A Novel Approach to Collision Avoidance in LoRa Networks

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***Abstract*—LoRa (Long-Range) is emerging as a promising platform in IoT technology because of its low power consumption and long-range coverage. We have been exploring the possibility of LoRa as a relay technology in linear and near linear networks. We have found that overlap of relay coverage has a negative effect on overall network performance because of signal interference caused by concurrent transmission. However, introducing a small offset delay at relay nodes can significantly improve the performance of the network overall. This article presents a novel approach to avoiding collision in LoRa-based linear networks. The proposed approach has been evaluated experimentally using LoRa transceivers that form a linear network. Our experiments show promising results with a significant increase in Packet Reception Rate (PRR).**

***Index Terms*—LoRa networks, relay networks, concurrent transmission.**

I. Introduction

Owing to the rapid growth of the Internet of Things (IoT), Low Power Wide Area Networks (LPWANs) are becoming increasingly popular in a number of scenarios. They are of particular importance in areas where traditional cellular networks have limited coverage or deployment costs are not viable [1]. LPWANs are ideal for situations where low bit rates and long ranges are needed such as remote sensing applications [2].

Many LPWAN technologies have been proposed that work in the licensed and unlicensed frequency bands. LoRa, Sigfox, and NB-IOT are leading LPWAN technologies that are commercially available. According to [2] and [3], LoRa outperforms Sigfox and NB-IoT in many areas.

While LoRa is typically deployed with a gateway device or in a mesh network, one emerging topology is that of linear or near-linear networks. This important use case would see LoRa deployed in a linear manner for monitoring applications (e.g., pipelines, roads, tunnels, borders, railways) where end devices (sensor nodes) are connected in such a way to form linear wireless sensor networks (LWSNs), alternatively known as chain-type wireless sensor networks [4], [5]. In this type of network, multiple nodes are connected in such a way that 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. This type of topology is used to extend the network coverage over long ranges [6].

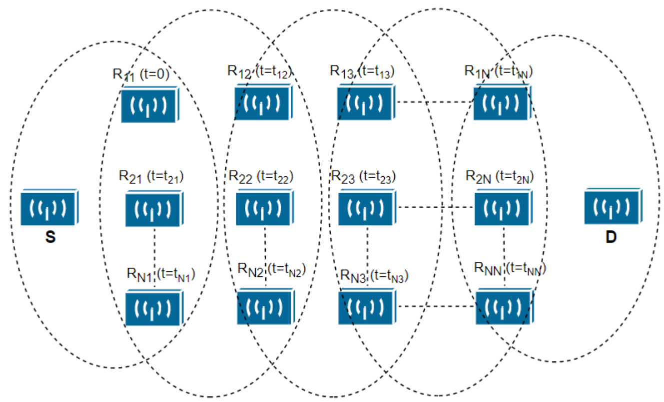

Fig. 1. Linear network of width three

The feasibility of LoRa-based linear networks has been evaluated in various monitoring applications. However, a challenging issue is dealing with contention in such networks where coverage of multiple nodes overlaps. In the presence of multiple relay nodes, transmission coverage overlapping can affect overall network performance.Previous research has addressed this problem by introducing a fixed slot wait time at each relay node before transmitting. Therefore, traditional delay-based approaches of collision avoidance may not be effective for LoRa-based linear networks because of the large message delivery time. [7], [8], [9].

In this paper, we present a novel approach to dealing with collisions at relay nodes in linear networks based on the characteristics of the LoRa physical layer. We show that provided there is a small offset delay between coverage of relay nodes then it is unnecessary for any node to wait before transmitting. Adopting this approach results in a dramatic increase in successful message transmission.

The rest of the paper is divided into six sections. Section 2 presents the related work in this context. Section 3 presents the Problem formulation. We have briefly discussed the survival of LoRa concurrent transmission in section 4. Section 5, discusses the network design and experimental setup. Evaluation of the proposed technique and results are discussed in section

6. Lastly in section 7, we have concluded our work.

II. Related Work

Contention management in wireless networks during concurrent transmission is challenging task. LoRa-based networks are considered a good candidate to enable concurrent transmissions. Adoption of higher spreading factors can slightly improve performance with respect to interference during concurrent trasmission in a LoRa-based network [11]. A Received Signal Strength Indicator(RSSI) based evaluation model was proposed that shows LoRa holds the non-destructive communication property during concurrent transmission. A slight difference in RSSI values (2 dBm to 3 dBm) increases the chances of packet delivery rate (PDR) from 82% to 97% respectively during concurrent transmission [12].

An analytical model was proposed to avoid the collision in LoRa based mesh network. The proposed model is based on an adaptation of link quality (RSSI value) during concurrent transmission. Optimal path and route selection from the source to the destination depends upon the best route among all available routes. However with the increase in the number of relay nodes transmission overhead and network latency increase [16]. In [17] Triantafyllou et al. present a scheduling approach to increase network reliability and collision avoidance. Simulation results show introducing a time slot-based mechanism performs better as compared to standard ALOHA and further ensures energy efficiency [17], [24].

Improvement in reliability and overall performance in LoRa-based relay networks has been reported by introducing automatic repeat request (ARQ), especially in a noisy environment. This study's preliminary focus is on reliability improvement by adding a relay node instead of collision management in a dense relay network [13]. Adding a timing offset at relay nodes significantly improves network performance in multi-packet reception. The simulation result shows the proposed technique (CoLoRa) improves network performance by up to 14 percent as compared to standard LoRaWAN [14]. In [15] Chengduc and Muhammad Ehsan present a lightweight collision avoidance mechanism to increase the packet delivery rate, especially in dense networks. The proposed mechanism is based on the neighbor discovery (ND) protocol. However, the proposed mechanism is not suitable for delay-constrained applications.

Collision in LoRa-based networks can be avoided by using the pipelined multihop transmission (pm-LoRa) mechanism. The proposed protocol is based on a reactive approach, where the on-demand topology is constructed using all nodes that participate in the communication. A channel and time slots are allocated to each node during the topology creation. Experimental evaluation of the proposed approach show that sensor data can be collected with high reliability in LoRa-based networks [18].

A LoRa relay-based system was introduced that uses multiple relays to establish communication in underground mining. 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. Simulation results show that this condition can be applied to avoid the coverage overlapping problem. However, in a real environment, LoRa as a relay technology along with its characteristics and performance evaluation further needs to be explored [8], [9].

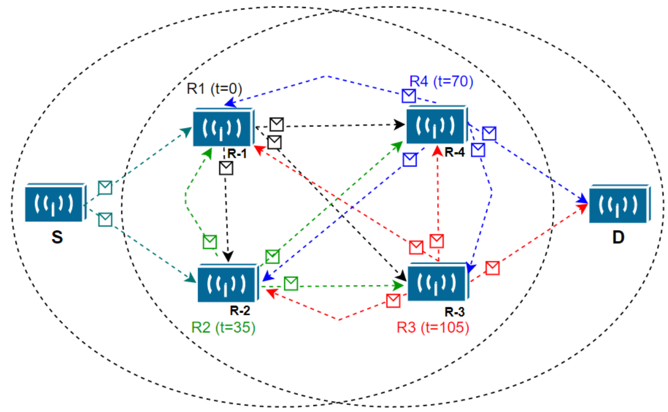

Fig. 2. LoRa network four relay nodes

A considerable amount of work has been done related to the collision avoidance problem. Collision avoidance has usually been addressed by delaying transmission, usually using a random delay. The traditional offset-based approach of collision avoidance may not be effective for LoRa-based linear networks because of the large message delivery time. Instead, the LoRa Channel Activity Detection (CAD) process allows the possibility of a new approach based on physical offsets rather than programmed delays. To the best of our knowledge, there is no empirical research as to the effectiveness of this approach for LoRa-based linear networks.

III. Problem Formulation

Network reliability and optimization of deterministic delay especially in LoRa-based linear networks is a challenging task [9], [10]. By introducing additional offset delay at relay nodes, overall network throughput decreases. Consider the situation where we have a long thick relay network where 'S' represents the source node and 'D' represents the destination node (receiver) and all the nodes between the source node and the destination node are set up as relay nodes as shown in Figure 1.

The offset delay at each relay node (R_{11}, $R_{12} \ldots R_{NN}$) should be greater than the sum of all delays (serialization delay, processing delay, propagation delay, and offset delay of each node within the same coverage overlap). The processing delay and propagation delay can be considered negligible as the LoRa signal travel with the speed of light and clock speed is typically 16 MHz. However, serialization delay (SD) depends on network setting such as spreading factor (SF), bandwidth (BW), packet header, packet payload, coding rate (CR), and the number of preamble symbols used during the network configuration.

$$T_s = \frac{2^{SF}}{BW} \quad (1)$$

Consider a scenario where the total payload (including the header) is 10 bytes, SF is 7, BW is 125 kHz, CR=4/5, and the number of preamble symbols is 8+4.24. In this case we can calculate the serialisation delay using the formula in (1) to be 27.174ms. The offset delay needs to be configured larger than this to avoid collisions caused by coverage overlap.

To explore the threshold value of offset delays, a network with two nodes overlapping (four relay nodes) was formed as shown in Figure 2. In this network, the first node was configured as a source node (S) whereas R-1, R-2, R-3, and R-4 were set up as relay nodes to forward the messages to the destination node (D). All four relay nodes form an overlap as they are within the coverage of both the source and destination. Using the same time slot at relay nodes can cause a packet collision at the destination. Time slot allocation using four nodes overlapping is shown in Figure 2. The LoRa configuration parameters for this network is shown in Table 1.

TABLE I
LoRa Configuration

Packet Size	10 bytes
Spreading Factor (SF)	7
Bandwidth (BW)	125 kHz
Coding Rate (CR)	4/5

Consequently, if we want to build a network that takes into account having different offset delays to minimize collisions we are naturally going to have varying offset delays, depending upon the network configuration, throughout the network. As the network gets larger not in terms of overlapping nodes but in terms of the length of the linear network. This can be an additive delay which eventually will get high enough to become unsustainable for reasonable traffic and message delivery time.

Introducing offset delays can potentially remove the problem of collisions in traditional LoRa-based networks, but for the case of a LoRa-based linear network, the cost may be too high. This inspires us to quantify the effectiveness of offset delays in Lora-based linear networks.

IV. LoRa Receiver CAD Process

In LoRa-based concurrent transmission, receiver performance depends upon preamble detection that uses the CAD mechanism. A preamble is a signal that is used to synchronize the receiver with the incoming data stream. For every incoming signal, the LoRa receiver decodes the transmission based on preamble synchronization. In LoRa, A symbol or Chirp depends on the spreading factor (7 to 12). The Total number of symbols depending upon the spreading factor (SF) can be calculated by this relation 2^{SF}. Equation (1) defines the symbol time T_s where SF represents the configured spreading factor and BW the configured bandwidth settings. The numerator in this equation is equal to the total number of symbols. For the

Fig. 3. LoRa standard demodulation [20]

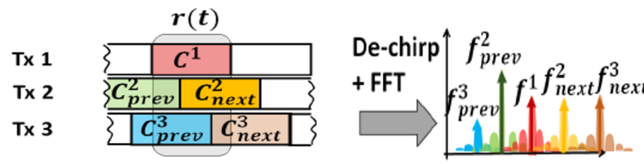

Fig. 4. LoRa signal superposition [20]

scenario where SF=7 and BW=125 kHz, T_s will resolve to 1.024ms.

LoRa signal detection purely depends upon preamble length that is programmable (6 to 65535). When programming LoRa devices for embedded systems, the most commonly used support library is the Radiohead library [23]. This sets the default preamble length to 8 symbols, In LoRa chips default symbols are 4.25 symbols (two up chirps, two down chirps, half up chirp).

During concurrent transmission, the LoRa radio signal that traverses the shortest path (over the wireless medium) will be treated at the receiver as the wanted signal. All other signals will be treated as interference.

The basic purpose of CAD is to detect the LoRa preamble from the radio channel. During the preamble detection process, the receiver captures the preamble symbols from the channel and tries to match it with the ideal waveform. On success, it synchronizes to this signal and generates an interrupt to initiate receiver RX Single Mode OR RX continuous mode depending on settings. However, if the preamble length at receiving node is not previously known it should be equal to or greater than the preamble length as compared to the transmitting node.

In standard decoding of LoRa without collision, each preamble symbol can be mapped with the unique frequency with high reliability via applying inverse chirp along with Fast Fourier Transform (FFT) as shown in Figure 3 [20].

As a result of a multi-packet collision during concurrent transmission, a superposition signal is formed at receiving node because of several interfering transmissions. Demodulation of such a received signal results in a superposition of multiple sinusoids as shown in Figure 4. An FFT of such received signal then forms multiple frequencies. In such a scenario a standard LoRa receiver may not be able to decode the correspondence of each frequency because of the signal superposition [20].

During the concurrent transmission, a stronger signal is treated as a wanted signal and another signals (in the presence of concurrent transmission) are treated as an interference (capturing effect). Due to the effects of both frequency domain

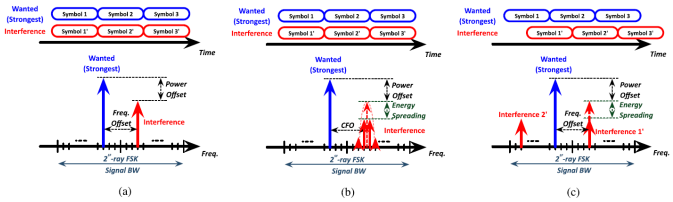

Fig. 5. CFO and time offset effect in LoRa [20]

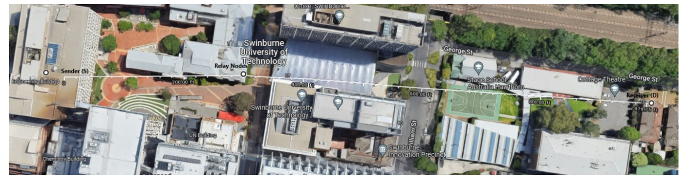

Fig. 6. Aerial view network deployment

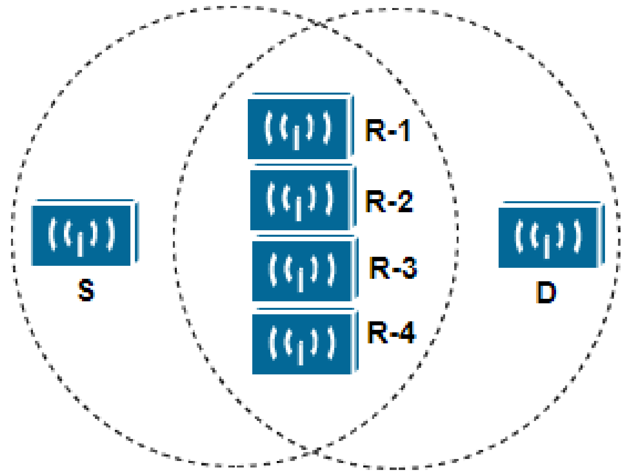

Fig. 7. Network architecture collocated relay nodes (relay nodes were placed adjacent with approximately zero distance between them)

and time domain energy spreading, it becomes possible to successfully receive a packet during concurrent transmission. As CFO (carrier frequency offset) continues random in nature that shows the very low probability that interference tones will locate at the same sub-carriers. In this case, the energy of interference will spread on adjacent sub-carriers (as shown in Figure 5-b) which results in extra power offset between two captured signals. In another effect (time domain offset) the reception of a packet during the concurrent transmission can be survived because of different timing offsets between the received packets (Figure 5-c) that also result in extra power offset between two captured signals on FFT output [21].

During concurrent transmission the signals time offset varies at receiving node because of hardware imperfection and air channel invariant nature. Due to the timing offset misalignment and carrier frequency deviation of chirp, multiple symbols during the concurrent transmission can be successfully demodulated [19]. Concurrent transmission may not be a problem due to the CAD process and that as long as one signal arrives "first", it is likely to be successfully read.

V. Network design and experimental setup

The potential for successful reception during concurrent transmissions has the potential to remove programmed offsets at sender nodes. This can have a big impact in the design of linear networks as it significantly reduces delays in the network and can improve throughput. We propose to evaluate the performance of LoRa in a linear network where no delays are programmed.

We establish a series of experiments where we calculate network performance by measuring the Packet Reception Rate (PRR) at the destination node. The network is a short linear network with 1, 2, 3 or 4 relay nodes, all within the coverage range of the source and destination node, creating a topology where packet need to traverse on hop to reach the destination. As all relay nodes are within range of the source, this will create a scenario where concurrent transmissions will occur.

Figure 6 displays an aerial view of the network deployment. The distance between the source and the relay nodes is approximately 95 metres, and between the relay and destination nodes approximately 188 metres. The relay nodes are deployed on the second floor of the building. This slight elevation significantly improves both signal strength and range (almost double that of the source node). Network configuration parameters are listed in Table 1.

A. Case 1: Collocated relay nodes

This network consists of a source node, four relay nodes, and one destination as shown in Figure 7. The packet reception rate via each relay node was recorded to ensure packet loss is occurring only because of signal interference instead of LoRa coverage. PRR at destination nodes via each relay node varies from 98 to 100 percent which ensures all the relay nodes are working perfectly individually. We have noted down the ping success rate (PSR) at the destination node (D) by activating all relay nodes simultaneously. During this experiment, we have configure the source node (S) to send continuous pings every four seconds.

B. Case 2: Physical offset between relay nodes

In this network, we now introduce a slight physical offset between relay nodes. Whereas d_{12} denotes the physical offset between relay node 1 (R-1) and relay node 2 (R-2). Similarly, d_{23} and d_{34} represent the physical offset between relay node 2 (R-2), relay node 3 (R-3), and relay node 4 (R-4) respectively. One way of generating a physical offset is shown in Figure 9, and that other mechanisms can be achieved by moving the relay nodes along the y-axis to create differing distances. In the case of linear physical offset, as shown in Figure 9, destination node (D) should successfully receive a packet via relay node 4 (R-4) in the presence of all active relay nodes when there is no hardware imperfection in relay nodes. In the case of hardware, imperfection and variant nature of the air channel strong signal

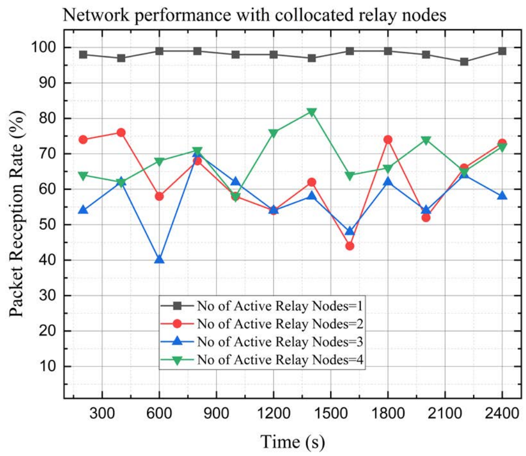

Fig. 8. Network performance with collocated relay nodes

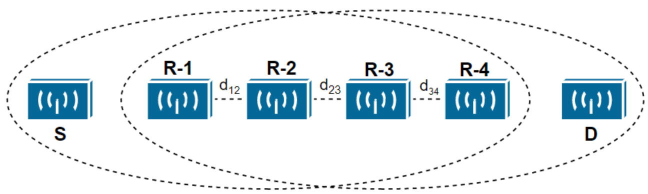

Fig. 9. Network architecture with physical offset at relay nodes

will be treated as a wanted signal and all other signals will be treated as interference at D because of the capturing effect.

VI. Result Evaluation and Discussion

Receiver performance in presence of concurrent transmission with collocated relay nodes is shown in Figure 8. Figure plots the packet reception rate (PRR) at the destination node over time for scenarios where a single relay node is activated, as well as when two, three, and four relay nodes are activated. Multiple relay nodes has a significant impact on the overall network performance as the nodes are very closely collocated, this implies that the signal strengths and reception times for each relay are very similar, increasing the possibility of the CAD being unable to detect the individual signals and synchronise to one for reception. The PRR is calculated over a period of 200 seconds (50 packets sent) for the duration of the experiment.

A slight change in physical offset help to increase the preamble symbol time (Ts) that purely depends upon LoRa network configuration. If SF=7 and BW=125 Khz then the time taken for one preamble symbol will be 1.024 ms using Eq.(1). Physical displacement offset between relay nodes (d_{12}, d_{23}, d_{34} $\ldots$ d_{nn}) is directly proportional to bandwidth. Higher bandwidth with a constant spreading factor can further reduce the displacement but it can decrease the receiver sensitivity because of the additional noise integration that reduces the SNR ratio. There is a trade-off between high data rate and

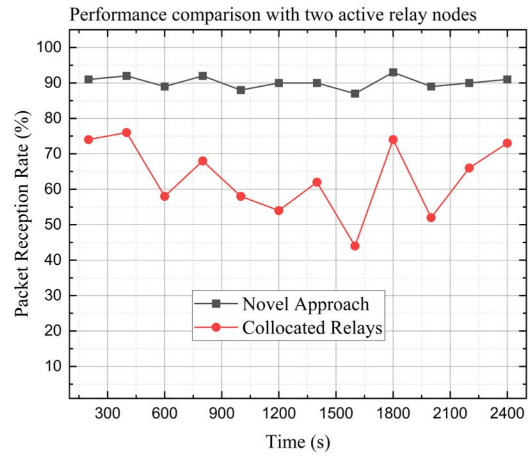

Fig. 10. Performance comparison two active relay nodes

receiver sensitivity in terms of network reliability [22]. Figures 10-12 plot the performance of the network with physically different relay locations against the case for collocated relays. We have separated the graphs for each case (number of relays) to make comparisons easier.

Introducing the offset delay at nodes has significantly improved the overall performance for all cases. Physical offset at relay modes created enough of a difference in the signals to allow the CAD to more accurately separate the signals from multiple relay nodes during concurrent transmissions. This approach continues to work well, delivering approximately 90% success for 2, 3 and 4 relay nodes. We have also noted concurrent transmission has a negligible impact on the receiver sensitively but it significantly drops the SNR as shown in Table 2.

This provides evidence that offset delays may not be necessary in linear networks as the CAD will perform well in separating signals. This also has significant implications for improved throughput/delay characteristics in linear networks, and that is an important consideration when designing routing protocols for linear networks.

TABLE II
Impact of Concurrent Transmission on RSSI and SNR

No of Active Relays	RSSI Range (dbm)	SNR Range (db)
1	(-101, -102)	(8,9)
2	(-100, -102)	(2,4)
3	(-100, -102)	(1,2)
4	(-101, -102)	(0,2)

VII. Conclusion

In this paper, we have described the simplest approach to improve the performance of LoRa-based linear networks. The proposed approach takes advantage of the LoRa physical layer to eliminate the need for nodes to wait before transmitting. Introducing the additional offset delay in LoRa-based relay

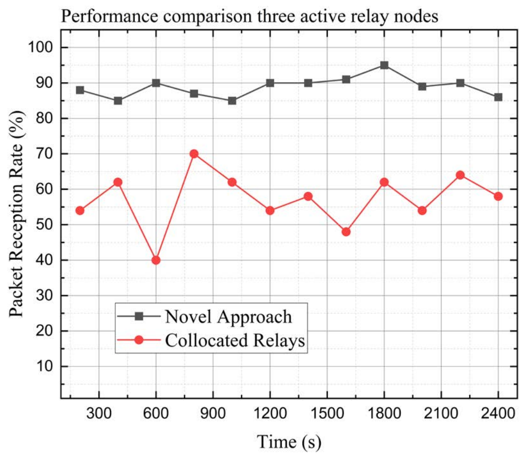

Fig. 11. Performance comparison three active relay nodes

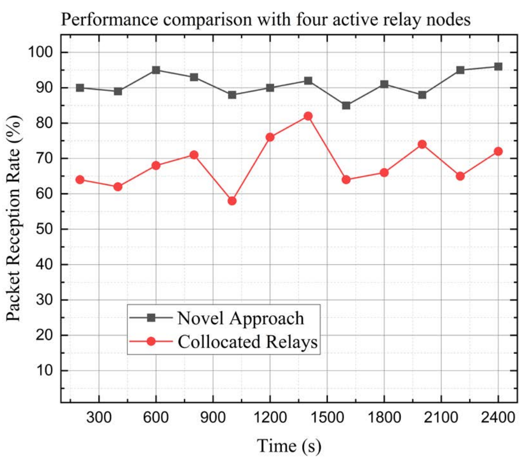

Fig. 12. Performance comparison four active relay nodes

networks can significantly improve the performance but it can also undermine the throughput, especially in LoRa-based thick networks as we discussed in the problem formulation. We have presented the novel approach without using the offset delay in LoRa-based relay networks by discussing two cases. The proposed novel approach and preliminary results imply that LoRa can survive concurrent transmission and further improve the performance in LoRa-based linear networks. This approach can be applied in such applications that are based on thin linear networks without maintaining the routing overhead at relay nodes.

The proposed approach might not be effective with a high spreading factor and in thicker networks. In these types of networks with the increase in the number of relay nodes in terms of network length, instead of coverage overlapping the SNR value decreases because of the concurrent transmission. However, quantifying the effectiveness of offset delays and physical offset between relay nodes in LoRa-based linear networks further needs to explore.

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