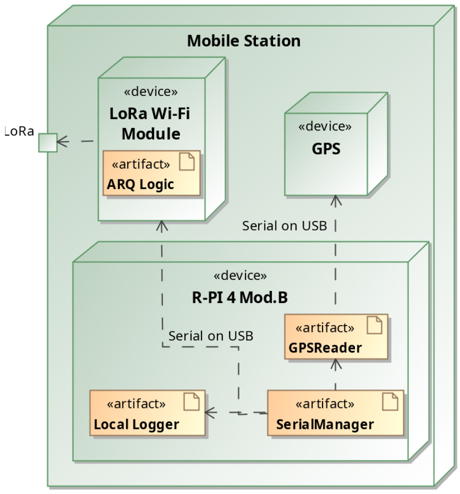

Figure 3: Mobile Station Architecture.

Figure 4: Mobile Station.

artifact for sending and receiving data from the *LoRa Wi-Fi module* related to communication packets and the *GPS* device from which it receives the current GPS position. These data are stored locally by the *LocalLogger* artifact. Also, in this case, the *Receiver-ARQ* artifact is the component developed on top of the *LoRa Wi-Fi Module* for executing the ARQ protocol (i.e., Selective Repeat or Stop and Wait).

In the proposed implementation, the *R-PI 4 Mod.B* device is realized by a Raspberry Pi 4 Model B device with 8GB of RAM, on which a 3.5-inch touchscreen display for debugging and management purposes has been connected. It is powered by a battery shield PiSugar 5000mah[3]. The *LoRa Wi-Fi Module* has been instantiated using a Heltec WiFi LoRa

[3]https://www.pisugar.com/

Figure 5: Base Station.

32(V3) device equipped with an ESP32-S3FN8 and an SX1262 LoRa node chip powered directly by a USB port of the *R-PI 4 Mod.B* node. The *GPS* device is a generic GPS USB dongle capable of providing data according to the GPS & GLONASS standard on a serial port.

The software for running the *SerialManager* and the *GPSReader* artifacts has been developed using Java, while the *ARQ Logic* software has been developed using Arduino IDE. The *LocalLogger* artifact has been developed using a Python script for storing data gathered by the *SerialManager*. The prototype of the *Mobile Station* is shown in Figure 4.

4.3 Implementation of ARQ Methods

As discussed in Section 2.2, the standard LoRa protocol suffers from a high packet loss rate, which causes low transmission reliability. The ARQ methods have been implemented to address and mitigate this issue, enhance transmission, and recover any missing packets. In the current implementation, the ARQ protocols are implemented both on the *Mobile station* (i.e., the transmitter) and on the *Base Station* (i.e., the receiver) to enable re-transmission each time a missing packet is detected. The ARQ logic was implemented from scratch in Arduino IDE using low-level control structures, without relying on pre-existing ARQ libraries. This allowed full customization for constrained environments and provided valuable insights into practical limitations during integration and tuning.

Figure 6 shows the enhanced packet structure used for communicating the GPS position on which the *Mobile station* is located to the *Base station*. The packet structure has been developed to incorporate the ARQ mechanism and include an integrity check of the data. As depicted in Figure 6, it includes:

- Two bytes to identify the transmitting node;
- Two checksum bytes to control packet integrity;
- Two bytes to determine the role of the transmitter, i.e., the *Base Station* or the *Mobile Station* according to the “master” or “slave” protocol.
- Two chars, one at the beginning and one at the end, to clearly define the packet’s start and end.

Implementing the ARQ mechanism requires identifying the sender and receiver because data transfer can occur simultaneously in two directions, generating packet loss, errors, and collisions. Additionally, the implementation requires a mechanism for checking transmission errors to improve the reliability of the data received. Finally, information regarding the order of the sent packets is necessary to reconstruct the transmitted data.

Due to the computational limitation of the employed LoRa devices, it is possible to execute only a single process with a main ”loop” cycle on which both send and receive operations must be executed. To enhance transmission quality, LoRa devices are programmed to have their main cycle in listening mode for incoming messages. Transitioning to transmit mode happens only when a new message is queued in the buffer, and the system is not busy receiving a message. This approach reduces reception errors by ensuring the receiver is always ready to process data while minimizing packet collisions by prioritizing incoming signals over outgoing transmissions.

An optimal interleave time of approximately 1000 ms has been calculated, balancing message scheduling to improve throughput and reduce interference, particularly in dense IoT networks. This mechanism forms the foundation for implementing Stop & Wait and Selective Repeat ARQ protocols, which enhance reliability by enabling acknowledgment and retransmission of lost or corrupted packets. The selective repeat mechanism benefits from the receiver’s continuous mode by ensuring efficient reordering and error recovery without compromising transmission quality.

5 SHOWCASE SCENARIOS

The experiments have been executed in a specific showcase scenario to provide a comparative performance analysis of the ARQ mechanism in an actual situation. In particular, experimental data have been collected around the *omissis* research campus in *omissis* (see Figure 7). Even if the location is not the typical environment of a SAR operation, the topology includes green areas, buildings, areas with a density of

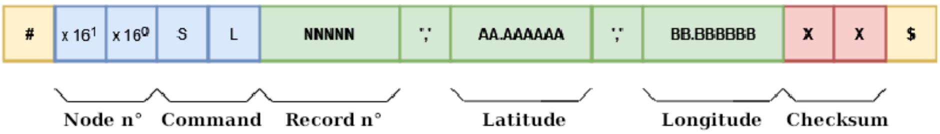

Figure 6: Structure of the enhanced packet with ARQ features.

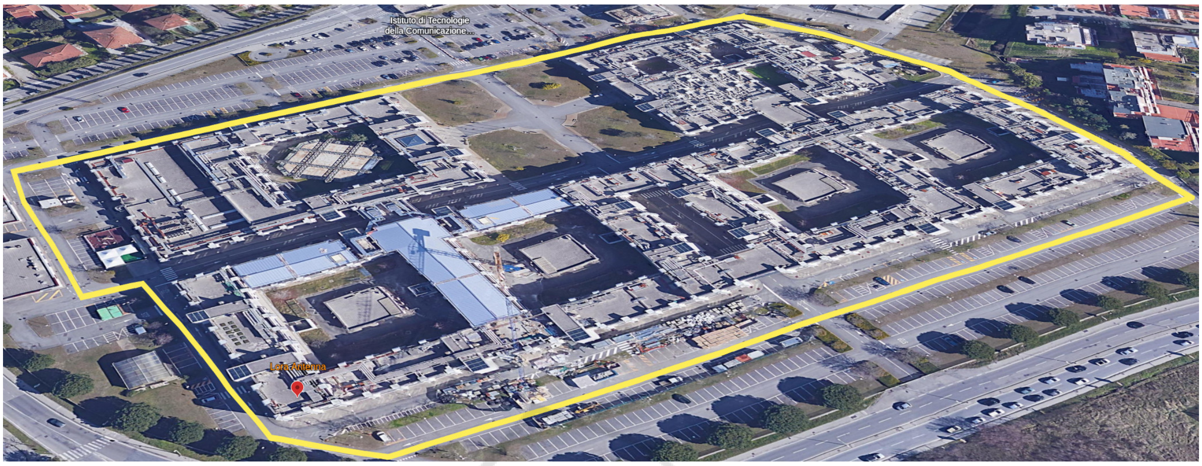

Figure 7: Scenario's path to execute.

different signals, and rooms and buildings with signal shielding for research purposes.

In Figure 8, it is possible to identify the LoRa antenna placed at the bottom left of the figure. The path selected for the experiments has a radius of 150m (light yellow line in Figure 7), and the antenna has been placed in the building's roof corner to increase transmission difficulties (red spot in Figure 7).

The experiment has been executed in favorable weather conditions without rain or fog to prevent signal attenuation. The device shown in Figure 4 has been placed on a bike that travels across the path at an average speed of around 10 Km/h.

The scope of the experiments was to determine the quality of the received signals and the number of packets correctly delivered as the communication distance between two nodes varies. The transmitter sends the detected GPS position to the receiver at a constant frequency (1000ms).

Three instances of the experiments have been executed:

1. The path has been crossed without any retransmission mechanism: see Figure 8 (NO-ARQ);
2. the path has been crossed enabling Stop & Wait ARQ mechanism: see Figure 9 (S&W-ARQ);
3. the path has been crossed, enabling the Selective Repeat ARQ mechanism: see Figure 10 (SR-ARQ).

In all three experiments, the path has been crossed, moving in the direction of the arrows in the figures. Additionally, in all the figures, the parts of the path colored in green represent the messages correctly sent from the transmitter and received by the LoRa Antenna without relying on requiring a retransmission mechanism (if enabled). Notably, consistent message loss in specific areas corresponds to known shadow zones caused by building structures and vegetation density, which impede line-of-sight (LOS) transmission and are typical challenges in SAR deployments.

In all three experiments, the data (transmitted and received) were stored locally on the database instance of the *Base Station* and *Mobile Station*. For evaluating the packet loss rate, the following formula has been considered:

$$PacketLossRate = 1 - \frac{N_{rx}}{N_{tx}} \tag{1}$$

where N_{rx} and N_{tx} are the total number of received and transmitted packets, respectively.

6 EXPERIMENT EXECUTION

In this section, details about the execution of the three experiments are provided. Each experiment lasted approximately 15 minutes, with the mobile station continuously transmitting GPS packets every 1 second. All trials were repeated under similar conditions to ensure consistency in results.

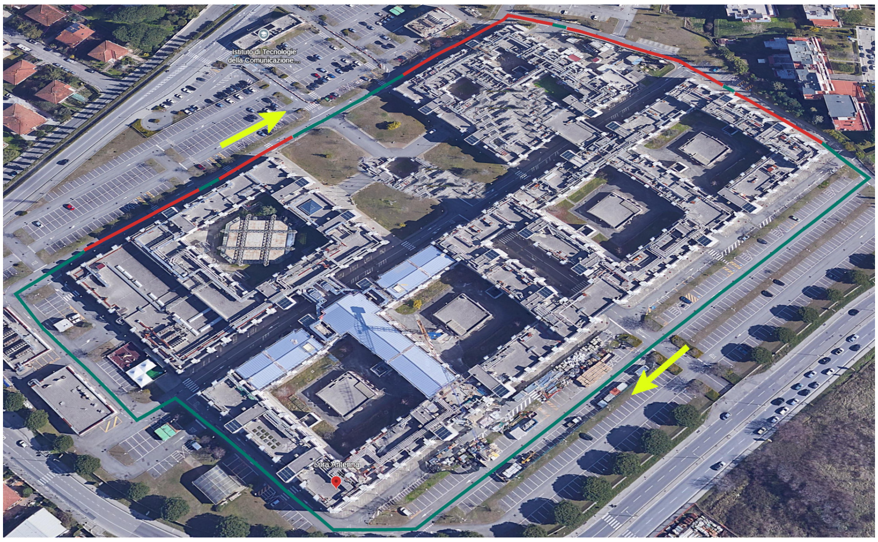

Figure 8: TX-RX data without ARQ.

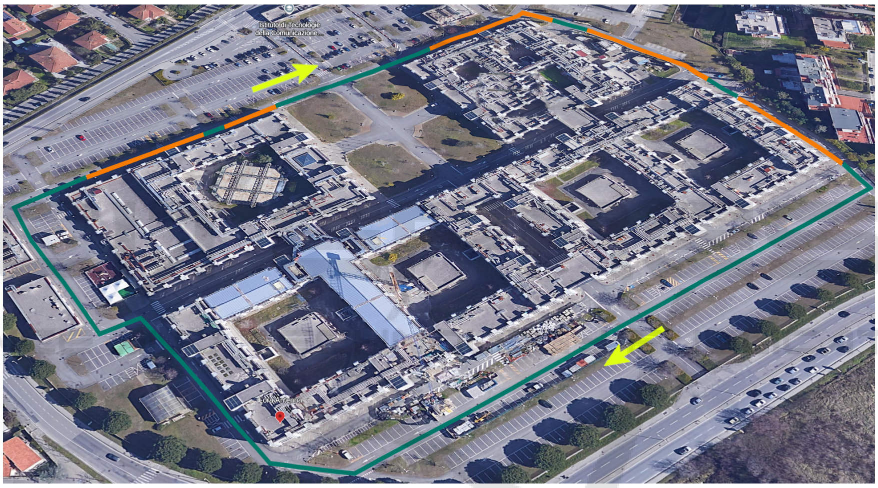

Figure 9: TX-RX data with Stop & Wait ARQ.

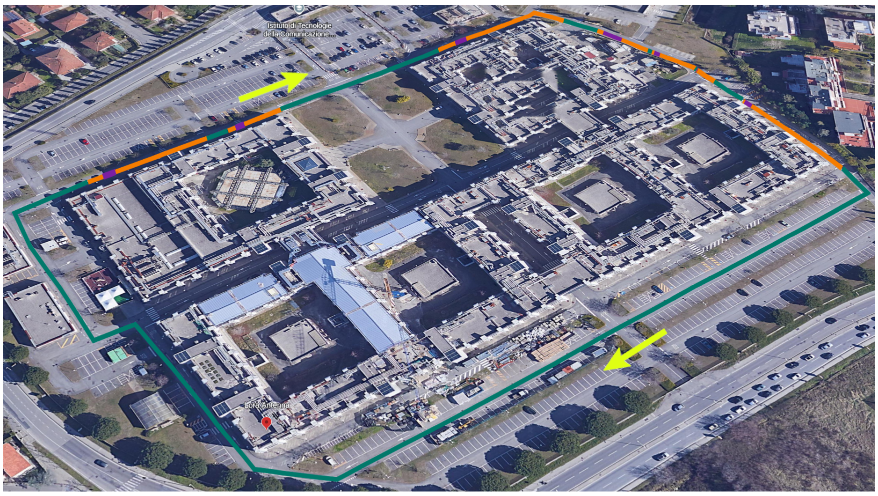

Figure 10: TX-RX data with Selective Repeat ARQ.

In this regard, the use of color-coded geographic maps was intentionally preferred over numeric tables to visually highlight the spatial impact of packet loss concerning the surrounding environment—an essential factor in SAR contexts. Rather than proposing a theoretical model, we focused on experimental validation, emphasizing computational limitations, implementation simplicity, and the realistic effectiveness of the protocols. Therefore, metrics such as energy consumption or theoretical delay were deliberately not explored in depth, in favor of producing results that are easily replicable in practical scenarios.

Execution with NO-ARQ Enabled. The results of the execution of the first experiment are depicted in Figure 8. As shown, the part of the path colored in red identifies the areas where the antenna has received no messages.

A post-analysis of the data collected during the first experiment by the *Base Station* and the *Mobile Station* allows the computation of the packet loss rate in the executed path. In particular, the derived data were as follows:

- #packets generated by the *Mobile Station* = 3148;
- #packets received by the *Base Station* = 1287.

Consequently, the packet loss rate is:

$$PacketLossRate = 1 - \frac{1287}{3148} = 59,11\% \qquad (2)$$

Execution with S&W-ARQ Enabled. The execution of the second experiment is depicted in Figure 9. As in the figure, the part of the path colored in orange identifies the areas where the antenna has received messages after retransmission, while the *Mobile Station* comes back in LOS (green part of the path). The part colored in green represents the situation that did not require a retransmission mechanism.

The packet delivery has been guaranteed using the ARQ mechanism, and the results of the second experiment provide a 100% delivery rate.

- #packets generated by the *Mobile Station* = 3291;
- #packets received by the *Base Station* = 3291.

The computed packet loss rate is:

$$PacketLossRate = 1 - \frac{3291}{3291} = 0\% \qquad (3)$$

Execution with SR-ARQ Enabled. The execution of the third experiment is depicted in Figure 10. As in the previous experiment, in the figure, the part of the path colored in orange identifies the areas where the antenna has received messages after retransmission.

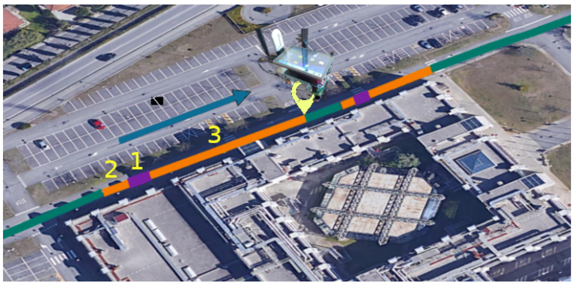

Figure 11: Segment of the SR-ARQ execution with packet receiving order.

The parts colored in purple identify the areas where Selective Repeat has an effect, causing the messages in the purple set to be received before those of the previous orange segment.

To clarify, Figure 11 shows a segment of the executed path. The order of sent messages was reconstructed after the data analysis. As depicted in the figure, when the *Mobile Station* reached the marked position in the green segment, the *Base Station* received in order first the messages of the purple segment numbered *1*, then the messages of the orange segment numbered *2* and finally the messages of the orange segment numbered *3*. The number of packets generated by the Mobile Station was 3364, with all successfully received by the Base Station, resulting in a packet loss rate of 0%. However, transmission order required post-processing due to reordering inherent to SR-ARQ.

Experiment Evaluation. Analyzing the data gathered during the experiment, several key insights can be drawn regarding selecting an appropriate ARQ protocol, as summarized in Table 1.

1. `Channel Utilization and Memory Requirements`: Selective Repeat necessitates buffering out-of-order packets at both the sender and receiver, alongside additional mechanisms for managing cumulative ACKs. The simpler Stop & Wait protocol may suit systems with limited computational resources or memory.
2. `Bandwidth Efficiency and Energy Consumption`: In scenarios where minimizing energy consumption is crucial, such as LoRa transmissions, the overhead associated with managing the sliding window in Selective Repeat may outweigh its benefits, making Stop & Wait a more efficient choice.
3. `Packet Size and Buffer Limitations`: Given the constrained buffer resources available on LoRa low-power devices, Selective Repeat demands substantial computational power to

manage retransmissions and maintain packet order, particularly in environments with frequent packet errors. In such contexts, the straightforward Stop-and-Wait protocol offers a more feasible solution due to its simplicity.

7 DISCUSSION AND CONCLUSION

The paper discussed the crucial role of effective communication in Search and Rescue (SAR) operations, particularly in challenging environments where traditional communication methods are often unreliable. It highlighted the advantages of low-power wide area network (LPWAN) protocols, specifically the LoRa protocol, which allows for long-range communication with minimal power consumption, making it suitable for SAR missions where resources are limited.

The paper aimed to investigate the effectiveness and cost-efficiency of these communication strategies in SAR environments, particularly focusing on the Selective Repeat ARQ protocol. It included an overview of the literature about current methodologies, the implementation of tailored algorithms for simpler systems, and a comparative performance analysis of these algorithms in real-world scenarios. In particular, the paper evaluated the performance and cost-effectiveness of ARQ protocols that can be applied in the context of Search and Rescue (SAR), focusing mainly on Stop and Wait (S&W) and Selective Repeat (SR). The ultimate goal was to provide valuable insights and guidelines for selecting optimal communication strategies in SAR missions, addressing the operational constraints these missions face.

The analysis revealed that while SR offers theoretical advantages in managing lost packets and reducing latency, these benefits are largely negated in scenarios involving small packets, low latency requirements, and frequent messages, as demonstrated through the showcased scenario. In such cases, the higher implementation costs and complexity of SR are not justified, as S&W achieves comparable performance with significantly lower resource demands. Implementing tailored algorithms and conducting comparative performance analyses under real-world conditions, we provided actionable insights into the practical application of LoRa for small packets and frequent message transmission. These findings highlight the importance of context-specific communication strategies that strike a balance between reliability and simplicity, particularly in resource-constrained and time-sensitive operations.

Furthermore, the system architecture was intentionally kept minimal (point-to-point) to reflect the real operational limits typical of SAR missions, where complex infrastructures or multi-hop networks are often unavailable. However, we acknowledge that exploring scalability in broader contexts would be valuable and is considered a direction for future work.

While the article does not include a direct comparison with alternative technologies (e.g., Wi-Fi mesh, LTE, BLE), the choice of LoRa is motivated by its favorable characteristics for SAR missions: low energy consumption, long-range coverage, and suitability for remote environments.

This study is a foundation for decision-making in choosing communication protocols for SAR scenarios, enhancing effective and dependable communication while reducing operational costs and complexity. While the study's analysis is mostly qualitative, it highlights practical deployment trade-offs that are often overlooked in more theoretical evaluations. These insights are valuable for practitioners facing real SAR mission constraints. Future work may explore hybrid approaches or further optimization of S&W by tuning parameters such as the Spreading Factor or other transmission settings to enhance performance across more diverse SAR environments.

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