Routing in LoRaWAN: Overview and Challenges

Alfonso Osorio, Maria Calle, Jose D. Soto, and John E. Candelo-Becerra

The authors present an overview of the major characteristics of LoRaWAN. They present the results of a systematic literature review to find the main approaches employed for routing in LoRa. They describe different routing algorithms and compare them according to their implementation characteristics as a guideline to analyze their possible usefulness.

Abstract

LPWAN technologies are playing a major role in the IoT scenario due to their extensive radio range, use of free frequency bands, and low energy consumption. Among these technologies, long-range WAN (LoRaWAN) transmits through several kilometers with data rates up to 5.5 kb/s, making it useful for applications such as smart city monitoring, precision agriculture, and environmental tracking. However, LoRaWAN supports only one-hop communication between end nodes and gateways. Because links can be kilometers long, LoRaWAN signals may encounter obstacles or interference, affecting packet reception. Therefore, different studies have proposed using routing schemes to create multihop communication and improve LoRaWAN performance. The article has the following contributions: first, we present the main approaches to build multihop communication in LoRa networks. Second, we summarize different routing protocols proposed for the technology. Finally, we describe different challenges to improve the performance of routing protocols for LoRaWAN.

Introduction

As part of LPWAN technologies, long-range WAN (LoRaWAN) is attracting attention from service providers, researchers, and technology manufacturers [1]. LoRaWAN applications include diverse Internet of Things (IoT) use cases such as smart metering, industrial sensor communications, and remote environmental monitoring. Furthermore, LoRaWAN allows sensing nodes to transmit information to one gateway located several kilometers away with low energy consumption.

However, LoRaWAN nodes send data to the gateway through one hop. This situation may overload gateway capacity, because IoT solutions imply thousands of devices sending through an individual link to the gateway. For example, smart metering may include one LoRa device on each utility meter and tens or hundreds of them in buildings. Even though LoRaWAN allows multiple transmissions, the traffic may disrupt communications.

Moreover, the one-hop topology prohibits the use of neighbor nodes to relay data. However, due to LoRa radio ranges, every node may have different neighbors within transmission range. These neighbors can act as relays to forward information from some other nodes that cannot communicate directly to the gateway. Therefore, the one-hop topology underutilizes network resources that could increase packet delivery.

Additionally, LoRaWAN long-distance links may experience packet losses created by obstacles or electromagnetic interference. Some example obstacles are vehicles and buildings in smart cities, and trees, tall crops, and hills in remote monitoring. These obstacles create non-line-of-sight (NLoS) conditions that significantly increase packet losses [2]. Moreover, electromagnetic interference examples come from other wireless communication systems and from the same LoRa devices, decreasing information delivery [3].

Consequently, multihop communication schemes emerge as alternatives to improve LoRa performance and to better utilize the nodes. These schemes also increase the variety of applications for the technology, thus making it a more versatile competitor in the IoT arena. Different researchers have proposed routing schemes to allow multihop communication in LoRa; to the best of our knowledge, this is the first review focused on routing protocols proposed for LoRa networks.

This article presents an overview of the major characteristics of LoRaWAN. Then the article presents the results of a systematic literature review to find the main approaches employed for routing in LoRa. The data was obtained from peer reviewed articles and citation analysis, following a method similar to the one presented in [4]. Thus, the article describes different routing algorithms and compares them according to their implementation characteristics as a guideline to analyze their possible usefulness. Finally, we present challenges for working in routing protocols in LoRa, and we conclude the article.

LoRaWAN

LoRaWAN is a technology for transmitting small amounts of data through long distances with low energy consumption. Use cases include precision agriculture, smart cities, remote environment monitoring, infrastructure monitoring, and smart grids. All these applications require measuring variables few times a day, such as temperature, humidity, and energy usage [1]. Therefore, LoRaWAN seems like a technology developed for wireless sensor networks (WSN); however, LoRaWAN transmits in one hop through several kilometers, and the technology is robust to interference.

LoRaWAN's main features are as follows. The technology uses a physical layer named LoRa

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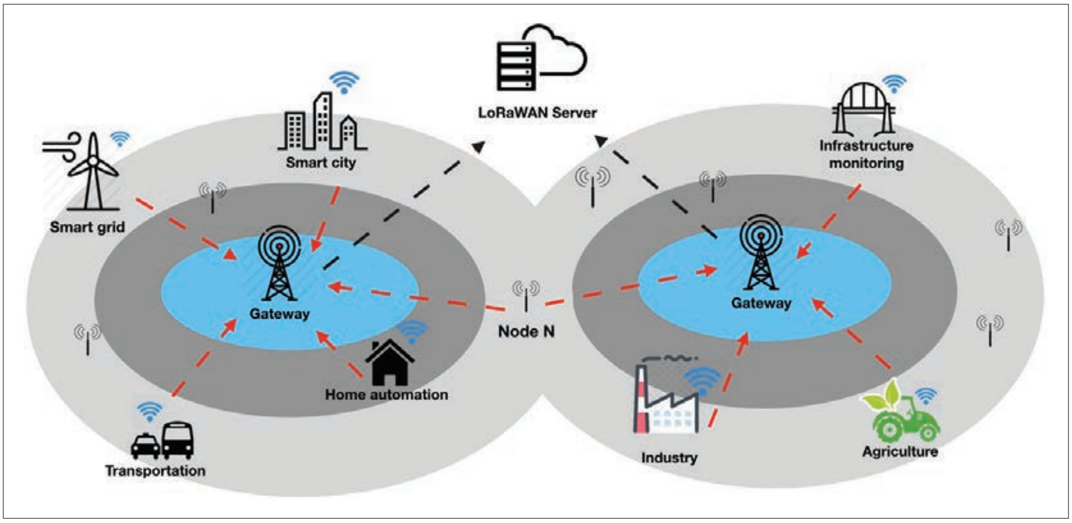

Figure 1. Applications of LoRaWAN

(long range), created by Semtech and the LoRa Alliance. LoRa radios use frequency shift keying (FSK) or chirp spread spectrum (CSS), with data rates from 250 b/s to 5.5 kb/s with CSS and up to 50 kb/s with FSK. A LoRa transmission requires defining four values: spreading factor (SF), carrier frequency, bandwidth, and coding rate. SF is an integer value from 7 to 12. Higher spreading factors increase symbol length, thus decreasing the data rate. LoRa radios include adaptive data rate (ADR), to select a transmission speed that better suits the channel conditions. The technology uses free frequency bands such as 868 MHz in Europe, 915 MHz in America, and 433 MHz in Asia. LoRaWAN uses bandwidths of 125, 250, or 500 kHz. The coding rate shows the number of bits employed for error detection and correction [5]. All these features combined allow for very long-distance transmission, making LoRaWAN a powerful technology for IoT.

The technology defines two basic types of devices. The first type is the end node, a simple device that sends information to gateways using an uplink and receives information from the gateway, through a downlink. The second type is the gateway, a device with a complex radio that simultaneously listens in different channels; therefore, they support thousands of nodes at the same time. Gateways send data to a main server using Internet connections [5].

Figure 1 shows different example applications for one LoRaWAN network, with two different gateways that relay information to the main server. Note that the ovals represent different distances with node locations possibly spanning several kilometers, as may be the case in agriculture and infrastructure monitoring. Also, Fig. 1 shows one characteristic of LoRaWAN networks: one node located within transmission range of different gateways sends information to all of them, leading to a topology called "star-of-stars" [5]. The example is node N, whose packets are received by both gateways.

LoRaWAN defines three node types [1]: classes A, B, and C. All nodes must implement class A, where devices send information at any time to the gateway using an ALOHA type of protocol. After sending, the node opens two reception windows to wait for downlink traffic. If the node receives a message in the first window, it must not open the second one. Class B is optional, and it is useful for devices that receive more information from the gateway than just an acknowledgment. The gateway sends synchronization beacons to open more reception windows even if there was no previous transmission from the node. Finally, in class C, nodes keep their reception windows open all the time, only closing them to send a packet through the uplink. Nodes that support class C do not implement class B. Because Class C makes the nodes receive continuously, these devices increase energy consumption.

Every device connected to a LoRaWAN network must be activated in one of two possible mechanisms: activation by personalization (ABP) or over-the-air activation (OTAA) [6]. Regardless of the mechanism employed, nodes and gateways only communicate using a star-of-stars topology; therefore, nodes communicate in one hop, and the standard does not specify a routing algorithm.

Every device connected to a LoRaWAN network must be activated in one of two possible mechanisms: Activation-by-Personalization or Over-the-Air-Activation. Regardless the mechanism employed, nodes and gateways only communicate using a star-of-stars topology; therefore, nodes communicate in one hop, and the standard does not specify a routing algorithm.

Thus, different studies propose and test alternatives to create multihop communication using LoRa technology. Routing algorithms make a packet traverse a network from source to destination through different hops. These algorithms either explicitly search for a route (e.g., computing the smallest distance) or just forward the packet without looking for specific routes.

Routing Strategies Proposed for LoRaWAN

This section describes the two main approaches found in the literature used in LoRaWAN. The first approach builds a tree topology, computing a route from source to destination. The second approach uses flooding, where the packet received is retransmitted [7].

Tree Topology

A tree topology is a hierarchical network where nodes can play one of at least three roles: root, parents, and children. The tree starts at the root (main node) that communicates directly to a set of parents. In turn, parent nodes can discover routes and forward data. Child nodes usually send information only directly to their parents.

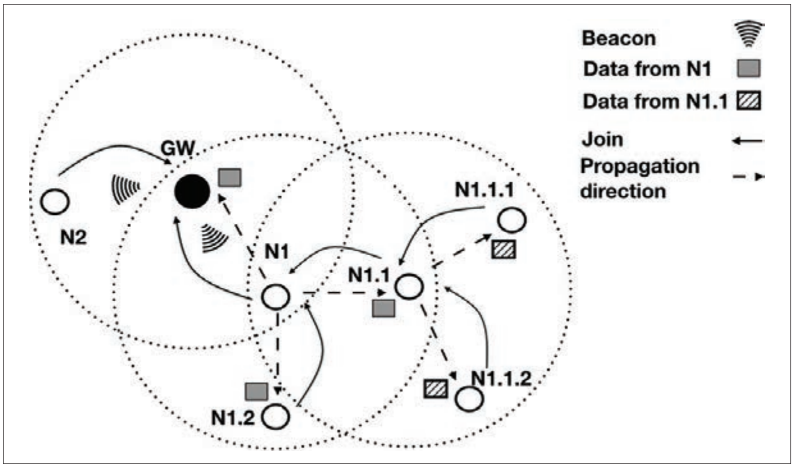

Figure 2. Tree algorithm presented in [8]. Circles show transmission range of the nodes.

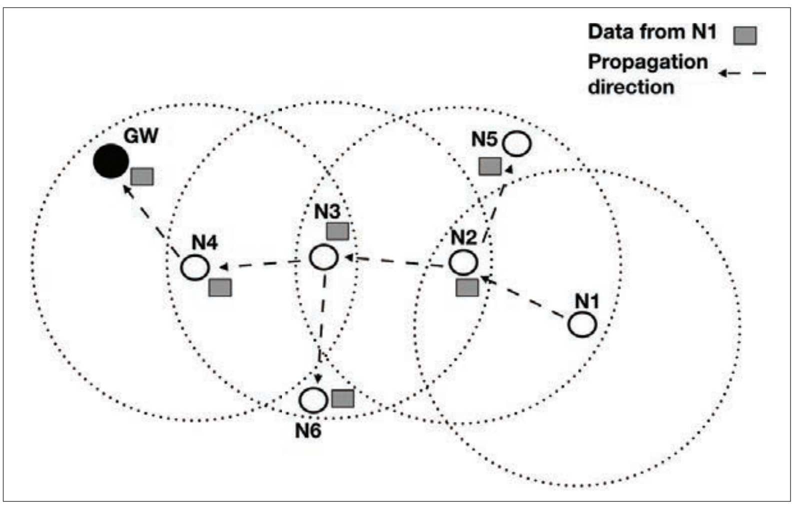

Figure 3. Flooding approach. Circles show transmission range of the nodes.

Different research used a tree topology to solve some transmission problems between nodes, improving reliability and energy consumption. Figure 2 shows the communication process in one example study [8]; the protocol, called LoRa Mesh, creates a tree rooted at a LoRa gateway that sends beacons during an initial time. All nodes listening to these beacons enter the network by sending a JOIN message, adding the gateway as their parent, with hop count one. When the gateway has a list of children, it does not send more beacons; instead, when nodes send data messages, these packets become beacons to other nodes that cannot hear the gateway. These new nodes send a JOIN message to the other nodes, becoming their children. The gateway knows the complete network topology because all intermediate nodes send their children list. Moreover, the gateway queries all nodes, even the ones located further along the tree, using intermediate nodes to forward the request.

A different approach suggests creating trees rooted at the gateway, where each tree is a subnet using a different SF. The method, called the Tree-Based SF Clustering Algorithm (TSCA), assumes that the gateway can listen to all its one-hop nodes simultaneously with different SFs. TSCA starts by creating a tree where all nodes in the network use SF7. Then the algorithm creates subnetworks with nodes that join different trees with different SF values. The goal is to minimize the number of hops and the delay, because higher SF values mean more airtime, increasing the end-to-end delay. Additionally, TSCA strives to achieve airtime balance among the trees; hence, subnetworks with high SF should have fewer hops than trees with small SF [9].

Another study uses Routing Protocol for Low Power and Lossy Networks (RPL) as the basis for multihop LoRa communications. The original RPL creates a tree topology called a directed acyclic graph, with three types of nodes: the root (main node), routers (potential parents to other nodes), and leaves (nodes that cannot be parents). RPL provides upward and downward routes, depending on the destination: the root or the nodes. Route selection employs a distance vector algorithm with a metric defined by an objective function (OF). The study includes a medium access control (MAC) protocol for RPL and LoRa, named RLMAC, a method of neighbor discovery, and a process for each node to select the SF to communicate with its parent. The article also creates an OF related to SF to minimize bit duration [10].

One more example is synchronous LoRa mesh, where sensor nodes (SNs) transmit their data and relay information from other SNs located underground. The protocol forwards these transmissions along a tree rooted on one router node (RN). Each RN sends the information of all its children to the gateway, using the payload of one LoRa packet. The protocol creates a communication cycle using time-division multiple access (TDMA), where the RN assigns time slots for SNs to listen. The cycle includes phases for synchronization, joining the network, uplink communications, and downlink transmission. Then a LoRaWAN period allows the RN to send information from its children to the gateway. Finally, the cycle includes a guard phase, where all nodes are inactive. The protocol requires synchronization, achieved by sending beacons in different hops through the whole network. One limitation of the protocol is the number of children the RN can manage, given by the maximum payload in the LoRa packet [11].

Another paper uses destination-sequenced distance vector (DSDV), where each node stores a table with routing information. The table includes all destinations reachable from that node, the next node in a path, the number of hops to the gateway, a sequence number, and a timestamp to eliminate old packets. The algorithm includes routing nodes (RNs) that forward the information to the gateway, and end nodes that cannot directly communicate with the gateway, called leaf nodes (LNs). The protocol only delivers information in the upward direction, using LoRa packets to transmit routing protocol information [12].

Flooding Approach

Flooding is a general algorithm where all nodes play the same role in the network, and the packet received is retransmitted [7]. Figure 3 shows one general flooding protocol where all nodes send information from node 1 (N1) to all other nodes within their transmission range. Different studies have shown that this approach allows sending packets simultaneously without explicitly computing routes.

Protocol	Routing	Test	Nodes	Hops (max)	Env	PDR (max)	D_{Max}/area (m)	Application
LoRa Mesh [8]	T	HW	19	3	NLoS	99,90%	500/800 x 600	Indoor-outdoor IoT monitoring
TSCA [9]	T	HW	36	8	NLoS	90%	NA/72 × 127	Infrastructure monitoring
RLMAC [10]	T	HW	2–4	2	NA	86%	NA/NA	Physical or chemical variables
Synchronous LoRa mesh [11]	T	HW	16	2	NLoS	< 95%	1830/NA	Underground infrastructure, smart city
DSDV [12]	T	HW	5	5	NA	98%	NA/NA	Small sensor data – uplink
CT-LoRa [7]	F	HW	18	2	NA	95%	NA/195 × 290	Multiple buildings
Abrardo and Pozzebon [13]	F	SW	20	19	NA	> 95%	200/25,000	Aqueducts
LoRaBlink [14]	F	HW	6	2	NLoS	80%	186/NA	Sensors and actuators

Table 1. Summary of test conditions. NA means information is not available in the paper.

One example study uses the Concurrent Transmission protocol applied to LoRa nodes (CT-LoRa). CT is a flooding protocol where only one node is the source of data, and all other nodes that receive information for the first time must retransmit it. CT does not use a collision avoidance mechanism; instead, CT relies on the capture effect to detect at least one of the forwarded packets. The paper shows simulations and field results, locating nodes in different buildings [7].

A different study by Abrardo and Pozzebon [13] presents one alternative for underground environments with total length of 15 km, specifically, medieval aqueducts in Siena, Italy. LoRa nodes in these settings have a maximum radio range of 200 m. Consequently, the paper proposes a linear sensor network (LSN) where every LoRa node must transmit and receive only to its immediate neighbors. The protocol uses three phases: synchronization, data, and sleep. The first phase sends a SYNCH packet flooded through the line topology to establish the schedule for transmission and reception. After sending the SYNCH packet, every node switches to low power listening to overhear the retransmission, using it as an implicit acknowledgment. Then the source node sleeps for a short time and transmits the first data packet, which the immediate neighbor receives and forwards. All nodes sleep and wake up according to the schedule.

The last example is LoRaBlink, one of the early proposals for routing in LoRa. The protocol uses time slots for transmission and reception, assuming all nodes and the gateway are synchronized. The gateway starts the process by sending a beacon. All nodes receiving the beacon must forward it, including the hop count, to the gateway. A node listening to different beacons will transmit to the node with the smallest hop count to the gateway. After several time slots, the nodes that want to transmit data send their packets. The relay node that receives the packet will forward it if the hop count of the relay is smaller than the one in the source of the original packet [14]. A recent study uses the same flooding algorithm, adding one adaptive spreading factor selection mechanism. Thus, the paper uses different SF values to increase network throughput [15].

Summary and Analysis

The surveyed approaches showed diverse prospective applications, and they were verified with different experimental settings, as presented in Table 1. In the table, T refers to tree, F means flooding, HW refers to hardware, SW means software (simulations), Env denotes environment, PDR is packet delivery ratio, D_{Max} is the maximum distance between nodes, and NA means the specific data was not available in the paper.

According to Table 1, most surveyed papers chose an implementation with a tree topology, and the majority chose to evaluate their protocols using hardware nodes in realistic settings. Therefore, results in these tests demonstrate the expected behavior in actual applications. Also, using mostly hardware nodes shows that the technology is readily available, and the research community is highly engaged in studying and improving LoRa performance.

The number of nodes and hops gives an idea of the scalability of the protocol because if the packet travels through more hops, the algorithm may be adequate for large networks. However, experiments included less than 40 nodes and eight hops, probably not enough for IoT scale. Moreover, higher node density (i.e., many nodes in a small area), as in TSCA, shows that the protocol survives intranetwork interference, an essential concern in LoRaWAN networks where thousands of nodes communicate with one gateway.

The column reporting environment (Env) shows whether nodes have LoS or NLoS conditions. LoS wireless channels generally allow for better communication performance [2]; therefore, protocols tested with NLoS environments cope with more difficult circumstances than those tested with LoS links. Furthermore, LoRa applications will benefit from protocols tested in NLoS conditions, because long-distance links will probably be subject to obstacles, increasing packet losses.

Regarding PDR, all studies reported values greater than or equal to 80 percent, regardless of the type of protocol (flooding or tree). Hence, both types seem adequate for applications tolerant to packet losses, such as the ones presented in the last column: smart grids, infrastructure, indoor and outdoor monitoring, and smart cities.

Finally, experiments used separations from 186 m to 1830 m, using a fraction of LoRa radio range capabilities. Because LoRa links extend through several kilometers, more work is needed to study the applicability of routing in LoRa communications with long-distance links.

Another challenge is to take advantage of all the features of LoRaWAN communications that are not fully explored in the literature. The interplay between ADR, SF, BW, the different node classes and modulations, along with cross-layer design techniques and other routing options (other than trees and flooding) create exciting opportunities to improve the performance of routing algorithms in LoRaWAN.

Challenges and Future Work

Although researchers have worked on various LoRaWAN routing protocols, several problems need to be discussed. Hence, we describe some challenges and provide suggestions for future work.

Packet Transmission Delay: Low data rates increase airtime, creating challenges at both the MAC and routing levels. Traditional mechanisms employed at the MAC layer for avoiding collisions, such as carrier sense multiple access (CSMA), may not be adequate because they increase the time required for transmission. This situation adds up for every hop in a routing protocol; thus, the end-to-end delay may be high for some applications, especially when using algorithms that explicitly look for routes throughout the network. Besides, the time required for communications decreases the number of total nodes that can use the network. This last issue is important because one gateway is supposed to manage thousands of nodes in a one-hop configuration. Nonetheless, surveyed examples show multihop communication experiments with less than 40 nodes; thus, studies with bigger networks should test delay performance and scalability to determine the usefulness of LoRa routing for different IoT applications.

Security: The privacy of information may be a concern in LoRa, where a malicious gateway can listen to data from different nodes in the network, taking advantage of the star-of-stars topology. This gateway can gather routing and user information, and it can even provide false data to disrupt network communication. The surveyed papers did not address this topic; however, future work should include security for routing in LoRaWAN, analyzing different attacks and countermeasures.

Exploiting LoRaWAN: Another challenge is to take advantage of all the features of LoRaWAN communications that are not fully explored in the literature. The interplay between ADR, SF, BW, the different node classes and modulations, along with cross-layer design techniques and other routing options (other than trees and flooding) create exciting opportunities to improve the performance of routing algorithms in LoRaWAN.

Energy Consumption: Energy use and network lifetime of routing algorithms in LoRaWAN is an essential topic because many IoT field devices use batteries. Furthermore, most of the surveyed algorithms require routing nodes to stay awake all the time, increasing energy consumption and making those nodes vulnerable to battery depletion. Future multihop schemes in LoRa should include energy-saving mechanisms such as sleeping (turning radios off) and parent rotation in tree topologies to spread energy use through different nodes and increase network lifetime.

Conclusions

The article provides useful information for researchers, IoT engineers, designers, and society at large who require long distance monitoring applications. The article shows the main two approaches proposed in the literature for routing in LoRa networks: tree topologies and flooding. We describe different examples of each method, showing their primary functions. Even though surveyed protocols did not use the same settings, the article highlights some guidelines for evaluation, such as the number of nodes, the test environment, and the primary metric used so far in experiments, packet delivery ratio.

Additionally, the article depicts different challenges to be addressed in future work on routing protocols for LoRaWAN, such as packet transmission delay, energy consumption, and security. Future work should also analyze the effect of LoRaWAN mechanisms such as OTAA, ADR, and the use of different SFs (e.g., the approach in [15]) to exploit the interplay of LoRaWAN characteristics.

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