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Performance Analysis of Long-Range Propagation Above 1 GHz for LoRa Applications in Agriculture

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***Abstract*—The paper presents the technical setup and results of field tests aimed at verifying the propagation and communication performance of LoRa links in the ISM2400 band. The LoRa technology has spread worldwide in recent years as an effective solution to connect low-power sensors over long distances. Its typical applications occur below 1 GHz, e.g. in the EU868 band in Europe and in the US915 band in the Americas. Very recently, few chips have been made available to run LoRa applications above 1 GHz, specifically in the ISM band between 2.400 GHz and 2.485 GHz, with notable advantages in terms of worldwide portability and absence of duty cycle enforcement. This is particularly promising for agriculture, where time-unconstrained transmissions enable effective implementations of LoRa-based actuators and bidirectional controls. Unfortunately, propagation above 1 GHz is potentially limited, necessitating range verification. Building on our previous success with stable links up to 18 km, we extended our testing to greater distances, achieving excellent performance over 24 km in a different rural area, always under Line-of-Sight conditions. Additionally, we deployed permanent installations to facilitate future outdoor tests over longer periods of time, with multiple terminal nodes at varying distances. The results obtained have been successful, demonstrating the validity of LoRa technology in the ISM2400 band.**

I. Introduction

Modern agriculture increasingly relies on wireless communications, such as Wireless Sensor Networks (WSNs), to support precision monitoring and decision-making processes. These networks can be implemented in licensed or unlicensed bands, the latter being preferred to avoid additional subscription costs. The most common unlicensed radio frequency bands that can be adopted are sub-1 GHz, such as the Industrial, Scientific and Medical (ISM) band (in Europe EU868 at 868 MHz and in America US915 at 915 MHz), and above 1 GHz, such as the ISM2400 band (2.400–2.485 GHz). The former has the advantage of reaching longer distances, at the cost of lower data rates, due to regional limitations, such as the duty cycle in Europe [1]. The latter provides global compatibility, simplifying hardware deployment, and eliminates duty cycle constraints, allowing for transmission without temporal limitations. For the listed reasons, the ISM2400 band is particularly suitable for devices requiring frequent data exchange, such as actuators or sensors to monitor water usage. However, higher frequencies introduce challenges, such as reduced propagation range, a more congested frequency spectrum, and, consequently, susceptibility to interference.

In agriculture, various radio communication technologies are employed, each with advantages and drawbacks. For instance, Wi-Fi [2] is characterized by high data rate support, but has limited coverage and high power consumption, which is suitable for indoor applications. ZigBee [3] is another option for Internet-of-Things (IoT) applications, though its limited propagation range discourages outdoor use. Similarly, Bluetooth Low Energy [4] is very energy efficient, but constrained by short communication ranges. Finally, Low-Power Wide-Area Networks (LPWANs) [5] have gained significant attention in recent years for connecting low-power sensors over long distances.

Among LPWANs, LoRa (Long-Range) [6] emerged in the last decades, thanks to its low energy consumption and strong immunity to interference. Traditionally, it operates in the sub-1 GHz ISM bands [7]. The recent introduction of LoRa chipsets, such as SX1280, operating in the ISM2400 band, offers a promising alternative [8], [9], which has triggered innovative research and new studies about LoRa performance in the sub-1 GHz band. A maximum range of 443 m was achieved in an outdoor urban area with spreading factor (SF) 12 and bandwidth (BW) 203 kHz [10], while in [11] the maximum range was estimated for urban and metropolitan areas using propagation models. Authors in [12] developed a simulation tool for urban environments which confirmed the distance lower than 3 km over a lake obtained in [13]. Further tests presented in [14] obtained a distance in Line-of-Sight (LOS) of almost 10 km, using the highest spreading factor with packet delivery rate (PDR) higher than 80%. Authors in [15] proposed a signal emulator that allows a Wi-Fi device to generate LoRa signals, with a transmission distance of 300 m in condition of Non-Line-of-Sight (NLOS). A further study presented an alternative physical-layer architecture for LoRa in the ISM2400 band to face the cross-technology-interference from Wi-Fi networks [16]. [17] instead described an RF-Transformer, a backscatter radio hardware abstraction that can use the LoRa protocol at 2.4 GHz, achieving a maximum distance over 600 m, with SF 12, BW 250 kHz, and an error rate below 1%. The experimental study in [18] performed outdoor measurements in urban area under NLOS condition, with a distance of 500 m between the transmitter and the node, and indoor scenario, with a distance of 200 m. Another work proposed a method to maximize the throughput of LoRa networks working in the ISM2400 band, introducing a dynamic spreading factor adjustment algorithm based on node distance and traffic conditions [19]. Other studies evaluated LoRa performance in indoor scenarios [20] and outdoor without exceeding 2 km of range [21], [22]. Several research works investigated the interference issues caused by the coexistence of LTE [23], Bluetooth [24] and Wi-Fi [25] in the same ISM band, to aid in spectrum sharing.

Finally, in our previous work [26], we explored the potential of LoRa technology in the ISM2400 band for agricultural applications, demonstrating the feasibility of achieving reliable communication distances of up to 18 km with 100% PDR, with measurements taken in different sessions in September 2024. The activity described in [26] has been carried forward during the subsequent fall and winter, trying to extend the transmission range to farther distances, considering that a very recent experimental work reached a distance of 36 km [27]. We continued the research activity by increasing the range, maintaining the LOS condition and applying the technology in rural areas. Moreover, we assembled permanent installations with the future perspective to conduct extensive tests over longer periods, incorporating several fixed nodes transmitting at various distances and exploring different configurations. In this work, we thus present an analysis of LoRa performance above 1 GHz, demonstrating successful communication over 24 km in rural areas and highlighting its potential for long-range applications in precision agriculture.

II. Methodology

The objective of the test was to measure the maximum range and reliability of the signal received by the gateway, collecting data such as Received Signal Strength Indicator (RSSI), Signal-to-Noise Ratio (SNR) and PDR percentage.

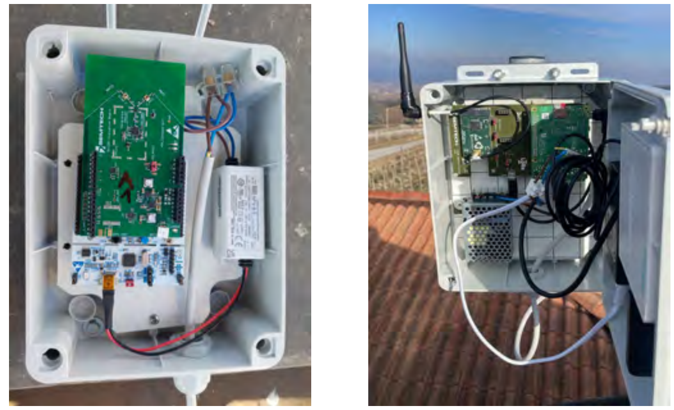
In our experiments, both the gateway and end-nodes were based on the SX1280 LoRa transceiver, produced by Semtech. It supports 4 channel bandwidths (203 kHz, 406 kHz, 812 kHz, and 1625 kHz) and spreading factors from SF5 to SF12.

The end-node was implemented using the STMicroelectronics NUCLEO-L073RZ development board, equipped with a Semtech SX1280ED1ZHP LoRa shield, which features on-board printed antennas. The device was powered by a 5V/7W supply, and enclosed in a waterproof plastic box, as shown in Fig. 1a, to enable outdoor deployment.

The gateway consisted of a Raspberry Pi 4 model B equipped with a Semtech SX1280Z3SDFGW1 LoRa board. An external omnidirectional antenna with a maximum gain of 2.3 dBi was connected via a 20 cm RF pigtail, which replaced the monopole antenna setup of previous tests. To connect the Raspberry Pi to the Internet, we used a MikroTik RB750UPr2 hEx PoE Lite router, with a 4G dongle. The system was powered by a 5V/25W switching power supply and enclosed in a waterproof plastic box, shown in Fig. 1b.

Finally, as network server we adopted The Things Network (TTN), which supports 3 frequency channels (2.403 GHz, 2.425 GHz, and 2.479 GHz, respectively for channel 1, 2 and 3) in the ISM2400 band [28]. Fig. 2 summarizes the architecture of the system, with the gateway setup on the left block, the end-node on the right one. Fig. 3 shows the map of the geographical setup, highlighting the positions of the gateway and the end-nodes.

The gateway was configured with three channels, all set to the frequency of 2.403 GHz, and each assigned a distinct spreading factor: SF12, SF10, and SF8. For this test, only SF12 was used, although the configuration will be reused in future experiments involving different spreading factors. Channel 1 was selected based on findings from our previous study [26], which demonstrated that the channel was less affected by interference, compared to channels 2 and 3. The gateway was mounted on the rooftop of a building in Monforte d'Alba, located in the Piedmont region of Italy, at an altitude of 555 meters.



(a) End-node (b) Gateway

Fig. 1. Devices deployment: end-node (left) and gateway (right) contained in waterproof plastic boxes, here opened for visualization purposes.

The end-node was programmed to transmit a packet every minute, at the maximum power output of +12.5 dBm. Using SF12, a BW of 812 kHz, a code rate of 4/8, and a payload length of 4 bytes, the configuration resulted in a Time on Air (ToA) of 127.29 ms and an effective data rate of 1.9042 kbps. With this configuration, the SX1280 radio draws approximately 45 mA in transmission mode, 15 mA in reception mode and 1 μA in sleep mode. Initially, it was placed in Fossano at a distance of 18 km from the gateway, to validate the results of the previous field test. Then, it was placed in Mondovì, at a panoramic viewpoint, approximately 517 meters above the sea level, in LOS with the gateway, at a distance of 24.7 km. Lastly, a test was conducted from a farther location atop the civic tower of Saluzzo, situated 39 km away from the gateway in Monforte d'Alba. As in the previous tests, only LOS conditions were considered to evaluate the maximum potential of the technology, since NLOS conditions are more challenging, even though they would provide a more comprehensive assessment of the technology.

III. Results and Discussion

Building upon the methodology previously adopted in our earlier field test [26], we collected RSSI and SNR values measured by the gateway for each transmitted packet, as shown in Fig. 4, which includes also the results presented in [26] for comparison purposes. The packet reception success rate reached 100 %, over a distance of nearly 25 km. In particular, we achieved successful packet reception even under extreme signal conditions, with SNR values as low as -21 dB below

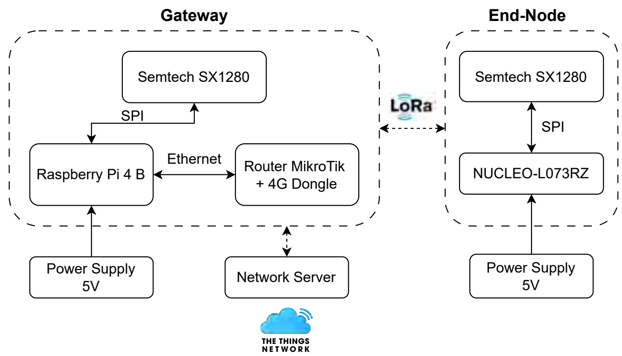


Fig. 2. System architecture of the setup.

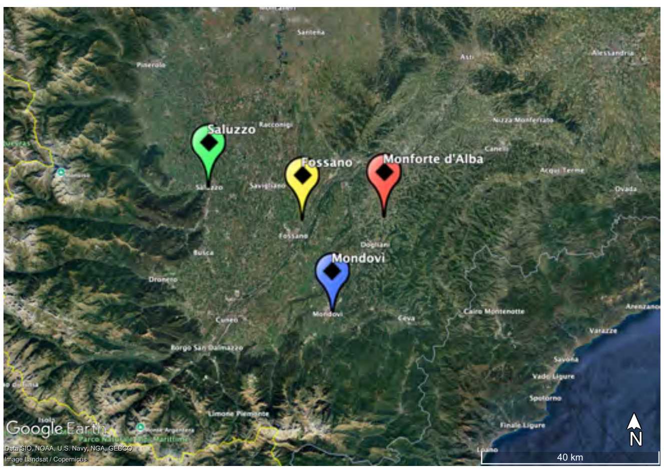


Fig. 3. Locations of the gateway (red marker) in Monforte d'Alba and the end-nodes in Fossano (yellow marker), Mondovì (blue marker) and Saluzzo (green marker).

the noise floor, with RSSI equal to -101 dBm. Unfortunately, we did not obtain the same results in the last position in Saluzzo. Indeed, the gateway was able to receive the join request attempts by the end-node sporadically, but the end-node never received the acceptance packet. This result suggests that it is crucial to investigate alternative antenna solutions to improve signal propagation.

IV. Conclusions

The permanent installation of the gateway enables the opportunity to expand the number of end-nodes in fixed positions and to collect data over extended periods. This approach will allow us to perform tests at greater distances and with diverse configurations, and, hence, to validate the reliability of the LoRa system in challenging conditions.

Furthermore, we are considering exploring different types of antennas to evaluate their impact on signal propagation and range. To achieve these objectives, a detailed investigation of the geographical characteristics of the area will be essential to identify suitable installation sites that ensure LOS operational conditions.

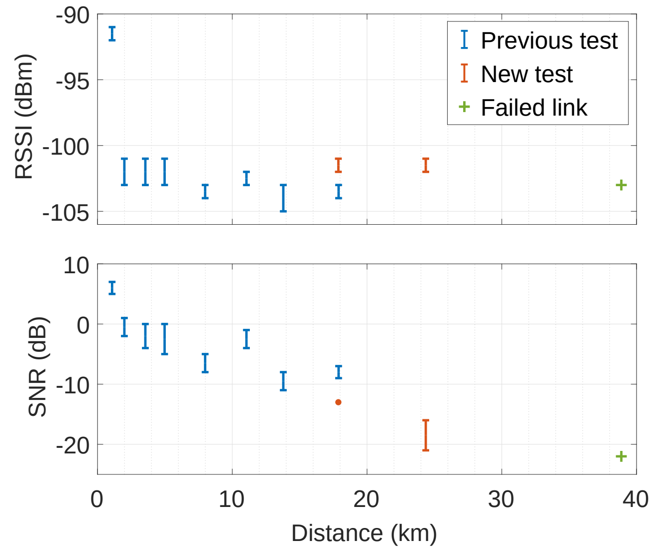


Fig. 4. RSSI and SNR of each frame received by the gateway during previous test session (blue markers) and new ones, (red markers). In green, the RSSI and SNR values measured by the gateway at each join attempt of the end-node located in Saluzzo.

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