Trilateration-based Multi-hop for the Long Range Wide Area Network

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Abstract

Long Range Wide Area Network (LoRaWAN) has an open specification that defines the Medium Access Control (MAC) protocol for LoRa networks, mainly based on pure-Aloha with beacon option. The LoRaWAN has a star of star topology where end-devices are directly linked to the gateway and up-link packets are primary traffics. This paper contributes an approach of multi-hop in LoRaWAN. The potential benefits of multi-hop in LoRaWAN is investigated. A RSSI-based trilateration algorithm for graph construction is proposed. The shortest path for multi-hop and forwarding mechanism without local beacon are designed and implemented in simulation. This novel approach is tested in ns-3 simulator and different scenarios are run. Results show that multi-hop can decrease the energy consumption of LoRaWAN, by reducing Time on Air and TX power.
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1 Introduction

This section introduces the background of LoRaWAN technology and the motivation of this work. It gives a review on related work, states the contribution of this paper and provides a content outline as well.

1.1 LPWAN

The Internet of things (IoT) is 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. Each thing is uniquely identifiable through its embedded computing system but is able to inter-operate within the existing Internet infrastructure. It is bringing revolution to industrial world, academic area and daily life and experts estimate that the IoT will consist of about 30 billion objects by 2020. Typically, IoT is expected to offer advanced connectivity of devices, systems, and services that goes beyond machine-to-machine (M2M) communications and covers a variety of protocols, domains, and applications. The interconnection of these embedded devices, is expected to usher in automation in nearly all fields, while also enabling advanced applications.

As the connectivity among Things is usually assured by wireless network, telecommunication technology plays an important role in the IoT system. Low Power Wide Area Network (LPWAN) represents a novel communication paradigm, which will complement cellular network and short range wireless technologies in addressing diverse requirements of IoT applications. One feature is that most of currently proposed long range and low power IoT technologies use the unlicensed bands. LPWAN technologies offer unique sets of features including wide-area and single-hop communication, trading off low data-rate for long range, which are not yet provided by legacy wireless technologies. Their market is expected to be huge: approximately one fourth of overall 30 billion IoT/M2M devices are to be connected to the Internet using LPWANs by using either proprietary or cellular technologies. These business sectors include but not limited to smart city, personal IoT applications, smart grid, smart metering, logistics, industrial monitoring, agriculture, etc[1].

There exists various LPWAN technologies, such as LoRa, SigFox (Ultra Narrow Band), NB IoT (Narrow Band), LTE-M. LoRa is modulation technology invented by Semtech[1] for low power and long range wireless communication. It uses Chirp Spread Spectrum (CSS) modulation to provide high sensitivity, orthogonal channels and good resistance to interferences. LoRaWAN is a competitive type of LPWAN with a open specification[2] for Medium Access Control (MAC) defined by LoRa Alliance[2]. A typical LoRaWAN is defined to have four components: end-devices, gateways, network servers and applications. It has a star of star topology where the end-devices communicate with the gateways directly by LoRa wireless channels (figure[1]). The gateway holds a back-haul

1Semtech Corporation is a supplier of analog and mixed-signal semiconductors.
2https://www.lora-alliance.org
to the network server through the traditional IP link and the applications are deployed, linked to the server by IP as well. It should be noted that the gateway does not proceed packets but only do a role of forwarder, instead, it is the network server who controls the whole network topology and patterns of traffics.

### 1.2 Localization

Localization can be used in various applications such as determining coverage area of network, monitoring location changes, geographical area-based routing, and location directory services. Localization of a target node with unknown position in a wireless system is performed using a few nodes with fixed position, called anchor nodes[3]. The trilateration technique is used to compute the location of a node with the distance measurements obtained by three anchor nodes. The localization process is generally comprised of three phase: distance estimation, position computation, and localization algorithm.

In the distance estimation, the relative distances between the nodes are estimated via the measurement techniques. The four common measurement techniques can be classified as the angle of arrival (AoA), time of arrival (ToA), time difference of arrival (TDoA), and received signal strength indicator (RSSI)[4][5]. This RSSI technique has the advantage of requiring no additional hardware since the RSSI feature exists in most wireless devices, and there is no significant impact on the local power consumption[4]. Localization with the RSSI is possible due to its relationship with distance: the nearest are the nodes, the higher is the RSSI value. It is not accurate enough to use the RSSI because it is very unstable, due to path-loss, fading, and shadowing effects of the radio waves. On other side, it is the RSSI donates the link quality in a real environment, which can be a key factor to decide the network topology. Real geographic position does not equals to the position estimated by RSSI, and the latter can be used to determine a network topology based on link quality in fact.
1.3 Related Work

RSSI has been introduced to multi-hop forwarding as a decision parameter in proposed approaches. For multi-hop WSN, [6] proposes a cross-layer integrated medium access control routing protocol called RSSI-based Forwarding, based on a RSSI as a routing parameter. Furthermore, [7] proposes an improvement of the suppression scheme in which a contender closer to the sink is favored with a higher probability for being selected as a next-hop node. When a beacon transmitted by the sink arrives on nodes in the network, receiver power levels are computed and then they are used as a decision parameter for the nodes to contend for the forwarding task. This approach requires for Device-to-Device (D2D) communications, thus the local broadcast and handshakes among nodes for relay will introduce more complexity. The WSN is supposed to be Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and the approach uses four way RTS-CTS-DATA-ACK handshake. The proposed protocol shows a low latency and robust data delivery.

An RSSI-based opportunistic routing protocol for mobile WSN is proposed in [8], named OR-RSSI. Opportunistic probability based on the RSSI of the sinks beacon packets and mobility vector are established. The best node with the highest probability available at that instant is used to store and relay packets at each hop after packets are broadcast. OR-RSSI is more feasible for sparse mobile WSN and outperforms TinyAODV. Furthermore, [9] proposes a similar opportunistic routing protocol but for multiple alternative sinks. This approach also needs to introduce more D2D communication in order to avoid multiple forwarding candidates because the source node is always sending packets by a broadcast.

Another method is proposed in [10], which is a RSSI-based AODV protocol. It measures signal strength between nodes and compare with RSSI threshold values if it is greater than threshold value then it is accepted for further processing otherwise it is discarded. The benefit of this scheme is by selecting a strong route to the destination we can increase the lifetime of the network. Simulation results show that the proposed approach has performance better than AODV routing protocol in terms of the metrics: packet delivery ratio, throughput, routing overhead. This approach takes benefits of local beacon RSSI to estimate routing.

A balanced-clustering, energy-efficient hierarchical routing protocol is proposed in [11], called BCEE. The protocol BCEE operates in two phases. The balanced cluster formation is achieved by applying the k-means clustering strategy, which requires no exact position of each node but use RSSI. The optimal paths between each cluster head to sink node are found by using algorithm which provides an effective multi-hop data transmission method. The results show that cluster and relay offer significant reductions of energy consumption and prolongs network lifetime hugely. This approach encourages to discovery the possibility of clustering, i.e. a closest gateway for LoRa.

Besides the use of RSSI, existing multi-hop for LoRaWAN take use of relay eligible nodes. The paper [12] proposes static multi-hop of LoRaWAN in
order to expand network coverage. A protocol was implemented on the LoRa end-devices by adding a Time Division Multi Access (TDMA) technique to the standard specification. The key idea is that each relay eligible node must periodically send a beacon to advertise itself to nearby end-devices. In the paper [13], LoRaBlink was proposed, which is a MAC protocol for LoRa transceivers intended to support static multi-hop communication. 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. Multi-hop improves the reliability of communication and energy efficiency, meanwhile it effectively enlarges the coverage area. All nodes communicate by constant range, instead LoRa provides a dynamic range.

Another work [14] analyzes the impact on LPWAN energy consumption of multi-hop communication in the up-link, allowing nodes to transmit data packets in lower power levels and higher data rates to closer parent nodes, reducing their energy consumption consequently. Results show that enabling such multi-hop connections entails higher network lifetimes, reducing significantly the bottleneck consumption in LPWAN with up to thousands of nodes. A simple and ideal TDMA MAC layer with no packet collisions is assumed in this approach, and the network topology is a multi rings structure, which is assumed to be a known premise.

A multiple access protocol with time-slot reservation is proposed in [15] that can increase the success rate of the up-link data transmission with collision avoidance in the LPWAN. The end device performs frequency hopping and slot reserving between retransmissions until retry counter does not exceed the number of the used channel frequencies, it opened receive window after each retransmission until the time slots have expired. The gateway encodes the usable slot mask field to indicate the slots not used by end-device which uses the same frequency as the up-link.

A detailed survey [16] on routing protocols of WSN indicates the main design criteria are to lower algorithmic complexity to facilitate low-power solutions for end-devices and not to jeopardize reliable and efficient communications for others. Most of existing protocols for WSN, like proactive routing and reactive routing, depend on end-devices to calculate the routing path by themselves. While in a center controlled network like LoRaWAN, it is considered that the network topology can be decided by the server.

In a network with unpredictable mobility, multi-hop communication, and no clock synchronization, the necessary use of beacon plays an important role in power management [17]. TDMA technique [12] on channel and using Carrier Activity Detection (CAD) [13] are both generally proposed solutions using local beacon for requesting a multi-hop and avoid interference. All approaches above require local beacon for broadcast information, while LoRa simply implements a pure-Aloha mechanism by default. The position discovery for topology construction and multi-hop without local beacon are not studied before. Since the final destination of up-link is always the gateway, each node can send or forward packets to only one specific destination, i.e. whether gateway or next hop. An approach of gateway allocation and multi-hop without use of local beacon is
studied in this paper.

1.4 Contribution

As a LPWAN solution, LoRaWAN has its significant advantage and limitation due to MAC\[18\]. First of all, the Aloha-based access is considered as one of main limitation as it decreases the network capacity due to a high collisions rate. Due to the non-listen-before-talk access in such unlicensed bands, some strategic allocation mechanisms of gateways for end-devices have to be studied to limit the collisions. Secondly, in the current state of the art, long range network for IoT, especially LoRaWAN, is organized with a single-hop star of star topology. However multi-hop strategies can be investigated to figure out their potentials in reducing the Time on Air and TX power therefore improving the capacity by reducing power consumption. Hence a new approach in LoRa MAC is required and has to be proposed to enhance the system capacity of LoRaWAN.

In a IoT system, end-devices usually has limited capacity and power, while most of previous work use end-devices to do local processing for find the forwarding path, this work focusing on an approach using the centered network server to do whole calculation and to control the network topology globally. The motivation of this work is to propose specific gateway allocation and beacon-free multi-hop strategy for LoRaWAN, taking benefits of the star topology and center controlled mechanism, as an enhancement on MAC protocols.

This paper proposes a strategy controlled by the central network server for up-links in LoRaWAN. It is based on RSSI trilateration, for the purposes of best gateway allocation with proper parameters and shortest path multi-hop without local beacon. The RSSI trilateration is contributed to graph construction, especially for the purpose of gateway allocation and finding shortest up-link path. The simulation scenario of this strategy is also carried out and results show the benefits of delivery ratio and power consumption.

1.5 Outline

The remainder of this paper is organized as follows: Section 2 illustrates the RSSI-based trilateration for constructing the graph, section 3 describes the specific benefits of multi-hop in a single path LoRa wireless network, section 4 presents the algorithm to find the shortest path for up-link, and the forwarding procedure, section 5 demonstrates an experiment in simulation, showing the enhancement result of this approach, followed by section 6 giving an limitation analysis of this approach. Section 7 concludes this paper.

2 RSSI-based Trilateration

This section carries out the trilateration approach based on RSSI, according to the specific propagation model, for the purpose of building network topology.
Trilateration scope is attained from the proposed propagation model, and the trilateration procedure by broadcast is also presented.

2.1 Propagation Model

The propagation model is the key factor for distance estimation in trilateration procedure, as it deduces the relationship among propagation distance, transmission power and RSSI. The received signal strength is affected by three phenomena: path-loss, fading and shadowing\[19\]. 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. The 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. Shadow is the loss of signal due to obstacles (walls, buildings, trees, cars, people, etc.) between a transmitter and a receiver. Shadow fading combination can be modeled as a random process in simulation.

A specific LoRa propagation model is proposed to be utilized briefly estimating the communication distance for LoRa technology in free space areas, i.e. a Line-of-Sight (LoS) environment. This proposed model is also implemented in the ns-3 simulation module. Although the majority of embedded system operates in a Non-Line-of-Sight (NLoS) environment. Based on empirical data, this fairly general model has been available for both LoS and NLoS propagation\[20\]. Practically, a simplified form of the relation between distance and received power is often used as a form below\[19\]:

\[
P_R = P_T - EPL - \sigma_{SF} \tag{1}
\]

where \(P_R\) (in dBm), \(P_T\) (in dBm), \(EPL\) (in dBm) and \(\sigma_{SF}\) (in dBm) are received signal power (RX Power), transmitted signal power (TX Power), expected path loss and shadow fading combination respectively.

In embedded devices, the received signal strength is converted to a received signal strength indicator (RSSI) which is defined as ratio of the received power to the reference power \(P_{ref}\). After converting the ratio to a form in dBm unit, RSSI is represented by:

\[
RSSI = P_R - P_{ref} \tag{2}
\]

where typically, the reference power \(P_{ref}\) represents an absolute value of \(P_{ref} = 1mW = 0dBm\)[5]. Hence this deduces an propagation model to estimate the RSSI (in dBm) according to TX power and expected path loss in simulation:

\[
RSSI = P_R = P_T - EPL - \sigma_{SF} \tag{3}
\]

where \(P_T\) is by default 14dBm at LoRa end-device. RSSI is expected to be the measured value on LoRa receivers.

In fact the shadow fading \(\sigma_{SF}\) is attained from real measurement and regressed expectation, as a standard deviation. Taking into account the shadow and fading factor, the measured deviation depends on the environment:
\[ \sigma_{SF} = \text{std}(PL - EPL) \] (4)

where \( PL \) is the measured path loss in a specific environment. For an on-ground LoS scenario it can be \( \sigma_{SF} \leq 2.382 \).

The log distance propagation model is typically used in the simulation to calculate the expected path loss in long distance which is estimated by geographical positions[21]. The expected propagation path loss is calculated as below:

\[ EPL = PL_0 + 10n\log_{10}\left(\frac{d}{d_0}\right) \] (5)

where \( PL_0 \) (in dB) is path loss at reference distance, \( n \) is the path loss distance exponent, \( d \) (in m) is the distance between the transmitter and the receiver, \( d_0 \) (in m) is reference distance.

| Frequency | Bandwidth | \( n \) | \( d_0 \) | \( PL_0 \) |
|-----------|-----------|-------|--------|-------|
| 868.10MHz | 125kHz    | 2.101 | 10m    | 80.310dB |

From the measurement scenario with testbed, path loss parameters for on-ground LoS case was taken into consideration. The results were obtained from large up-link traffics, i.e. the data transmitted from a end-device to the gateway in a LoRaWAN system. In a NLoS environment, the path loss has typically higher than the value of in free space. This may be caused by buildings and other obstacles blocking the path between the end-device and the gateway. The path loss exponent and path loss intercept for the on-ground LoS case are attained from a regression on measured data set. Considering a expected free space without shadow fading (\( \sigma \)), the path loss exponent \( n \), the reference distance \( d_0 \) and the path loss intercept (reference loss) \( PL_0 \) have values in table 1. Thus the expected propagation path loss can be estimated:

\[ EPL = 80.310 + 10 \cdot 2.101 \cdot \log_{10}\left(\frac{d}{10}\right) \] (6)

The TX Power of transceivers is 14dBm by default in this paper. Figure 2 illustrates the RSSI values along with the propagation distances under the given configuration and parameters in table 1. The maximum propagation range of a LoRa transceiver can reach 20 km in such a LoS free space on ground. It also show the minimum Spreading Factor (SF = 7) and maximum spreading factor (SF = 12) of LoRa can give lowest and highest sensitivities for RSSI respectively.

Since the RSSI is calculated by propagation path loss model, inversely, if the RSSI is known and the TX power is informed, a receiver can estimate the distance from itself to the transmitter. In this case, the distance from a node to the gateway can be deduced by RSSI value. When the RSSI does not equals (less
in fact) to TX power, which means a path loss, according to (5), the estimated distance can be given by:

\[ d = 10^{\frac{EPL - PL_0}{10}} \cdot d_0 \]  \hspace{1cm} (7)

It should be noted that a distance under \( PL_0 \) can not be estimated because a range under 10m has no propagation loss according to the model illustrated below. That is, if the RSSI in a gateway equals to the transmitted signal power, which means the propagation range is less than or equal to 10m, then the node can not be positioned accurately because the distance cannot be estimated. It does not affect much compared to the whole trilateration scope, and it is close enough to the gateway. Except these too closed nodes, a propagation distance \( d \) beyond 10m can be estimated by:

\[ d = 10^{\frac{EPL - 80.310}{10^{2.301}}} \cdot 10 \]  \hspace{1cm} (8)

While the expected \( EPL \) without shadow fading \( \sigma_{SF} \) is the difference between TX Power and RSSI in dBm. But in a real world environment with shadow fading, only real PL can be calculated by measurement:

\[ PL = PT - RSSI \]  \hspace{1cm} (9)

Because the random factor, shadow fading cannot be estimated and RSSI is an integer value (dBm), the inverse calculation from RSSI to distance introduces inaccuracy. The propagation of the radio signals may be affected by reflection, diffraction, and scattering. Especially in indoor environments, such effects may impact the measurement accuracy. Therefore, this technique is more suitable for
outdoor, rather than indoor applications\[4\]. In order to overcome the problem introduced by random variable: shadow fading, RSSI measure can be done in bi-direction. For example, one up-link requiring one acknowledgment (down-link), followed by another up-link including down-link RSSI information. Multiple RSSI values can be utilized to estimate distance, and a possible solution will be then to realize an important averaging to smooth these variations. Since the deviation elimination is not main consideration of this work, for simplification, the expected path loss without shadow fading is assumed in this paper. The rest of this paper take use of this propagation model and is all under the assumption:

**Assumption 1:** The environment for wireless propagation is a free space without shadow and fading deviation:

\[
EPL \approx PL
\]  

Till now the formula to attain the distance estimation from a known RSSI value and the TX power is introduced below:

\[
d = 10^{\frac{P_T - RSSI - PL_0}{10n}} \cdot d_0
\]

This propagation model, including RSSI-based distance estimation, will be utilized in both trilateration and optimised parameter configuration of LoRa in section 3.

### 2.2 Trilateration Scope

Since the distance can be estimated by two given conditions: TX power and RSSI, localization od end-devices can be done by taking use of these distances. There are various known range-based localization techniques. A number of methods based on the strength of RSSI have been proposed with different complexity. Three of the most used methods for RSSI-based localization use only three reference sinks, which is the minimum to triangulate a target's position. Two of the techniques are based on geometric considerations, Min-Max and Trilateration, while the last one is a statistical method based on the Maximum Likelihood of the measured values\[3\][19][22].

Trilateration\[3\][20] is a geometry-based algorithm requiring least data and giving large scope. The distance \(d_i\) estimated from the RSSI values is used to compute circles centered in the three reference nodes. The radius \(r_i\) of three circles is supposed to be equal to \(d_i\). Ideally, the target should be exactly at the intersection of the circles. In the LoRaWAN system, gateways are sinks since each up-link’s final destination is the gateway, whose positions are fixed and known, thus the anchor nodes for LoRaWAN should be the gateways. Once the gateway calculates the distances from the target nodes, it can compute its relative position with this appropriate approach.

In order to accurately and uniquely determine the relative location of a point on a 2D plane using trilateration alone, generally at least 3 reference points are needed (at least 4 points are needed in the 3D plane)\[5\]. The requirement of trilateration is to have three gateways or anchor nodes whose positions are
known. Figure 3 shows the geometric scheme of trilateration. The distance $d_i$ represents the distance from the i-th gateway to the unknown node $(x, y)$. It is estimated from the RSSI value on i-th gateway and is used to compute circles centered in the three reference gateways. The radius $r_i$ of the circle is supposed to be equal to $d_i$. Ideally, the target should be exactly at the intersection of three circles, as shown in figure. Nevertheless, in most of the cases the radius $r_i$ is not sufficiently accurate because the intersection of the circles can result in an area instead of a point, or there could not be intersection at all. If the circles do not intersect, two circles are drawn around two anchor nodes and in this case, the radius are increased proportionally until their intersection is an unique point. If the equations do not produce real solutions, it means the two sphere does not have intersection point (possibly the spheres does not meet). For simplification, the assumption 1 can decrease this inaccurate situation and give an ideal estimation on $r_i$ such that:

$$d_i = r_i$$  \hspace{1cm} (12)

Given the coordinates of the center of the i-th circle $(x_i, y_i)$ and its radius $r_i$, the equation of this circle is:

$$(x - x_i)^2 + (y - y_i)^2 = r_i^2$$  \hspace{1cm} (13)

According to three RSSI values on three gateways, $\{r_1, r_2, r_3\}$ are estimated. Then the intersection of these three circles is calculated solving the equation system:
\[(x - x_1)^2 + (y - y_1)^2 = r_1^2\]
\[(x - x_2)^2 + (y - y_2)^2 = r_2^2\]
\[(x - x_3)^2 + (y - y_3)^2 = r_3^2\]  

To attain the coordinate \((x, y)\) presented by known coordinates \((x_1, y_1), (x_2, y_2), (x_3, y_3)\), it can be further expanded:

\[r_1^2 = x^2 - 2x_1 x + x_1^2 + y^2 - 2y_1 y + y_1^2\]
\[r_2^2 = x^2 - 2x_2 x + x_2^2 + y^2 - 2y_2 y + y_2^2\]
\[r_3^2 = x^2 - 2x_3 x + x_3^2 + y^2 - 2y_3 y + y_3^2\]  

(15)

Rearranging the equation system below by two-two subtraction, to produce real variables \(a, b, c, d, e, f\) as follows:

\[a = r_1^2 - r_2^2 - x_1^2 + x_2^2 - y_1^2 + y_2^2\]
\[b = 2(x_2 - x_1)\]
\[c = 2(y_2 - y_1)\]
\[d = r_2^2 - r_3^2 - x_2^2 + x_3^2 - y_2^2 + y_3^2\]
\[e = 2(x_3 - x_2)\]
\[f = 2(y_3 - y_2)\]  

(16)

Resolving the equation system to gain the intersection point \((x, y)\). Then the simplified \((x, y)\), which is the coordinate of positioned node, can be deduced and represented by:

\[x = \frac{af - cd}{bf - ce}\]
\[y = \frac{ae - bd}{ce - bf}\]  

(17)

As shown in the scheme, the scope of trilateration is limited by the boundary of \(r_i\). The maximum intersection of three circles with radius \(r_i\) is the area that can be positioned. Figure 4 illustrates an example of the trilateration scope. All nodes are uniform-randomly distributed in a square area of width 20 Km. Three gateways are deployed in known positions, at the edge of an equilateral triangle mostly covering the square of nodes to maximize the intersection. The red dotted lines are drawn circles, showing the boundary of trilateration area, which is limited by the propagation range of LoRa. Here the longest range is around 20 Km (Figure 2), thus the corresponding largest \(r_i\) is 20 Km approximately.

In figure 4, three gateways are colored by red, real end-devices are represented by blue color and positions estimated by trilateration are drawn by green color. It can be observed that all nodes in trilateration area are positioned correctly, that is, blue nodes are covered by green marks. Some nodes outside the boundary are positioned on wrong coordinates but close to their real positions. In principle, the trilateration scope is constrained by maximum
propagation range \( r_{\text{max}} \) and the control of gateways’ positions to expand the intersection area.

2.3 Trilateration Procedure

Previous part introduces the principle of trilateration, where the LoRaWAN is assumed to have numerous end-devices and three gateways in known and fixed positions. In principle, in order to obtain the RSSI value versus the distance, gateways need to collect RSSI values from target node’s packet and then the network server does data processing for distance estimation and trilateration. These three gateways are controlled by one LoRa network server, as illustrated in figure 1. Thus once any of the three gateways has received a packet, it will forward the packet directly to the network server. The network is informed the coordinates of three gateways and their LoRa ID addresses. It holds a list of gateway, a list of nodes, and it uses the propagation model for calculation. Once the three anchor gateways have received a broadcast packet form the blind node, the network server can localize the position of blind node using reference informations received from gateways.

An algorithm in [4] uses a similar functionality of the system to locate the target node. One shared LoRaWAN server is attached to several gateways (three for trilateration) to monitor RSSI informations and stores them as positioning references for nodes. The unique network server linked to gateways will wait

Figure 4: Trilateration Scope
for a packet sending from one end-device. The blind node’s device ID (MAC address), packet RSSI on gateway, fixed gateway’s device ID (MAC address) and fixed gateway’s coordinates are stored in the network server, it is updated once a new packet comes (arrives at a gateway). Once a packet containing source address information arrives at a gateway, the position of the gateway and distance to the node will be stored in the server, until information from three gateways are stored in the server for the same transmitter, while the trilateration will be executed to estimate the position of the transmitter and its information will be completed in the server. After several steps, the server will be aware of the positions of all nodes in the trilateration area.

More precisely, all nodes send empty payload broadcast packet to all gateways by a constant TX power (e.g. 14dBm, negotiated with the network server) initially. When the network server detects that one gateway has received a broadcast packet, it will trigger a callback function to collect informations from the packet and the gateway, including RSSI, source node address, gateway address and gateway coordinate. Then it will perform this algorithm (Figure 1) to search the node record by MAC address or create a new node record in its node list, update node record list when another gateway receives the same packet, and wait until three gateways received the same packet to conduct a trilateration. The network server holds a list [node record] where each element is a set of information related to a node i: \( node_i = \{ \text{gateway index}, (x_{g1}, y_{g1}), (x_{g2}, y_{g2}), (x_{g3}, y_{g3}), r_1, r_2, r_3, (x_i, y_i) \} \). Elements in this set \( node_i \) are respectively: gateway index \( \in \{1, 2, 3, 4\} \), three gateways’ coordinates \( (x_{gi}, y_{gi}) \), three distances \( r_i \) to these gateways and coordinate \( (x_i, y_i) \) of node i to be calculated.

**Algorithm 1 Server’s Localization Algorithm**

**Input:** A packet from \( node_i \) to a gateway

**Output:** The trilaterated position of the \( node_i \)

1. if \( \exists node_i \in [\text{node record}] \) then
2. if \( node_i \) gateway index \( \neq 4 \) then
3. if \( node_i \) gateway index = 3 then
4. update \((x_{g3}, y_{g3}), r_3\) for \( node_i \)
5. calculate trilateration for \( node_i \)
6. update \((x_i, y_i)\) for \( node_i \)
7. \( node_i \) gateway index \( \leftarrow 4 \)
8. else if \( node_i \) gateway index = 2 then
9. update \((x_{g2}, y_{g2}), r_2\) for \( node_i \)
10. \( node_i \) gateway index \( \leftarrow 3 \)
11. end if
12. end if
13. else
14. insert new \( node_i \) into [node record]
15. update \((x_{g1}, y_{g1}), r_1\) for \( node_i \)
16. \( node_i \) gateway index \( \leftarrow 2 \)
17. end if
This algorithm runs for each node. The server will always wait for all nodes being trilaterated, knowing relative positions of all nodes, to perform next steps like topology construction.

3 Single Path Multi-hop

This section describes potential benefits of multi-hop in LoRa wireless network, starting by introducing the network range, data-rate and TX power associated with the LoRa modulation parameters. The procedure of finding the best multi-hop configuration among couple of nodes for a single path is modeled as an optimization problem.

3.1 Range and Data-rate

LoRa uses the unlicensed band frequency 863 to 870 MHz in Europe and in this paper it is assumed to be 868.10 Mhz. It has three key parameters for modulation which affect the network performance dramatically: they are Spreading Factor (SF), Bandwidth (BW) and Coding Rate (CR) respectively. Especially the SF with 6 options, which is defined as the ratio of chip rate to symbol rate, as a power number of 2, plays an important role in modulation and propagation.

The Sensitivity (S) of a LoRa communication system receiver is the minimum magnitude of the input signal required to produce a specified output signal having a specified Signal-to-Noise Ratio (SNR). Because receiver sensitivity indicates how faint an input signal can be to be successfully received by the receiver, i.e. the sensitivity is a RSSI threshold of a LoRa reception, which decides whether the packet can be received or not. It is the capability to receive signals with negative SNR that increases the sensitivity of the LoRa receiver. $SNR$ (in dB) can be calculated by:

$$SNR = 10 - 2.5SF$$

where: spreading factor $SF \in \{7, 8, 9, 10, 11, 12\}$.

Based on the information from Semtech SX1272, the sensitivity $S$ (in dBm) of a radio receiver attached to a channel at room temperature is given by:

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

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 it is assumed to be 6. $SNR$ represents the signal to noise ratio required by the underlying modulation scheme.

A packet is considered as received if and only if $RSSI \geq S$ on the receiver. For a given bandwidth, different SF parameters will result in various $SNR$, thus the sensitivity varies significantly. The propagation range of LoRa is affected by receiver’s sensitivity and received signal power, i.e. the RSSI. In a free
space alike environment, the propagation follows a Line of Sight (LoS) and the model is introduced in previous section. For a minimum bandwidth 125 kHz (250, 500 kHz otherwise), LoRa network can reach a maximum propagation approximately 20 km. Under the configuration Transmission Power (TP) 14 dBm, figure 5 shows the propagation range of LoRa wireless network for a set of parameter $SF \in \{7, 8, 9, 10, 11, 12\}$ and $BW \in \{125, 500\}$ kHz.

![Figure 5: Propagation Range for Different Spreading Factors](image)

It can be observed that generally 500 kHz BW performs a shorter propagation range than 125 kHz BW. For a a given bandwidth, a larger SF can always provide a longer propagation range, varying from 500 km to 2000 km for 125 kHz. However, the cost of a higher SF is a lower data-rate for transmission that is introduced below. A LoRa packet is assumed to be 1 byte (8 bits) and the transmission time is calculated for one packet. Figure 6 shows the Time on Air (ToA) of a packet in LoRa network for a set of parameter $SF \in \{7, 8, 9, 10, 11, 12\}$ and two BW values.

![Figure 6: Time on Air (ToA) for Different Spreading Factors](image)

It can be compared with the propagation range and the same result shows that generally a higher BW leads to a shorter ToA and shorter range, while the increasing SF gives a longer ToA and longer range. The selection of a proper SF parameter determines both the network range and ToA of a packet. Since this work focus on the flexible parameter SF, BW 125 kHz will always be a constant configuration in following sections.

### 3.2 Range and TX Power

Another parameter of LoRa transmission affecting the propagation range is the TX power. According to figure 6, to reduce the ToA, the smaller the SF, the
better because of a higher data-rate. Regarding to figure 5 for a given distance, the proper SF can be found. When TX power $P_T$ is known, expected path loss $EPL$ is calculated with distance $d$, $S$ can be attained and thus the proper $SF$ is deduced, following:

$$P_T - EPL(d) = RSSI \geq S(SF)$$ (20)

That is, for any distance $d \leq$ the maximum range of a $SF$, this $SF$ is the best choice for minimum transmission time. However, after choosing the proper $SF$, different TX power can also give different propagation ranges. As indicated in propagation model, the RSSI is linear related to TX power, resulting in changes in propagation range. In brief, for a given $SF$, a lower TX power leads to a shorter propagation range. On the other side, a shorter distance can be reached by a lower TX power to reduce the energy consumption.

After finding the proper $SF$ for $d$, the minimum TX power $P_T$ for the given distance $d$ can be deduced by:

$$\text{Min}(P_T(SF,d)) = S(SF) + EPL(d)$$ (21)

where $P_T(SF,d)$ is the TX power for a distance $d$ and parameter $SF$, $S(SF)$ is the sensitivity of this $SF$, $EPL(d)$ is the expected path loss of this distance.

Figure 7 illustrates the minimum TX power along with distance. The 6 $SF$ values are configured for 6 distance intervals respectively. The threshold of TX power is assumed to be 14 dBm and for each line of $SF$ value, the cross point on the threshold line indicates the maximum propagation range of this $SF$. The principle is: firstly find the proper $SF$ for a propagation distance under
the condition TX power = 14 dBm, then according to the distance, choose the minimum TX power (≤ 14 dBm) to reach the distance.

Since the relationship between SF and propagation range, the relationship between SF and ToA, the relationship between TX power and distance are all presented. The next step is to apply multi-hop to perform an optimized configurations.

3.3 Optimized Multi-hop

For wireless networks, the multi-hop can extend the network coverage\cite{17}. It is the main purpose of multi-hop in the low power wireless network. On the other side, in LoRaWAN, for a given distance, a lower spreading factor gives a higher data-rate\cite{18}. A distance less than 20 km between the transmitter and receiver can be reached by a single hop with the maximum SF on cost of the longest ToA. It can be equivalently reached by multi-hop if there exist relay nodes, and it consumes less Time on Air under some conditions. The multi-hop forwarding is expected to reduce the channel load by decreasing the total Time on Air, and to ameliorate the performance. The performance of a manually defined multi-hop to replace single hop in a single path, namely total ToA, is studied in this part.

Considering the propagation range of each SF, a figure of corresponding ToA is drawn in the previous part. For a given distance, the proper SF parameter can be estimated to minimize the ToA of the packet. Assuming there is an end-device using a constant bandwidth $BW_0 = 125$ kHz and a constant coding rate $RC = 1$, as assumed conditions mentioned in this paper. In a single hop
transmission path, the data-rate $r(SF)$ of the transceiver is decided by the spreading factor, as shown below:

$$r(SF) = RC \times BW \frac{SF}{2SF} \text{bits/sec}$$  \hspace{1cm} (22)$$

A multi-hop path from a source to a destination is defined as better if it consumes less Time on Air than a single hop path for the same pair of nodes. In an ideal case, if the distance among two nodes is known and there exist relaying nodes, the best multi-hop path can be estimated. An expected propagation distance $d$ can be divided by $n$ hops (sub ranges) and let the hop index be $i \in [1, n]$. Let the spreading factor of each hop $i$ be $SF_i$, and $d(SF_i)$ is the maximal reachable distance (propagation range) of $SF_i$. Assuming the packet is comprised of size $p = 1KB = 8000bits$, as a unit for calculation. The total transmission time, i.e. the ToA of the whole path is thus $\sum_{i=1}^{n} \frac{p}{r(SF_i)}$. At the same time the propagation range for each hop $i$ should be reached by using $SF_i$ as the condition $\sum_{i=1}^{n} d(SF_i) \geq d$. Thus the optimized proposal is to find a best choice for $n$ and a set of $\{SF_i\}$, such that:

$$\arg \min_{SF_i} \left( \sum_{i=1}^{n} \frac{p}{RC \times BW \frac{SF_i}{2SF_i}} \right) \text{subject to } \sum_{i=1}^{n} d(SF_i) \geq d$$ \hspace{1cm} (23)$$

Figure 8: Time on Air for different number of hops

Considering different options of $SF \in [7, 12]$, which gives a various of propagation range and ToA. Every node prefers to use minimum $SF$ in order to reach the highest data-rate (local optimization), a greedy geographic approach can
be applied to construct a tree structure from gateway as root, and each branch is a single relaying path. With this multi-hop forwarding mechanism, nodes always 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 time can be found (2, 3 and 4 hops here, table 2, figure 8).

Table 2: Configuration of Minimum Spreading Factors (*Best)

| Range(m) | 1 hop | 2 hops | 3 hops | 4 hops |
|----------|-------|--------|--------|--------|
| ≤ 5290.630 | 7* | 7, 7 | 7, 7, 7 | 7, 7, 7, 7 |
| ≤ 6958.230 | 8* | 7, 7 | 7, 7, 7 | 7, 7, 7, 7 |
| ≤ 9151.447 | 9 | 7, 7 | 7, 7, 7 | 7, 7, 7, 7 |
| ≤ 12035.959 | 10 | 7, 8* | 7, 7, 7 | 7, 7, 7, 7 |
| ≤ 15829.663 | 11 | 8, 9 | {7, 7, 7} | {7, 7, 7, 7} |
| ≤ 20819.133 | 12 | {8, 8} | {7, 7, 7} | {7, 7, 7, 7} |

The single hop propagation range varies from 0 to 20819 m, that can be replaced by multi-hop. As shown in figure 8, compared to the single hop, where increasing SF dramatically boosts the ToA, after 6958 m, multi-hop has a lower Time on Air especially in long range relay, which is expected to 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 sufficiently large, the path with more hops of smaller SF is relatively better.

The star symbol in table 2 shows the SF configuration for the shortest ToA to reach the indicated range. Applying the forwarding rule driven by spreading factor for distance [0, 20819] m, result shows that for range [0, 5290] m and [5290, 6958] m single hop with SF 7 and 8 respectively is the best, for range [6958, 9151] m and [9151, 12035] m, two hop with SF {7, 7} and {7, 8} is the best, for range [12035, 15829] m three hop with SF {7, 7, 7} is the best and for range [15829, 20819] m 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 20819 m can be combined from shorter distance relays, as indicated in the work 12.

ToA of a path has been pointed out to be shorted by multi-hop with proper SF configurations, then next step is to construct multi-hop paths among positioned nodes. With the help of trilateration, all nodes are known to construct a graph.

4 Shortest Path Multi-hop

Previous section indicates the benefit of multi-hop on single path of LoRaWAN. This section gets into the procedure to find the shortest path of multi-hop among all nodes to gateways. The construction of graph is introduced below and following the MAC forwarding is described to perform multi-hop.
4.1 Initialization Procedure

In section 2, with the help of trilateration, all nodes are positioned for their relative coordinates. The LoRa network server is aware of MAC addresses, coordinates of all nodes and it will use these informations to decide the transmission parameters of each node. Firstly it needs to construct a graph where all nodes and three gateways are vertexes and edges representing the transmission path. Since this approach focus on the multi-hop for up-link, it need to be defined that an edge between two vertexes $u, v$, where $v$ is closer to the gateway allocated than $u$ in the graph, means that the node $u$ will send packet to the node $v$. The weight of the edge is the ToA related to the edge. A vertex in this graph can be whether an end-device (node) or a gateway (sink). Globally the procedure of the graph construction follows such five steps:

1. Allocation of potential gateways for all nodes.
2. Potential edges for relaying among all nodes.
3. Floyd Warshall algorithm to update all edges.
4. Allocation of optimized gateway for all nodes.
5. Allocation of next hop information for all nodes.

Being aware of positions of all nodes and three gateways, the calculation starts on the LoRa network server. Step one allows all nodes to have potential gateways for up-link and down link, that is to build a cluster on each gateway. Optimized parameters for LoRa transmission includes SF, TX power and destination, and they can be initially configured in this step.

Three matrices of parameter configuration need to be introduced. They are respectively TOA, PATH, SF and PW. Let the number of nodes be $n$ and there are three gateways, thus in the graph there will be $n + 3$ vertexes. TOA, PATH, SF and PW are all matrices with size $[n + 3, n + 3]$. Let $i, j \in [1, n + 3]$ be the indexes of vertexes in the graph. With any $i, j \in [1, n + 3]$, $TOA[i][j]$ indicates the ToA from vertex $i$ to vertex $j$, $PATH[i][j]$ means the next-hop for vertex $i$ to reach vertex $j$, $SF[i][j]$ is the proper SF parameter for vertex $i$ going to vertex $j$, and $PW[i][j]$ represents the minimum TX power for vertex $i$ to go to vertex $j$. A list $GW$ of size $n$ is also stored in the server, $GW[i]$ represents the gateway index of node $i \in [1, n]$. Initially elements in matrices $TOA$, $PATH$, $SF$, $PW$, $GW$ are filled with empty values (or infinity). A function $distance(i, j)$ can estimate the distance between vertex $i$ and $j$. Three functions $GetToA(d)$, $GetSF(d)$ and $GetPower(d)$ are used to get the proper ToA, SF and TX power respectively for a given distance $d$. The algorithm in figure 2 shows the procedure of initial gateway allocation.

This step allows the graph to be initialized to have an optimized single hop topology, as shown in figure 2. These edges represent single hop links from end-devices to gateways while these end-devices have optimized configurations, that is, the shortest ToA, proper SF and lowest TX power. Until now all nodes have its’ geographically closest gateway allocated.
Algorithm 2 Server’s Gateway Allocation Algorithm

Input: Number of nodes \( n \), Number of gateways \( 3 \)
Output: Matrices \( TOA \), \( PATH \), \( SF \) and \( PW \)

1: \( \textbf{for } i = 1 \textbf{ to } n \ \textbf{do} \)
2: \( d_{\text{min}} = 30000 \)
3: \( \textbf{for } j = n + 1 \textbf{ to } n + 3 \ \textbf{do} \)
4: \( \text{if } \text{distance}(i, j) < d_{\text{min}} \text{ then} \)
5: \( d_{\text{min}} = \text{distance}(i, j) \)
6: \( \textbf{end if} \)
7: \( \textbf{end for} \)
8: \( TOA[i][j] = \text{GetToA}(d_{\text{min}}) \)
9: \( PATH[i][j] = j \)
10: \( SF[i][j] = \text{GetSF}(d_{\text{min}}) \)
11: \( PW[i][j] = \text{GetPower}(d_{\text{min}}) \)
12: \( GW[i] = j \)
13: \( \textbf{end for} \)

Figure 9: Initial Allocation of Gateways

4.2 Update Multi-hop Paths

Step two to step five are building the multi-hop paths which provide less ToA and lower TX power. Firstly step two needs to be performed to construct all potential edges, in other words, potential forwarding paths among nodes. Not any pair of nodes in the graph will have a link, instead, the principle is, if the distance between two nodes are shorter than the distance from any of them to
its gateway, an edge will be built between them. This does not make the graph complete but only draw possible edges, since the forwarding path should always be shorter than a direct link to the gateway.

Again the matrices $\text{TOA}$ as the weight of path, $\text{PATH}$, $\text{SF}$, $\text{PW}$ and functions from step 1 are used and updated in following algorithm (figure 3):

**Algorithm 3** Server’s Potential Edges Algorithm

**Input:** $n$, Matrices $\text{TOA}$, $\text{PATH}$, $\text{SF}$ and $\text{PW}$

**Output:** Updated matrices $\text{TOA}$, $\text{PATH}$, $\text{SF}$ and $\text{PW}$

```
1: for $i = 1$ to $n$ do
2:     for $j = i$ to $n$ do
3:         $d = \text{distance}(i,j)$
4:         if $d < \text{distance}(i, GW[i])$ or $d < \text{distance}(j, GW[j])$ then
5:             $\text{TOA}[i][j] = \text{TOA}[j][i] = \text{GetToA}(d)$
6:             $\text{PATH}[i][j] = j$
7:             $\text{PATH}[j][i] = i$
8:             $\text{SF}[i][j] = \text{SF}[j][i] = \text{GetSF}(d)$
9:             $\text{PW}[i][j] = \text{PW}[j][i] = \text{GetPower}(d)$
10:        end if
11:     end for
12: end for
```

The four updated matrices represents the updated graph shown in figure 10. Compared with previous graph, besides the edges for each cluster, much more edges are built among nodes. It should be noted that the potential edges are not only built in each cluster but among all nodes, even cross clusters. That is because a node in its cluster may find a shorter path to another gateway in other clusters.

Following step two, the step three is the key factor of shortest multi hop. In computer science, the Floyd-Warshall algorithm is an algorithm for finding shortest paths in a weighted graph with positive or negative edge weights. A single execution of the algorithm will find the lengths (summed weights) of the shortest paths between all pairs of vertexes. Although it does not return details of the paths themselves, it is possible to reconstruct the paths with simple modifications to the algorithm. This algorithm in figure 4 is applied for matrix $\text{TOA}$ to update informations in $\text{PATH}$, $\text{SF}$ and $\text{PW}$.

After updating all these four matrices, step four and five will be performed to allocate optimized gateway for all nodes and inform next hop information to all nodes. The algorithm in figure 9 will be executed again to find the new gateway with the least ToA for each end-device. $\text{PATH}[i][GW[i]]$ indicates the ID of next hop for node $i$ to reach its closest gateway $GW[i]$, and thus the MAC address of next hop. A special short down-link packet carrying SF parameter $\text{SF}[i][GW[i]]$, TX power $\text{PW}[i][GW[i]]$ and the MAC address of next hop, will be sent one by one to the corresponding node.

Finally figure 11 shows the state of the graph, which is also the final topology of the shortest multi-hop. It can be observed that some nodes previously
attached to a cluster are allocated to another gateway via multi-hop paths. Especially for the nodes far away from their initial gateways.

The procedure of finding shortest multi-hop paths are presented by algorithm and visualization. In the simulation of a network scenario, the protocol, in other words, the inter-operation among components in LoRaWAN, need to be implemented and will be described below.
4.3 MAC Forwarding

The theoretical approach for building shortest multi-hop path is modeled by graph and shown in visualization above. To implement the proposed approach in simulation or in a real testbed, a MAC forwarding protocol is necessary. For simplification, a simply receive-and-forward MAC is deployed on nodes in experiments for evaluation on the approach.

By default the LoRa node does not communicate to each other, only up-link from end-devices to gateways and down-link from gateways to end-devices are essential. Most of the traffic in LoRaWAN is up-link and thus multi-hop can be enabled only for up-links. If a down-link is required, the gateway sends a packet to the destination node using single hop because gateways have no power limitation. If the Device-to-Device communication is enabled in LoRaWAN, a node only needs to know the next-hop address for up-link to perform relay, while the next-hop can be whether a relaying node, or the gateway directly. A source end-device always sends a packet targeting at its next-hop, the source address in packet stays unchanged. The receiver examines the header of every successfully decoded packet: if the packet is addressed for it, the node buffers and forwards the packet to its next hop; otherwise, it ignores the packet simply and do nothing else.

Pure-aloha MAC is kept in LoRa MAC for relay, because the local beacon leads to more traffics among devices. Instead of using beacon, all devices are assumed to be attached to all channels on 868.10MHz frequency, 125kHz bandwidth:
Assumption 2: All end-devices and gateways are continuously working on channels of all $SF \in \{7, 8, 9, 10, 11, 12\}$.

The benefits of multi-channel transmissions towards channel hopping is introduced in [23]. In this MAC relay protocol, all LoRa devices are assumed to work on multi-channels on same frequency, same bandwidth but only different spreading factors. These orthogonal channels are parallel but half-duplex on each one. The half-duplex feature makes LoRa device whether on TX state or on RX state, but not both of them on same time. Every end-device and gateway listen to all available channels for any reception during their IDLE period.

5 Experiment in Simulation

This section carries out experiment results both in Python and ns-3 simulator, for the purpose of evaluation on the proposed multi-hop approach, according to two metrics: Time on Air and power consumption. The different among default single hop, allocated single-hop and shortest path multi-hop are compared in simulation to study the performance.

5.1 Simulation Scenario

In the simulation scenarios, common configuration keeps constant. The propagation model implemented in simulation follows these parameters in table 1: Frequency is $868.10 MHz$, $BW = 125 kHz$, $n = 2.101$, $d_0 = 10 m$, $PL_0 = 80.310 dB$, $CR = 1$ and default TX power is $14 dBm$. Assuming a packet has the size of $p = 20 bytes$ ($8 bytes$ of payload + $12 bytes$ of header). The positions $(x, y)$ of a number of nodes are randomly initialized in a 2D square area with a given width $w \in [12, 22] km$. Three gateways are deployed on the edge of this square with coordinates $(0.1w, 0.1w)$, $(0.5w, 0.9w)$ and $(0.9w, 0.1w)$ respectively. A visualization of network topology can be demonstrated in figure 11. There are 100 end-devices and 3 gateways in the network. All end-devices has at least one packets to send to the gateway on a random time point. Gateways are normally sinks, except in initialization phase, they inform the nodes their next hop address.

The proposed algorithms for localization, gateway allocation, parameter optimization and shortest path multi-hop are implemented in two platforms: Python and ns-3. The MAC protocol for packet forwarding is deployed in ns-3 simulation platform. Scenarios related to Time on Air and TX power measurements are simulated in Python. The width of network square, number of relaying nodes in it, Time on Air of a packet and TX power of end-devices are monitored variables. Scenarios related to delivery ratio is run in ns-3 simulator with the LoRa simulation module. The packet density and delivery ratio in the network are monitored variables. All the simulations are run by 100 times in Python and 10 times in ns-3 with different random seeds to get an average result.
The duty cycle of each end-device on a channel is imposed by regulation in Europe: maximum 1%[2]. For a given $SF$ taken into configuration initially, let one packet have a transmission duration (ToA) of $t(SF,p)$. If the maximum duty cycle of 0.01 is reached, which means that at most 1 packets can be transmitted during a period of $t(SF,p)$, the transmission interval should be $0.99 \times t(SF,p)$ (0.99* total time period) for each end-device. Every end-device can send numerous packets in total and it should start to send the first packet by uniform randomness during initial $t(SF,p)$ seconds. The optimized SF value is always less than or equal to 12, thus it will result in a duty cycle below the maximum boundary, which is absolutely legal ($\leq 0.01$).

5.2 Experiment Result

First experiment shows the relationship between the number of relaying nodes and the width of network area. The width of network square varies from 12km to 22km, where all nodes in this area can be trilaterated. In figure 12, it can be seen that the larger the network area is, the more nodes are forwarding. When network width is 12km or smaller, there is no relaying node, while for the maximum width 22km, there are up to 48% of all nodes doing multi-hop relay. In fact there can be 2 hops, 3 hops or even 4 hops int he network.

![Number of Relaying Nodes](image)

Figure 12: Number of Relaying Nodes

This experiment also demonstrates the relationship between the average ToA and the width of network area. The width of network area varies in the same way and a comparison between single hop and multi-hop is drawn. This ToA in figure 13 measured on each end-device, is the ToA of the whole path for a packet sent to the gateway. It should be noted that the single hop here means
all nodes are allocated to the closest gateway and configured with the proper SF parameter, as shown in figure 9. Although the single hop has the optimized parameter SF, the multi-hop still shows a significant decrement in ToA. As the maximum number of relaying nodes occurs on width 22 km, the ToA also shows a different of 0.027s (0.077s for single hop and 0.050s for multi-hop).

![Figure 13: Mean Time on Air of Packets](image)

On the same time, this experiment investigates the relationship between the average TX power of end-devices and the width of network area. In spite of SF, the TX power is the other optimized parameter proposed for end-devices. In figure 14, it can be observed that along with the increment of network width, the average TX power also shows a reduction from single hop to multi-hop. The threshold of TX power is 14 dBm by default and the single hop here is also optimized. When the width is 20 km and the most nodes can do relay, single hop shows a mean TX power of 11.344 and multi-hop shows a mean TX power of 11.204. Although the TX power does not show an apparent difference, according to ToA and TX power, it can be estimated the power consumption in figure 15 shows an improvement. The use of default TX power in single hop always consume the most energy, while the optimized single hop decreases the energy consumption by reducing ToA and TX power. When the width of network is larger enough, the multi-hop brings more benefits on power consumption by reducing ToA and TX power again.

Results have shown that multi-hop has benefits especially in the network of large area. Nevertheless, the absence of beacon and continuous listening mode may introduce potential problem. Second experiment investigates the relationship between the delivery and the traffic density in network area of width 20 km, which is supposed to be the large area network. As shown in figure 16.
a delivery ratio comparison is made among default single hop, optimized single hop and optimized multi-hop, along with the traffic density. It should be noted that this traffic density indicates the amount of up-link packets in a time unit (1s) for the whole network. It can be observed that both optimized single hop and multi-hop give better performance than default single-hop with $SF = 10$
(required to reach 10\(km\) to assure the range for single hop). Although multi-hop in the Aloha way without beacon results in a lower delivery ratio than optimized single hop, especially on a higher traffic density 1.0, the delivery ratio still keeps above 98%, while the default \(SF = 10\) only gives a delivery ratio below 90%.

![Figure 16: Delivery Ratio with Traffic Density](image)

RSSI-based trilateration, optimized single hop and optimized multi-hop are all deployed in simulation and tested in experiments. It can be concluded that the proposed approach for multi-hop improves the performance of power consumption by reducing ToA and TX power when the width of network is large. Although in dense traffic environment the optimized single hop provides higher delivery ratio than the optimized multi-hop, they are both better than the default single hop. For a network with loose traffic density (\(\leq 0.5 \text{ packet / s}\)), the optimized multi-hop shows a approximately equality in high delivery ratio of the optimized single hop, but with a much lower energy consumption. The extreme situation for proposed approach is analyzed in following section.

6 Approach Analysis

This section analyzes the limitation of the proposed approach, especially in a network with dense traffic. Simulation scenarios are executed in ns-3 platform, and the delivery ratio of packets is measured. Potential limitation is presented first and then the results from simulation are illustrated below.

In real testbed, 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 at least two working channels: one for reception and one for transmission. By default LoRa devices have a continues listening mode (Class C\cite{2}) that cost more power consumption, which is assumed and implemented in this approach. Compared to one sink on a single channel, potential problem occurs on relay nodes, which are always in listening mode, where collision can be highly increased since the multi-hop cases more receptions and interferences on multi-channels. Besides the collision, the half-duplex also introduces risks: although end-devices have FIFO queue for TX, while the relay node is on TX state, it cannot receive packets, thus causes a packet loss.

![Figure 17: Delivery Ratio with Traffic Density](image)

It can be seen in figure 17 the delivery ratio in network with dense traffic. When the traffic is as dense as 10 packets / second, the single hop with constant $SF = 10$ parameter shows a delivery ratio below 20%. While the optimized single hop gives the highest delivery ratio ($\approx 86\%$) and the optimized multi-hop provides a relatively low delivery ratio ($\approx 83\%$). Potential risk of collision and packet loss among relay nodes lead to an negative effect on delivery ratio, but not as obvious as expected. The difference of delivery ratio between optimized single hop and multi-hop tends to be stable on 3%, along with the traffic density. According to the statistic on simulation result, most SF parameters of nodes are 7 ($> 96\%$ in the matrix), and few of them are 8. In fact an end-device only needs to work on one channel with $SF = 7$ (at most two), which provides the highest data-rate and shortest range.
7 Conclusion

In conclusion, this paper proposes an approach enabling the optimized multi-hop in LoRaWAN. The contribution of this paper can be listed as: 1. A RSSI-based trilateration algorithm for graph construction, 2. Gateway allocation with optimized TX parameters, and 3. Shortest path multi-hop without beacon for up-links in LoRaWAN. The novel approach is implemented and tested in simulation. Experiment results show that the multi-hop in LoRaWAN has its benefits: the average energy consumption for TX is reduced by decreasing the Time on Air of packet and the TX power of end-device. While without complexity of local beacon, the delivery ratio of multi-hop still keeps on an acceptable level > 80 for dense traffic.

In future work, since the absence of beacon mechanism has negative influence on the performance of multi-hop, a global scheduling needs to be investigated to balance this. Besides, ad-hoc method, frequency-division multiplexing and time-division multiplexing are three methods of parallel channel use, that can be introduced into LoRaWAN to avoid interferences among relay nodes.

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