Exploring Multi-Hop LoRa for Green Smart Cities

Muhammad Shehryar Aslam, Alishba Khan, Abeera Atif, Syed Ali Hassan, Aamir Mahmood, Hassaan Khaliq Qureshi, Mikael Gidlund

***Abstract*—With the growing popularity of Internet-of-Things (IoT)-based smart city applications, various long-range and low-power wireless connectivity solutions are under rigorous research. LoRa is one such solution that works in the sub-GHz unlicensed spectrum and promises to provide long-range communication with minimal energy consumption. However, the conventional LoRa networks are single-hop, with the end devices connected to a central gateway through a direct link, which may be subject to large path loss and hence render low connectivity and coverage. This article motivates the use of multi-hop LoRa topologies to enable energy-efficient connectivity in smart city applications. We present a case study that experimentally evaluates and compares single-hop and multi-hop LoRa topologies in terms of range extension and energy efficiency by evaluating packet reception ratio (PRR) for various source to destination distances, spreading factors (SFs), and transmission powers. The results highlight that a multi-hop LoRa network configuration can save significant energy and enhance coverage. For instance, it is shown that to achieve a 90% PRR, a two-hop network provides 50% energy savings as compared to a single-hop network while increasing 35% coverage at a particular SF. In the end, we discuss open challenges in multi-hop LoRa deployment and optimization.**

I. Introduction

In the upcoming era of Internet-of-Things (IoT), smart systems for applications such as predictive maintenance and traffic flows are expected to be widely deployed across the globe. The smart device market is growing considerably, while 20 billion IoT devices are estimated to be deployed by 2020 [1]. With such a massive number of devices, the concept of smart cities is now realizable. A smart city is an integrated urban system involving the use of infrastructures such as smart surveillance and control systems. Hundreds of thousands of end devices are utilized to gather real-time data from city systems. This data is then used to analyze the trends and to make decisions to not only maximize the efficiency but also automate most of the major city operations. Areas of application include smart homes, smart traffic control, smart metering, agriculture, health care, manufacturing, and urban infrastructure management, to name a few.

To realize such systems, it is essential to have a wireless network with wide-area coverage and low-power consumption in order to connect battery-operated devices deployed across a city. Although the fifth generation (5G) systems make use of the licensed bands for most of their applications, however, many new applications such as the millimeter wave (mmWave) communications and IoT-based technologies make use of the unlicensed bands. A major reason for this adoption is the spectrum scarcity in the licensed bands that renders the new applications to work in other portions of the spectrum. In this perspective, low power wide area networks (LPWANs) provide a feasible solution not only in terms of their operation in the unlicensed bands but also their performance envisions wide-area coverage range and energy efficiency. LPWAN technology is designed for networks with massive battery-operated devices which are typically required for a smart city and machine-to-machine (M2M)-based applications. At present, the prominent competing unlicensed LPWAN technologies are SigFox, LoRa, and Weightless whereas the licensed technologies include Long Term Evolution for M2M (LTE-M), and narrowband IoT (NB-IoT) [3]. However, Long Range (LoRa) stands out among the others because of its spread spectrum technology [4], whereas it operates in the frequency bands of 433 MHz, 868 MHz and 2.4 GHz unlicensed radio spectrum. The technology, as the name indicates, promises long-range communication based on excellent receiver sensitivity and chirp spread spectrum (CSS) modulation. The range goes up to as high as 13 km in a rural setting. However, with the increased range, the data rates are compromised, with a minimum of 0.3 kbps and a maximum of 50 kbps. Consequently, the power consumption for each device is minimal, which makes the technology ideal for a green smart city implementation where a slower data rate is acceptable as long as the battery life can be increased.

In a smart city, a large number of battery operated devices need to uplink information with minimal energy consumption. It has been forecasted that approximately 60 thousand devices per square kilometers will be installed in a smart city [5]. Such a large number of devices requires a large amount of power. Therefore, to envision a green smart city, a robust system model is required which may use the multi-hop topologies to conserve energy. Multi-hop networks are considered a maturing area of research and an important mechanism for efficient energy usage and range extension [6]. The communication devices in wireless sensor networks and other IoT applications have limited battery life. Under right conditions, multi-hop networks, in addition to enhancing throughput due to shorter hops, can also extend battery life due to lower required transmission power. It has been shown that to achieve the same quality-of-service (QoS), lower transmission power at each device is required for a multi-hop network as compared to single-hop networks where the end devices communicate directly with the base station [8].

The main contributions of this article are as follows.

- We present an empirical proof of range extension and increased energy efficiency of the network using multi-hop LoRa configurations. The single-hop serves as a reference topology, against which the operations of the multi-hop have been compared.
- We test various topologies such as two-hop, three-hop,

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and star-of-stars to provide a comprehensive comparison under various system parameters such as spreading factors (SFs), transmission powers and distances.
- To further improve the energy and range efficiency of the network, optimal relay node placement in two or three hops is considered which elevates the system performance in terms of QoS.
- The work is finally concluded with futuristic recommendations and open research challenges.

With an extensive analysis provided in this article, it can be concluded that multi-hop LoRa configuration can be used as an enabler wireless communication technique for IoT devices deployed in large numbers for smart city applications.

II. Smart City Technologies using Unlicensed Bands

Unlicensed bands provide an *extra* space for the technologies to operate which otherwise would be difficult. Although many IoT-based applications would still be operable in licensed bands with 2G/3G/4G compatibility, examples include LTE-M, NB-IoT, EC-GSM etc., but because of rising costs of licensed bands and bandwidth limitations, the unlicensed technologies are gaining momentum for smart city applications [15]. Herein, we briefly enlist the unlicensed IoT technologies, which are potential candidates for future smart cities.

SigFox. SigFox operates in the sub-GHz unlicensed spectrum with a physical (PHY) layer consisting of ultra-narrow band technology which enables a long-range operation at the cost of data rates. The data rates for a SigFox transceiver do not exceed 100 bps. At the network layer, a simple star topology enables a robust network operation.

Random Phase Multiple Access (RPMA). RPMA envisions a wide area network that is capable of providing services deep inside buildings and underground. Although the data rates of RPMA are low (31 kbps download and 15.6 kbps upload), however, the inherent security features of the RPMA make it vulnerable to threats. The key application areas for RPMA include smart buildings, agricultural monitoring, personal tracking, smart metering, asset tracking, and oil & pipeline monitoring etc.

Weightless. The Weightless is a low-cost technology specifically designed for M2M communications. A salient feature of Weightless is the handling of a large number of devices efficiently. There are various sub-categories of Weightless such as Weightless-P, Weightless-N, and Weightless-W that differ in specifications such as range of operation, data rate, and battery life.

The LoRa Technology. LoRa enables a long-range operation with its special modulation technique, which is discussed in details in the subsequent sections of this article. From a research perspective, many aspects of LoRaWAN technology such as energy efficiency, range and coverage are investigated recently in a smart city scenario [9].

III. The Conventional LoRa Network

A LoRa network is comprised of two main solutions: *LoRa*, a proprietary PHY layer modulation scheme developed by Semtech[1] and *LoRaWAN* developed by LoRa Alliance[2], defining the protocol stack, network architecture, device classes, and regional regulations. In this section, we briefly describe these solutions before discussing our multi-hop extension of the conventional LoRa network.

A. LoRa PHY Layer

LoRa PHY uses a proprietary derivative of chirp spread spectrum (CSS) modulation scheme. In CSS techniques, the data symbols are modulated by chirp pulses, which are frequency varying sinusoidal pulses of fixed bandwidth B and time interval. One way to overcome the scarcity in the unlicensed bands is to vary the chirp duration so that quasi-orthogonal signals can be created and serve as virtual channels. The chirp duration, however, leads to a trade-off between the throughput and the robustness against noise and interference.

For a fixed chirp duration, data symbols are coded by unique instantaneous frequency trajectory, obtained cyclically shifting a reference chirp. Chirp wrapping is discretized, i.e., only 2^{SF} possible edges in the instantaneous frequency exist, each one representing SF bits where SF is referred to as the spreading factor. The network controller can adapt the data rate by changing the bandwidth $B \in \{125, 250\}$ kHz and SF $\in \{7, \cdots, 12\}$, which together relate to chirp duration as $T_c = 2^{\text{SF}}/B$. Note that the chirp rate remains the same, and equals to B, while the chirp duration (consequently time-on-air) increases drastically with the SF. On the positive side, a higher SF yields higher processing gain and thus reduces the target signal-to-noise ratio for correct reception at the receiver [7].

B. LoRaWAN

In terms of network coverage and architecture, LoRaWAN connectivity solution is similar to cellular systems. However in LoRaWAN, the primary focus is on energy efficient communication for smart city IoT applications based on battery-operated devices. A typical LoRa network consists of a star-of-stars topology, where the end devices can communicate to a single or several gateways using LoRa PHY. The gateways, or base stations as some may refer, are connected to a common network server via the standard IP protocol. The network server is connected to an application server, as shown in Fig. 1 (left).

Role of each network entity. The *end devices* can transmit(receive) to(from) the gateway. However, the emphasis is on the event-triggered uplink transmissions. The *gateway* functions transparently as a relay between the end devices and the network server. The *network server* manages the overall network. It allocates resources, for example, the spreading factor or the bandwidth for an efficient data rate and also authenticates the end devices The *application server* handles data encryption and decryption and the admission of the end devices to the network.

[1]https://www.semtech.com/

[2]https://www.lora-alliance.org/about-lorawan

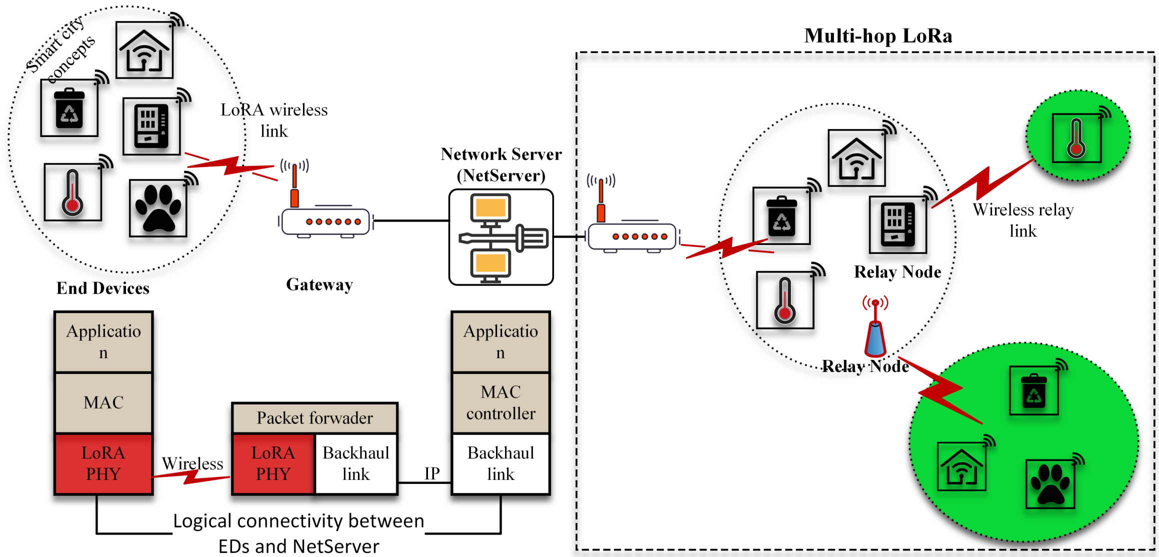

Fig. 1: LoRaWAN architecture and its extension for multi-hop communication

Medium access. LoRa operates on unlicensed sub-GHz frequency bands. The ISM band is subject to regulation on either the listen before talk, medium access duty cycling or effective radiated power (ERP). A simple duty-cycled ALOHA protocol, regulated by the network server, serves as the most common approach for accessing wireless medium.

IV. Multi-Hop LoRa Network: A Case Study

As the devices in IoT wireless networks are mostly battery-operated, they have a limited energy. To increase their lifetime, the energy utilization must be managed efficiently. In addition, the wide-area coverage is an intrinsic demand of smart city applications. To address these issues, we propose two different topologies forming a multi-hop LoRa network, as illustrated in Fig. 1 (right).

The first topology introduces a relay node between an end device and the gateway. The relay node employs decode-and-forward scheme based on LoRa modulation. The second topology extends the LoRaWANs star-of-star architecture by allowing a LoRa gateway to connect to multiple LoRa gateways over LoRa PHY. As wide-area networks in urban settings employ massive devices, it becomes difficult for a central gateway to gather/process information from all the devices simultaneously.

In a star-of-stars topology, the devices are categorized into several clusters. Clustering is considered a powerful tool to streamline the operations of the network to maximize energy efficiency and consequently prolonging network lifetime [10]. Each cluster contains multiple end devices and a gateway of its own. Each end device communicates with the gateway of the cluster. Thus, each gateway has to deal with a smaller number of devices as compared to the scenario when a single central gateway receives data from every device. Cluster gateways, then transmit the data to a central gateway where it can be processed and relayed to the network server. This formation realizes a two-hop LoRa network, which is tested in this paper for range extension and power efficiency for different SFs and the permitted range of transmission powers.

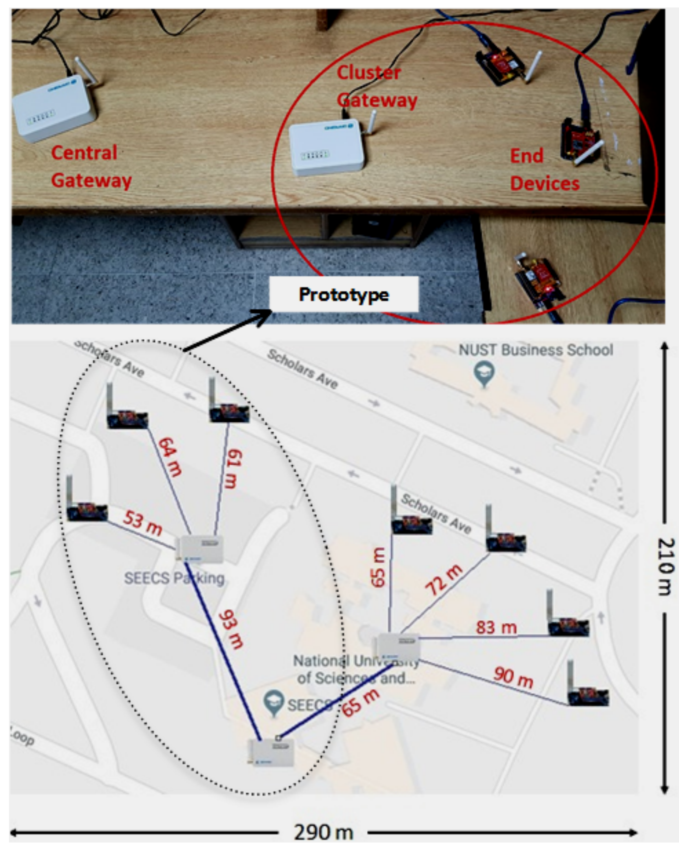

Fig. 2: Setup for star-of-stars topology experiments

V. Performance Evaluation

This section outlines the experimental setup for the proposed case study and presents the results obtained.

Hardware Prototype. The experimental setup for the tests is shown in Fig. 2. The tests were carried out using LG01-S, which is an open source single channel LoRa gateway. It enables the users to bridge LoRa wireless network to an IP network via WiFi or Ethernet. Dragino LoRa shields were used as end devices. The communication between the gateway and the end device took place in the 433 MHz frequency band. As this band is not used for any local transmission, negligible interference was present during the experiments. LoRa shields used as end devices has a maximum transmit power of 20 dBm. We evaluate the packet reception ratio (PRR) based on the data transmission period of 2 minutes. This implies that the nearly 10 thousand packets are transmitted in each test.

Single-Hop vs. Two-Hop LoRa Network. To investigate the range extension with a two-hop network, where a relay node assisted the end device to send its data to the gateway, the following setup was established. The gateway was placed in an indoor environment; a lab, situated at the premises of SEECS, NUST, Islamabad, whereas, a relay node was placed outdoor at a point where all of the messages were conveyed from the relay to the gateway. Similarly, an end device was placed further outdoor at different locations, such that the distance between the end device and the gateway varied with each location.

A comparison between the PRR of single-hop and two-hop network for two SFs is shown in Fig. 3. It can clearly be seen that the maximum range is significantly extended by introducing a relay node in the network. For example, if the QoS, which is the PRR in this case, is set at 80%, a single-hop network with SF7 can provide communication up to 180 m whereas, with the same settings, the range of a two-hop network goes up to 260 m, i.e., an increase of 80 m. One would expect the range to be almost doubled, but the communication link between the end device and the relay node is not as strong as the link between the end device and the gateway. Therefore, the communication range between end device and relay is limited.

Note that for different SFs, the range of communication between the end device and the gateway is different [7]. It is also evident from Fig. 3 that for larger spreading factors, the range extension, because of the introduction of the relay node, is greater as compared to the single-hop. For example, for 90% QoS, extension in range for SF7 is about 60 m which goes up to 100 m for SF9.

As compared to a single-hop network, a two-hop strategy results in the reduction of transmit power to obtain a specific PRR. Even though, the configuration demands two devices to transmit individually, as compared to one device in a single-hop network, the total power by both devices is collectively less than that of a single-hop device to cover the same range of operation with same QoS.

Relay Node Placement. The position of the relay node in the network has a direct impact on both range extension and power reduction. The network is energy efficient only if the relay is placed optimally. Fig. 4 shows the trends of required transmit power at various positions of the relay node to obtain a certain PRR. The abscissa refers to the distance of the relay from the gateway, whereas, the total distance between the end device

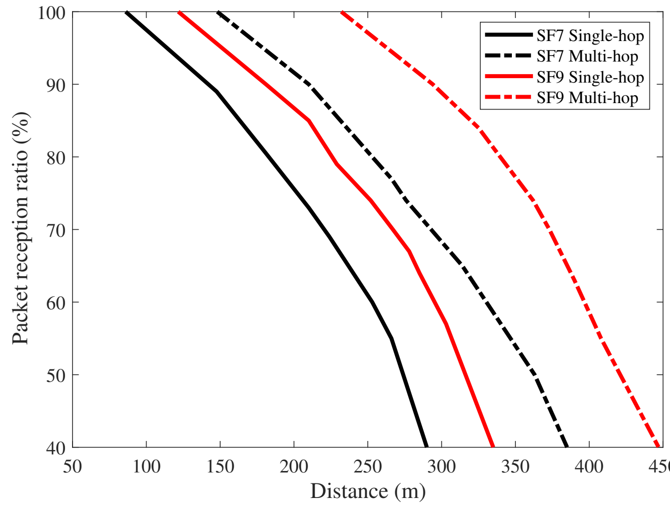

Fig. 3: Packet reception ratio (PRR) for single-hop and two-hop networks at two different SFs. The transmit power of end device in both topologies is 20 mW.

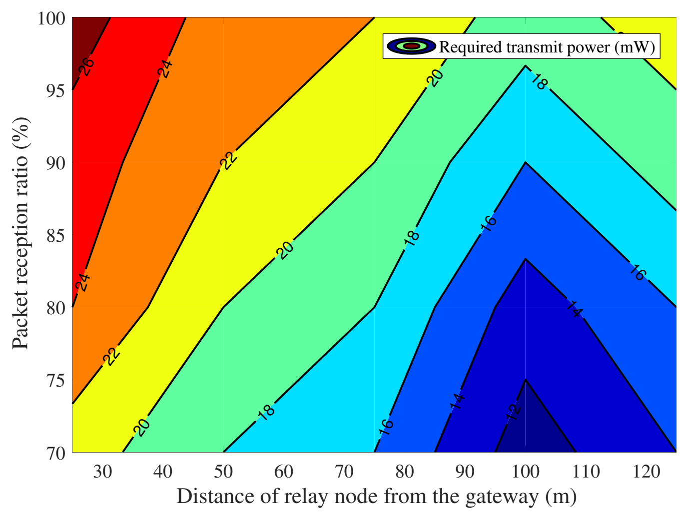

Fig. 4: Required transmit power as a function of PRR and location of relay node for SF = 7

and the gateway, however, is kept constant at 150 m. It can be seen that the least amount of power is required when the relay node is placed farther from the gateway, implying that the distance between the end device and relay node is small. For example, for a QoS of 90%, the system requires 22 mW if the relay node is placed at 50 meters from the gateway. However, if the relay is placed at 100 m from the gateway, only 16 mW of transmit power is required to maintain the same QoS. This trend changes if the relay node is moved further away from this point. At 120 m, the required transmit power is about 18 mW.

Star-of-Stars LoRa Network. To evalute a star-of-star network, a central gateway was placed in the campus lobby. Two clusters were formed, as shown in Fig. 2, where one cluster had four end devices including the gateway while the other had three end devices. Each end device transmitted data to the cluster gateway, and the cluster gateway concatenated data

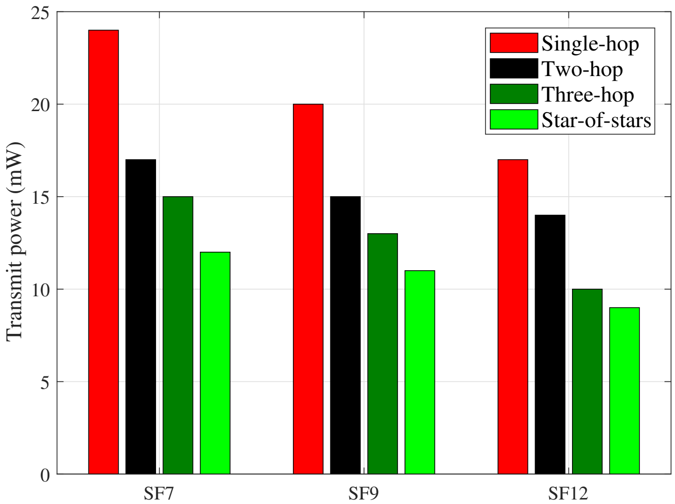

Fig. 5: Comparison of transmit power required for single hop, two-hop, three-hop networks and star-of-stars networks for different spreading factors.

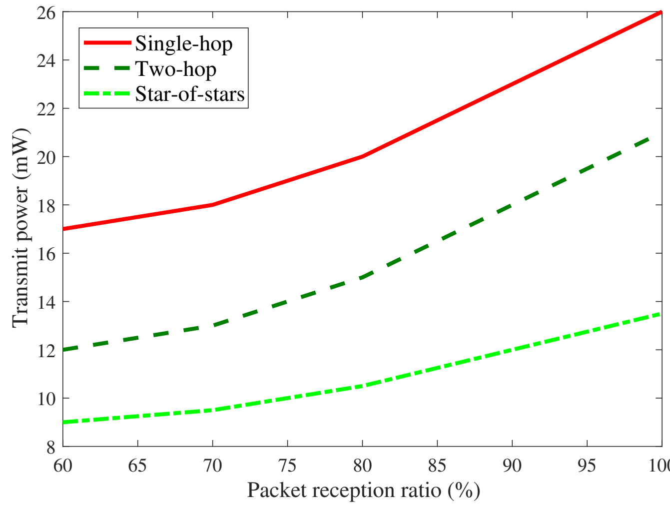

Fig. 6: Comparison of transmit power required for single-hop, multi-hop, and star-of-stars networks for various SFs.

from all the devices in an array and transmitted it to the central gateway.

The transmit power required to maintain a PRR of 90% for different SFs under all network topologies is compared in Fig. 5. It is evident that multi-hop topologies require less transmit power than a single-hop configuration to cover the same distance. For instance, a two-hop network required 18 mW transmit power to achieve a 90% PRR at SF7 while for the same settings a single-hop required 24 mW power, thus giving 25% power saving. Whereas, a three-hop setup makes the network even more energy efficient giving 37.5% energy saving compared to the single-hop network. Similarly, the star-of-stars is a lot more energy efficient than the single or multi-hop network as it requires only 12 mW of transmit power. The power shown in the graph for star-of-stars topology is the average power required by one device to transmit data to the central gateway via the cluster gateway. With the increase of SF, how required transmit power falls down even further for multi-hop and star-of-star topologies can also be observed from Fig. 5.

The required transmit power with respect to PRR target is compared for single-hop, two-hop, and star-of-stars in Fig. 6. To obtain these results, the distance between the end device and gateway is kept constant at 150 m in all three cases. It is observed that both the two-hop and star-of-stars require less transmit power than a single-hop network. In fact, the average power used by one device in a star-of-stars topology is almost half of that required by an end device in a single-hop configuration. In addition, as the PRR target is increased (i.e., higher required QoS), the gain in power saving for multi-hop and star-of-stars is also increased.

To quantify the energy efficiency of the clustering technique in comparison with a single-hop topology, we define the metric, fraction of energy saved (FES), as

$$\text{FES} = \left(1 - \frac{\text{Power required in star-of-stars}}{\text{Power required in single-hop}}\right). \quad (1)$$

We observed that the FES for star-of-stars topology is 28%, 41%, 48%, 51% and 54% for 1, 2, 3, 4, and 5 devices in the cluster, respectively.

VI. Challenges and Future Directions

Our results have shown that multi-hop and star-of-stars topologies are potential candidates to extend the coverage and improve the energy efficient of LoRa networks simultaneously. However, to capitalize on such gains, there are plenty of challenges and research opportunities to the LoRa system in general and the multi-hop LoRa system in particular, which we highlight below.

Intelligent LoRa Networks. LoRa/LoRaWAN provides many tunable transmission parameters such as transmission power, coding rate, spreading factor, bandwidth etc., resulting in hundreds of possible combinations. Increasing the spreading factor nearly halves the data rate and doubles the energy consumption and airtime, thereby improving the link reliability, as we have depicted in some of our results. Similarly, the increased bandwidth doubles the data rate and halves the energy consumption and airtime, reducing link reliability (due to additional unwanted noise). These configuration parameters must be optimally tuned while taking into account the local electromagnetic environment, constraints, and objectives, i.e., the performance metrics.

The recent research on LoRa/LoRaWAN has mainly focused on LoRa performance evaluation in terms of coverage, capacity, scalability and lifetime. Furthermore, recent work has also proposed adaptive approaches to allocate optimal transmission parameters [14]. However, most of these methods are based on state-of-the-art mathematical/statistical models and suffer from limited modeling assumptions, limited learning, inability to deal with non-linear complex behaviors, poor scalability, and no time series/temporal data exploitation. Machine learning and deep learning could, therefore, be a potential area of research in forming intelligent LoRa networks complying intelligent radio resource management and diverse communication requirements in massive IoT perspective.

Multi-Hop Deployment Optimization. Although, the initial experimental results stated in this article motivates the use of multi-hop transmissions in LoRa networks, however, the scalability issues in multi-hop communications renders an important challenge to overcome [11]. The number of devices per cluster and the number of clusters, the number of hops to the gateway, and the power consumption per node/cluster remain an optimization issue that should be looked upon from the perspective of the sensor density in a city. For instance, the requirements of a well-connected urban city differ greatly from a rural area. How and where multi-hop transmission would complement the performance remains an open challenge. Another challenge specific to multi-hop deployments is denial of service attack (e.g., black-hole and grey hole attacks) that would require intrusion detection techniques.

Multi-hop Duty Cycling. Because of the unlicensed usage of spectrum in LoRaWANs, the occupied transmission time of a LoRa link is subject to a stringent requirement of duty cycling, i.e., the IoT devices cannot occupy the band for an infinite amount of time [12]. This critical requirement becomes prominent in case of multi-hop scenario since the entire multi-hop link should be in the ON state for data delivery to the gateway. However, making an entire multi-hop link to work in ON state would affect the transmission duty cycle (TDC) of other links, which cause an imbalance in legal regulations of ISM band, which permits a specific amount of transmission time per hour to be occupied by various devices.

Synchronization and Queuing in Multi-Hop LoRa Networks. Cooperative Multi-hop networks, although promising, requires tight synchronization among different hops for their efficient operation [13]. Similarly, if various hops are subject to different spreading factors, which affect the data rates on each link, the problem of queuing appears as the intermediate nodes have to store the information accordingly to link adaptation. This may create unavoidable delays in the network that requires the use of sophisticated techniques to alleviate the problem.

VII. Conclusion

LoRaWAN has been designed to meet the requirements of modern age massive IoT and can be considered a potential candidate for realizing a smart city network. This article briefly encompassed the various unlicensed IoT techniques and focused on the architecture and working of LoRa system in particular for their operation. An experimental case study on multi-hop LoRa systems has been provided that ought to make the system more energy efficient and long range. Two topologies were presented; the first one was based on introducing a forwarding relay node, whereas, the second one was oriented towards clustering the devices and forming a star-of-stars topology. The results indicated that the two-hop networks can significantly extend the range as compared to a single-hop network. In terms of energy efficiency, both the two-hop topologies required less power to achieve the same QoS as compared to a single-hop network. As the star-of-stars network saved more energy for a higher number of end devices in a cluster, it can be concluded that LoRa networks can greatly benefit from the proposed scheme.

Although there are many research challenges with multi-hop LoRa networks, however, in summary, as the smart city concept would require hundreds of thousands of end devices to be deployed across a city, multi-hop assisted star-of-stars topologies may be considered a viable option for clustering many end devices together and making the network more energy efficient.

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