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Design Considerations and Performance Evaluation of Gossip Routing in LoRa-Based Linear Networks

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Abstract: Linear networks (sometimes called chain-type networks) occur frequently in Internet of Things (IoT) applications, where sensors or actuators are deployed along pipelines, roads, railways, mines, and international borders. LoRa, short for Long Range, is an increasingly important technology for the IoT with great potential for linear networking. Despite its potential, limited research has explored LoRa's implementation in such networks. In this paper, we addressed two important issues related to LoRa linear networks. The first is contention, when multiple nodes attempt to access a shared channel. Although originally designed to deal with interference, LoRa's technique of synchronisation with a transmission node permits a novel approach to contention, which we explored. The second issue revolves around routing, where linear networks permit simpler strategies, in contrast to the common routing complexities of mesh networks. We present gossip routing as a very lightweight approach to routing. All our evaluations were carried out using real equipment by developing real networks. We constructed networks of up to three hops in length and up to three nodes in width. We carried out experiments looking at contention and routing. We demonstrate using the novel approach that we could achieve up to 98% throughput. We compared its performance considering collocated scenarios that achieved 84% and 89% throughputby using relay widths of two and three at each hop, respectively. Lastly, we demonstrate the effectiveness of gossip routing by using various transmission probabilities. We noticed high performance up to 98% throughputat $T_{prob} = 0.90$ and $T_{prob} = 0.80$ by employing two and three active relay nodes, respectively. The experimental result showed that, at $T_{prob} = 0.40$, it achieved an average performance of 62.8% and 73.77% by using two and three active relay nodes, respectively. We concluded that LoRa is an excellent technology for Internet of Things applications where sensors and actuators are deployed in an approximately linear fashion.

Keywords: LoRa networks; relay networks; linear networks

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1. Introduction

This work builds upon a previously presented paper at the Fourteenth International Conference on Ubiquitous and Future Networks (ICUFN) [1]. This paper discusses the potential of LoRa as a relay technology and describes a novel approach to dealing with channel contention, where multiple relays' transmission time overlaps. It expands upon that paper by presenting additional results and showing how gossip routing can be used to build robust linear LoRa networks.

Because of the rapid growth of the Internet of Things (IoT), Low-Power Wide-Area Networks (LPWANs) are becoming increasingly important in a number of scenarios. They are of particular importance in areas where traditional cellular networks have limited coverage or deployment costs make them unviable [2]. LPWANs are ideal for situations where low bit rates and long ranges are needed such as smart farming, electric metering, building monitoring, and logistic tracking applications [3].

Many LPWAN technologies have been proposed that operate in both licensed and unlicensed frequency bands. LoRa, Sigfox, and NB-IOT are leading LPWAN technologies that are commercially available. According to [3,4], LoRa outperforms Sigfox and NB-IoT in many areas. In a real-world scenario, LoRa, despite its relatively high packet loss ratio (up to 15%), holds significant potential, particularly in the field of environmental monitoring [5].

While LoRa is typically deployed with a gateway device, one important use case is to consider LoRa technology as a linear or near-linear network [6]. This important use case provides an opportunity to adopt LoRa technology for various monitoring applications (e.g., pipelines, roads, tunnels, borders, railways), where end devices (sensor nodes) are connected in such a way as to form Linear Wireless Sensor Networks (LWSNs), alternatively known as chain-type wireless sensor networks [7,8]. In this type of network, multiple nodes are connected in such a way that the network forms a long and thin topology, and data packets are transmitted by using a series of nodes that are connected in a multi-hop fashion using a relaying mechanism. In a linear network, sensor nodes strictly follow a straight-line pattern, such as roads or railway tracks. In near-linear networks, sensor nodes can be deployed in a more loosely linear pattern, such as tunnels or pipelines. Nodes within the network may have sensors or actuators connected to them and, so, generate or act on the data received or they may simply pass the data on to the next node, in which case they are called "relay" nodes. This type of topology is used to extend the network coverage over long distances [9].

This paper explored the practicalities of using LoRa as a linear network. This topology finds applications in a range of IoT scenarios, including road monitoring, traffic surveillance, and gas pipeline oversight, as illustrated in Figure 1. Within these network setups, data collection occurs through a series of sensor nodes arranged in a linear or near-linear manner. These nodes facilitate the transmission of the data to a central node. Furthermore, Linear Wireless Sensor Networks (LWSNs) from the topological point of view can be deployed as linear parallel wireless sensors. These networks, also referred to as chain-type wireless sensor networks, involve deploying sensor nodes in two parallel lines following a near-linear pattern. This strategic arrangement significantly extends the network coverage over long distances. Notably, these types of networks are considered well-suited for meeting specific design requirements, such as monitoring railway tracks [6].

The feasibility of LoRa-based networks has been evaluated in various monitoring applications [10,11]. However, for them to be widely deployed, a number of challenges need to be addressed, in particular link coordination, reliable transmission, and resource allocation. Network reliability and the optimisation of deterministic delay in LoRa-based linear networks are the main challenges [12]. Despite its importance and perhaps because of LoRa's relative novelty, very little research has been carried out on these topics.

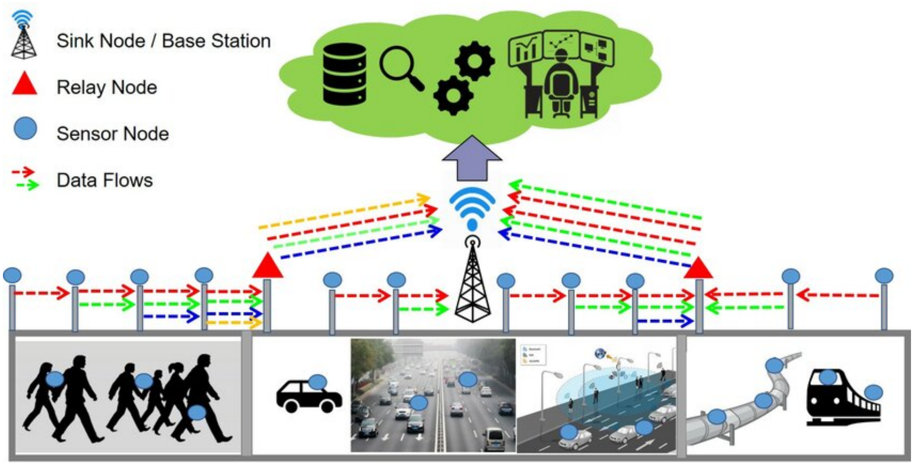

Figure 1. Linear wireless sensor networks and applications [13].

In this paper, we addressed these issues. We discuss the issue of managing contention in LoRa-based linear networks. Our results showed that the inherent interference-rejecting characteristics of LoRa lead to a very simple design approach for managing contention. We explored this approach with network widths of one, two, and three relays. We demonstrate that the approach, although simple, achieved 98% throughput for a three-hop network. We also discuss the effectiveness of a gossip-based probabilistic approach in the presence of various active relay nodes using a one-hop model.

The contribution of this paper can be summarised as follows:

- We describe a simple and effective scheme to deal with contention within relays in linear networks that makes use of the fundamental behaviour of LoRa.
- We evaluated the performance of the approach in linear networks of up to three hops and up to a thickness of three nodes.
- We evaluated a gossip-routing-based approach applied to linear networks.

The rest of the paper is structured as follows. Section 2 presents the related work in this context. Section 3 presents the motivation for this research. Section 4 presents the network designs and experimental setup. The evaluation of the proposed design approaches and the results are discussed in Section 5. Section 6 discusses the impact of hardware imperfection on network performance. Lastly, in Section 7, we summarise our work and point to future research.

2. Related Work

Typically, LoRa technology has been deployed as a hub and spoke topology based on the Layer 3 LoRaWAN protocol [14]. LoRa exhibits substantial potential, particularly as a candidate for a long-range multi-hop network. With its capacity to reliably cover distances of up to 103 km, LoRa emerges as a compelling choice [15].

A small number of researchers have focused on adopting LoRa as a mesh network technology. Very few have considered the issues related to using it as a linear network technology. We summarise the key contributions in this context.

Fernandes et al. explored the issues of concurrent transmission in LoRa communications [16]. A Received-Signal-Strength-Indicator (RSSI)-based evaluation model was proposed that shows LoRa has an unusual communications property, whereby concurrent transmissions do not necessarily result in all communications being corrupted. By synchronising with one transmitter, a receiver will treat other concurrent transmissions as noise. The authors described this as a "non-destructive communications property". A slight difference in RSSI values (2 dBm to 3 dBm) increases the chances of a Packet Delivery Rate (PDR) from 82% to 97%, respectively, during concurrent transmission [16].

Chain-type wireless sensor networks can be very effective, especially for underground mine monitoring. The consideration of the new deployment strategy of "chain-type" networks promotes the WSNs for special types of environment monitoring such as mines, roads, tunnels, bridges, rivers, pipelines, and greenhouses [17,18]. Chain-type networks are fundamentally different from other types of networks naturally fit for these types of applications, which may spread over hundreds of miles in distance. These types of networks are also referred to as linear WSNs [19]. Furthermore, in a chain-type network, sensor nodes can be deployed randomly, forming a near-linear pattern (as shown in Figure 2); such a type of formation is still technically known as a chain-type WSN [20]. Simulation results have shown that chain-type WSNs are considered ideal for optimal energy consumption, which results in the extended lifespan of the network [21]. Much research on linear (chain)-type networks has been performed, but very few researchers have considered LoRa as a linear network.

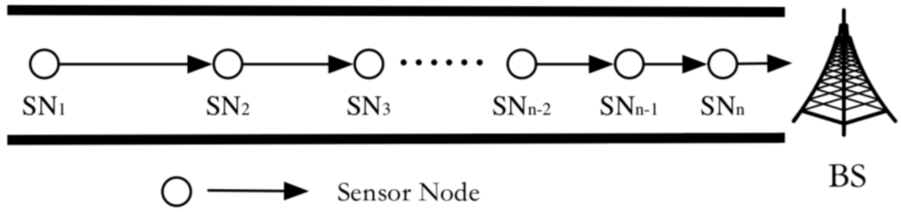

Figure 2. An example of a chain-type wireless sensor network [20].

The feasibility of LoRa as a linear network has been proposed for pipeline monitoring [22]. The simulation outcomes indicated that LoRa could be regarded as a viable relaying technology for enhancing the reliability and network coverage of IoT applications [23]. The adoption of LoRa technology as a linear network and employing different time slots has great potential and establishes a high degree of reliability [24].

In LoRaWAN, the introduction of a LoRa gateway as a relay node significantly extends the network coverage and improves the packet delivery rate by up to 50% compared to direct communication [25].

An analytical model was proposed, providing new insights by considering LoRaWAN as a multi-hop technology. The proposed model investigates power consumption and throughput using both single-hop and multi-hop relay networks [26]. The LoRaWAN protocol within the thin linear network has been proposed as a multi-hop solution for monitoring applications. Experimental results have demonstrated that the synchronisation of different nodes, considering various time slots and active periods, has a significant impact on network performance, affecting network packet loss and power consumption [27].

LoRa technology has been proposed as an effective solution for implementing a railway signalling system. The performances of network architectures with reference scenarios have also been compared, laying the foundation for innovative railway communication systems [28].

The potential of LoRa LPWAN as a communications technology for underground mining was explored in [29]. LoRa as a multi-hop solution has been proposed for underground sensor networks. The proposed multihop cooperation solution can be effective in terms of energy efficiency and network scalability [30].

A LoRa relay-based system has been introduced that uses multiple relays to establish communication in underground mining [31]. To ensure robust communications, a condition was proposed that time slots and node arrangements should be selected such that each node slot delay should not be equal to the sum of other slot delays [32]. However, by applying the proposed scheduling technique, the total introduced delay increases with the square of the number of nodes. Therefore, the traditional offset-based approach may not be equally effective, especially delay constraint applications [1,32].

The flooding-based approach is regarded as the simplest way of propagating messages across a mesh network. In this method, whenever a node receives data packets, it forwards them to all neighbouring nodes, effectively selecting the fastest route without any complex routing overhead. However, as the network expands, this flooding-based approach leads to the creation of numerous duplicate packets, which in turn hinders performance in terms of energy consumption and introduces additional traffic to the network [33,34].

Gossip routing is a modified version of the flooding-based approach. It uses a predefined random approach to send a packet, rather than simple broadcasting [35]. The gossip-based approach reduces the transmission overhead, which can further improve the message reachability in ad hoc networks [36]. Gossip routing is considered more-energy-efficient as compared to traditional flooding-based approaches [37]. A comparative study was conducted that measures the performance of various gossip routing approaches to estimate the network size [38]. A gossip-based approach can be highly effective in addressing both the dynamic loading problem and failure detection. Simulation results have demonstrated that the gossip-based approach reduces communication overhead by balancing the load at both local and global network levels [39].

The gossip-based approach offers a way to enhance energy efficiency and optimise radio resource utilisation in comparison to the traditional flooding-based approach. In gossip routing, a message is forwarded with a probability less than one. Researchers have evaluated the feasibility of implementing gossip-based routing in wireless sensor networks, and the experimental results have demonstrated several advantages. The combination of gossip routing with flooding results in reduced power consumption, minimal traffic overhead, and improved network transmission delay [40,41].

The integration of a gossip-based approach with different ad hoc routing protocols is highly beneficial in minimising unnecessary transmission overhead. Simulation studies have revealed that utilising the gossip-based approach can lead to a reduction of traffic overhead by up to 35% when compared to the flooding approach. However, the extent of transmission savings largely depends on the chosen gossip probability. Furthermore, the effectiveness of transmission savings is influenced by both the gossip probability and the specific design applications of the network, such as network-wide broadcast or point-to-point communication [42,43]. The evaluation of LoRa technology with a gossip-based approach can be very effective as compared to conventional routing approaches, particularly within linear networks. Very little research has been carried out in this context.

In this section, we highlighted some important contributions where LoRa has been proposed as a multi-hop technology. Mostly, authors have focused on relay synchronisation to avoid the contention issue. Introducing the slot time among different relay nodes can significantly solve the contention issue, but it also increases the communication delay. For larger networks with more relays, this problem becomes unmanageable; ideally, we need an alternate approach as the network scales. We demonstrated LoRa's feasibility as a multihop relay technology without introducing additional delay at relay nodes. Lastly, we discussed the effectiveness of gossip routing by exploring various transmission probabilities.

3. Motivation

The feasibility of LoRa as a relay technology has been proposed in various IoT applications. Our focus was to consider LoRa as linear or near-linear networks for reliable communication. LoRa is designed to be very resistant to interference [44]. Furthermore, the LoRa Channel Activity Detection (CAD) process enables a simpler, more-effective approach to contention management based on physical offsets rather than programmed delays [1]. We took advantage of this "non-destructive communications" characteristic of the LoRa physical layer to provide reliable communications in a LoRa-based linear network.

LoRa is a spread spectrum technology that makes use of chirp spread spectrum modulation. A receiver will synchronise with a transmitter and, thereafter, expect communications at specific starting frequencies at the beginning of each symbol time. Transmissions outside those frequencies are ignored and treated as noise. This approach to the spread spectrum makes communications very robust, giving LoRa its impressive transmission distance, but it also makes possible a novel approach to dealing with contention in relay networks.

Relay networks comprise a source, multiple relay nodes, and a destination. Contention is an issue in such networks where the recipient of a message (either the destination or another relay node) may receive the same message from multiple relays. Usually, concurrent reception of a message results in it being corrupted. Consequently, complex scheduling algorithms or strict limitations on transmission distance are usually necessary.

However, because LoRa nodes synchronise with one transmitter and treat other transmissions as noise, LoRa makes it possible to avoid such complexity. So long as transmissions are not completely concurrent, two nodes transmitting the same message will result in the receiver synchronising with one transmitter and treating the other as noise. This is the "non-destructive communications" characteristic of LoRa. Furthermore, during the current transmission, a LoRa signal that traverses the shortest path will be treated as a wanted signal and other signals will be treated as interference. A preamble signal (depending on the LoRa configuration) is used to synchronise the receiver with an incoming data stream. The receiver captures the preamble symbols from the shared channel and tries to match them to the ideal waveform. Upon a successful match, it generates an interrupt to initiate the receiver process. We discussed the survival of LoRa during concurrent transmissions as presented in [1], which laid the foundation for this study.

We show how this LoRa characteristic can be used to build simple and robust linear networks. We explored the situation with networks of different widths where a receiver can see one, two, or three nodes and demonstrate that a small physical offset of the nodes is sufficient to allow the receiver to synchronise with one of the relays and treat the others as noise.

This characteristic of LoRa also means that simple networking routing becomes possible. Linear networks usually have simple routing requirements. We show that simple gossip routing provides high throughput with minimal complexity.

We demonstrate how this characteristic can be used in managing contention and evaluated the performance of a number of networks of different thicknesses. We evaluated the performance of a LoRa-based linear network up to three hop counts by introducing the various thickness levels at each hop. Furthermore, we demonstrate the gossip-based approach by considering the various probabilistic distributions to reduce the traffic overhead and effective utilisation of radio resources.

To the best of our knowledge, there is no empirical research as to the effectiveness of this approach for LoRa-based linear networks.

4. Experimental Setup

In order to develop the linear network using LoRa technology and incorporate different relay widths, we undertook the task of assessing the potential coverage range. This assessment involved utilising two nodes and considering up to three hop counts. We used actual devices throughout the study (Figure 3 (configuring the relay node during the experimental trial)). The subsequent section discusses the transmission coverage estimation and design possibilities. An aerial view of the network deployment is shown in Figure 4.

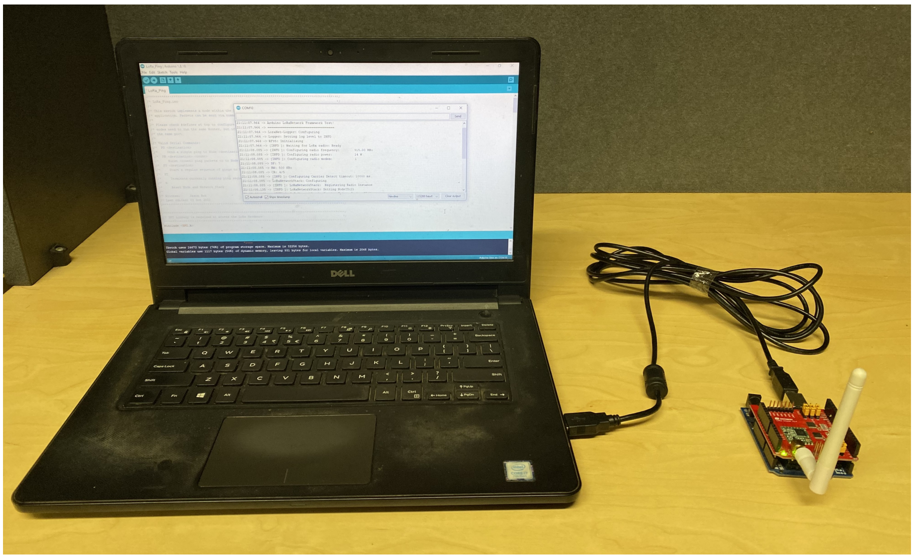

Figure 3. Configuring relay node during the experimental trial.

Figure 4. Aerial view of network deployment (source: Google maps).

4.1. Coverage Estimation and Placement of Relay Nodes

It is a challenging task to estimate the exact coverage overlap. We tried to estimate the transmission coverage range by using two end nodes with almost zero packet loss at each station (packet loss increases with the increase of the physical distance between nodes as the RSSI and SNR values become low). To set up more relay nodes between the source and destination nodes, we used the lowest transmission power (14 dBm) and highest bandwidth (500 Hz). Using the highest bandwidth (500 kHz) significantly dropped the SNR ratio by 4 dB to 5 dB as compared to a lower bandwidth (125 kHz). The transmission coverage range also significantly depends on hardware imperfection. We discuss the impact of hardware imperfection on the RSSI and SNR in Section 6.

However, based on a single pair of nodes, we identified where on our campus nodes can be placed to avoid overlap.

4.2. Network Design and Configuration

We conducted four sets of experiments with different numbers of relay nodes at each station. The number of co-located relay nodes represented the 'width' of the network. In the first set of trials, we only used a single node at each station. The network formation along with ideal coverage estimation is shown in Figure 5. In the second and third trials, we added the additional relay nodes at each station to increase the thickness of the LoRa-based linear network. However, the additional relay nodes at each station can be added in two ways, either collocated or using a physical offset between relay nodes. Collocated nodes are placed adjacent with approximately zero distance between two nodes, whereas the physical offset between relay nodes can be achieved via moving the relay nodes along the x-axis or y-axis.

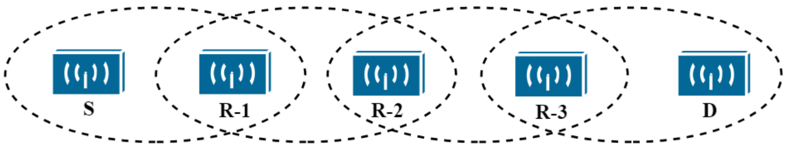

Figure 5. Network architecture using a single relay node at each hop with ideal coverage estimation.

In the second trial, we added an additional relay node at each hop. The network architectural designs with a relay width of two nodes considering both cases are shown in Figures 6 and 7, respectively.

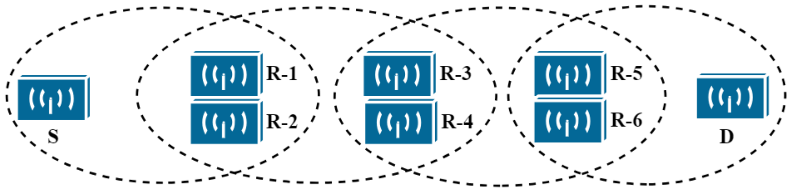

Figure 6. Network architecture of collocated relay nodes of a width of two with ideal coverage estimation.

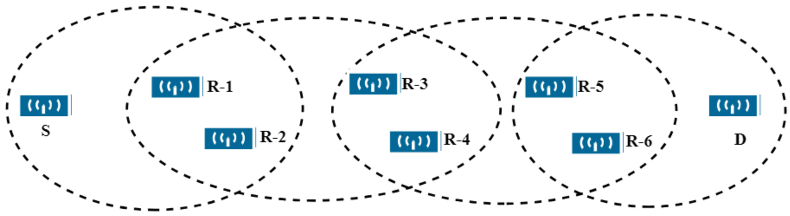

Figure 7. Network architecture of physically offset relay nodes of a width of two with ideal coverage estimation.

In the third experimental trial, we further increased the width of the LoRa-based linear network by introducing another additional relay node at each hop. We considered both cases of collocated and a physical offset between relay nodes. The network architectural designs with a relay width of three nodes considering both cases are shown in Figures 8 and 9, respectively.

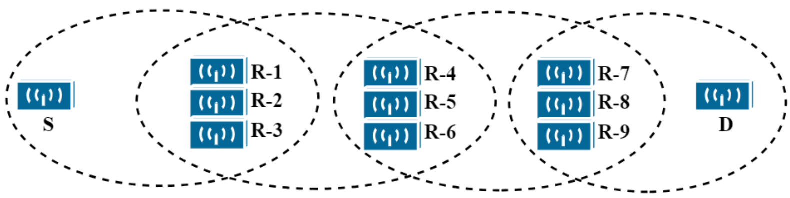

Figure 8. Network architecture of collocated relay nodes of a width of three with ideal coverage estimation.

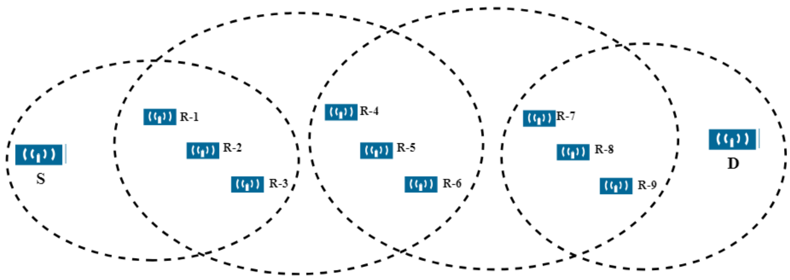

Figure 9. Network architecture of physically offset relay nodes of a width of three with ideal coverage estimation.

During the experimental trials (1, 2, 3), at least 500 packets were sent from the source to the destination via the relay nodes. We used the same configuration throughout the experiments (please see Table 1). The selection of the LoRa transmission parameters can play an important role in ensuring efficient and reliable communication. LoRa technology provides different configurable settings such as the spreading factor, bandwidth, coding rate, and transmission power to optimise the performance depending on the application use cases. The adoption of a higher SF increases the LoRa signal quality with an improved SNR value at the costof air time. Employing the higher bandwidth helps to increase the data rate, but it also lowers the receiver sensitivity because the utilisation of a wider band allows the integration of additional noise. Lower coding rates can offer more resilience in the presence of interference, but also increase the time on air because of the additional redundant bits. The use of higher Transmission Power (TP) can slightly improve the RSSI (up to 2 to 3 dBm) by changing the transmission power to 11 dBm, 17 dBm, and 23 dBm, respectively. The usage of higher transmission power significantly increases the power consumption in LoRa-based networks, which also depends on the hardware. However, it is very challenging to evaluate the performance against each configurable parameter (6720 possible settings) [45,46].

Table 1. LoRa configuration.

Parameter	Value
Packet Size	10 Bytes
Transmission Power (TP)	14 dBm
Spreading Factor (SF)	7
Bandwidth (BW)	500 kHz
Coding Rate (CR)	4/5

In the fourth experimental trial, we explored the gossip-based approach with two and three active relay nodes using the one-hop model.

Gossip routing is often regarded as the preferred solution, particularly in decentralised and resource-limited environments. Within such networks, nodes possess the capability to communicate directly, eliminating the need for a centralised mechanism to disseminate information. The adoption of a gossip-based approach ensures the resilience required to establish reliable communication under challenging network conditions. In the event of node failure, gossip-based routing offers a high probability of successfully relaying information. The gossip-based approach, depending on the transmission probability, can be tailored to minimise energy consumption compared to continuous broadcasting. It also provides adaptability by allowing adjustments to various aspects, such as the speed of information dissemination (based on T_{prob}) and the reduction of transmission interference. However, as the network scales up in terms of both length and width, it can experience performance degradation due to interference. While the allocation of dedicated time slots can effectively address this issue, it introduces a trade-off by increasing the transmission delay. Consequently, gossip-based approaches prove highly effective, especially in the context of long, thin networks.

We used the various combinations of the transmission probabilistic distribution (T_{prob}) in the presence of two and three active relay nodes, respectively.

To evaluate the performance, we sent at least 1000 pings from the source to the destination node via all active nodes and noted the performance by calculating the Packet Reception Rate (PRR) at the Destination node (D) using the one-hop model.

We used Equation (1) to calculate the ideal packet reception rate using various probabilistic values in the presence of different numbers of active relay nodes.

$$1 - ((1 - T_{prob})^n), \tag{1}$$

where:

- T_{prob} stands for Transmission probability;
- n stands for the number of relay nodes.

5. Result Evaluation and Discussion

In this section, we discuss the outcome of all experimental trials that we designed in the previous Section 4.2. The experimental result outcomes during each particular design are further discussed below.

5.1. Thin Linear Network

In the initial experimental trial, we constructed a long, thin network with up to three hops, as shown in Figure 5. During this trial, a total of 500 packets were transmitted from the Source node (S) to Destination node (D) through three relay nodes. We calculated the Packet Reception Rate (PRR) via all relay nodes (R-1, R-2, and R-3) at D. The experimental result showed that D had a PRR of 99.3 %. The overall performance analysis at D during the first experimental trial is shown in Figure 10. The Packet Loss (PL) by using a single relay node at each hop (tested with a three-hop count) was almost negligible.

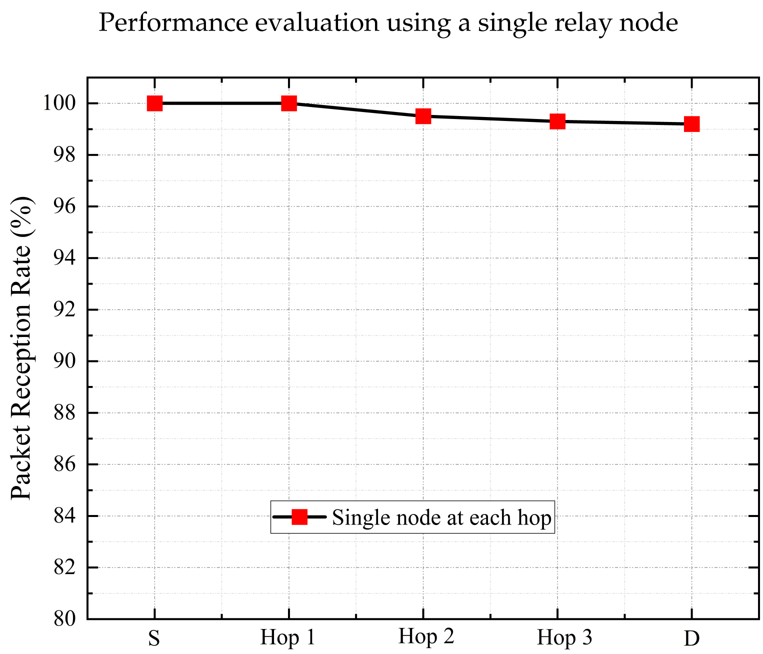

Figure 10. Overall performance using a single relay node at each hop.

5.2. Linear Network of a Width of Two

In the second trial, we evaluated the network performance at D by considering both cases as shown in Figures 6 and 7. To evaluate the performance of the network as shown in Figure 6, we sent 500 packets to D in the presence of all active relay nodes (R-1, R-2, R-3. . . R-6). We calculated the PRR at D with respect to all active relay nodes.

From the experimental results, we can say that the net PRR at D was approximately 84.21%, as shown in Figure 11. To evaluate the network performance, as depicted in Figure 7, we transmitted 500 packets from S to D in the presence of all active relay nodes, considering the physical offset between relay nodes. The results showed that the PRR via all active relay nodes was about 98.15%, as shown in Figure 11. These results demonstrated the non-destructive characteristic of LoRa transmission. When the nodes at the station were colocated, this resulted in a high probability that both of these nodes would receive a message simultaneously and choose to retransmit it simultaneously, increasing the probability of collision at the next receiving station. Instead, when the nodes had a physical offset, the offset in the reception time was replicated in the subsequent retransmission time. This offset helped the next receiving station lock onto the first transmitter and ignore the collision.

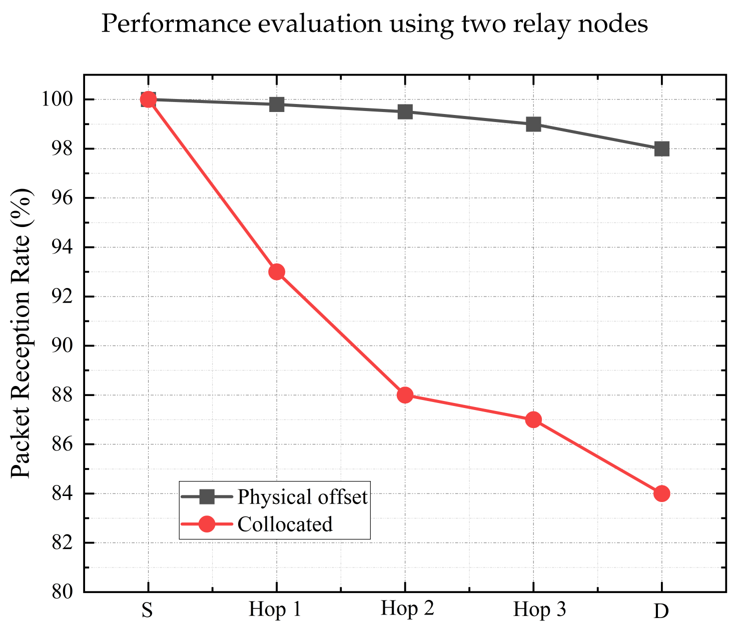

Figure 11. Overall performance using two relay nodes at each hop.

5.3. Linear Network of a Width of Three

In the third trial, we noted the network performance at D by considering both cases, as shown in Figures 8 and 9. To evaluate the performance of the network, as shown in Figure 8, we sent 500 packets to D in the presence of all active relay nodes (R-1, R-2, R-3... R-9). We calculated the PRR at D with respect to all active relay nodes. From the experimental results, the net PRR at D was recorded to be about 89.25%, as shown in Figure 12.

To evaluate the network, as shown in Figure 9, we sent 500 packets from S to D in the presence of all active relay nodes along with a physical offset between the relay nodes. The results showed the PRR via the relay nodes be about 98%, as shown in Figure 12. As with the linear network of a width of two, these results successfully demonstrated the non-destructive characteristic of LoRa transmission through reduced packet loss when nodes are offset physically.

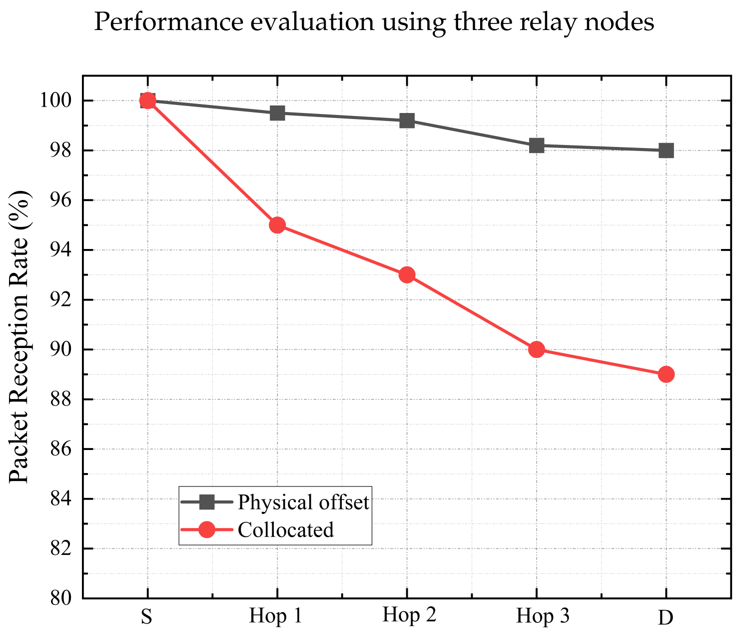

Figure 12. Overall performance using three relay nodes at each hop.

During the third experimental trial, by adding the additional relay node at each station, we also realised that replacing identical nodes can significantly impact the overall performance. We discuss the impact of hardware imperfection by considering different manufactures along with identical nodes in Section 6.

5.4. Gossip Routing

Lastly, in the fourth trial, we used the random probabilistic distribution (T_{prob}) in the presence of two and three active relay nodes using a one-hop model. The evaluation of gossip-based probabilistic transmission involved the following steps:

- Set up the network, and configure a transmitting node to continuously transmit at least 1000 packets, with a rate of 1 packet every four seconds.
- Relay nodes that relay packets to the destination node using various probabilities (1.00, 0.95, 0.90, 0.80, 0.70, 0.60, 0.50, 0.40).
- Re-run the experiments by configuring the relay nodes using various T_{prob} at the relay nodes.
- Compare the performance using two and three active relay nodes using a one-hop model.

The concept of employing a gossip-based probabilistic method is quite straightforward. In this approach, a relay node is configured with a designated probability threshold, denoted as T_{prob}. Once the relay node receives a packet from the source, it calculates the probability of forwarding the packet. If this calculated probability is equal to or less than T_{prob}, the packet is forwarded. Alternatively, if the probability is greater than T_{prob}, the packet is discarded. When T_{prob} is set to 1, the Packet Reception Rate (PRR) attains its peak performance. Every incoming packet is relayed to the destination node without loss. At T_{prob}= 0.9, around 10% of packets are dropped. Due to the utilisation of a random function for packet dropping, it is highly improbable that both relay nodes will discard the exact same packets. To verify the arbitrary dropping at each relay node, we logged the instances of dropped packets. To ensure the robustness of the gossip-based probabilistic method, we conducted two sets of experimental scenarios with two and three active relay nodes. The results of these experiments are presented in Tables 2 and 3. We sought to determine the optimal threshold values for the probability values in the presence of both two and three relay nodes, using the one-hop model, as illustrated in Figure 13.

Table 2. Impact on performance using various T_{prob} with two active relay nodes with a single-hop count.

T_{prob}	**1.00**	**0.95**	**0.90**	**0.80**	**0.70**	**0.60**	**0.50**	**0.40**
Ideal	100.00%	99.75%	99.00%	96.00%	91.00%	84.00%	75.00%	64.00%
Experiment 1	96.21%	93.43%	98.00%	94.72%	90.54%	80.99%	73.73%	61.99%
Experiment 2	99.40%	98.40%	98.01%	93.83%	89.86%	79.82%	74.82%	63.61%
Average	97.80%	95.91%	98.00%	94.27%	90.20%	80.40%	74.27%	62.81%

Table 3. Impact on performance using various T_{prob} with three active relay nodes with a single-hop count.

T_{prob}	**1.00**	**0.95**	**0.90**	**0.80**	**0.70**	**0.60**	**0.50**	**0.40**
Ideal	100.00%	99.98%	99.90%	99.20%	97.30%	93.60%	87.50%	78.40%
Experiment 1	98.90%	99.00%	97.71%	97.61%	91.24%	91.14%	81.29%	74.02%
Experiment 2	96.31%	98.31%	96.41%	98.51%	92.13%	90.24%	80.49%	73.53%
Average	97.60%	98.65%	97.06%	98.06%	91.68%	90.69%	80.89%	73.77%

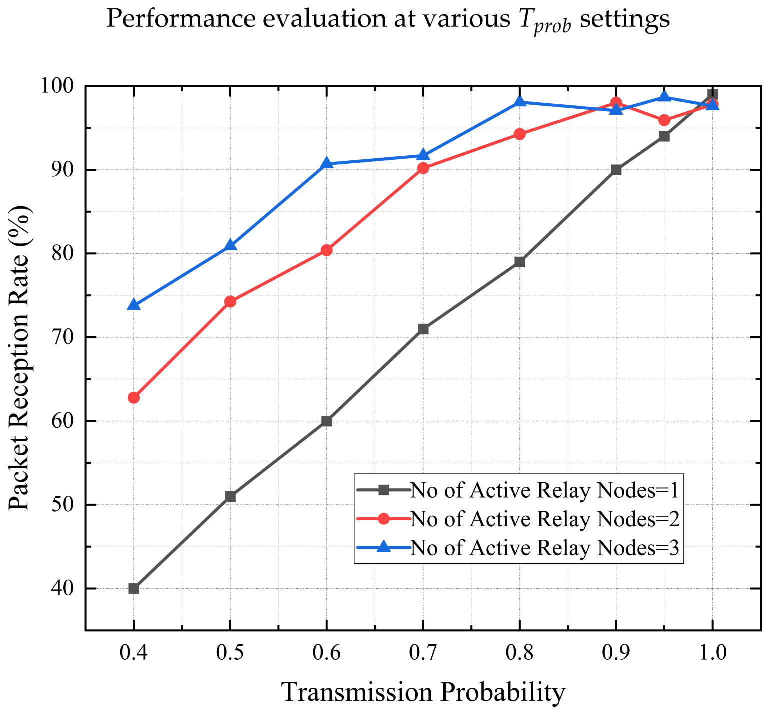

Figure 13. Performance comparison at various T_{prob} using the data from Tables 2 and 3.

5.5. Summary

Our experimental results can be broadly categorised into two tasks. In the first task, we explored two design approaches: physical offset and collocated, along with their respective performance metrics. We demonstrated the effectiveness of the simpler design approach, referred to as "physical offset", in achieving a throughput of up to 98%. Additionally, we examined the performance of both design approaches across different relay widths (widths of 1, 2, and 3) within a network of up to three hops. However, the robustness of a linear network depends purely on its network architecture. If we use a single relay node at each hop that falls within the exact coverage overlap (Figure 5), in such a case, the failure of a single relay can lead to network failure. In the presence of different relay widths (two or more), even with the failure of a few individual relay nodes, network connectivity can still be maintained.

Furthermore, we conducted a comparative analysis between the performance of the physical offset design approach and the collocated approach, utilising various relay widths. This analysis is elaborated upon in Sections 5.2 and 5.3 of our discussion.

In the second task, we conducted experiments using gossip routing with different transmission probabilities in the presence of two active relay nodes. The average performance we observed was 98% and 94.27%, at T_{prob} = 0.90 and T_{prob} = 0.80, respectively. As we continued to reduce the transmission probability, we noticed a corresponding decrease in performance. However, when the probability was set to 0.4, we achieved a notable Packet Reception Rate (PRR) of 62.8%. To further assess the impact, we introduced an additional relay node and evaluated the performance across various T_{prob} settings. The introduction of this extra relay node significantly improved the packet reception rate when compared to the scenario with only two active relay nodes, as depicted in Figure 13. Specifically, at T_{prob} = 0.80, we achieved a performance level of 98.06%. With further reductions in the transmission probabilities (T_{prob} = 0.70, T_{prob} = 0.60, and T_{prob} = 0.50), the performance results were 91.68%, 90.69%, and 80.89%, respectively. At T_{prob} = 0.40, the performance reached approximately 73.77%.

Lastly, we also mapped the performance of the gossip routing results with conventional broadcasting (T_{prob} = 1.00) by considering different relay widths, as shown in Figure 14.

Based on the experimental results, it was evident that, at T_{prob} = 0.90 and T_{prob} = 0.80, we could achieve nearly identical outcomes as at T_{prob} = 1.00, when employing two and three active relay nodes, respectively. Based on the experimental data, it was evident that our result closely aligned with the theoretical calculation. This not only allows for the efficient utilisation of radio resources, but also results in reduced energy consumption compared to continuous broadcasting. With these findings, we can extrapolate the consideration of gossip routing over a longer linear network for power savings and reducing transmission overhead for optimal performance.

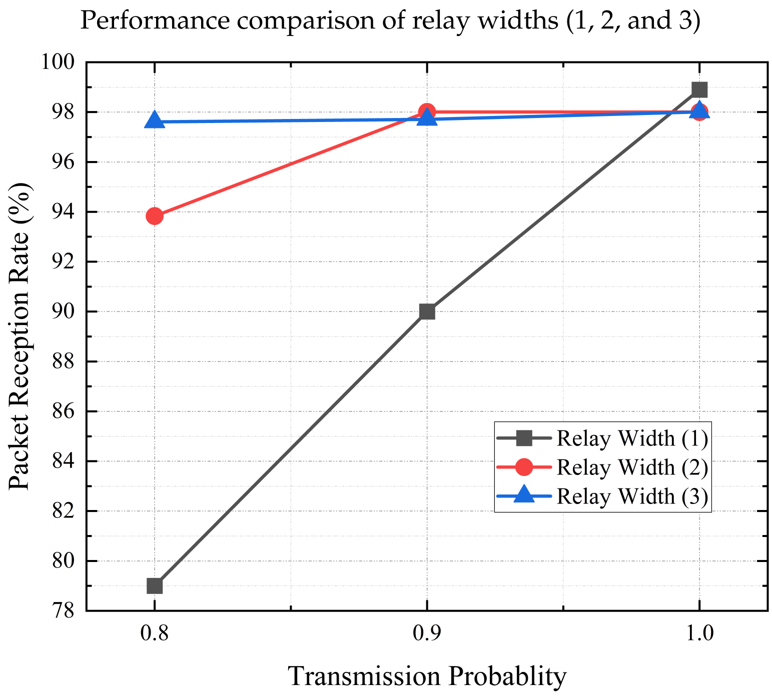

Figure 14. Performance comparison using a one-hop model.

6. Impact of Hardware Imperfection on Network Performance

Hardware imperfection can significantly impact the coverage overlapping estimation. To explore the hardware imperfection and its impact on the RSSI and SNR, we ran a few trials by using different Arduino boards and LoRa shields (with a constant distance of 175 cm approximately between two nodes). We used two types of Arduino boards (one with standard USB and the other with a micro USB port) and two types of LoRa shields (chip manufacturer H RF96 and SX 1276). We used the same network configuration and kept changing the physical nodes (Arduino + LoRa shields) to explore the hardware imperfection. The impact of hardware imperfection on the RSSI and SNR is shown in Table 4.

Table 4. Impact of hardware imperfection on the RSSI and SNR using different manufacturers.

Source Arduino Board	Destination Arduino Board	Source LoRa Shield	Destination LoRa Shield	RSSI	SNR
Arduino UNO	Arduino UNO	H RF96	H RF96	−40	5
Arduino UNO (Micro USB)	Arduino UNO (Micro USB)	H RF96	H RF96	−35	5
Arduino UNO	Arduino UNO	SX 1276	SX 1276	−35	5
Arduino UNO (Micro USB)	Arduino UNO (Micro USB)	SX 1276	SX 1276	−77	5
Arduino UNO	Arduino UNO	H RF96	SX 1276	−35	5
Arduino UNO (Micro USB)	Arduino UNO (Micro USB)	H RF96	SX 1276	−40	5

However, it is not guaranteed that using identical nodes (with the same Arduino boards and LoRa shields from the same manufacturers) will yield consistent RSSI values.

We observed variations in the RSSI values among three identical nodes, primarily due to hardware imperfections, as shown in Table 5.

Table 5. Impact of hardware imperfection on the RSSI and SNR using the same manufacturer.

	Arduino Boards	LoRa Shields	RSSI	SNR
Node 1	Arduino UNO	SX 1276	−35 (via 1 to 3)	5 (via 1 to 3)
Node 2	Arduino UNO	SX 1276	−60 (via 1 to 3)	5 (via 2 to 3)
Node 3	Arduino UNO	SX 1276	−65 (via 1 to 3)	5 (via 1 to 2)

7. Conclusions

In this paper, we evaluated the performance of LoRa-based linear networks using a novel approach to contention management. Introducing an additional offset in LoRa-based relay networks can significantly improve performance. The proposed design approach was tested in real scenarios along with various relay widths (one, two, and three). Our results showed that this approach achieved high performance of up to 98% successful delivery of packets. This approach can be applied in such applications that are based on thin linear networks without maintaining the routing overhead at the relay nodes. The proposed approach has advantages over traditional delay-based approaches in terms of network throughput. Lastly, We explored the performance using gossip routing.

Gossip-based routing can be considered an effective solution, especially in decentralised and resource-constrained environments. We thoroughly examined the performance of gossip routing across a range of probabilistic distributions (T_{prob} = 0.90, T_{prob} = 0.80, T_{prob} = 0.70… T_{prob} = 0.40) using two and three relay widths, respectively. In our experiments, we observed that, with a relay width of two, there was approximately a 10% reduction in transmission overhead at T_{prob} = 0.90, while the average performance remained consistently high at 98%. However, as we decreased the transmission probability, the performance declined, reaching 62.8% at T_{prob} = 0.40. Interestingly, when we introduced an additional relay node, widening the relay width to 3, we noticed an improvement in performance across various T_{prob} settings compared to the relay width of 2. The experimental results indicated that, in the presence of an additional relay node, particularly at T = 0.40, the performance reached approximately 73.77%.

To further assess the implications of our findings, we conducted a performance comparison of gossip routing, considering different relay widths. Based on our experiments, it was clear that, at T_{prob} = 0.90 and T_{prob} = 0.80, we could achieve nearly identical outcomes as at T_{prob} = 1.00, when employing two and three active relay nodes, respectively. This not only enables the efficient utilisation of radio resources, but also leads to reduced energy consumption compared to traditional broadcasting. With these insights, we can contemplate extending the use of gossip routing to longer linear networks, aiming for power savings and minimising transmission overhead to achieve optimal performance.

The presented design approach may not be equally effective for thicker networks and higher spreading factors. Reducing the transmission probabilities can significantly reduce the transmission overhead, but it can increase the communication delay. Future work will consist of quantifying the effectiveness of the gossip-based probabilistic approach in thicker and much-longer LoRa-based relay nodes.

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