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Analysis of low power wide area network wireless technologies in smart agriculture for large-scale farm monitoring and tractor communications

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ABSTRACT

In this paper, the assessment of multiple scenario cases for large-scale farm monitoring using Low-Power Wide-Area Network (LPWAN) based near-ground sensor nodes with the interaction of both tractors and farmers are presented. The proposed scenario under analysis considers multiple communication links, namely nodes to infrastructure, nodes to tractor, nodes to farmer, tractor to infrastructure and farmer to infrastructure communications. Moreover, these scenarios are proposed for tractors and agricultural equipment performance improvement and tracking, as well as resources management within the farm field. Different link type configurations are tested in order to consider the impact of ground, spatial distribution as well as infrastructure elements. The results show that LPWAN-based WSNs can provide better performance in terms of coverage and radio link quality results than ZigBee for a non-flat large-scale farm field in both cases of near-ground fixed nodes and moving tractor and farmer. The proposed systems are validated by cloud-based platforms for LoRaWAN, Sigfox and NB-IoT communications, providing flexible and scalable solutions to enable interactive farming applications.

1. Introduction

The world's population is expected to reach 8.5 billion by 2030. This implicates the need to increase agriculture production. However, the growing agriculture labor shortage, especially during the recent COVID-19 pandemic, has results in increased interest and research in WSN deployment in smart agriculture to fill the labor shortage, improve the production quality and minimize costs. Reviews and surveys on the benefits and the challenges of Internet of Things (IoT) in smart agriculture are highlighted in [1–4]. Moreover, research studies on security and privacy challenges and solutions in smart agriculture are presented in [5,6]. In this context, when first WSNs were adopted in agriculture, most networks were based on short-range communication technologies. Wi-Fi-based WSNs for environmental parameters monitoring in farm fields are presented in [7,8]. In [9–12], ZigBee-based control systems for environmental parameters monitoring in multiple farms are proposed. However, deploying WSN based on these technologies in large-scale farm fields results in high-cost systems due to the need for a big number of nodes to cover the large-scale area and the high energy consumption.

Recently, Low-Power Wide-Area Networks (LPWAN) technologies have become more popular in the IoT market, due to their low cost, low power and wide range wireless communication features. Comparative studies and surveys of the deployment of LPWAN technologies in IoT applications are presented in [13–16]. The most famous LPWAN technologies are Long Range Wide-Area Networks (LoRaWAN), Sigfox and Narrow-Band IoT (NB-IoT). Hence, LPWAN based WSNs have become widely used in different fields, such as air quality monitoring [17], smart health monitoring [18], botanical parks monitoring [19], environmental monitoring [20] and vehicular communications [21]. Concerning LPWAN technologies in agriculture, some works are presented in the literature. A LoRa and Sigfox based irrigation system is proposed in [22]. A combination of EnOcean and Sigfox for real-time data collection for agriculture is proposed in [23]. An NB-IoT-based system for WUSN in

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potato crops is proposed in [24]. Other NB-IoT-based experiments for IoT in smart farming are presented in [25,26]. A LoRaWAN-based real-time soil health monitoring system is proposed in [27]. Underground to above-ground LoRaWAN-based communication analysis for different soil types is presented in [28]. Other contributions on LoRaWAN use in agriculture are presented in [29–34]. Moreover, a survey of LPWAN technologies in smart agriculture is presented in [35]. Table 1 summarizes the research works related to the use of LPWAN technologies in agricultural environments. However, the interaction of farmers and agricultural machinery with the network for monitoring and tracking purposes is not discussed in the literature.

The advancement in agricultural machinery is noticeable. Autonomous and semiautonomous tractors are used for navigation, mapping and surveillance. In literature, some works on autonomous tractor systems for video surveillance and mapping are presented. In [41], multipath routing protocols for semiautonomous tractors remote supervision through real-time video transmission are evaluated. An autonomous multi-tractor system for citrus orchard mowing and spraying under human supervision when it is needed are presented in [42,43]. In [44], a semiautonomous tractor system with human intervention is proposed. In [45], a robust, easy to implementation and low-cost solution for heavy tractors-trailers path following in GPS denied environments is presented. Finally, an automated ground-level mapping and navigating using robot vehicles in agriculture based on computer vision is proposed in [46]. However, tractors tracking and monitoring using LPWAN-based WSN and their interaction with the network for collecting field data are missing from the literature.

The autonomous and the semiautonomous tractors besides the traditional ones can interact with the monitoring system within the large-scale farm field while doing their tasks. Thus, make more use of the fuel consumed and help in covering wider areas within the network. In this context, multiple LPWAN-based WSNs scenarios deployment assessment in a large-scale farm field of around 300.000 m^2 with the interaction of the farmer and the tractor are presented in this work. Multiple scenarios are considered to provide different solutions for various applications in smart agriculture. The first scenario is based on near-ground nodes to infrastructure communication using LoRa 868 MHz, LoRaWAN 868 MHz, LoRa 433 MHz, Sigfox and NB-IoT along with the classic ZigBee Mesh 2.4 GHz for comparison. The near-ground nodes are placed on the ground and at 1 m from the ground around the farm field, sending packets to the corresponding gateways and base stations, then to the clouds. The importance of near-ground communication scenarios in agriculture is highlighted in [47,48].

The second scenario is based on near-ground nodes to tractor communication in one case and near-ground nodes to farmer communication in the other case, where the tractor and the farmer can play the role of the coordinator by collecting near-ground data for storage using LoRa 868 MHz and ZigBee Mesh 2.4 GHz. Finally, the last scenario is based on tractor to infrastructure communication in one case and farmer to infrastructure communication in the other case, where the collected data by the tractor and the farmer can be sent using LoRaWAN, SigFox and NB-IoT to the cloud. As well, this scenario is proposed for a tractor tracking and monitoring system. Real-time autonomous tractor's status as location, speed, fuel level and current tasks can be sent to the cloud for decision making. The effect of the tractor on the wireless communication is taken into account in the performed measurements.

The paper is organized as following: Section 2 describes the targeted large-scale farm field. An overview of LPWAN technologies and the used material for measurements are presented in Section 3. The proposed scenarios description, measurement results and comparison are provided in Section 4. Finally, concluding remarks are presented in Section 5.

2. Description of the farm field

The scenario under analysis is located on the experimental farm field at the Agricultural Engineering School on the Public University of Navarra, Pamplona (Spain), placed in Pamplona (Spain). The farm fields cover an area of 300,000 m^2, as it is illustrated in Fig. 1, and has been in operation since 1996. In Europe, the average farm size is 16 ha (160.000 m^2) and farms with size higher than 30 ha (300.000 m^2) represent less than 25% and two-thirds of the total agricultural holdings are less than 5 ha (50.000 m^2) in size [49]. Therefore, the experimental farm in this study represents a large-scale farm. The topography is slightly hilly, with an altitude range between 430 and 455 m above sea level (asl). The area is distributed as follows: 68% is dedicated to extensive crops, with a vegetation height of less than one meter; 28% for permanent crops, such as fruit trees and vineyards with vegetation heights of less than 3–4 m, and 4% for horticultural crops, of which 30% are grown in plastic and glass greenhouses, with heights around 3–5 m. There are also warehouses where the farm machinery is stored and used for the cultivation of the farm and teaching. As well, as two tractors and their corresponding supplementary machinery. Finally, there are gravel pathways that connect each of the plots and buildings of the experimental fields. a radius overlay and the gateway and node locations to give a better idea about the actual size of the farm.

3. LPWAN technologies

3.1. Overview of LPWAN technologies

In the presented work, different LPWAN technologies are tested. NB-IoT, which is a licensed LPWAN, runs on public cellular networks using licensed frequency spectrum, co-exist with 2G, 3G and 4G mobile networks, and supports roaming to avoid interoperability problems. Moreover, NB-IoT offers a bandwidth of 200 KHz, a maximum payload size of 1600 bytes and unlimited transmitted packets per day. In terms of power consumption, NB-IoT offers up to 10 years of battery life to its devices.

Also, unlicensed LPWAN LoRa, LoRaWAN and Sigfox, using unlicensed frequency spectrum, are tested. The difference between LoRa and LoRaWAN is that LoRa is a communication technology that allows Peer to Peer (P2P) communication and LoRaWAN is a network communication protocol based on LoRa and used for communications between nodes and gateways. Channels with bandwidths of 125 KHz, 250 KHz and 500 KHz can be used by LoRaWAN. The spreading factor (SF) in LoRaWAN varies between 7 and 12. Due to the duty cycle restrictions in Europe, the number of the transmitted packets per day is limited. In terms of power consumption, LoRaWAN offers up to 15 years of battery life to its devices.

Finally, Sigfox is an unlicensed LPWAN for small packets of 12 bytes with a bandwidth of 100 Hz. Due to the duty cycle restrictions in Europe, the number of the transmitted packets per day is limited to 140 messages in the uplink and 4 messages in the downlink. In terms of power consumption, Sigfox is extremely low power consumption with up to 15 years of battery life. An overview of the tested LPWAN technologies is presented in Table 2.

From Table 2, it can be concluded that every LPWAN technology has its own advantages and challenges compared to the other technologies. Thus, the choice of adequate technology for a specific application depends on the needs in terms of bandwidth, power consumption, payload size, number of messages and budget.

3.2. Transceivers used for measurements

In this work, multiple nodes with different transceiver modules were used. The Things Uno nodes were used for LoRaWAN 868 MHz measurement. It is based on Arduino Leonardo with an integrated omnidirectional antenna and Microchip 2483 LoRa transceiver module. These nodes join the LoRaWAN 868 MHz network using Over-the-Air Activation (OTAA) and SF7BW125 data rate for the uplink with a transmitted

Table 1
Related works.

Ref	Aim of the work	Description	Technology
[22]	A low-cost design and solution for automatic IoT-based irrigation.	The combination of both LoRa and Sigfox for the implementation of a cloud-based WSN for agricultural irrigation.	- LoRa - Sigfox
[23]	A low-cost WSN for real-time intruder detection and crop cultivation data collection.	The combination of EnOcean sensors operating in energy harvesting and Sigfox for storing real-time agricultural data in the cloud.	- EnOcean - Sigfox
[24]	Underground soil parameters data collection in potato crops using UAV-aided network.	NB-IoT-based wireless underground system assessment with the interaction of Unmanned Aerial Vehicles for nodes buried at four different depts in dry and wet potato field soil.	- NB-IoT
[25]	Field experiments for NB-IoT assessment in agriculture environment.	The evaluation of a Raspberry-based NB-IoT node in terrace, ground, underground and cellar conditions.	- NB-IoT
[26]	Real-time data collection and storage for smart greenhouse management.	Smart greenhouse management based on NB-IoT for data storage and visualization and a Bluetooth-based Android application for on-sited management.	- NB-IoT - Bluetooth
[27]	Self-powered nodes for real-time soil health monitoring system.	The implementation of a LoRaWAN-based soil health monitoring units for data storage and analysis. Also, the visualization of the agricultural data through a web-based dashboard.	- LoRaWAN
[28]	Underground to aboveground communication under different soil types conditions.	LoRaWAN-based measurements for underground to aboveground communication for nodes buried under gravel, sand and clay soils at a depth of 50 cm.	- LoRaWAN
[19]	An end to end system for interaction with a distributed botanical campus garden.	3D Ray launching simulations and measurements for LoRaWAN and ZigBee based multilevel communication links, considering underground, near-ground and over-ground conditions.	- LoRaWAN - ZigBee
[36]	Hybrid LPWAN mesh network design for large-scale farm fields.	The implementation of a hybrid WSN with 2.4 GHz short-range radio and LoRaWAN mesh communication links for large-scale IoT applications.	- LoRaWAN – 2.4 GHz short-range radio
[37]	Low-cost sensor node design for Agro-intelligence IoT.	The development of a LoRaWAN-based low-cost of small size sensor node for smart farming applications.	- LoRaWAN
[38]	Smart farming modular IoT architecture for farm management.	The development of a LoRaWAN-based platform "LoRaFarM" and a web-based visualization tool for farm product management.	- LoRaWAN
[39]	Wildfire monitoring wide area wireless network in a forest vegetation area.	Experimental LoRa 433 MHz and LoRa 868 MHz assessment for wildfire monitoring application for highly dense and not so dense forest vegetation environment.	- LoRa 433 MHz - LoRa 868 MHz
[40]	Autonomous sensor node development for environmental monitoring.	The development of a Sigfox-based solar powered autonomous sensor node for meteorological parameters collection and its assessment in a vineyard.	- Sigfox
This work	In this contribution, the assessment of various LPWAN technologies for large-scale farm applications with the interaction of the farmer and the tractor.	Experimental-based analysis for the implementation of LoRa, Sigfox and NB-IoT LPWAN technologies in near-ground communication scenarios with the interaction of the farmer and the tractor for various topologies and applications possibilities; Nodes to Infrastructure, Nodes to Farmer/Tractor and Farmer/Tractor to Infrastructure.	- LoRa 868 MHz - LoRaWAN 433 MHz - LoRaWAN 868 MHz - Sigfox - NB-IoT -ZigBee 2.4 GHz

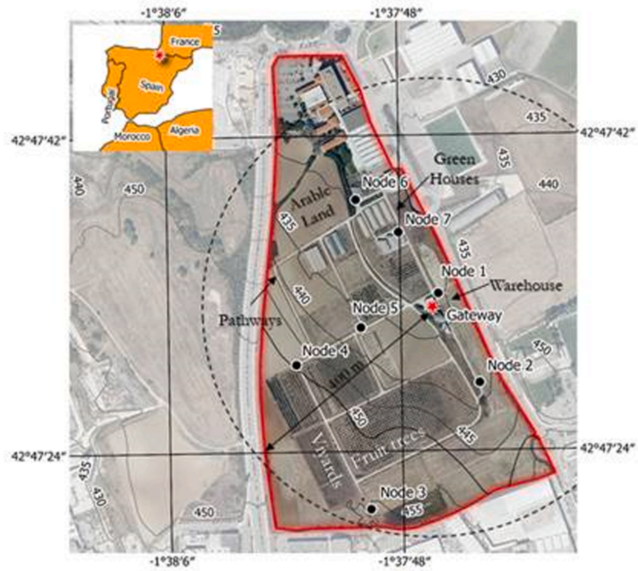

Fig. 1. Study area: Experimental field at the Agricultural Engineering School at the Public University of Navarra, Pamplona (Spain).

Table 2
Overview of LoRaWAN, Sigfox and NB-IoT technologies.

	LoRaWAN	Sigfox	NB-IoT
Frequency Ranges	EU863-870 MHz / EU433 MHz / US902-928 MHz / CN470-510 MHz / CN779-787 MHz / AU915-928 MHz / AS923 MHz	EU868 MHz / US902 MHz/ AS920 MHz	LTE Bands
Modulation	LoRa modulation / CSS	UNB / BPSK	QPSK
Transmitted Power	EU: 14 dBm US: 20 dBm	EU: 14 dBm US: 22 dBm	23 dBm
Bandwidth	EU: 125 KHz/250 KHz US: 125 KHz/500 KHz	0.1 KHz	200 KHz
Data Rate	50 Kbps	0.1 Kbps	200 Kbps
Sensitivity	−148 dBm	−142 dBm	−141 dBm
Payload Size	EU: 222 bytes US: 242 bytes	12 bytes	1600 bytes
Messages / Day	EU: UL: airtime of 30 s / DL: 10 messages US: Unlimited	UL: 140 messages DL: 4 messages	Unlimited
Coverage	Urban: 5 km Rural: 20 km	Urban: 10 km Rural: 40 km	Urban: 1 km Rural: 10 km
Battery life	Very high	Very high	High
Security	AES 128 bits	AES 128 bits	3GPP (128–256 bits)

power of 14 dBm. The payload size of the transmitted packets is 12 bytes.

For LoRaWAN 433, P-NUCLEO-LRWAN3 nodes based on the STM32L071 MCU and Semtech SX1278 transceiver modules connected to external omnidirectional antennas were used. These modules are programmed to join the network using OTAA and SF9BW125 data rate for the uplink with a transmitted power of 14 dBm. For LoRaWAN 433 MHz, packets with a payload size of 16 bytes are programmed to be transmitted.

Moreover, Arduino MKR WAN 1300 modules with integrated MuRaTa CMWX1ZZABZ LoRa transceivers were used for LoRa 868 MHz network. The modules were connected to external omnidirectional GSM antennas with a gain of <0 dBi. The LoRa modules were programmed to P2P communication using SF7BW125 data rate with a transmitted power of 14 dBm. The size of the payload is 12 bytes.

The Sigfox network is based on Arduino MKR FOX 1200 modules. ATA8520 transceivers are integrated into the Sigfox modules. These modules were connected to the same external omnidirectional GSM antennas as MKR WAN 1300. The transmitted power of the Sigfox modules is 14 dB and the payload size is 12 bytes.

For NB-IoT, Digi XBee 3 Cellular LTE-M/NB-IoT modules were used. These modules were connected to the network using Vodafone NB-IoT sim cards and through external omnidirectional antennas. The transmitted power of the NB-IoT modules is 20 dBm. In this case, the size of the transmitted payload is 12 bytes.

Moreover, a ZigBee Mesh 2.4 GHz network was implemented to be compared to the LPWAN networks. This network consists of Digi XBee Pro modules with antenna gains of 5 dBi for the farthest nodes and 3 dBi for the nearest nodes. The transmitted power of the ZigBee nodes is 18 dBm.

Finally, a Dragino LoRa GPS shield connected to Arduino Uno was used to track the location of the mobile farmer and tractor while sending or receiving packets for packet processing and analysis purposes.

The characteristic of the modules used in measurements are summarized in Table 3.

In order to evaluate the performance of LoRaWAN technology in the worst conditions, the interval between packets in the presented scenarios is set to 30 s. Thus, for a payload size of 12 bytes and using the Li-ion (2000mAh) low cost battery type in the case of SF = 7, the estimated battery life is about 8 months and 2 weeks using LoRa Energy calculator [50]. However, for an interval of 5 min between packets, the estimated battery life is about 6 years and 7 months. The battery life can be significantly increased using battery with higher capacity.

Based on the available information in datasheets on the transceivers used in measurements, the current consumption of transceivers in deep sleep modes, Idle mode and transmit mode is illustrated in Fig. 2. The current consumption unit in deep sleep mode is in uA. However, the current consumption unit in Idle and transmit modes is in mA. In deep sleep mode, the current consumption of the NB-IoT module is much higher than the Sigfox and LoRaWAN 868 MHz transceivers. In this case, the current consumption of the Sigfox transceiver is 0.005 uA. In the Idle mode, the current consumption of the LoRaWAN 868 MHz transceiver is higher than the Sigfox and NB-IoT modules. Finally, in the transmit modes, the current consumption of the NB-IoT module is significantly higher than the Sigfox, LoRaWAN 868 MHz and LoRa 868 MHz. Hence, it can be concluded that the current consumption of the Sigfox transceiver is lower in all modes compared to the other transceivers.

4. The proposed scenarios for measurement and results

Multiple scenarios are considered for LPWAN-based WSNs for large-scale farm field and resource monitoring and tracking. These scenarios can be summarized in nodes/tractor/farmer to infrastructure using LoRaWAN 868 MHz, LoRaWAN 433 MHz, Sigfox, NB-IoT and ZigBee

Table 3
Measurement nodes and its characteristics.

Nodes	Wireless Technology	Sensitivity (dBm)	Transmitted Power (dBm)	SF	BW (KHz)
The Things Uno	LoRaWAN 868 MHz	−146	14	7	125
P-NUCLEO-LRWAN3	LoRaWAN 433 MHz	−137	14	9	125
Arduino MKR WAN 1300	LoRa 868 MHz	−135.5	14	7	125
Arduino MKR FOX 1200	SigFox	−142	14	–	0.1
Digi Xbee 3 Cellular ITE-M/NB-IoT	NB-IoT	−113	20	–	62.5
Digi XBee PRO	ZigBee 2.4 GHz	−101	18	–	250

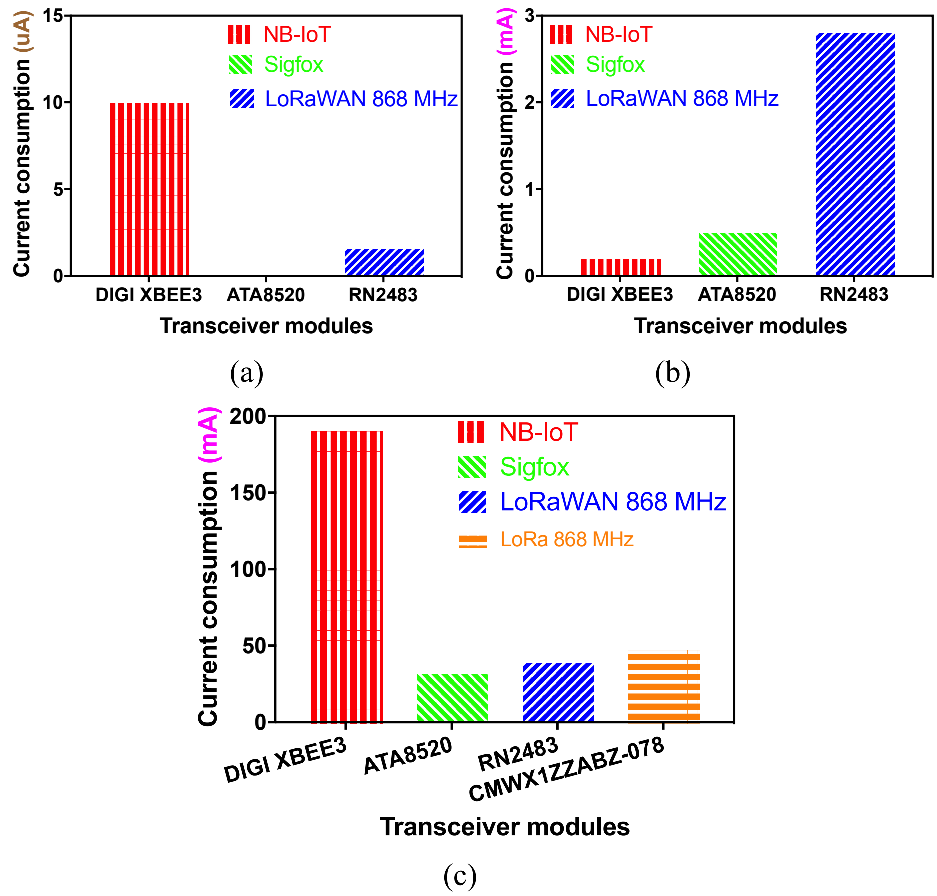

Fig. 2. Transceivers modules current consumption in (a) deep sleep mode; (b) Idle mode; (c) transmit mode.

2.4 GHz and nodes to tractor/farmer using LoRa 868 MHz and ZigBee Mesh 2.4 GHz. These scenarios are represented in Fig. 3.

4.1. Nodes to infrastructure communication

In nodes to infrastructure scenario, LoRaWAN 868 MHz, LoRaWAN 433 MHz, NB-IoT, Sigfox and ZigBee Mesh 2.4 GHz technologies were used. The nodes were placed at seven different locations within the farm field and the LoRaWAN 433 MHz / 868 MHz and ZigBee 2.4 GHz gateways were placed on the roof of one of the central warehouses, as it is illustrated in Fig. 4(a) and Fig. 5. The NB-IoT and Sigfox gateways are the corresponding base stations at the city of Pamplona.

The nodes locations were chosen based on the spatial distribution of the farm field and the topography, as it is illustrated in Fig. 4(a), in order to cover all possibilities, short and long distance; and under Line of Sight

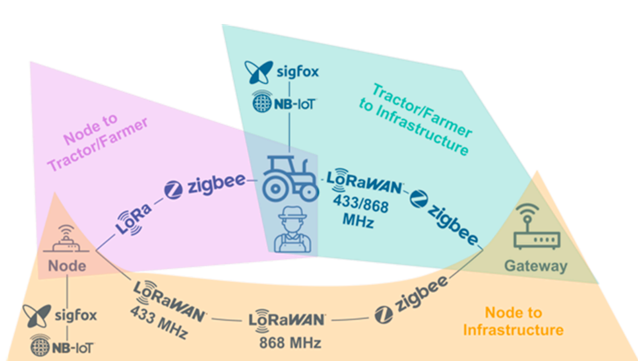

Fig. 3. The proposed scenarios for large-scale farm monitoring.

(NLoS) and Non Line of Sight (N-LoS) conditions, as it can be seen in Fig. 4(b). Moreover, nodes were placed at different heights to analyze the effect of the ground on the wireless communication in the presented scenario, sited on the ground and at 1 m from the ground (Fig. 5). Moreover, the choice of the location of the LoRaWAN and ZigBee gateways is based on multiple reasons. First of all, electricity. As gateways communicate with both the existing nodes and the cloud, the power consumption is higher. Thus, a direct connection to the power socket would avoid power problems. Secondly, the internet connection. Gateways can be connected via Ethernet cables directly to the switch located at the central warehouse. Thus, the communication with the clouds is assured. Also, the location of the warehouse. Unlike the rest of the warehouses, the chosen warehouse is surrounded by the existing nodes. Thus, a better coverage is offered. Finally, the height of the roof of the warehouse. The gateways are located at 4 m from the ground, which provides a higher number of LoS communication with the existing nodes.

In the proposed scenarios, LoRaWAN and ZigBee nodes are communicating with the corresponding installed gateways. However, Sigfox and NB-IoT nodes are communicating with the corresponding existing base stations close to the farm field.

LoRaWAN 868 MHz and LoRaWAN 433 MHz nodes are sending packets to The Things gateway and ST LoRaWAN 433 MHz gateway respectively. The received data are encoded with Cayenne Low Power Payload (Cayenne LPP) to be displayed and saved on the Cayenne platform via internet. Cayenne is a cloud-based IoT solution for quick application design and data storage and visualization. ZigBee Mesh 2.4 GHz nodes are exchanging packets to be sent to the coordinator. ZigBee data are stored in a laptop for processing. Sigfox nodes are sending payloads to the Sigfox station and then to the Sigfox cloud for storage and visualization. Finally, NB-IoT nodes are sending data to thethings.io

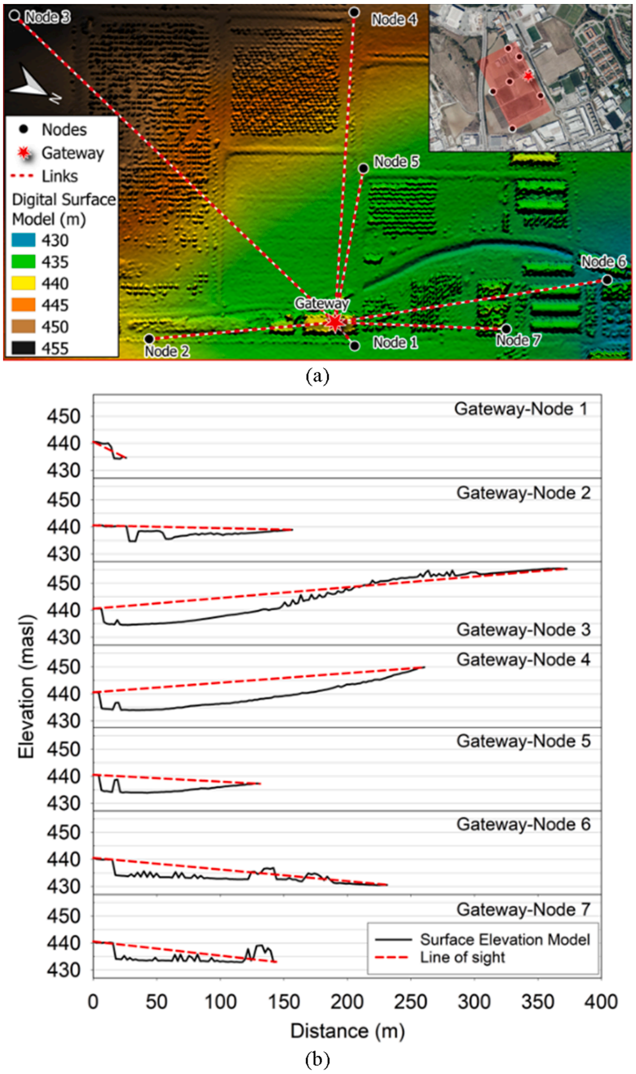

Fig. 4. (a) Spatial distribution of nodes and gateways over the digital surface elevation model and (b) the longitudinal cross-profile of node-gateway link.

cloud through the base station. These networks are illustrated in Fig. 6.

To evaluate the radio link quality for all the tested wireless communication technologies, received packets, RSSI and SNR were measured for LoRaWAN 433/868 MHz and SigFox. For ZigBee and NB-IoT, only the received packets were measured. Samples from the LoRaWAN 868 MHz measured RSSI, SNR and received packets are illustrated in Fig. 7. The average RSSI, SNR and packet loss rate for all the tested technologies are presented in Table 4 and Fig. 8.

From Fig. 8 and Table 4, it can be seen that all the NB-IoT, Sigfox and LoRaWAN 433 MHz packets were successfully received from the 7 nodes at both heights.

In the case of Sigfox, the average RSSI for nodes placed on the ground and at 1 m from the ground are respectively −117 dBm and −110 dBm for node 1, −106 dBm for node 2, −113 dBm and −109 dBm for node 3, −109 dBm and −102 dBm for node 4, −111 dBm and −102 dBm for node 5, −114 dBm and −112 dBm for node 6, and −120 dBm and −109 dBm for node 7. Moreover, the average SNR are respectively 11.4 dB and 15.79 dB for node 1, 15.85 dB and 15.97 dB for node 2, 19.18 dB and 19.56 dB for node 3, 20 dB and 16.94 dB for node 4, 17.54 dB and 17.92 dB for node 5, 15.53 dB and 16.02 dB for node 6, and 14.94 dB and 16.09 dB for node 7. The average RSSI and SNR of the LoRaWAN 433 GHz received packets are presented in Fig. 8 and Table 4.

For LoRaWAN 868 MHz, all the packets were received except from

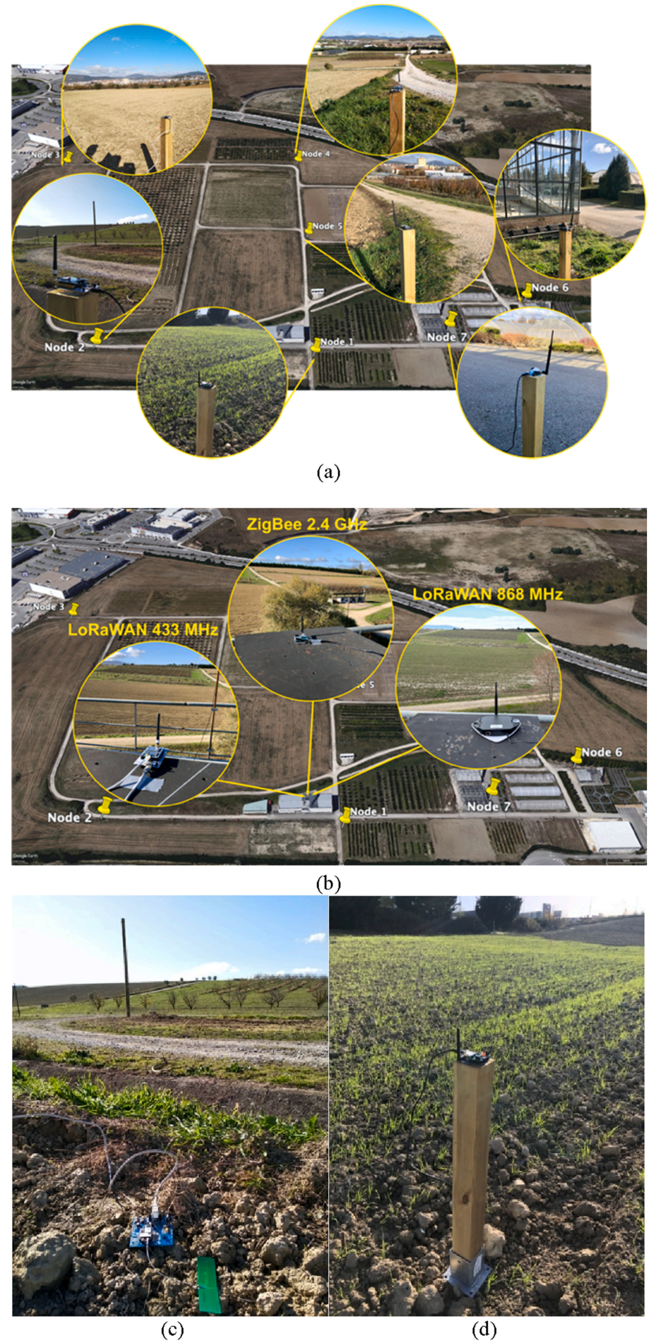

Fig. 5. (a) Nodes and (b) gateways locations; (c) node on the ground; (d) node at 1 m from the ground.

Node 3 when it was placed on the ground. The packet loss in this case is 100%. The reason for packet loss is the landform as node 3 is placed on the top of a hill, (Fig. 4(a)), where the LoS condition is lost after a distance of 210 m between the gateway and node 3 from a total distance of 370 m, as it is demonstrated in Fig. 4(b). Thus the attenuation level, in this case, is very high. In this case, to enhance the LoRaWAN 868 MHz radio, the spreading factor (SF = 7) can be increased. Thus, Increasing the airtime, which results in better sensitivity. Thus, packets can be received further away.

For ZigBee, the packet loss rate is 100% and 27.27% for node 3 on the ground and at 1 m from the ground respectively. Moreover, for other nodes placed on the ground, the packet loss rate is 3.33% for node 2, 60% for node 6 and 13.33% for node7.

Thus, in this scenario case, it is obvious that LPWAN technologies are

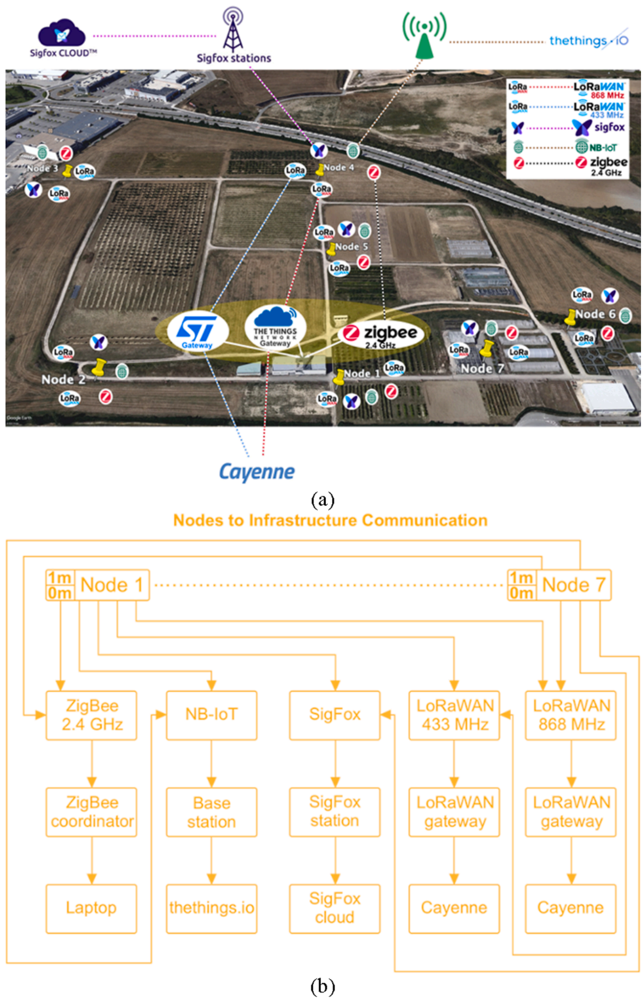

Fig. 6. Nodes to infrastructure communication (a) schema, and (b) data flow diagram.

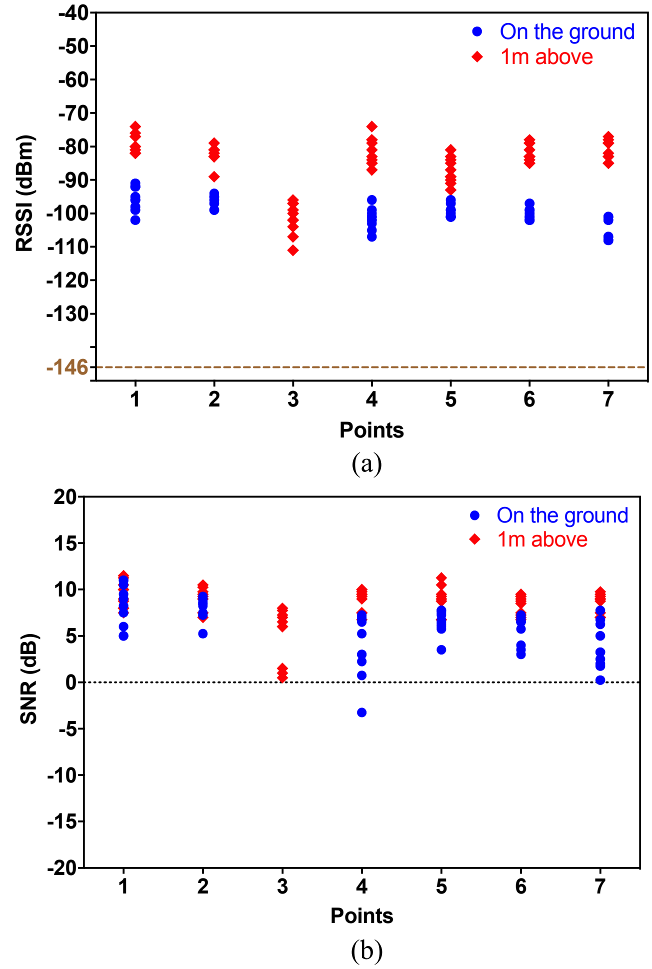

Fig. 7. LoRaWAN 868 MHz (a) RSSI; (b) SNR.

offering better results than ZigBee, especially for nodes placed on the ground, although that ZigBee is a mashed network and consumes more energy than the LPWAN technologies. Moreover, RSSI and SNR values increase with the increase of the height of the nodes and packet loss decreases with the increase of the height of the nodes for LoRaWAN 868 MHz and ZigBee Mesh 2.4 GHz.

Based on the 10 samples taken using the tested technologies, the RSSI interval of confidence, variance and standard deviation values have been calculated for different nodes placed at both heights. These values are demonstrated in Fig. 9. It can be seen that the LoRaWAN interval of confidence, variance and standard deviation values are higher than Sigfox, due to the interferences in the LoRaWAN radio link caused by the near-ground condition. Moreover, higher values occur when decreasing the height of the nodes. Also, for LoRaWAN, higher values are shown for node 3, where NLoS link between the node and the gateway, obstructed by the hill is presented.

In this scenario, the coexistence impact of Sigfox and LoRaWAN 868 MHz on each other's performance can be extracted from the packet loss rate in Fig. 8, where packets are sent every 30 s and 10 samples are taken for each node at different height. From Fig. 8, the packet loss rate for both LoRaWAN 868 MHz and Sigfox is 0% for nodes placed at both heights, except for the LoRaWAN node 3 placed on the ground, where the packet loss rate is 100% due to the NLoS communication between the node and the gateway, which is obstructed by the hill and the near-ground effect. Thus, it can be concluded that LoRaWAN 868 MHz and Sigfox can coexist in the presented scenarios without affecting each other's performance. This conclusion is compatible with the study presented in [51], which confirms that Sigfox and LoRaWAN can coexist with minor performance degradation, especially in the case of a low number of messages per minute.

Moreover, the aim of testing the interval of 30 s between packets is to evaluate the performance of the suggested technologies in the worst conditions. Then, this interval can be adjusted according to the implemented sensor, the transmitted data and the required application.

4.2. Farm monitoring with the interaction of the farmer

Around the world, many farm fields, mainly rural, lack internet coverage. Thus, the farmer can't access to the cloud for data visualization or notifications. For this purpose, a direct LoRa 868 MHz/ZigBee Mesh 2.4 GHz based communication link for Nodes to Farmer communication is proposed. With this solution, the farmer can receive real-time data while being walking around the farm, which helps in fast decision-making. Moreover, the farmer can play the role of a coordinator by collecting the sensors data for local storage or for retransmitting to the cloud. This second scenario is LoRaWAN 868 MHz, LoRaWAN 433 MHz, Sigfox, NB-IoT and ZigBee 2.4 GHz based Farmer to Infrastructure communication. In this scenario, the farmer can send urgent notifications or data for decision making. Finally, since a big number of farmers work in large-scale farm fields, farmers can send their location for staff management and organization. These two scenarios with the interaction of the farmer are represented in Fig. 10.

Table 4
Nodes to Infrastructure communication measurements results.

			Node 1	Node 2	Node 3	Node 4	Node 5	Node 6	Node7
LoRaWAN 868 MHz	RSSI (dBm)	0 m	−95.5	−96	–	−101.5	−100.5	−101	−104.5
		1 m	−80	−81.5	−101	−82	−88	−83	−80.5
	SNR (dB)	0 m	8.63	8.38	–	4.13	6.63	6.5	3.25
		1 m	9.5	9.13	6.25	9.38	9	8.63	9
	Packet Loss	0 m	0%	0%	100%	0%	0%	0%	0%
		1 m	0%	0%	0%	0%	0%	0%	0%
LoRaWAN 433 MHz	RSSI (dBm)	0 m	−60	−63	−75	−66	−63	−64	−61
		1 m	−57	−59	−65	−63	−60	−61	−59
	SNR (dB)	0 m	4.3	2	−6.3	1.8	2.2	1.3	2.4
		1 m	6.8	7.5	0.5	2.3	4.3	2.1	3.7
	Packet Loss	0 m	0%	0%	0%	0%	0%	0%	0%
		1 m	0%	0%	0%	0%	0%	0%	0%
SigFox	RSSI (dBm)	0 m	−117	−106	−113	−109	−111	−114	−120
		1 m	−110	−106	−109	−102	−102	−112	−109
	SNR (dB)	0 m	11.4	15.85	19.18	20	17.54	15.53	14.94
		1 m	15.79	15.97	19.56	16.94	17.92	16.02	16.09
	Packet Loss	0 m	0%	0%	0%	0%	0%	0%	0%
		1 m	0%	0%	0%	0%	0%	0%	0%
NB-IoT	Packet Loss	0 m	0%	0%	0%	0%	0%	0%	0%
		1 m	0%	0%	0%	0%	0%	0%	0%
ZigBee 2.4 GHz	Packet Loss	0 m	0%	3.33%	100%	0%	0%	60%	13.3%
		1 m	0%	0%	27.8%	0%	0%	0%	0%

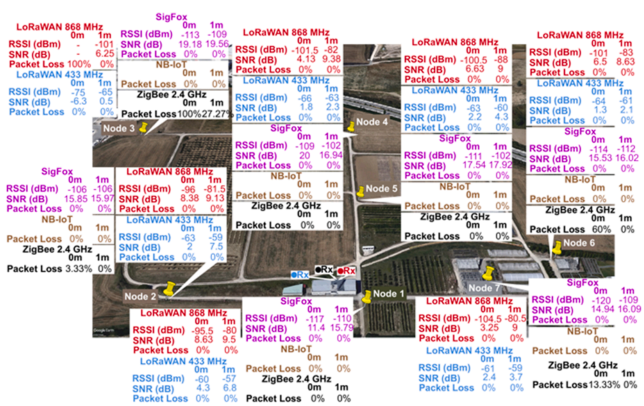

Fig. 8. Average RSSI, SNR and packet loss using different wireless technologies at different locations and heights.

4.2.1. Nodes to farmer communication

In nodes to farmer scenario, LoRa 868 MHz and ZigBee Mesh 2.4 GHz nodes were placed on the ground and at 1 m from the ground at 5 main locations of the farm field. LoRa technology was chosen for this scenario due to its P2P communication possibility. The coordinators were carried by the farmer. Also, the farmer has carried the Dragino LoRaWAN GPS shield for localization. The implemented networks in this scenario are represented in Fig. 11. When the farmer was at the starting point, nodes have started sending packets every 30 s to the farmer while walking through the farm, as illustrated in Fig. 11, with the average walking speed. The RSSI, SNR of the LoRa received packets were stored in an SD memory card and the ZigBee received packets were stored in a laptop. Collecting data measurement is depicted in Fig. 12.

The LoRa 868 MHz received packets by the walker farmer from the 5 nodes placed at both heights are localized using GPS and represented in Fig. 13. It is demonstrated that more packets were received when the nodes were placed at 1 m from the ground. Moreover, packets were lost mostly when the farmer was walking through the hill, where node 3 is placed. Also, most of the lost packets are the ones sent from node 3.

The received packets RSSI and SNR for both heights at every location are illustrated in Fig. 14. From Fig. 14(e), it is shown that the RSSI values of the received packets from node 3 are lower than the RSSI of the received packets from the other nodes. Moreover, the SNR values of the received packets from node 3 are less stable than from the other nodes due to hill surface, as it is illustrated in Fig. 14(f). These conclusions are proven in the comparison between the received packets RSSI and SNR from the 5 nodes at 1 m from the ground, which is presented in Fig. 15(a) and Fig. 15(b).

Fig. 15(c) presents the interval of confidence, variance and standard deviation values calculated for the five LoRa nodes at 1 m from the ground while the farmer is in movement condition through the farm, which explains the high obtained values since the RSSI is much higher when the farmer is walking close to the node than far from it. Moreover, higher values are shown for node 3, where the majority of the packets are received by the farmer under NLoS condition with the node.

Finally, Fig. 16 presents the packet loss rate for both LoRa 868 MHz and ZigBee 2.4 Mesh GHz. For nodes 2 and 4, the packet loss rate is 0% for both ZigBee Mesh 2.4 GHz and LoRa 868 MHz when placing the nodes at 1 m from the ground. For the rest of the nodes, the packet loss rate is less than 10% at this height. However, the packet loss rate increases when placing the nodes on the ground, especially for node 3, where the packet loss becomes 85% for LoRa and 92.5% for ZigBee Mesh, which is a significant difference. To enhance the LoRa radio link, the spreading factor (SF) can be increased. From, it can be seen that the SF used for LoRa 868 MHz is 7. Increasing the SF increases the airtime, which results in better sensitivity. Thus, packets can be received further away. However, to enhance the ZigBee Mesh radio link, more nodes are needed to be deployed. Thus, increasing the cost of the implemented network.

4.2.2. Farmer to infrastructure communication

In the farmer to infrastructure communication, the farmer was carrying the Dragino GPS shield and LoRaWAN 433 MHz, LoRaWAN 868 MHz, NB-IoT, Sigfox and ZigBee transmitters. The communication schema is represented in Fig. 17. The farmer has started sending packets to the infrastructure from the starting point and continues sending packets every 30 s while walking through the farm with the average speed, as illustrated in Fig. 17. The received packets, RSSI and SNR were measured for LoRaWAN 433/868 MHz and SigFox. For ZigBee and NB-IoT, only the received packets were measured.

The status of the transmitted packets by the walker farmer are localized and represented in Fig. 18. It can be seen that all the transmitted packets were successfully received for all the technologies through the whole farmer's path. Moreover, a LoRaWAN 868 MHz coverage map is depicted in Fig. 19. It is demonstrated that the RSSI decreases when the farmer walks upon the hill. Finally, a comparison

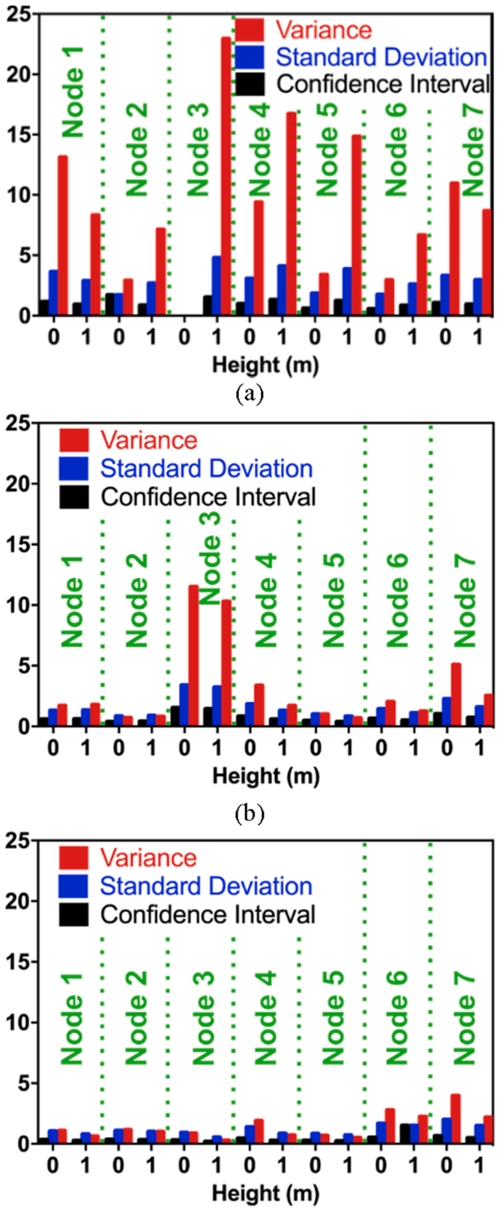

Fig. 9. Interval of confidence, variance and standard deviation values for nodes placed at 0 m and 1 m from the ground for (a) LoRaWAN 868 MHz, (b) LoRaWAN 433 MHz, (c) Sigfox.

between LoRaWAN 433 MHz, LoRaWAN 868 MHz and Sigfox received packets RSSI and SNR is illustrated in Fig. 20(a) and Fig. 20(b).

The RSSI interval of confidence, variance and standard deviation values for farmer to infrastructure communication using LoRaWAN and SigFox technologies are presented in Fig. 20(c). These values are calculated based on the RSSI values obtained while the farmer is walking through the farm and sending packets to the infrastructure, which explains the high variance values for LoRaWAN. However, it can be seen that even that the farmer is in movement and changing location while sending packets, the calculated values are very low, due to the stable RSSI values obtained for Sigfox in this scenario.

From Fig. 20, it is observed that the LoRaWAN 433 MHz RSSI is higher than the other technologies (between −40 dBm and −72 dBm upon the hill). For LoRaWAN 868 MHz, the RSSI is between −63 dBm and −100 dBm. Finally, for Sigfox, the RSSI is between −100 dBm and −109 dBm. The hill is not affecting the Sigfox radio link due to the high

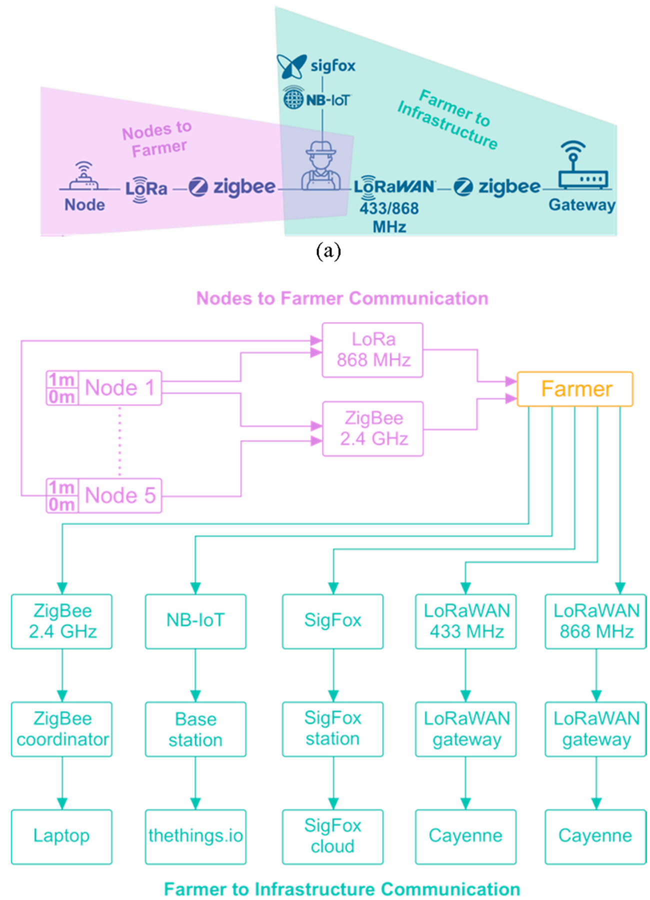

Fig. 10. (a) Farm field monitoring with the interaction of the farmer; (b) Nodes to Farmer and Farmer to Infrastructure communication data flow diagram.

Fig. 11. Nodes to farmer communication schema.

elevation of the base stations. For the SNR, it can be seen that the values are higher for Sigfox (between 14.5 dB and 9 dB). The SNR is between 10.5 dB and −1.75 dB for LoRaWAN 868 MHz and between 12.8 dB and −12.3 dB for LoRaWAN 433 MHz. Again, the lowest values are observed upon the hill due to the near-ground effect.

4.3. Farm monitoring with the interaction of the tractor

Normally, an average of 13.6 gallons per hour is the fuel consumption of a 310 PTO HP tractor [52]. This significant amount of fuel can be consumed with high profits in return. While a tractor is doing its tasks, it can collect WSNs data within the farm field for local storage or data

Fig. 12. Farmer receiving packets from the nodes.

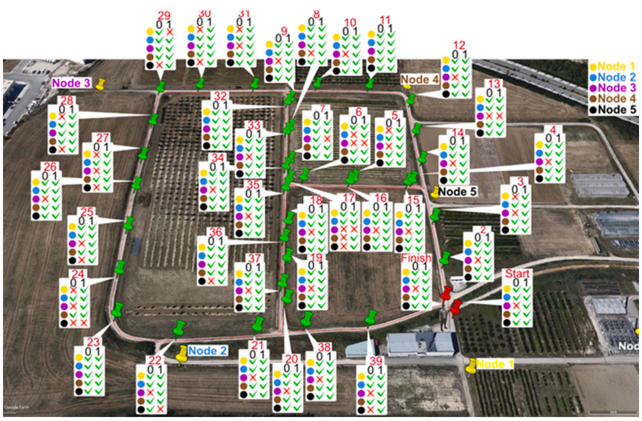

Fig. 13. LoRa 868 MHz received packets by the farmer at different locations.

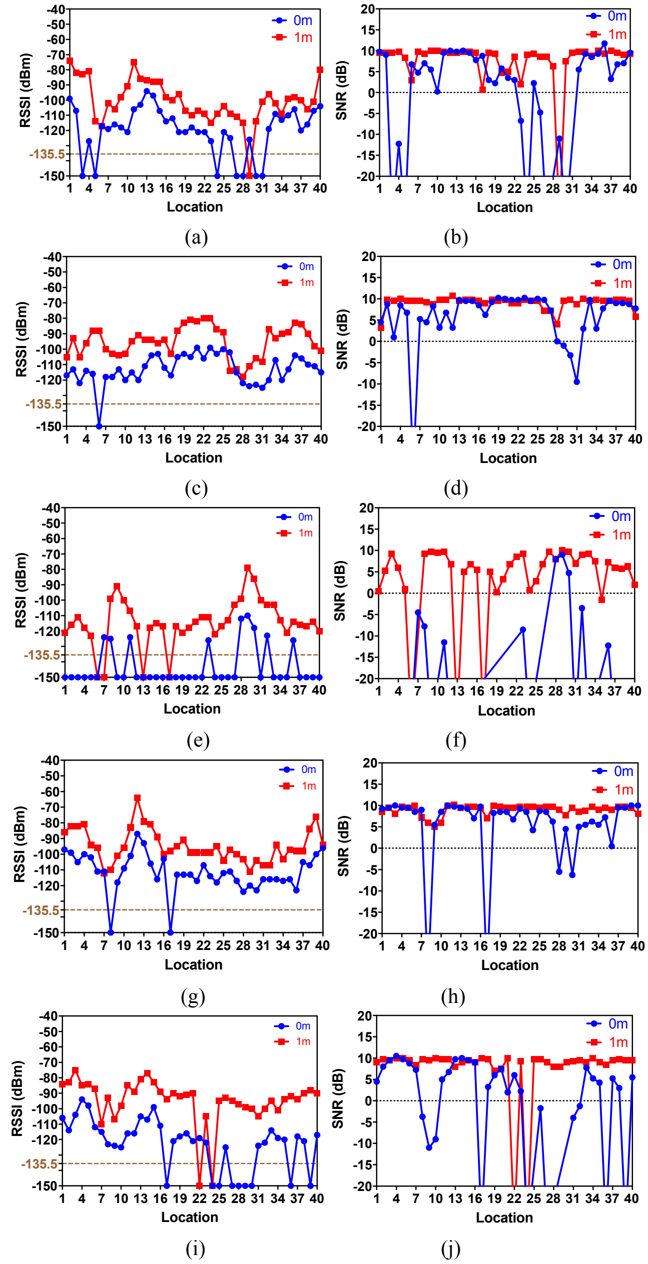

Fig. 14. LoRa 868 MHz (a), (c), (e), (g), (i) RSSI; (b), (d), (f), (h), (j) SNR in several farmer locations from nodes 1, 2, 3, 4 and 5 respectively.

retransmitting to the cloud. For data local storage, LoRa 868 MHz and ZigBee Mesh 2.4 GHz based WSNs are tested for near-ground nodes to tractor communication. The data collected by the tractor for crop monitoring can be sent to the cloud via LPWAN technologies, in tractor to infrastructure communication, for storage, visualization and notification. Moreover, this scenario can help the tractor's owner or renter in tracking and monitoring the tractor's status through the CAN BUS data like fuel level, speed, location and trailer info. The proposed scenarios are illustrated in Fig. 21.

4.3.1. Nodes to tractor communication

In nodes to tractor communication, 5 LoRa 868 MHz and ZigBee Mesh 2.4 GHz nodes were placed on the ground and at 1 m from the ground and the coordinators were fixed on the roof of a John Deere 6330 Premium tractor. Also, the Dragino LoRaWAN GPS shield is putted in the tractor for packet localization. When the tractor was at the starting point, nodes have started sending packets every 30 s to the tractor while driving through the farm with an average speed of 20 Km/h, as it is shown in Fig. 22. The RSSI, SNR of the LoRa received packets were stored in an SD memory card and the ZigBee received packets were stored in a laptop. Measurement for data collecting using the tractor is depicted in Fig. 23.

The LoRa 868 MHz received packets by the tractor from the 5 nodes placed at both heights are localized and represented in Fig. 24. It can be seen that all the transmitted packets are successfully received by the tractor when nodes were placed at 1 m from the ground. However, some of the ground nodes transmitted packets were lost. Comparing the results presented in Fig. 24 with the results of the near-ground nodes to farmer communication in Fig. 13, it can be observed that more packets were received in nodes to tractor communication scenario. The reason for the packet loss rate decrease, in this case, is the elevation of the coordinators. In the tractor scenario, the elevation of the coordinators is about 4 m. However, in the farmer scenario, the elevation of the coordinators was about 1.1 m. The elevation of the coordinators, in this case, is also the reason for the radio link enhancement upon the hill.

The received packets RSSI and SNR from the 5 nodes at both elevations are illustrated in Fig. 25. Again, a remarkable improvement in the received signal strength and the signal-to-noise ratio for all nodes compared to the farmer scenario in Fig. 14. This improvement is due to the reduced effect of the near-ground on the radio propagation link. Moreover, a comparison between the received packets RSSI and SNR of the five nodes at 1 m from the ground is presented in Fig. 26. From Fig. 26(a), it can be seen that the higher RSSI values are from nodes 2

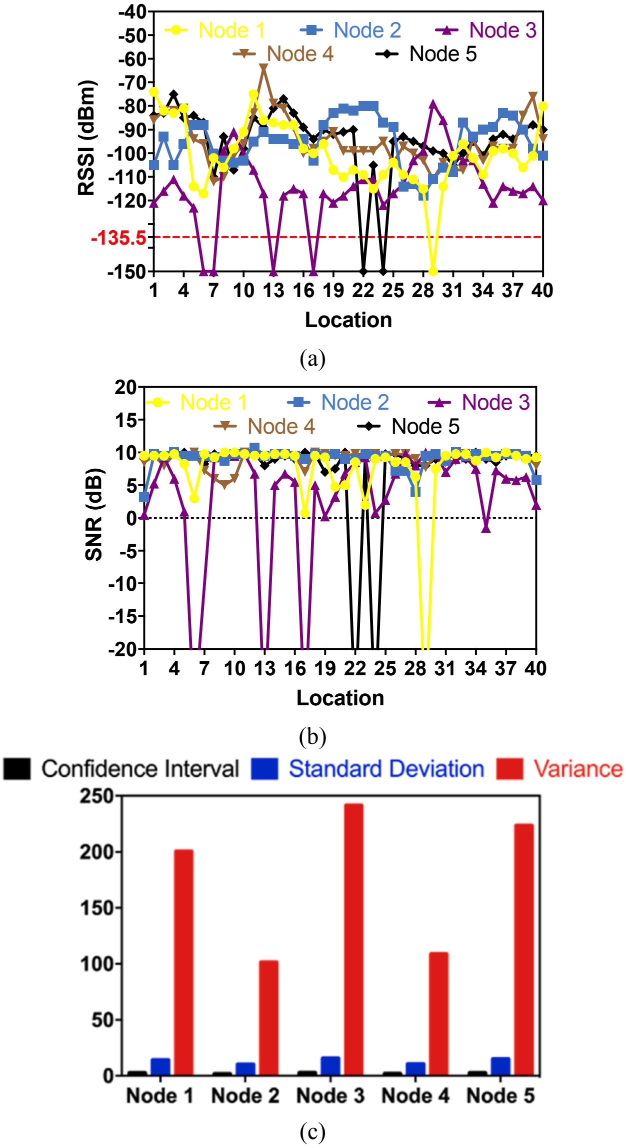

Fig. 15. (a) RSSI; (b) SNR values; (c) Interval of confidence, variance and standard deviation values for the five LoRa 868 MHz nodes at 1 m from the ground for different farmer locations.

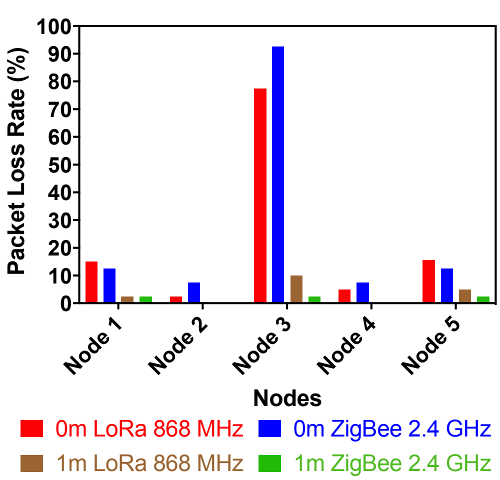

Fig. 16. LoRa 868 MHz and ZigBee 2.4 GHz nodes to farmer packet loss rate for different nodes at different heights.

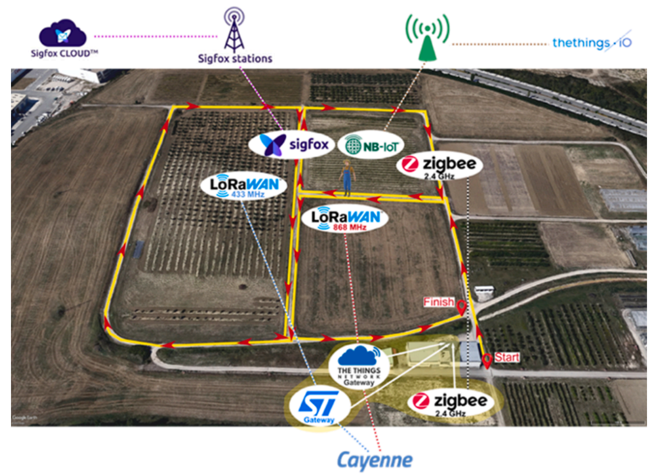

Fig. 17. Farmer to infrastructure communication schema.

Fig. 18. Received packets from different farmer locations using different technologies.

Fig. 19. LoRaWAN 868 MHz coverage map for farmer to gateway communication.

(between −71 dBm at the location 14 and −98 at the location 17, upon the hill), and the lower RSSI values are from node 3 (between −83 dBm close to the node location and −123 dBm at the location 1). From Fig. 26 (b), it is observed that the SNR of nodes 1, 2, 4 and 5 is more stable at around 10 dB. However, The SNR of node 3 is not stable due to the ground effect and varies between 9.5 dB and −4 dB.

Fig. 26(c) presents the interval of confidence, variance and standard deviation values calculated for the five LoRa nodes at 1 m from the ground while the tractor is in movement condition through the farm, which explains the high obtained values since the RSSI is much higher

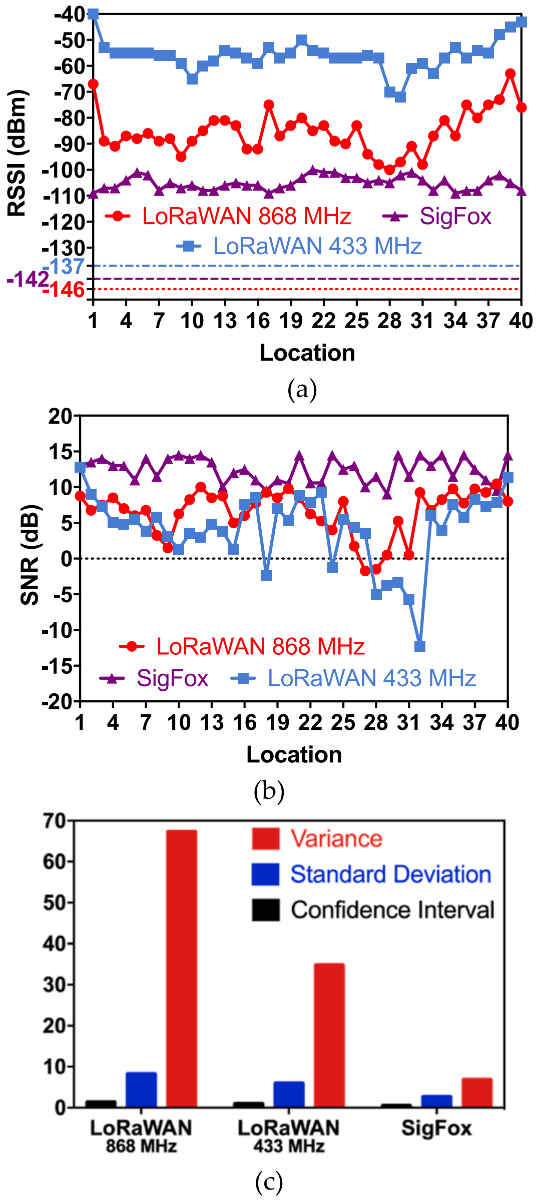

Fig. 20. (a) RSSI; (b) SNR values at several farmer locations; (c) Interval of confidence, variance and standard deviation values for Sigfox, LoRaWAN 868 MHz and 433 MHz.

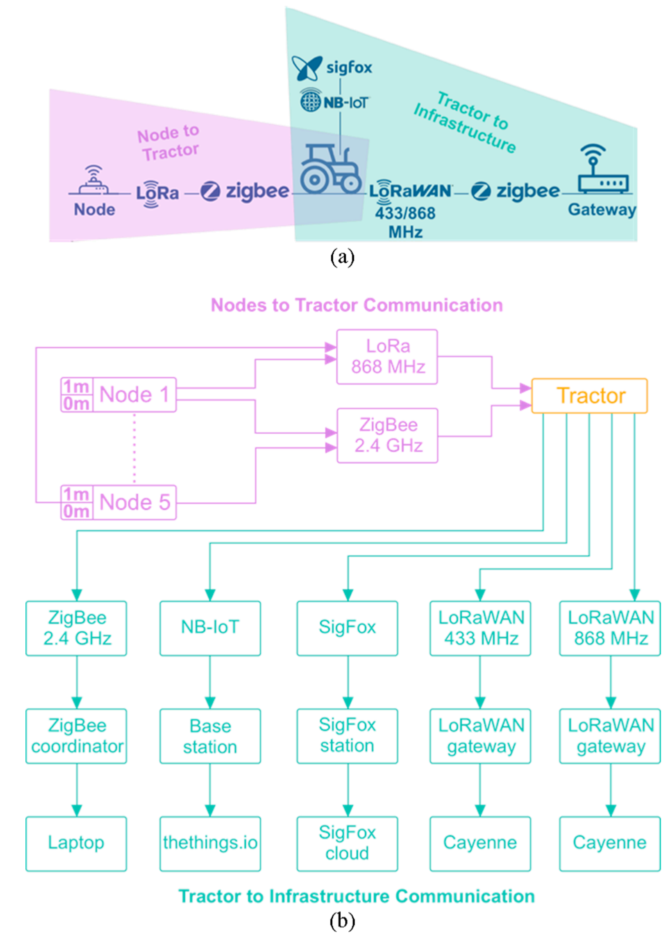

Fig. 21. (a) Farm field monitoring with the interaction of the tractor; (b) Nodes to Tractor and Tractor to Infrastructure communication data flow diagram.

Fig. 22. Nodes to tractor communication schema.

when the tractor is driving close to the node than far from it. Moreover, higher values are shown for node 1, where the majority of the packets are received by the tractor under NLoS condition caused by the warehouse. However, these values are lower than the ones obtained in the case of nodes to farmer communication in Fig. 15(c).

Finally, Fig. 27 illustrates the packet loss rate of both LoRa 868 MHz and ZigBee Mesh 2.4 GHz nodes at both elevations. For nodes placed at 1 m from the ground, the LoRa packet loss rate is 0% for all nodes. However, ZigBee Mesh packet loss rate is 61.9% for node 3, 4.76% for node 2 and 0% for the rest 0%. For the ground nodes, the LoRa packet loss rate high for node 3 with a value of 52.17%, 13.04% for node 1, 17.39% for node 2, 4.35% for node 4 and 13.04% for node 5. For ZigBee Mesh, the packet loss rate is 85.71% for node 3 and 4.76% for nodes 1, 2, 4 and 5.

In order to enhance the LoRa 868 MHz radio link, the spreading factor (SF) can be increased. However, to enhance the ZigBee Mesh radio link, more nodes are needed to be deployed. Thus, increasing the cost of the implemented network.

4.3.2. *Tractor to infrastructure communication*

In tractor to infrastructure communication, the Dragino GPS shield and LoRaWAN 433 MHz, LoRaWAN 868 MHz, NB-IoT, Sigfox and ZigBee 2.4 GHz transmitters were fixed on the roof of the tractor. LoRaWAN and ZigBee nodes are sending data to the corresponding gateways placed on the roof of the farm building. For Sigfox, data are transmitted to the Sigfox cloud through the Sigfox base station. Finally, the NB-IoT data are stored in the TheThings.io cloud. The communications schema is illustrated in Fig. 28. The tractor has started sending packets to the infrastructure from the starting point and continues sending packets every 30 s while driving through the farm with the average speed of 20 Km/h. The received packets, RSSI and SNR were measured for LoRaWAN 433

Fig. 23. Tractor sending packets to the infrastructure.

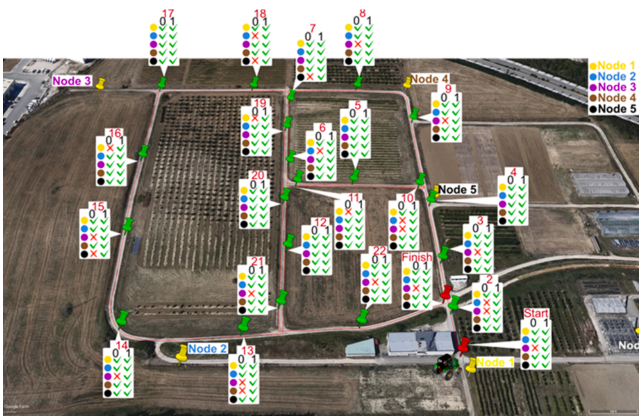

Fig. 24. LoRa 868 MHz received packets by the tractor at different locations.

MHz, LoRaWAN 868 MHz and SigFox. For ZigBee and NB-IoT, only the received packets were measured.

The status of the transmitted packets by the tractor is localized and represented in Fig. 29. It can be seen that all the transmitted packets were successfully received for all the technologies through the whole tractor's path. Moreover, a LoRaWAN 868 MHz coverage map is depicted in Fig. 30. It is demonstrated that the RSSI decreases when the driver is driving to the hill. A comparison between LoRaWAN 433 MHz, LoRaWAN 868 MHz and Sigfox received packets RSSI and SNR is illustrated in Fig. 31.

For LoRaWAN 868 MHz, GPS data were collected by the Dragino node to track the location of the tractor when packets are transmitted or received. High accuracy in LoRaWAN-based GPS data are observed in the test scenarios.

From Fig. 31(a), it is observed that the LoRaWAN 433 MHz RSSI is higher than the other technologies (between −40 dBm and −64 dBm upon the hill). For LoRaWAN 868 MHz, the RSSI is between −69 dBm and −109 dBm. Finally, for Sigfox, the RSSI is between −100 dBm and −108 dBm. The hill is not affecting the LoRaWAN radio link as in the case of the farmer due to the elevation of the tractor. For the SNR, From Fig. 31(b), it can be seen that the values are more stable for all the technologies due to the absence of the ground influence. The SNR is between 9.25 dB and 12.75 dB for Sigfox, between 6.25 dB and 9.5 dB for LoRaWAN 868 MHz and between 4.3 dB and 12.8 for LoRaWAN 433 MHz.

The RSSI interval of confidence, variance and standard deviation values for tractor to infrastructure communication using LoRaWAN and SigFox technologies are presented in Fig. 31(c). These values are

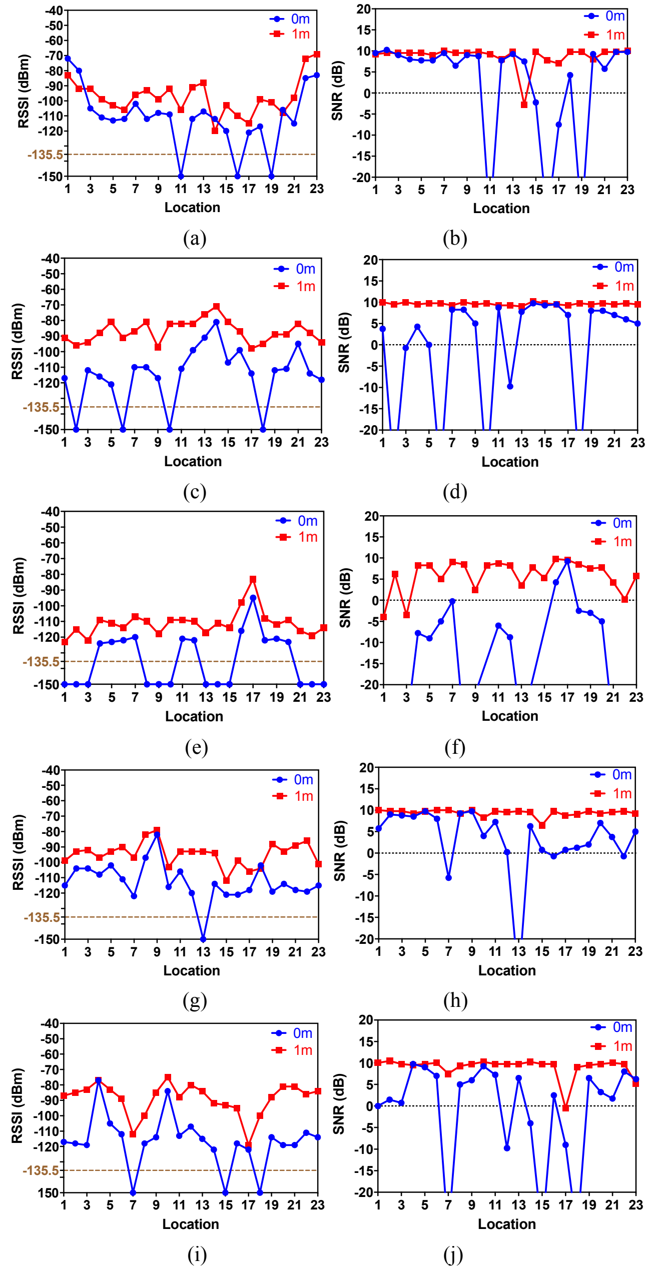

Fig. 25. LoRa 868 MHz (a), (c), (e), (g), (i) RSSI; (b), (d), (f), (h), (j) SNR in several tractor locations from nodes 1, 2, 3, 4 and 5 respectively.

calculated based on the RSSI values obtained while the tractor is driving through the farm and sending packets to the infrastructure, which explains the high variance values for LoRaWAN. However, it can be seen that even that the tractor is in movement and changing location while sending packets, the calculated values are very low, due to the stable RSSI values obtained for Sigfox in this scenario.

Moreover, in order to analyze the impact of the metallic structure of the tractor on the radio propagation, other LoRaWAN 868 MHz transmitter nodes were fixed above the back wheel and on the front part of the tractor, as shown in Fig. 32(a). The choice of the nodes locations is based on the proposed setups in literature for autonomous agricultural machinery [53,54]. Usually, antennas are placed on the roof of the tractor. Moreover, in some cases, antennas are placed on the front or on the side of the vehicle.

From Fig. 32(b), it is observed that the RSSI is higher for the roof node and lower for the wheel node. For the wheel node, depending on

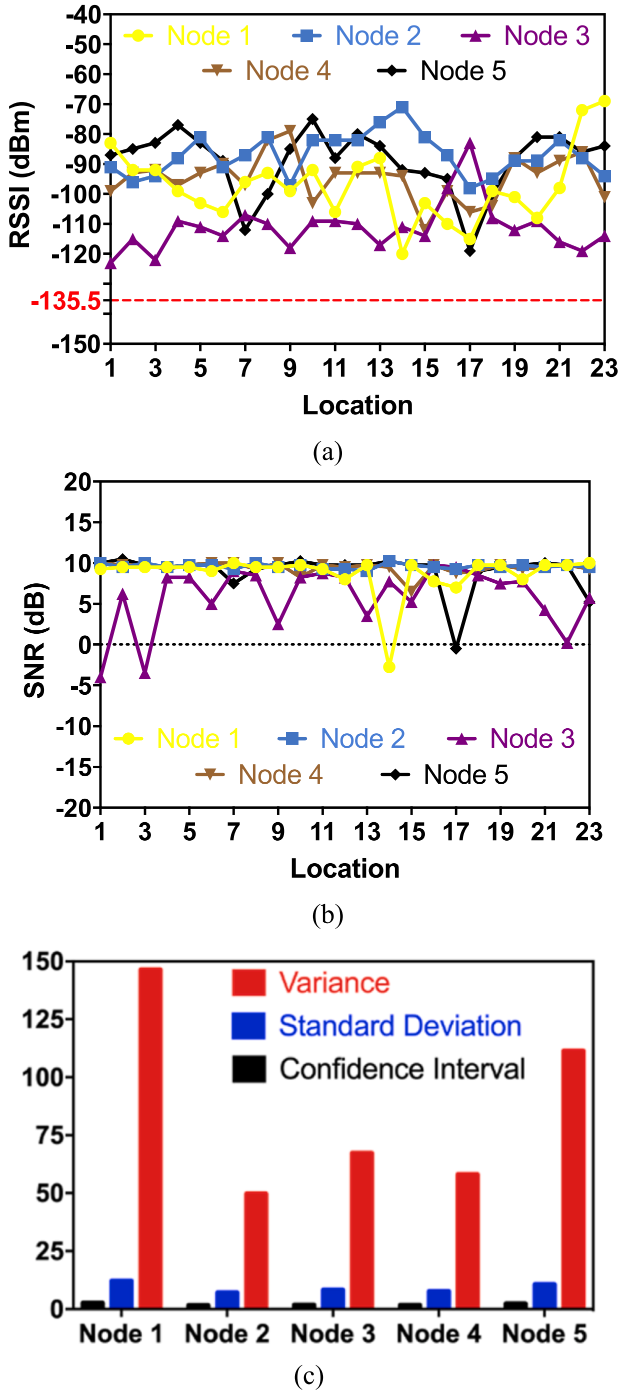

Fig. 26. (a) RSSI; (b) SNR values; (c) Interval of confidence, variance and standard deviation values from the five LoRa 868 MHz nodes at 1 m from the ground for different tractor locations.

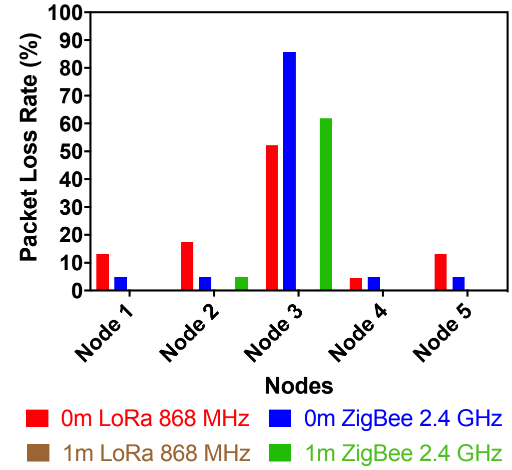

Fig. 27. LoRa 868 MHz and ZigBee 2.4 GHz nodes to tractor packet loss rate for different nodes at different heights.

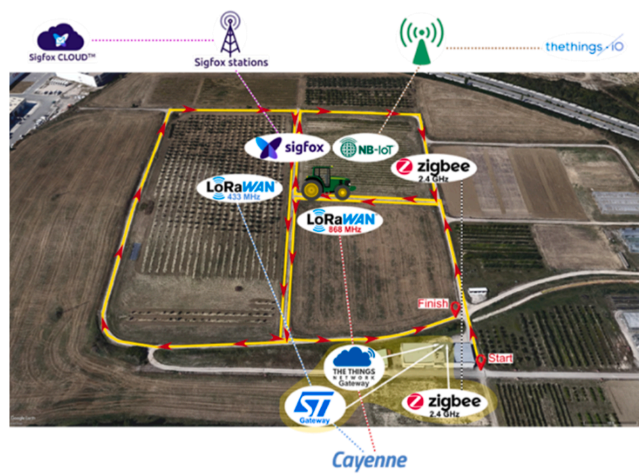

Fig. 28. Tractor to infrastructure communication schema.

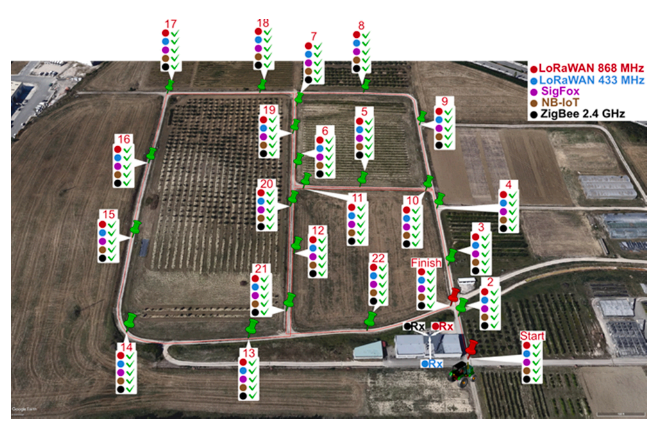

Fig. 29. Received packets from different tractor locations using different technologies.

the tractor's direction regarding the gateway's location, the tractor itself becomes an obstacle for the node to gateway communication. In Fig. 32 (c), it can be seen that the SNR is more stable, between 6 dB and 11 dB, for the roof and the front nodes. However, for the wheel node, the SNR is dropping in some locations. In these locations, the tractor is obstructing the radio link between the node and the gateway.

From Fig. 32(d), it can be seen that the RSSI interval of confidence, variance and standard deviation values are lower for the LoRaWAN node placed on the roof of the tractor.

Finally, a screenshot of the real-time received LoRaWAN data on the Cayenne platform is depicted in Fig. 33. These data are the location of the tractor, temperature, humidity and pressure beside the RSSI and the SNR.

4.4. Received packet rates comparison

The received packet rates (RPR) from the experimental

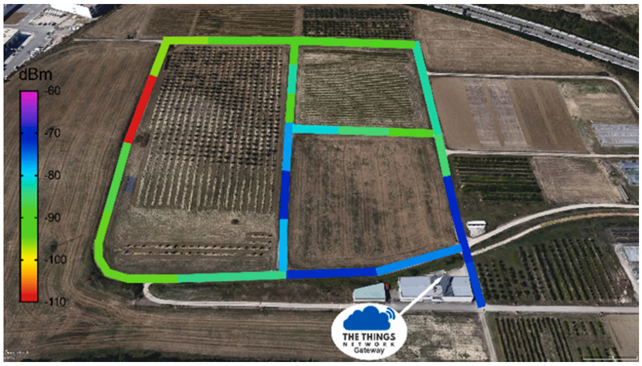

Fig. 30. LoRaWAN 868 MHz coverage map for tractor to gateway communication.

measurements for all the implemented scenarios are presented in the following tables.

The received packet rates for nodes to infrastructure communication scenario using LoRaWAN 868 MHz, LoRaWAN 433 MHz, Sigfox, NB-IoT and ZigBee Mesh 2.4 GHz nodes placed on the ground and at 1 m from the ground are presented in Table 5. It can be seen that the RPR for all nodes at both elevations are 100% for LoRaWAN 433 MHz, Sigfox and NB-IoT. For LoRaWAN 868 MHz, the RPR are 100% for all nodes placed at 1 m from the ground. For nodes placed on the ground, the RPR is 0% for node 3. In this case, the RPR can be increased by increasing the SF of node 3. In the case of ZigBee Mesh 2.4 GHz nodes, the RPR is 100% at both elevations only for nodes 1,4 and 5. Even though a mesh network topology has been used for the ZigBee nodes, where every node sends messages and acts as a router at the same time resulting in higher power consumption, additional nodes are required for better coverage. Thus, increasing the power consumption and the cost of the network.

For nodes to farmer and nodes to tractor communication, the RPR results for LoRa 868 MHz and ZigBee 2.4 GHz nodes placed at both elevations are presented in Table 6. For nodes to tractor communication, the RPR are 100% for all LoRa nodes placed at 1 m from the ground. The RPR is decreased with the decrease of the nodes height. For ZigBee nodes, the RPR is 100% for nodes 1, 4 and 5 when placed at 1 m from the ground. For ZigBee nodes 3 placed at 1 m from the ground, the RPR is 38.1%.

From Table 6, it can be seen that the obtained RPR values are higher in the scenario of nodes to tractor communication than in the scenario of nodes to farmer communication. This difference is due to the elevation of the LoRa and ZigBee coordinators attached to the tractor (about 4 m), compared to their elevation in the case of the farmer, which is about 1.1 m. In the case of nodes on the ground to tractor and nodes to farmer communication using LoRa 868 MHz, the RPR can be increased by increasing the SF, which is 7 in the presented scenarios. For ZigBee, additional nodes implementation is required.

Finally, the RPR for tractor to infrastructure and farmer to infrastructure communication are presented in Table 7. From this table, it can be observed that the RPR is 100% using all the technologies for both scenarios. For ZigBee, the RPR is increased compared to the obtained results for nodes to infrastructure communication due to the elevation of the transmitter node in the case of the tractor and the farmer, which is higher than the elevation of the near-ground nodes.

In scenarios under mobility condition, the LoRaWAN nodes are connected to only one gateway. Thus, when a sensor node sends an uplink packet, the acknowledgement (ACK) from the network server is guaranteed to be received through the same gateway using the same spreading factor as the one used in the uplink packet [55]. Moreover, since it is demonstrated that LoRaWAN coverage is achieved through the proposed scenarios using stationary nodes, it can be assured that mobility won't affect the LoRaWAN wireless communication in the mobile tractor and farmer transmitter cases (tractor/farmer to

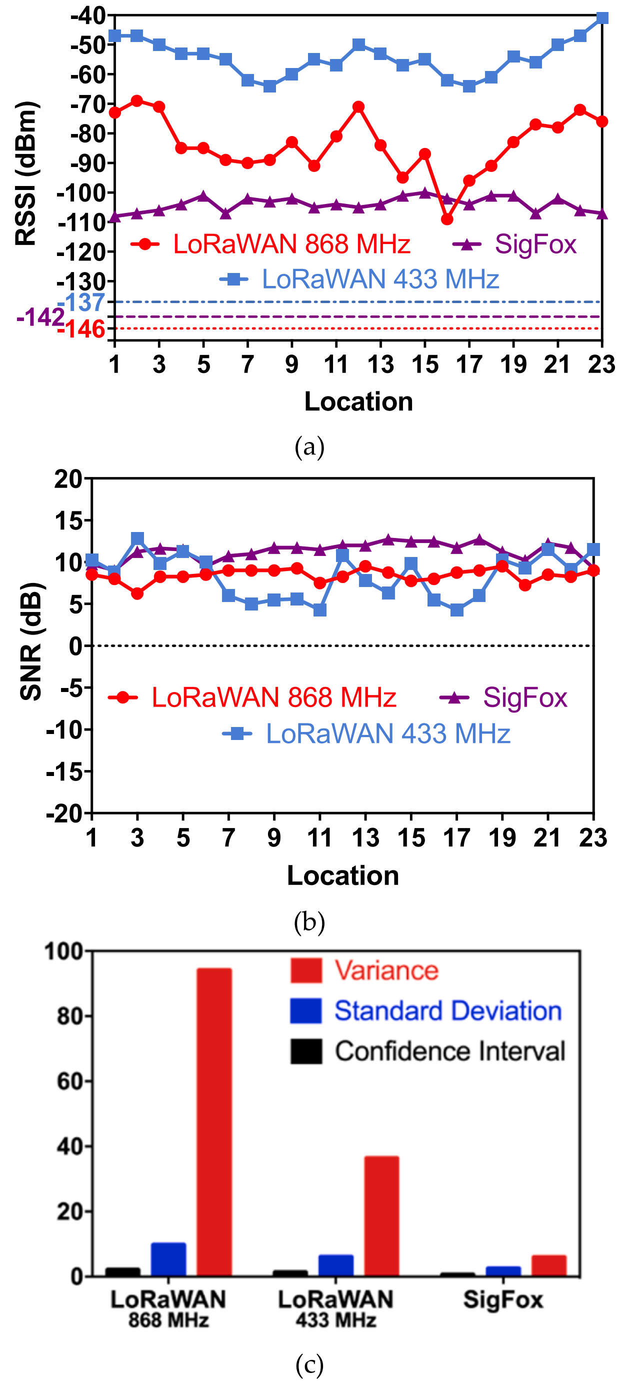

Fig. 31. RSSI; (b) SNR values at several tractor locations; (c) Interval of confidence, variance and standard deviation values for Sigfox, LoRaWAN 868 MHz and 433 MHz.

infrastructure communication), which is demonstrated in Table 7. However, in nodes to tractor/farmer communication scenarios, where the transmitter nodes are stationary and the coordinator is moving, the received packet rates are decreasing when decreasing the height of both nodes and coordinator, which is illustrated in Table 6. In this case, higher SF and more Adaptive Data Rate (ADR) will be taken into account in next analysis [56,57].

From the obtained results for the proposed smart agriculture scenarios in this work, advantages and disadvantages of the tested technologies have been concluded and presented in Table 8.

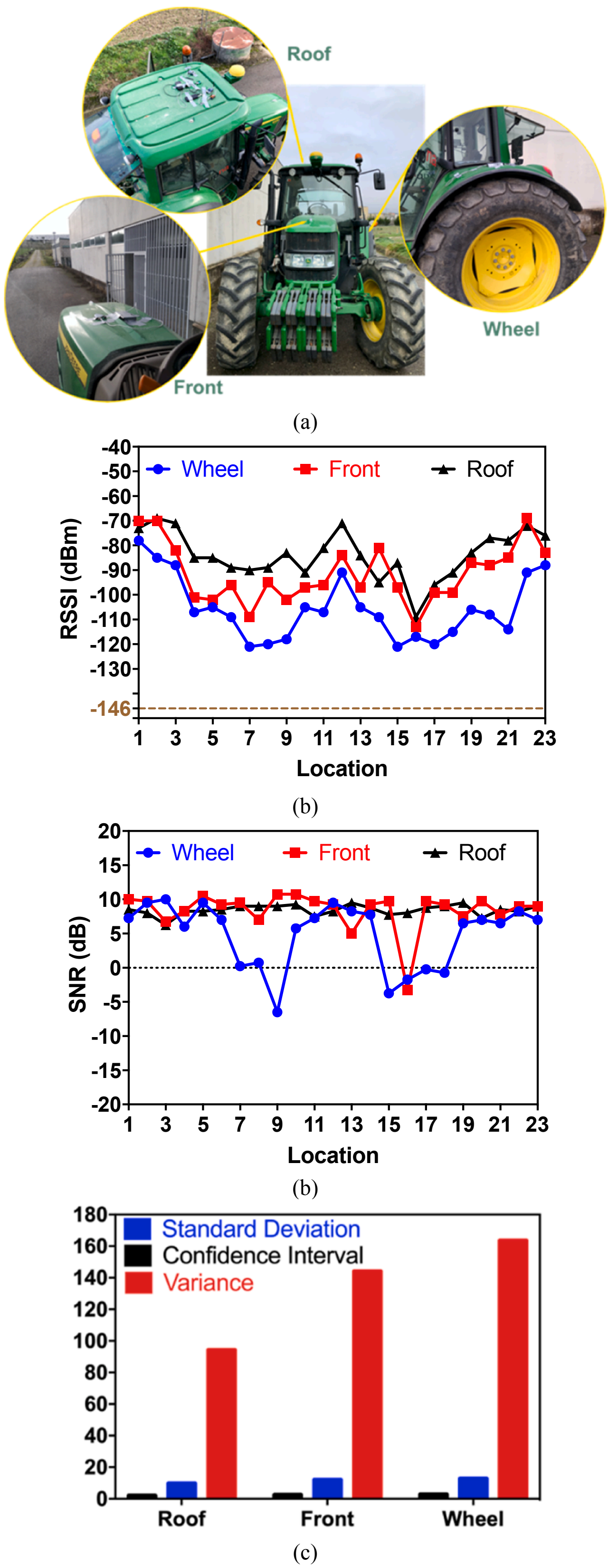

Fig. 32. (a) Nodes location on the tractor; (b) RSSI; (c) SNR values; (d) Interval of confidence, variance and standard deviation values for different LoRaWAN 868 MHz nodes located on the tractor.

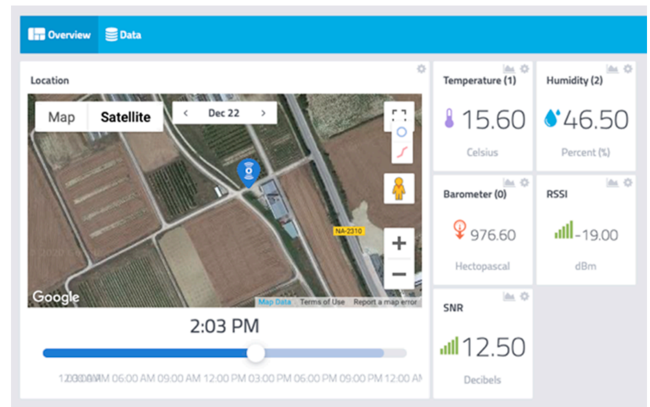

Fig. 33. Real-time received tractor location, temperature, humidity and pressure.

Table 5
Received packet rate for nodes to infrastructure communication.

		LoRa WAN 868 MHz	LoRa WAN 433 MHz	Sigfox	NB-IoT	ZigBee Mesh 2.4 GHz
Node 1	0 m	100%	100%	100%	100%	100%
	1 m	100%	100%	100%	100%	100%
Node 2	0 m	100%	100%	100%	100%	96.67%
	1 m	100%	100%	100%	100%	100%
Node 3	0 m	0%	100%	100%	100%	0%
	1 m	100%	100%	100%	100%	72.73%
Node 4	0 m	100%	100%	100%	100%	100%
	1 m	100%	100%	100%	100%	100%
Node 5	0 m	100%	100%	100%	100%	100%
	1 m	100%	100%	100%	100%	100%
Node 6	0 m	100%	100%	100%	100%	40%
	1 m	100%	100%	100%	100%	100%
Node 7	0 m	100%	100%	100%	100%	86.67%
	1 m	100%	100%	100%	100%	100%

Table 6
Received packet rates for nodes to tractor/farmer communication.

		LoRa 868 MHz		ZigBee Mesh 2.4 GHz	
		Tractor	**Farmer**	**Tractor**	**Farmer**
Node 1	**0 m**	86.96%	85%	95.24%	87.5%
	1 m	100%	97.5%	100%	97.56%
Node 2	**0 m**	82.61%	97.5%	95.24%	92.5%
	1 m	100%	100%	95.24%	100%
Node 3	**0 m**	47.83%	22.5%	14.29%	7.5%
	1 m	100%	90%	38.1%	97.56%
Node 4	**0 m**	95.65%	95%	95.24%	92.5%
	1 m	100%	100%	100%	100%
Node 5	**0 m**	86.96%	84.5%	95.24%	87.5%
	1 m	100%	95%	100%	97.56%

Table 7
Received packet rates for tractor/farmer to infrastructure communication.

	LoRa WAN 868 MHz	LoRa WAN 433 MHz	Sigfox	NB-IoT	ZigBee 2.4 GHz
Tractor	100%	100%	100%	100%	100%
Farmer	100%	100%	100%	100%	100%

Table 8
Advantages and disadvantages of the tested technologies in the proposed smart agriculture scenarios.

	Advantages	Disadvantages
LoRaWAN 868 MHz	- Low power. - Low cost. - Good performance under mobility. - Good performance for nodes at 1 m. - High data rate. - Private network support.	- Higher attenuations for nodes on the ground for SF = 7.
LoRaWAN 433 MHz	- Low power. - Low cost. - Good performance under mobility. - Good performance for nodes at both heights. - High data rate. - Private network support.	
LoRa 868 MHz	- Low power. - Low cost. - Good performance under mobility for nodes at 1 m. - High data rate. - Private network support.	- Higher attenuations under mobility for nodes on the ground.
Sigfox	- Low power. - Good performance under mobility. - Good performance for nodes at both heights. - Low path loss.	- High cost. - Low data rate. - Sigfox coverage dependent.
NB-IoT	- Low power. - Good performance under mobility. - Good performance for nodes at both heights. - High data rate.	- High cost. - LTE coverage dependent.

5. Conclusions

Combining near-ground WSNs and vehicular communications, LPWAN-based radio channel characterization for multiple scenarios for farm monitoring with the interaction of both the farmer and the tractor is proposed. Different link type configurations are tested in order to consider the impact of ground by height variation, spatial distribution as function of network topology and morphological variations as well as the presence of infrastructure elements. Wireless channel performance has been analysed as a function of different link types for metrics related with received power levels as well packet error ratio for end to end analysis. The deployment of multiple scenario cases, near-ground nodes to infrastructure, near-ground nodes to farmer or tractor, farmer or tractor to infrastructure, are not important for farm field real-time data monitoring only, but as well for resources management and agricultural machinery tracking and monitoring in large-scale farms. In tractor to infrastructure communication, the effect of the structure and the material of the tractor on the attached antenna was taken into account. The experimental measurements were based on the collection of the received packets' RSSI and SNR levels for fixed near-ground nodes and moving farmer and tractor. The obtained results demonstrate the efficiency of the LPWAN-based networks for the implementation of the proposed scenarios. Future work is envisaged in relation with the impact of interference in high node density scenarios and the evolution of new incoming and alternative communication standards.

CRediT authorship contribution statement

Hicham Klaina: Investigation, Validation, Writing – original draft. **Imanol Picallo Guembe:** Software, Validation. **Peio Lopez-Iturri:** Investigation, Validation. **Miguel Ángel Campo-Bescós:** Conceptualization. **Leyre Azpilicueta:** Methodology, Software. **Otman Aghzout:** Methodology. **Ana Vazquez Alejos:** Conceptualization, Formal analysis. **Francisco Falcone:** Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] S.I. Hassan, M.M. Alam, U. Illahi, M.A. Al Ghamdi, S.H. Almotiri, M.M. Su'ud, A Systematic Review on Monitoring and Advanced Control Strategies in Smart Agriculture, in: *IEEE Access*, vol. 9, pp. 32517-32548, 2021.
[2] M.S. Farooq, S. Riaz, A. Abid, K. Abid, M.A. Naeem, A Survey on the Role of IoT in Agriculture for the Implementation of Smart Farming, IEEE Access 7 (2019) 156237–156271.
[3] M. Ayaz, M. Ammad-Uddin, Z. Sharif, A. Mansour, E.M. Aggoune, Internet-of-Things (IoT)-Based Smart Agriculture: Toward Making the Fields Talk, IEEE Access 7 (2019) 129551–129583.
[4] O. Elijah, T.A. Rahman, I. Orikumhi, C.Y. Leow, M.N. Hindia, An Overview of Internet of Things (IoT) and Data Analytics in Agriculture: Benefits and Challenges, IEEE Internet Things J. 5 (5) (Oct. 2018) 3758–3773.
[5] M. Gupta, M. Abdelsalam, S. Khorsandroo, S. Mittal, Security and Privacy in Smart Farming: Challenges and Opportunities, IEEE Access 8 (2020) 34564–34584.
[6] M.A. Ferrag, L. Shu, X. Yang, A. Derhab, L. Maglaras, Security and Privacy for Green IoT-Based Agriculture: Review, Blockchain Solutions, and Challenges, IEEE Access 8 (2020) 32031–32053.
[7] P. Serikul, N. Nakpong, N. Nakjuatong, Smart Farm Monitoring via the Blynk IoT Platform: Case Study: Humidity Monitoring and Data Recording, 2018 16th International Conference on ICT and Knowledge Engineering (ICT&KE), Bangkok, Thailand, 2018, pp. 1-6.
[8] C. Tsai, T. Liang, Application of IoT Technology in The Simple Micro-farming Environmental Monitoring, 2018 IEEE International Conference on Advanced Manufacturing (ICAM), Yunlin, Taiwan, 2018, pp. 170-172.
[9] S. Yang, S. Tong, L. Liang, Remote farm environment monitoring system based on embedded system and ZigBee technology, 2015 IEEE International Conference on Signal Processing, Communications and Computing (ICSPCC), Ningbo, China, 2015, pp. 1-5.
[10] A. Matese, F. Vaccari, D. Tomasi, S. Di Gennaro, J. Primicerio, F. Sabatini, S. Guidoni, CrossVit: Enhancing Canopy Monitoring Management Practices in Viticulture, Sensors 13 (6) (Jun. 2013) 7652–7667.
[11] Chen Hong, Zhang Shuhui, A temperature auto-monitoring and frost prevention real time control system based on a Z-BEE networks for the tea farm, 2012 IEEE Symposium on Electrical & Electronics Engineering (EEESYM), Kuala Lumpur, Malaysia, 2012, pp. 644-647.
[12] H. Zhang et al., Design of pig farm environmental parameters monitoring system based on wireless sensor networks, 2012 3rd International Conference on System Science, Engineering Design and Manufacturing Informatization, Chengdu, China, 2012, pp. 332-335.
[13] K. Mekki, E. Bajic, F. Chaxel, F. Meyer, A comparative study of LPWAN technologies for large-scale IoT deployment, ICT Express 5 (1) (2019) 1–7.

[14] W. Ayoub, A.E. Samhat, F. Nouvel, M. Mroue, J.C. Pre- votet, 'Internet of mobile things: Overview of LoRaWAN, DASH7, and NB-IoT in LPWANs standards and supported mobility', IEEE Commun. Surveys Tuts. 21 (2) (2019) 1561–1581.
[15] Q.M. Qadir, T.A. Rashid, N.K. Al-Salihi, B. Ismael, A.A. Kist, Z. Zhang, Low Power Wide Area Networks: A Survey of Enabling Technologies, Applications and Interoperability Needs, IEEE Access 6 (2018) 77454–77473.
[16] U. Raza, P. Kulkarni, M. Sooriyabandara, Low power wide area networks: An overview, IEEE Commun. Surveys Tuts. 19 (2) (2017) 855–873.
[17] K. Zheng, S. Zhao, Z. Yang, X. Xiong, W. Xiang, Design and Implementation of LPWA-Based Air Quality Monitoring System, IEEE Access 4 (2016) 3238–3245.
[18] S. Popli, R.K. Jha, S. Jain, A Survey on Energy Efficient Narrowband Internet of Things (NBIoT): Architecture, Application and Challenges, IEEE Access 7 (2019) 16739–16776.
[19] H. Klaina, I. Picallo, P. Lopez-Iturri, J.J. Astrain, L. Azpilicueta, O. Aghzout, A. V. Alejos, F. Falcone, Implementation of an Interactive Environment With Multilevel Wireless Links for Distributed Botanical Garden in University Campus, IEEE Access 8 (2020) 132382–132396.
[20] J. Tong, M. Cui, M. Tian, Y. He, Surrogate Model-Based Energy-Efficient Scheduling for LPWA-Based Environmental Monitoring Systems, IEEE Access 6 (2018) 59940–59948.
[21] H. Klaina, I. Picallo, P. Lopez-Iturri, J.J. Astrain, L. Azpilicueta, O. Aghzout, A. V. Alejos, F. Falcone, Aggregator to Electric Vehicle LoRaWAN Based Communication Analysis in Vehicle-to-Grid Systems in Smart Cities, IEEE Access 8 (2020) 124688–124701.
[22] L.M. Fernández-Ahumada, J. Ramírez-Faz, M. Torres-Romero, R. López-Luque, Proposal for the Design of Monitoring and Operating Irrigation Networks Based on IoT, Cloud Computing and Free Hardware Technologies, Sensors 19 (10) (May 2019) 2318.
[23] J. Dai, M. Sugano, Low-Cost Sensor Network for Collecting Real-Time Data for Agriculture by Combining Energy Harvesting and LPWA Technology, 2019 IEEE Global Humanitarian Technology Conference (GHTC), Seattle, WA, USA, 2019.
[24] G. Castellanos, M. Deruyck, L. Martens, W. Joseph, System Assessment of WUSN Using NB-IoT UAV-Aided Networks in Potato Crops, IEEE Access 8 (2020) 56823–56836.
[25] G. Valecce, P. Petruzzi, S. Strazzella, L. A. Grieco, NB-IoT for Smart Agriculture: Experiments from the Field, 2020 7th International Conference on Control, Decision and Information Technologies (CoDIT), Prague, Czech Republic, 2020, pp. 71-75.
[26] F. Zhang, X. Wan, T. Zheng, J. Cui, X. Li, Y. Yang, Smart Greenhouse Management System based on NB-IoT and Smartphone, 2020 17th International Joint Conference on Computer Science and Software Engineering (JCSSE), Bangkok, Thailand, 2020, pp. 36-41.
[27] S. R. J. Ramson et al., A Self-Powered, Real-Time, LoRaWAN IoT-based Soil Health Monitoring System, in IEEE Internet of Things Journal, doi: 10.1109/JIOT.2021.3056586.
[28] G. Di Renzone, S. Parrino, G. Peruzzi, A. Pozzebon, D. Bertoni, LoRaWAN Underground to Aboveground Data Transmission Performances for Different Soil Compositions, in IEEE Transactions on Instrumentation and Measurement, vol. 70, pp. 1-13, 2021, Art no. 5501713.
[29] N. H. N. Ibrahim, A. R. Ibrahim, I. Mat, A. N. Harun, G. Witjaksono, LoRaWAN in climate monitoring in advance precision agriculture system, in Proc. Int. Conf. Intell. Adv. Syst. (ICIAS), Kuala Lumpur, Malaysia, Aug. 2018, pp. 1–6.
[30] R. K. Kodali, S. Yerroju, S. Sahu, Smart farm monitoring using LoRa enabled IoT, in Proc. 2nd Int. Conf. Green Comput. Internet Things (ICGCIoT), Bengaloru, India, Aug. 2018, pp. 391–394.
[31] E. Nurellari, S. Srivastava, A practical implementation of an agriculture field monitoring using wireless sensor networks and IoT enabled, in: Proc. IEEE Int. Symp. Smart Electron. Syst. (iSES) (Formerly iNiS), Hyderabad, India, Dec. 2018, pp. 134–139.
[32] Y. Wang, Y. Huang, C. Song, A new smart sensing sys- tem using LoRaWAN for environmental monitoring, in Proc. Com- put., Commun. IoT Appl. (ComComAp), Shenzhen, China, Oct. 2019, pp. 347–351.
[33] M. Y. Thu, W. Htun, Y. L. Aung, P. E. E. Shwe, N. M. Tun, Smart air quality monitoring system with LoRaWAN, in Proc. IEEE Int. Conf. Internet Things Intell. Syst. (IOTAIS), Bali, Indonesia, Nov. 2018, pp. 10–15.
[34] J. P. Amaro, H. Marcos, R. Cortesao, An energy study of a LoRaWan based electrical impedance spectroscopy module for tree health monitoring, in Proc. 45th Annu. Conf. IEEE Ind. Electron. Soc. (IECON), Lisbon, Portugal, Oct. 2019, pp. 2916–2921.
[35] M. L. Liya, D. Arjun, A Survey of LPWAN Technology in Agricultural Field, 2020 Fourth International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud) (I-SMAC), Palladam, India, 2020, pp. 313-317.
[36] X. Jiang et al., Hybrid Low-Power Wide-Area Mesh Network for IoT Applications, in IEEE Internet of Things Journal, vol. 8, no. 2, pp. 901-915, 15 Jan.15, 2021.
[37] A. Valente, S. Silva, D. Duarte, F. Cabral Pinto, S. Soares, Low-Cost LoRaWAN Node for Agro-Intelligence IoT, Electronics 9 (6) (2020) 987.
[38] G. Codeluppi, A. Cilfone, L. Davoli, G. Ferrari, LoRaFarM: A LoRaWAN-Based Smart Farming Modular IoT Architecture, Sensors 20 (7) (Apr. 2020) 2028.
[39] M.O. Ojo, D. Adami, S. Giordano, Experimental Evaluation of a LoRa Wildlife Monitoring Network in a Forest Vegetation Area, Future Internet 13 (5) (Apr. 2021) 115.
[40] L. Joris, F. Dupont, P. Laurent, P. Bellier, S. Stoukatch, J. Redouté, An Autonomous Sigfox Wireless Sensor Node for Environmental Monitoring, in IEEE Sensors Letters, vol. 3, no. 7, pp. 01-04, July 2019, Art no. 5500604.
[41] T. M. Sousa, C. B. Margi, R. M. Silveira, B. C. Albertini, A. M. Saraiva, Evaluating multipath routing protocols to improve video transmission for precision agriculture, 2014 International Telecommunications Symposium (ITS), Sao Paulo, Brazil, 2014, pp. 1-5.
[42] S.J. Moorehead, C.K. Wellington, B.J. Gilmore, C. Vallespi, Automating orchards: A system of autonomous tractors for orchard maintenance, Proc. IEEE Int. Conf. Intell. Robot. Syst. Work. Agric. Robot. (2012).
[43] S.J. Moorehead, M. Kise, J.F. Reid, Autonomous Tractors for Citrus Grove Operations, Int. Conf. Mach. Control Guid. (2010) 309–313.
[44] A. Stentz, C. Dima, C. Wellington, H. Herman, D. Stager, A system for semi-autonomous tractor operations, Auton. Robots 13 (1) (2002) 87–104.
[45] S. Zhou, et al., Robust Path Following of the Tractor-Trailers System in GPS-Denied Environments, IEEE Rob. Autom. Lett. 5 (2) (2020) 500–507.
[46] W. Zhao, X. Wang, B. Qi, T. Runge, Ground-Level Mapping and Navigating for Agriculture Based on IoT and Computer Vision, IEEE Access 8 (2020) 221975–221985.
[47] H. Klaina, A.V. Alejos, O. Aghzout, F. Falcone, Narrowband Characterization of Near-Ground Radio Channel for Wireless Sensors Networks at 5G-IoT Bands, Sensors 18 (8) (2018) 2428, https://doi.org/10.3390/s18082428.
[48] H. Klaina, I. Picallo, P. L. Iturri, L. Azpilicueta, M. C. Echarri, O. Aghzout, F. Falcone, A. V. Alejos, "Deterministic Radio Channel Characterization for Near-Ground Wireless Sensor Networks Deployment Optimization in Smart Agriculture," 2020 14th European Conference on Antennas and Propagation (EuCAP), Copenhagen, Denmark, 2020, pp. 1-5.
[49] Agriculture, forestry and fishery statistics. Statistical books. 234 pp. ISBN 978-92-76-21522-6, doi: 10.2785/143455.
[50] https://dramco.be/tools/lora-calculator/.
[51] M.I. Hossain, J.I. Markendahl, Comparison of LPWAN Technologies: Cost Structure and Scalability, Wireless Pers Commun (2021).
[52] G. Schnitkey, D. Lattz, Machinery Cost Estimates for 2017, farmdoc daily (7):117, Department of Agricultural and Consumer Economics, University of Illinois at Urbana- Champaign, June 27, 2017.
[53] D. Drenjanac, S. Tomic, J. Agüera, M. Perez-Ruiz, Wi-Fi and Satellite-Based Location Techniques for Intelligent Agricultural Machinery Controlled by a Human Operator, Sensors 14 (10) (Oct. 2014) 19767–19784.
[54] P. Herrera, J. Dorado, Á. Ribeiro, A Novel Approach for Weed Type Classification Based on Shape Descriptors and a Fuzzy Decision-Making Method, Sensors 14 (8) (Aug. 2014) 15304–15324.
[55] A. Farhad, D.-H. Kim, B.-H. Kim, A.F.Y. Mohammed, J.-Y. Pyun, Mobility-Aware Resource Assignment to IoT Applications in Long-Range Wide Area Networks, IEEE Access 8 (2020) 186111–186124.
[56] N. Benkahla, H. Tounsi, Y. Song, M. Frikha, Enhanced ADR for LoRaWAN networks with mobility. 2019 15th International Wireless Communications & Mobile Computing Conference (IWCMC), 2019.
[57] W. Ayoub, A.E. Samhat, F. Nouvel, M. Mroue, J. Prévotet, Internet of Mobile Things: Overview of LoRaWAN, DASH7, and NB-IoT in LPWANs Standards and Supported Mobility, IEEE Commun. Surv. Tutorials 21 (2) (2019) 1561–1581.