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A study of LoRaWAN protocol performance for IoT applications in smart agriculture

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ABSTRACT

The use of Internet of Things (IoT) is becoming increasingly common in agribusiness to increase food production capacity for the expanding global population. Recently, low-power wide-area networks (LPWANs) have been used in the development of IoT applications that require low power consumption and low data transmission rates. LoRaWAN is considered the most suitable communication network for LPWANs for IoT applications in smart agriculture. In this paper, we present an in-depth study of the performance of the LoRaWAN communication network in the context of an IoT application for a pilot farm. We consider several scenarios and analyze simulation results by using Network Simulator 3. We then propose a mathematical model that precisely predicts the successful packet delivery rate for this type of network considering the number of nodes and the transmission interval duration. Finally, we validate the results of our model by comparing them with other simulation results under different scenarios.

1. Introduction

For farmers and agricultural producers, a wide variety of information about soil and crop behavior, animal behavior, condition of machinery, the status of storage tanks from remote sites are presented to farmers to enable them to make decisions and improve their production. The advancement of communications technologies and sensors for agriculture, as well as its low production cost, allow measurement of parameters, such as soil moisture, temperature, and soil acidity [1]. Therefore, the IoT applications allow farmers to analyze these data, predict future conditions, and therefore, improve productivity, minimize expenses and conserve resources. With this, IoT is used in several intelligent agriculture applications, such as open-field agriculture, controlled environment agriculture (greenhouse), livestock breeding, agricultural machinery, storage grains and others [1–5].

Recently, a new generation of low-power wide-area networks (LPWAN) has emerged to bridge the gap between wireless and mobile network technology. These LPWANs are gaining ground and calling into question previous technologies because LPWANs offer wireless connectivity by using a star topology and long-range radio transmission with low power consumption [6–8]. LPWAN technology reduces the data transmission rate and increases network coverage [9]. It is used over long distances (up to 40 km) and is energy efficient, using a battery that can send a few messages every day for 10 years [10–12]. Therefore, LPWAN is proving useful and practical in smart agriculture [6,11]. Several studies have investigated the reliability of LPWANs for Internet of Things (IoT) applications [8,9,13–15].

The most important LPWAN communication technologies are SigFox, LoRa, and NB-IoT. Since 2015, the research community has been increasingly interested in LoRa technology and its LoRaWAN communication protocol. On June 2020, more than 8000 publications listed by Google Scholar contained the keyword “LoRaWAN”. Some articles studied the performance and scalability of LoRaWAN on the NS-3 [9,16,17]. Each article considered the performance of the LoRaWAN in different aspects. However, additional simulations are needed to evaluate the performance of the LoRaWAN, including the network performance according to the number of messages sent on the network.

Magrin et al. [9] study the performance of a LoRaWAN based IoT network in a typical urban scenario, this study analyzes network performance with simulation tools. As a result, the LoRaWAN network can scale well, mainly due to the fact that an increase in the number of gateways enhances the coverage and reliability of the uplink as well. In an urban scenario, the successful packet delivery rate reaches a rate of 95% for more than 1000 nodes served with several gateways. Loriot et al. [13] presents a field study concerning the use of LoRaWan technology for data communication in a Scientific Campus of the University.

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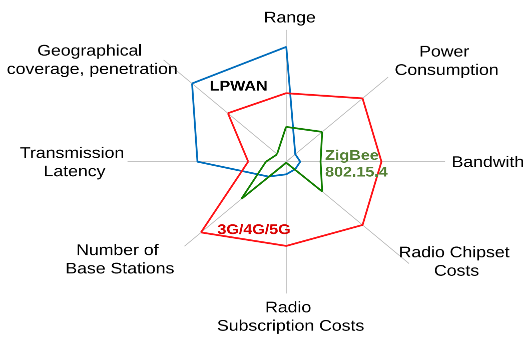

Fig. 1. Comparative communicating technology [24].

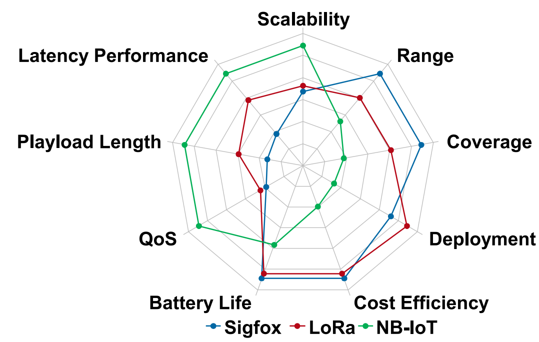

Fig. 2. Advantages of Sigfox, LoRa, and NB- IoT in terms of IoT factors [11].

The tests were conducted in outdoor and indoor environments using a single gateway. They have shown that LoRaWAN technology performs well on most of the campus. Ortiz et al. [18] study the performance of LoRa technology operating in an urban mobility environment, through real and simulated experiences. Conclusions are drawn on the impact of distance, speed levels and spreading factors in vehicle communication. Peruzzi et al. [14] demonstrate the feasibility of a LoRaWAN network to be used for data collection in marine environments, with the transmitting device placed in the middle of the sea and the Gateway placed ashore. Test results prove that efficient data transmission can be achieved at a distance of 8.33 km. In smart farming domain, Codeluppi et al. [19] propose an IoT platform based on the LoRaWAN network called LoRaFARM to improving the management of farms. The architecture was deployed on a real farm and the performance of the data collected for 3 months was analyzed. The majority of the data collected was correctly transmitted both in outdoor (i.e., vineyard) and indoor (i.e., greenhouse) environments. Focusing on rural environments, Feltrin et al. [20] evaluated the capacity of a LoRaWAN gateway and a multi-gateway network to serve a large area. A system-level analysis is performed through simulations, which confirm that the use of several gateways improves the network capacity and guarantees a higher success rate. There are other research works in literature focused on optimizing energy consumption [21,22], allocating and optimizing IoT resources based on the heuristic algorithm [23].

Despite the studies found in the literature, we still find unanswered research questions, such as

- Is LoRaWAN suitable for IoT applications in intelligent agriculture?
- Is it possible to predict the behavior and performance of the LoRa network and to choose its right parameters during the design phase without performing new simulations?
- How to choose the adequate compromise between the number of nodes and the duration of the transmission interval?

Our main motivation is therefore to provide answers to these questions. In this context, we present interesting and promising results on the reliability of the LoRaWAN for IoT applications in the field of smart agriculture. We obtain the results from several simulation scenarios that can occur in a pilot farm by using Network Simulator 3 (NS-3), a powerful network simulation tool. In addition, we propose a mathematical model that predicts the successful packet delivery rate of LoRaWAN for a pilot farm on the basis of the number of nodes and the duration of the transmission interval. Using the proposed model, we can predict the behavior and performance of our LoRa network and choose the parameters during the design phase. Our model assesses the compromise between these two parameters. Finally, we validate the proposed model by analyzing the trend line between the results predicted by the model and the results obtained with new simulation scenarios.

The rest of this article is structured as follows: In Section 2, we summarize the main LPWAN technology and describe the operating principles of the LoRaWAN communication protocol. In Section 3, we study the performance of the LoRaWAN on the NS-3. In Section 4, we describe a general view of methodology, the assumptions and simulation results of different experiments for a pilot farm. In Section 5, we analyze the results obtained from the performance of the LoRaWAN, and we propose and validate our mathematical model to predict the successful packet delivery rate of the LoRaWAN of our pilot farm. In Section 6, we discuss the results obtained in this study. In Section 7, we present our conclusions.

2. LoRaWAN specification

2.1. LPWAN technology

Currently, a wide variety of technologies are used for IoT applications. Each technology has its own strengths to satisfy the requirements of certain domains. Bluetooth, Wi-Fi, ZigBee, and cellular networks (2G/3G/4G/5G) are among the most commonly used technology. Wi-Fi and ZigBee are ideal for applications where communication distance does not exceed 100 m. Smart homes and cellular networks (2G/3G/4G/5G) allow a long communication distance, but they are energy-intensive and expensive. New LPWAN technologies offer long-range communication, low power consumption, and low data transmission rate. These three characteristics are specific to agricultural applications, thereby making the new LPWAN technologies suitable for the requirements of this domain. Fig. 1 shows a comparison among different technologies [24].

The most popular LPWAN communication technologies are SigFox, LoRa, and NB-IoT. SigFox technology provides good coverage in urban areas, especially in buried places. LoRa technology makes it possible to make trade-offs between the amount of data to be transmitted, the range, and energy autonomy. NB-IoT technology is based on cellular networks. This technology offers superior quality of service (QoS) and also improves penetration inside buildings or in basements compared to 2G/3G/4G coverage. Table 1 presents an overview of the technical aspects of these technologies. More details of the three technologies are presented below.

SigFox was developed in 2010 by SigFox (in Toulouse, France) and LPWAN network operators. SigFox operates and markets its own IoT solution in 60 countries with a network coverage of 5 million square kilometers [25]. SigFox uses ISM unlicensed bands and can send messages at a maximum range of 40 km with a limit of 140 messages per day and a payload of 12 bytes for each send message in the uplink. Downlink messages are limited to 4 messages per day and a payload of 8 bytes.

LoRa was developed by Cycleo in 2009 (in Grenoble, France) and then bought by Semtech (USA). LoRa is a physical-layer technology that modulates signals in the sub-GHZ ISM band. The communication protocol based on LoRa technology was standardized by the LoRa Alliance

Table 1
Overview of LPWAN technologies: SigFox, LoRa, and NB-IoT [11].

	SigFox	LoRa	NB-IoT
Allow private network	No	Yes	No
Frequency bands	Unlicensed	Unlicensed	Licensed (paying)
Max messages per day	140 (sends) and 4 (receptions)	Unlimited	Unlimited
Localization	Yes (RSSI)	Yes (TDOA)	No
Encryption of sent messages	No	Yes (AES 128b)	Yes (LTE encryption)
Interference immunity	Very high	Very high	Low
Range	10 km (urban), 40 km (rural)	5 km (urban), 20 km (rural)	1 km (urban), 10 km (rural)
Maximum payload length	UL : 12 bytes DL : 8 bytes	243 bytes	1600 bytes
Bandwidth	100 Hz	250 kHz and 125 kHz	200 kHz
Maximum data rate	0.1 kbps	50 kbps	200 kbps
Modulation	BPSK	CSS	QPSK
Standardization	SigFox company is collaborating with ETSI on the standardization of SigFox-based network	LoRa-Alliance	3GPP

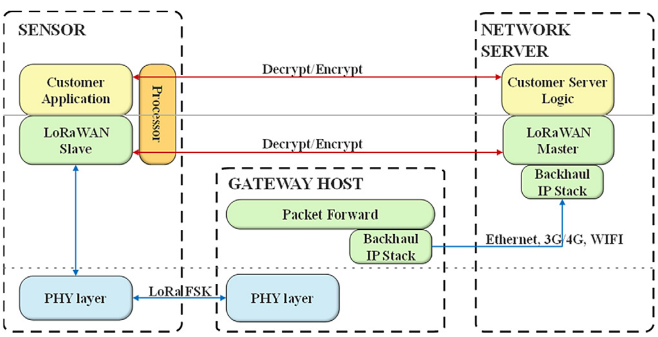

Fig. 3. Structure of a LoRa network [26].

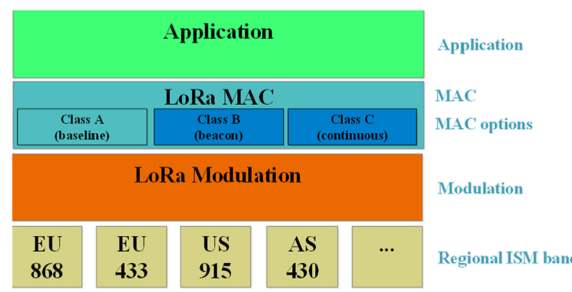

Fig. 4. LoRaWAN classes [31].

in 2015. LoRa is operational in 51 countries [27]. It uses unlicensed ISM bands and can send unlimited messages with a maximum payload of 243 bytes. Communication can reach a range of 20 km in rural areas and 5 km in urban areas. LoRaWAN provides various classes of terminals to meet the different requirements of a wide range of IoT applications. Class A is the most economical in terms of energy.

NB-IoT is an LPWAN technology based on narrowband radio technology and standardized by the 3GPP project. Its specifications were published in Release 13 of the 3GPP in June 2016. The NB-IoT communication protocol is based on the LTE protocol, and it minimizes and improves the functionality of the LTE protocol in accordance with the needs of IoT applications. It uses a licensed spectrum by providing optimal quality of service (QoS) at the expense of costs.

Many studies compared these LPWAN technologies in terms of physical characteristics and communications [6,11,28], such as QoS, coverage, range, latency, battery life, scalability, payload length, deployment, and cost. Fig. 2 shows the respective advantages of Sigfox, LoRa, and NB-IoT in terms of IoT factors. Existing studies attempted to highlight which technology is best suited for which IoT application scenario. Mekki et al. [11] and Sinha et al. [6] concluded that LoRa is the most suitable technology for applications dedicated to smart agriculture. LoRa offers the possibility to deploy private networks, which is useful especially for farms that do not always have network coverage. One of the challenge associated with the use digital technologies and therefore for digital transformation of the agriculture and food sector is that network coverage in rural areas remains limited [29]. Despite 4G becoming the most common mobile connection globally and 90% of being able to access the internet through 3G or higher quality network, only around a third of rural populations in least-developed countries receive coverage by 3G networks [30]. LoRa technology offers high network coverage up to 20 km in rural areas, consumes minimal energy, and presents the possibility to create a private network. However, LoRa offers many advantages for IoT applications in smart agriculture. These advantages motivate us to use this technology, further understand it, and know its limits.

2.2. LoRaWAN

LoRa communication has been proposed to connect a large number of peripherals in large areas (up to 20 km) with low energy consumption. LoRa modulates signals in a sub-GHZ ISM band by using a spread spectrum technique, through which messages can be sent at a longer range at the detriment of data rate. It uses six spreading factors (SF), from SF7 to SF12, to allow a compromise between transmission range and data rate. The largest SF (SF 12) allows a long range and low data rate. LoRa is a physical-layer technique and is associated with the LoRaWAN MAC layer solution to realize IoT applications. The LoRa architecture includes three important elements, namely, nodes, gateways, and network servers. The LoRa network layers can be seen in Fig. 3 [26].

To meet the different requirements of a wide range of IoT applications, the LoRaWAN communication protocol offers three class types for sending and receiving packets, as shown in Fig. 4.

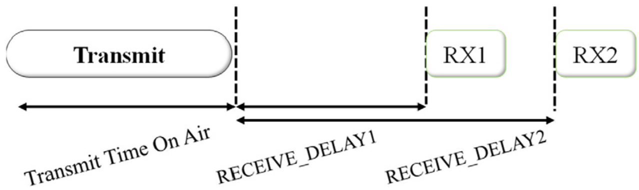

Fig. 5. Reception windows after sending messages (Class A) [31].

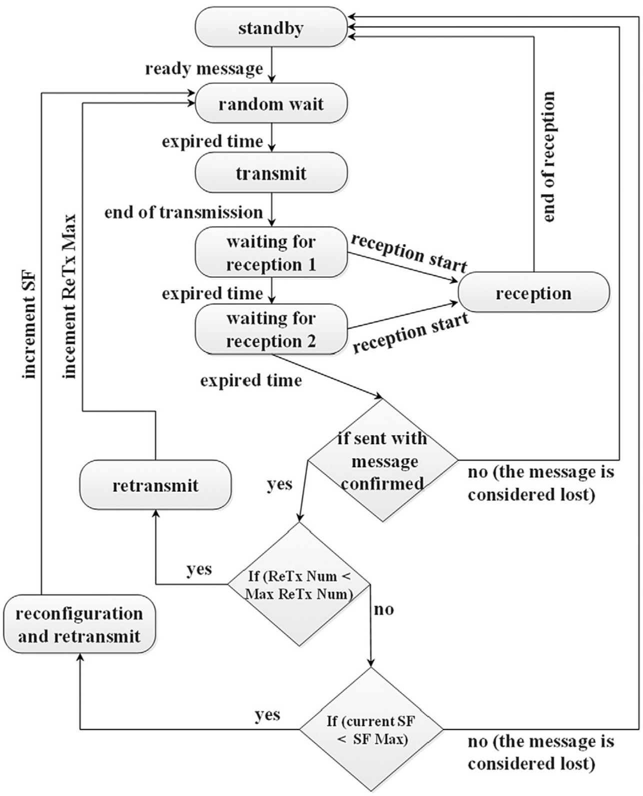

Fig. 6. LoRaWAN protocol operating process for class A.

Class A is the basic class of LoRaWAN. Classes B and C are optional classes [31].

Class A: Class A nodes have the lowest power consumption. They send a small number of data packets to the gateway and stay idle most of the time. Class A nodes allow bidirectional communications. As shown in Fig. 5, the uplink communication to the gateway is followed by two downlink reception windows with a random time.

Class B: In addition to the reception windows in class A, the nodes of class B open reception windows in scheduled time slots. The nodes receive a beacon synchronized with the time of the gateway.

Class C: The nodes of class C have a window that is always open for reception, except during data transmission. The nodes of the class C consume more energy than those of the two other classes.

Two types of data messages can be transmitted by the LoRaWAN communication protocol: confirmed and unconfirmed messages [31]. A confirmed data message must be acknowledged by the receiver, whereas an unconfirmed data message does not require an acknowledgment of receipt [31]. The first traffic retransmits the packet a number of times until the gateway responds with an acknowledgment of receipt. The second traffic sends the packet only once.

The number of retransmissions for the same message when an acknowledgment is requested but not received is left to the discretion of the terminal equipment and may be different for each terminal equipment. It can also be defined or adjusted from the network server. If a terminal has reached its maximum number of retransmissions without receiving an acknowledgment of receipt, then it may decide to switch to robust modulation schemes by selecting a high SF or decreasing the bandwidth to retransmit the message; otherwise, it gives up transmission and considers the message as lost [31].

The gateway must send an acknowledgment when it receives a message. The gateway listens all the time to the different channels (up to 8 channels) except in the case where it transmits a message; the channel can be used for sending or receiving and not both at the same time [31].

Fig. 6 describes the LoRaWAN protocol operating process for class A in a node. More detailed information for LoRaWAN [31–33].

3. Analysis of LoRaWAN performance

Simulators and test-beds can be used to make repetitive experiments and determine overall network performance. Until now, the test-beds have already been deployed on a small scale for the LoRaWAN network [4,34–38]. However, the simulators have been used to perform reproducible experiments, considering the impact of several parameters in the overall performance of the system. Using such an approach, LoRaWAN network level performance under certain heavy condition scenarios, such as large number of end nodes or high traffic loads, can be studied [4].

NS3 is one of the most common used network level simulators [39]. Due to this, a number of LoRaWAN simulators are NS3 compatible [9,16,17]. Some studies evaluated the performance and scalability of LoRaWAN on the NS-3 [9,16,17] in different aspects through simulation experiments, and they provided interesting and complementary conclusions about the performance of LoRaWAN, as summarized in Table 2.

Den Abeele et al. [17] and Reynders et al. [16] confirmed the LoRa network reliability (successful packet delivery rate) by comparing traffic using confirmed messages with that using unconfirmed messages. Moreover, they conducted experimental studies on limiting the number of nodes that the system can support. Magrin et al. [9] studied the performance of the LoRaWAN for class A considering urban obstacles (buildings) with traffic using only unconfirmed messages. Reynders et al. [16] and Magrin et al. [9] experimented on the performance of the LoRaWAN considering the value of the SF. These three studies provide interesting results on the evolution of the LoRa network of class A by increasing the density of the gateways to meet the limits observed when using a single gateway. In addition, the authors in [16] compared this scalability in the case of traffic sending unconfirmed messages to the traffic sending confirmed messages.

The previous study clarified a number of points about the scalability of the LoRaWAN. On this basis, increasing the number of nodes in the network has a negative impact on the reliability (successful packet delivery rate) of the network. Choosing an initial SF adapted to the distance between the node and the gateway is important to achieve good packet delivery rates. The nodes farthest from the gateway have a lower packet delivery rate than those closer to the gateway. In a large configuration (more than 100 nodes), the use of unconfirmed messages gives better reliability results than the use of confirmed messages. However, the LoRaWAN architecture may be evolving mainly because an increased number of gateways improves the coverage and reliability of the uplink. The simulations by Magrin et al. in [9] proved that a network with several gateways serving more than 15,000 nodes results in a packet delivery rate greater than 95% with an unconfirmed message traffic model.

Therefore, using LoRaWANs is favorable for smart agriculture applications. Nevertheless, another point that has not been considered in previous studies needs to be clarified, specifically, the impact of the duration of the transmission interval on the successful packet delivery rate of the network. The major cause of packet loss is the interference of messages [40], which is caused by the density of messages in the

Table 2
Studies on the evolution of the LoRaWAN.

	Studies by Reynders et al. in [16]	Studies by Den Abeele et al. in [17]	Studies by Magrin et al. in [9]
Sending message confirmed compared with unconfirmed messages	The use of confirmed messages is more reliable when the number of nodes is small (<100 nodes). However, when the number of nodes is large (>100 nodes), the packet delivery rate is greater when unconfirmed messages are used than when confirmed messages are sent.	* When the number of nodes is low (<100 nodes), the packet delivery rate sent in the confirmed mode is significantly higher than that of messages sent in the unconfirmed mode. * When the number of nodes is high (>100 nodes), the packet delivery rate sent in the unconfirmed mode is significantly higher than that of messages sent in the confirmed mode.	/
Impact of increasing the number of nodes	The packet delivery rate decreases with the increase in the number of nodes.	The packet delivery rate decreases with the increase in the number of nodes.	/
Increased number of gateways	Increasing the number of gateways increases the packet delivery rate and does not completely eliminate packet losses.	* For unconfirmed messages, the packet delivery rate increases considerably with an increase in the number of gateways. * For confirmed messages, the packet delivery rate increases with increasing gateways. This situation does not apply in the case of unconfirmed messages.	Increasing the number of gateways improves network coverage and uplink reliability.
Effect of the distance of the nodes from the gateway.	The packet delivery rate is also related to the distance between the node and the gateway. The loss rate increases as the node moves away from the gateway.	/	/
Choice of initial SF	/	Choosing an initial SF adapted according to the distance of the node relative to the PER Strategy gateway gives better results at the level of the delivery rate of the packets compared with the assignment of fixed or random SF.	Excluding terminals with the highest SF when the system load is large greatly improves the packet delivery rate.

air. This density is caused by two main factors: the number of nodes that send messages in the network and the quantity of messages sent by these nodes. Such interference is reflected in IoT applications by the transmission interval between two sent messages.

We simulate several possible configurations for agricultural applications by considering the two previous points. In this manner, we can draw conclusions about the potential of LoRaWAN technology for agricultural applications on the one hand and take advantage of our simulation experience to develop real applications on the other hand.

4. Methodology

4.1. General view

To answer the research questions asked in the introduction section, we will follow a 3-phase methodology: performance evaluation with simulations, mathematical model development, and validation of our model. Fig. 7 shows a three-phase process for the design and validation of our mathematical model.

• Phase 1: a number of initial experiments (scenarios) are simulated on NS-3 to assess the successful packet delivery rate. Two types of curves are drawn, the first curve represents the successful packet delivery rate considering the number of nodes and the second corresponds to the successful packet delivery rate considering the transmission interval. These two curves make it possible to propose the mathematical model. Many experiments are simulated on NS-3 until obtaining complete curves.

• Phase 2: First, the successful packet delivery rate based on the number of nodes and the successful packet delivery rate based on the transmission interval are analyzed separately. Following this analysis, two functions of the successful packet delivery rate are proposed (f (T) see Table 5 and f (N) see Table 6). f (T) corresponds to the mathematical model of the successful packet delivery rate considering the transmission interval and f (N) corresponds to the mathematical model of the successful packet delivery rate considering the number of nodes. Inspired by the two functions f (T) and f (N) a function f (T, N) is proposed (see Table 7). It corresponds to the successful packet delivery rate considering both the transmission interval and the number of nodes.

A MATLAB tool is used to fit the proposed functions. The quality of fit is evaluated by the correlation coefficient R^2, which reveals a perfect fit if it is equal to 1.

• Phase 3: new experiments, not yet considered during phase 1, are simulated on NS-3. Based on these new experiments, our model is compared with the results of the simulation. The trend line is drawn and adjusted (see Fig. 13).

To validate our mathematical model, the slope of the trend line is calculated. A perfect match between the simulated (experimental) and predicted successful packet delivery rates would yield a slope of 1 and R^2 of 1.

4.2. Simulations assumption

We perform simulation experiments on NS-3 using the LoRaWAN module developed by [9]. The simulator is available as open source software in [41]. We adapted the LoRaWAN module at its application layer to simulate a number of experiments (scenarios) designed to evaluate and model the performance of the LoRaWAN as a service quality (on the successful packet delivery rate) for agriculture applications. Before presenting the simulation results, we present the assumption of the simulation.

We consider an open-air farm (without obstacles) that includes a single gateway and a variable number of final devices (called nodes) deployed on a disc with a radius of 7.5 km. The gateway is positioned in the origin of the disc. The nodes are distributed uniformly on the disc using "UniformDiscPositionAllocato" on NS-3. The positions of nodes and gateway are fixed for the duration of the simulation using "ConstantPositionMobilityModel" on NS-3.

All experiments simulate a class A LoRaWAN traffic. The nodes transmit unconfirmed data packets. A packet transmitted by a node is considered lost when no acknowledgment is received in the first and the second reception windows. This unacknowledged packet is not retransmitted.

The size of the packets transmitted by the nodes is 23 bytes. Throughout the duration of the simulation for an experiment, the nodes periodically generate and transmit packets with the same time interval. For each configuration (a given number of nodes), several simulation experiments are performed by varying the duration of the transmission

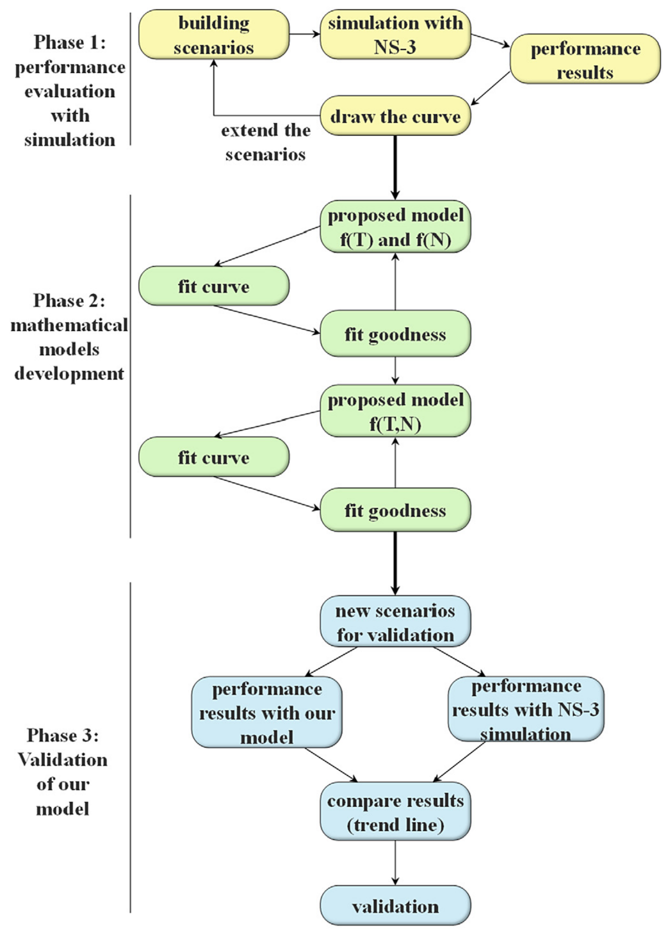

Fig. 7. A three-phase process for the design and validation of our mathematical model.

Table 3
Parameter table used in simulations.

Parameters	Value
Simulation time (s)	86 400
Gateway radius (m)	7500
Positions of nodes	Distributed uniformly
Mobility of nodes and gateway	Fixed
Number of nodes	10–2000
Number of gateways	1
Packet size (bytes)	23
Duration of the transmission interval (s)	180–86 400
Spreading Factors (SF)	7–12
Type of transmission	Unconfirmed
LoRaWAN Class	A
Receive paths (total) at gateway	8
Antenna height (m)	15
Nodes height (m)	1.2

interval. The transmission interval corresponds to the waiting time between two transmissions of data packets. The transmission process is cyclic with constant intervals. The duration of the minimum transmission interval is 3 min to meet the requirements of duty cycle imposed by the LoRaWAN specifications. The transmission intervals vary between 3 min and 24 h for each experiment.

The SF is assigned to the nodes at the start of the simulation. SF is defined based on the signal strength received from the gateway. The assigned SF takes a value between SF7 and SF12.

Each simulation experiment is run for 24 h. Each node chooses a random delay to start transmitting the first packet. The value of

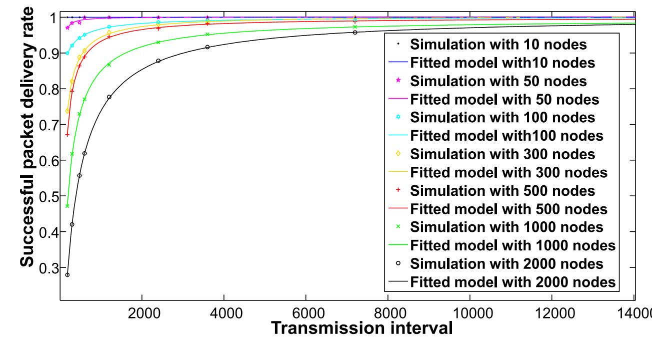

Fig. 8. Successful packet delivery rate based on the transmission interval. The points represent the result obtained by simulation. The curves represent the fit of the mathematical model proposed in Table 5 for each configuration.

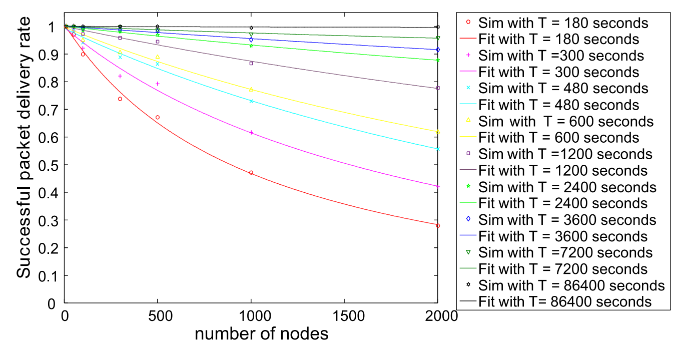

Fig. 9. Successful packet delivery rate based on the number of nodes. The points represent the result obtained by simulation. The curves represent the fit of the mathematical model proposed in Table 6 for each transmission interval.

this delay is between zero and the duration value of the transmission interval of the experiment.

We measure the successful packet delivery rate for all simulation experiments. A packet is considered received if it is acknowledged in one of the two reception windows. The successful packet delivery rate is the ratio of the sum of the packets sent by all nodes to the sum of the successfully received packets throughout the duration of the simulation for an experiment.

We simulate the network behavior and calculate the packet delivery rate for nine transmission intervals (180, 300, 480, 600, 1200, 2400, 3600, 7200, and 86 400 s). These simulation experiments with the transmission intervals mentioned above are conducted for several configurations of the LoRaWAN (10, 50, 100, 300, 500, 1000, and 2000 nodes).

Table 3 summarizes the parameters used in the simulation. Table 4 summarizes the simulation results for all experiments.

5. Analysis and modeling

5.1. Network performance analysis

The studied problem is the effect of the scalability of the number of nodes and the variation of the transmission interval on the reliability of the network (successful packet delivery rate).

First, we study the successful packet delivery rate when the packet transmission interval increases up to 24 h, as shown in Fig. 8.

As shown in Fig. 8, the successful packet delivery rate increases nonlinearly as the transmission interval increases. Then, the packet delivery rate recovers quickly when the transmission interval is between 180 s (3 min) and 3600 s (1 h).

Table 4
Results of the packet delivery rate for all simulation experiments.

Number of nodes	Duration of the transmission interval (s)								
	180	300	480	600	1200	2400	3600	7200	86 400
10	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
50	0.970	0.984	0.984	1.000	1.000	1.000	1.000	1.000	1.000
100	0.899	0.920	0.942	0.950	0.972	0.986	0.993	0.993	1.000
300	0.737	0.820	0.888	0.905	0.957	0.980	0.987	0.998	1.000
500	0.672	0.792	0.864	0.888	0.945	0.968	0.982	0.988	1.000
1000	0.471	0.617	0.729	0.770	0.866	0.929	0.952	0.972	0.995
2000	0.279	0.419	0.556	0.619	0.776	0.878	0.916	0.957	0.997

Table 5
Goodness of fit of the model with the fit coefficients obtained for each configuration (T represents the transmission interval; p1, p2, and q1 represent the coefficients to find for our equation).

Mathematical model representing the successful packet delivery rate: f(T) = (p1 ∗ T + p2)/(T + q1)							
Number of nodes	p1	p2	q1	SSE	R^2	Adjusted R^2	RMSE
10	1	0.1996	0.1996	1.91E−23	1	1	1.79E−12
50	1.002	−36.37	−31.72	9.58E−05	0.8967	0.8623	0.003996
100	1.001	182.7	224	2.06E−05	0.998	0.9973	0.001853
300	1.006	−3.135	61.59	8.16E−05	0.9988	0.9984	0.003687
500	0.9995	−38.51	30.29	2.60E−05	0.9997	0.9996	0.00208
1000	0.9955	−29.41	137	3.49E−05	0.9999	0.9998	0.002413
2000	1.004	−49.84	293.4	5.20E−05	0.9999	0.9999	0.002942

Table 6
Goodness of fit of the model with the fit coefficients obtained for each transmission interval (N represents the number of nodes; p1, p2 and q1 represent the coefficients to find for our equation).

Mathematical model representing the successful packet delivery rate: f(N) = (p1 ∗ N + p2)/(N + q1)							
Transmission interval	p1	p2	q1	SSE	R^2	Adjusted R^2	RMSE
180	−0.0952	1053	1045	1.38E−03	0.9968	0.9952	1.86E−02
300	−0.1662	2043	2051	0.002156	0.9919	0.9879	0.02322
480	−0.3187	3990	4019	0.001001	0.9934	0.9901	0.01582
600	0.1703	4164	4173	0.001115	0.9903	0.9854	0.0167
1200	−0.03426	7210	7208	0.000437	0.9891	0.9837	0.01045
2400	0.3383	8778	8773	7.75E−05	0.9935	0.9903	0.004401
3600	0.2518	1.56E+04	1.56E+04	4.85E−05	0.9916	0.9874	0.9874
7200	0.8083	6851	6846	6.61E−05	0.9574	0.9362	0.004064
86 400	0.9943	1057	1056	1.05E−05	0.5463	0.3195	0.001623

The slope of decrease of the successful packet delivery rate when the transmission interval decreases is more significant when the number of nodes is bigger.

The threshold of the packet delivery rate is always higher than 95% for configurations lower than 100 nodes regardless of the transmission interval. However, for configurations greater than 100 nodes, to reach a packet delivery rate greater than 95%, the transmission interval must be increased.

A thorough analysis of the graphs reveals that the curves of the packet delivery rates are similar to those of a rational function. As shown in Fig. 8, we fit each curve that corresponds to a configuration with a rational function of the order of 1 by using the curve fitting tool in MATLAB. Curve fitting aims to find the best fit of the curve for a series of data points, where the best coefficients of our mathematical equation represent the series of data points. Table 5 shows the function fit coefficients and the statistics on the goodness of fit (SSE, R-square, adjusted R-square, RMSE).

We then study the successful packet delivery rate when the number of nodes increases up to 2000 nodes.

As shown in Fig. 9, the successful packet delivery rate decreases when the number of nodes increases. This result reflects expectations and confirms the results in the literature. The decrease is more important and is faster when the transmission interval is small than when it is large.

A thorough analysis of the graphs reveals that the curves of the packet delivery rates are similar to those of a rational function. As shown in Fig. 9, we fit each curve for a given transmission interval with a rational function of the order of 1 by using the curve fitting tool in MATLAB. Table 6 shows the function fit coefficients and the statistics on the goodness of fit (SSE, R-square, adjusted R-square, RMSE).

In conclusion, transmission interval and the number of nodes are the essential and influential parameters on the successful packet delivery rate. Increasing the number of nodes and reducing the transmission interval can lower the successful packet delivery rate. A mathematical equation based on the two previous parameters needs to be established to predict the successful packet delivery rate, thereby enabling us to study the tradeoff between the number of nodes and the transmission interval in our LoRaWAN.

5.2. Modeling

In this section, we propose a mathematical model that evaluates the successful packet delivery rate in our LoRaWAN in accordance with two parameters, namely, the number of nodes in the network configuration and the duration of the transmission interval between two successive data packet transmissions.

The proposed mathematical function is a ratio of two quadratic functions of degree 2. The function of the successful packet delivery rate $f(N,T)$ is defined according to the number of nodes (N) and the transmission interval (T). Eq. (1) describes the proposed function (f).

$$f(N,T) = \frac{Q_1(N,T)}{Q_2(N,T)} \tag{1}$$

$$Q_1(N,T) = a_1 + a_2T + a_3N + a_4T * N + a_5T^2 + a_6N^2 \tag{2}$$

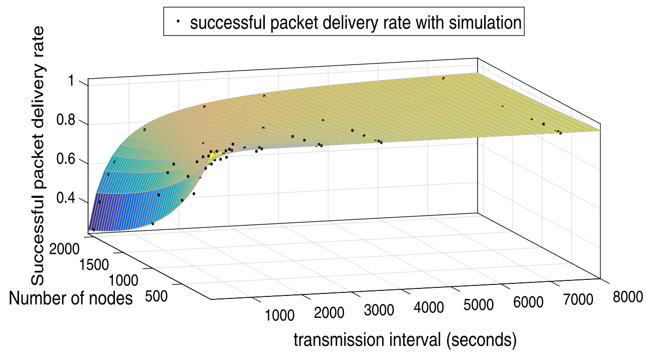

Fig. 10. Surface of the successful packet delivery rate based on the transmission interval and the number of nodes in our model (3D view). The points represent the result obtained by simulation. The surface represents the fit of the mathematical model proposed in Table 7.

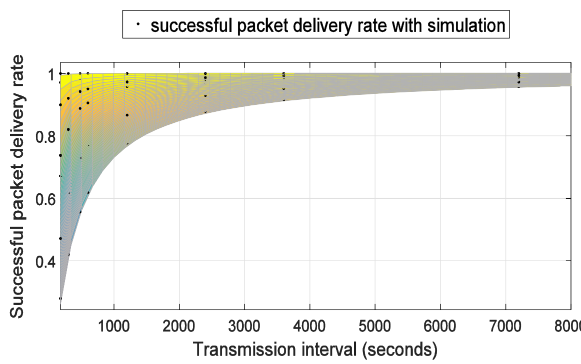

Fig. 11. Surface of the successful packet delivery rate of our model (2D view on the two axes of the successful packet delivery rate and transmission interval). The points represent the result obtained by simulation. The surface represents the fit of the mathematical model proposed in Table 7.

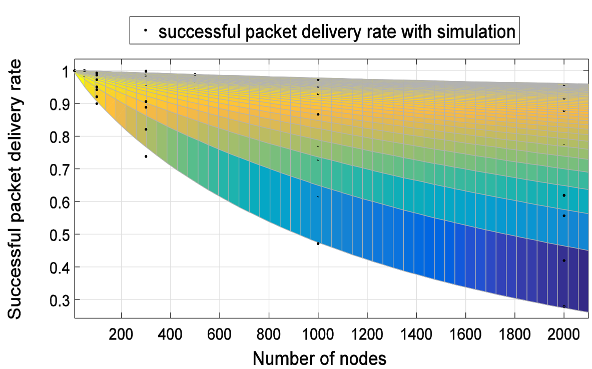

Fig. 12. Surface of the successful packet delivery rate of our model (2D view on the two axes of the successful packet delivery rate and number of nodes). The points represent the result obtained by simulation. The surface represents the fit of the mathematical model proposed in Table 7.

$$Q_2(N,T) = a_7 + a_8T + a_9N + a_{10}T * N + a_{11}T^2 + a_{12}N^2 \tag{3}$$

To define the most appropriate coefficients (a_1 to a_{12}) and plot the surface of the successful packet delivery rate, we use MATLAB Curve Fitting toolbox to adjust the surface of our model to the simulation results. To evaluate the predictive quality of the fitted model, we calculate the value of the coefficient of determination (R^2) to characterize the goodness of fit of the model. The values of R^2 are between 0 and 1. The goodness of fit of the model improves when the R^2 is closer to 1. In addition, we calculate the root mean square error (RMSE) to

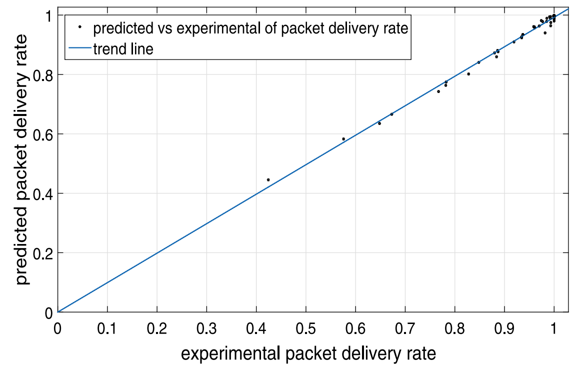

Fig. 13. Trend line between the predicted and experimental packet delivery rate adjusted, fitted, and plotted using the MATLAB Curve Fitting toolbox (slope = 0.9925, R^2 = 0.9928, RMSE = 0.0153).

quantitatively assess the adequacy of the proposed model to the values obtained by simulating the successful packet delivery rate.

Table 7 presents the coefficients (a_1 to a_{12}) and the goodness of fit obtained by curve fitting. The fit obtained from the model is characterized by an adjustment quality of the correlation coefficient R^2 equal to 0.9963 and an RMSE equal to 0.0106. These results show that the model precisely predicts the successful packet delivery rate, as shown graphically in Fig. 10.

Fig. 10 presents the fit surface of the successful packet delivery rate of our model, which is defined according to the number of nodes and the transmission interval. The points in the figure represent the result of the successful packet delivery rate obtained from a simulation experiment with a configuration having a number of nodes (N) and periodically sending data packets over a transmission interval (T). Figs. 11 and 12 show a 2D view of Fig. 10.

As shown in Fig. 10, the surface of the model touches the majority of the experimental points.

Increasing the number of nodes and reducing the transmission interval will lower the successful packet delivery rate. In addition, when the transmission interval is small, the decrease in the delivery rate is more significant when the number of nodes increases and takes a nonlinear form. However, when the transmission interval is large, the successful packet delivery rate decreases minimally as the number of nodes increases.

When the number of nodes is small (fewer than 10 nodes), the successful packet delivery rate is high even with a small transmission interval.

In conclusion, the fit surface of the model is adequate for the obtained experimental points either in terms of the observations that are presented visually on the graph or from the statistical viewpoint of the obtained goodness of fit.

5.3. Validation

To validate the model, we conduct other simulation experiments with new configurations (30, 75, 200, 400, 750 and 1500 nodes) in which each node periodically sends data packets at new transmission intervals (240, 390, 540, 900, 1800, 3000, 5400 and 46 800 s). These simulation experiments were not taken into account during the fitting phase of the model. Table 8 shows the successful packet delivery rate obtained by the new simulation experiments performed with NS-3.

For the same configurations (number of nodes) and transmission intervals of the new simulation experiments, we calculate the successful packet delivery rate predicted by our model. Table 9 shows the results.

Finally, to verify that the model predicts the successful packet delivery rate with great accuracy, we plot the trend line by comparing the predicted successful packet delivery rate with experimental values

Table 7
Goodness of fit of our model and the coefficient adjustment (N represents the number of nodes; T represents the transmission interval; a1 to a12 represent the coefficients to find for our equation).

General model: f(T,N) = (a1 + (a2 ∗ T) + (a3 ∗ N) + (a4 ∗ T ∗ N) + (a5 ∗ T^2) + (a6 ∗ N^2))/(a7 + (a8 ∗ T) + (a9 ∗ N) + (a10 ∗ T ∗ N) + (a11 ∗ T^2) + (a12 ∗ N^2))													
Coefficients obtained												Goodness of fit	
a1	a2	a3	a4	a5	a6	a7	a8	a9	a10	a11	a12	R^2	RMSE
1.89	1.035	0.2292	0.01204	0.001707	−0.0004617	−1.428	1.026	0.592	0.01228	0.001709	0.001468	**0.9963**	**0.0106**

Table 8
Successful packet delivery rate obtained with new simulation experiments for validation.

Number of nodes	Duration of the transmission interval (s)							
	240	390	540	900	1800	3000	5400	46 800
30	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
75	0.981	0.993	0.993	1.000	1.000	1.000	1.000	1.000
200	0.884	0.919	0.937	0.958	0.974	0.985	0.990	1.000
400	0.781	0.848	0.886	0.934	0.970	0.984	0.992	1.000
750	0.648	0.767	0.827	0.880	0.936	0.960	0.976	0.998
1500	0.424	0.575	0.672	0.782	0.887	0.934	0.960	0.992

Table 9
Successful packet delivery rate predicted by our model for validation.

Number of nodes	Duration of the transmission interval (s)							
	240	390	540	900	1800	3000	5400	46 800
30	0.980	0.989	0.993	0.996	0.998	0.998	0.999	0.998
75	0.940	0.964	0.974	0.986	0.993	0.996	0.997	0.998
200	0.859	0.909	0.934	0.961	0.981	0.989	0.994	0.998
400	0.763	0.840	0.880	0.926	0.963	0.978	0.988	0.997
750	0.635	0.742	0.801	0.872	0.933	0.960	0.978	0.996
1500	0.445	0.582	0.666	0.774	0.876	0.923	0.957	0.994

(see Fig. 13). The fit of the trend line produces a slope of 0.9925, with the correlation coefficient (R^2) having a goodness of fit equal to 0.9928 and an RMSE equal to 0.0153. All these results indicate the excellent fit of the slope. The value for the slope (0.9925) affirms that the model predicts the successful packet delivery rate well.

6. Discussion

The in-depth study emerging from the methodology followed (see Fig. 7) when carrying out research work made it possible to answer fairly clearly the questions raised at the beginning of this article.

The preliminary study shows that LoRaWAN's influential performance parameters are essentially — sending messages with or without confirmation – network size – increasing the number of gateways — and the placement distance of the nodes from the gateway. The influence of certain parameters on network performance did not necessarily produce the expected results. We can cite the case of the successful packet delivery rate, when sending messages in confirmed mode, which tends to be less interesting than for sending messages without confirmation for the case of large size networks. We extended the previous study by analyzing the influence of the packet transmission interval conjointly with the number of nodes on the successful packet delivery rate; the results confirm that these two parameters influence the successful packet delivery rate. Thus, we have observed that the decrease in the transmission interval between packets has a negative impact on the packet delivery rate. This impact becomes important when the transmission interval is less than one hour when the number of nodes is greater than 100.

Finally, the model obtained proved to be invaluable, because it made it possible to mathematically predict the behavior of certain configurations (scenarios) without having to waste a lot of time in simulating them.

7. Conclusion

This article presents a performance evaluation of the LoRaWAN by using NS-3. First, we have presented some conclusions that have emanated from the state of the art. Then we were interested in choosing right values of some parameters, which are not yet explored in the literature though they are critical in the performance of LoRaWAN.

We also proposed and validated a mathematical model for accurately estimating the successful packet delivery rate of the LoRaWAN for a pilot farm based on the transmission interval and the number of nodes. This model assesses the compromise between the number of nodes and the transmission interval on the successful packet delivery rate. This result will help developers during the first stages of analysis and design and allow them to adequately choose the parameters to obtain a good performance of the LoRaWAN.

Consequently, the present study showed that LoRaWAN IoT architecture based on a single gateway network connecting up to 1000 nodes sending packets at a minimum transmission interval of one hour is a suitable configuration for many agricultural applications like soil and air monitoring, irrigation, controlled environment agriculture (greenhouse), livestock breeding, etc.

This study confirms the good potential of LoRaWAN for IoT applications in smart agriculture. It encourages future uses of LoRaWAN networks for real IoT applications in smart agriculture. To consider external and environmental conditions (humidity, temperature, vegetation, etc.), we intend to conduct additional research to study their influence on LoRaWAN performance.

CRediT authorship contribution statement

Badreddine Miles: Software, Methodology, Writing - original draft, Writing - review & editing, Visualization. **El-Bay Bourennane:** Conceptualization, Writing - original draft, Writing - review & editing. **Samia Boucherkha:** Conceptualization, Writing - review & editing. **Salim Chikhi:** Supervision, Conceptualization, Methodology, 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] A. Tzounis, N. Katsoulas, T. Bartzanas, Internet of things in agriculture, recent advances and future challenges, Biosyst. Eng. 164 (2017) 31–48.
[2] H.M. Jawad, R. Nordin, S.K. Gharghan, Energy-efficient wireless sensor networks for precision agriculture: A review, Sensors (Basel) 17 (8) (2017).
[3] J. Martín, et al., Review of IoT applications in agro-industrial and environmental fields, Comput. Electron. Agric. 142 (118) (2017) 283–297.
[4] J. Haxhibeqiri, E. De Poorter, I. Moerman, J. Hoebeke, A survey of lorawan for IoT: From technology to application, Sensors (Basel). 18 (11) (2018).
[5] A. Khanna, S. Kaur, Evolution of internet of things (IoT) and its significant impact in the field of precision agriculture, Comput. Electron. Agric. 157 (2018) (2019) 218–231.
[6] R.S. Sinha, Y. Wei, S.H. Hwang, A survey on LPWA technology: Lora and NB-IoT, ICT Express 3 (1) (2017) 14–21.
[7] J. Navarro-ortiz, S. Sendra, P. Ameigeiras, J.M. Lopez-soler, Integration of lorawan and 4g / 5g for the industrial internet of things, IEEE Commun. Mag. 56 (February) (2018) 60–67.
[8] C. Marco, V. Lorenzo, Z. Andrea, Z. Michele, Long-range communications in unlicensed bands: the rising stars in the IoT and smart city scenarios, IEEE Wirel. Commun. (October) (2016) 60–67.
[9] D. Magrin, M. Centenaro, L. Vangelista, Performance evaluation of lora networks in a smart city scenario, in: IEEE International Conference on Communications, 2017.
[10] D. Patel, M. Won, U. States, Experimental study on low power wide area networks (LPWAN) for mobile internet of things, in: IEEE 85th Vehicular Technology Conference (VTC Spring), 2017.
[11] K. Mekki, E. Bajic, F. Chaxel, F. Meyer, A comparative study of LPWAN technologies for large-scale IoT deployment, ICT Express (2018).
[12] M. Chen, S. Member, Y. Miao, X. Jian, X. Wang, S. Member, Cognitive-LPWAN: Towards intelligent wireless services in hybrid low power wide area networks, IEEE Trans. Green Commun. Netw. 3 (2) (2019) 409–417.
[13] M. Loriot, A. Aljer, I. Shahrour, Analysis of the use of lorawan technology in a large-scale smart city demonstrator, in: Sensors Networks Smart and Emerging Technologies, 2017.
[14] G. Peruzzi, S. Parrino, A. Pozzebon, L. Parri, Low power wide area networks (LPWAN) at sea: Performance analysis of offshore data transmission by means of lorawan connectivity for marine monitoring applications, Sensors (Basel). (July) (2019).
[15] C. Pham, F. Ferrero, M. Diop, L. Lizzi, O. Dieng, O. Thiaré, Low-cost antenna technology for LPWAN lot in rural applications, in: IEEE International Workshop on Advances in Sensors and Interfaces, 2017, pp. 121–126.
[16] B. Reynders, Q. Wang, S. Pollin, A LoRaWAN module for ns-3: implementation and evaluation, in: Proceedings of the 10th Workshop on ns-3 - WNS3 '18, 2018, no. June, pp. 61–68.
[17] F. Van Den Abeele, J. Haxhibeqiri, I. Moerman, J. Hoebeke, Scalability analysis of large-scale lorawan networks in ns-3, IEEE Internet Things J. 4 (6) (2017) 2186–2198.
[18] F.M. Ortiz, T.T. De Almeida, A.E. Ferreira, L. Henrique, M.K. Costa, Experimental vs. simulation analysis of lora for vehicular communications, Comput. Commun. 160 (June) (2020) 299–310.
[19] G. Codeluppi, A. Cilfone, L. Davoli, G. Ferrari, LoRaFarM: a LoRaWAN-based smart farming modular IoT architecture, Sensors 20 (7) (2020).
[20] L. Feltrin, et al., LoRaWAN: Evaluation of link- and system-level performance, IEEE Internet Things J. 5 (3) (2018) 2249–2258.
[21] A.K. Sangaiah, et al., Energy-aware green adversary model for cyberphysical security in industrial system, IEEE Trans. Ind. Inform. 16 (5) (2020) 3322–3329.
[22] A.K. Sangaiah, M. Sadeghilalimi, Energy consumption in point-coverage wireless sensor networks via bat algorithm, IEEE Access 7 (2019) 180258–180269.
[23] A.K. Sangaiah, A.A.R. Hosseinabadi, M.B. Shareh, S.Y.B. Rad, A. Zolfagharian, N. Chilamkurti, IoT resource allocation and optimization based on heuristic algorithm, Sensors 20 (2) (2020).
[24] P.R. Egli, LPWAN Technologies for internet of things (IoT) and m2m scenarios, 2015, [Online]. Available: https://fr.slideshare.net/PeterREgli/lpwan.
[25] Sigfox, 2019, [Online]. Available: https://www.sigfox.com/en [Accessed: 18-Feb-2019].
[26] J.de C. Silva, Bounceur, Joel J.P.C. Rodrigues, Antonio M. Alberti, P. Solic, Andre L.L. Aquino, Lorawan - a low power WAN protocol for internet of things: a review and opportunities, in: 2017 2nd International Multidisciplinary Conference on Computer and Energy Science (SpliTech), No. July, 2017, pp. 1–6.
[27] Lora-alliance, 2019, [Online]. Available: https://lora-alliance.org/ [Accessed: 18-Feb-2019].
[28] K. Mekki, E. Bajic, F. Chaxel, F. Meyer, Overview of cellular LPWAN technologies for IoT deployment: Sigfox, lorawan, and NB-IoT, in: International Workshop on Mobile and Pervasive Internet of Things (IEEE PerCom 2018), 2018, pp. 197–202.
[29] N.M. Trendov, S. Varas, M. Zeng, Digital Technologies in Agriculture and Rural Areas Report, Food and Agriculture Organization of the United Nations, Rome, 2019.
[30] GSM Association Intelligence Annual Report, The Mobile Economy, London, 2019.
[31] N. Sornin, M. Luis, T. Eirich, T. Kramp, O. Hersent, Lorawan technical specification, lora alliance version 1.0, 2015, [Online]. Available:https://lora-alliance.org/resource-hub.
[32] LoRa Alliance Technical Commitee, LoRaWAN 1.1 Specification, LoRaWAN 1.1 Specification, no. 1.1, 2017, p. 101.
[33] Workgroup LoRa Alliance Technical Committee Regional Parameters, LoRaWAN 1.0.3 Regional Parameters, 2018.
[34] J. Petäjäjärvi, K. Mikhaylov, T. Hänninen, On the coverage of LPWANs: Range evaluation and channel attenuation model for lora technology, in: 14th International Conference on ITS Telecommunications (ITST), 2016, pp. 55–59.
[35] A.J. Wixted, P. Kinnaird, H. Larijani, A. Tait, A. Ahmadinia, N. Strachan, Evaluation of LoRa and LoRaWAN for wireless sensor networks, in: 2016 IEEE SENSORS, 2016.
[36] T. Petrić, et al., Measurements, performance and analysis of lora FABIAN, a real-world implementation of LPWAN, in: IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), 2016, pp. 1–7.
[37] J.M. Marais, R. Malekian, Lora and lorawan testbeds: a review, in: IEEE AFRICON, 2017, pp. 1496–1501.
[38] G. Pasolini, L. Feltrin, R. Verdone, O. Andrisano, C. De Castro, Smart city pilot project using lora, Sensors (Basel) (2018) 62–67.
[39] Network Simulator NS-3. [Online]. Available: https://www.nsnam.org/.
[40] T. To, A. Duda, Simulation of lora in NS-3: Improving lora performance with CSMA, in: 2018 IEEE Int. Conf. Commun, 2018, pp. 1–7.
[41] D. Magrin, M. Capuzzo, S. Romagnolo, M. Luvisotto, An ns-3 module for simulation of lorawan networks, 2018, [Online]. Available: https://github.com/signetlabdei/lorawan [Accessed: 28-Dec-2018].