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Zigbee Protocol-Based Communication Network for Multi-Unmanned Aerial Vehicle Networks

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ABSTRACT This paper proposes a communication protocol for Unmanned Aerial Vehicles (UAVs) using ZigBee technology. A review of the state-of-the-art of Flying Ad-hoc Networks (FANETs) and its main respective technologies is presented in detail. A comparison among Long Term Evaluation (LTE), WiFi, and ZigBee is performed, thus showing that ZigBee stands out as a good alternative to scenarios without proper infrastructure. A Raspberry Pi 3 Model B board associated with module XBEE PRO S3B 915 MHz is embedded in a UAV model DJI Phantom 3 Standard to carry out the tests. The obtained results show that the adopted protocol is capable of sending and receiving images between the UAV and the ground station. Tests are also performed using a flying aircraft, where it is demonstrated that the transmission is successfully executed for all cases and the communication protocol operates accurately. In addition, a brief analysis of the time interval required by the process is presented, as there are no significant differences among the existing scenarios.

INDEX TERMS Unmanned aerial vehicles, communication networks, protocols, zigbee, mobile ad-hoc networks.

I. INTRODUCTION

A wide variety of applications has taken advantage of the increasing technological advancement of unmanned aerial vehicles (UAVs). Currently, such aircrafts are used to perform distinct actions in the most diverse areas, e.g., environmental scanning in terms of remote sensing [1] and mapping [2]; impact analysis of natural disasters and establishment of temporary emergency networks [3]; search and rescue procedures [4]; civil infrastructure for visual inspection of buildings [5], highways [6] and power line [7]; mobile crowd sensing [8]; among others.

However, in some of these applications, the use of a single aircraft may lead to unsatisfactory results associated with the completeness of a given mission. In such cases, an attractive alternative lies in the use of groups of UAVs. For such purpose, the aircraft must be able to exchange information cooperatively to achieve a common objective. Literature usually refers to this solution as a multi-UAV system [9].

Multi-UAV systems are involved in the exploration of unknown areas [10], provision of coverage services for telephone networks [11], search and rescue missions in remote access areas [12], [13], data collection [14], among many other examples.

For the proper operation of this system, the establishment of a communication network that ensures the exchange of information among the aircraft is an essential issue. For this purpose, flying ad-hoc networks (FANETs) are often required [15].

FANET can be considered as a special type of mobile ad hoc network (MANET) in which the nodes are UAVs and usually there is a ground base station.

In this context, we propose a new multi-UAV system architecture for monitoring environmental protection areas, where each UAV is equipped with an embedded system capable of detecting boats in forbidden regions. When the system finds a watercraft, an image will be sent to a human operator in the ground control center, who will verify the detection and decide whether it is necessary to put in action a team to investigate the occurrence.

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FIGURE 1. **Boat detection example.**

This solution was presented by the authors in a previous work [16].

We chose the ZigBee technology to build the communication links between the UAVs and the ground control center (GCC). The proposed system allows increasing the coverage area and the daily rounds inspections in the environmental protection area. Furthermore, financial costs also decrease, since nowadays there are limited boats to perform the patrolling and they do not cover the entire area efficiently. Figure 1 shows an example of boat detection in a forbidden region.

The main objective of this work is to present a message-based communication strategy to enable the operation of this multi-UAV system used for monitoring an environmental protection area. The solution must be able to send data from an aircraft to a ground control center and vice-versa.

The remainder of this paper is organized as follows. Section II presents the related works. The stat-of-art of FANET related to main architectures, technologies and applications is presented in Section III. Section IV details the proposed communication startegy. The test methodology is presented in section V. Section VI discusses somo obtained results. Finally, Section VI presents conclusions and future work.

II. RELATED WORKS

ZigBee has been recently used in many studies related to unmanned aerial vehicles. Zhou *et al.* [17] use ZigBee to exchange telemetry information between aircraft and ground base and estimate the location of each UAV. The results showed that the estimation is reliable after using a Kalman filter.

Similarly, Sineglazov and Daskal [18] propose an UAV navigation system using radio units based on IEEE 802.15.4. They showed that it is possible to use a wireless network to estimate the location of a UAV.

Wireless network applications using ZigBee and UAVs is another interesting topic that has emerged significantly in recent years. For example, Bacco *et al.* [19] implemented a test in a smart farming scenario to evaluate the performance of IEEE 802.15.4 considering a sensor network composed of fixed ground sensors and a UAV. In this configuration, they found out that aerial mobility limits the transmission range among the ground nodes and the UAV to approximately one third of the nominal value.

Ueyama *et al.* [20] present a UAV system to provide resilience in wireless sensor networks and reduce the effect of faulty nodes or nodes destroyed by a natural disaster, such as floods and landslides. The idea is to transport UAVs to the disaster area and reduce problems related to faults by making the UAV work as a router or a data mule. Experiments made with real UAVs and a Wireless sensor network (WSN)-based prototype prove the viability of the proposed approach. The wireless communication is made using ZigBee modules and only small text files were transmitted to obtain the results.

Mushtaq *et al.* [21] use ZigBee to implement a fly-by-sensors (FBS) control system, which is often used for dominant associated observance of in-flight functions, starting and landing, speech communications, etc. The authors highlight some advantages provided by the ZigBee technology, such as low cost, low power consumption, as well as reliable and secure operation to regulate and monitor the controlling function.

Nasution *et al.* [22] discuss the design of a telemetry system in UAV using ZigBee protocol. Experiments showed that it is possible to change information from the UAV to a ground base satisfactorily, where messages have a maximum data length of 120 characters.

Some authors prefer to use more than one technology in the wireless network communication link, defined as a hybrid network. For example, Asadpour *et al.* [23] used IEEE 802.15.4 to perform long distance communication (between UAV and ground base). They evaluated only the WiFi network, in which the results show that the network performance is drastically affected by the UAV's movement and the antenna position.

ZigBee technology is an interesting option to perform network communication in UAVs systems. However, most developed works use ZigBee to exchange files with low data, mainly in telemetry information. Therefore, this work proposes a new message system created in the application layer capable of sending images, despite the restrictions in the communication link.

III. FLYING AD-HOC NETWORK (FANET)

A FANET is a communication network based on an ad-hoc approach to meet the requirements of applications that require UAVs capable of operating cooperatively to complete a mission [24]. The network must be robust and handle eventual communication instability properly.

The cooperative aspect of such applications requires some issues to be properly addressed to ensure that the FANET provides an accurate exchange of information during the mission execution. In this context, communication coordination functions should be used, owing to the ad-hoc nature of such

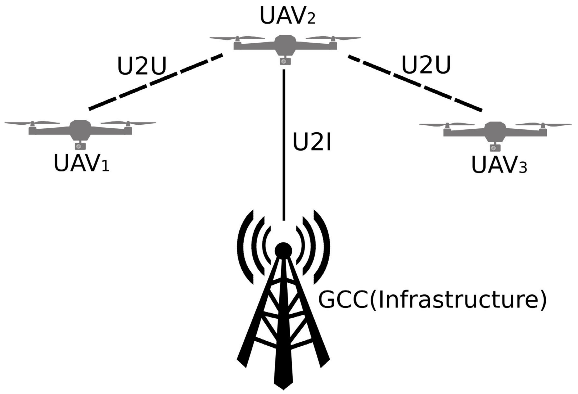


FIGURE 2. **Main communication approaches used by multi-UAV systems.**

networks, as well as the absence of a central element to coordinate the operation.

FANETs have some unique characteristics when compared with other ad-hoc networks [25], i.e.:

- Topology: the most common one is the star type, which is based on a central controller and an ad-hoc/mesh between the UAVs that compose the FANET;
- Mobility: the movement may occur in up to three dimensions with varying speed, which is controlled according to the mission;
- Energy Constraints: UAVs have intrinsic constraints related to the operating time. Tradeoffs must be made among size, weight, and flight time when batteries are employed;

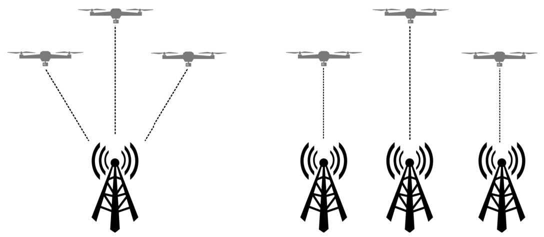
In order to provide a better explanation on FANETs, the next section is dedicated to the analysis of architectures and technologies that are typically used in this type of network.

A. ARCHITECTURES

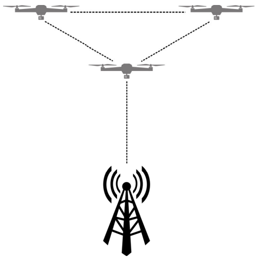
To deal with communication architectures applied to FANETs, it is necessary initially to introduce some communication architectures employed in multi-UAV applications. In general, such architectures are composed of two main elements: the aircraft and the GCC.

Communication between the elements may occur in two distinct manners: UAV-UAV (U2U) and UAV-infrastructure (U2I), which are represented in Figure 2. U2U communications occur through the aircraft that constitute the network, while U2I depends on the existence of a GCC.

Considering the aforementioned communication systems, some architectures for multi-UAV systems exist, which can be classified as centralized and decentralized. In centralized networks, all the aircraft are connected to the GCC, which acts as the central element of the network. In decentralized networks, the communication between aircraft does not need to be necessarily intermediated by the GCC. The most common architectures used for this purpose are shown in Figure 3.



(a) Directly connected. (b) Multi-GCC.



(c) FANET.

FIGURE 3. **Multi-UAV system architectures.**

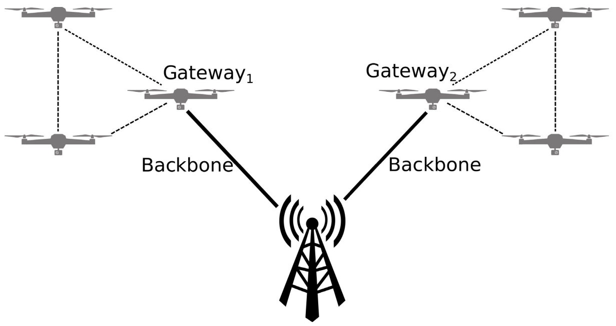
Figure 3(a) shows the directly-connected architecture. When using star topology, a single element is required, i.e., the GCC, which characterizes a centralized architecture where all aircraft must maintain the connectivity. In this case, U2U communication is not possible. The distance between the GCC and the UAV is limited by the range that can be reached by the technology adopted in the U2I link. In this scenario, if communication among the aircraft is necessary, the GCC is responsible for forwarding the information associated with the UAVs, thus adding a delay to the system [26].

The multi-GCC architecture is represented in Figure 3(b), where multiple GCCs are used to coordinate the aircraft in terms of a centralized topology. This architecture is not viable for applications involving disasters and military operations since it needs an existing infrastructure and it has a high implementation cost. Besides, it is solely based on U2I communication analogously to the previous approach [27].

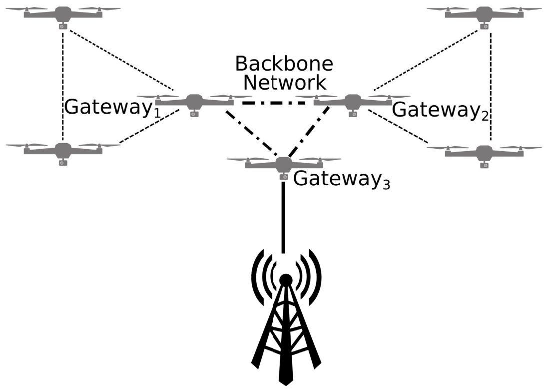
Figure 3(c) shows a FANET, where the UAVs can communicate with each other without the need of the GCC in a decentralized architecture. The existing network comprising the aircrafts is of ad-hoc type and allows the messages to be exchanged among all the network components, thus characterizing the U2U communication. In addition to this, the restriction associated with the GCC and UAVs is overcome, provided that at least one aircraft in the network has established connectivity with the GCC, thus allowing a wider area to be covered by the system. The aircraft that maintains the connectivity with the GCC is called gateway and consists in the network backbone, being responsible for ensuring the connectivity between the ad-hoc network and the GCC, thus characterizing a U2I link [26].

Considering slight variations of architectures employed in FANETs, the literature addresses two cases, defined as semi-centralized architectures according to Figure 4: multigroup and multilayer, which are also called hierarchical by some authors [26].

Figure 4(a) shows the multi-group architecture, where the FANETs are treated as groups interconnected by the



(a) Multi-group.



(b) Multi-layer.

FIGURE 4. **Multi-UAV system architectures associated with FANETs.**

TABLE 1. **Comparison between multi-group and multi-layer architectures.**

Architecture	Multi-group	Multi-layer
Scalability	Yes	Yes
Fault tolerance (common aircraft)	Yes	Yes
Fault tolerance (gateway aircraft)	No	No
Fault tolerance (gateway-GCC link)	Yes	No
GCC data flow	High	Low
Delay	Long	Short
Design Complexity	Low	High

GCC. The internal communication of the groups is performed through the ad-hoc network independently of the GCC. However, data sent to the GCC or aircraft of another group should necessarily be forwarded to the group gateway. This element is responsible for forwarding messages to the GCC, which in turn sends them to the respective gateway of the destination group.

Analogously, Figure 4(b) presents the multilayer architecture. The major difference concerning the previous approach lies in the fact that part of the aircraft constitute an internal network (backbone) with direct connection with the GCC. All data traffic from the most external layer and the GCC flows through the backbone. Some authors also call it hierarchical architecture due to the existence of several layers, which are composed of UAVs with different functions. Thus, a proper hierarchy is established in the system. Besides, the aircraft composing the backbone are the group gateways.

Table 1 presents a comparison among some important characteristics of multi-group and multi-layer architectures. For this purpose, all communication links and UAVs are considered to be identical.

B. COMMUNICATION TECHNOLOGIES

One of the major challenges of FANETs lies in the communication links between the aircraft (U2U), as well as between the aircraft and the GCC (U2I). Most of the constraints associated with this type of network are due to its respective nodes. UAVs have a high degree of mobility, causing intermittency in the communication link, as they can often be connected and disconnected from the network. Several issues that include high speed, the distance between aircraft, and execution of unpredicted movements, e.g., deviation from obstacles, may affect and compromise the network operation. Other factors also contribute to this behavior, which include the signal reflection, shading from components embedded in the aircraft, antenna radiation pattern, and environmental conditions. Therefore, the communication technologies employed in FANETs must handle such undesirable effects, which are typically inherent to wireless communication channels [28].

In this context, the requirements of communication links, i.e., U2U or U2I, must be accurately defined. It can be also stated that the application, type of mission, and the architecture employed in the network have a close relationship with the technologies that can be adopted, given their intrinsic characteristics in terms of the maximum operating distance between sender and receiver, bandwidth, latency, security, among others aspects.

Regarding the operating range between the sender and receiver, such technologies can be classified into two categories: long-range and short-range communication. Long-range communication provides a large area coverage of hundreds of meters, e.g. LTE, Wimax, and satellite communications (SATCOM). Short-range communication is used for short-distance links rated at tens of meters, e.g., WiFi, Zigbee, and Bluetooth [29].

Among the communication technologies adopted for FANETs, most of the existing works employ IEEE 802.11 standard (WiFi) and its respective variations, as well as LTE. The widespread use of such technologies is due to standard and commercial aspects, as well as a good cost-benefit ratio. However, some publications employ other solutions, e.g, ZigBee. Table 2 lists some works found in the literature, the technology adopted in each case, and the involved application.

In this context, Table 3 highlights the main characteristics associated with LTE [35], WiFi [36], and Zigbee [37], which have direct impact on the operation of a FANET. Considering the existing advantages and disadvantages, it is observed that the LTE technology presents wide bandwidth and range, but also high implementation cost due to the need for a fixed infrastructure. WiFi technology has a transfer rate higher than LTE and, also, aggregates lower cost. Another important

TABLE 2. Communication technologies and applications to FANETs.

Tecnology	Application
WiFi and ZigBee [23]	Image transfer in multi-UAV systems
LTE [30]	Crowd surveillance in urban areas
ZigBee [31]	Cluster communication for performance optimization
WiFi [32]	Selection of the best path for performance optimization
WiFi [33]	Emergency network in disaster conditions
LTE [34]	Expansion of coverage area in an LTE network

TABLE 3. Comparison among LTE, WiFi and ZigBee technologies.

Technology	LTE	WiFi	ZigBee
IEEE	LTE	802.11n	802.15.4
Operating frequency	>20 MHz	2.4/5 GHz	915 MHz
Licensed spectrum	Yes	No	No
Outdoor range	100 km	250 m	6.5 km
Transfer rate	300 Mbps	600 Mbps	200 Kbps
Latency	10 ms	< 5ms	<70 ms
Physical infrastructure	Yes	No	No
Topology	Plan	ad hoc, star, mesh, hybrid	mesh, point-to-point point-multipoint

factor lies in the possibility to operate without a fixed infrastructure, thus allowing the creation of ad-hoc networks. The main disadvantage of WiFi is the short range, since this technology is dedicated to local networks. Finally, Zigbee technology operates at longer and shorter distances when compared with WiFi and LTE, respectively. In addition, the implementation cost is low due to the lack of a fixed infrastructure. Latency and low transfer rate are the main drawbacks in this case, which can be a challenge for applications involving FANETs.

Figure 5 represents an example of such technologies applied to the search in a region of risk. The scenario is composed of different types of aircraft, whose links employ distinct technologies. The airship is a high-altitude platform (HAP) aircraft based on a communication link that requires wide operating range and bandwidth, since all the traffic of the FANET must be routed through the backbone to the GCC. The internal communication of the FANET associated with U2U links occurs through WiFi communication, since the low-altitude platform (LAP) aircraft operate at low heights and are close to each other.

The forthcoming section presents the communication strategy proposed in this work for sending and receiving data in a multi-UAV system based on ZigBee communication link.

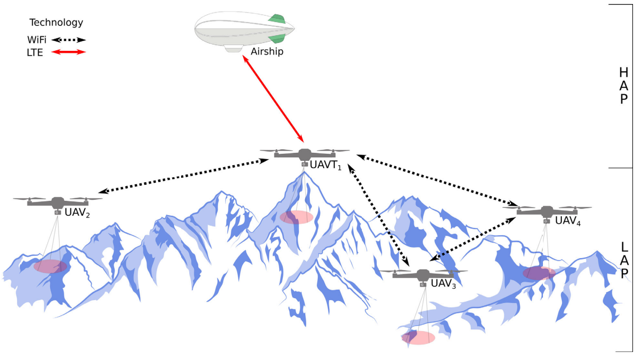


FIGURE 5. FANET with distinct aircrafts and technologies.

TABLE 4. IM format.

Field		Size (bytes)
ID	Identification	4
HA	Hash	4
TY	Type	1
TG	Tag	4
SN	Source Node	2
DN	Destination Node	2
PS	Position	18
TI	Time	10
LD	Last Identification	4

IV. COMMUNICATION STRATEGY

In order to make the application viable, a communication strategy for exchanging messages between the multi-UAV system and GCC was developed. In general, the adopted strategy is based on the well-known concepts of transmission control protocol (TCP) and user datagram protocol (UDP) associated with the particular requirements of the application. Therefore, it is possible to aggregate the functions performed by the transport and application layers, adopting the stacked TCP/IP protocols as a reference. The following communication requirements are necessary in this case:

1) image and text transmission;
2) identification and position of an aircraft;
3) time and chronology of events;
4) verification of data integrity.

A. TYPES OF MESSAGE

Based on the aforementioned requirements, a message system was implemented. Two types of headers are used: the first one is for the transmission of control information, entitled introduction message; the second one is dedicated to sending useful information, called data message.

1) INTRODUCTION MESSAGE (IM)

The IM has the purpose of transmitting control information among the elements of the multi-UAV system, thus allowing all components to identify the aircraft employed mission and their respective positions. The IM format is presented in Table 4 and a description of the fields that compose the header is given as follows.

- Identification: unique identifier of the message within a sequence of packages. Each initial package will assume

TABLE 5. Types and description of IMs.

Type	Description
Zero	It is used for data transmission. The protocol should be aware of which type of data is embedded, i.e. image or text, so that decoding is accurately performed after data are received.
Confirmation	It is sent after data transmission. If any data message has not been received, the retransmission of all IDs that were not initially received is requested.
Keep alive	It is used to notify that an aircraft is active, in addition to informing position and timestamp.

TABLE 6. Message types as defined by the "Type" field.

Type	Identification	Type Field
Keep alive	0	0
Zero (text)	0	1
Zero (image)	0	2
Confirmation	0	3

null value. The forthcoming packages are incremented by one until their respective values equal that of the LD field;

- Hash: It contains the value resulting from the hash operation of the data transported by the package, i.e., the operation is performed in the payload;
- Type: This parameter indicates the type of package and data being transported, i.e., the payload. It may be a keep alive or confirmation message, or also a data package, which in turn may contain image or text;
- Tag: Unique identifier for a sequence of packages. All packages that belong to the same sequence have a constant value associated with this field, which is used in the reassembly. A given node should never assign the same tag to distinct sequences;
- Source node: Identifier of the aircraft that generated the message;
- Destination node: Identifier of the aircraft to which the message is sent;
- Position: It contains the geographic coordinates of the source;
- Time: It informs the date and time of the source package in Unix timestamp format;
- Last Identification: It indicates the number of the last package that comprises a sequence;

Table 5 lists the types of IMs available in the system and their respective purposes, while Table 6 details how they are distinguished according to the type field.

2) DATA MESSAGE (DM)

DMs are only sent when images or text are properly sent. It aims at reducing the head size to increase the payload, thus justifying the need for a message whose header is different from that of an IM. The DM has two fields: tag, which identifies the data message referring to a particular data sequence; and identification, which contains the position of that data segment at the reassembly time of the original data. It is possible to embed up to 248 bytes in a DM. Table 7 presents the detailed description of a DM.

TABLE 7. DM format.

Field		Size (bytes)
ID	Identification	4
TG	Tag	4
DA	Data	up to 248

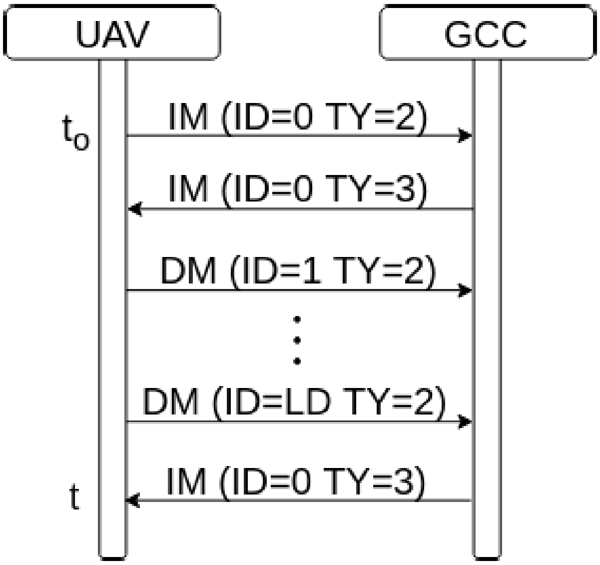


FIGURE 6. Message flow for the transmission of an image.

B. OPERATION

The system operation when transmitting a image is shown in Figure 6. In this scenario, a UAV sends an image to a GCC. At the initial time instant, the UAV sends an IM to request the transmission of an image (type-2 IM). The GCC responds with a type-3 IM, thus denoting availability to receive the data. Then the UAV starts the image transmission through a number of data messages. It is observed that the ID field contains the position of each message, where the last one assumes an ID equal to LD (last identification). Upon receipt, the GCC checks if all messages have been received correctly. In this case, it sends a type-3 IM without requesting retransmission. Otherwise, this message would contain the IDs required for data retransmission.

V. TEST METHODOLOGY

To perform the experimental tests, we used two quadrotor drone DJI Phantom 3 Standard to compose the UAV network and a Dell notebook model Inspiron 15 5567 as the base station. All devices were equipped with a XBee Pro S3B 915 MHz module and one of the drones was also equipped with a Raspberry Pi 3 board. The main objective of this experiment is to evaluate the behavior of the proposed communication protocol to send an image in different scenarios. Figure 7 shows an example of UAV used in the tests.

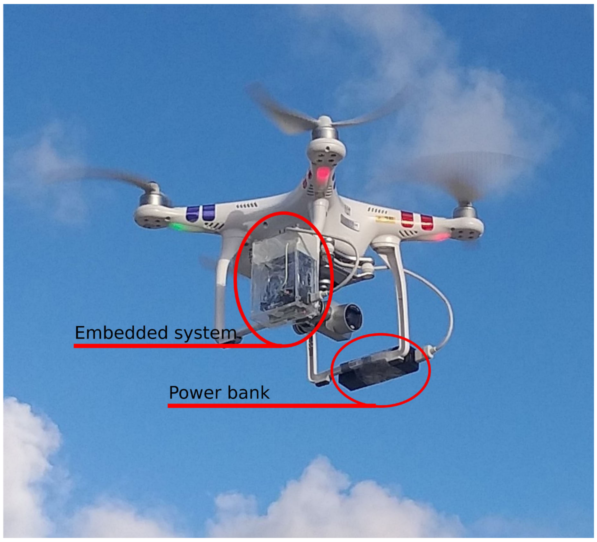


FIGURE 7. UAV model DJI Phantom 3 Standard with embedded system.

To evaluate the performance of the proposed system, four scenarios were considered. Scenarios 01, 02, and 03 comprise a base station and only one UAV, for which 10 tests were performed. On the other hand, scenario 04 has one base station and two UAVs, comprising 20 tests.

In the first scenario, the aircraft remained still at a certain fixed position employing navigation via global positioning system (GPS), hovering at the same point during the experiment.

Scenarios 02 and 03 were analyzed with the aircraft in cruise flight. For both cases, the UAV went through a sequence of determined points using autonomous navigation according to the course defined in Figure 8. The only difference between the scenarios is the flight speed: we set 12 km/h and 20 km/h for scenarios 02 and 03, respectively.

In the fourth scenario, one UAV, defined as the sender UAV, is equipped with an embedded system that sends the image through the network to the base station, which is out of range. Therefore, a second UAV had to be added as a relay node, enabling the communication between the base station and the sender UAV. Moreover, the relay node had to be positioned between the base station and the other UAV, characterizing a multi-UAV delivery. Both UAVs flew in stationary mode, hovering at the same point during the test.

Figure 1 was used as a reference to carry out the tests to validate the ZigBee communication protocol. The image type is JPEG (Joint Photographics Experts Group), with a resolution of 400 x 300 pixels and size of 49,145 bytes. Considering that each DM message contains up to 248 bytes, the proposed protocol requires 202 messages for the complete transmission of the image, i.e., 3 IM messages and 199 DMs messages. The parameters for the flight tests are listed in Table 8.

VI. RESULTS

The results obtained in scenario 01 are summarized in Table 9. The image transmission was successful in the ten tests, i.e., the GCC was able to decode the data sent by the UAV. It was observed that the transmission interval did not change significantly under such conditions, varying from 62.166 s to 63.743 s, being the difference lower than 1.5 s. The average time for the transmissions was 63.084 s with a standard deviation of 0.499 s.

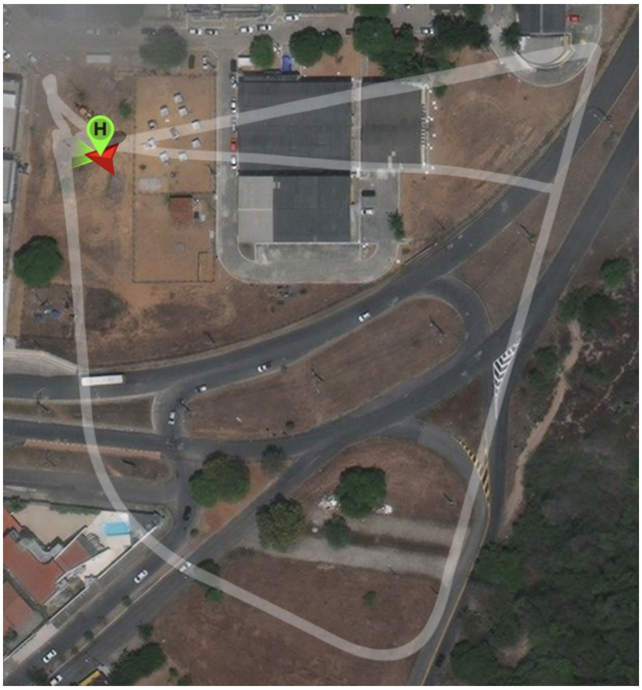


FIGURE 8. UAV course performed in autonomous flight.

TABLE 8. Elements used in the tests.

	Parameter	Value
XBee PRO S3B	Power Level(Tx)	+24 dBm
	Baud rate	115200 bps
DJI Phantom 3 Standard	Height (y axis)	90 m
	Distance (x axis)	20 m
Image	Size	49.145 bytes
	Resolution	400x300 pixels

TABLE 9. Results obtained for scenario 01: hovering flight.

Test	Time(s)	Image Receipt
1	63.51	Yes
2	62.449	Yes
3	63.743	Yes
4	62.166	Yes
5	63.052	Yes
6	62.934	Yes
7	62.918	Yes
8	63.417	Yes
9	63.501	Yes
10	63.155	Yes

Table 10 presents the results obtained for scenario 02. Ten tests were performed and a single one presented problems during the image decoding. The shortest transmission time was 61.779 s, while the highest one was 63.203 s, being the difference equal to about 1.424 s. The average transmission time was 62.927 s with a standard deviation of 0.527 s.

TABLE 10. Results obtained for scenario 02: cruise flight at 12 km/h.

Test	Time(s)	Image Receipt	Lost Packages
1	62.820	Yes	0
2	63.380	Yes	0
3	61.779	No	1
4	62.480	Yes	0
5	62.866	Yes	0
6	63.852	Yes	0
7	62.716	Yes	0
8	63.163	Yes	0
9	63.016	Yes	0
10	63.203	Yes	0

TABLE 11. Results obtained for scenario 03: cruise flight at 20 km/h.

Test	Time(s)	Image Receipt	Lost Packages
1	62.179	Yes	0
2	62.350	No	1
3	63.839	Yes	0
4	63.510	No	1
5	66.569	Yes	0
6	67.847	Yes	0
7	64.657	Yes	0
8	62.592	Yes	0
9	62.572	Yes	0
10	65.228	Yes	0

The results obtained with the tests performed in scenario 03 are shown in Table 11. It can be stated that The GCC was unsuccessful in image decoding in two tests. The shortest and longest transmission times were 62.179 s and 67.847 s, respectively, corresponding to a difference of 5.688 s. The average transmission time was 64.134 s with a standard deviation of 1.829 s.

Table 12 shows the results obtained with the tests performed in scenario 04 (multi-UAV delivery). The image decoding process failed in five tests. The shortest transmission time was 60.747 s and the longest one was 69.956 s. The average transmission time was 64.783 s with a standard deviation of 3.072 s.

This average transmission time is longer than the ones previously presented because the distance between the GCC and the source UAV is bigger than the previous scenarios, requiring more processing time.

The experimental results are summarized in Table 13. It is observed that although the UAV is in motion and with different cruising speeds in scenarios 02 and 03, the image was transmitted successfully in most of the tests. In addition, the time spent for the image transmission is nearly the same for all scenarios, with special focus given to scenarios 01 and 02, since the results are quite similar in such conditions.

Scenario 04 has the biggest standard deviation, which characterizes the dynamic behavior of this type of network. The delivery process was fast enough and did not present any problem. However, sometimes some uncontrolled variable, such as wind, signal interference, among others, may impair the delivery process. In summary, when the scenario complexity increases, the delivery success decreases.

The relationship between the decoding errors and scenario conditions was not evaluated. However, despite the small number of tests, faults tend to occur in scenarios with higher cruising speeds.

TABLE 12. Results obtained for scenario 04: multi-UAV delivery in hovering flight.

Test	Time(s)	Image Receipt	Lost Packages
1	61.818	No	1
2	64.683	Yes	0
3	66.236	Yes	0
4	62.214	Yes	0
5	67.445	No	2
6	61.786	No	2
7	63.726	Yes	0
8	60.818	No	2
9	67.978	Yes	0
10	69.956	Yes	0
11	68.166	Yes	0
12	68.414	Yes	0
13	62.296	Yes	0
14	67.299	Yes	0
15	61.248	Yes	0
16	64.948	No	4
17	62.020	Yes	0
18	69.076	Yes	0
19	60.747	Yes	0
20	64.799	Yes	0

TABLE 13. Summary of experimental results.

Scenario	Speed (km/h)	Average time (s)	Standard deviation	Image receipt (%)
01	Hovering	62.884	0.478	100
02	12	62.927	0.527	90
03	20	64.134	1.829	80
04	Hovering	64.783	3.072	75

VII. CONCLUSION

This work presented a communication strategy for multi-UAV systems using ZigBee technology based on the exchange of messages. Four types of tests were performed. The first test considers that the aircraft hovers in a fixed position, while it is in motion during the second and third ones. Scenario 04 introduces the multi-UAV delivery. In scenario 01, image decoding was successful in 100% of the cases. On the other hand, the image was successfully sent in 90% and 80% of the cases considering scenarios 02 and 03, respectively. Scenario 04 presented 75% of the success transmission. In addition, a brief analysis of the time interval required for transmission has been performed, thus showing that there is no significant difference when the aforementioned scenarios are compared with each other.

The purpose of this work is to evaluate the implementation logic adopted in the communication strategy. Considering a total of 50 tests, the transmission was successful in 42 sessions, thus corresponding to 84% of the evaluated cases. Therefore, the results showed that the developed strategy is able to send and receive images between a UAV and the GCC successfully.

Future work includes the development of additional tests considering larger traveled distances and a detailed study about the network behaviour over latency for messaging, influence on the UAV autonomy, throughput and others.

A limiting factor lies in the flight time of the aircraft and autonomy, which limits the repetition of consecutive tests or even the distance to be covered. Besides, it is essential to evaluate the performance of the introduced communication strategy in a scenario with multiple UAVs, since in this work the analysis is restricted to a single aircraft associated with a GCC, aiming at validating the data transmission and also the message headers.

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