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Performance evaluation of LoRa and ZigBee technologies applied to FANETs

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***Abstract*— Wireless communication technologies are applied in different activities and performance evaluations are important issues. This paper presents a comparison of transmission rate and packets delivery rates between LoRa and ZigBee technologies, whose main interest is to investigate the performance in ad hoc networks, especially in flying ad hoc networks (FANET). Hardware-in-the-loop bench scale and human-in-the-loop ground scale experiments were performed for the LoRa RD42C and XBee-PRO S3B radios, regarding their transmission rate and packets delivery rates on the bench and at distances ranging from 100 to 500m, using different transmission rates, powers and scattering factors. The results indicate that the XBee radio outperformed the LoRa radio on the bench in terms of transmission transfer rate and delivery at the analyzed potencies. In ground experiments, XBee was more efficient than LoRa overall, but only up to 300m at 21dBm.**

I. INTRODUCTION

Wireless communication technologies can be used in a variety of activities, and as their importance grows, more projects use them while also evaluating their performance in accordance with the proposed objective. This work aimed to investigate, for the implementation of flying ad hoc networks (FANET), the transfer rate and packet delivery rate (PDR) of ZibBee and LoRa technologies in point-to-point communications, since they are similar in terms of data rate, range, performance, and cost. Every year, the use of unmanned aerial vehicles (UAVs) becomes more promising and combining them to form fleets of ad hoc networks has proven to be effective in a variety of activities.

The ad hoc network consists of a router and a host, in the same unit, performing both functions, which allows any other node of the network to transmit/broadcast to any node of the network that is within its radio transmission range. A special type of network is known as Wireless Sensor Network (WSN) [1], which is a subset of ad hoc multipoint networks designed to detect and collect data autonomously by sensors with the intention of transmitting it to the intended destination for analysis. In contrast to WSNs, which are stationary and interact with the environment, mobile Ad hoc network (MANET) [2] devices move randomly with a dynamic topology. As shown in Fig. 1, if a device wants to send a message to another device that is out of range, it uses an intermediate node to forward the message. Vehicle ad hoc networks (VANET) [3] are a subset of MANET that consists of a series of vehicles that travel on urban roads and can communicate with each other without fixed infrastructure, forming an intelligent transportation system capable of exchanging information about traffic and road conditions. In this context, according to [4], FANET can be viewed of as a specialized form of MANET and VANET, with greater challenges than other networks due to its complex dynamics, high degree of mobility in 3D, and intermittent network connectivity. Some particularities are: (i) *mobility*- the behavior related to the speed and direction of UAVs locomotion; (ii) *variable topology* - the topology updates a lot depending on mobility, distance, link failures or, inclusion of new aircraft into the mission; (iii) *latency* - the delay may vary according to the communication technology employed, the routing protocol in use, the expected range and the antennas used; and, (iv) *routing* - the robustness of having multiple ways to send information to the destination added to the efficiency of selecting the best path.

According to [5], routing protocols are topology-based, geographic, hybrid, and bioinspired. FANETs use existing ad hoc routing protocols. In this paper, results from hardware-in-the-loop (HIL) and human-in-the-loop (HITL) bench experiments are presented to evaluate the transmission rate and delivery of the technologies LoRa, LoRa RD42C radio, and ZigBee, XBee-PRO S3B radio, for application in a FANET.

The paper is organized as follows: section 2 presents relevant work related to the performance evaluation of LoRa and ZigBee technologies in UAV and FANET networks; section 3 presents the experiments, results, and their considerations; finally, section 4 presents the conclusions.

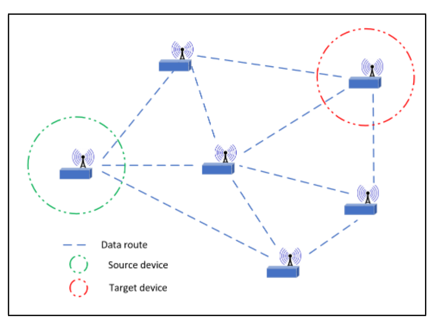

Fig. 1. Basic mobile ad hoc network architecture.

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II. RELATED WORKS

Different wireless communication technologies have different specifications, and FANET networks can also be used for a wide range of purposes. The following works aim to apply these technologies in UAVs/FANETs while also analyzing their performance in relation to the proposed goal.

A. ZigBee radios in UAVs

Considering ZigBee radios in UAVs, in [6] the author uses a FANET for rocket impact area scanning, using point-to-point and mesh network ZigBee with ad-hoc on-demand distance vector routing (AODV). Finally, latency, transmission rate, packet transmission rate, and signal strength were calculated for each scenario, yielding a stable transmission for 100 Kb up to 5 km in an average time interval of 67 s. In [7], the authors present a study of a UAV-assisted WSN with ZigBee to improve the connectivity of the ground network. Communication parameters such as packet loss rate, final delay and transmission rate were analyzed. They showed that the UAV's altitude should be kept around 150 m to avoid noise, and that performance degrades in extreme weather conditions. [8] demonstrated the performance of ZigBee in Internet of Things (IoT) sensor networks for UAV data collection. A practical evaluation of signal strength and packet reception rate was performed for various antenna orientations and UAV altitudes. The authors concluded that at higher altitudes, interference is reduced. The work was successful in capturing a packet at a distance of 297 m.

B. LoRa radios in UAVs

In terms of LoRa-enabled UAVs, [9] describes a system that uses a single UAV to collect WSN data for monitoring marine environments. The authors investigated range and transmission rate by using LoRa to communicate between buoy sensors, the UAV, and the ground control station (GCS). The UAV had an 8.62 km range and a high transmission rate. In the work of [10], the objective was to develop a long-range communication system using LoRa with a UAV, for environmental monitoring. Experiments were conducted at various locations to assess the performance by examining the relationship between power × transmission rate, distance × transmission rate and data rate × data delivery rate. PDR was greater than 90% in the experiments at a distance of 400 m. The authors [11] investigated the performance of LoRa/LoRaWAN in a UAV communication delivery system by measuring distance, signal to noise ratio (SNR), packet loss, and received signal strength indication (RSSI) for different LoRa spreading factors (SF). The study's findings showed that LoRaWAN, which can send up to 20 $bytes$ in a 3 s interval, can be used for UAV telemetry. In addition, using a lower SF, coverage of up to 8 km in urban areas can be obtained with tolerable packet loss of up to 5%. The authors of [12] use LoRa to connect a GCS, a UAV, and the "end device". They verified in real flight the delivery rate and power consumption of the UAV moving along a circular orbit of 4 to 6 km radius. The experiments demonstrate that using a UAV operating as a gateway allowed them to reduce the energy consumption of the network communication by up to 59%. The authors of [13] present a simulation of a system with 5 to 20 UAVs-LoRa used for air quality monitoring. They investigated the delay and delivery rate in UAV mobility models.

C. Use of two or more radios

In some studies, multiple radios are used and evaluated in UAV missions. The authors of [14] compare the success of packet transmission and delays between 16, 32, 64, and 128 UAVs in simulated environments using IEEE 802.11n and IEEE 802.15.4, operating in star and mesh topology with AODV routing. The authors concluded that the star topology produces more collisions, impacting the delivery rate and end-to-end delay. FANETs with IEEE802.11n have been shown to be more secure than star topologies. The authors of [15] conduct tests with radios in a UAV swarm, where reliability analyses were performed to evaluate the quality of LoRa UAV and Wi-Fi UAV communications in rural scenarios, as well as UAVs using Long Term Evolution (LTE) in urban areas. The first experiment tested the reliability of a single LTE, LoRa, and Wi-Fi link with a single UAV flying separately at distances ranging from 10 to 2500 m. The second experiment investigated the communication delay between ten UAVs connected via LoRa and Wi-Fi over a FANET network. According to the results of the first experiment, 100% reliability is achieved up to 320 m and 40 m for LoRa and Wi-Fi, respectively. The results of a single LTE-connected UAV show that LTE in the urban area provides ultra-reliable, 100% communication within $2500\ m$. According to the results, UAVs connected via LTE provide a lower delay compared to LoRa and Wi-Fi, with an average latency of 19 ms. The authors discovered that LoRa has an eight-fold greater range than Wi-Fi, but that LTE has better reliability than both LoRa and Wi-Fi.

D. Comparison of the related work

Few studies compared radios and their routing protocols as they apply to FANET. Table I compares the evidenced works with the proposed approach, which aims to analyze the practical performance of LoRa and ZigBee radios in FANET in terms of range, transmission rate, and consumption of their routing protocols (RP), as well as others like RSSI and SNR.

TABLE I
RELATED WORKS ISSUES DISCUSSED COMPARATIVE

	LoRa				ZigBee				Network		
	Distance	Transfer rate	Consumption	Others	Distance	Transfer rate	Consumption	Others	Star-UAV	FANET	Disclosed RP
[6]					x	x		x	x	x	x
[7]						x		x	x		
[8]					x	x		x	x		
[9]	x	x							x		
[10]	x	x		x					x		
[11]	x	x		x					x		
[12]	x	x	x						x		
[13]		x		x					x		
[14]						x		x	x	x	x
[15]	x			x					x	x	x
Proposed analysis	x	x	x		x	x	x			x	x

III. PERFORMANCE EVALUATION OF LORA AND ZIGBEE TECHNOLOGIES

This section will present some details of the wireless communication technologies employed in the experiments.

A. ZigBee

According to [16], ZigBee technology is based on the IEEE 802.15.4 standard, which implements the media access control (MAC) and physical layers, while ZigBee is responsible for the upper layers. As reported by [17], ZigBee uses ad hoc protocols to support star, cluster, and mesh topologies. According to [18], radios that use this technology from the XBee family can operate in different frequency ranges with varying data rates. The radio model XBee-PRO S3B [19] used in this study operates in frequency ranges ranging from 902 to 928 MHz, with data rates ranging from 10 $Kbps$ to 200 $Kbps$ depending on the topology. As stated in [19], the power levels (PL) used for the objectives of this work range from 0 to 4, with PL0 having an approximate value of $+7$ dBm (5 mW) and PL3 having an approximate value of $+21$ dBm (125 mW).

B. LoRa

Low power wide area networking (LPWAN), presented by [20] and characterized by low energy consumption, low power, and long-range, is one of the main technologies used in large area and low consumption networks. LoRa operates in the Industrial Scientific and Medical (ISM) frequency bands of 433, 868, and 915 MHz, with a transmission rate ranging from 0.3 to 37.5 $Kbps$ and a range of up to 5 km in urban areas and up to 15 km in rural areas, according to [21]. The star topology is the native architecture of LoRa networks, but according to [22], they can also implement the "LoRaMesh" mesh architecture. The LoRa RD42C model radio [23] used in this study has a frequency range of 902 to 928 MHz and a data rate of up to 21.9 $Kbps$. This radio has spreading factors ranging from SF7 to SF12, with the lower the SF resulting in a higher data rate with a shorter range and transmission time. For this study, SF7 and SF9 were used, with the transmission power remaining similar to that of the XBee radio. Transmission power (TP) at $+7$ dBm and $+20$ dBm, according to [23]. From this point on, this radio will be referred to as LoRa.

IV. EXPERIMENTS AND RESULTS

This section will present the structure of the experiments developed, and lastly, the results obtained.

A. Organization and experiments structure

The required structure was made up of XBee radios, LoRa, USBxserial shields, a notebook, external power supplies, and a Raspberry Pi3 Model B computer, similar to the processing unit found in UAVs. The scheme was similar for both radios, with the only differences being the radios connections to the Raspberry's "General Purpose Input/Output" (GPIO) power supply/GND and UART RX/TX, as well as the send/receive codes and transmission rate analysis in Python, which were the same for both radios, with only the differences being the power supply/GND and UART RX/TX connections. The radio transmission rate and PDR tests were carried out at speeds of 9600 bps, 38400 bps, and 57600 bps, respectively. In terms of routing protocols, the XBee radio used the proprietary DigiMesh protocol, while the LoRa radio used the proprietary LoRaMesh protocol, both of which were based on dynamic reactive protocols.

In order to analyze the radios, both point-to-point, the hardware was used in experiments, as shown in Fig. 2. First HIL with 3 m and then HITL experiments varying the distances from 100 to 100 m until the limit of 500 m, in an open urban area. The hardware remained the same, except for 2 (two) XBee-PRO S3B radios with 1.9 dBi wire antennas being replaced by 2 (two) LoRa RD42C radios with 2.15 dBi antennas.

B. Experimental setup

The investigation was carried out in the HIL and HITL stages at various transmission rates and powers/SF defined during the sending of 50 packets of 232 $bytes$, which is the maximum size allowed for LoRa RD42C radio packets [23]. As a result, a total of 11.6 $Kbytes$ were sent; however, despite the radios accuracy, each scenario of sending 50 packets was repeated 5 $times$, with an 8 s interval between each new sending. Finally, the standard deviations of the average transfer rates, PDR, and time-wasting scenarios were calculated. According to Fig. 2, the monitoring took place in the (0) coordinator radios, which sent packets to the (1) router and received 9 $bytes$ "ACK" acknowledgment packets from the (1) router. The maximum waiting time for a sent packet's "ACK" response was set to 1 s.

C. Experimental results and considerations

Below are the comparative results of the radios concerning the average transmission rate, PDR and total transfer time.

*1) **9600 bps Transmission Rate Experiments**:* In Fig. 3, a transmission rate comparison shows that XBee was more efficient in both PLs, achieving transmission rates approximately four times higher than LoRa. The XBee in PL0 did not transfer rate at 200 m in the HITL experiments, but at PL3 the transfer rate was only about 5% at 100 m, compared to HIL. At 200 m, there is a 6% decrease from

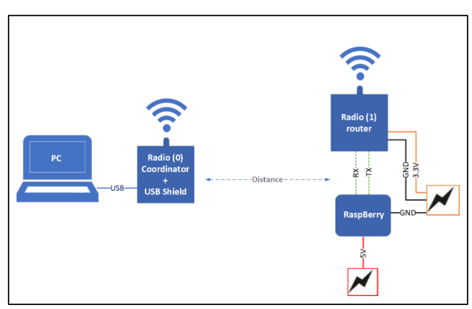

Fig. 2. Schematic diagram for distances of 3 m (hardware-in-the-loop) and 100 to 500 m (human-in-the-loop).

100 m, and at 300 m, there is a 2% increase from 200 m. The transfer rate drops by approximately 72% at 400 m compared to 300 m, and by approximately 49% at 500 m compared to 400 m.

In terms of LoRa in HITL, there is a noticeable decrease in transfer rate compared to HIL, but the rates remains similar with small decreases and small improvements in both powers/SF up to 400 m. There is no transfer rate from 400 m at power 7dBm with SF7. At the same power with SF9, the rate drops by about 36% at 500 m when compared to the bench test. At 500 m, the transfer rate with SF7 at 20 dBm power decays by about 12% compared to the bench test. There is a 12% rate drop at the same power at 500 m with SF9.

Fig. 4 illustrates the comparative PDR where, in HIL, it is clear that the XBee, in both PLs, outperforms LoRa with a PDR of 100%. Regarding the HITL scenarios, it was discovered that XBee in PL0 stops delivering packets within 200 m, whereas in PL3 the PDR remains at about 100% until 300 m, with a drop at 400 m of about 63% compared to 300 m. When compared to the PDR obtained at 400 m, there is a drop of 16% at 500 m.

In terms of LoRa in HITL, the HIL is reduced, but the PDR remains similar in both powers/SF up to 400 m. There is no packet delivery after 400 m at 7 dBm power with SF7. At 500 m, the PDR decreases by about 13% when using the same power as SF9 as in the bench test. In 500 m, the PDR drops about 3% in 20 dBm power with SF7 compared to the bench test. PDR is reduced by 4% when using the same power and distance as SF9.

Fig. 5 displays the comparative total transfer time between the radios in their analyzed parameters and scenarios. Thus, at 9600 bps in the HITL scenarios at 7 dBm the XBee was more efficient than LoRa at the same power only up to 100 m. As for the XBee at PL3, it was more efficient than LoRa only up to 400 m.

*2) **Experiments at the transmission rate of 38400 bps:*** The transfer rate comparison between the radios is shown in Fig. 6, wherein HIL, the XBee in both PLs was more efficient at 38400 bps than the LoRa radio. At SF7 (at both powers), XBee maintained its transmission rate nearly 6 $times$ higher than LoRa, and 13 $times$ higher than LoRa at SF9. In HITL, it was discovered that the XBee at PL0 power has no transmission rate at 200 m; however, at PL3, the transmission rate decays by about 6% at 100 m, 11% at 200 m, 26% at 300 m, and 89% at 400 m in comparison to the previous distances. Finally, there is no transmission rate at 500 m in PL3.

As for the LoRa in HITL, in 7 dBm with SF7, comparing the transfer rate to the results of previous distances, it was noted that they were similar to HIL in 100 m, falling about 14% in 200 m; 13% in 300 m; 12% in 400 m; and 17% in 500 m. At the same power in SF9, the rate compared to previous distances dropped about 13% at 100 m; remained similar at 200 m and 300 m; dropped 3% at 400 m; and remained similar at 500 m. With 20 dBm in SF7, the rate dropped about 16% at 100 m compared to HIL; improved by 12% at 200 m; dropped 9% at 300 m; dropped 13% at 400 m; and dropped 1.5% at 500 m. Finally, at 20 dBm with SF9, the rate dropped about 2% at 100 m, remained similar at 200 m and 300 m, dropped 5% at 400 m, and fell 7% at 500 m.

In HIL, the XBee radio kept its PDR at 100%, as shown in Fig. 7. In HITL, it was discovered that the XBee radio at PL0 power stops delivering packets at 200 m, whereas the PDR at PL3 remains at 100% until 200 m, with a drop in

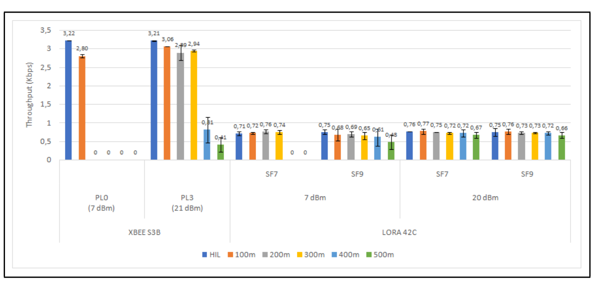

Fig. 3. Transfer rate of LoRa RD42C and XBee-PRO S3B, at 9600 bps.

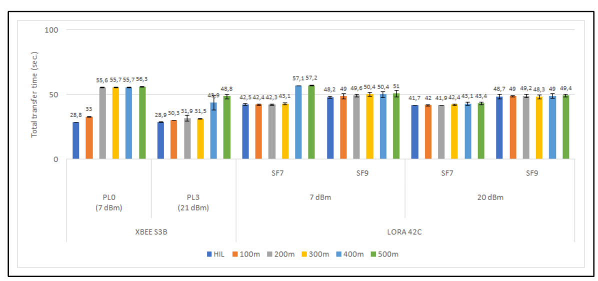

Fig. 5. Time lapse of LoRa RD42C and XBee-PRO S3B, at 9600 bps.

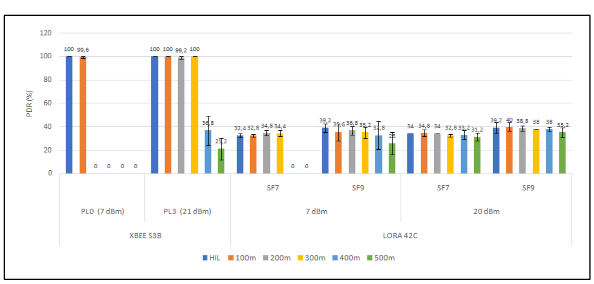

Fig. 4. PDR of LoRa RD42C and XBee-PRO S3B, at 9600 bps.

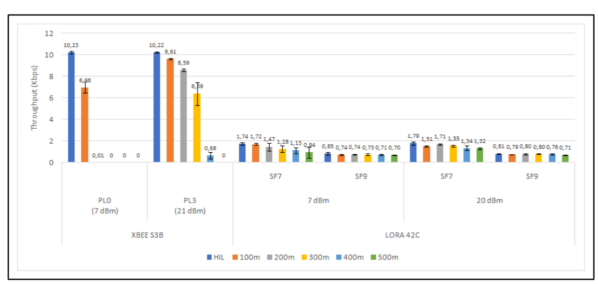

Fig. 6. Transfer rate of LoRa RD42C and XBee-PRO S3B, at 38400bps.

comparison to the bench test of about 3% only at 300 m and a reduction of 64% at 400 m. Finally, there is no packet delivery at 500 m in PL3.

In terms of LoRa in HITL, at 7 dBm with SF7, compared to the previous distances, the PDR was similar to HIL at 100 m, falling about 16% at 200 m, 6% at 300 m, 12% at 400 m, and 10% at 500 m. At the same power in SF9, the PDR dropped about 4% at 100 m and remained consistent from 200 m to 500 m. With 20 dBm on SF7, the PDR dropped 10% on 100 m compared to HIL; they had an 8% improvement in PDR on 200 m; a 7% drop on 300 m; a 10% reduction on 400 m; and an 8% reduction on 500 m. Finally, at 20 dBm with SF9, the PDR remained constant until 300 m, then dropped 2% at 400 m and 1% at 500 m.

Fig. 8 shows the total transfer time comparison between the radios in their analyzed parameters and scenarios. Thus, in the HITL scenarios at 7 dBm, the XBee was much more efficient than the LoRa at the same power only up to 100 m at 38400 bps. The XBee at PL3 was only slightly more efficient than LoRa up to 300 m. LoRa outperformed XBee from 400 m in both power levels.

*3) **Experiments at the transmission rate of 57600 bps**:* Fig. 9 shows a transfer rate comparison between the radios, with HIL, the XBee radio, keeping its transfer rate about 5 $times$ higher than LoRa at SF7 (at both powers) and about 15 $times$ higher than LoRa at SF9. At HITL, it was discovered that the XBee radio at PL0 has a 35% reduction in transmission rate when compared to the bench. PL0 does not show any handoff rate after 200 m in the other distances. In terms of PL3, the transmission rate drops by about 6% at 100 m, 15% at 200 m, 3% at 300 m, 95% at 400 m, and 94% at 500 m when compared to the previous distance.

Concerning LoRa in HITL at 7 dBm with SF7, when comparing the transfer rate to the results of previous distances, it was discovered that the rate was similar to HIL at 100 m, dropping about 2.5% at 200 m, dropping by 2% at 300 m, dropping by 4% at 400 m, and dropping by 16% at 500 m. At the same power in SF9, they were similar at 100 m and 200 m compared to the HIL result, but at 300 m, the rate dropped about 2%; at 400 m, the rate dropped about 4%; and at 500 m, the rate dropped about 3%. At 20 dBm in SF7, it was observed that the rate dropped approximately 4% at 100 m compared to HIL; at 200 m they had a rate drop of 2%; at 300 m the rate remained similar to the previous distance; at 400 m the rate dropped about 2%; at 500 m the rate dropped 4%. Finally, at 20 dBm with SF9, the rate dropped by about 5%. At 100 m, the rate increased by 5%; at 200 m, it decreased by 5%; at 300 m, it decreased by 5%; at 400 m, it decreased by 5%; and at 500 m, it dropped slightly by 1%.

Fig. 10 shows the comparative PDR, wherein HIL, it is noted that the XBee radio maintained its PDR at 100% in both PLs. During the HITL experiments, it was discovered that the XBee radio in PL0 maintained its PDR relative to the bench at 100 m. The XBee in PL0 stops delivering packets after 200 m at other distances. When compared to previous distances, the PDR in PL3 remains around 100% until 300 m, with a drop of 74% at 400 m and a reduction of 24% at 500 m.

When comparing the LoRa in HITL results at 7dBm with SF7 to the previous distances, it was discovered that the PDR was similar to HIL at 100 m and 200 m, with a 3% decrease at 300 m, a 2% decrease at 400 m, and a 14% decrease at 500 m. The PDR in SF9 was similar up to 300 m; at 400 m, there was a 2% decrease in PDR compared to 300 m; and at 500 m, it remained similar to 400 m. With 20 dBm in

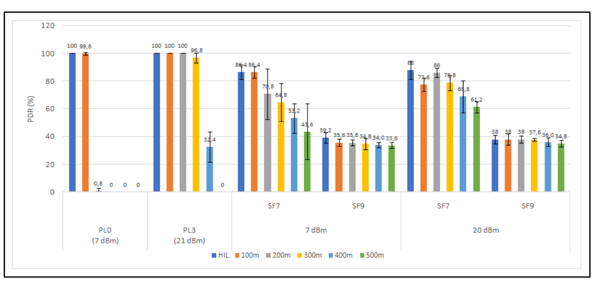

Fig. 7. PDR of LoRa RD42C and XBee-PRO S3B, at 38400 bps.

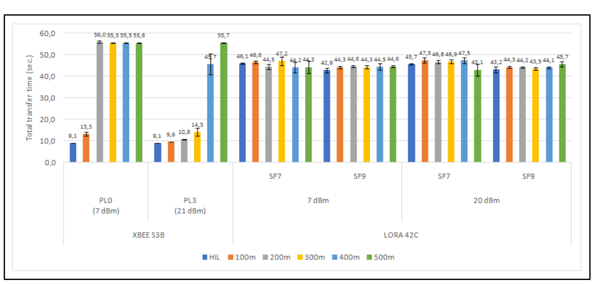

Fig. 8. Time lapse of LoRa RD42C and XBee-PRO S3B, at 38400 bps.

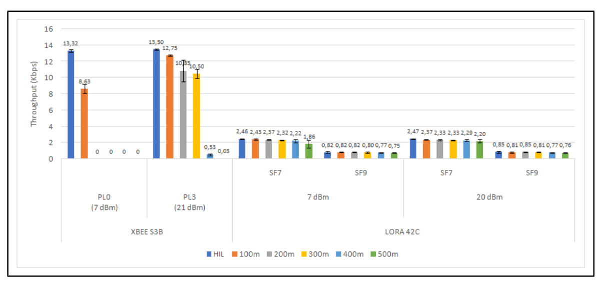

Fig. 9. Transfer rate of LoRa RD42C and XBee-PRO S3B, at 57600 bps.

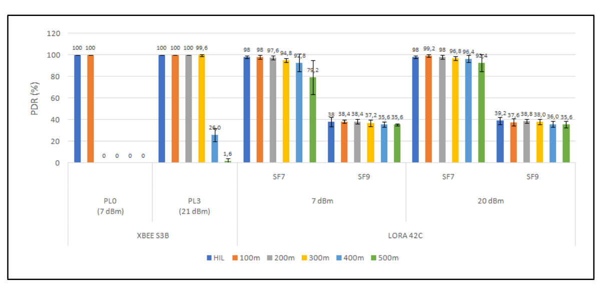

Fig. 10. PDR of LoRa RD42C and XBee-PRO S3B, at 57600 bps.

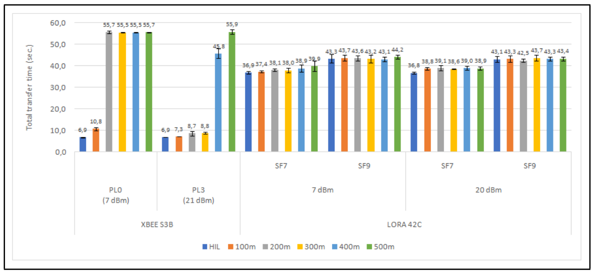

Fig. 11. Time lapse of LoRa RD42C and XBee-PRO S3B, at 57600 bps.

SF7, it was observed that the PDR increased by 1% in $100\ m$ compared to HIL; it decreased by 1% in $200\ m$; it decreased by 1% in $300\ m$; it remained similar to $300\ m$ in $400\ m$; and it decreased by 4% in $500\ m$. Finally, at $20\ dBm$ with SF9, the PDR decreased by 2% at $100\ m$ and increased by 1% at $200\ m$; at $300\ m$, the PDR decreased by 1% relative to $200\ m$; at $400\ m$, the PDR decreased by 2%; and at $500\ m$, the PDR remained similar to $400\ m$.

Fig. 11 compares the total transfer time between the radios in their analyzed parameters and scenarios. Thus, in the HITL scenarios at $7\ dBm$, the XBee was more efficient than the LoRa at the same power only up to $100\ m$ at $57600\ bps$. At PL3, XBee had a higher efficiency than LoRa but only up to $300\ m$. Thus, only LoRa was able to obtain some transmission rate/PDR at low power in the scenario from $100\ m$ onwards. Only at $400\ m$ did LoRa outperform XBee in terms of higher potency.

V. CONCLUSION

This paper presented a comparison of LoRa and ZigBee radios for the application in FANET networks, focusing on transfer rate and PDR obtained experimentally on the HIL bench and HITL ground at distances up to $500\ m$. The proposed experiments were used to compare LoRa and XBee radios at different transmission rates and potencies. The results showed that the XBee radio had a higher efficiency in both PLs in HIL, but on the ground in PL0, the XBee was only more efficient at $100\ m$. In terms of PL3, the XBee proved to be more efficient in all data rates only up to $300\ m$, while LoRa was superior at all other distances. Future work will concentrate on new tests involving the asynchronous packet sending rate, transfer rates, and PDR using mesh networks on the ground, followed by experiments in real flight using a fleet of quadcopters, with the goal of determining the sending rate/PDR and radio range.

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