Experimental vs. Simulation Analysis of LoRa for Vehicular Communications

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Abstract

LoRa, a Low Power Wide Area Network (LPWAN) technology, demands reduced network infrastructure to cover a large area, with low power consumption. In the context of vehicular communications, LoRa has the potential to support monitoring and cooperative navigation applications, where small amounts of data can be transmitted asynchronously through the network. Nevertheless, the literature lacks evaluations of LoRa in the context of vehicular communications. Thus, in this paper we analyze the performance of this technology operating in an urban mobility environment, using LoRa terminal devices embarked on vehicles and a LoRa receiver unit, acting as infrastructure. Moreover, we evaluate the equivalence between experimental and simulated results, obtained from the communication link between the LoRa module inside a vehicle and a LoRa receiver comparing to those produced by NS-3 simulations. Three metrics of interest are evaluated: Packet Delivery Ratio (PDR), Packet Inter-Reception (PIR) time, and Received Signal Strength Indicator (RSSI). Field experiments are performed at the campus of the Federal University of Rio de Janeiro (UFRJ), Brazil. Results revealed that all the metrics evaluated in the simulated experiments are consistent with the results of the real experiments, however, we concluded that the model can be improved by looking for a stronger

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correlation with real experiments.

Keywords: Low Power Wide Area Network, Vehicular communications, LoRa, Performance evaluation

1. Introduction

Smart devices have the capacity to connect and integrate multiple "things", allowing to communicate across the Internet. Such devices have become intelligent, capable of capturing, processing and transmitting data. As a result, the growth trend of smart objects transmitting information to the Internet is estimated at 50 billion devices by 2020 [1]. Smart objects are an essential part of smart cities, where geographically-wide scenarios demand higher performance in terms of range and low power consumption. In this context, Low Power Wide Area Networks (LPWAN), such as LoRa (Long Range) technology, play an important role in the communication of sensor networks data in environments with distant sensing points, with low power consumption. LoRa is a wireless communication technology designed to complement legacy mobile networks and short-range wireless technologies. It is especially suitable for Internet of Things (IoT) applications that require coverage of large areas [2, 3, 4].

Also, in the context of smart cities, vehicular networks provide support to mobile and large-area applications. Vehicular networks are a research area with a direct impact on daily life. In particular, areas of interest are safety, driver assistance, *infotainment*, and road traffic monitoring. The latter depends on the sharing of information among all parties involved in vehicular communication, aiming to reduce the impact of traffic conditions and to distribute accurate and updated information as fast as possible. Moreover, information exchange is interactive, and the communication needs to be distributed, meaning that all network participants have the ability to exchange information intuitively and cooperatively. On the other hand, vehicular networks have a constant increase of vehicles on the roads, while the growth of road infrastructure is not proportional to this fact, which is represented by congestion and slow flow on highways.

Therefore, the technological development of wireless communication devices in vehicles has become key to the evolution of intelligent transport systems. Such evolution has been converging on the Cooperative Intelligent Transportation Systems (C-ITS) [5], infrastructure applications that mean close participation between the private (vehicles and personal devices), and standalone systems that can work cooperatively between them. In this way, support monitoring and cooperative navigation applications present a challenge for efficient data dissemination, with wide coverage, among others.

To establish a C-ITS platform with LPWAN technology cooperation, it is necessary to study the behavior of the system in different environments. Given that the literature lacks evaluations of simulated environments of LoRa technology in the context of vehicular communications, we investigate the equivalence between the results of simulations performed in NS-3 (Network Simulator version 3) [6, 7] and experimental tests involving the communication of real devices compatible with LoRa technology in an urban mobility environment. To achieve this goal, we perform field experiments using hardware prototypes based on Arduino micro-controllers and LoRa adapters. We build a link consisting of a transmitter and a receiver unit, to evaluate the communication range, for different spreading factors (SF), a configuration parameter of LoRa modulations. For the simulations, we used a LoRaWAN network library [8], developed for the NS-3 network simulator. Three metrics of interest are evaluated: Packet Delivery Ratio (PDR), Packet Inter-Reception (PIR) time, and Received Signal Strength Indicator (RSSI). Real field experiments are performed at the campus of the Federal University of Rio de Janeiro (UFRJ), Brazil. We investigate the correlation of experimental and simulation results, to identify the spots where simulation models should evolve.

Since current LPWAN technologies (LoRa and SigFox) in the PHY layer are proprietary, few simulation solutions have been developed to model their behavior in different Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) environments. Thus, several authors have developed experimental tests evaluating their various characteristics (especially LoRa) instead of simulation. Despite this growing development of practical solutions implementing LoRa technology, variations in propagation medium conditions, short contact time between nodes, attenuation issues, and multi-path phenomena, make these implementations very specific and need to be evaluated. Different behaviors through simulations can be easily reproduced in predetermined situations. In addition, large experiments are more difficult to perform in the real scenario compared to those designed in a simulated environment. The treatment of the data generated by simulation also allows a better understanding of the performance of a link before it is implemented in practice and the identification of anomalous behavior before it goes into operation.

To the best of our knowledge, this is the first study that compares experimental tests and simulated technique with LoRa technology in a vehicular environment and analyzes the correlation between the experiment results. Through this analysis, we hope to contribute to the integration of the LPWAN technologies inside of a vehicular communication, in addition to evaluating the efficiency of the simulated model. Our results show that real and simulated results are strongly correlated, replying to characteristic behaviors of the LoRa technology in scenarios of urban mobility. Moreover, we observed that PDR and PIR are strongly correlated, in both scenarios, mobility and maximum communication range. For these scenarios, there is a direct relationship between RSSI level and PDR, both for increasing distance and speed. Concerning to PIR time, despite distance and speed variations, time intervals are constant between packet receptions. Moreover, we compare the response time for representative applications of vehicular networks, and present a QoS analysis based on the results of PIR time.

This paper is organized as follows. Section 2 discusses work related to experimental performance evaluations and simulations with LoRa technology. Section 3 briefly reviews LoRa technology with emphasis on the physical layer aspects that are relevant to the analysis. Section 4 presents the experimental methodology used, as well as the hardware and software prototypes. Section 5 presents the experiment results and analysis. Section 6 discusses the results, and finally, Section 7 concludes the work and identifies future challenges.

2. Related Work

The literature is very rich in works involving vehicular networks. Vehicles are mobile nodes, generally equipped with sensors, processing, storage, and communication capacity, which allow them to form Vehicular Ad Hoc Networks (VANETs). Different network technologies may be used, such as IEEE 802.11p, 802.11, or 3G/4G/5G. Moreover, given that the vehicles are potentially spread over a wide area, LPWAN technologies can also be useful in the vehicular environment. In this section, we focus on the papers that investigate LPWAN performance in the vehicular environment.

Centenaro *et al.* [9] make a comparison of different Low Power Wide Area Network (LPWAN) technologies, and give a specific description of LoRa technology. Two experiments are performed: (i) A LoRa private network is implemented to control the temperature and humidity variables of a building (19 floors), and (ii) A coverage analysis is performed in Padova, Italy, allowing to cover approximately 2 km of radius. The authors conclude that radio links based on LoRa can connect devices in order of tens of kilometers. James and Nair [10] propose a public transport tracking system using Wi-Fi and LoRa wireless transmission using a hybrid model, with no dependency on GPS localization. They built a test-bed with two transmitters and one receiver based on LoRa, and a Wi-Fi module to send the data received from the LoRa receiver to upper layers. The authors conclude that the cost can be reduced six times less than the system with GPS, and the power consumption up to four times less with the solution proposed.

Sanchez-Iborra *et al.* [11] propose to integrate LoRa technology in a vehicular communication architecture. They explore two scenarios: (i) A V2I (Vehicle-to-Infrastructure) topology, and (ii) V2V (vehicle-to-Vehicle) topology. In the first scenario, the authors study the RSSI level for SF7 and SF12, concluding that SF12 has a higher RSSI level, obtaining a maximum range of 10 km, larger than

SF7 (6 km). For the second scenario, they evaluate the distance covered by an embarked device inside a vehicle, sending warning notifications. The SF12 has reached a range of 6 km, with more shadow zones compared with SF7, which reached a range of 2.5 km. The authors conclude that the attained performances in terms of distance are superior to any other cellular technology and that V2V results decreased coverage range in comparison with the V2I scenario by the height of the base station antenna.

Patel and Won [12] conduct an experimental study with LPWAN in both indoor and outdoor mobile environments. For the indoor environment, the authors use an end device moving with constant speed inside a hall, varying the distance to the gateway. For the outdoor environment, they use an end device inside a vehicle, varying speed and distance. The author conclude that LPWAN is easily impacted by mobility, increasing the packet loss rate as it moves faster. Chou *et al.* [13] propose a vehicle diagnostic system based in LoRa technology. The system consists in send diagnostic messages obtained from the OBD-II vehicle interface through the LoRa module embarked in the vehicle. The packets are transmitted to the cloud platform through MQTT protocol. Boshita *et al.* [14] introduce a bus location system using LoRaWAN as wireless communication technology, in Nisshin City, Japan. This system implements a compression method for location information, and evaluate the information reception rate for different traveling speeds. The maximum distance for receive packets was established in 2.1 km. At 50 km/h, the system has an information reception rate of 71.4%. Matthews *et al.* [15] develop a park management system for scalable traffic control using RFID. The system employs LoRa technology to transmit vehicle data information in a wireless communication network.

Petäjäjärvi *et al.* [16] provide an analysis performance of LoRa technology, and investigate its robustness against the Doppler effect. This effect arises in environments involving non-uniformly moving boundaries [17], when a source of a wave is moving relative to an observer, receiving a frequency that differs from the one radiated. Petäjäjärvi *et al.* evaluate the impact of the Doppler effect in two scenarios: (i) applying different angular velocities, and (ii) with an end device embarked inside a vehicle, driven on a road passing the gateway. For the first scenario, the authors conclude that applying higher angular velocity, the packet success ratio decreases. Additionally, the results have large variations in the Packet Delivery Ratio (PDR) between repetitions, due to the low number of packets transmitted. For the second scenario, the authors introduce mobility with an end device mounted inside a vehicle, studied in [18], characterizing the communication range and introducing mobility varying the speed. To this end, the authors conduct real experiments to evaluate coverage in different environments: (i) an aquatic environment, with an end device transmitting from a boat at the sea; and (ii) with an end device transmitting from a car in a city environment. The authors evaluate the packet loss rate, packet success ratio, and the received signal strength. In the experiments was observed that in different areas the RSSI level was stronger, but all distance ranges presented packet loss, especially in larger distances.

The previous works are based on experimental setups, where energy consumption, cost, signal power, mobility effect and delay with variations in speed, distance, and compression frame are analyzed and discussed. Nevertheless, it is important to note that implementations and initiatives can vary greatly from one scenario to another (environments with vegetation, buildings, etc.). Moreover, there is a scalability challenge: the number of devices used in field experiments is often low. Therefore, it is inevitable to also analyze the behavior of LoRa technology using simulation. It allows estimating the performance of the link and predicting anomalies that interfere in the communication.

Bor *et al.* [19] develop a discrete event simulation tool called *LoRaSim* using the *SimPy* framework. This tool allows to allocate N nodes and M gateways in a two-dimensional space. Each node is defined by transmission parameters specific to LoRa technology to evaluate the maximum number of end devices in a LoRa link. To establish the parameters of range and packet delivery ratio, the authors develop an experimental model in [20]. The communication range is determined as a function of the Spreading Factor (SF) and the Bandwidth (BW), and packet delivery ratio as a function of transmission time and signal strength. The authors conclude that the scalability in the network depends on multiple sinks, as well as the dynamic device configuration.

Magrin *et al.* [8] evaluate the performance of LoRa networks in a smart city scenario. The authors propose a LoRaWAN library on NS-3 to evaluate the performance of a link in a simulated environment. The authors show that LoRaWAN provides higher throughput than the basic ALOHA scheme and that LoRaWAN networks can scale as the number of gateways increases. At the same time, this work studies the impact of downlink traffic. The authors conclude that the network capacity results are due to the orthogonality between SFs. Moreover, the architecture is easily scalable, especially as the number of gateways increases, improving uplink coverage and reliability. Abeele *et al.* [21] implement a LoRaWAN library on NS-3 that includes an error model used to determine range, as well as interference between multiple simultaneous transmissions. In addition, the module also supports bidirectional communication. The authors conclude that the dynamic parameter setting on end devices is critical to network performance. They also conclude that the limited flow of the downlink degrades considerably the packet delivery ratio; increasing the number of gateways the challenge can be mitigated. The LoRa PHY layer implemented in [8] and [21] support all SFs and all code rates defined in the specification.

In a preliminary work [22], we analyze the performance of LoRa on a static urban scenario, under LoS conditions. We analyze the radio range, loss rate, throughput and RSSI metrics. In the present paper we go further by including mobile scenarios and analyzing a vehicular-specific performance metric, PIR time. Table 1 summarizes the main characteristics of the present and most similar related work, according to the following items: Type of Analysis, Mobility, Scenario, and Performance Metrics evaluated. Fields with a "-" mean that the criterion was not identified in the approach.

Different from the related work, we evaluate the packet inter-reception (PIR) time, a metric important for the analysis of situational awareness in vehicular networks, and we improve the coverage, the RSSI level, and the packet delivery ratio (PDR) with the SF12 operating in an urban environment, based on

Table 1: Comparison with related work.

Ref.	Type of Analysis *Exp.*	*Sim.*	Mobility	Scenario	Performance Metrics
[9]	✓	–	–	Wide Area	Coverage
[11]	✓	–	✓	Vehicular	RSSI level Coverage
[12]	✓	–	✓	Indoor walking Vehicular	End to End delay Packet loss rate
[16]	✓	–	✓	Analytical Rotation analysis Vehicular Boat	Packet success ratio Coverage RSSI level Doppler effect
[19]	✓	✓	–	Wide area	Packet reception rate Data extraction rate
[8]	–	✓	–	Urban	Packet delivery ratio Duty cycle limitation Packet success probability Coverage
[21]	–	✓	–	Fixed position	Scalability analysis Packet delivery ratio
[22]	✓	✓	–	Urban	Propagation loss model Coverage RSSI level Packet Loss Rate Throughput
Present work	✓	✓	✓	Vehicular	Propagation loss model Coverage RSSI level Packet delivery ratio Packet inter-reception time

the performance analysis of [22]. We add mobility for both real and simulated scenarios (varying speed, distance, and spreading factors), to analyze the data transfer between a vehicle in movement and fixed infrastructure (V2I communication) using LoRa technology. Our goal is to investigate the performance of LoRa in the vehicular environment, where LPWAN technologies can serve as sensing and control networks and complement VANET operation. To achieve that objective, we investigate performance metrics relevant to VANETs. We evaluate the use of the simulated environment to analyze the contact capacity between vehicles and infrastructure in a scenario with mobility, to get results closer to reality. Moreover, we analyze the propagation model for the simulated scenario, and identify a gap in the simulator implementation, the absence of randomness. To fix that we add a normal variable to get stochastical variations and produce more realistic simulation results.

3. LoRa Technology

LoRa is a Semtech proprietary physical layer (PHY) specification [23], designed for long range and low power networks. The technology allows the connectivity of intelligent objects at distances of the order of kilometers, with low energy consumption, essential for IoT networks. To do this, LoRa implements a proprietary spectral spreading modulation technique, which is a variant of Chirp Spread Spectrum (CSS) [24], which modulates frequency chirp pulses without changing the phase between adjacent symbols [25], encoding the data [20, 23]. Thereby, LoRa modulation makes the resulting signal resistant to noise interference or signals with close frequencies. LoRa is also characterized by a reduction in hardware complexity, a reduction in header size and network complexity in terms of hops and addressing, enabling simple two-way communication using minimal infrastructure with low energy consumption.

LoRa PHY modulates signals in sub-gigahertz radio frequency bands of the unlicensed frequency band Industrial, Scientific, and Medical (ISM). For Brazil, according to the National Telecommunications Agency (ANATEL), the regulated frequency band for ISM is between 915 and 928 MHz (AU915-928MHz) [26]. In the same way, the 433 MHz frequency can be implemented for networks with few devices [27].

Some parameters for setup the LoRa PHY are as follows: Carrier frequency, Bandwidth (BW), Code Rate (CR), and Spreading Factor (SF). The carrier frequency defines the center frequency for the transmission band. It is defined according to the region of operation of the equipment. Therefore, this parameter is generally not adjustable according to the application. Bandwidth defines the size of the frequency range used, with three programmable values: 125 kHz, 250 kHz, and 500 kHz. SF determines how many chirps are used to represent a symbol. [28, 20]. Thus, it establishes the ratio between the bit rate and the chirp rate. The LoRa specification defines six different values for the SF parameter: SF7, SF8, SF9, SF10, SF11, and SF12 [24], which allows orthogonal channels to be formed, making links with different SFs have no collisions with each other. Higher SF enhances the level of the reception threshold in terms of signal strength, but increases the propagation Time on Air (ToA) and decreases the transmission rate of the link [3].

3.1. Time On Air

Due to vehicular communications have specific time requirements to reduce the response time depending on the application type [29, 30], it is necessary to evaluate the behavior of LoRa technology in mobility environments. Based on the configuration parameters related in Section 4.3, we calculate the Time on Air (ToA). The ToA parameter changes according to the variation of the SF. With a higher SF, the LoRa module needs more time to send the information. Therefore, ToA is the time it takes from the beginning of the transmission to the end of reception of the packet at the receiver. It is calculated through of the variables present in a given configuration. Calculation of ToA requires to define the symbol duration, which describes the time taken to send 2^{SF} chips at the chip rate [24]. It is defined by:

$$T_{sym} = \frac{2^{SF}}{BW}, \quad \text{with } SF \in \{7 - 12\}. \tag{1}$$

The preamble duration is given by:

$$T_{preamble} = (n_{preamble} + 4.25) \times T_{sym}. \tag{2}$$

The number of symbols that compose the payload and header is given by:

$$payloadSymbNb = 8 + \max\left(\left\lceil \frac{8PL - 4SF + 28 + 16 - 20H}{4(SF - 2DE)} \right\rceil (CR + 4), 0\right). \tag{3}$$

The payload duration is equal to the number of payload symbols multiplied by the symbol period. It is defined by:

$$T_{payload} = payloadSymbNb \times T_{sym}. \tag{4}$$

Therefore, the packet duration is given by:

$$T_{packet} = T_{preamble} + T_{payload}. \tag{5}$$

Table 2 shows the theoretical ToA values for different SFs, for a CR = 4/5 and BW = 500 kHz. These theoretical values are used as a reference to analyze the reception time interval between subsequent packets, allowing to assess the level of situational awareness of the vehicle and its surroundings. We compare these values with experimentally obtained values in order to lay the groundwork for applications that use LoRa and LoRaWAN as communication technology.

Table 2: Theoretical values of the Time on Air as function of the SF.

Spreading Factor	**ToA (ms)**
SF7	23.104
SF8	41.088
SF9	77.056
SF10	133.632
SF11	267.264
SF12	493.568

4. LoRa Experimentation Setup

The experiments to test LoRa technology in a vehicular environment are performed in real and simulated scenarios, varying SF, speed, and distance.

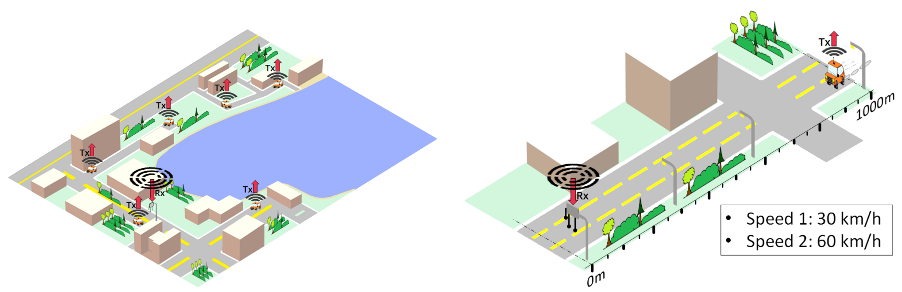
The metrics analyzed are RSSI, PDR, and PIR time. Realistic measurements are carried out through a hardware prototype; simulations are executed using the LoRaWAN library implemented in [8] for the NS-3 simulation tool. Two scenarios were defined for the experiments with real devices::

1st Scenario - Maximum communication range: The goal of this scenario is to verify the maximum coverage range of the prototype in hardware with LoS. For this, a transmitter unit sends messages to the receiver unit placed on top of a building. The scenario is depicted in Figure 1(a). The transmitter unit sends data tuples stationary every 1000 m distance, up to 5000 m. For each value of SF (7-12), we carry out a comparative study of the behavior of the communication link in the LoRa PHY, as a function of the distance. We use the results of this scenario as a starting point for the calibration of the simulated environment.

2nd Scenario - Mobility communication range: The goal of this scenario is to verify the impact of mobility on the communication link with LoRa. For this, a transmitter unit is embarked inside a vehicle and sends messages to the receiver unit located at the end of the route, while traveling at 30 km/h and 60 km/h. The vehicle starts at a distance of 1000 m from the receiver unit, with constant speed and transmitting packets continuously. The scenario is depicted in Figure 1(b). The transmitter unit sends data tuples while it is in motion. For each SF (7, 9, 12), we carry out a comparative study of the behavior of the communication link in the LoRa PHY, as a function of distance and speed.

4.1. Real Experiments Setup

To carry out the experiments on the real scenario, we develop a hardware prototype based on the Arduino development kit. For both transmitter and receiver units, we use Arduino UNO controllers each one connected to a Dragino LoRa module respectively, with 6 dBi antennas. The transmitter unit also adds a GPS shield and a temperature and humidity sensor. The LoRa modules are based on the RF96 controller and operate at a frequency of 915 MHz. Table 3 shows the description of the components for the transmitter and receiver units.



(a) (b)

Figure 1: Experiment scenarios: (a) Maximum communication range scenario; (b) Mobility scenario.

Table 3: Components used in the transmitter and receiver unit.

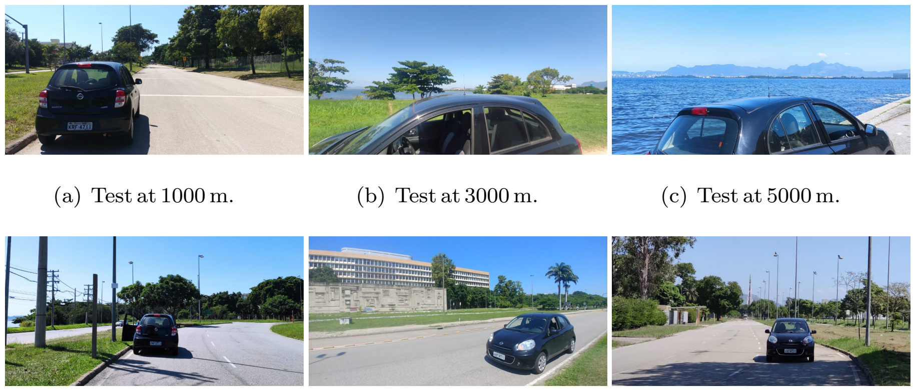
Module	**Equipment**	**Tx**	**Rx**
Controller	Arduino Uno R3	✓	✓
Wireless Interface	Dragino LoRa *Shield* RF96	✓	✓
Antenna	6dBi of gain	✓	✓
GNSS	U-blox NEO-6M	✓	
Sensor	Temperature and Humidity DHT22	✓	

The experiments include points placed around the campus of the Federal University of Rio de Janeiro (UFRJ), as seen in Figure 2. Figures 2(a), 2(b) and 2(c) show stationary points of the maximum communication range scenario; Figures 2(d), 2(e) and 2(f) show the experiment in progress in the mobility scenario.

4.2. NS-3 Simulation Setup

The simulations are executed in the NS-3 simulation tool version 3.28. We implement the LoRaWAN public library available in[1] [8], which simulates the LoRaWAN network and PHY layers. This library is adjusted to the requirements of the experimental scenarios proposed for this work. For this, we recre-

[1]https://github.com/signetlabdei/lorawan



(a) Test at 1000 m. (b) Test at 3000 m. (c) Test at 5000 m.

(d) Receiver Unit. (e) 100 m road segments test. (f) Vehicle in motion.

Figure 2: Measurement locations, equipment used, and surroundings (vegetation, sea waves, and buildings) of the experimental scenarios.

ate a simulation environment in which the nodes communicate at distances and speeds established in real experiments.

To characterize the behavior of the vehicular communication link in a simulated environment, it is necessary to determine the propagation model that fits the real scenario. It describes the behavior of electromagnetic waves, and how they are radiated from the transmitter to the receiver. The propagation model that best describes the scenario chosen for real experiments is *LogDistance*. This model is widely used in sub-GHz radio frequency bands links and large-scale scenarios. Furthermore, predicts signal attenuation, close to the values that were measured in real experiments, using as parameters the signal strength and distance in the Equation 6:

$$PL(d) = PL(d_o) + 10nLog(\frac{d}{d_o}). \tag{6}$$

Due to *LogDistance* be a deterministic model, we implemented a random normal distribution variable that describes the losses caused by the fading phenomenon [31]. Thus, the propagation model used for the comparison between real and simulated experiments uses the following Equation 7:

$$PL(d) = PL(d_o) + 10nLog(\frac{d}{d_o}) + X_\sigma, \tag{7}$$

where n describes the empirical propagation coefficient and X_σ describes the fading power variation (dB). The range of values for X_σ was obtained from the RSSI level data in the real experiments; the values calculated was $\mu = 0$ and $\sigma^2 = 1{,}47$.

4.3. LoRa Configuration Parameters

LoRa configuration parameters are described in Table 4. These parameters are necessary for the configuration of the LoRa PHY, they are used in real and simulated experiments.

Table 4: Setup parameters for real and simulated experiments.

Parameter	**Setup**	**Experimental**	**Simulated**
Frequency	915 MHz	✓	✓
Tx power	14 dBm	✓	✓
Spreading Factor (SF)	(7-12)	✓	✓
Bandwidth	500 kHz	✓	✓
Code Rate	4/5	✓	✓

5. Results

In our experiments, we collect data in the receiver unit every time the vehicle transmits data from the road segments chosen for each scenario and experiments proposed in this work. For each transmission, we execute 10 rounds for the 1^{st} scenario, and execute 5 rounds for the 2^{nd} scenario. Each round transmits 50 packets, which includes a sequence number (from 1 to 50), geographical coordinates, and speed (obtained from the GPS every 250 ms), temperature and humidity (both obtained from the sensor), with 64 preamble bits; the total size of each packet sent is 47 bytes. To determine the correlation of real and simulated experiments, we use Pearson's correlation analysis.

5.1. *Maximum Communication Range Analysis*

To assess the maximum communication range, we set up an experimental scenario to perform LoRa technology. Our scenario includes points placed around the campus of the Federal University of Rio de Janeiro (UFRJ), as seen in Figure 3. From these points, we establish links with LoS and variable distances. We use two reference points for the receiver unit: the top of the Technology Center building, and the Mineral Technology Center.

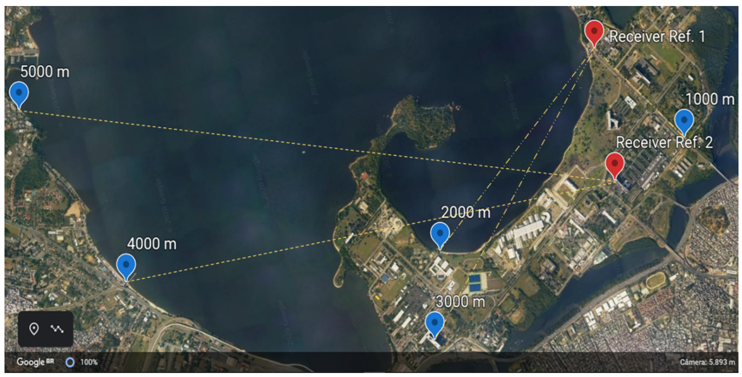


Figure 3: Aerial view of the maximum communication range scenario.

5.1.1. *RSSI level*

RSSI measurements are obtained by the libraries implemented in the LoRa RF96 driver, without using any external measurement instrument. Despite communication being with LoS, it varies about the RSSI level. Figure 4 shows the RSSI level obtained in the receiver unit. It is possible to appreciate that, although the links are with LoS, some links more distant can have a better performance in the RSSI level. For example, the data transmission at 3000 m is higher than at 2000 m for the real experiments. This is explainable considering the environmental conditions of the scenario, where different natural segments (vegetation, sea waves, among others) impact the communication performance, which explains these variations in the RSSI level.

As can be seen in Figure 4, the behavior of the RSSI level is similar for both real and simulated experiments. This maintains a decreasing exponential

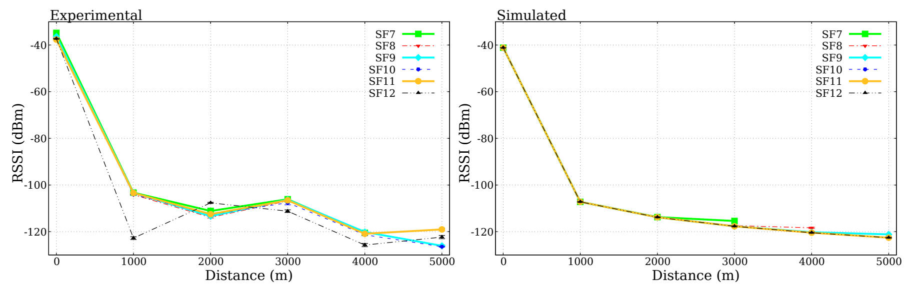


Figure 4: Level of RSSI obtained in the receiver unit for the maximum communication range scenario by using different SFs (experimental and simulated).

behavior as the distance increases. At 0 m there is a difference of ±7 dBm between both environments. Furthermore, in the real experiment at 1000 m, SF12 reflects variations in the RSSI level that shows a representative statistical difference when compared to the simulated experiment; this is attributed to link attenuation and wave propagation itself, as previously described. In contrast, at 2000 m and 3000 m there is a statistical difference, even so not representative. Meanwhile, comparing the measurements at 1000 m, 4000 m and 5000 m, the RSSI level decreases below –120 dBm, as described in the literature. As a result of the comparison between the real and simulated experiments, these are strongly correlated ($r \approx 1$). This means that both environments increase and decrease together.

5.1.2. Packet Delivery Ratio (PDR)

Figure 5 shows the calculated PDR for each interval of distances. In the simulated experiment, SF7 has a null PDR at 4000 m, while in the real experiment it achieves a PDR of ± 75%. Comparing the results, the PDR in both real and simulated environments shows a similar behavior, with the PDR decreasing with the gradual attenuation of the RSSI level related in Section 5.1.1. In this way, the PDR tends to decrease in all SFs as the distance increases. In contrast, in the real scenario we observe that at 5000 m the PDR is higher than 80% with SF9, SF10 and SF11, whereas SF12 has 100%. Meanwhile, in the simulated scenario at 5000 m, the PDR is higher than 90% with SF10 and SF11, whereas SF12 has

100%. This shows that it is possible to reach an effective communication range over 5000 m. This is consistent with the literature, which indicates that LoRa technology can achieve distances close to 10 km [2, 3, 4]. Therefore, this information confirms that larger SFs are suitable for applications that require higher coverage. As a consequence, lower SFs result high bit rates and low packet reception rate in larger distances. Otherwise, the modified *LogDistance* (Section 4.2) implemented in the NS-3 simulator achieves a behavior very close to the experimented in the real scenario, showing results consistent in both distance and PDR variations, with a moderate positive correlation ($0.60 \leq r \leq 0.99$).

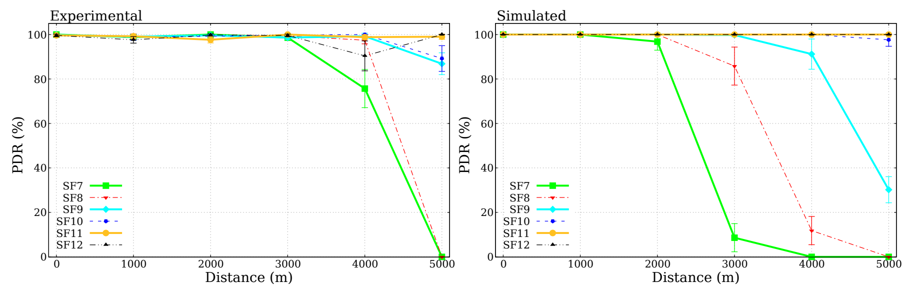


Figure 5: PDR obtained in the receiver unit for the maximum communication range scenario by using different SFs (experimental and simulated).

5.1.3. Packet Inter-Reception (PIR) Time

Vehicular networks are characterized by high mobility, being prone to frequent topology changes and rapid interactions between nodes. Since many of the applications of vehicular networks are typically aimed to addressing safety issues, these applications have critical latency requirements (≤ 100 ms). Therefore, the response time should be immediate. Additionally, vehicle networks provide services with flexible time requirements (from 100 ms to 1000 ms), based on event-driven activities [29, 30]. One way to analyze latency in vehicular communications is the packet inter-reception (PIR) time. It describes time patterns in link communication failures through the reception time between pairs of messages from the same source [32]. PIR times higher than 1 s represent “blackouts” during which no beacon is received in a specific vehicle [33]. In LoRa technology, time assumptions are associated with the time on air described in Section 3.1. So, it is important to analyze the behavior of PIR time on a communication link with LoRa.

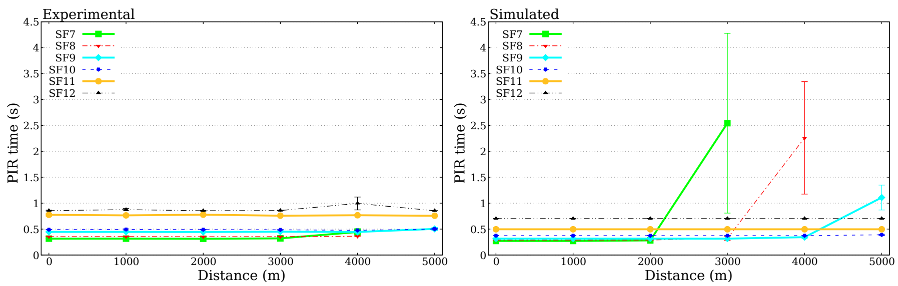


Figure 6: PIR time obtained in the receiver unit for the maximum communication range scenario by using different SFs (experimental and simulated).

Figure 6 shows the behavior of the PIR time for the maximum communication range scenario. In the real experiment, the PIR time is constant up to 4000 m; it occurs because the PDR at this point is higher than 70%, causing a minimal variation in the PIR time. In contrast, at 5000 m PIR time for SF7 and SF8 is not possible to calculate, since there is no successful transmissions. Furthermore, SF12 at 4000 m reaches the threshold of 1 s, with error bars above 125 ms; it implies the absence of reception as the distance increases. In the simulated environment more significant variability in the PIR time is observed, because the PDR does not decrease instantaneously as in the real experiment. These results allow us to observe that, in both real and simulated environments, blackouts occur exclusively within the limits of the RSSI level attenuation; in the simulated scenario, at 3000 m and 4000 m, the PIR time is higher than 2000 ms for the SF7 and SF8 respectively. These blackouts are not evident in the real scenario, where the variation is not statistically representative. For both real and simulated experiments are moderate to strong correlated ($0.52 \leq r \leq 0.99$).

5.2. Mobility Communication Range Analysis

The scenario chosen to carry out mobility experiments using LoRa technology comprises points located in the campus of the Federal University of Rio de

Janeiro (UFRJ). An end device is embarked inside a vehicle, and an antenna was placed on the roof of the vehicle, next to the GPS antenna. Two reference points was used for the experiment: The Mineral Technology Center, where the receiver unit was placed, and the Institute of Nuclear Engineering, the starting point of the vehicle at 1000 m. For this experiment, the SFs with higher impact in the data rate communication are programmed (SF7 and SF12), and was used an intermediate (SF9), in order to analyze the behavior of the link with respect to the speed.

5.2.1. Static analysis per segment

To study the impact of mobility on communication with LoRa devices, we analyzed the variations in the RSSI level in 100 m road segments, as seen in Figure 7, to observe how the conditions of an urban environment with concentrations of vegetation and physical structures can affect the link quality.

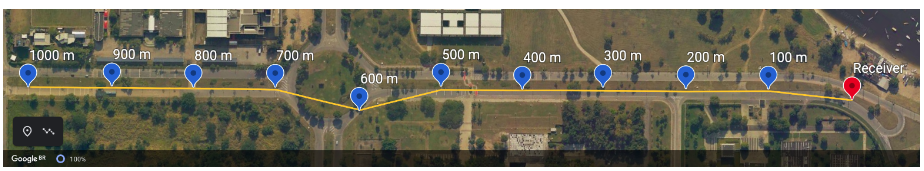


Figure 7: Aerial view of the mobility scenario.

Figure 8 shows the behavior of the RSSI and PDR level for the mobility scenario. The presence of vegetation and infrastructure changes the characteristics of the link described in Section 5.1. This occurs because this scenario includes NLoS components that interfere with communication, as shown in Figure 2. Thus, with SF7 the maximum range was 900 m, and SF9 achieved a PDR of ± 20% at 1000 m. In contrast, SF12 achieved a PDR of ± 90%, being the only SF to maintain similar conditions to those presented in the results of Section 5.1.2. Next, we will present the result of the mobility experiments.

To examine the scenario with mobility, the data is analyzed in 100 m road segments for each speed used. Next, we describe the results of measurements with the vehicle in motion.

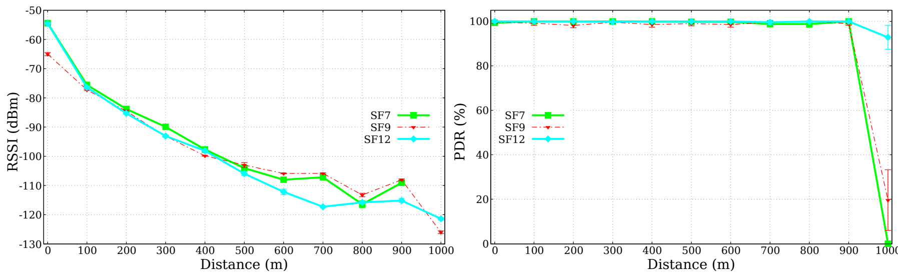


Figure 8: Analysis of the RSSI level and the PDR for the mobility scenario.

5.2.2. *RSSI level*

Figure 9 shows the RSSI level with the vehicle in motion. For all SF parameters, the signal strength exhibits similar behavior, with an RSSI level varying between ± -120 dBm for the real experiment, and ± -110 dBm for the simulated experiment at 1000 m. For both experiments, the RSSI level variation is exponential, reaching the highest RSSI level at 0 m, being ± -40 dBm for the real experiment, and ± -50 dBm for the simulated experiment. Between 600 m and 800 m the real experiment presents an abnormal behavior product of a layout in the mobility scenario chosen for the experiments; it presents a light traffic roundabout, and therefore, altered the RSSI level in the receiver unit. Despite it, RSSI measurements in mobility scenario are similar for all configurations, due to distance be equal for all SFs. Moreover, these continue inside the communication range before established in Section 5.1; for both real and simulated experiments are strong positive correlated ($0.88 \leq r \leq 0.99$).

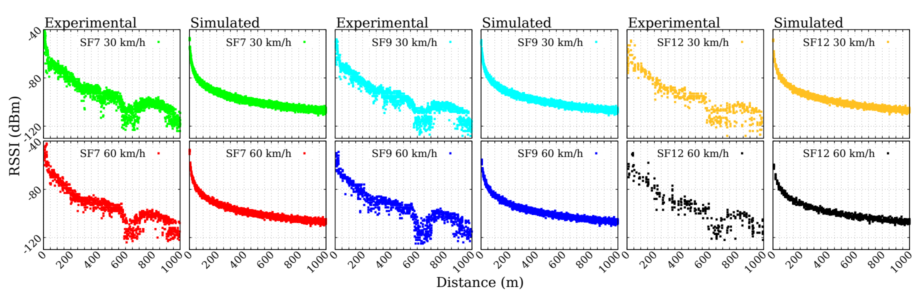


Figure 9: Level of RSSI obtained in the receiver unit for the mobility communication range scenario by using different SFs (experimental and simulated).

A heat map of the RSSI level while the vehicle travels along the road is shown in Figure 10. Comparing the impact of SF and speed variables, we detect blackout areas with SFs higher, which added to speeds variations, highlighting the absence of transmissions in the layout. It is relevant to the type of service where LoRa technology can be implemented. Services that require immediate response times, such as safety applications, will present constraints in such areas without transmission. The performance of the RSSI level is consistent with related in Section 5.1, showing a behavior expected as the transmitter approaches to the receiver unit. Moreover, the behavior of the RSSI level is homogeneous for all SFs in presence of speed.

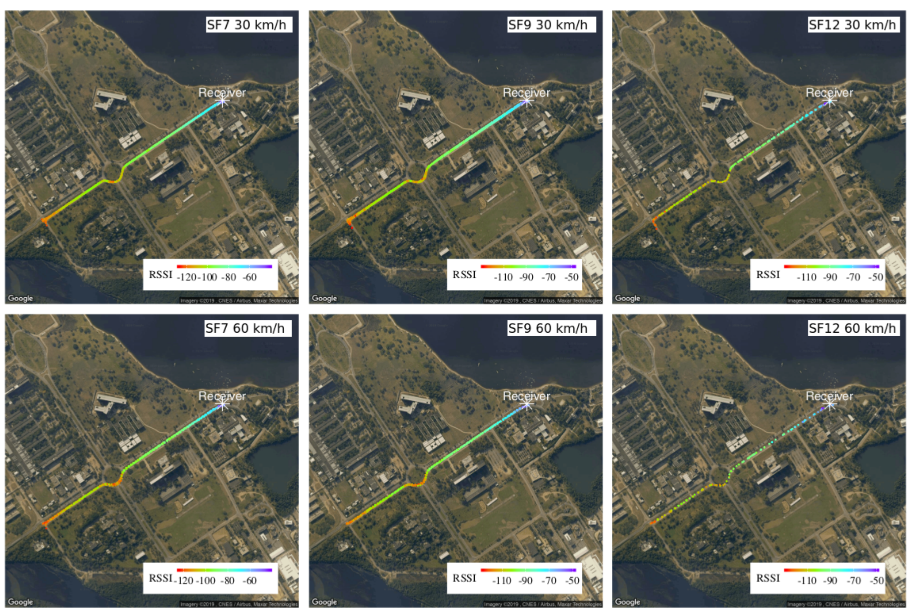


Figure 10: Heat map of the RSSI level in the receiver unit in the mobility communication range experiment.

5.2.3. Packet Delivery Ratio (PDR)

Figure 11 shows the PDR calculated for each point registered by the GPS in the receiver unit. It is possible to observe that SF7 and SF12 maintain a similar behavior, with a PDR higher than 90% after the layout for both the speeds. SF9 maintains a PDR lower than 90% compared with SF7 and SF12. Specifically, we observed that all SFs suffer variations between 600 m and 800 m, a product of the layout aforementioned and all reflected in the RSSI level behavior. For both SF7 and SF9 at 30 km/h and 60 km/h, between 600 m and 800 m shows a drop to 70%; from 800 m resumes the previous behavior up to 900 m; at 1000 m the PDR drops to 90% and 75% respectively. In contrast, SF12 between 600 m and 800 m drops to 90% just at 60 km/h. At 800 m resumes the previous behavior to 100%. SF12 at 30 km/h does not suffer drops. Differently of minor SFs, SF12 at 60 km/h presents variations with speed increase: e.g., at 30 km/h, PDR maintains in 100%, but at 60 km/h, variations occur at the end, decreasing progressively from 200 m below 70%. This behavior occurs because the vehicle travels the last 100 m faster before the number of packets sent are received.

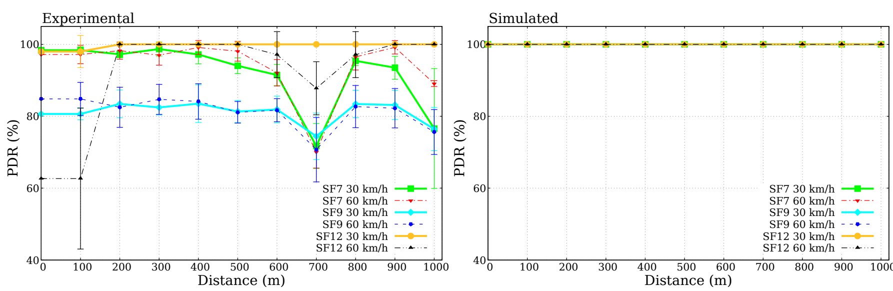


Figure 11: PDR obtained in the receiver unit for the mobility communication range scenario by using different SFs (experimental and simulated).

In another way, the simulated experiments maintain the PDR in 100% for all SFs evaluated in the mobility scenario. This is a result of the link behavior in terms of RSSI level related in Figure 9, where the level detected in the receiver unit was $\pm{-110}$ dBm, a value higher than the sensibility threshold defined by the manufacturer chip in LoRa technology. Indeed, this behavior is more visible in the correlation analysis, varying from $-0.19 \leq r \leq 0.56$, which allows deducing the variability of the PDR in this scenario for all SFs.

5.2.4. Packet Inter-Reception (PIR) Time

PIR time in the scenario with mobility shows behavior consistent with that presented in Section 5.1.3, where despite the speed variations, the reception time between pairs of received packets is constant. However, in the segment between 600 m and 800 m all SFs show an increase in PIR time resulting from the design (light traffic roundabout); this trend is repeated in the segment between 900 m and 1000 m, which corresponds to the most distant point between the transmitter and receiver units. These behaviors have also been reproduced in the PDR and RSSI level analysis, so the result is consistent, and the consequence of this is the time fluctuation. In the same way of Section 5.1.3, the results are similar between real and simulated environments, therefore, correlation coefficient is moderate ($-0.35 \leq r \leq -0.60$), showing some variations between real and simulated experiments. Figure 12 shows the behavior of the PIR time in the mobility scenario. We detailed some minimal time variations no significant between speeds, but this time response can be relevant to define blackouts in the communication link. Thus, PIR time higher than 1000 ms represents blackout areas, as observed in Figure 10, where we can check zones with packet transmission absences in the SF12 for the two speeds, different of the SF7 and SF9, whose PIR time is shorter. Compared to the theoretical ToA described in Table 2, the PIR times in both real and simulated experiments are higher. This is explained by the 250 ms delay used to get updated GPS coordinates and the time difference between non-consecutive packets in the communication.

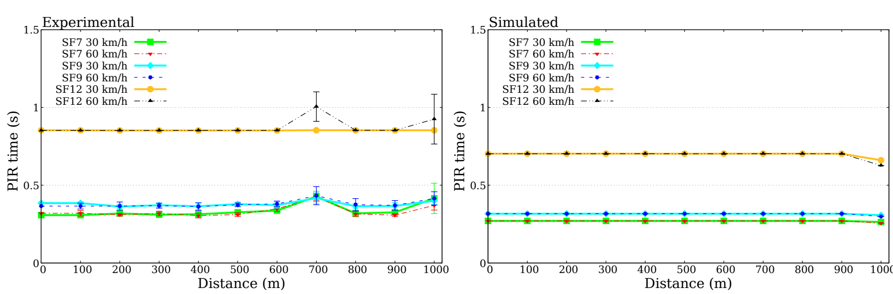


Figure 12: PIR time obtained in the receiver unit for the mobility communication range scenario by using different SFs (experimental and simulated).

6. Discussion

We use a LoRa PHY layer model in the NS-3 simulation tool, with a propagation model for large areas, to reproduce a vehicular environment. To add a stochastic analysis, we calculate a normal distribution variable to analyze fading signal loss, an attenuation characteristic of an urban environment. For the maximum communication range, all the performance measurements are consistent between simulated and real experiments. About the mobility scenario, the RSSI level shows a moderate to a strong correlation between simulated and real experiments, as expected by the coverage results reported in Section 5.1. We define two scenarios to analyze the RSSI level, PDR, and PIR time metrics. In the 1st scenario, the experiments confirm that the range of LoRa can pass 5000 m with the most robust spreading factors (SF9-SF12), with a PDR above 80%, under LoS conditions. Nevertheless, in the mobility scenario, performance decreases in terms of range, PDR and PIR; this is also because in the second scenario the condition is of partial LoS. That characteristic is inherent to the vehicular networking environment, which include obstacles such as vegetation, buildings, and other vehicles. Moreover, the vehicle speed impacts the link performance. This is demonstrated by the RSSI level perceived at the receiver unit in road segments, and the PDR; in contrast, despite the speed change, no statistical difference was observed in the PDR with the exception of the 700 m road segment, as shown in Sections 5.2.2, 5.2.3. Compared to real experiments, the simulated environment was consistent in the maximum range scenario; in the mobility scenario, the simulated experiment shows a RSSI level consistent with the real experiment, but it does not reproduce failures caused by the interference. On the other hand, the behavior of the PDR remained at 100% throughout the journey. This is shown in the weak to moderate correlation observed in Section 5.2.3.

We also analyze the PIR time, a metric that is directly related to the information lifetime for safety applications in the vehicular environment. In both scenarios, maximum communication range and mobility, the PIR time is similar between real and simulated experiments, with a moderate to strong correlation, as described in Sections 5.1.3 , 5.2.4 respectively. Furthermore, the results show that PIR variations due to mobility are minimal. In the mobility scenario, the PIR time variations are inherent to the scenario with partial LoS, e.g., road segments with PIR time higher than 1000 ms. From this fact, it is possible to define a QoS analysis associated with the PIR time, based on broadcasting applications for vehicular communications [34, 35]. Ultra-low latency applications have response time defined from 50 ms to 100 ms, since these serve safety and emergency applications. On the other hand, low latency applications are associated with warning and event-driven applications, with response times defined from 100 ms to 1000 ms. From these latency requirements, we provide a QoS analysis based on PIR time results from the mobility scenario. Figure 13 shows that LoRa can be used for applications that require low latency. Our results show that LoRa technology is limited for safety applications, where broadcasting and transmit mode requires a periodic communication between vehicles and infrastructure, with latency shorter than 100 ms. Given that our set of experiments requires GPS data updated (250 ms added in the end device), latency aggregated prevents to reach response times required for safety applications in vehicular communication. Thus, applications with updated localization requirements and fast response time (100 ms) are not appropriated to use with LoRa.

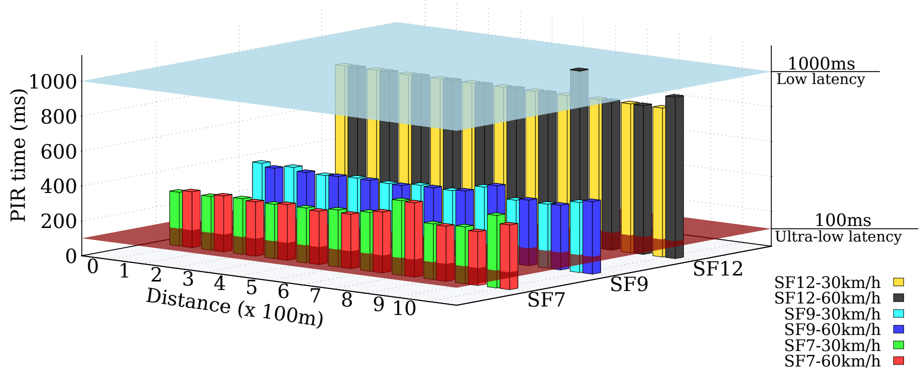


Figure 13: QoS for vehicular applications and PIR time.

We observe that for all SFs the PIR time is constant as the distance increases. Since that PDR cannot be used to estimate PIR, i. e., PDR does not depend of the PIR and vice versa [36, 32], the impact of consecutive packet losses is minimal with respect to the response time of the LoRa technology, strongly associated with the ToA. It was observed that PDR and PIR for both maximum communication range and mobility scenarios was strongly negative correlated ($-0.88 \le r \le -0.99$), while in the simulated experiments there was a strong positive correlation ($r \approx 1$). On the other hand, from the LoRaWAN public library [8], it was not possible to identify any parameter to simulate the antenna gain for both transmitter and receiver. Therefore, a proposal to extend the library can be focused on this requirement, allowing the simulation model to real world scenarios with accuracy. This reinforces the need to calibrate the simulation from real experiments. Thus, these differences found in the results of real and simulated experiments suggest the necessity of an improvement in the LoRa PHY model used for simulation and consider other factors that can affect the communication. Thereby, we concluded that the model can be improved by looking for a stronger correlation with real experiments.

LoRa technology in vehicular networks can reduce the complexity of network management tasks, both in coverage and in infrastructure reduction. LoRa increases the network coverage, different from short-range technologies, and can be integrated in a hybrid way to develop communication strategies based on the development of distributed networks with other wireless networks cooperatively [37, 38]. On the other hand, LoRa technology can co-exist with other technologies to reduce the network traffic, managing control messages, while short-range networks transfer raw data sensor. Moreover, due to long range capabilities, LoRa technology can contribute to location management for communication V2V. In this case, LoRa can be used as a DGPS (Differential Global Positioning System), a network reference station to broadcast the difference between GPS coordinates from the vehicles and known fixed positions. From the results obtained in this work, we conclude that LoRa is suitable for event-driven activities, i. e., messages delivered occasionally within a management application, like public safety, information from other vehicles, among others, with latency higher than 100 ms. Related to the infrastructure, the height of the receivers can influence the coverage of the communication, since the height of the vehicles is standardized.

To improve the performance of LoRa technology in the vehicular environment, there are issues to be addressed in terms of implementation and adapting existent infrastructure. One of the most critical challenges is scalability. Although some studies [19, 39] estimate that the number of nodes supported in a LoRaWAN network may be between hundreds and thousands, the coverage is also expected to decrease due to the number of connected devices in a given area. One reason for coverage decrease is both cross-interference (it happens when two devices are using different channels, but there is overlap between them), and self-interference (transmissions and receptions in the same channel or frequency band). Although LoRa technology implements different strategies to mitigate interference based on its type of modulation, channel diversity, adaptive data rate, and opportunistic access, these behaviors can be studied in a simulated way, together with different mobility models for vehicular networks. In this sense, simulation experiments are crucial to predict the communication performance. In the case of LoRa, a long-range technology, multiple changes in the environment that can affect its performance. In the case of vehicular communication with LoRa, simulated analysis can evaluate the scalability of the network in presence of multiple vehicles, high-speed variations, different mobility models, among others, to determine the most appropriate application in vehicular networks.

7. Conclusions

In this paper, we conducted a performance evaluation study using LoRa technology in a vehicular communication, through real and simulated experiments. The purpose is to analyze the performance of a simulated environment using LoRa and its capability to emulate a real vehicular communication. A

LoRa PHY model implemented in the NS-3 simulator was used for the simulation. Within this model, it was used a propagation model suitable for large areas, and a normal random variable was calculated for the analysis of signal fading losses, characteristic of LPWAN networks. We analyze two scenarios to study the impact of distance, speed levels and spreading factors (SFs) in the communication, collecting data for both real and simulated experiments for analyze and compare the RSSI level, PDR and PIR time variables. The results revealed that all the metrics evaluated in the simulated experiments were consistent with the results of the real experiments. As future work, we intend to investigate the impact of both high speed and density in a LoRaWAN network through of a simulated environment in a vehicular communication.

Acknowledgments

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