A Review of LoRaWAN Simulators: Design Requirements and Limitations

Jaco M. Marais*[1], Adnan M. Abu-Mahfouz*†[2], Gerhard P. Hancke*[3]
*Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria 0028, South Africa
†Council for Scientific and Industrial Research, Pretoria 0184, South Africa
[1]Correspondence: u11024063@tuks.co.za
[2]a.abumahfouz@ieee.org
[3]gerhard.hancke@up.ac.za

***Abstract*—Several wireless technologies are enabling the growth of the Internet of Things (IoT) industry. One of these, namely Long Range Wide Area Network (LoRaWAN), is very popular in the research community whose focus is on optimising the LoRaWAN protocol for effective use. A key tool in a researcher's arsenal is the use of LoRaWAN simulators. This work describes the considerations that are important when considering choosing a LoRaWAN simulator and presents a comparison of the currently available simulators. Recommendations are made for which simulators would be best for certain IoT use cases as well as a discussion on the reviewed simulators. Recommendations are also made on the focus of future simulation development.**

***Keywords*— LoRa, LoRaWAN, IoT, LPWAN**

I. Introduction

The Internet of Things (IoT) is a fast-growing industry, and the wireless communication technologies enabling this growth is a popular topic for the research community [1]. There are several Low Power Wide Area Network (LPWAN) technologies available, all aiming to cover large geographical areas whilst supporting thousands of devices all requiring minimal energy consumption. One of the most popular technologies to study is Long Range Wide Area Network (LoRaWAN), as its Physical Layer (PHY), namely LoRa, is proprietary but the LoRaWAN specification is open-source and hence is easily accessible. Due to this low barrier to adoption, the technology is also popular amongst developers of IoT products [2].

The business potential behind using a LoRaWAN based IoT solution is commonly only unlocked at a certain level of scale, i.e. a critical number of devices deployed [3]. Deploying large numbers of devices is very costly, and thus verification of the performance of technologies is required to ensure that that the correct technology decisions have been made. As noted in [1], the study of large-scale networks require approaches such as simulation and modelling to identify issues before these networks are deployed.

The LoRaWAN research community has started to develop LoRaWAN simulators to investigate issues such as scalability, interference, Quality of Service (QoS) and energy consumption. Currently, there is no definitive LoRaWAN simulator, and simulators differ in functionality, performance, usability and if they are kept up to date with the latest releases of the LoRaWAN specification.

A comparison between the currently available simulators is required, to guide companies designing networks, and researchers in selecting the correct simulator. This work aims to address this gap by examining the design considerations of LoRaWAN simulators before reviewing the available LoRaWAN simulators. Some suggestions are made to which simulators are best for a few IoT use cases and an overview of the key issues and future work required in the simulator domain is presented.

II. Background

A. LoRa and LoRaWAN

A LoRaWAN consists of two parts, namely the use of LoRa, developed by Semtech, as the network's physical layer and the use of the LoRaWAN protocol to provide the Medium Access Control (MAC) layer. LoRa modulation is derived from Chirp Spread Spectrum (CSS) modulation and operates in the Industrial, Scientific and Medical (ISM) bands. The LoRa Alliance develops and promotes the LoRaWAN standard as an open-source solution specifically designed for the IoT. This technology has gained the most traction in the European Union (EU) and most of the published research focuses on networks operating in the EU863-870 MHz band. However, worldwide interest is gaining as more and more countries finalise their channel plans [4].

LoRa's modulation consists of a series of frequency-modulated signals referred to as up-chirps and down-chirps [5] and offers considerable resistance to interference. A LoRa radio offers three Bandwidth (BW) settings namely 125 kHz, 250 kHz and 500 kHz, six different orthogonal Spreading Factor (SF) values namely 7-12 (in the EU) and employs Forward Error Correction (FEC) with a choice of 4 coding rates [6]. Some LoRaWAN literature refers to a radio having several Data Rates (DR) available, but this is not an additional setting. These are simply a method to specify a SF and a BW setting as one, for example, DR0 refers to the use of SF12 with a BW of 125 kHz [4].

To accommodate the long range transmission requirements of IoT devices (several kilometres even in urban areas), demodulation needs to be successful even when a packet is received with a very low Signal to Noise Ratio (SNR). By increasing the SF, data redundancy is improved by increasing the number of chips required per bit of information. This increase in data redundancy comes at the cost of increasing a packet's time on air, causing the duty cycle limitations of the channel used to be reached sooner [7]. The inverse is also true, higher data rates are possible with the use of low SFs (e.g. SF7) but should only be used by nodes close to the gateway. LoRa's SFs are considered orthogonal, and as a result, multiple packets can be received on the same channel successfully as long as they were sent using a different SF. This increases the network's scalability as through optimum SF choices, additional virtual channels can be added to the available channels.

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Early LoRaWAN research, such as [8] and the official Semtech documentation, reported that this orthogonality was perfect (no collisions). This assumption turned out to be incorrect, [9, 10], and these signals are only pseudo-orthogonal [5]. Transmissions sent using different SFs are not completely immune to interference and successful reception depends on the Signal-to-Interference Ratio (SIR) of the transmissions [10].

The LoRaWAN protocol provides a feature referred to the Adaptive Data Rate (ADR) scheme that aims to optimise the data rate and Radio Frequency (RF) output of devices in a network. When enabled, the network monitors each device's uplink messages and controls each device's data rate and transmit power through MAC commands. This feature aims to allocate the fastest possible data rate to devices as this increases the network's scalability by assisting with duty cycle limitations.

B. Simulation design considerations

In the development of a simulator, the performance of the PHY must be accurately captured. Whilst the channel access mechanism is pure ALOHA, research has shown that LoRa outperforms a pure Aloha approach and thus a simulator should not assume pure Aloha performance [11, 12]. Lab experiments, conducted in [12], showed that during packet collisions due to concurrent transmissions, one of the packets will be received as long as the last six symbols of the preamble and header did not collide.

Simulators should also take into account that LoRa is susceptible to self-interference [9, 10, 13] and exhibits the capture effect [12, 13, 14]. Self-interference can either be co-SF interference (the same SF) or inter-SF interference (between different SFs). LoRa transmissions are also subject to the capture effect: a stronger signal can suppress a weaker signal at the receiver [15], causing the stronger signal to be received successfully [16].

The accuracy of a simulator is dependent on how the environment and the physical layer is modelled. As LoRa is proprietary, the development of simulators has slowed down as experimental work must first be done to fully understand its design and performance. Simulators thus must be updated as new research refining our understanding of the physical layer is released.

Whilst the PHY layer is important, the features added by the LoRAWAN protocol are also important. Comprehensive simulators should support features such as the ADR scheme, acknowledgements, downlink traffic and Firmware Over The Air (FOTA).

C. The use of simulators

As the IoT is potentially a highly profitable space, the LPWAN providers compete with one another for market share. One way to attract more customers is with bold claims of 10-year battery life and support for 10's of thousands of devices. These claims are another reason to develop simulators as they are very hard to verify, without the use of accurate simulators.

The IoT has the potential to bring improvements to several sectors of society but almost all of these improvements rely on scale. The benefits are only unlocked once a sufficient amount of data can be collected from enough points of interest. For example, if a smart city solution wants to optimise traffic flow, it must have access to traffic data from throughout the city and not only from a few locations. Simulators play an important role during the development of the wireless networks enabling IoT solutions, as the networks must be scalable and energy efficient without compromising security.

Deploying a LoRaWAN network is a costly endeavour, and thus businesses looking for innovation through the use of IoT technologies can use simulators to ensure their planned solution is feasible. Simulators can assist during the planning phases of a project to ensure that if customer demand scales, the correct technology was chosen to ensure the network can handle the increased demand.

Many simulator platforms for Wireless Sensor Networks (WSNs) exist, such as ns-3, OMNET++ and SimPy. Extensions for these platforms have been created to allow for the simulation of LoRaWAN networks. As the LoRaWAN protocol is still fairly new, simulation tools primary focuses on simulating the PHY layer and emulators, capable of simulating hardware and software, does not yet exist. Tools such as Semtech's LoRa modem calculator [17] are useful for quick calculations but cannot be used to analyse a network.

III. LoRaWAN simulators available

One of the first simulation tools released was LoRaSim, a discrete-event simulator implemented using SimPy [15]. The user can simulate a network consisting of N nodes and M sinks (gateways) spaced either randomly or in a grid in a 2-dimensional space. LoRaSim provides two evaluation metrics: Data Extraction Rate (DER) and Network Energy Consumption (NEC), whose output is an indication of the network as a whole, and not of individual node behaviour. LoRaSim was extended by its creators to add directional transmissions in [8], and can be found at https://www.lancaster.ac.uk/scc/sites/lora/.

To validate a fine-grained scheduling scheme, the authors of [2] expanded LoRaSim into a more comprehensive version. This version supports bidirectional communication, has an expanded energy consumption profile, accounts for duty cycle limitations, fading and the imperfect orthogonality of SFs. Additionally, it uses LoRaSim's log-distance path loss model and can be found at https://github.com/kqorany/FREE.

Another discrete-event simulator written in Java aimed at 915 MHz networks is presented in [11]. The simulator does account for the capture effect by implementing the findings of [12]. This simulator compared a received packet's calculated Received Signal Strength Indicator (RSSI) with sensitivity thresholds for the popular RFM 95/96/97/98 (W) LoRa transceivers when determining the Packet Delivery Ratio (PDR). This simulator was the only found for 915 MHz networks and is available at http://things.cs.ucalgary.ca/lorasim.zip.

Another expansion of LoRaSim is the development of LoRaWANSIM, detailed in [16], which added MAC layer features such as bidirectional communication. LoRaWANSIM inherits some of the issues for LoRaSIM and thus still assumes perfect SF orthogonality and is not open-source [13]. LoRaSim was also used as the basis for the work conducted in [18], which examined the impact of multiple IoT applications in a single network. This version is also not open-source.

To ensure the accuracy of their simulation model, the authors of [12] first conducted experiments in an RF shielded lab to assess the impact of two concurrent LoRa signals on each other. The constructed simulator is not a system level simulator and focuses only on uplink traffic in a single gateway EU based network. This simulator is also not open-source.

A closed-source MATLAB simulator is presented in [19] and was used to investigate the performance impact of confirmed traffic on a network. The simulator assumes perfect SF orthogonality, considered duty cycle restrictions and matches the SF used by uplink traffic for their DL feedback traffic.

In [20], a LoRaWAN class A simulator ns-3 module is presented. The simulator's output was compared with measurements from a testbed and with the results presented in [12], with good accuracy. The module can be used to evaluate energy consumption, accounts for the capture effect and is available at https://github.com/drakkar-lig/lora-ns3-module.

A ns-3 module to simulate LoRaWAN networks is presented in [13], capable of studying multi-gateway networks and bi-directional traffic but not energy consumption. The simulator's error model was derived from base-band simulations of a LoRa transceiver over an Additive White Gaussian Noise (AWGN) channel. This simulator is used for the work conducted in [21], in which single device mobility and multiple devices uniformly distributed is evaluated. It can be found at https://github.com/imec-idlab/ns-3-dev-git/tree/lorawan.

A class A ns-3 based simulator is presented in [22] for which the authors added downlink traffic support in [23]. The simulator does account for SF pseudo-orthogonality and was compared with the analytical model presented in [14]. The authors disagree with some of the choices made in the model and showcased that it does not take into account duty cycle limitations or SF pseudo-orthogonality. Available at https://github.com/signetlabdei/lorawan.

As LoRaWANs are used outside of the academic community, resources on their performance can also be found outside of academic circles. One such as example is a LoRa and Sigfox simulator created by Maarten Weyn which can be found at https://github.com/maartenweyn/lpwansimulation/. This simulator, like many others, focuses on the PHY layer and can be used to study this layer but should not be used to evaluate a LoRaWAN compliant network as it would then be considered incomplete.

LoRaEnergySim is a simulator focusing on energy consumption and supports the ADR scheme and downlink messages [24]. The simulator supports two channels models namely a log-distance model with shadowing and a COST 231 model. This simulator assumes perfect SF orthogonality and bases its gateway model of the WiMOD iC880A gateway. This Python based simulator is available at https://github.com/GillesC/LoRaEnergySim.

OMNET++ was used for the development of FLoRa [25], and was used to evaluate the ADR scheme. FLoRa can simulate the PHY and MAC layers, supports bidirectional communication and can also simulate the backhaul network. FLoRa can also perform energy efficiency simulations and similar to [24] based their ADR implementation on the implementation used in The Things Network [26]. This simulator is available at http://flora.aalto.fi.

Table I compares the different LoRaWAN simulators that are available and open-source. Some of the closed-source simulators have advanced features, but as these are not available to other researchers, they have been excluded. The simulator created by Maarten Weyn has also been excluded as its Github page lacks some of the detail required for inclusion in the table. It should be noted that this simulator does not consider the imperfect nature of SFs.

IV. DISCUSSION

A. Comparison between IoT use cases

Different IoT use cases have different requirements of the wireless networks that enable them, which in turn influences the requirements when choosing a suitable simulator. Table II shows how different use cases can place different requirements on LoRaWAN simulators. The aim of this table

TABLE I. COMPARISON BETWEEN OPEN-SOURCE SIMULATORS.

Reference	**Description**	**Imperfect SF**	**Capture effect**	**Downlink traffic**	**Duty cycle limitations**	**Energy consumption**
[8, 15]	LoRaSim	No	Yes	No	No	Yes
[2]	FREE	Yes	Yes	Yes	Yes	Yes
[11]	Java, 915 MHz	No	Yes	No	Implements North American requirements	No
[20]	ns-3 module PHY focus	No	Yes	No	Yes	Yes
[13]	ns-3 module MAC focus	Yes	Yes	Yes	Yes	No
[22, 23]	C++ simulator	Yes	Yes	Yes	Yes	No
[24]	LoRaEnergySim	No	Presumably, is based on [15]	Yes	Yes	Yes
[25]	FLoRa	No	Yes	Yes	Yes	Yes

TABLE II. IoT USE CASES AND THEIR SIMULATOR REQUIREMENTS.

Use case	Description	Design requirements	Simulator requirements	Recommended simulators
Smart city traffic monitoring	Monitoring traffic requires a large amount of sensors over a large geographical urban area.	Network must be scalable, gateway locations must be planned and communication must be able to withstand a city's noisy radio conditions	Simulate large node and gateway numbers, use data traffic and city radio interference models.	[13, 23]
Smart cold chain monitoring	Monitor storage temperature and humidity of items such as food as well as tracking of shipments.	Network must be scalable, support mobile communication and provide a device's location.	Simulator must be able to accurately model large networks, LoRa's behaviour when moving (see [27]) and give location accuracy estimates.	[13, 23]
Environmental monitoring	Large scale continuous monitoring of the environment such as water quality monitoring or gas level monitoring in mines.	Long range communication, low power consumption and the ability for confirmed uplinks if required.	Simulate large geographically spread networks, accurate energy consumption capabilities and simulating the impact of downlink traffic.	[2]

is not to describe all the possible IoT use cases, but rather to illustrate that they result in different simulator requirements.

The table also makes some recommendations for which simulator will suit each use case best. For the first use case, the simulator presented in [13] allows multiple gateways at fixed locations and different types of traffic to be simulated. This simulator is one of the most complete simulators available, with the drawback that it does not calculate energy consumption. Another simulator to consider as it allows multiple gateways would be [11], assuming the simulated network will operate in North America. Whilst [2] is also a comprehensive simulator, it only focuses on one gateway networks and would thus not be suitable.

The second use case has a requirement (tracking) which no simulator currently supports. The impact of the Doppler effect on LoRa has been documented in [27], but these findings have not been integrated into LoRaWAN simulators. Either [13] or [23] can, however, be used to simulate the network to see how it would perform when all nodes are stationary.

For the final use case, environmental monitoring, the simulator presented in [2] is recommended. This simulator supports downlink traffic and the proposed scheduling scheme would be worth considering in environmental monitoring situations where the gateway is only present periodically.

B. *Simulator design*

Simulators tend to be either designed either around a specific LoRaWAN regional specification, with the most popular being Europe. This has a big impact on the simulator as the frequencies used, SFs available, BW and Transmit Power (TW) limits differ greatly. In some cases, all that is required is a minor modification to an EU based simulator but ideally, a comprehensive simulator would support all of the available regions.

A simulator's wireless propagation model has a big impact on the output, and should ideally be interchangeable so that the correct model can be used. Different simulators use different models, for example in [12], the Hata-Okumura model for medium cities is used, [11] prefers a log-normal shadowing model and [2] uses a log-distance path loss model. Rural networks will also perform differently from urban networks and simulators should consider this.

Depending on the use case, the generated traffic can differ significantly. A simulator with which it is easy to specify a traffic model for devices is thus highly desirable. For example, with [11] the user can specify the type of traffic (deterministic or stochastic) and model parameters such as packet inter-arrival time. The simulator presented in [2], enables the testing of sending immediately versus buffering application data and sending it in bulk. Whilst [18] is not open-source, it allows simulations to contain multiple IoT applications each with their number of nodes and traffic models.

Some simulators such as [11, 12, 15] use data from conducted measurements when developing models. This helps to ensure the creation of a simulator which can accurately reflect deployed networks but is reliant on the validity and accuracy of the conducted experiments. A simulator that was tuned with measurements taken in one location (e.g. urban area) may not accurately reflect the performance achievable when used to evaluate a proposed rural network.

A common trend amongst the presented simulators is that they were created with a specific research objective in mind. In the papers that present a simulator, the simulator is briefly introduced before the main focus of the paper: the outcome of simulations. The simulator itself was not the primary goal. As a result, simulators are only as complex as needed, as a general purpose simulator was not the focus of the work. This hinders the progress of simulators, as they are seen as only a ``tool'' and not worthy of publication on their own. A fine example of this is the FREE simulator [2], which was created to allow a scheduling scheme to be compared with standard LoRaWAN.

Currently, this is an up to date simulator but future development is likely to be focused on their proposed scheduling scheme and not on the simulator itself.

C. Recommendations for future work

One method to improve the progress of the development of simulators is to study the simulators used for other mature wireless protocol such as Zigbee or Wi-Fi. These mature simulators can be used to determine the areas for improvement in the development of LoRaWAN simulators. For example, a simulator that can calculate the optimum configuration settings for a proposed network would be extremely valuable. This would require not only a detailed model of all aspects of a LoRaWAN but would need to consider the complex issue of which SF to allocate to the various nodes. Research such as [5], has pointed out that simple suggestions such as always allocating the maximum spreading factor (SF12) to the furthest nodes, may not result in the expected improvement in their PDR. The use of higher SFs does reduce the SNR required for successful demodulation, but the increase in packet collisions could potentially result in a decrease in network performance.

At this point, LoRaWAN research, deployed networks and thus simulators are all focused on class A end devices. Classes B and C are very unrepresented and this is an area where there is room for improvement. Another LoRaWAN feature which has been newly released is FOTA, and simulating the impact of firmware updates on a big network is crucial to ensure updates are done successfully.

The successful and accurate simulation of the impact of multiple gateways on a network is another key simulator requirement. As the deployment of devices in a network scales up, one of the first actions would be to increase the gateway density in the hope of improving network performance. Accurate simulations can ensure that new gateways are deployed to the right locations and with the optimum network parameters. Simulators that can take a proposed network's geographical location into account, similar to the work being done in [28], are needed.

The impact of multiple gateways is however not necessary an improvement. As LoRaWAN lacks the network operator approach followed by Sigfox, an urban area will contain several gateways owned and operated by different entities. Operator A might not be aware that the reason his small network of 50 nodes struggle with connectivity is due to the 5000 node network located in the same area under the control of operator B. Simulation tools that can simulate network interference from other LoRaWAN networks is required. A key feature in the future will also be the ability to simulate the effects of a different LPWAN technology, occupying the same frequency bands, on a network. The ISM bands are quite popular and examples of technologies interfering with LoRaWAN on the 868 MHz band include Sigfox, IEEE 802.15.4g, Z-Wave and IO Home Control [29].

V. Conclusion

As the LoRaWAN protocol is still fairly new, simulation tools for LoRaWAN networks are in early stages. There is room to expand and improve the existing simulators, to better handle complex situations such as multiple gateways, mobility and multiple LoRaWAN networks in the same area. Other areas include specifying and developing device traffic models for different subsets of nodes within a network. Currently, the use of more than one simulator is likely required as no simulator is currently far superior and offers a complete feature set. There are also several simulators which are closed-source, preventing other researchers from building upon existing work.

One of the fastest ways a simulator will become obsolete is if it doesn't receive regular updates, the LoRaWAN protocol itself is still developing, and the simulators must develop with it. In the end, one of the key factors is that a LoRaWAN simulator should be user-friendly, and has an active research and development community that delivers frequent updates to keep up with the rapid deployment of wireless networks by businesses. History is filled with great tools which were superior to their competitors, but their difficulty of use or being last to the market outweighed their technical superiority.

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