Long Range Wide Area Network: 
A Simulation Module for ns-3

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Abstract

Long Range (LoRa) is a wireless communication technology for the Internet of Things (IoT), able to provide wide coverage networking to devices with low power consumption and low data-rate. This paper proposes and describes a simulation module of LoRa wireless networks, based on models of the LoRa physical and data-link layers, in order to enable simulation-based evaluation of LoRa performance in large-scale networks. The physical layer model uses path loss parameters estimated by way of real measurements performed at different scenarios. The data-link layer model relies on an Aloha-like medium access protocol. Both models for the physical and data-link layers are implemented in a NS3 module. Behavior and performance of this module are studied by way of a set of experiments that show the consistency of NS3 simulations and measurements on a real LoRa testbed. Finally, an evaluation of the simulation module scope shows that the time complexity of this module is exponential.
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1 Introduction

The Internet of Things (IoT), defined as the inter-networking of physical devices, vehicles, buildings, and other items embedded with electronics, software, sensors, actuators, and network connectivity which enable these objects to collect and exchange data, has been studied widely in both industrial and academic areas. Experts estimate that the IoT will consist of about 30 billion objects by 2020 [1].

The wireless networking technology is an important element on IoT, as it defines the connectivity among devices. Other than Wi-fi, there exist many Wireless Local Area Network (WLAN) technologies: among the most popular ones that are commonly associated with IoT, it can be mentioned the Radio Frequency Identifiers (RFID), short-range wireless communication technologies (NFC, Bluetooth, ZigBee), ad-hoc network and wireless sensor networks (WSNs) [2]. Most of these technologies are defined by short-range for low-power communication capabilities, while cellular network technologies, such as 3G or LTE, provide long-range communication but with high power consumption.

1.1 LoRa & LoRaWAN

Representing a novel communication paradigm, Low Power Wide Area Networks (LPWANs) are wireless networks for low-power devices (“things”) with wide communication coverage, communicating at low data rates. LPWAN networking is expected to complement cellular and short-range wireless technologies by addressing diverse requirements of IoT applications. LPWAN technologies offer a unique set of features including wide-area connectivity for low-power and low data-rate devices, not yet provided by other wireless technologies [1]. Long-Range (LoRa) is one of these main technologies for LPWANs.

LoRa wireless networks allow long range telecommunications at a low bit-rate among devices, such as wireless sensors, and provide features specifically needed to support low-cost, bi-directional communication in IoT systems. LoRa is a proprietary modulation technology, developed and commercialized by Semtech Corporation, and based on the Chirp Spread Spectrum (CSS) technique, in which signals are modulated in the sub-GHz ISM band. This technique spreads a narrow band input signal over a wider channel bandwidth; the resulting signal has noise like properties, making it more difficult to detect or jam and the processing gain enables resilience to interference and noise. The chirp modulation used at the physical layer allows for long-range, robust communications, with low complexity, low-power and low-cost receivers [1]. LoRa is designed to communicate by half-duplex, over 5km in an urban environment and supports large networks with millions of devices.

LoRaWAN is the MAC protocol for LoRa networks, specified by the LoRa Alliance. LoRaWAN is based on ALOHA and its architecture includes three types of devices (end-devices, gateways, network servers) connected through a star-of-stars topology: end-devices are connected to gateways using LoRa radio, and gateways are connected to the network server by way of an IP network (see
LoRa wireless network trades low data-rate for long range and low power consumption. In particular, the duty cycle, defined as the percentage of time during which the channel can be occupied, arises (from regulation) as a key limiting factor for the traffic served by LoRa network [3]. End-devices access to the medium with the pure-Aloha method, without Listen Before Talk (LBT), thus high collision ratio and low throughput are common drawbacks of this mechanism [4]. The use of duty-cycle based media access mechanism enables a LoRa device to send the data with no delays thus reducing the communication latency and energy consumption. However, the absence of clear channel assessment mechanism increases the probability of physical frame collisions thus compromising the reliability and may cause long channel access delays due to channel access back off after previous data transfers [5].

1.2 Related Work

An overview of LoRa and an in-depth analysis of its functional components are provided in [6]. The physical and data link layer performance of LoRa are evaluated by field tests and simulations. A theoretical model was proposed in the simulation to study the collision behaviors, showing that the performance of LoRa network is limited and quite similar to pure Aloha: Its throughput degrades quickly when the load on the link increases. The results show that LoRa modulation offers satisfactory resistance to interference, and, the spreading factor has significant impact on the network coverage and the data rate. The result also demonstrates that the LoRa sensitivity and propagation range of real testbed are lower than in theory. As an extension of that work, a more precise simulation is built on an event driven platform ns-3, with modeling parameters attained from real measurement, and the consistency is studied in this paper.

The coverage of the LoRa technology is studied via real-life measurements in [7]. Result shows that for an end-device operating in the 868MHz ISM band using 14dBm transmit power and the maximum spreading factor, the maximum communication range is observed of over 15km on the ground and
close to 30\textit{km} on water. The scope of LoRaWAN is clarified in [3], by exploring the limits of the technology and matching them to use cases. Result indicates that combination of the number of end-devices, selected SF and the number of channels will determine if the LoRaWAN Aloha based access and the maximum duty cycle regulation fits each use case. Another paper [8] surveys and analyzes LoRaWAN operation, focusing on performance evaluation of its channel accesses the most crucial component. Results show that capacity is restricted for large scenario and it needs increment of gateways to overcome the load. LoRaWAN performance is also analyzed in [5]: the high coverage and satisfactory scalability under low up-link traffic are strengths. The most critical drawbacks are low reliability, substantial delays and potentially poor performance in terms of down-link traffic. Instead of evaluation of LoRa, this paper takes benefits of the LoRa performance in real testbed to build the simulation module.

A LoRa error model is constructed from extensive complex baseband bit error rate simulations and used as an interference model in [9] to model the effects of path loss and intra-LoRa interference. The error model is combined with the LoRaWAN MAC protocol in a ns-3 module to study multi channel, multi spreading factor, multi gateway, bi-directional LoRaWAN networks with thousands of end devices. Scalability analysis of LoRaWAN shows that the limited downstream capacity highly deteriorates the delivery ratio of confirmed upstream messages. While the propagation model on physical layer remains a simulation in a theoretical calculation in that work, a diverse propagation model based on real test is studied in this paper.

The scalability in terms of the number of end devices per gateway of single-gateway LoRaWAN deployment is investigated in [10]. Intra-technology interference behavior with two physical end-devices, by checking the impact of an interfering end-device to a transmitting end-device is determined. Measurements show that even under concurrent transmission, one of the packets can be received under certain conditions. Take into account these measurements, a simulation model is created for assessing the scalability of a single-gateway LoRaWAN network. Result shows that LoRaWAN has better scalability than pure Aloha due to its robust physical layer. That special channel interference model defining collision behaviors is taken into consideration in the simulation module of this paper.

An extensive experimental study of the reliability of LoRa is presented in [11], focusing on evaluation of the impact of physical layer settings on the effective data rate and energy efficiency of communications. Results suggest that, when end-devices are at the edge of their communication range, using the fastest parameter setting and the highest transmission power is more efficient than selecting slower settings that maximize the link quality. Outdoor experiments show a sharp correlation between temperature, humidity, packet reception rate, and received signal strength. This work encourages experiments to study the influence of environment on signal strength of received packets, and thus to create an accurate simulation model, especially on propagation range.

The paper [12] investigates the capacity limits of LoRa networks using experiments models describing LoRa communication behavior to study scalability.
Several models describing LoRa communication behaviors have been developed by experiments and these models have been used to parameterize a LoRa simulation to study the scalability. The simulator LoRaSim: a custom-build discrete-event simulator implementation with SimPy was utilized to evaluate the performance and gives negative results related to the scalability of LoRaWAN. Result show it is not sufficient for future IoT deployments and utilizing dynamic transmission parameter selection and/or multiple gateways can improve. Another paper [13] establishes a series of models that cover various aspects of a LoRa network. A LoRa module has been developed for ns-3 to simulate LoRaWAN between end-devices and gateway in an urban scenario. Link measurement and link performance models are assumed to explore LoRaWAN. The module is composed of six core models and more associate models. Reception path is defined for gateway to deal with separated reception instead of distinct logical channels. It used some assumption in network topology (hexagonal grid) for the shadow fading estimation. Path loss parameters are extracted from the 3GPP radio frequency system scenarios. Simulation result shows a higher throughput than typical Aloha. The performance of LoRaWAN is evaluated and analyzed, showing that increasing gateways can enhance the coverage and reliability of up-link. LoRa behaviors have been modeled and simulation has been implemented to study the performance, ignoring the gap between simulation and reality. None of these works has paid attention to the consistency between the real testbed and simulation scenario, which is highly considered, and is studied and verified in this paper.

1.3 Contribution

The point here would be: build a simulation module to study LoRa/LoRaWAN performance in large-scale networks via network simulations, as real world deployments are not feasible.

As LoRa becomes a major LPWAN technology for IoT, it is relevant to have tools to understand its operation and evaluate its performance in different scenarios. Since real-world deployments are limited and sometimes not feasible, in particular for large-scale networks, it is important to have simulation tools that allow the study of main characteristics of LoRa in these scenarios.

This paper proposes a LoRa simulation model to simulate the physical layer and data-link layer of LoRa networks, taking parameters attained from real experiments. The model is implemented in NS3. Comparative experiments between simulation and real testbed are performed to validate the consistency of LoRa performance, especially for the purpose of link budget. The evaluation of simulation module scope, in time metric and memory metric, is also carried out by running the simulation in large scale scenarios.

1.4 Outline

The remainder of this paper is organised as follows. Section 2 describes LoRa basics, section 3 illustrates the measurement experiment, section 4 presents the
integration of module in NS3 and interaction among classes, section 5 presents the comparison between simulations and measurements from a real testbed, and section 6 provides an evaluation of the simulation module. Finally, section 7 concludes this paper.

2 Describing LoRa

This section describes LoRa basics: formats, parameters and key operations. Modulation and modulation parameters are described in section 2.1. Formats are described in section 2.2. Key operations include LoRa transmission (section 2.3), propagation of a LoRa signal (section 2.4) and reception of a LoRa stream (section 2.5).

Description of LoRa transmission and reception in this section is based on the operation of the Semtech SX1272 [14] transceiver.

2.1 Modulation and Parameters

LoRa modulation is based on the Chirp Spread Spectrum (CSS) scheme, which uses frequency chirps with a linear frequency variation over time to encode information.

A typical LoRa radio provides five configuration parameters [15]:

- **Transmission Power (TP)** is the transmitted power of the signal at the transmitter (in dBm).
- **Carrier Frequency (CF)** is the center frequency used for the transmission band (in MHz).
- **Spreading Factor (SF)** is the ratio of the chip rate to the symbol rate, as a power of 2 (adimensional).
- **Bandwidth (BW)** is the range of frequencies applied in the transmission band, (in kHz).
- **Coding Rate (CR)** is the Forward Error Correction (FEC) rate used by the LoRa modem and offers protection against bursts of interference.

Radios with different CR and same CF/SF/BW, can still communicate with each other [16]. These parameters impact the sensitivity of receivers and the network coverage.

2.2 Message Formats

A LoRa physical frame has three elements: a preamble, an optional header, and the payload with (possibly) the Cyclic Redundancy Check (CRC). The preamble (12 symbols by default, programmable) is used to indicate receivers the beginning of the physical frame. The optional header is set in the Explicit
Header Mode, active by default, and includes information of the payload: number of bytes, coding rate and whether a CRC is used in the physical frame. The payload has variable length and contains actual data frame coded at the error rate either as specified; this includes the MAC header (minimum 12 bytes). Depending on the configuration, a physical CRC may be appended to the frame.

This format is depicted in figure 2.

![Figure 2: Format of LoRa frames.](image)

2.3 LoRa Transmission: Time on Air

This section derives the expression for the Time on Air of a LoRa physical frame, i.e. the time needed to transmit a LoRa physical frame as described in figure 2; this is the main metric during the transmission phase.

When a LoRa device needs to transmit data, it constructs the frame and transmits the corresponding physical frame containing it, at the corresponding coding rate (CR ∈ \{1, 2, 3, 4\}), bandwidth (BW ∈ \{125, 250, 500\} kHz) and Spreading Factor (SF ∈ \{7, 8, 9, 10, 11, 12\}). The relationship between these parameters and the Time on Air is described in this section.

Bandwidth (BW) and Spreading Factor (SF) determine the LoRa symbol rate, \( R_s \), which is defined as follows:

\[
R_s = \frac{BW}{2^{SF}} \tag{1}
\]

For a given coding rate (CR), the bit rate, \( R_b \), can be then defined as follows:

\[
R_b = SF \cdot \left[ \frac{4 + CR}{2^{SF} \cdot BW} \right] \tag{2}
\]

According to the format depicted in figure 2, the Time on Air (the time required to transmit the whole frame, including preamble) for a LoRa transmission can be separated in the duration of the preamble transmission and the duration of the transmission of the rest of the physical frame.

The preamble duration \( T_{\text{preamble}} \) is calculated as follows:

\[
T_{\text{preamble}} = \frac{1}{R_s} (n_{\text{preamble}} + 4.25) \tag{3}
\]

Where \( n_{\text{preamble}} \) is the programmed preamble length, by default it is 8 symbols long, thus \( n_{\text{preamble}} = 8 \).
Then the duration of the rest of the frame depends upon the header mode that is enabled (physical header) and includes the physical header, the physical payload and the CRC. The following formula is simplified and it gives the duration $T_{\text{payload}}$ of a given number of payload symbols.

$$T_{\text{payload}} = \frac{1}{R_s} \left( 8 + \left\lceil \frac{8 \times PL - 4 \times SF + 44}{4 \times SF} \right\rceil (CR + 4) \right)$$

Where $PL$ is the number of bytes of payload, $SF$ is the spreading factor, and $CR$ is the programmed coding rate. It should be noted that according to the default configuration \footnote{ref}, explicit header mode with header CRC is used here. The low data rate optimization is disabled and the presence of the physical payload CRC is enabled by default.

Finally the Time on Air of a transmission can be calculated on the physical layer. For a given combination of $SF$, $CR$ and $BW$, the total Time on Air of a LoRa transmission $T_{\text{frame}}$ is computed as the addition of preamble and payload durations:

$$T_{\text{frame}} = T_{\text{preamble}} + T_{\text{payload}}$$

Where $T_{\text{preamble}}$ and $T_{\text{payload}}$ are two durations indicated in equation \footnote{ref} and equation \footnote{ref} respectively.

Compared to the Time on Air of a physical frame, in the order of msec, the propagation delay (i.e. the time after the start of transmission and before the start of reception) is negligible, as it is in the order of nsec.

## 2.4 LoRa Propagation

This section concentrates on the path loss model for estimating the Received Signal Strength Indicator (RSSI) and interference among wireless channels, which are the main aspects of interest in the propagation phase.

### 2.4.1 RSSI and Path Loss Model

It is known that the power of a transmitted signal decreases continuously, as it propagates, with the distance from the transmitter; path loss can be estimated to calculate the RSSI at the receiver.

Log distance path loss model is generally used in wireless sensor networks \footnote{ref}. It assumes an exponential path loss over the distance from the sender to receiver, and it is designed for suburban scenarios. Given the received signal power $P_R$ (in dBm), the transmitted signal power $P_T$ (in dBm), the receivers antenna gain $G_R$ (in dB), the transmitters antenna gain $G_T$ (in dB), the signal wavelength $\lambda$, the distance $d$ in meters and the signal propagation constant $n$, the Friis transmission equation in free space is:

$$P_R(d) = P_T + G_T + G_R + 20 \log_{10} \left( \frac{\lambda}{4\pi d} \right)$$

(6)
Friis propagation model assumes ideal conditions of unobstructed free space, perfect alignment and polarizations of antennas, and absence of path-loss and fading phenomena, normally in an open environment with high probability of Line of Sight (LoS) and low multi-path effect.

The majority of embedded systems operate in Non Line of Sight (NLoS) environments. It is known that three key phenomena have a major impact on the signal strength at a certain distance of the transmitter:

- **Path loss** is the reduction in power density of an electromagnetic wave as it propagates through space.

- **Fading** is deviation of the attenuation that a signal experiences. Fading varies with geographical position, time and radio frequency. As a result, fading can create either destructive or constructive interferences, amplifying or attenuating the signal power seen at the receiver.

- **Shadowing** is the loss of signal due to obstacles between a transmitter and a receiver.

Radio channel characteristics in a specific environment can be estimated by looking for a mathematical relationship between the RSSI value, in dBm, and the distance between transmitter and receiver. A simplified form of the relation between distance $d$ and received power $P_R(d)$ is often used [18]:

$$P_R(d) = P_T - PL(d) - X_0$$

Where $P_R$ (in dBm), $P_T$ (in dBm) and $PL$ (in dB) are received signal power, transmitted signal power and path loss, respectively. In this model, $X_0$ is the shadowing and fading factor, and is modeled as a Gaussian random variable with mean 0 and variance $\sigma_{SF}^2$, i.e. $X_0 \sim N(0, \sigma_{SF}^2)$.

The variation of propagation path loss, $PL$, is given by:

$$PL(d) = PL_0 + 10n \log_{10}\left(\frac{d}{d_0}\right)$$

Where: $n$ is the path loss distance exponent, $d_0$ is reference distance (m), $PL_0$ is path loss at reference distance (dB), $d$ is the distance between the end-device and the gateway (m), and $PL$ is path loss (dB).

Path loss parameters for on-ground environment ($PL_0$, $n$, $d_0$) can be estimated through measurements. In [7], measurements were performed to estimate the characteristics of the up-link connection, i.e. for the data transfer from an end-device to the gateway; the calculated path loss exponent and path loss intercept for the on-ground case were below the values of the free space model. $\sigma_{SF}$ describes the standard deviation of Shadow Fading, between expected path loss and path loss measurements. It is computed as follows:

$$\sigma_{SF} = std(PL - EPL)$$
Where $PL$ is measured path loss, and $EPL$ is expected path loss. Shadow and fading are taken into account and the measured deviation depends on environment. In [7], for an on-ground case, $\sigma_{SF}$ was estimated as $\sigma_{SF} \leq 7.8$.

In embedded devices, the received signal strength is processed in terms of RSSI, defined as the ratio of the received power to a reference power $P_{ref}$. Typically, the reference power is $P_{ref} = 1mW = 0dBm$. Hence this deduces the equivalence of $RSSI(d)$ (dBm) and received power $P_R(d)$ (dBm) on the receiver for a distance $d$:

$$RSSI(d) = P_R(d)$$  \hspace{1cm} (10)

### 2.4.2 Interference

In the end of the propagation phase, whether a physical frame is destroyed or not also depends on the channel interference. Unlike other wireless networks, LoRa employs an adaptive CSS modulation scheme, thus extending the communication range in the absence of any interference. Interference is however present when signals simultaneously collide in time, frequency, and Spreading Factor [19][12].

The notion of logical channel is used to model LoRa interference. A logical channel $CH$ is a tuple $(CF, SF, BW, CR)$, i.e. two transmissions occur in the same logical channel if they occur with the same carrier frequency, coding rate, Spreading Factor and bandwidth. Different logical channels are orthogonal, thus collisions only occur between transmissions in the same logical channel.

### 2.5 LoRa Reception and Collisions

In the reception phase, sensitivity and preamble detection are the primary consideration. They determine whether a physical frame is successfully received and processed by the receiver.

The sensitivity ($S$) of a LoRa receiver is the minimum magnitude of an input signal required to produce a specified output signal, for a minimum Signal-to-Noise Ratio (SNR), $SNR_{req}$, required by the modulation scheme. Sensitivity thus entails an RSSI threshold that a message needs to fulfill at the receiver so as to be successfully received. Different Spreading Factors at the transmitter imply different SNR values, $SNR_{req}$, required at the receiver to ensure successful reception.

According to the LoRa modulation SNR table (Table 13 of [14]), $SNR_{req}$ (in dB) depends linearly on the Spreading Factor $SF$, as follows:

$$SNR_{req} = 10 - 2.5 \times SF$$  \hspace{1cm} (11)

A physical frame is successfully received if and only if the following condition holds on the receiver:

$$RSSI \geq S$$  \hspace{1cm} (12)
Based on the information from Semtech SX1272 (sec. 2.2 [20]), the sensitivity $S$ (in dBm) of a radio receiver attached to a channel at room temperature is given by:

$$S = -174 + 10 \log_{10} BW + NF + SNR_{req}$$  \hspace{1cm} (13)

Where:

- $-174$ is due to thermal noise in $1\text{Hz}$ of bandwidth and can only be influenced by modifying the temperature of the receiver.
- $BW$ is the receiver bandwidth.
- $NF$ is the receiver noise figure and is fixed for a given hardware implementation, here it is assumed to be $6$ [15].
- $SNR$ represents the signal to noise ratio required by the underlying modulation scheme.

In the start of the reception phase on one channel, there can be competition among multiple physical frames instead of a collision. The feature of concurrent non-destructive transmissions and carrier detection in LoRa is demonstrated in [12]. Let $p$ be the preamble length (in symbols). A strong transmission can be successfully decoded when it arrives one physical frame time early up to at most $(p - 5)$ symbols late, successfully suppressing the weak transmission. However, with an offset of more than $(p - 5)$ symbols up to the end of the physical frame, no transmission gets through. The receiver requires 5 symbols to detect the preamble and synchronism. Physical frames can overlap, as long there are at least 5 preamble symbols left intact (in case of a weak frame). In other words, the critical section of a physical frame reception starts at the last 5 preamble symbols. Therefore, after $(p - 5)$ symbols, the receiver has locked on to the weak transmission, but its signal is suppressed by the strong transmission and the physical frame is corrupted. It is assumed to be the case of a collision for overlap after duration $T_{\text{non-critical}}$:

$$T_{\text{non-critical}} = \frac{1}{R_s}(n_{\text{preamble}} + 4.25 - 5)$$  \hspace{1cm} (14)

Where $R_s$ is the LoRa symbol rate and $n_{\text{preamble}}$ is the programmed preamble length (default value is 8).

In the period of $T_{\text{non-critical}}$, a new coming frame with stronger RSSI can suppress the current frame and be successfully received. Oppositely, a new coming frame with weaker RSSI will be ignored and it will not affect the reception of the current frame. After the period of $T_{\text{non-critical}}$, both new coming and currently receiving frames are dropped because of the collision.
3 Estimation of Path Loss Parameters

This section describes experiments performed on real LoRa devices, in various scenarios, to empirically estimate the parameters of the path loss model described in section 2.3 These parameters are then used to configure the simulation module.

3.1 Experiment Conditions

Two LoRa end devices, one as a transmitter and the other as a receiver, are used for measuring propagation range.

The LoRa end-device hardware used in the testbed is a transceiver of model HopeRF RF95, attached on a Dragino LoRa shield and an Elegoo UNO mote (Arduino device) (see figure 3). By default, the antenna gain is around 3dB on both transmitter and receiver. The height between transmitter and receiver is approximately 6 meters.

![Dragino LoRa Shield on Elegoo UNO.](image)

Experiments to estimate path loss are performed for a fixed value of the Transmission Power ($TP = 14dBm$), and different distances between devices ($d$).

A simple master-slave application is implemented and deployed in the LoRa devices (transmitter and receiver) in order to send frames from the transmitter and record the RSSI of received frames at the receiver. Experiments are performed in 5 different positions, each with a different distance $d$ between transmitter and receiver. For each position, 100 frames are transmitted in order to calculate the average RSSI and deviation at the receiver.

3.2 Experiment Scenarios

Experiments are performed in three typical scenarios for LoRa operation: a Non Line of Sight (NLoS) scenario on the ground, a Line of Sight (LoS) scenario on

1http://www.dragino.org
2https://www.elegoo.com
the ground, and an extreme Non Line of Sight (NLoS) underground scenario with dense obstacles. The path loss exponent $n$, the reference distance $d_0$ and the path loss intercept $PL_0$ (path loss at reference distance) are specific for each scenario. These three parameters are estimated from the dataset by using Least Squares regression (Figure 5).

3.2.1 Non Line of Sight

In the first scenario, this testbed is deployed from a campus with buildings to the road across the forest, which is similar to a suburban environment (a few obstacles), and the temperature is around 20 degree. Figure 4 displays a satellite view of the campus environment. From the measurement of RSSI on five positions of different distances, the parameters are regressed and utilised in generating the estimated RSSI. Figure 5 shows the measured RSSI values on five different distances and the result of linear regression.

![Figure 4: Map of Campus Environment.](image)

Figure 6 shows the expected RSSI values on different distances of this case. This on-ground scenario gives the result of an approximate suburban environment, where the path is NLoS because of trees and buildings. For minimum $SF = 7$, the maximum network range is no more than around 2000m.

3.2.2 Line of Sight

The second scenario consists of an empty road with very few obstacles – this setup allows to perform LoS experiments. The testbed is deployed in a university campus, which is a suburban environment. The outdoor temperature is around 20 degrees. Few moving cars and trees introduce shadowing and fading. Discrete points are measured on three positions to regress parameters
and based on parameters. Figure 7 shows the measured RSSI values on three different distances and the result of linear regression.

Figure 8 shows the estimated RSSI values on different distances. This case on the ground gives an approximate free space, where the path is a LoS. The maximum propagation ranges for the minimum $SF = 7$ is about 5000 m. Result
shows an ideal situation, where the maximum LoRa propagation range ($SF = 12$) is around 20$km$. This is consistent with the result indicated in the LoRa official datasheet [14].

Figure 7: RSSI Regression for LoS, TX Power 14dBm.

Figure 8: LoRa RSSI for LoS, TX Power 14dBm.
3.2.3 Extreme Non Line of Sight

The third scenario is carried out in an underground parking with many walls, dense obstacles and no available Line of Sight – this setup allows to perform extreme NLoS experiments. The temperature is around 23 degrees. Discrete points are measured at various positions to estimate parameters. Figure 9 shows the measured RSSI values on three different distances and the result of linear regression.

![Figure 9: RSSI Regression for extreme NLoS, TX Power 14dBm.](image)

Based on parameters gained from regression, the estimated RSSI can be drawn. Figure 10 shows the estimated RSSI values on different distances. This underground case gives an extreme environment, where the path is a definitely NLoS. Result shows the extreme situation, where the maximum LoRa propagation range \( (SF = 12) \) is only around 180m. This is the worst observed performance of LoRa. The zigzags in the building lead to this consequence.

3.3 Path Loss Parameters

This set of experiments above has the purpose to regress the simulated propagation model corresponding to the real testbed, in order to estimate accurately the propagation range of different SF parameters.

With the testbed experiment, RSSI measurements in various environments, with and without shadowing / fading, and on different distances, can be used to compute a linear regression for the simulation model. The path loss exponent \( n \), the path loss intercept \( PL_0 \) (dBm) and standard deviation \( \sigma_{SF} \) of shadow fading are shown in the table. Estimated path loss parameters vary significantly depending on different environments.
A comparison of the RSSI of three different scenarios is shown in figure 11. The reference distance is $d_0$ (in meters).

Result demonstrates that the path loss parameter strictly depends on the specific environment. The caused propagation ranges limited by same sensitivity are significantly different (Figure 11). It is important to choose the proper parameter for a specific environment before simulation. Moreover, shadowing and fading play an important role in the dynamic environment where exists winds, cars and moving objects, as the deviation is relatively significant to expected value. In a more stable environment, the deviation of path loss is smaller.

In this section, real world experiments are performed to estimate the parameters of the LoRa propagation model described in section 2.3. Three typical parameter sets are obtained: the LOS for the best idea scenario, the extreme NLOS for the most critical scenario and NLOS for normal suburb scenario. Those parameters can be used directly for simulating similar scenarios. The dataset is publicly available on line\footnote{https://github.com/Yifan-DU/LoRa_RSSI_Measurement_Dataset}. For other particular scenarios, it is sug-
gested to have collect field measurements to generate the parameters for such scenarios.

4 Integration in NS-3

This section describes the architecture, main elements and functionalities of the LoRa simulation module developed for NS-3. Section 4.1 provides an overview of NS-3. Section 4.2 describes the LoRa module architecture. Section 4.3 describes the procedure for LoRa transmission as implemented in the module.

4.1 Network Simulator 3

NS-3 is a discrete-event network simulator, based on C++. It is free software licensed under the GNU General Public License (GPL) v2 license, and is publicly available for research and development purposes. Compared to NS-2, NS-3 has new features such as new software core, more realism, software integration, support for the visualisation, testbed integration, attribute system, and tracing architecture [21]. N3 is widely used today in the networking community, partly due to its good overall performance, and its relatively low computational and memory demands with respect to other available network simulators [22].

https://www.nsnam.org/
4.2 LoRa Module Structure

The LoRaWAN architecture consists of end-devices, gateways and a network server. End-devices are connected to the gateway by way of LoRa wireless channels [2]. IP connectivity between gateways and the network server is taken for granted, and is not addressed in this study. Rather, the current paper focuses on the performance of the LoRa radio link between two LoRa devices (end devices or gateways).

The LoRa simulation module consists of three main components (C++ classes): the LoRa device, the LoRa channel and the LoRa MAC. Each of these components is described in the following sections. A LoRa device is responsible for processing on transceivers, wireless channel access and scheduling. Wireless LoRa channel deals with the physical layer propagation and the node mobility. LoRa MAC manages frames and processes reactive/proactive network events. Besides these three main components (classes), some additional auxiliary classes are also used (and have been developed/adapted), e.g. the LoRa physical frame header, network server, frame tracers, mobility class and propagation class.

Mobility and propagation classes are not specific from the LoRa module, but common NS-3 classes. In the simulation module, various parameters can be configured for customisation to test the performance of LoRa network. Figure 12 depicts the structure of the LoRa simulation module.

![Diagram of LoRa Module Structure](image)

**Figure 12: Components Structure of Simulation Module**

4.2.1 LoRa devices

LoRa devices work on the physical and the data-link layers; device instances are attached to LoRa channels.

They operate in half-duplex, i.e. they can handle transmissions and receptions, but not at the same time. For each TX/RX network event on devices, there is a call to the attached channel.

**Collision handling** LoRa network devices detect a reception collision and trace a reception loss, both in promiscuous or non-promiscuous mode.

When a collision is detected at the reception state (RX), the device drops both involved frames (the currently processed RX frame and the incoming frame). When a collision is detected on the transmission state (TX), the device stops the ongoing transmission and loses the incoming frame.

**Queues** Frames to be transmitted are stocked in a FIFO sending queue; this will be checked after each transmission, reception and collision.
Derived subclasses Both end-devices and gateways inherit the same LoRa device class, which implements functions in common (e.g. TX and RX). There exists three main differences between gateways and end-device:

- Gateways hold an always-on promiscuous reception; end-devices hold scheduled reception slots.
- Gateways have multiple channels in parallel; end-devices only use one channel and process.
- Gateways have a back-haul connection to the network server, which processes received frames; end-devices are only connected wirelessly to gateways.

4.2.2 LoRa channels

LoRa channel instances provide an abstraction to emulate the physical propagation of frames through the wireless medium and the collision of different frames. Note that, since the wireless medium is shared, multiple devices can transmit and receive over the same channel. As two transmissions on the same frequency, but at different Spreading Factors, can be decoded simultaneously by a receiving device, a logical channel is identified by the tuple \((CF, SF, BW)\), with \(CF\) being the Carrier Frequency (mHz), \(SF\) the Spreading Factor and \(BW\) the Bandwidth (kHz). Since the Coding Rate is a network configuration parameter (i.e. all device instances have the same CR value), orthogonal channels are defined only by the Carrier Frequency and the Spreading Factor. Each channel instance stores the minimum SNR to correctly decode a transmission, and the receiver sensitivity according to its parameters, while the data-rate is selected at device instances. These values are calculated and stored in the channel instances. When a transmission is scheduled, the channel calls calculates the corresponding path loss and estimated delay values by using the propagation model.

4.2.3 LoRa MAC

LoRa MAC instances simulate the code controlling LoRa device, and they are responsible directly for proactive and reactive network events. Various kinds of LoRa MAC instances can be generated to control the network events by defining multiple behaviours. It has flexibility on the medium access control. The scheduling and forwarding can be customised like a piece of code flashed into devices. For the proactive event, as of the current specification, devices and gateways can transmit at any time. There is no Listen-Before-Talk or CSMA mechanism. This makes LoRa MAC layer very similar to pure-Aloha [4], but, unlike Aloha, LoRa MAC uses a variable frame length. For the reactive event, normally medium access is controlled by scheduling reception time slot. Packet forwarding is also reactive event triggered by callback. Proactive actions for transmission and reactive actions after reception in promiscuous
mode and non-promiscuous mode, are defined in LoRa MAC instances. The flexibility, highlighted as reception slot scheduling and forwarding reaction, can be implemented as a procedure in the LoRa MAC instance.

4.3 Transmission Procedure

The source node starts a transmission, and triggers a transmission event at the corresponding attached channel. At the same time, it schedules a transmission end event on itself. The channel will calculate the propagation loss and delay according to the propagation model and the physical positions of nodes, to decide whether the transmission will result in a successful reception or a loss. Loss at the receiver is determined by the physical propagation loss model, according to the physical location of node, transmit power and receiver sensitivity. If the RSSI is below the receiver sensitivity, there is a propagation loss and the frame is not be parsed to the receiver. If the transmission is successful, a reception start event is scheduled on the receiving node after the propagation delay, and the received frame is recorded in the receiving node. If a device is busy sending a frame on a channel when another frame arrives on the same channel, a collision occurs and the frame RX loss will be triggered.

Reception of a frame includes a preamble detection time and a non-critical preamble time. After the non-critical preamble time, a device is busy receiving a frame on a channel, if another frame arrives on the same channel, a collision will be triggered on the device. Otherwise, if the destination is not busy with this channel or new frames wins RSSI during previous non-critical preamble time, it will immediately switch to the reception state. When the transmission finishes, source node will ask the channel, if transmission is not interrupted and the channel will detect destination whether on reception state for this frame, which means no collision neither loss, the channel will schedule a reception finish event at the destination node. Until now, the destination node finished a reception for one frame, in promiscuous mode.

5 Comparison Experiment

This section investigates consistency between simulations and real testbed measurements. In particular, performed experiments focus on Time on Air of transmissions (section 5.2) and the Signal-to-Noise ratio at the the receiver for successful transmissions (section 5.3). Experiment details are described in section 5.1.

It is verified, both for simulation and for real testbed experiments, that a higher spreading factor increases the SNR, thus better sensitivity and longer coverage range, but it also increases the Time on Air.
5.1 Experiment Settings

In both simulation and real testbed, two LoRa device instances are created for the point-to-point scenario. Experiment configuration is kept identical in both real testbed and simulation. In the Time on Air experiment, Spreading Factor (SF) and packet payload size are the key variables. In the SNR threshold experiment, Spreading Factor (SF) and distance are the principal variables. The two devices are attached to one channel with the same parameters. One device serves as the transmitter and the other one acts as the receiver. Table 2 indicates the values used for the different LoRa parameters on this experiment.

Table 2: Experiment Configurations

| CF      | BW    | CR | TP     | #Packets | SF |
|---------|-------|----|--------|----------|----|
| 868.10 MHz | 125 KHz | 4/5 | 14 dBm | 100      | 7...12 |

5.2 Time on Air

For the test of Time on Air, two devices are deployed in a short range inside a room, and the indoor temperature is approximately 24 degrees. This experiment holds the purpose to validate the simulated Time on Air corresponding to the Time on Air in real testbed, i.e. using higher SF can result in a lower data rate thus longer channel occupancy (Time on Air). An echo application is deployed between the transmitter and receiver in order to measure Time on Air (ms) of a packet, by dividing the total echo time by 2. The deviation of measured Time on Air is about 0.05 second. In the simulation environment, the preamble detection time of the packet is also figured out. A comparison of result between real testbed and simulation is illustrated below.

Figure 13.(top) shows the Time on Air for transmitting a packet with the physical minimum payload size 5 bytes, and the physical CRC is enabled. When the end-device uses a SF < 10, there are no significant difference between simulation and testbed. When a higher SF is used, however, real testbed spends significantly more time than simulation, especially for $SF = 12$. The maximum relative difference is around 3%. This is due to the preprocessing time of a packet on the device, which includes the time for dealing with CRC.

Figure 13.(bottom) shows the Time on Air for transmitting a packet with the maximal physical payload size 255 bytes, and physical CRC has to be disabled. The preprocessing time on the device is not noticeable with respect to the whole Time on Air. For all SF values utilised, there is no significant difference between the Time on Air in simulation and in real testbed. This result shows an acceptable consistency between the simulation and the real testbed.

5.3 SNR

In order to achieve the SNR threshold, two devices are deployed in an underground parking with dense walls and obstacles. The environment temperature
is approximately 23 degrees and there are no moving obstacles. All possible Spreading Factors are utilized until reaching the limit of their respective network ranges. The minimum SNR values that a device can successfully receive for the packet are recorded.

Figure 14 depicts the SNR threshold of different SF. Result shows approximately equivalent SNR value in simulation and in real testbed. Real testbed provides a slightly lower SNR than simulation, with a maximum difference around 1, although this gap is rarely attained. This can be caused by the variance of
environment temperatures. These results, both in simulations and with real measurements, indicate that devices can demodulate a packet with a low SNR by increasing the Spreading Factor.

6 Module Evaluation

This section describes the evaluation on efficiency of the specific LoRa simulation module, especially in large scale networks to understand how much time and memory are required to run certain simulations. Section 6.1 presents the characteristics of the simulation setup. Experiments are performed for different numbers of end-devices. Both run-time consumption and memory occupancy are measured and discusses in sections 6.2 and 6.3 respectively.

6.1 Simulation Scenarios

The simulation was ran in a Linux environment with the following characteristics:

- CPU: Intel Core i5-6360U 2.00GHz.
- RAM: 2060MB.
- OS: Ubuntu 17.04.

The simulation platform is NS3.26 release version.
For each scenario, the simulation is run by 5 times. Presented results correspond to the average of the corresponding 5 values. Observed variance is \( \leq 1\% \) with respect to the mean value.

The end devices and gateway(s) are randomly distributed in the graph. All the gateways are reachable for all the end devices with maximum SF 12.

All end devices send packets up-link (to the server, through gateways) with \( SF = 12 \). The LoRa parameters of end-devices are those described in Table 2. Packet payload is configured for the maximum 255\( \text{bytes} \) for LoRa.

Each end-device sends 100 packets and the duty cycle is configured as maximum 1\%. The simulation ends when all the packets are sent out. Packet trace is triggered when promiscuous reception happens, reception loss happens, and collision happens on gateways.

6.2 Time Consumption

Figure 15 shows the time consumed in simulations, for different numbers of end-devices (ranging from 1 to 330) and gateways (1, 10 and 20).

![Figure 15: Simulation Runtime Consumption.](image)

It can be observed that the runtime grows exponentially as the number of end-devices increase: mechanically, the more end-devices, the more events to be handled by the event-driven simulator. Including more gateways also increases time consumption – but in this case, as gateways are mostly passive elements, only slight increments are observed.
6.3 Memory Consumption

Figure 16 depicts the fraction (%) of consumed memory in function of the number of end-devices (ranging from 1000 to 10000 devices, in steps of 1000 devices) and gateways (for 1, 1000 and 2000 gateways).

Memory consumption increases linearly with both parameters, number of end-devices and number of gateways. This is expected, as memory consumption is associated with the number of objects, and each device (end-device or gateway) entails a new object. It can be observed, however, that the impact of increasing the number of end-devices in the consumed memory is relatively low: an increase of 1000 devices leads to a 0.1% growth of memory consumption.

The LoRa simulation module has a scope limited by the runtime cost factor. Hundreds of end-devices with maximum duty cycle events need several minutes to complete the simulation. Trace file is the result of the simulation to be analysed, and its size increases following the scale of events.

7 Conclusion

In this paper, a simulation model is proposed to simulate LoRa network. The behaviour of LoRa modulation and LoRaWAN MAC protocol is analysed and described. To model the radio propagation behaviour, real testbed is set up in different scenarios, based on which the parameters of the path loss model are explored. Three typical scenarios: line of sight, urban non-line of sight, extreme non-line of sight are studied. The results show that the parameters
vary significantly depend on the scenario tested so it is important to choose the model parameters carefully.

The model is implemented in NS3 as an additional LoRa module. The comparison of time-on-air and SNR between the simulation results and real testbed measurements shows that the simulation module is able to simulate the network behaviour correctly. The scalability of the module is also evaluated. When the number of simulated node increases, the time required for simulation increases exponentially, while the memory consumption increases linearly.

The LoRa model proposed in this paper is expected to be helpful to evaluate and simulation the LoRa network, as well as study new extensions for LoRa.

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