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Experimental analysis for comparison of wireless transmission technologies: Wi-Fi, Bluetooth, ZigBee and LoRa for mobile multi-robot in hostile sites

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ABSTRACT

This research paper conducts a thorough comparison of four prominent transmission technologies suitable for mobile robots operating in challenging environments. Emphasizing key factors such as signal strength, noise resistance, and data transfer efficiency, the study aims to identify the optimal communication solution in hostile conditions. The exploration delves into the intricacies of received signal strength indication (RSSI) and signal-to-noise ratio (SNR), revealing distinctive traits and trade-offs among the technologies. Navigating through the complexities of frequency bands, modulation types, and communication topologies, the paper examines the impact of obstacles, energy consumption dynamics, and potential real-world applications. Beyond contributing to the fields of robotics and communication, the study offers practical insights for stakeholders seeking resilient and efficient transmission methods for mobile robotic applications. Advocating for long range (LoRa) as the preferred transmission technology in hostile environments, the paper highlights its unmatched immunity to noise, stability, and minimal energy consumption. These findings provide valuable guidance for technology choices in collaborative mobile robot operations under challenging conditions. This research sets the stage for future developments in robotic communication, underscoring the crucial role of selecting the right transmission means for mission-critical applications in hostile environments.

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1. INTRODUCTION

In environments fraught with hostility and complexity, such as forest fires, industrial ruins, and disaster-stricken areas, human intervention is often hindered, if not impossible. Figure 1 shows the main examples of aggressive sites for intervention by human operators. These scenarios demand innovative solutions to mitigate risks and minimize human and material losses. Robotic systems offer a promising alternative, providing a safe and efficient means of intervention in hazardous sites [1]. The deployment of robotic agents, ranging from wheeled to aerial machines, represents a strategic investment for organizations seeking long-term reliability and operational efficiency [2]. However, optimizing interventions while containing costs remains a challenge, particularly as payload and energy consumption escalate exponentially. To address this challenge, the task is distributed among clusters of robotic agents, equipped with communication capabilities to facilitate efficient data exchange [3]. Communication plays a pivotal role in multi-robot systems, enabling coordination and collaboration among agents and the control station. Wireless communication emerges as the preferred choice to accommodate the dynamic movements of robotic agents. However, ensuring robustness in terms of bandwidth, range, and latency remains paramount for overall system performance [4]. While point-to-point communication suffices for small-scale systems, scalability becomes a concern in larger multi-robot deployments due to channel saturation and latency issues [4]. More sophisticated communication schemes, such as one-to-many or many-to-many approaches, are commonly employed to enhance efficiency. Nonetheless, the choice of communication technology hinges on the specific requirements of the application, particularly in terms of range and bandwidth [5].

Several wireless technologies, including Wi-Fi, ZigBee, Bluetooth, and LoRa, offer viable solutions for multi-robot communication. Wi-Fi, known for its ubiquity and affordability, presents a compelling option for covering large areas. Despite its widespread adoption, challenges such as antenna size and bandwidth management persist, especially in resource-constrained environments [6], [7]. Furthermore, the proliferation of onboard computers in robotic systems necessitates efficient data exchange within and between robots. While onboard computers host critical functions and process raw sensor data, bandwidth requirements vary depending on the application and system architecture [8].

This paper presents a comparative analysis of Wi-Fi, Bluetooth, ZigBee, and LoRa transmission technologies in the context of multi-robot communication in hostile environments. By examining signal strength, noise resistance, and data transfer efficiency, the study aims to elucidate the optimal communication solution for enhancing the reliability and resilience of multi-robot systems in challenging settings. Through a systematic comparison, we contribute to the advancement of communication strategies tailored to the demands of mobile robotic applications in hostile environments.

Figure 1. Main examples of aggressive sites for intervention by human operators

2. METHOD

Radio frequency (RF) transmission is a crucial aspect in the digitalization of decentralized collaborative robots (cobots) in hostile environments. Cobots are highly versatile robots that can be used in various industrial and manufacturing environments, ranging from clean rooms to hazardous and remote environments. The ability to transmit data and control signals wirelessly via RF transmission is essential to the smooth operation of these robots [9]. The objective is to discuss the different means of RF transmission and to identify the best solution for cobots in hostile environments.

Cobots can become an integral part of industry and all places in which humans exist and work, thanks to their ability to work alongside human workers, thereby enhancing their capabilities and improving overall productivity. These robots are designed to operate in a collaborative environment, providing a high level of flexibility and adaptability to changing production requirements. In hostile environments, such as those with high levels of interference, heat and dust, cobots must be equipped with robust and reliable RF transmission technologies.

2.1. Theoretical comparison

Various radio frequency (RF) transmission technologies are employed in mobile collaborative robots, as outlined in references [6], [7], [10]–[12]. Among these, Wi-Fi, ZigBee, LoRa, and Bluetooth are commonly utilized. In the subsequent subsections, we will delve into these technologies, providing a concise overview and conducting an analysis of their applicability within challenging environments. Additionally, we will present our findings in Table 1 via previous scientific publications, offering insights into their suitability for deployment in such hostile conditions.

2.2. Experimental methodology

In the constantly evolving field of mobile robotics, establishing reliable and efficient inter-robot communication plays a crucial role, especially in hostile environments where collaborating with each other is required to accomplish complex missions. This section focuses on a comparative experimental study of different wireless transmission technologies, each adapted to specific requirements, in the context of mobile robots collaborating in challenging environments. We investigate the performance of different technologies, namely LoRa, Wi-Fi, Bluetooth and ZigBee, in scenarios where reliability, range and resilience to interference are critical factors. Our experimental approach aimed to comprehensively evaluate the performance of wireless transmission technologies in harsh environmental conditions. We selected four technologies commonly used in collaborative mobile robotics: Wi-Fi, Bluetooth, LoRa and ZigBee, represented respectively by the Edimax EW-7611ULB modules for Wi-Fi and Bluetooth, the Waveshare SX1262 LoRa HAT for LoRa and the XBee S2C TH for ZigBee, as shown in Figure 2.

Table 1. General comparison

Criterion	Wi-Fi	Bluetooth	ZigBee	LoRa
Frequency band	2.4 GHz, 5 GHz	2.4 GHz (2400-2483.5 MHz)	2.4 GHz (Global), 868 MHz (Europe), 915 MHz (North America), 915 MHz (China)	868 MHz (Europe), 915 MHz (North America), 433 MHz (Asia)
Channels	Up to 14 (2.4 GHz), Variable (5 GHz)	79 (2.4 GHz), 40 (LE)	16 (2.4 GHz), 10 (868 MHz), 10 (915 MHz)	Variable, depends on the country (e.g., 64 channels in LoRaWAN)
Modulation type	Orthogonal frequency division multiplexing (OFDM), Direct sequence spread spectrum (DSSS), Frequency hopping spread spectrum (FHSS)	Gaussian frequency shift keying (GFSK), π/4 Differential quadrature phase shift keying (DQPSK), 8-ary differential PSK (8DPSK), FHSS	Binary PSK (BPSK), Quadrature PSK (QPSK)	Chirp spread spectrum (CSS), LoRa, Frequency shift keying, (FSK)
Data rate	600 Mbps - 7 Gbps	1 Mbps - 3 Mbps	20-250 kbps	0.3 kbps - 50 kbps (depending on spreading factor)
Transmission power	Generally higher	Moderate	Low	Low to moderate
Power consumption	Relatively high	Low to moderate	Very low	Very low
Receiver sensitivity	Moderate to high	Moderate	High	High
Communication topology	Point-to-point, Point-to-multipoint, Mesh	Point-to-point, Point-to-multipoint, Mesh	Point-to-point, Point-to-multipoint, Mesh	Point-to-point, Point-to-multipoint, Mesh
Network topology	Infrastructure, Ad-hoc, Mesh	Piconet/Scatternet	Mesh	Star, Point-to-point, Mesh
Range	Short to medium range (30-100 m)	Short range (10-20 m, can be 100 m with BLE 5.x)	Short to medium range (10-75 m)	Long range (Several kilometers in rural areas, up to a few hundred meters in urban areas)
Obstacle immunity (Shadowing)	Moderate to low	Moderate to high	High	High
Security	Wi-Fi protected access 3 (WPA3), WPA2, Wired equivalent privacy (WEP), Lightweight extensible authentication protocol (LEAP), Open	Advanced encryption standard (AES) encryption, pairing	AES-128, AES-256, Link layer security	AES-128, secure key exchange
Applications	Internet access, video streaming, IoT applications, home automation, enterprise networks	Personal area networks (PAN), wearables, audio streaming	Home automation, industrial automation, healthcare, smart meters, IoT applications	IoT, smart cities, agriculture, asset tracking, environmental monitoring, disaster management
Usage in a mobile robot cluster	Yes	Yes	Yes	Yes
References	[6], [13]–[16]	[6], [17]–[20]	[7], [21]–[24]	[25]–[30]

(a) (b) (c)

Figure 2. The used transmission modules, (a) Edimax EW-7611ULB Wi-Fi+Bluetooth key, (b) the RaspberryPi Waveshare SX1262 LoRa HAT module, and (c) the ZigBee XBee S2C TH transmission module

Through this comprehensive comparison, we endeavor to offer valuable insights aimed at facilitating informed decisions regarding the selection of transmission technology. By aligning the choice of technology with the unique demands of each mission, we aim to contribute to the development of highly efficient collaborative robotic systems. These systems are designed to thrive in environments characterized by unpredictability and hostility, thus enhancing their overall performance and effectiveness.

2.2.1. Experimental setup

We set up an experimental devices based-on point-to-point communication for each technology, simulating communication between mobile robots working together in a complex environment, see Figure 3, Figure 4, and Figure 5. The distances between the points were systematically varied to cover a significant range, from short distances to larger values, reflecting realistic scenarios. In addition, each robot is integrated with a Raspberry Pi for data processing and control. The robots use configurations and algorithms to extract key information, which is then stored in local databases within each robot for subsequent analysis. The robots employ process for odometry are utilized for accurate navigation, while global positioning system (GPS) technology is employed for large displacement experiments, particularly in the case of LoRa communication. Fixed and dynamic obstacles present between the robots, ensuring the hostility environment of data transmission. A central computer is employed to collect data from their local databases. The received signals from each robot are captured and utilized for statistical analysis, enabling comprehensive evaluation of the performance of the different transmission technologies in hostile environmental conditions. Overall, this experimental setup provides a scientifically rigorous framework for evaluating and comparing the performance of different transmission technologies, contributing valuable insights to the field of mobile robotics in hostile environments.

Figure 3. The used mobile robot for experimentation

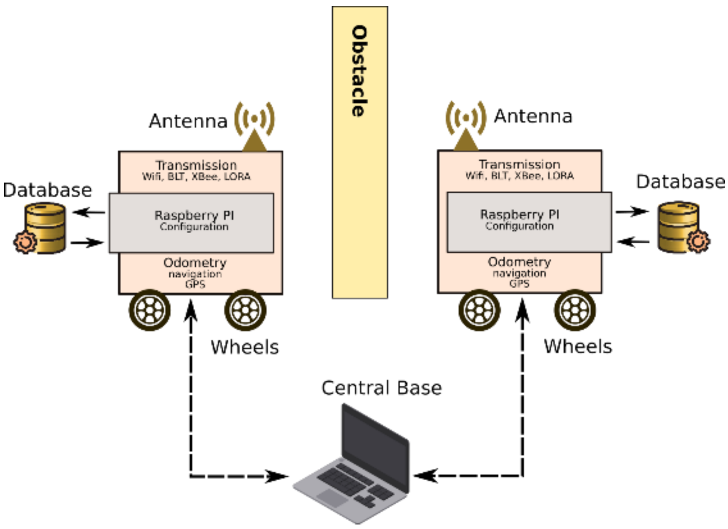

Figure 4. Illustration of the experimental setup

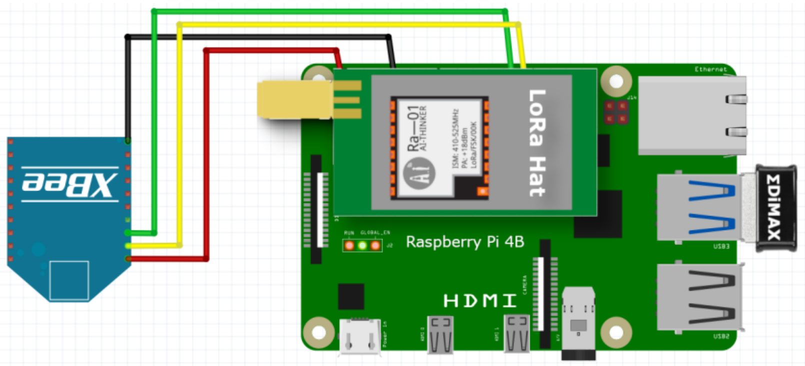

Figure 5. The processing tool with RF modules

2.2.2. Performance measures

In assessing the performance of different transmission technologies, various measures are employed to gauge their effectiveness in challenging environments. These measures include distance-based received signal strength indication (RSSI) calculation, distance-based signal-to-noise ratio (SNR) calculation, and throughput versus distance analysis, contributing to a comprehensive understanding of technology suitability in hostile conditions:

- Distance-based RSSI calculation: At each predefined distance, we measured the RSSI for each technology. This metric provides insight into received signal strength, crucial for assessing communication robustness in disrupted environments.
- Distance-based SNR calculation: Similarly, we recorded the SNR at each distance. SNR provides an indication of signal quality relative to ambient noise, an essential parameter for anticipating potential interference.
- Throughput versus distance: To evaluate data transmission speed, we measured throughput versus distance for each technology. This helps understand how transmission performance varies in dynamic and hostile environments.

3. RESULTS AND DISCUSSION

Our experiments were carried out in a realistic environment, integrating obstacles such as walls, water, iron, and living organisms. These conditions replicate hostile situations such as mine zones or buildings impacted by earthquakes, where reliable communication between robots is crucial despite external disturbances. This rigorous experimental approach aims to provide reliable and detailed data, thus providing a solid basis for the optimal choice of transmission technology in real and hostile contexts. The results obtained, as shown in Figures 6 to 17, will be analyzed in depth to draw significant conclusions oriented towards concrete applications in the field of collaborative mobile robotics.

In analyzing RSSI, a notable trend emerges as Wi-Fi, Bluetooth, and ZigBee exhibit higher signal attenuation in comparison to LoRa. This observation aligns with expectations, considering LoRa's characteristic slower attenuation rate. Interestingly, as frequencies transition towards FR-2 and FR-3, signal weakening occurs at shorter distances, contrasting with the extended reach observed in lower frequency regions such as FR-1.

The significant standard deviations for Bluetooth and Wi-Fi reflect their increased sensitivity to ambient noise, leading to frequent data packet disruptions. Bluetooth, in particular, is distinguished by its complexity of capturing and calculating signal parameters due to the security mechanisms. In contrast, Wi-Fi, which is more accessible, also exhibits marked variability, highlighting its vulnerability to interference.

The SNR results demonstrate a general decrease with increasing distance, consistent with expectations. However, Wi-Fi and Bluetooth exhibit high SNRs at short distances, highlighting their ability to emit robust signals in the face of noise. This feature, although beneficial in proximity scenarios, implies higher energy consumption compared to LoRa and ZigBee, especially LoRa. We have noticed a drop-in signal quality of Wi-Fi and Bluetooth the moment there is a water obstacle which makes the impact of water on the quality of the signal, particularly observed in Wi-Fi and Bluetooth, highlights the sensitivity of these technologies to physical obstacles, particularly aquatic ones. Conversely, ZigBee and LoRa are more resistant to this interference, highlighting their adaptability to hostile environments.

If we now focus on the flow, the resilience of LoRa to noise is clearly demonstrated in the analysis of the flow as a function of the SNR and the quantity of traffic remains stable even if the energy of the noise is greater than the energy of the signal (SNR<0), this property, resulting from its robust modulation, positions

LoRa as a preferred option for sensitive information or missions, despite a slight overhead (low throughput). While Wi-Fi offers the highest throughput, its efficiency drops significantly when the SNR becomes low. Bluetooth, due to its low noise resistance, sees its throughput decline rapidly, which makes Bluetooth a poor choice for mobile robots in hostile locations despite providing high information security.

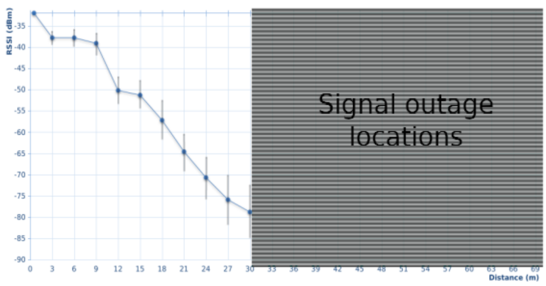

Figure 6. RSSI versus distance, ZigBee technology

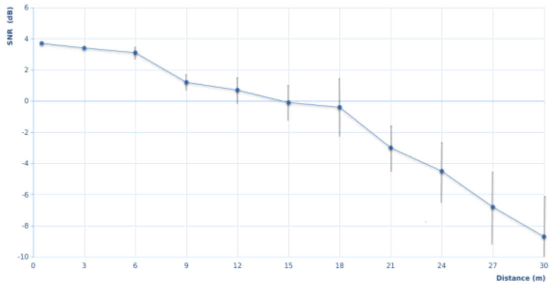

Figure 7. SNR versus distance, ZigBee technology

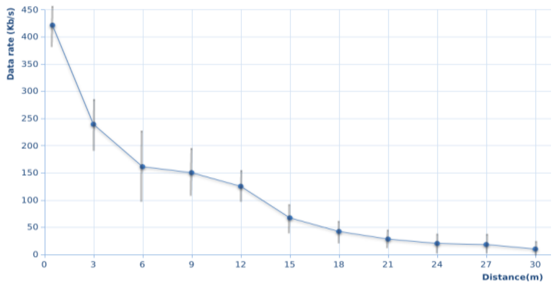

Figure 8. Data rate versus distance, ZigBee technology

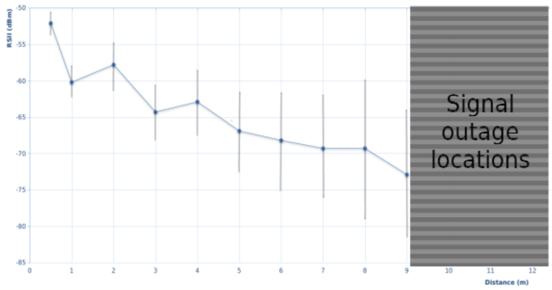

Figure 9. RSSI versus distance, Bluetooth technology

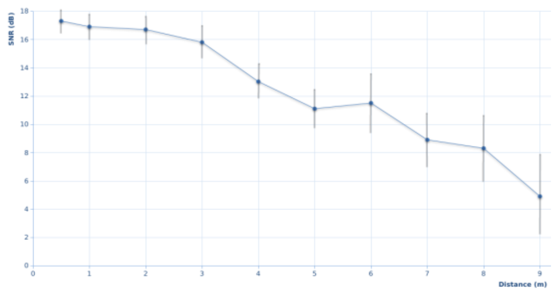

Figure 10. SNR versus distance, Bluetooth technology

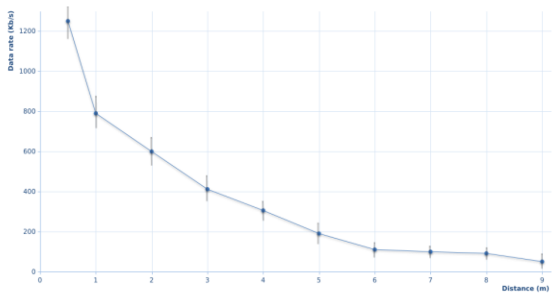

Figure 11. Data rate versus distance, Bluetooth technology

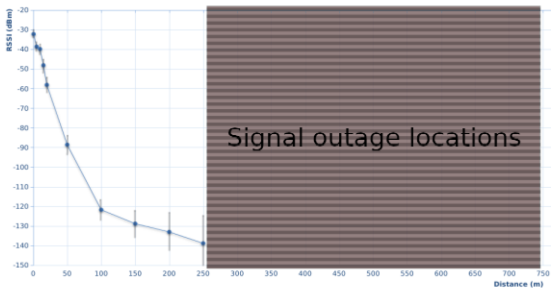

Figure 12. RSSI versus distance, LoRa technology

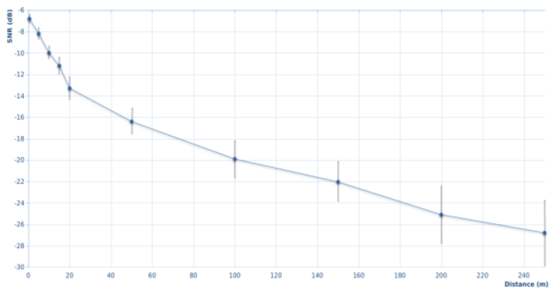

Figure 13. SNR versus distance, LoRa technology

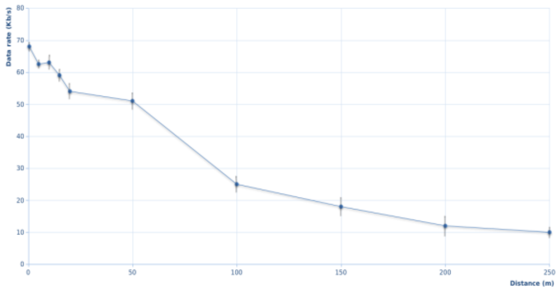

Figure 14. Data rate versus distance, LoRa technology

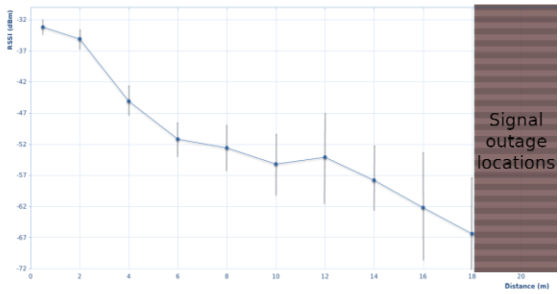

Figure 15. RSSI versus distance, Wi-Fi technology

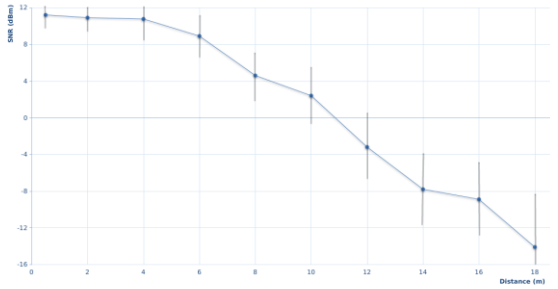

Figure 16. SNR versus distance, Wi-Fi technology

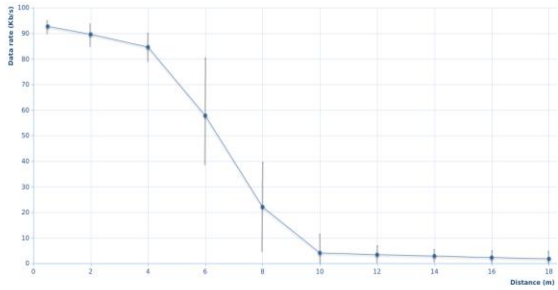

Figure 17. Data rate versus distance, Wi-Fi technology

In conclusion, LoRa technology is positioned as the preferred solution, offering increased noise immunity, notable stability and reduced energy consumption. Its ability to maintain stable speeds even in noisy environments makes it an optimal choice for applications where reliability of transmissions is paramount, and the security provided by LoRa wide area network (LoRaWAN) in the transmission control protocol/internet protocol (TCP/IP), reinforces its position in the choice of technology for collaborative mobile robots. For complex scenarios, a hybrid solution, combining LoRa with other technologies such as Wi-Fi or ZigBee as needed, could provide additional flexibility. These results provide valuable insights to guide the choice of transmission technologies in real contexts of collaborative mobile robots operating in hostile environments.

4. CONCLUSION

In conclusion, this comparative analysis of Wi-Fi, Bluetooth, ZigBee, and LoRa transmission technologies for mobile robots in hostile environments has shed light on their distinct strengths and limitations. The research highlighted the critical factors of signal strength, noise resistance, and data transfer efficiency, providing valuable insights for applications in challenging settings such as disaster-stricken areas, industrial facilities, and outdoor terrains. The findings emphasize the robustness of LoRa in hostile conditions, showcasing its superior performance in maintaining communication stability, even when faced with obstacles and interference. The technology's low power consumption and extended range make it particularly well-suited for scenarios requiring long-distance communication with minimal energy consumption.

Looking forward, the perspectives from this study suggest a promising future for the integration of LoRa in mobile robotic applications within hostile sites. Its resilience to signal degradation and adaptability to various environmental challenges position LoRa as a preferred choice for collaborative robotic missions. Moreover, the exploration of hybrid solutions, combining LoRa with other technologies based on contextual demands, opens avenues for tailored and flexible communication strategies.

As technology evolves, further research can delve into optimizations and advancements in these communication technologies, considering emerging standards and protocols. Additionally, practical implementation trials in real-world scenarios will be crucial for validating the theoretical findings and ensuring the seamless integration of these technologies into diverse robotic applications. This paper lays the foundation for future endeavors, guiding the development of communication systems that empower mobile robots to navigate and collaborate effectively in the face of adversity.

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