IoT

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Maximal LoRa Range for Unmanned Aerial Vehicle Fleet Service in Different Environmental Conditions

Lorenzo Felli [1,*], Romeo Giuliano [2], Andrea De Negri [1], Francesco Terlizzi [3], Franco Mazzenga [4] and Alessandro Vizzarri [4]

1 Italian Institute for Environmental Protection and Research (ISPRA), Via Vitaliano Brancati 48, 00144 Rome, Italy; andrea.denegri@isprambiente.it
2 Department of Innovation & Information Engineering, Guglielmo Marconi University, Via Plinio 44, 00193 Rome, Italy; r.giuliano@unimarconi.it
3 aCrm NET, Via Fiume Giallo, 3, 00144 Rome, Italy; francesco.terlizzi@acrmnet.it
4 Department of Enterprise Engineering "Mario Lucertini", University of Rome Tor Vergata, Via del Politecnico 1, 00133 Rome, Italy; alessandro.vizzarri@uniroma2.it (A.V.)
* Correspondence: lorenzo.felli@isprambiente.it

Abstract: This study investigates communication between UAVs using long range (LoRa) devices, focusing on the interaction between a LoRa gateway UAV and other UAVs equipped with LoRa transmitters. By conducting experiments across various geographical regions, this study aims to delineate the fundamental boundary conditions for the efficient control of a UAV fleet. The parameters under analysis encompass inter-device spacing, radio interference effects, and terrain topography. This research yields pivotal insights into communication network design and optimization, thereby enhancing operational efficiency and safety within diverse geographical contexts for UAV operations. Further research insights could involve a weather analysis and implementation of improved solutions in terms of communication systems.

Keywords: drone fleet; unmanned aerial vehicle; LoRa; LoRaWAN; search and rescue; surveillance; IoT

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1. Introduction

The usage of drones, also referred as unmanned aerial vehicles (UAVs), is experiencing rapid growth across several domains, e.g., from military applications [1,2] to search and rescue missions [3,4]. New use cases continue to emerge, each presenting unique technological hurdles to overcome [5–7]. The applications of drones can require different types of on-board sensors (i.e., the payload), such as those used for environmental monitoring [8] and/or audio and video cameras [9]. In any case, ensuring reliable communication stands out as a critical necessity for safe and efficient operations [10]. This study delves into UAV-to-UAV communication using long range (LoRa) technology, which can offer considerable promise for enhancing connectivity in complex environments. In this setup, one UAV acts as the LoRa gateway, while the remaining UAVs in the fleet are equipped with LoRa transmitters [11]. The primary objective of this study is to comprehensively understand the maximal range conditions that impact the communication capabilities of a UAV fleet operating across different geographical areas. By configuring one UAV as a LoRa gateway and equipping the other UAVs with LoRa transmitters, an experimental framework is established to evaluate the robustness and reliability of LoRa communication in real-world conditions. The connectivity service is provided and managed in accordance with LoRa wide area network (LoRaWAN) protocols, which includes MAC, networking, and encryption [12] functionalities. The main aims are to identify and analyze critical variables such as inter-device distances, environmental radio interference, and terrain topography, which play pivotal roles in determining communication performance. This research activity holds the potential to provide tangible benefits to the practical implementation of UAV systems.

By elucidating the key factors influencing LoRa communication in UAV networks, this study aims to offer guidelines for the design, deployment, and optimization of communication infrastructure in many UAV fleet use cases [13,14]. This, in turn, is expected to yield substantial improvements in operational efficiency and flight safety across a wide range of geographical contexts. Addressing the challenges associated with coverage conditions in LoRa communication between drones holds profound implications for the advancement of unmanned aerial system (UAS) technology. It not only promises to enhance fleet management capabilities [15] but also has the potential to catalyze the development of more sophisticated and interconnected applications within the burgeoning UAV ecosystem [16]. By fostering a deeper understanding of the intricate interplay between communication protocols and environmental variables, this research seeks to lay the groundwork for the seamless integration of UAVs into existing infrastructure and the realization of their full potential across various domains.

Energy savings in UAV systems play a crucial role in extending flight time and increasing the payload capacity. Efficient energy management is essential for maximizing the operational lifespan of UAVs and enhancing their performance [17]. In terms of network operations, there are several strategies to achieve significant energy savings [18,19]. The reduction and optimization of transmitted data are then critical. By minimizing unnecessary data transmission and compressing essential information, UAVs can conserve a substantial amount of energy. Techniques such as data aggregation and selective data transmission ensure that only the most pertinent information is sent, reducing the overall energy consumption [20]. Secondly, task-based selection of the best UAV is an effective strategy. By evaluating the energy efficiency and suitability of each UAV for specific tasks, the network can allocate tasks to the most appropriate UAV [21]. This approach ensures that UAVs with higher energy reserves or more efficient energy usage are prioritized for energy-intensive tasks, thereby optimizing the overall energy utilization of the fleet. Implementing energy-efficient routing protocols is vital for conserving energy. These protocols focus on selecting the most energy-efficient paths for data transmission, minimizing the energy expenditure required for communication between UAVs and ground stations. Routing algorithms that account for energy metrics and dynamically adjust paths based on current energy levels can significantly enhance the energy efficiency of UAV networks. But all the necessary measures required to save energy and guarantee acceptable transmission conditions depend on the environment that the drone is operating. As previously outlined, this paper highlights the problems and challenges related to LoRa-based transmission for drones in different operating environments. This allows us to evidence the problems encountered at the transmission level and to identify the solutions that should be adopted possibly avoiding resorting to techniques/technologies which could be expensive in terms of energy and that could not be necessary to solve the transmission problem in the considered environment i.e., being aware of the environment characteristic could permit to select the “best” transmission solution so to safeguard the drone’s energy.

Finally, the insights gained from this study could serve as a catalyst for innovation, driving the evolution of UAV technology towards more adaptive, resilient, and efficient systems. By addressing the challenges inherent in long-range communication among UAVs, this research endeavor aspires to contribute to the ongoing transformation of aerial operations, paving the way for safer, more efficient, and more interconnected skies in the future.

The paper is organized as follows. Section 2 addresses safety considerations pertinent to long-range communication, encompassing key factors such as signal integrity, interference mitigation, and transmission reliability over extended distances. Section 3 describes the basic concepts of the LoRaWAN protocol. Section 4 models the choice of materials and methods. Section 5 develops the analysis by comparing data. Section 6 concludes with a brief discussion of results and future implementations.

2. UAV Communication Security

Nowadays, multiple (synchronized) UAVs often perform critical operations together. In these scenarios, drone communication plays a critical role [22]. In the use of an unsecure Internet of Drones (IoD) environment, numerous malicious attacks may arise, targeting the manipulation of location data or disruption of data transmission through the deployment of fake nodes. Protecting drones communication involves a combination of techniques, operational practices and, very important, adherence to security protocols designed to counteract unauthorized access, interception, and other forms of cyber threats.

To ensure an appropriate communication channel, secure communication protocols that support mutual authentication and encryption should be established. Protocols such as TLS (Transport Layer Security) or DTLS (Datagram Transport Layer Security) for UAV communications ensure that only authorized devices can connect and exchange data.

Frequency Hopping Spread Spectrum (FHSS) helps to mitigate the risk of jamming and interception by rapidly switching the frequencies used for communication [23,24]. FHSS enhances UAV communication security, reliability, and interference resistance by rapidly switching carrier frequencies according to a predefined sequence, making it hard for unauthorized parties to intercept or interfere with the signal. This technique is particularly advantageous in drone communications for several reasons:

- UAVs use synchronized, pseudo-random frequency hopping to prevent eavesdroppers from easily intercepting communications.
- Transmission over a wider bandwidth reduces susceptibility to interference and jamming, making signals harder to intercept
- UAVs use a predefined frequency hopping pattern, staying synchronized and hidden from unauthorized listeners
- FHSS enables multiple drones to operate in the same area with minimal interference, ideal for swarm and dense drone activity.
- FHSS can help ensure compliance with regulatory requirements for wireless communications

3. Brief Overview of LoRaWAN

LoRa is a spread spectrum modulation technique derived from chirp spread spectrum (CSS) technology and it is a low-cost implementation of chirp spread spectrum for commercial use. It was developed by Cycleo of Grenoble, France, acquired later by Semtech in 2012, a founding member of the LoRa Alliance [25]. Semtech's LoRa devices and Long Range Radio Frequency Wireless Technology (LoRa technology) is a long-range, low-power wireless chipset that is used in the implementation of many Internet of Things (IoT) device networks. Long Range-Frequency Hopping Spread Spectrum (LR-FHSS) is a new physical layer option that was recently added to the LoRa family with the aim of improving network capacity and security with respect to the previous versions. Using a classical star architecture, the end devices communicate bidirectionally to one of the available gateways in the service area. Authentication and identification between the parties is carried out using AES128 encryption through the generation of a network security key associated with a unique device identifier. A LoRaWAN gateway receives information from the devices and broadcasts it via TCP-IP network through a connection to a network server. The network server part handles security, authentication, authorization, data reception and redundancy. A general architecture is shown in Figure 1. In addition, a Multi-access Edge Computing (MEC) may be installed onboard in order to add further functionalities as well as to reduce communication latencies (i.e., the round trip time), increase the network data rate and to reduce processing constraints of other terminals and UAVs of the fleet [26]. The LoRaWAN protocol assigns different frequencies to each end node depending on the applications. The main parameters of LoRa technology are spectral broadening factor (S_F), bandwidth (B_W), transmission power (T_P) and code rate (C_R), which can be configured to best suit the working scenario.

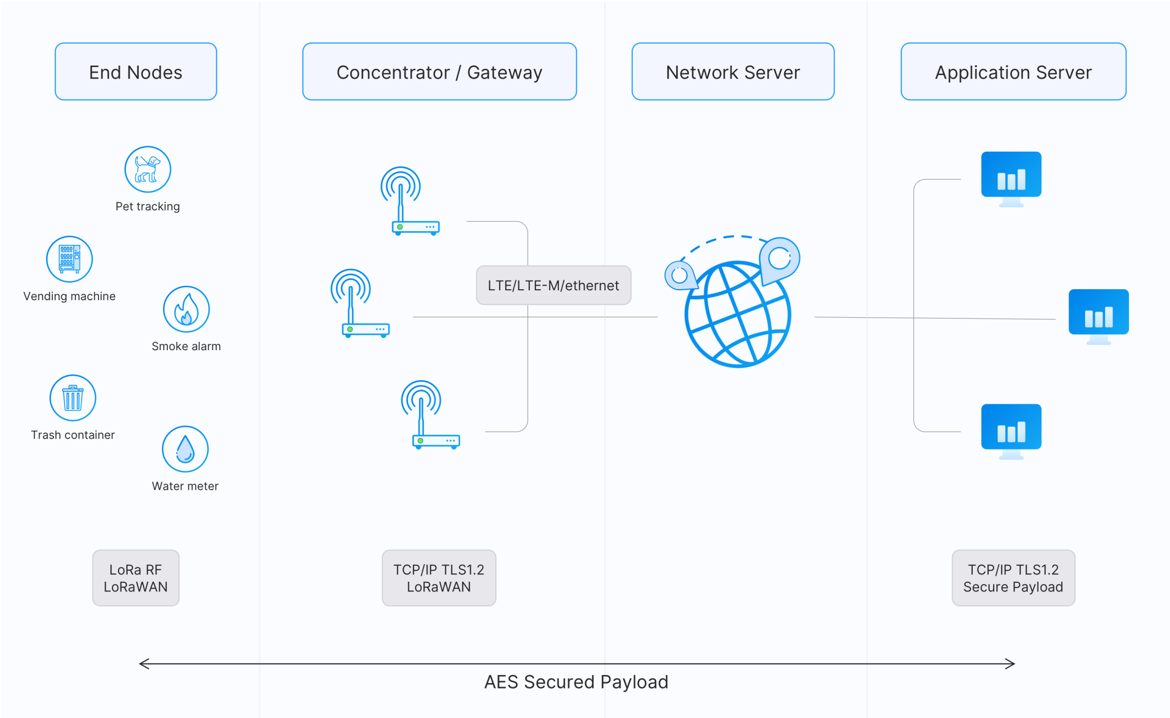

Figure 1. Classical LoRaWAN architecture.

4. Materials and Methods

4.1. Hardware Specifications

The reference network architecture of the system considered in this paper is derived from the overall architecture in Figure 1. In this architecture multiple end nodes equipped with LoRa transmitters serve as data sources. These end nodes, often spread across a wide geographical area, send data wirelessly to a centrally located LoRa gateway. The LoRa gateway, functioning as a bridge, collects the transmitted data from the end nodes. In the production configuration, the gateway interfaces with a network server. For the purposes of this study, all data received from the gateway is directly written to the filesystem of the Raspberry Pi mounted on the drone and subsequently read for downstream analysis The proposed system consists of a LoRaWAN gateway built on a Raspberry Pi platform which incorporates an iC880A concentrator, that is a high-performance device capable of handling multiple LoRa signals simultaneously, thus enhancing the system's capacity and efficiency.

The selected UAV's radio moduleis the iU880B which utilizes Semtech's LoRa® modulation technology. The iU880B radio module also includes the FTDI's FT232RQ serial-to-USB converter chip. The iM880B radio module is a compact and efficient device that provides reliable wireless communication, while the FT232RQ chip ensures seamless data transfer between the radio module and the Raspberry Pi platform.

The iC880A concentrator is equipped with an iSMA-Antenna operating at 868 MHz, ensuring robust and long-range communication capabilities. This antenna is specifically chosen for its ability to provide reliable connectivity in diverse environments. The entire setup is mounted on a Parrot branded UAV, as shown in Figure 2. Parrot UAVs are known for their durability, stability, and ease of operation, making them an ideal choice for this project. The UAV platform allows the system to be mobile and flexible, capable of being deployed in hard-to-reach areas or across large geographic regions.

One of the key features of this system is its operating voltage of 5 V and a maximum RF power of +20 dBm. This ensures that the system is energy-efficient while still providing strong signal transmission capabilities. During testings maximum transmission power has been set to +14 dBm. The Raspberry Pi platform, housed inside the gateway, can be customized and guarantees the scalability of the system. In particular, users can modify and expand the software to meet specific project requirements, making the system highly adaptable to different use cases thanks to the Linux operating system on the platform.

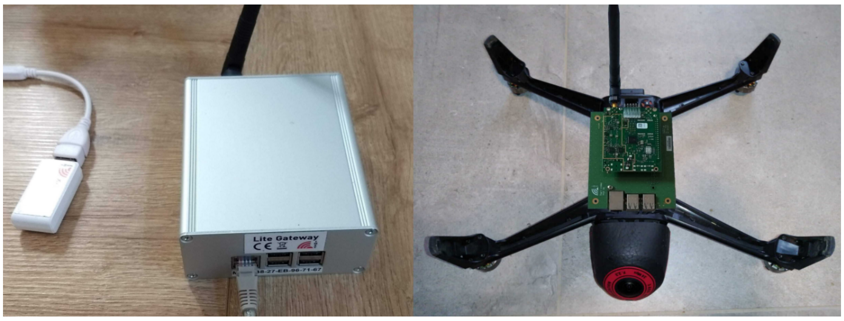

Figure 2. The IU880B node and the Raspberry IC880A platform (**left**). The IC880A platform mounted on the bottom of the drone (**right**).

The integration of these components results in a flexible system that can be used in a wide range of applications. For instance, in environmental monitoring, the UAV can collect data from remote sensors and transmit them back to a central server for subsequent analysis. In agriculture, the system can be used to monitor crop health and soil conditions, providing valuable data to farmers for imrpoving decision-making. In smart cities, the system can be utilized to monitor air quality, mobile traffic conditions etc. so to contributie to the efficient management of urban environments.

The hardware shown in Figure 2 proved to be extremely efficient and flexible for prototyping purposes and it offers significant advantages for developers and engineers. This flexibility extends beyond just the hardware aspects, encompassing a wide range of customization options that enhance the system's overall adaptability. Thanks to its modular design this hardware platform can be easily tailored to meet specific project requirements. Components can be also swapped out or upgraded, allowing for a high degree of personalization that can accommodate various technical needs and constraints.

Furthermore, the open-source operating system installed on the platform allows customization and optimization by enabling developers to modify, enhance, and extend the system's capabilities. In particular, developers can easily write custom scripts, create new applications, and implement specific functionalities that are essential for their unique use cases.

The combination of efficient hardware and a versatile open-source operating system creates a powerful platform for innovation. Developers can experiment with different configurations and settings, iterating rapidly to find the optimal setup for their applications. This is particularly beneficial in prototyping endeavors, where the ability to quickly test and refine ideas is crucial. The open-source nature of the operating system also fosters a collaborative environment, where developers can share their modifications and improvements with the broader community, further driving innovation and the development of new features.

In summary, the hardware depicted in Figure 2 is efficient and flexible from a hardware standpoint and allows for full software reprogrammability and adaptability.

4.2. Geographical Areas

To assess the effectiveness of the proposed system, we conducted tests in three locations with different environmental characteristics. These locations were selected to represent a broad range of conditions that the system might encounter in real-world applications. The first location is a densely vegetated area, characterized by thick forests, abundant foliage, and significant natural barriers. This environment was selected to test the system's ability to maintain communication in challenging conditions with substantial physical obstructions. It provides insight into the system's robustness and signal penetration capabilities in an area with a high vegetation density, allowing for the evaluation of long-range communication performance and energy efficiency in a setting drone-to-signal attenuation and reflection.

The second location is an urban area that is characterized by high-density buildings, significant electromagnetic interference, and heavy traffic. This environment provided a challenging setting for assessing the system's ability to maintain reliable communication in the presence of numerous potential obstructions and sources of interference.

Finally, the third location is a rural area, with vast open fields, a sparse population, and minimal electromagnetic interference. This environment was selected to test the system's ability to cover large distances with minimal physical obstructions, providing insight into its long-range communication capabilities and energy efficiency in a low-interference setting.

By conducting these tests across diverse environments, a comprehensive understanding of the system's sustainability and communication efficiency was achieved, evidencing its strong features and identifying possible improvements. The characteristics of the three selected areas are detailed in the following points.

- Dense vegetation: Dense vegetation characterizes the Castel Porziano Reserve' an area, spanning approximately 60 km^2, which is close to Rome and not entirely accessible. The specific area of interest highlighted in Figure 3 covers about 9.3 km^2 and is notable for its dense coverage of medium to tall trees. The vegetation within the designated test area is dense and poses both challenges and opportunities for testing purposes, particularly in evaluating the system's communication efficiency and sensor capabilities in environments with significant natural obstacles. Conducting tests in such environments provides valuable insights into how well the system performs under real-world conditions where dense vegetation can affect signal propagation and data collection by sensors. These tests are crucial for assessing the system's adaptability and robustness in diverse environmental settings, ensuring its effectiveness in applications such as environmental monitoring, wildlife conservation, and ecosystem management within protected areas like the Castel Porziano Reserve.

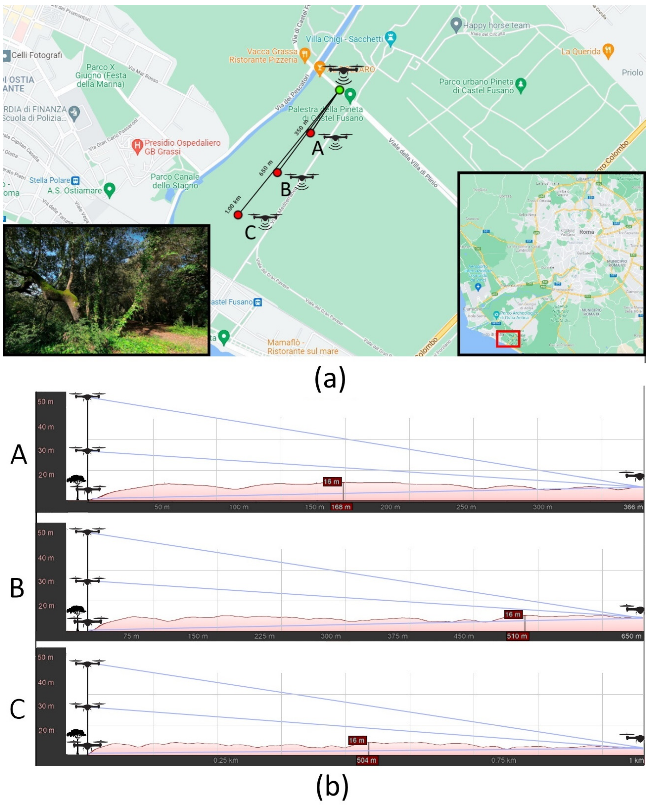

Figure 3. Dense vegetation: (**a**) aerial view with survey points, a photo taken from ground and the position of area in the red box, (**b**) terrain profile.

- Urban area. Figure 4 provides a visual representation of the spatial distribution of three drone radio modules positioned strategically within the historical center of Rome. These locations were chosen near Castel Sant'Angelo, the Trevi Fountain, and the Colosseum, highlighting the system's deployment in densely populated urban settings. Due to flight restrictions within the historical center, the drone operated along a strictly vertical trajectory, remaining within the confines of the departure location's property perimeter. To ensure privacy compliance, all onboard cameras were deactivated during flight operations. Testing in urban environments presented substantial challenges for establishing reliable communication links, even when operating at an altitude of 50 m. The gathered data revealed significant hurdles stemming from both man-made structures and the natural topography of Rome's historic center. The city's undulating terrain, characterized by hills and valleys, posed a barrier to signal propagation, complicating the efforts required to maintain consistent communication between the drone and ground stations. Moreover, the presence of dense buildings further exacerbated signal attenuation and interference. These urban conditions underscored the importance of adaptive communication protocols and robust signal processing techniques to overcome obstacles and ensure uninterrupted data transmission. Despite these challenges, conducting tests in urban environments allowed us to evaluate adaptive strategies to optimize communication reliability and efficiency in complex urban landscapes. Such testing is crucial for enhancing the system's resilience and adaptability, ensuring its effectiveness in urban applications such as emergency response, infrastructure monitoring, and cultural heritage preservation, where reliable communication and data transmission are paramount.

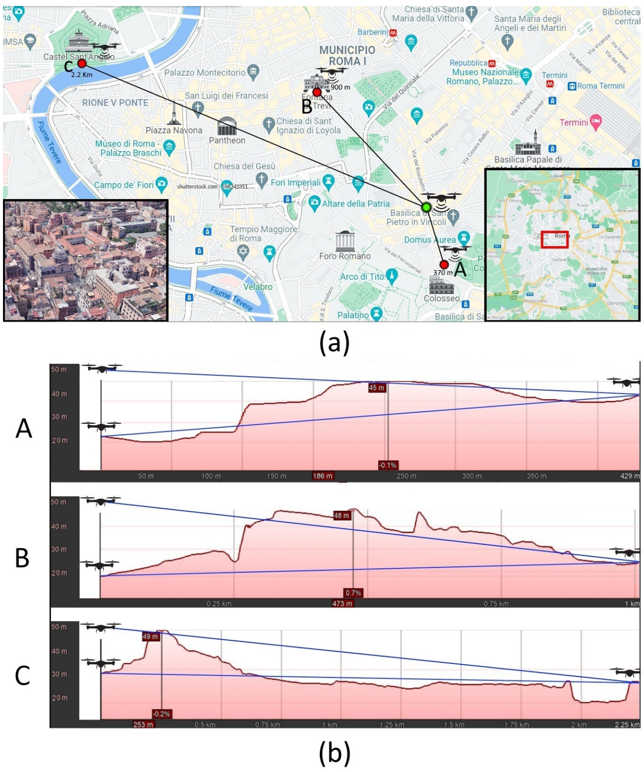

Figure 4. Urban area: (**a**) aerial view with survey points, a photo taken from ground and the position of area in the red box, (**b**) terrain profile.

- Agricultural area: Figure 5 depicts the strategic positioning of both the gateway and drone radio modules within an agricultural area. This area is primarily devoted to the cultivation of wheat and maize, characterized by wide-open spaces that are devoid of obstructive elements that might interfere with signal transmission. The placement of three survey points along a designated bicycle path, along with the strategically located gateway, was carefully planned to maximize coverage and data collection efficiency. The topography of the surveyed locations is flat, contributing to optimal conditions for signal propagation. Additionally, the vegetation density is small, and natural obstacles are typically under 50 cm in height throughout the entire designated area. This ensures minimal attenuation of signals, thereby facilitating robust communication between the drone radio modules and ground-based equipment. The testing in this environment offers distinct advantages for assessing the system's performance in rural and crop cultivation settings. The absence of tall structures and the uniform terrain simplify signal management and data transmission processes, highlighting the system's adaptability and reliability under favorable environmental conditions. These tests provide valuable insights into optimizing communication protocols and sensor deployment strategies tailored to agricultural monitoring and management applications.

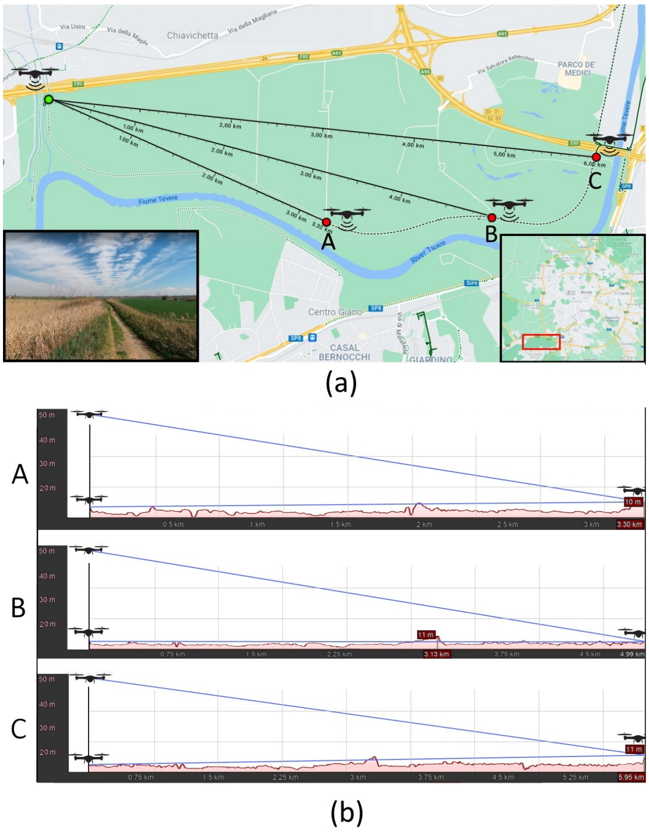

Figure 5. Agricultural area: (**a**) aerial view with survey points, a photo taken from ground and the position of area in the red box, (**b**) terrain profile.

4.3. Experimental Procedures and Parameters

The experimental setting were keep unchanged when passing from one area to another one to ensure the consistency, comparability, and reproducibility of the results. These included standardizing hardware configurations, as well as environmental variables such as weather conditions, time of day, and season. By keeping these parameters uniform, the data obtained could be interpreted more accurately and reliably, reducing potential confounding factors that could skew the results. All the tests were conducted in and near Rome during November 2023, specifically at 11 a.m. local time. This timing was chosen to minimize variations in environmental conditions and maximize the repeatability of measurements. Due to the nature of the terrain and accessibility constraints, most measurements were conducted either on foot or on a bicycle along designated trails within the specified area of interest. Each measurement session involved positioning the transmitting device and keeping it stationary for a time period that was long enough to ensure the possibility of capturing and analyzing at least three received messages. This approach provided a robust basis for assessing the quality and reliability of the reception under varying conditions. For each scenario, three distinct reference points were selected at different distances from the gateway, all positioned 1 m above the ground. This methodology aimed to capture variations in signal strength and reception quality as the distance from the gateway increased. The gateway itself was deployed at two different heights: 1 m and 50 m above ground level. This variation in height is helpful to evaluate the impact of antenna elevation on signal propagation and coverage area. In scenarios with dense vegetation, an additional measurement point was added at a height of 30 m from the ground. This specific measurement aimed to provide deeper insights into the transmission dynamics within these environments characterized by dense foliage, where signal attenuation and obstruction could significantly affect communication reliability. By systematically varying these parameters and documenting the results, this study aimed to comprehensively characterize the system's performance across diverse operating conditions. This approach facilitated a thorough understanding of the system's capabilities and evidenced potential areas for improvement or optimization of the system for future deployments.

As previously outlined, each measurement was made by keeping the transmitting device in the same position for a few seconds and waiting for at least 3 received messages to determine the quality of reception. For each scenario, three points were taken as references at three different distances (Table 1) from the gateway, all at a height of 1 m above the ground. The gateway was positioned 1 m above ground level and 50 m above ground level. In the case of the scenario with dense vegetation, a further measurement at 30 m was taken in order to better characterize the transmission dynamics. These setting are summarized in Table 1.

Table 1. Position and distance from the gateway.

	Dense Vegetation	**Urban Area**	**Agricultural Area**
Position	***dist* [m]**	***dist* [m]**	***dist* [m]**
A	350	430	3320
B	650	1000	5000
C	1000	2250	6000

In addition, for each environment, the packet delivery ratio (PDR) was calculated as a function of the payload as follows (1):

$$PDR = \frac{\sum N_R}{\sum N_S} \tag{1}$$

where N_R represents the number of packets correctly received by the gateway, and N_S denotes the total number of packets transmitted within the specified time interval. Throughout the testing process, other critical configuration were kept unchanged in the tabular results, including the following: the spreading factor (SF) was set to 12, the coding rate (CR) was maintained at 4/5, and the frequency of operation was set and fixed at 868 MHz. This allowed for a direct comparison of the packet delivery ratio (PDR) across the selected scenarios and for the considered environmental conditions. Then, to further detail the signal behavior, we further varied the LoRa parameters as shown in the bar graphs.

5. Maximal Coverage Condition Analysis

5.1. Dense Vegetation

LoRa was originally designed for extensive coverage, boasting theoretical ranges of up to 15 km in suburban areas and 5 km in urban settings. The measurements conducted within densely vegetated scenarios (see Figure 6) provided different results. Specifically, it was observed that the effective range at a height of one meter fell substantially short of theoretical predictions. Despite utilizing a spreading factor $S_F = 7$, the drone radio module in position 'A' at 350 m away was successfully reached, whereas no signal was received from the drone radio module in position 'B' at 650 m. This notable reduction in range can be attributed to the challenging propagation conditions that are inherent to densely wooded environments. Despite the inherent robustness of the CSS modulation technique, the tests underscored LoRa's susceptibility to signal degradation due to electromagnetic absorption by natural obstacles. The utilization of drones for testing provided valuable insights, demonstrating that elevating the onboard gateway's height resulted in significant improvements in packet reception quality, notably observed at an altitude of 30 m (see Figure 6). At this elevation, utilizing a code rate C_R of 4/8 enabled successful reception of the packets from the drone module at position 'C' at 1000 m away, even with a spreading factor S_F of 7. Notably, increasing the S_F led to an immediate enhancement in signal stability. Remarkably, at an altitude of 50 m above ground level, the signal stability remained good across all S_F and C_R configurations, even for the most distant drone module at position 'C', as shown in Table 2. Regarding payload testing, significant signal degradation due to payload size was only evident for the farthest drone module in position 'C' at 30 m above ground level. This is shown in Table 3.

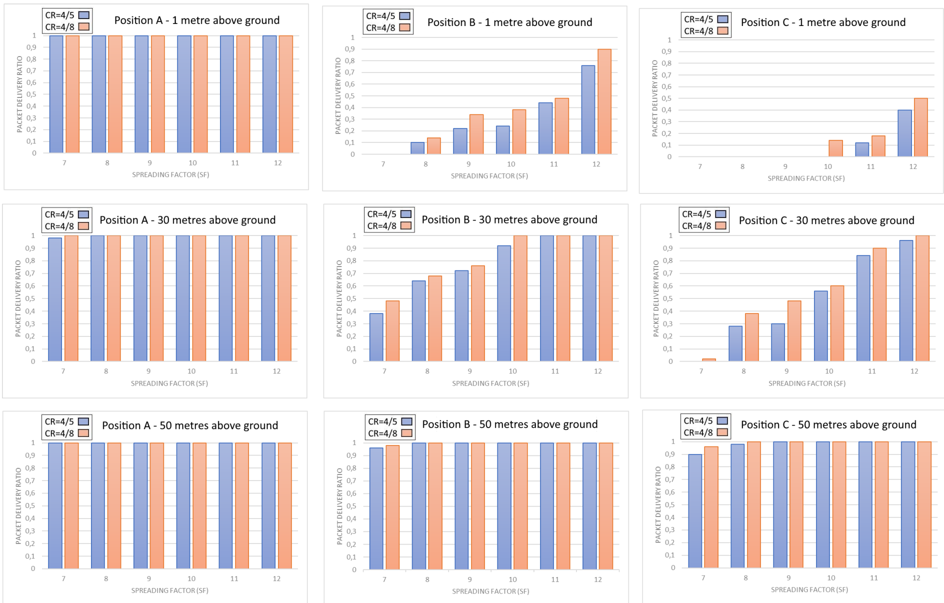

Figure 6. Dense vegetation: PDR obtained for different S_F values using C_R = 4/5 and C_R = 4/8 and a payload of 20 bytes.

Table 2. Dense vegetation: S_F = 12 C_R = 4/5 at 868 MHz, 50 m from the ground.

	POS A	**POS B**	**POS C**
Payload [bytes]	***PDR***	***PDR***	***PDR***
20	1	1	1
25	1	1	1
30	1	1	1
35	1	1	1
40	1	1	1

Table 3. Dense vegetation: S_F = 12 C_R = 4/5 at 868 MHz, 30 m from the ground.

	POS A	**POS B**	**POS C**
Payload [bytes]	***PDR***	***PDR***	***PDR***
20	1	1	0.95
25	1	1	0.9
30	1	1	0.8
35	1	0.95	0.65
40	1	0.85	0.45

5.2. Urban Area

The urban settings posed the highest challenge in establishing communication, even at a height of 50 m. The collected measurements underscored the complexity arising not only from artificial structures but also from the topography of Rome's historic center, where hills served as natural barriers to signal propagation. Despite LoRa's designed long-range capabilities, which theoretically offer urban coverage of up to 5 km, practical challenges were evident. Achieving reliable communication with a drone module positioned 2.2 km away required an elevation of 50 m above ground level, starting with a S_F of at least 10 and a C_R of 4/8, which was sufficient to receive just one packet out of ten, and going up to 6 out of 10 packets with a S_F of 12 and a C_R of 4/8. The trials highlighted LoRa's susceptibility to both natural and artificial obstructions. Buildings, walls, and other urban structures significantly disrupted signal continuity, while the hills in Rome's historic center further exacerbated these issues. The drone-based testing revealed that signal transmission in urban settings occurred discontinuously, heavily influenced by the presence and layout of artificial structures along the drone's flight path (see Figure 7). This discontinuity underscores the importance of strategic positioning and signal planning in urban deployments. Maintaining a spreading factor of 12 and a C_R of 4/5 at a frequency of 868 MHz, further analysis was conducted to understand the impact of payload size on communication efficiency in urban environments. The data presented in Table 4 indicate a significant effect of payload size on the packet delivery ratio (PDR). Specifically, there was a notable reduction in PDR as the payload size increased. For instance, the PDR was halved when comparing payloads of 40 bytes to those of 20 bytes. This finding suggests that smaller payloads are more effective in urban settings where signal propagation is challenging and characterized by fast variations with time. The trials demonstrated that while LoRa technology is robust and capable of long-range communication, its performance in dense urban environments is significantly hindered by both artificial and natural barriers. This highlights the necessity of optimization techniques such as (adaptively) adjusting the spreading factor and coding rate to enhance communication reliability. Additionally, the impact of payload size must be considered, as smaller payloads tend to yield higher delivery ratios in complex urban landscapes. These insights are crucial for planning and deploying LoRa-based communication systems in urban areas. They provide a clear understanding of the limitations and necessary adjustments needed to maintain effective communication. Future work could explore advanced strategies to mitigate these challenges, such as the use of repeaters or adaptive modulation techniques, to further enhance the reliability and efficiency of LoRa networks in urban settings. By addressing these challenges, the potential of LoRa technology in smart city applications, environmental monitoring, and other urban-centric use cases can be fully realized, ensuring robust and reliable data transmission, even in the most challenging environments.

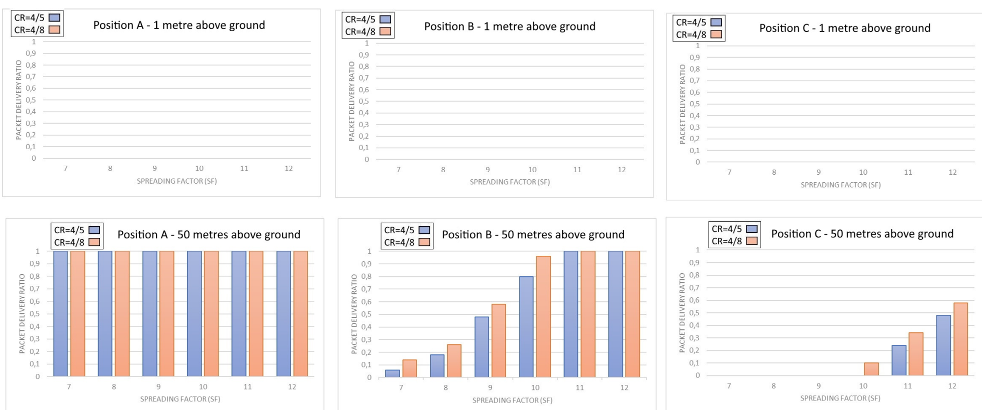

Figure 7. Urban area: PDR obtained for different S_F values using C_R = 4/5 and C_R = 4/8 and a payload of 20 bytes.

Table 4. Urban area: S_F = 12 C_R = 4/5 at 868 MHz, 50 m from the ground.

	POS A	POS B	POS C
Payload [bytes]	*PDR*	*PDR*	*PDR*
20	1	1	0.45
25	1	0.75	0.4
30	1	0.5	0.35
35	0.9	0.45	0.25
40	0.85	0.45	0.2

5.3. Agricultural Area

In this experimental setup, the range capabilities of LoRa technology were tested. In particular, the devices demonstrated robust and uninterrupted transmission capabilities extending up to 6 km. This achievement was particularly noteworthy, given the use of a low spreading factor, which underscores the efficiency and reliability of the LoRa protocol in long-range communication scenarios. The ability to maintain strong signal integrity over such distances highlights LoRa's potential for applications in wide and open areas where long-range connectivity is crucial. Despite our initial expectations, the incremental improvement observed by elevating the gateway to an altitude of 50 m above ground level yielded only marginal benefits. This is illustrated in Figure 8. This finding underlines the resilience of LoRa communication, even in relatively flat terrains, even where altitude adjustments may have limited impacts on signal propagation. The data suggest that in such environments, the elevation of the gateway does not significantly enhance the communication range or quality. This resilience is attributed to the absence of substantial physical impediments, such as buildings or dense vegetation, which typically obstruct signal pathways, as also shown in the previous two scenarios. The lack of obstructions in the test area facilitated unobstructed communication pathways, allowing the devices to traverse expansive distances with minimal signal attenuation. The clear line of sight in this flat terrain environment played a crucial role in maintaining the integrity of the signal, thereby enhancing the overall performance of the LoRa system. The results suggest that in open environments, LoRa technology can be effectively utilized without the need for significant elevation of the transmission/reception equipment. Furthermore, the experiments revealed that modifying the payload size did not significantly impact the communication performance in this scenario (see Table 5). This contrasts with findings from urban environments, where payload size was a critical factor affecting the packet delivery ratio (PDR). In the open, flat terrain of the experimental setup, the devices maintained a consistent performance, regardless of payload adjustments, highlighting the robustness of the LoRa protocol under these conditions. These findings have important implications for the deployment of LoRa networks in rural and agricultural settings where the terrain is typically flat and obstructions could be minimal. The ability to maintain long-range communication without the need for elevated gateways can simplify the deployment process and reduce costs. Additionally, the consistent performance across different payload sizes offers flexibility in designing applications that require variable data transmission volumes. In summary, the experimental results demonstrate the range capabilities and robustness of LoRa technology in open, flat terrains. The marginal benefits of elevating the gateway and the negligible impact of payload modifications highlight the protocol's efficiency in such environments. These insights can guide the strategic deployment of LoRa networks in similar settings, ensuring reliable and cost-effective long-range communication.

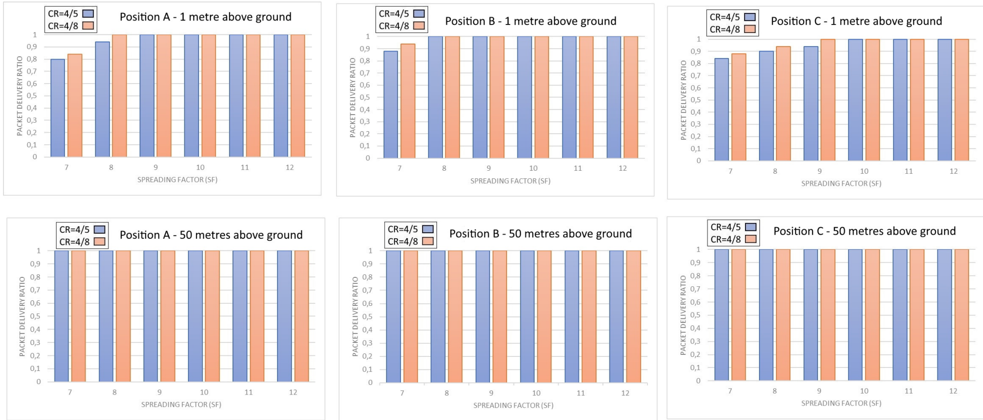

Figure 8. Agricultural area: PDR obtained for different S_F values using C_R = 4/5 and C_R = 4/8 and a payload of 20 bytes.

Table 5. Agricultural area: S_F=12 C_R = 4/5 at 868 MHz, 50 m from the ground.

	POS A	POS B	POS C
Payload [bytes]	***PDR***	***PDR***	***PDR***
20	1	1	1
25	1	1	1
30	1	1	1
35	1	1	1
40	1	1	1

6. Conclusions

In this paper, we tried to provide guidance on the best parameters, including height, that could be established for a hypothetical flyover based on the terrain type, as well as when and how to use (sophisticated) adaptive transmission techniques to cope with impairments related to the environment in which the drone is operating. The test sessions were conducted by keeping the UAV in a stationary position for a few seconds and waiting for at least three received messages to determine the quality of reception. This method ensured an accurate assessment of signal stability and reliability in the considered environments. As expected, the stability of the LoRa signal was strongly influenced by the environment in which the signal propagation occurred.

In agricultural areas, the signal is significantly more stable than in urban or densely wooded areas. This increased stability is primarily due to the presence of fewer obstacles, resulting in less signal reflection and attenuation. Open fields, characterized by minimal physical barriers, allow the LoRa signal to travel more directly and consistently, leading to better reception quality. The lack of buildings, tall structures, and dense foliage in these areas provides a clear path for the signal, minimizing interference and ensuring a more reliable communication link.

Conversely, in urban environments, the situation is markedly different. Numerous buildings, walls, and other structures create significant interference, causing signal reflections, diffraction, and scattering. These factors disrupt the direct path of the signal, resulting in reduced stability and reliability. Urban settings are characterized by a complex landscape of artificial structures that can absorb, reflect, or scatter the LoRa signal, leading to a considerable decrease in signal quality and consistency.

Similarly, densely wooded areas present a multitude of obstacles, such as trees and foliage, which absorb and scatter the signal, further degrading its stability. The thick canopy and underbrush in forested areas create a challenging environment for signal propagation. The presence of leaves, branches, and trunks causes multiple reflections and absorptions, significantly weakening the signal before it reaches the receiver.

These findings highlight the critical importance of environmental considerations in the deployment, management, and operation of LoRa-based UAV systems. Understanding the impact of various surroundings on signal propagation can guide the optimization of UAV communication strategies, ensuring better performance and reliability in diverse operational settings as well as reductions in power consumption by avoiding unnecessarily power-hungry strategies. This knowledge is essential for designing efficient and effective UAV communication networks that can adapt to different environmental challenges and provide robust performance across various terrains and landscapes. This study shows how the increase in flight height contributes differently depending on the environments examined:

- Urban. There is evidence of a less-linear and more-sudden improvement when increasing the height of the gateway due to the presence of buildings and wall structures, and in general, there is greater inhomogeneity in the structure of the obstacles. The possibility of reducing the length of the payload allows for improved communication capabilites.
- Agricultural: The extreme uniformity and absence of both natural and artificial obstacles that make up a vast agricultural environment were reflected in the almost uniformity of the measurements taken both at ground level and at a height of 50 m.
- Woodland: There is evidence of an almost linear improvement of the signal quality as the height of the gateway increases due to the extreme homogeneity of the obstacles constituted by tall trees.

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References

1. Utsav, A.; Abhishek, A.; Suraj, P.; Badhai, R.K. An IoT based UAV network for military applications. In Proceedings of the 2021 Sixth International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET), Chennai, India, 25–27 March 2021; pp. 122–125.
2. Zhu, X. Analysis of military application of UAV swarm technology. In Proceedings of the 2020 3rd International Conference on Unmanned Systems (ICUS), Harbin, China, 27–28 November 2020; pp. 1200–1204.
3. Martinez-Alpiste, I.; Golcarenarenji, G.; Wang, Q.; Alcaraz-Calero, J.M. Search and rescue operation using UAVs: A case study. *Expert Syst. Appl.* **2021**, *178*, 114937. [CrossRef]
4. Viguria, A.; Maza, I.; Ollero, A. Distributed service-based cooperation in aerial/ground robot teams applied to fire detection and extinguishing missions. *Adv. Robot.* **2010**, *24*, 1–23. [CrossRef]
5. Gu, X.; Zhang, G. A survey on UAV-assisted wireless communications: Recent advances and future trends. *Comput. Commun.* **2023**, *208*, 44–78. [CrossRef]
6. Al-lQubaydhi, N.; Alenezi, A.; Alanazi, T.; Senyor, A.; Alanezi, N.; Alotaibi, B.; Alotaibi, M.; Razaque, A.; Hariri, S. Deep learning for unmanned aerial vehicles detection: A review. *Comput. Sci. Rev.* **2024**, *51*, 100614. [CrossRef]
7. Chen, C.; Zheng, Z.; Xu, T.; Guo, S.; Feng, S.; Yao, W.; Lan, Y. Yolo-Based UAV Technology: A Review of the Research and Its Applications. *Drones* **2023**, *7*, 190. [CrossRef]
8. Jouhari, M.; Saeed, N.; Alouini, M.-S.; Amhoud, E.M. A Survey on Scalable LoRaWAN for Massive IoT: Recent Advances, Potentials, and Challenges. *IEEE Commun. Surv. Tutorials* **2023**, *25*, 1841–1876. [CrossRef]
9. Giuliano, R.; Innocenti, E.; Mazzenga, F.; Vegni, A.M.; Vizzarri, A. IMPERSONAL: An IoT-Aided Computer Vision Framework for Social Distancing for Health Safety. *IEEE Internet Things J.* **2022**, *9*, 7261–7272. [CrossRef]
10. Mozaffari, M.; Lin, X.; Hayes, S. Toward 6G with Connected Sky: UAVs and Beyond. *IEEE Commun. Mag.* **2021**, *59*, 74–80. [CrossRef]

11. Khalifeh, A.; Aldahdouh, K.A.; Darabkh, K.A.; Al-Sit, W. A Survey of 5G Emerging Wireless Technologies Featuring LoRaWAN, Sigfox, NB-IoT and LTE-M. In Proceedings of the 2019 International Conference on Wireless Communications Signal Processing and Networking (WiSPNET), Chennai, India, 21–23 March 2019; pp. 561–566.
12. Bianco, G.M.; Giuliano, R.; Mazzenga, F.; Marrocco, G. Multi-Slope Path Loss and Position Estimation With Grid Search and Experimental Results. *IEEE Trans. Signal Inf. Process. Over Netw.* **2021**, *7*, 551–561. [CrossRef]
13. Lagkas, T.; Argyriou, V.; Bibi, S.; Sarigiannidis, P. UAV IoT framework views and challenges: Towards protecting drones as "Things". *Sensors* **2018**, *18*, 4015. [CrossRef] [PubMed]
14. Eun, J.; Song, B.D.; Lee, S.; Lim, D.E. Mathematical investigation on the sustainability of UAV logistics. *Sustainability* **2019**, *11*, 5932. [CrossRef]
15. Cordova, F.; Olivares, V. Design of drone fleet management model in a production system of customized products. In Proceedings of the 2016 6th International Conference on Computers Communications and Control (ICCCC), Oradea, Romania, 10–14 May 2016; pp. 165–172.
16. Shakhatreh, H.; Sawalmeh, A.H.; Al-Fuqaha, A.; Dou, Z.; Almaita, E.; Khalil, I.; Othman, N.S.; Khreishah, A.; Guizani, M. Unmanned aerial vehicles (UAVs): A survey on civil applications and key research challenges. *IEEE Access* **2019**, *7*, 48572–48634. [CrossRef]
17. Thibbotuwawa, A.; Nielsen, P.; Zbigniew, B.; Bocewicz, G. Energy consumption in unmanned aerial vehicles: A review of energy consumption models and their relation to the UAV routing. In *Information Systems Architecture and Technology: Proceedings of 39th International Conference on Information Systems Architecture and Technology–ISAT 2018: Part II*; Springer International Publishing: Berlin/Heidelberg, Germany, 2019; pp. 173–184.
18. Boukoberine, M.N.; Zhou, Z.; Benbouzid, M. A critical review on unmanned aerial vehicles power supply and energy management: Solutions, strategies, and prospects. *Appl. Energy* **2019**, *255*, 113823. [CrossRef]
19. Debnath, S.K.; Omar, R.; Latip, N.B.A. A review on energy efficient path planning algorithms for unmanned air vehicles. In Proceedings of the Computational Science and Technology: 5th ICCST 2018, Kota Kinabalu, Malaysia, 29–30 August 2018; pp. 523–532.
20. Xiong, F.; Zheng, H.; Ruan, L.; Wang, H.; Tang, L.; Dong, X.; Li, A. Energy-saving data aggregation for multi-UAV system. *IEEE Trans. Veh. Technol.* **2020**, *69*, 9002–9016. [CrossRef]
21. Jin, Y.; Minai, A.A.; Polycarpou, M.M. Cooperative real-time search and task allocation in UAV teams. In Proceedings of the 42nd IEEE International Conference on Decision and Control (IEEE Cat. No. 03CH37475), Maui, HI, USA, 9–12 December 2003; Volume 1, pp. 7–12.
22. Barka, E.; Kerrache, C.A.; Benkraouda, H.; Shuaib, K.; Ahmad, F.; Kurugollu, F. Towards a trusted unmanned aerial system using blockchain for the protection of critical infrastructure. *Trans. Emerg. Telecommun. Technol.* **2022**, *33*, e3706. [CrossRef]
23. Simon, M.; Omura, J.; Scholtz, R.; Levitt, B. *Spread Spectrum Communications Handbook*; McGraw-Hill: New York, NY, USA, 1994.
24. Strasser, M.; Capkun, S.; Popper, C.; Cagalj, M. Jamming-resistant key establishment using uncoordinated frequency hopping. In Proceedings of the IEEE Symposium on Security and Privacy (May 2008), Oakland, CA, USA, 18–22 May 2008; pp. 64–78.
25. Silva, F.S.; Neto, E.P.; Oliveira, H.; Rosário, D.; Cerqueira, E.; Both, C.; Zeadally, S.; Neto, A.V. A Survey on Long-Range Wide-Area Network Technology Optimizations. *IEEE Access* **2021**, *9*, 106079–106106. [CrossRef]
26. Mao, Y.; You, C.; Zhang, J.; Huang, K.; Letaief, K.B. A Survey on Mobile Edge Computing: The Communication Perspective. *IEEE Commun. Surv. Tutor.* **2017**, *19*, 2322–2358. [CrossRef]