

Long Range Wide Area Mesh Network Routing in High Signal Attenuation Environment using Prim's Algorithm

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Abstract This research proposes the LoRa mesh network routing using Prim's algorithm to solve the communication issue encountered by a conventional star topology of LoRaWAN. The focus is to increase successful data transmission rate and decreasing transmission time in high attenuation environment. By using the Prim's algorithm approach, the data extraction rate (DER) was 98.04%, around 36% over that of the star topology and 74% of the routing paths have lower time-on-air (ToAs) than the star topology.

Keyword Internet of Thing, LoRaWAN, mesh network, Prim's algorithm, high signal attenuation environment, log-distance path loss model

1. INTRODUCTION

In recent years, the IoT (Internet of Things) has played an increasingly significant role in various sectors, including industry, transportation systems, energy, cities, and even healthcare. In each application, different communication networks are chosen based on their suitability for the task. These range from short-range wireless communication technologies such as Bluetooth, WiFi, Zigbee, and NFC to LPWAN (Low Power Wide Area Networks) like Sigfox and NB-IoT, and even LoRaWAN (Long Range Wide Area Networks). This research focuses on presenting LoRaWAN communication because it is a private network that can be managed internally, ensuring high data security and avoiding additional costs to third-party service providers.

Normally, LoRaWAN network uses the star topology, where each end-device directly transmits and receives data to and from a gateway. However, this configuration can sometimes lead to issues such as data collisions, data loss, or limitations in data transmission range, especially in environments with high signal attenuation, such as factories with restricted gateway installation spaces and metallic structures. In such cases, signals can be significantly attenuated, causing the mentioned problems.

Previous research has solved these problems by introducing the mesh network topology into the LoRaWAN network. One approach is to combine both star and mesh network topologies [1]. In this setup, each group has one end-device serving as the cluster head, communicating directly with the gateway in the star network topology. Other end-devices within the same cluster can communicate with each other in the mesh network topology. On the other hand, the end-devices will be disconnected when the cluster head device loses connectivity. Thus, the data will be lost

or be not sent successfully, resulting in lower successful data transmission rate. Another approach is to replace the entire star network with a mesh network that can resolve distance-related data transmission issues to the gateway without the need for additional gateway installations. However, these methods still encounter challenges in balancing the workload between transmitting signals from the powerful gateway to the end-devices compared to the signals transmitted from small end-devices back to the gateway [2].

In this research, Prim's algorithm is proposed for the LoRa mesh network to optimize the data packet routing path in high signal attenuation environment such as an obstruction in a factory. Prim's algorithm is the algorithm for finding the minimum weight edge to connect all nodes. This minimum spanning tree algorithm is typically applied for reducing the number of links in the network topology [3]. In [4], the Prim's algorithm was proposed to increase the coverage area via a relay node or repeater. Although the successful transmission rate was improved, the ToA (Time-On-Air) also increased.

In this research, Prim's algorithm will be used for maximizing distance between device nodes or device nodes and gateway that the hopping nodes act as relay node and send their data at the same time. Furthermore, this algorithm chooses the minimum SF (Spreading Factor) route to increase the transmission efficiency and decrease probability of collision. Its performances including DER (Data Extraction Rate) and ToA (Time-On-Air) will then be compared with the star topology.

This paper is divided into 5 sections. Next section describes related works. Prim's algorithm is presented in section 3. The results of simulation and conclusions are shown in section 4 and 5, respectively.

2. RELATED WORKS

2.1. LoRa AND LoRaWAN

LoRa [5] is the protocol in a physical layer which the transmission distance depends significantly on the modulation method. LoRa uses the CSS (Chirp Spread Spectrum) method for modulation and the link budget is calculated by received and lost signal during data transmission. The one parameter that is emerged from the CSS modulation is SF (Spreading Factor), which contains 6 typical values from SF7 to SF12. This parameter is important to determine the performance for data transmission such as distance, data rate, and transmission time. The sensitivity used for identifying the SF [6] can be calculated from

$$S = -174 - 10 \log BW + NF + SNR_{lim} , \quad (1)$$

where S is sensitivity (dBm)

BW is the bandwidth (Hz)

NF is the noise floor (dB) that is set as 6 dB in this research.

SNR_{lim} is signal-to-noise ratio shown in Table 1.

TABLE 1. SNR LIMIT VALUES [5]

SF	SNR limit
7	-7.5
8	-10
9	-12.5
10	-15
11	-17.5
12	-20

Normally, LoRaWAN [7] uses the star topology to transmit the data from one end-device or node to the servers. LoRaWAN consists of 4 main components that are end-device, gateway, network server, and application servers as shown in Fig.1.

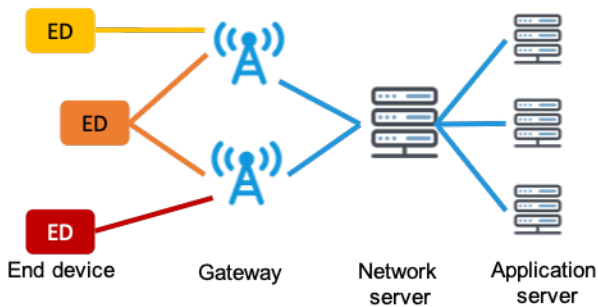


Fig.1. LoRaWAN topology [8].

Furthermore, the transmission time or ToA (Time-On-Air) in LoRaWAN depends largely on SF and BW (bandwidth) [9], and can be calculated from

$$ToA = N_{sym} \times \frac{2^{SF}}{BW} , \quad (2)$$

where N_{sym} is the number of symbols.

2.2. LOG-DISTANCE PATH LOSS MODEL

The location, frequency range, and density all affect the signal propagation [10]. The Log-Distance path loss model [11] is a widely used propagation model in environments with a large number of device nodes in both indoor and outdoor environments. The attenuation varies with distance as

$$PL(d)[dB] = 10n \log_{10} \left(\frac{d}{d_0} \right) + PL_0 + X_\sigma , \quad (3)$$

where n is the path loss exponent

d is the distance between receiver and transmitter (m)

PL_0 is the path loss at reference distance (d_0) (dB)

X_σ is the attenuation signal is presented by Zero-mean Gaussian random variable (dB).

The PL_0 is calculated using the Friis free-space path loss model [12] and can be shown as

$$FSPL = \left(\frac{4\pi df}{c} \right)^2 \quad (4)$$

where f is the frequency (Hz)

c is the speed of light (3×10^8 m/s)

The path loss exponent depends largely on the environment and can be approximated as shown in Table 2.

TABLE 2. PATH LOSS EXPONENT IN VARIOUS ENVIRONMENTS [13]

Environment	Path Loss Exponent
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building LOS	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factory	2 to 3

2.3. MESH TOPOLOGY

In mesh topology [14] as shown in Fig. 2, the device nodes can communicate with others thus it can be an end-device or a relay node to transmit the data to a gateway.

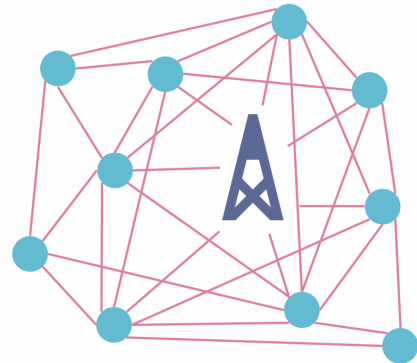


Fig.2. Mesh topology.

The mesh network topology offers several advantages, including re-routing when a particular node loses connectivity or becomes unavailable, other nodes can dynamically re-route their connections to maintain network continuity. Furthermore, the mesh network can effectively extend network coverage by allowing nodes to act as relays. Data packet can hop through multiple device nodes to reach its destination, which is particularly useful in scenarios where the distance between device nodes and gateway is substantial or where there are obstacles that affect signal propagation.

3. PRIM'S ALGORITHM

The concept of Prim's algorithm [3, 15] is a spanning tree that finds the minimum weight edge to connect all nodes with the path of undirected graphs as demonstrated in the pseudocode below.

Prim's algorithm	
	// Open node_set to collect the nodes in minimum spanning tree
1.	node_set = empty set
	// Select the first node to start
2.	startNode = node_0 in graph
3.	node_set.add(node_0)
	// Open edge_set to consider
4.	edge_set = edge_set connected to node_0
	// Iterate until all nodes are in minimum spanning tree
5.	while node_set has less nodes than graph:
	// Find the minimum edge in edge_set
6.	minEdge, minWeight = find_minEdge(edge_set)
7.	node_set.add(minEdge) // Add minimum node
	// Add edge that connect to node in edge_set
8.	for edge in edge_set connect to minEdge:
9.	if edge is not in node_set:
10.	edge_set.add(edge)
11.	edge_set.remove(minEdge) // Remove minimum edge from edge set
12.	return node_set as array

Figure 3 shows an example of a routing using Prim's algorithm. The black lines show the selected paths relaying via nodes with the minimum weight edges.

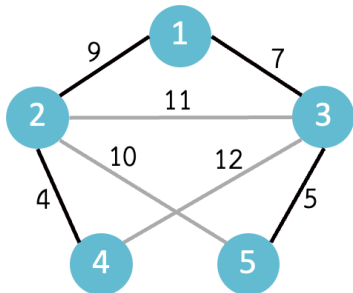


Fig.3. An example of a routing using Prim's algorithm.

Prim's algorithm is applied in this research to optimizing the transmission of the data packet from the device nodes to the gateway in the LoRa mesh network. The core concept is to take a routing path that uses a minimum SF. In addition, the path must be at a maximum distance in order to use a minimum number of relay nodes. Note that, the defined SF is accounted for both node-to-node and node-to-gateway. The flowchart of the proposed mesh routing algorithm is shown in Fig.4.

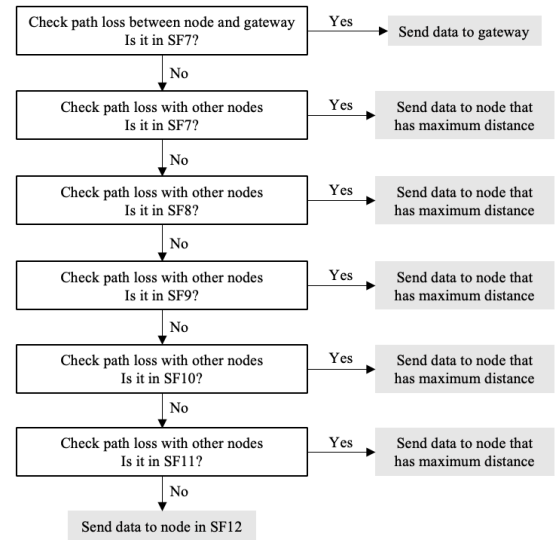


Fig.4. Flowchart of the proposed mesh routing algorithm.

A device node initially considers path loss to the gateway. If the path loss is equal or less than that in SF7, the device node will directly send the packet to the gateway. If this is not the case, the device node will consider the path loss with surrounding nodes and hop to the one whose path loss is in the minimum SF. In this research, the maximum coverage area is calculated based on SF12 whose sensitivity is shown in Table 3 [6]. Note that, the sensitivity of each SF is calculated following the widely used SX1276 LoRa chipset. Thus, the minimum path loss for the successful transmission from a device node in this simulation is -137.03 dB in SF12.

TABLE 3. SF VALUES [6]

SF	Sensitivity (dBm)
7	-124.53
8	-127.03
9	-129.53
10	-132.03
11	-134.53
12	-137.03

In this paper, LoRaSIM [16] is used for network performance simulation. The proposed scenario is the high attenuation environment namely, the obstruction in factory. The Log-Distance path loss model is calculated by using a pertinent value of path loss exponent in Table 2. The simulation parameters are

shown in Table 4. All nodes transmit the packet simultaneously and in 30 s interval. The packet transmission and reception by a node are assumed independent.

TABLE 4. SIMULATION PARAMETERS

Parameters	Values
Carrier frequency (MHz)	923
Bandwidth (kHz)	125
Packet length (byte)	255
Number of gateways	1
Number of nodes	20
Transmitting power (dBm)	14
Reference distance (m)	1
Path loss exponent	2.5
Coverage area (km)	16.28
Average sending interval (s)	30
Simulation time (s)	86,400

Note that, the coverage area of 16.28 km is calculated from equation (3) as

$$d_{max} = d_0 10^{\frac{PL-PL_0}{10n}}, \quad (5)$$

where PL is the path loss in SF12.

4. SIMULATION RESULTS

The routing paths are shown in Fig.5 and the number of hops associated with routing paths including the total ToAs is shown in Table 5. The starting nodes are highlighted.

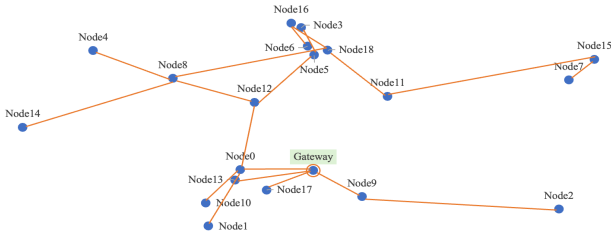


Fig.5. Routing paths from the simulation.

TABLE 5. NUMBER OF HOPS AND ToA FOR THE ROUTING PATHS IN THE PROPOSED MESH TOPOLOGY

	Number of hops to gateway							ToA (s)
	1	2	3	4	5	6	7	
Gateway	N13							0.400
	N17							0.400
	N0	N1						0.799
	N0	N10						0.799
	N9	N2						2.695
	N0	N12	N5	N3				1.906
	N0	N12	N8	N4				1.906
	N0	N12	N8	N14				2.757
	N0	N12	N8	N18	N16	N6		3.556
	N0	N12	N8	N18	N11	N15	N7	5.852

When compared with the similar starting nodes in the star topology network of LoRaWAN as shown in Table 6, we found that the total ToAs for a single hop from N13 and N17 are identical to that of the star topology. For a number of hops of 2 or more, the total ToAs are significantly lower for the proposed mesh routing algorithm due to the algorithm prioritizing minimum SF at the maximum distance limited within that SF. However, we found a slight glitch in the case of N10, which is assigned as SF8. Considering the proposed mesh routing algorithm which is designed to route to the minimum SF node; therefore, N10 is directed first to N0 that has SF7. As a result, the total ToA for this specific routing path is slightly higher than the ToA of N10 in the star topology.

TABLE 6. ToA FOR THE STAR TOPOLOGY

Node	ToA (s)
N1	1.250
N2	5.001
N3	5.001
N4	9.019
N6	5.001
N7	9.019
N10	0.707
N13	0.400
N14	5.001
N17	0.400

The DERs and ToAs within the designed simulation time are compared between the star topology and proposed mesh routing algorithm. The successful DERs of the star topology and the proposed algorithm are 62.16% and 98.04%, respectively. The mesh topology thus can significantly improve data transmission efficiency and as mentioned above, utilizes lower ToA.

5. CONCLUSIONS

Prim's algorithm is applied to optimize the routing path in the LoRa based mesh network to improve a success of data transmission and ToA in high signal attenuation such as the obstruction in a factory. The corresponding Log-Distance path loss model along with LoRaSim were used to simulate the network performance of 20 device nodes. As a result, the successful DER of the proposed mesh network using Prim's algorithm was 98.04%, around 36% over that of the star topology. The total ToAs of most paths are significantly lower than that of the star topology due to the algorithm prioritizing minimum SF at the maximum distance limited within that SF. For the future work, lowering ToA for the proposed mesh routing algorithm will be studied and the optimization of energy consumption will be focused.

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