The Contributions of LoRa as a Multi-Hop Technology

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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.

LoRa networks relay networks linear networks

1. Introduction

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 [1]. 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 [2].

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 [2][3], 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 [4].

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 [5]. 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 [6][7]. 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 us

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 [5].

The feasibility of LoRa-based networks has been evaluated in various monitoring applications [8][9]. 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 [10]. Despite its importance and perhaps because of LoRa's relative novelty, very little research has been carried out on these topics.

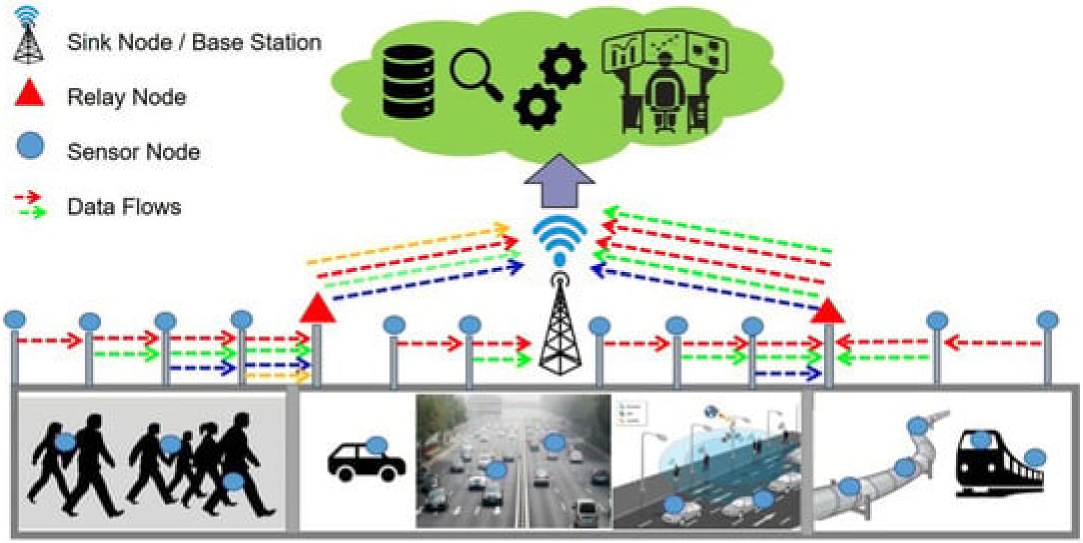

Figure 1. Linear wireless sensor networks and applications [11].

2. The Contributions of LoRa as a Multi-Hop Technology

Typically, LoRa technology has been deployed as a hub and spoke topology based on the Layer 3 LoRaWAN protocol [12]. 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 [13].

Fernandes et al. explored the issues of concurrent transmission in LoRa communications [14]. 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 [14].

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 [15][16]. 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 [17]. 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 [18]. Simulation results have shown that chain-type WSNs are considered ideal for optimal energy consumption, which results in the extended lifespan of the network [19]. Much research on linear (chain)-type networks has been performed, but very few researchers have considered LoRa as a linear network.

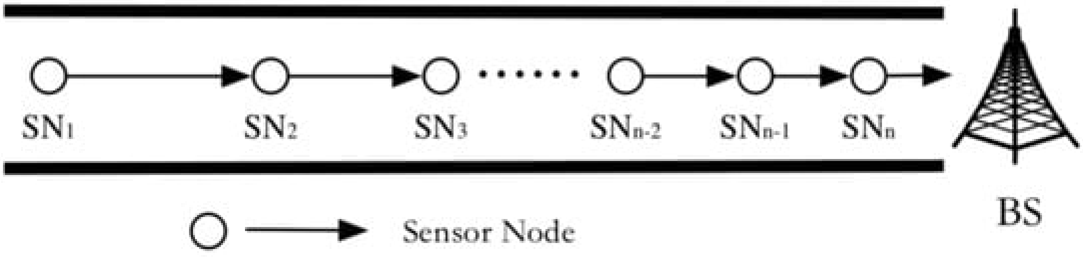

Figure 2. An example of a chain-type wireless sensor network [18].

The feasibility of LoRa as a linear network has been proposed for pipeline monitoring [20]. The simulation outcomes indicated that LoRa could be regarded as a viable relaying technology for enhancing the reliability and network coverage of IoT applications [21]. The adoption of LoRa technology as a linear network and employing different time slots has great potential and establishes a high degree of reliability [22].

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 [23].

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 [24]. 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 [25].

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 [26].

The potential of LoRa LPWAN as a communications technology for underground mining was explored in [27]. 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 [28].

A LoRa relay-based system has been introduced that uses multiple relays to establish communication in underground mining [29]. 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 [30]. 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 [30][31].

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 [32][33].

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 [34]. The gossip-based approach reduces the transmission overhead, which can further improve the message reachability in ad hoc networks [35]. Gossip routing is considered more-energy-efficient as compared to traditional flooding-based approaches [36]. A comparative study was conducted that measures the performance of various gossip routing approaches to estimate the network size [37]. 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 [38].

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 [39][40].

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 [41][42]. 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.

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