Optimizing Multi-hop Mechanism for the Long Range Wide Area Network

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Abstract

Long Range (LoRa) is a modem technology for wireless communication in Internet of Things (IoT), which trades off low data-rate for low power consumption. Long Range Wide Area Network (LoRaWAN) has an open specification that defines the Medium Access Control (MAC) protocol for LoRa networks. This paper contributes a simulation module in Network Simulator 3 (ns-3) to evaluate the limitation of LoRaWAN in various metrics. The result shows the performance of LoRaWAN in a simulation environment and a large scale scenario, indicating the feature of flexible propagation range on physical layer, and limited channel capacity on data-link layer. The feasibility of optimized multi-hop in LoRaWAN is analyzed. Based on the simulation result, a multi-hop mechanism driven by spreading factor is proposed, not only to extend the network coverage but to reduce the channel load. The novel approach takes benefit of the dynamic feature of LoRa and estimates optimized forwarding hops with parameter configuration. The result shows that Time on Air can be dramatically decreased.
1 Introduction

LoRaWAN is a Low Power Wide Area Network (LPWAN) specification intended for wireless battery operated things in a wide area. It is a type of wireless network designed to allow long range telecommunications at a low bit-rate among devices, such as wireless sensors, and to provide features specifically needed to support low-cost, bi-directional communication in IoT systems [1]. It is designed to communicate by half-duplex, over 5000m in an urban environment and supports large networks with millions of devices. LoRaWAN protocol is optimized for battery-powered end-devices that may be either mobile or at a fixed location [2]. When referring to this technology, LoRa defines a physical layer for low power wide area connectivity using the Semtech’s Chirp Spread Spectrum (CSS) radio modulation technique. Although the LoRa communications system implies a specific access on physic layer, the upper layer, data-link layer mechanism and MAC protocol are defined under LoRaWAN Specification [2] that was released to the public in July 2015. It is an open source standard being developed by the LoRa Alliance.

LoRa modulation is based on the CSS scheme which uses wide band linear frequency modulated pulses whose frequency increases or decreases correspond to the encoded information. A typical LoRa radio provides five configuration parameters: Transmission Power (TP), Carrier Frequency (CF), Spreading Factor (SF), Bandwidth (BW) and Coding Rate (CR) [3]. The ratio of chip rate to symbol rate is defined as the Spreading Factor (SF) in LoRa [4]. These parameters influence the modulation and propagation of LoRa, which impact the sensitivity of receivers and the coverage range. Time on Air of a LoRa transmission also depends, besides the payload size, on the combination of SF, BW, and CR. LoRa network is optimized specifically for energy limited end devices, and it does not use the Clear Channel Assessment (CCA) mechanisms [5] but relies exclusively on the end device duty cycle based channel access mechanism. A pure-ALOHA scheme is utilized on the data-link layer that in combination with LoRa physical layer enables multiple devices to transmit at the same time but using different channels and/or orthogonal codes.

LoRaWAN has three types of components: end-device, gateway and network server. End device serves as the role of a node in WAN of an IoT system. Gateway is the link between the wireless WAN and Internet. Network server on Internet is the processing center for packets via gateways. LoRaWAN has a star of stars on topology: end-devices are directly attached to gateways by wireless channels and they communicate with gateways using LoRa. Gateways are transparent bridges only responsible for bidirectional relays, or protocol converters. Gateways listen to multiple transmissions on multiple wireless channels [6] and they forward raw LoRaWAN frames from devices to a network server over a back-haul interface with a higher throughput. Network server, which is the brain of the LoRaWAN system, is responsible for decoding the packets sent by the devices and generating packets that should be sent back to the devices.

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1Semtech Corporation is a supplier of analog and mixed-signal semiconductors.
2https://www.lora-alliance.org
Relay and multi-hop option is not available by default. Neither Device-to-Device (D2D) communication mechanism is applied in LoRaWAN [7].

When LoRa devices have data to transmit, they use pure-ALOHA without Listen-Before-Talk (LBT) [8]. In particular, the duty cycle, defined as the percentage of time during which the channel can be occupied, arises as a key limiting factor for the traffic served by LoRaWAN. It is imposed by regulation in Europe with value 1% [9]. High coverage and satisfactory scalability under low up-link traffic are attractive. Nonetheless, the most decisive limitation, like low reliability and substantial delays for long ranges, can be problems for LoRaWAN.

1.1 Related Work

Related work of LoRaWAN is reviewed on three main themes: simulation implementation of LoRaWAN, evaluation and analysis of LoRaWAN performance: both in testbed experiments and in simulation, and multi-hop mechanism enabled for LoRaWAN, in real testbeds.

Based on information from the official LoRaWAN specification, simulations are implemented. Simulation proposed in the work [3] focuses on communication behavior of LoRaWAN. That simulator implemented in PySim is utilized to evaluate the performance and gives results related to the scalability of LoRaWAN. Another paper [7] proposes theoretical collision behavior simulation, showing the performance of LoRaWAN is limited and similar to pure ALOHA [8]. Compared to these two works, this paper proposes a network specified, integrated simulation module on physical layer, data-link layer and application layer. This simulation module can be applied to experiments, more customizable and ready for testing protocols on higher layers.

Actual experiments and analysis were conducted in the open air and several test beds consist of multi end-devices and a single gateway. The paper [5] indicates that the absence of CCA mechanism in LoRaWAN increases the probability of packet collisions thus compromising the reliability and may cause long channel access delays. It shows the limitation and condition of the capacity of an up-link channel available to a LoRaWAN node. Experiments in [10] also show the limitation of LoRa technology and that LoRaWAN is extremely sensitive to the channel load. Another work [11] investigates LoRaWAN capacity limits by combining practical experimentation and a simulation of theoretical collision behaviors. Based on these works, this paper focus on one specific parameter of LoRa and demonstrates the influenced coverage range and delivery ratio measurement.

Existing multi-hop [3, 11] for LoRaWAN take use of relay eligible nodes. These nodes must periodically send a beacon to advertise itself to nearby end-devices. Beacons are used for time synchronization and mark the start of an epoch. In the work [3], LoRaBlink was proposed, which is a MAC protocol for LoRa transceivers intended to support static multi-hop communication. The paper [11] also proposes static multi-hop of LoRaWAN in order to expand network coverage, by using unique spreading factor. Ground experiments are performed
to evaluate single relay path performance on various TX powers and packet sizes. Multi-hop protocols for low power are reviewed in the work [12]. As an extension of these work, where multi-hop mechanism is proposed all by using stationary relay node while the cluster is predefined by people, this paper focus on the dynamic parameter of LoRa and proposes a optimized multi-hop mechanism, not only for extending the network coverage but for reducing the channel load.

1.2 Statement of Purpose

This paper contributes a specific LoRa simulation module in ns-3, intended to evaluate the performance of LoRaWAN. Several metrics are selected to evaluate the LoRaWAN performance in simulation: Propagation ranges, delivery ratios, collision ratios and channel throughput. The result indicates effects of different spreading factors and finds the limitation of LoRaWAN in massive nodes scenario. Another contribution of this paper is one possible enhancement of MAC protocol, proposed as multi-hop forwarding among nodes driven by spreading factor, showing effects of multi-hop on the performance of LoRaWAN. Because of the flexibility of LoRa parameters, this idea is supposed to shorten the Time on Air, which will apparently reduce channel load, increase delivery ratio and expand network coverage range at the same time.

1.3 Paper Outline

This paper is structured as following: Section II presents the simulation approach with details into the module, followed by the simulation results and performance analysis. Section III indicates the benefit of multi-hop mechanism and proposes the forwarding rule among nodes driven by spreading factor. Section IV concludes this paper and outlooks the future work.

2 LoRa Simulation Module for ns-3

This section introduces key points of the simulation mechanism, including a logical channel model and a device model. The propagation loss model is detailed to evaluate the propagation range of LoRa. Typical simulation scenarios are created to measure the performance and result is shown afterward.

2.1 Overview of LoRa module for ns-3

Ns-3\footnote{https://www.nsnam.org/} is a reliable discrete-event network simulator for network systems and it is widely used today in the networking field. LoRaWAN module was implemented in ns-3 and test scenarios are arranged in it. In the simulation module, various parameters can be configured for customization to test the performance of LoRaWAN. Figure\footnote{Figure 1} illustrates the structure of the LoRa module in ns-3.
It is constructed as on three layers: physical layer deals with the propagation model and the mobility model. Data link layer is responsible for the wireless channel access and RX/TX scheduling on device. Application layer manages packets and processes reactive/proactive network actions. All models on different layers are associated horizontally and vertically. A detailed study on this simulation module will be presented in another paper.

LoRa devices work on the data-link layer. Device instances are attached to channels while channels share the propagation model. For each network event like TX/RX on devices, there is a link with the channel attached. Devices are responsible directly for proactive and reactive network events. Taking into account the half-duplex feature of LoRa device, there is a FIFO (First In, First Out) queue on device for TX. End devices and gateway inherit the same class, which implements functions in common like TX and RX. Meanwhile there exists three main differences between the gateway and the end-device by default: Gateway holds a continuous reception mode and the end-device can depend on reception slots. Gateway has multi channels process, while the end-device uses only one channel and process. Gateway does not have reception window, always listening to all channels for the reception.

LoRa channel instances simulate logical behaviors of LoRaWAN on data-link layer, and related to physical layer. The LoRa logical channel includes a set of parameters: CF (in mHz), SF, CR and BW (in kHz). When a device is busy receiving a packet on a channel, if another packet arrives, a collision will be detected and both packets will be lost. If a device is busy sending a packet on the channel and a packet arrives, the new arrival will be dropped. Multi devices can work on the same channel. Physical behaviors of transmission on the channel are associated with the propagation model. When a transmission is scheduled, the channel calls the propagation model to calculate delay information. Each channel defines its Signal Noise Ratio (SNR), receiver sensitivity and data-rate according to its parameters. These information is calculated and stored in the channel, as the calculation details are presented next.
2.2 LoRa Propagation Range

Log distance propagation model is typically used in the simulation to calculate the path loss in long distance which is estimated by geographical positions. A specific LoRa propagation model is implemented in the simulation module. This proposed model can be utilized to briefly estimating the communication distance for LoRa technology in typical urban areas. The propagation path loss is calculated as below:

\[ L = L_0 + 10n\log_{10}(\frac{d}{d_0}) \]  

where:
- \( n \): the path loss distance exponent,
- \( d_0 \): reference distance (m),
- \( L_0 \): path loss at reference distance (dB),
- \( d \): distance (m),
- \( L \): path loss (dB).

Considering the expected free space without shadow fading (\( \sigma \)), the path loss exponent \( n \) is 2.00 and the path loss intercept (reference loss) \( L_0 \) is 91.22 dB. The reference distance \( d_0 \) is 1km. In real environment, the path loss is typically higher than the value of in free space (shown in figure 2). For a simulation correspondent to the outdoor urban environment, the on-ground value is implemented in ns-3. The expected path loss exponent \( n \) is 2.32 and the path loss intercept (reference loss) \( L_0 \) is 128.95 dB. This may be caused by buildings and other obstacles blocking the path between the end-device and the base station. It can be observed that a part of the LoRa receiver RSSIs in on-ground case is located between the boundary of LoRa minimum and maximum sensitivities, which indicates a reasonable model parameter.

According to LoRa modulation SNR table, a linear equation is figured out. SNR can be calculated by:

\[ SNR = C - L - L_{int} \]
\[ SNR = 10 - 2.5SF \]  

(2)

where: \( SF \) is the spreading factor ranging \((7, \ldots, 12)\).

Based on the information from Semtech SX1272 [1], the sensitivity \( S \) of a radio receiver attached to a channel at room temperature is given by:

\[ S = -174 + 10 \log_{10} BW + NF + SNR \]

(3)

where: \(-174\) is due to thermal noise in \(1Hz\) 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 is 6 [4]. \( SNR \) represents the signal to noise ratio required by the underlying modulation scheme.

**Estimation:** To evaluate the propagation range of LoRa networks, \( SF \) and \( BW \) are selected to be variables. The network topology is simple: a single node and a single sink. CF is 868.1\(MHz\), CR is 1, and TX power is 14\(dBm\).

![Figure 3: Propagation range and spreading factor](image)

Depending on the minimum sensitivity of different channels and using the propagation model described before, the LoRa propagation range is illustrated in figure 3. This calculation in simulation shows the limitation of LoRaWAN maximum coverage range, which is approximately 8\(km\). It can be observed that a lower bandwidth gives a longer propagation range. It needs to be noted that a higher spreading factor always increases the propagation range, thus network coverage.
2.3 LoRaWAN Channel Performance

As the result of simulation on physical layer is presented above, target of this experiment is to study the performance of LoRaWAN on data-link layer. Thus the first part is to test the network performance like delivery ratio related to SF, and to find collision rate and throughput in limitation.

**Experiment parameters:** In following tests, CF is 868.1 MHz, BW is 125 kHz, CR is 1, and TX power is 14 dBm. A packet has payload of 59 bytes, which is the maximum value for the lowest data-rate, with additional 12 bytes for the header. Thus frame size is 71 bytes. Star network topology is constructed by placing nodes in a grid while ensuring the gateway is reachable for all nodes. Up-link traffics are captured on the gateway side to simulate the information collection. In this network, multi nodes (end-devices) and a single sink (gateway) share one LoRa channel. Simulation ends after all transmissions finish. Scenarios were run by an automated script for multi times (10 runs in this paper) with different random parameter for scheduling. Then generated traffic traces are captured to calculate the average (with variance< 0.025). The time resolution of the event trace is on millisecond level and propagation delay is ignored because it is on the nanosecond level.

**Experiment 1:** First experiment has the purpose to evaluate the performance of LoRaWAN with different spreading factors. SF and number of nodes are variables in this test. Each node sends 100 packets in total and the retransmission delay is 191.961 second (max duty cycle). All nodes begin to send the first packet randomly during initial 193.9 seconds.

![Figure 4: Arrival ratio and spreading factor](image)

In simulation result figure 4, four lines with points show the delivery ratios obtained on the gateway. Obviously larger amount of node leads to lower
delivery ratio. It can be observed that a higher spreading factor dramatically decreases the delivery ratio. As similarly indicated in [1], a higher SF gives a lower data-rate for transmission, which results in a longer Time on Air. There is a significant influence of different spreading factors on the delivery ratio, the lower, the better.

**Experiment 2:** Second experiment was performed to estimate the limitation of LoRaWAN capacity, while the duty cycle is fixed in condition. Number of nodes is variable in this test. Maximum $SF = 12$ is taken and one frame has a transmission duration of $1.939$ s. In order to reach the maximum duty cycle of $0.01[2]$, which means 1 packets should be transmitted during a period of $193.9$s, the transmission interval should be $191.961$s ($0.99\times$ total time period) for one node. Each node sends 100 packets in total. All nodes start to send the first packet randomly during initial $193.9$ seconds.

![Figure 5: LoRaWAN limitation for duty cycle 0.01](image)

Figure 5 shows the result in ns-3, estimating the collision rate on the gateway and throughput of a single LoRa channel where there is different number of nodes with a constant duty cycle. It can be observed that under the stress of high loading, a system with LoRaWAN uses at most $26\%$ approximately of the total resources on one shared channel. Larger amount of node reduces throughput on a single channel.

Experiments show that on physical layer, LoRa propagation range is flexibly related to SF. On data-link layer, LoRaWAN channel capacity, represented by delivery/collision ratio and throughput, is significantly affected by parameter SF.
3 Multi-hop Forwarding for LoRaWAN

As concluded in previous section, LoRa’s dynamic parameter: spreading factor, has a significant impact on the communication range and delivery ratio. This section analysis multi-hop influence on LoRaWAN and describes the multi-hop mechanism driven by spreading factor on data-link layer as a possible enhancement.

3.1 LoRa: Single hop v.s. Multi-hop

For wireless networks, multi-hop extends network coverage [12]. On the other side, in LoRaWAN, for a given distance, using multi-hop can reduce the channel occupancy because lower spreading factor gives a higher data-rate, thus, a shorter Time on Air [10]. An expected distance less than 8km can be reached by a single hop (refer previous section). It can be reached by multi-hop equivalently, and, it consumes less Time on Air under some conditions. The multi-hop forwarding is expected to reduce the channel load by decreasing the transmission delay and to ameliorate the performance. The performance of a manually defined multi-hop is assessed in the simulation.

Compared to one sink on a single channel, problem occurs on relay nodes in always listening mode, where collision is highly increased since the multi-hop cases more receptions and interference on channels. Time Division Multiple Access (TDMA) technique [11] on channel and using Carrier Activity Detection (CAD) [3] are both proposed solutions using local beacon for requesting a multi-hop and avoid interference. By default LoRa devices have a continues listening mode (Class C [2]) that cost more power consumption. End-devices which will act as relays often have only one LoRa interface, thus they need to do a channel switch, i.e. change LoRa modulation parameters. For simplification in this study, the relay node is assumed to keep awake in a always listening mode and hold two channels: one for reception and one for transmission.

![Figure 6: Single hop v.s. multi-hop topology](image)

**Experiment 3:** In ns-3, a comparison was carried out between single hop and static 2 hop forwarding cases. Experiment parameters in common stay unchanged as in previous section. Assuming there is a network of star topology,
which includes single sink and 5 nodes, being replaced by a tree topology including single sink, 5 leaf nodes and 5 additional relay nodes (figure 3.1 and 3.1). Each leaf node sends packets to one corresponding relay node. Leaf node sends 100 packets in total and transmission intervals is a variable. Individual channels linking leaves to relay nodes use $SF_1$ and the shared channel linking to gateway uses $SF_2$. In this case, the distance between nodes and gateway is assured reachable, different SF sets $\{SF_1, SF_2\}$ are tested. Collision happens on the shared channel, among relay nodes and the gateway. Relay nodes are assumed to be only working for reception and forwarding in continuous listening mode (Class C LoRa device).

![Figure 7: Single hop v.s. multi-hop arrival rate](image)

As shown in the result (figure 7), apparently by slowing down the duty cycle (TX intervals), delivery ratio increases. Although traffic density is not too dense, in the worst case, single hop with large spreading factor 11 gives its delivery ratio less than 0.8. Result show that multi-hop with a lower SF combination provides a higher delivery ratio: SF set $\{7,9\}$ is better than $\{8,10\}$ and $\{8,9\}$ is better than $\{9,11\}$, all better than a single hop with SF $\{11\}$. Even TX may block in relay nodes, the mechanism of forwarding is shown to dramatically increase delivery ratio without touching TX intervals. However, this is not optimized: propagation range related to SF should be highly considered because SF cannot be directly switched if the distance is unknown.

### 3.2 Spreading Factor-Driven Multi-hop

Without considering propagation range of each SF, a comparison is drawn between the transmission delays of a single hop and multi-hop (2 hops) in the previous part. In that case, if the distance is known, the best multi-hop can be
Table 1: Optimized SF Configuration

| Range(m) | ≤ 3003 | ≤ 3849 | ≤ 4933 | ≤ 6322 | ≤ 8103 |
|----------|--------|--------|--------|--------|--------|
| 1 hop SF | 7 or 8 | -      | -      | -      | -      |
| 2 hops SFs | - | {7, 7} | {7, 8} | -      | -      |
| 3 hops SFs | - | -      | -      | {7, 7, 7} | -      |
| 4 hops SFs | - | -      | -      | -      | {7, 7, 7, 7} |

estimated. Assuming there is an end-device using a constant bandwidth $BW$ and a constant coding rate $RC$ as conditions. In a single hop transmission, the data-rate $r(SF)$ of the node is limited by the spreading factor, as shown below:

$$r(SF) = RC \times BW \frac{SF}{2^{SF}} \text{bits/sec}$$

(4)

An expected propagation distance $d$ can be divided by $n$ hops as hop number $i \in [1, n]$. The spreading factor for each hop $i$ is $SF_i$, and $d(SF_i)$ is the maximal reachable distance of $SF_i$. Assuming the packet is comprised of size $p = 1KB = 8000bits$ for simulation. The transmission delay of the whole path is thus $\sum_{i=1}^{n} \frac{p}{SF_i}$. At the same time propagation range should be reached by using $SF_i$ as the condition $\sum_{i=1}^{n} d(SF_i) \geq d$. The optimized proposal is to find a best choice for $n$ and set $\{SF_i\}$, which means to find:

$$\arg \min_{SF_i} \left( \sum_{i=1}^{n} \frac{p}{RC \times BW \frac{SF_i}{2^{SF_i}}} \right) \text{subject to } \sum_{i=1}^{n} d(SF_i) \geq d$$

(5)

Considering different $SF \in [7, 12]$, which gives a various of propagation ranges. Everyone prefers to use minimum $SF$ in order to reach the highest data-rate (local optimization), a greedy geographic approach [15] can be applied to construct tree structure from gateways as roots, and each branch is a single relay path. With this multi-hop forwarding mechanism, nodes transmit messages to closer neighbors by using lower SF values. By using the simple enumeration and comparison, the best multi-hop with switched spreading factor can be figured out, thus, optimized total transmission delay can be found (2, 3 and 4 hops here, table 3.2 figure 8).

As shown above, compared to the single hop, where increasing $SF$ dramatically boosts TX time, after $3003m$, multi-hop has a lower Time on Air especially in long range relay, which will result in a lower channel occupancy rate. A larger number of hops does not always lead to a smaller TX time, and it tends to have a final and stable boundary. When the distance is sufficient, the path with more hops of smaller $SF$ is relatively better. Applying the forwarding rule driven by spreading factor for distance $0 - 8103m$, result show that for $0 - 3003m$ single hop with SF 7 or 8 is he best, for $3003 - 4933m$ two hop with SF $\{7, 7\}$ and $\{7, 8\}$ is the best, for $4933 - 6322m$ three hop with SF $\{7, 7, 7\}$ is the best.
and for 6322 – 8103m four hop with SF \{7, 7, 7, 7\} is the best. The multi-hop number and SF set allocated to the corresponding distance is thereby found. Any distance longer than 8130m can be combined from shorter distance relays, as indicated in the work [11]. How to construct multi-hop paths in a graph will be studied in future.

4 Conclusion and Future Work

This paper presents a simulation module of LoRaWAN in ns-3, on physical, data-link and application layer. Simulation scenarios are set up to evaluate the performance of LoRaWAN, showing the flexible coverage range and channel capacity according to diverse spreading factors. Considering this dynamic feature of LoRa, the multi-hop forwarding mechanism driven by spreading factor is proposed as an enhancement of the LoRaWAN MAC protocol. Locally optimized spreading factor switching is proposed and experiments show that Time on Air is reduced while channel capacity is thus improved.

As the proposed multi-hop introduces more complexity of LoRaWAN. In future, allocation of channel and scheduling of beacon are problems remaining to be studied. An approach depending on RSSI-based trilateration will be explored to control and define the topology in order to manage multi-hop paths according to the estimated position information.
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