Multi-GW Simulation for LoRa LPWANs

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***Abstract*—The rapid growth of Internet of Things (IoT) has led to LowPower Wide Area Network (LPWAN) technologies like Long Range (LoRa), which offer long-range coverage, low power consumption, and scalability, making them ideal for IoT applications. LoRa technology utilizes spreading factors to optimize signal transmission. It uniquely relies on six different Spreading Factors (SFs). Each End Device (ED) uses a SF that ensures correct signal demodulation at the intended Gateway (GW). The long communication range LoRa provides relies on utilizing high values of SF. Such high values of SF also impose low data rate and consequently longer duration of packet transmission time resulting in greater collision probability and reduced network performance. Therefore, for a certain network area under inspection, multiple GW deployments will allow EDs to have more options for GW connectivity, enabling them to select GWs that are closer, utilize lower SFs and thus enhance overall network performance. This paper emphasizes the importance of multiple GW deployment in LoRa telecommunication and investigates its impact on overall network performance. We first developed an OMNeT++ LoRa multi GW simulation model. We tested two different deployment strategies and analyzed the network performance by observing the effects on two key metrics: success rate and success probability. The developed simulation model serves as a valuable tool for testing and analyzing detailed multiple-GW LoRa LPWANs prior to actual deployment.**

***Keywords*—Long Range (LoRa), LowPower Wide Area Network (LPWAN), Internet of Things (IoT), multiple Gateway (GW) deployment, network performance, simulation study**

I. Introduction

Long Range Low Power Wide Area Network (LoRaWAN) technology enables devices to connect using low power and low data rate transmission, which is not provided by legacy technologies [1]. Several LowPower Wide Area Network (LPWAN) technologies are dominant in the industry, including Long Range (LoRa) [2], Sigfox [3], Random Phase Multiple Access (RPMA) [4], Telensa [5], and Weightless [6]. Among all these technologies, LoRa LPWAN stands out and is widely deployed worldwide. Its widespread adoption can be attributed to its key features, which could be listed as:

- Flexibility and Customization: LoRa offers flexibility and customization for deployment allowing users to customize their network parameters such as data rate, transmission power, and bandwidth according to their specific requirements.
- Scalability: LoRa technology can easily scale to connect thousands or even millions of end-devices, making it the perfect choice for large-scale IoT deployments in smart cities, industrial monitoring, agriculture, and more.
- High Capacity: LoRa technology can support a high number of end-devices per GW, allowing for dense deployments without sacrificing performance. This makes LoRa suitable for applications requiring a large number of sensors or devices in close proximity.
- Cost-Effectiveness: LoRa infrastructure is more cost efficient than other technologies [7], as its devices operate on ultra-low power which reduces the need for battery replacements or external power sources, lowering operational costs.
- Community Support and Adoption: LoRa gained a lot of community support and adoption due to its reputation in the industry from large companies such as IBM, cisco and HP [8].

LoRa technology utilizes a technique called Spreading Factor (SF) to optimize its performance. The SF determines how a LoRa signal is spread over a wider frequency range, allowing for long-range communication. In LoRa networks, the SF varies from 7 to 12 [9]. Each device uses a SF that ensures correct demodulation of the signal at the intended Gateway (GW). High values of SF result in lower receiver sensitivity and thus longer communication range. However, such high values of SF also impose low data rate and consequently longer duration of packet transmission time [10]. Using a single GW in LoRa LPWAN deployments comes with multiple drawbacks, such as difficulties managing congestion, vulnerability to network overload, and inability to withstand outages. These problems result in higher latency, decreased network performance, and unstable connectivity.

The main perception of this paper is that adding multiple GWs within the same network cell will enable end-devices to connect to the nearest GW, resulting in higher data rates and shorter packet transmission times by utilizing lower (SFs). By incorporating multiple GWs into the LoRa deployment, we can alleviate congestion and bottlenecks

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on the GW side, enhance communication efficiency for each client, improve reliability and fairness among clients, boost network security, and increase overall network throughput [11].

Therefore, this paper investigates the use of multiple GWs to maximize network performance in order to resolve all aforementioned single GW drawbacks by developing a simulation model using OMNeT++. Using simulation allows for the evaluation of network performance under various conditions without physical hardware. It enables large-scale scenarios that may be impractical or costly in real-world settings, providing insights into potential optimizations before deployment.

This paper is organized as follows: Section II includes background information and related work, Section III provides detailed insights into the developed simulation model using OMNeT++, Section IV discusses the development of multiple GWs within the OMNeT++ model and the various deployment scenarios considered, Section V present the simulation setup used for our experiments, Section VII showcases our findings and provides a detailed analysis of the results and the last section addresses limitations and future work.

II. Literature Review

A. Background

LoRa is designed and patented by Semtech Corporation, which also makes the chipsets. LoRa is a novel physical layer LPWAN technology [12].

LoRa Physical Layer is based on the Chirp Spread Spectrum (CSS), which was developed to guarantee phase continuity between various chirp symbols in the physical layer packet's preamble [13]. CSS allowed for more straightforward and precise timing and frequency synchronization without the need for costly components to produce a reliable local clock in the LoRa node.

The technology uses a spreading factors technique, which reduces the signal-to-noise-plus-interference ratio needed at the receiver for proper reception without altering the wireless signal's frequency bandwidth. A symbol is encoded in a longer series of bits. The spreading code's length is equal to double the SF, where SF is a variable that can be adjusted from 7 to 12, also known as the spreading factor in LoRa terminology. This allows for the provision of variable data rates, allowing for the trade-off of throughput for coverage range, link robustness and energy consumption [2]. The service radius of the GW is affected by SF in LoRa modulation, which enhances signal robustness and range at the expense of data rate and energy efficiency. This is demonstrated by Eq. (1).

$$\mathrm{T} = \mathrm{Ptx} + \mathrm{Gant\text{-}K\text{-}10nLog(R)\text{-}Pnoise} \quad (1)$$

where Ptx is the transmit power set to 14 dBm, $Gant$ denotes the antenna gain set to 2 dB, K represents the intercept of the path-loss model set to 128.95 dB, n is the path-loss exponent equals 3, $Log(R)$ calculates the logarithm base 10 of the coverage radius and $Pnoise$ stands for the background noise, set to 117 dBm [14].

LoRa network works with BW of 125 KHz, 250 KHz, and 500 KHz. Eq. (2) and Eq. (3) presented blow, clearly reveals the relation between Rs, Rb, BW, CR and SF.

$$Rs = \frac{BW}{\frac{SF}{2}} \quad (2)$$

$$Rb = BW \times Rs \times CR \quad (3)$$

LoRa MAC Layer According to the LoRaWAN specifications [15], the medium access control (MAC) layer is essentially an ALOHA protocol that is mostly managed by the LoRa Network Server. The protocol is described in [15]. Overall, the LoRa MAC was designed to closely mirror IEEE 802.15.4 MAC which was designed for low data rates in order to achieve long battery life and very low complexity [13]. The goal of the LoRa MAC layer is to make it easier to accommodate the main protocols that are now running on top of the IEEE 802.15.4 MAC and Constrained Application Protocol (CoAP) [13], on top of the LoRa MAC. One notable similarity is the authentication method, which utilizes the 4-octet message integrity code, a feature directly inspired by the IEEE 802.15.4 standard [13].

The LoRa Alliance is in charge of overseeing LoRaWAN, an open-standard MAC and networking layer. The three primary components of its topology are the Network Server (NS), End-Device (ED) and GW (GW). EDs use LoRa modulation to communicate with one or more GWs. Multiple GWs may receive a message sent by an ED, and these GWs may then transfer the gathered messages to an NS that communicates with the various application servers. EDs run on batteries and are meant to last between ten and twenty years. Packets received by GWs from ED are forwarded to NS via a high-throughput IP backhaul channel, like Ethernet or 3G. Since an ED is not linked to a specific GW, multiple GWs may handle the same data packet. The packets sent by the EDs are de-duplicated by the NS, which also creates packets that, if any, should be sent back to the EDs. Finally, a GW is selected to transmit those answers to the intended ED. The star topology of the LoRaWAN network aids in the technology's ability to retain an inexpensive, simply maintained, and straightforward network design. Despite the great dominance of uplink transmission from EDs to NS, bidirectional communication is supported [2].

Adaptive Data Rate (ADR) plays a pivotal role in optimizing the performance of LoRaWAN networks. ADR is an essential feature that seeks to minimize battery usage and maximize throughput by altering the data rate and TP for each end node in the LoRa network. With the addition of GWs, a LoRaWAN's data rate adaptability facilitates easy network scalability. In addition, since data packets transferred via different SFs are orthogonal and can be transmitted concurrently, the use of ADR greatly expands the capacity of such a network [16].

B. Related Work

Georgiou and Raza [17] offered a framework to model the performance of a LoRa network with a single GW using stochastic geometry. They found that as the number

of ED increases, the coverage probability decreases exponentially. They came to the conclusion that the LoRaWAN access mechanism causes LoRa networks to become interference-limited in dense deployment scenarios rather than noise-limited. We will test the same parameter of coverage area but using multiple GWs instead of a single GW.

Augustin *et al.* [18] provided testbed throughput measurements, proving that less than 10% loss rate over a 2 km distance for SF 9-12 and that more than 60% loss rate over 3.4 km for SF 12. Additionally, they analyzed the behavior of LoRa for a higher number of devices and demonstrated that with a maximum channel capacity of 18% and a growing collision ratio—that is, about 60% for a link load of 0.48—it performs similarly to ALOHA. In our simulation, we will test the success rate over different spreading factors but using multiple GWs instead of a single GW.

Adelantado *et al*. [19] examined LoRa from the perspectives of network size and capacity. They found that throughput is constrained by collisions at low duty cycle values, while devices are prevented from raising their packet transmission rates and throughput is limited at higher duty cycle values by the maximum duty cycle specified by ETSI standards. For example, the maximum packet through put per node for 1000 devices is 38 pkt/hour (packets of 50 B), with only 13% of packets being successfully received. In our simulation, we will assess the rate and probability using multiple GW with 1000 to 5000 device with step of 1000 and packet size of 160b.

Bor *et al*. [20] created a LoRa simulation in order to investigate its scalability. They demonstrated that the 120 nodes per 3.8 ha that a typical Smart City implementation can handle is insufficient for upcoming IoT deployments. Additional research in the literature examined the LoRa modulation's performance. We will increase number of GWs and number of hosts to test the modulation performance.

Goursaud and Gorce [21] considered other technologies (SigFox, Weightless, and RPMA by Ingenu) in addition to LoRa to highlight their pros and cons. Ochoa *et al*. [22] suggested a number of strategies to modify LoRa radio settings for various deployment situations. According to their simulation results, we can acquire the best scaling-up/down approach for LoRa radio parameters in a star topology to gain low energy consumption and either high data rate or long range. We will test the data rate with a different placement strategy.

Our research expands on the discoveries made by El-Aasser *et al*. [23], who observed a correlation between higher network density and diminished success probability when utilizing different applications through a single GW. In contrast, our objective is to further investigate network performance by considering a larger number of hosts and multiple GWs, while concentrating solely on the utilization of a single application.

Chen *et al.* [24] explored routing and GW assignment in mega-constellation networks, using a simulation with specific parameters, such as a 1 kB packet length, 1×10^5 packets per second of network traffic, and link capacities of 20 Mbps (inter-satellite) and 200 Mbps (satellite-ground). Despite its focus on these aspects, the study's complexity and assumptions, like error-free links, may not fully reflect real-world challenges. However, unlike this study, I used different parameters in my research and accounted for potential errors, making my simulations more reflective of real-world challenges.

Naghdiani *et al*. [25] described a simulation for GW placement in Wireless Mesh Networks (WMNs), utilizing a CBR (UDP) traffic model with 30 randomly positioned GWs over a duration of 1000 s. GWs were positioned using the Garter Snake Optimization Algorithm to enhance performance. In our simulation model, we strategically placed GWs at the edges of the tested area to maximize the distance between them, extended the simulation period to five days, and adjusted additional parameters to meet our research requirements.

III. Developed Simulation Model

Building on a previous study of LoRa wide area network deployments for heterogeneous IoT applications using different Spreading Factors (SFs) [23], we augmented the existing simulation to incorporate multiple GWs, examining only homogenous IoT applications. Following the work done in [23], our developed simulation model was conducted using OMNeT++, which offers greater flexibility for creating and modifying models compared to other simulators. Additionally, OMNeT++ is well-suited for large-scale simulations, making it ideal for complex scenarios that require significant computational resources. Its extensive range of models and libraries, along with its strong reputation in academic research, further enhance its utility.

Our developed Multi-GW LoRa network simulator contains three components: ED, GW and Server. To facilitate a deeper understanding and enable reproducibility, the code repository is found on GitHub which could allow readers to access it for further exploration and verification of our findings[1].

The EDs used in our simulation are represented by a module named "Host". Hosts represent the devices that send their messages to the GWs following Aloha-like LoRaWAN protocol and incorporating all duty cycle specifications. Every host uses the applicable SF ensuring correct signal demodulation at the nearest GW, taking into account the distance between them. In a circular bi-dimensional space, a variable number of EDs are randomly distributed within the network cell under inspection.

Although the simulation model has the flexibility of experimenting with heterogenous applications deployed on EDs, yet in this simulation model we are only concerned with homogenous EDs with respect to the installed application and the used transmit power. An application is defined by the packet payload to be transmitted and the inter-arrival times between generated

[1] Multi-GW LoRa LPWAN Github Repository: https://github.com/Alaa828/Multiple-Gateway-LoRa-LPWAN

packets. The used transmit power is 14 dBm which is the maximum allowed transmitted power in the European band for LoRa transmissions [10]. EDs handle tasks such as buffering events, adding frame headers, and managing duty cycles. EDs select available channels for transmission and update their status based on the simulation's events, ensuring efficient and coordinated communication with the GWs.

The GW acts a relay between hosts and server. A lot of GWs deployment can be used differing from one central GW to multiple GWs distributed throughout the boundaries of the network cell under inspection. Each GW defines its parameters of coordinates, network radius, path loss exponent, bandwidth, and the number of channels. GWs receive messages from hosts within its range wirelessly and forward the messages to the server through using a high throughput IP backhaul interface. To concentrate on the LoRa Network, we have simplified our assumptions by neglecting the effects of collisions and interference from the IP backhaul. The developed simulator has the flexibility of deploying GWs with various placement strategies and quantities to determine the optimal number of gateways required for enhanced network performance under a network area under inspection.

The developed server module in our simulation is used to manage network communications and process data from all GWs. It functions by taking in and processing messages from all GWs that carry data from EDs. The server checks on duplicates and identifies collisions. It further calculates network metrics such as success rates, success probability and relative density of hosts, and processes data to maintain efficient network operations.

IV. Multiple GWs

We expanded the simulation to implement multiple GWs to enhance network performance by analyzing success rate, success probability, and increasing coverage area. First, we updated the LoRa network to support multiple GWs instead of just one. We then customized the hosts to broadcast their packets to all GWs, ensuring all hosts could connect and send packets to all GWs. The straight-line distance between each host and each GW was calculated using the Euclidean distance equation, derived from the Pythagorean theorem. This step is essential for effective data transfer and reducing power usage, optimizing network performance. End nodes dynamically choose the closest GW based on these distances, improving network performance by optimizing the Data Extraction Rate (DER). Hosts are assigned to the spreading factor of the closest GW, with hosts outside the network radius considered unconnected. Our simulation model evaluates the placement of multiple GWs to cover a pre-determined network area cell initially covered by a single GW. This approach tests deployment strategies by placing the GWs at the edge of the network cell radius, both with and without a central GW. We placed the GWs using their X and Y coordinates.

We examined two deployment scenarios for multiple GWs. In the first scenario, namely the on-edges scenario, where all gateways are located at the edges of the tested cell area. The second scenario includes these edge GWs plus an additional central gateway. This central GW significantly enhances performance by enabling many hosts to switch from higher SFs to lower order SFs, ensuring that all hosts within the cell are covered by the transmission range of at least one gateway. The work in this paper doesn't delve into the specific applications of individual scenarios, we aimed to showcase the adaptability of our simulation model for investigating different deployment setups. The strategies introduced involved placing multiple gateways within a network cell for assessment, aiming to gather initial insights into network performance iteratively. The flexibility of our simulation model supports the testing of diverse multi-gateway deployments, fostering continued exploration and experimentation.

To guarantee an evenly distributed placement of GWs in a circular configuration around the central point of the network cell being analyzed, we utilized Eq. (4) to calculate the X coordinates and Eq. (5) to determine the Y coordinates for the newly inserted GWs in the simulation model focusing on edge scenarios.

$$Xi = R \times Cos(\frac{2\pi \times M}{i}) \quad (4)$$

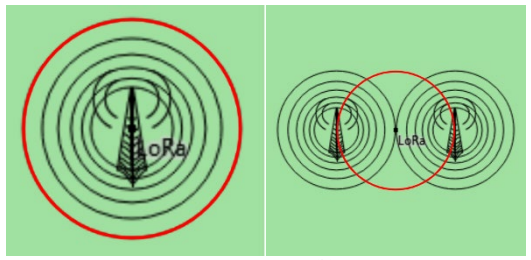
$$Yi = R \times Sin(\frac{2\pi \times M}{i}) \quad (5)$$

where R is the radius of the network cell, i is the index of the GW and $M$is the total number of GWs to be included in a single simulation run. Next, we updated the code to ensure that each host has a broader view of all available GWs and that the code can detect and communicate with all the GWs falling within their coverage range ensuring correct signal demodulation. Every host must determine the appropriate GW to transmit its packets to. This selection process should rely on proximity, with each host opting for the nearest GW by computing the distance between itself and each GW utilizing the Euclidean distance formula. After calculating the distance, we compare the obtained value with those listed in Table I to accurately assign each host to the SF corresponding to its closest GW. This step is crucial for determining the optimal spreading factor (SF) for each host based on its proximity to the nearest gateway.

Fig. 1 displays the different simulation setup GW deployments. The figure demonstrates the network area under inspection as a bold red circle. It also displays the placement of a GW with the 7 concentric circles of SF coverage regions around each GW. The various areas that a GW can successfully communicate with devices using different spreading factors are represented by circles of SF. The closest circle to the GW represents SF 7. Considering a single GW at the center of the network cell and moving away from the center, the utilized SF for a host increases until SF 12 is reached to ensure correct signal demodulation. Higher-order SFs allow communication over longer distances. However, it also comes with a trade-off of lower rates of data transfer and higher power consumption.

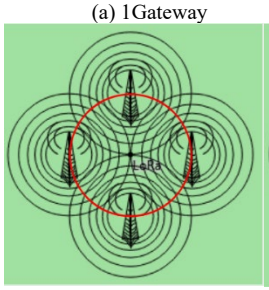
TABLE I. SPREADING FACTOR RADIUS

Spreading Factors SF	Distance (Km)
7	2.42661
8	2.93991
9	3.56178
10	4.31519
11	5.22797
12	6.33383

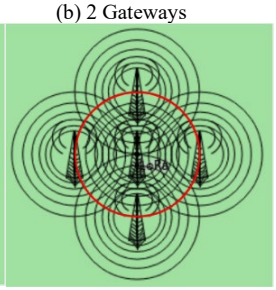


(a) 1Gateway

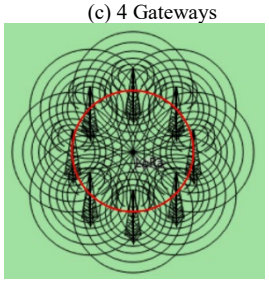
(b) 2 Gateways



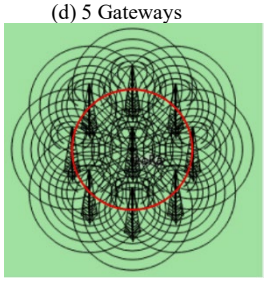
(c) 4 Gateways



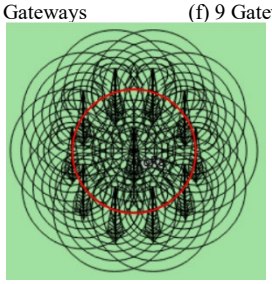
(d) 5 Gateways



(e) 8 Gateways



(f) 9 Gateways



(g) 11 Gateways

Fig. 1. Placement of GWs with different scenarios.

Lower data rates imply higher transmission time and thus this makes transmission prone to more probability of collision and degraded performance of the network. All GW placements are allocated on the edges of the network area under inspection. This placement allows EDs to use lower SFs. The intuition of this strategy is to offload some of the EDs previously utilizing higher SFs, to connect to near GWs and thus exploit lower SFs. This is beneficial for uses where low-latency or real-time communication is necessary. Additionally, because of shorter transmission periods, lower SFs typically result in lower power consumption. When there is a lot of interference, lower SFs could work better. This is because the broadcast signal can be distinguished from noise more clearly by the receiver, which usually has greater sensitivity at lower SFs. Finally, lower SFs are typically more resistant to multi-path fading effects, which occur when signals bounce off obstacles and reach the recipient at different times. In densely populated metropolitan areas, this can enhance overall network dependability. That means using multiple GWs will lead to having the EDs at a lower SF which gives out a reliable, secure and stable network. Fig. 1 illustrates the GWs' location and deployment plan. It provides a visual representation of where the GWs are situated in the different scenarios and helps the reader understand the specific GW placements that were evaluated as part of this research. In Fig. 1(a), one GW is located at the center of the network at coordinates (0,0). In Fig. 1(b), two GWs are positioned at the edge of the network at coordinates (–6333.83, 0) and (6333.83, 0). Fig. 1(c) includes four GWs at the edge at (–6333.83,0), (6333.83, 0), (0, 6333.83) and (0, –6333.83). In Fig. 1(d), five GWs are placed at the edge at (–6333.83, 0), (6333.83, 0), (0, 6333.83), (0, –6333.83) and one at the center (0, 0). Fig. 1(e) depicts eight GWs at the edge at (–6333.83, 0), (–4491.94, 4491.94), (0, 6333.83), (4491.94, 4491.94), (6333.83, 0), (4491.94, –4491.94), (0, –6333.83) and (–4491.94, –4491.94). Similarly, Fig. 1(f) has eight GWs at the edge at the same coordinates, with an additional GW at the center (0, 0). Finally, Fig. 1(g) illustrates ten GWs at the edge at (-6333.83, 0), (-5124.66, –3722.39), (–1955.48, –6022.43), (1955.48, 6022.43), (5124.66, –3720.35), (6333.83, 0), (5124.66, 3720.35), (1955.48, 6022.43), (–1955.48, 6022.43) and (–5124.66, 3722.39) with one GW at the center (0, 0). The bold red circle represents the network area where EDs are located.

V. SIMULATION SETUP

We carefully investigated a lot of different simulation scenarios. We conducted experiments on a wide range of conditions, including seven different cases with different numbers of GWs: 1, 2, 4, 5, 8, 9, and 11. We further varied our strategy in each of these cases by testing several host configurations, ranging from 1000 to 5000 with a step of 1000. By using the developed simulation model, we have the flexibility of methodically examining a wide range of multiple GW deployments with a range of hosts and driving insights about the relation between such deployments' scenarios and total network performance. At first, we used a traditional approach in which the GWs were mostly located at the network's edges with equidistant from each other. Secondly, we added one more GW at the center of the tested area in each scenario.

In our simulation setup, we consider the homogeneous operation of EDs where a Home Security application is running on all EDs. According to Ref. [23], the home security application is modeled by generating a 20 Byte sized packet that is transmitted every 600 s. The network area under inspection is a circular area with a radius of 6.3 km based on a study done by Semtech. The simulation parameters included a path loss value of 3 dB, a bandwidth of 125 kHz, a packet length of 160 bits, the use of 3

channels, code rate of 0.8. The simulation run time was conducted over a period of 5 days. Table II summarizes key simulation parameters used in the developed simulation model setup.

TABLE II. SIMULATION PARAMETERS

Items	Description
Home security application	20 Byte every 600 s
Network Radius (Meter)	6333.83
Path loss	3 dB
BW	125 kHz
Packet length	160 bits
Number of Channels	3
Code Rate	0.8
Simulation Time	5 days
Number of Hosts	1000...5000
Number of GWs	1,2,4,5,8,9,11

VI. RESULTS AND ANALYSIS

This section presents the findings of the experimental evaluation conducted to assess the performance and effectiveness of the multiple GWs. It provides a detailed analysis of network performance metrics, including packet success rate and success probability. The results offer insights into the behavior of the system under different number of hosts and GWs and highlight the threshold value for the number of GWs within the experiment parameters. The success rate represents the quantity of effectively transmitted packets from the EDs within a specified time frame. This metric is quantified in kilobits per second. Success rate is used to assess the reliability of data transmission in each simulation setup and it is calculated using Eq. (6).

$$SuccessRate = \frac{TotalNumberOfSuccessfulPackets}{TotalSimulationTime} \quad (6)$$

Fig. 2 illustrates the influence of varying the number of GWs and hosts on the success rate. Notably, the graph reveals that employing two GWs, as demonstrated in scenario 1.b in Fig. 1, resulted in the lowest success rate due to incomplete coverage of the test area. Results display that employing four GWs yields better outcomes than using two, and employing eight outperforms the previous two configurations. While a single GW exhibits a respectable success rate, it is not the optimal choice. Notably, with the introduction of five GWs, success rates converge closely. Scenarios featuring an even number of GWs lack a central GW, resulting in reduced success rates compared to other configurations. This underscores the significance of GW placement strategies in achieving optimal communication performance in multi-GW setups.

Success probability denotes the likelihood of a packet sent by the EDs being successfully transmitted within a defined time interval, expressed as a percentage. Successful probability offers a measure of the system's effectiveness in transmitting data accurately and consistently and it is calculated using Eq. (7).

$$Success\ Pr\ o\ bability = \frac{SuccessfulPackets}{TotalPackets} \quad (7)$$

In Fig. 3, we observe a similar pattern to that of success rates. The use of two GWs resulted in the lowest success probabilities, mainly due to inadequate coverage of the test region. With four GWs, coverage improved marginally. The deployment of eight GWs outperformed the previous setups. A single GW positioned centrally achieved a superior success probability. Introducing five GWs led to success probabilities closely aligned with those of higher GW counts. Notably, scenarios featuring an even number of GWs without a central one showcased reduced success rates compared to other scenarios.

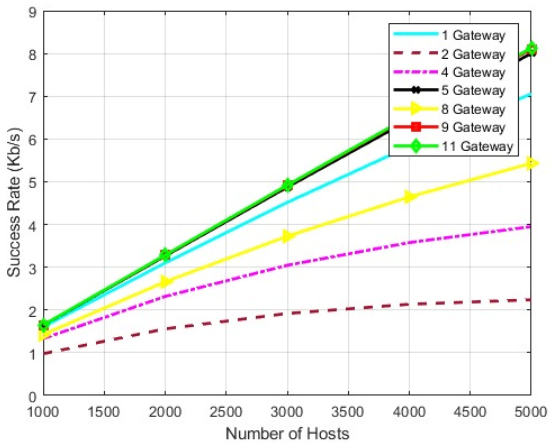


Fig. 2. GW Variation Impact on success rate across host count.

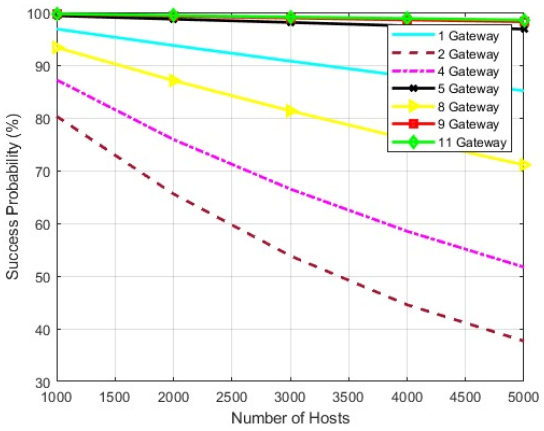


Fig. 3. GW Variation Impact on success probability across host count.

To further extend our analysis, we magnify the success rate and success probability when running the largest simulation setup of 5000 hosts in Figs. 4 and 5, respectively. Fig. 4 shows that configurations with 5, 9, and 11 GWs achieve the highest success rates. Specifically, the success rates for these scenarios are 8.00 Kb/s, 8.10 Kb/s, and 8.12 Kb/s, respectively. The percentage improvements in success rates for these scenarios are notably close to each other. When comparing the success rate of using 5 GWs to that of 9 GWs, there is a 1.30% enhancement. Similarly, comparing the success rate of using 5 GWs to that of 11 GWs, the enhancement is slightly higher, at 1.57%. Fig. 5 shows that configurations with 5, 9, and 11 GWs yield the highest success probabilities. Specifically, these probabilities are

96.82%, 98.22%, and 98.55%, respectively. The percentage improvements in success probabilities for these configurations are quite close to one another. Comparing the success probability of 5 GWs to that of 9 GWs, we observe an enhancement of 1.45%. When comparing the 5 GWs setup to the 11 GWs configuration, the improvement is slightly greater, at 1.79%.

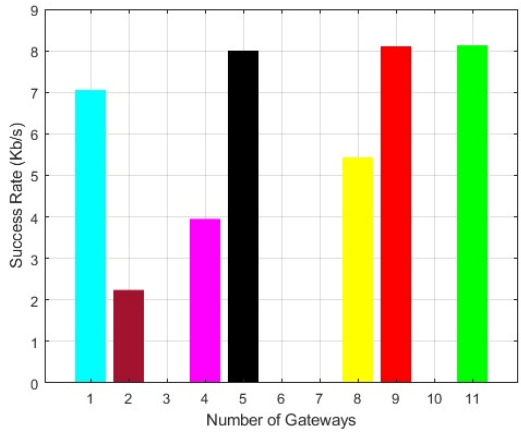


Fig. 4. GW Variation Impact on success rate using 5000 hosts.

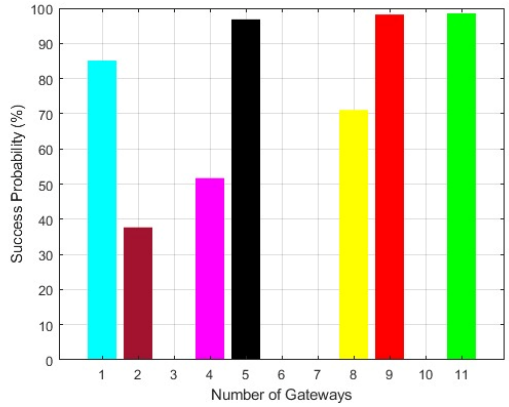


Fig. 5. GW Variation Impact on success probability using 5000 hosts.

As observed, the difference between the three scenarios shows only a slight enhancement in network performance based on success rate and success probability. The percentage improvement in success rate between using 5 GWs and 9 GWs is 1.30%, while the increase between 5 GWs and 11 GWs is 1.57%. For success probability, the improvement between 5 and 9 GWs is 1.45%, and between 5 and 11 GWs, it is 1.79%. By taking into consideration the expenses of deploying more 4 and 6 GWs the performance enhancement may not justify the cost. Therefore, we concluded that using 5 GWs represents the threshold value for our simulation. For the comparison between 1 and 5 GWs, both the success rate and success probability showed significant enhancements of 13.42% and 13.75%, respectively. This substantial improvement justifies the cost of deploying an additional 4 GWs.

Our simulation consists of two strategies which are on edges strategy or on edges plus central strategy. In the past part, we found out the threshold value of strategy with central GW is using 5 GWs. For the other strategy, the best performance we concluded was while using 8 GWs.

In Fig. 6, we have a comparison between the two strategies of deployment we tested during our simulation using 5000 hosts. So here in this comparison, we are comparing between 5 GWs from central strategy and 8 GWs from the on-edges strategy. As seen in Fig. 6(a) we can see that 5 GWs have a success rate of 8.00Kb/s and 8 GWs have a success rate of 5.43Kb/s. For Fig. 6(b) success probability for 5 GWs was equal to 96.82% and 8 GWs equal to 71.07%. We can see here that the central strategy has better network performance it has greater success rate and success probability despite having less number of GWs which is also cost-effective.

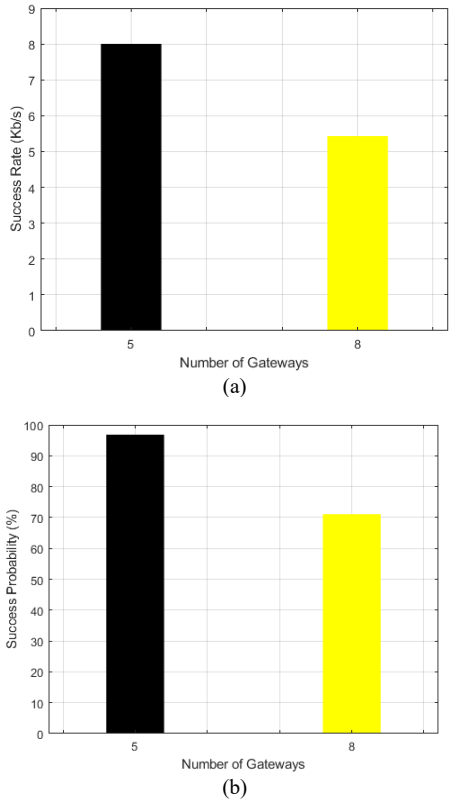
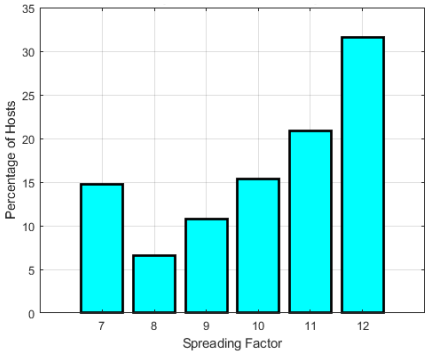
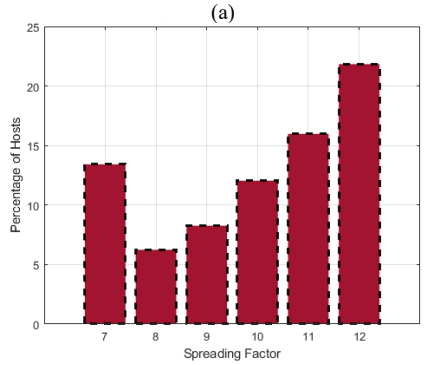


Fig. 6. Strategies comparison. (a) Success rate; (b) Success probability.

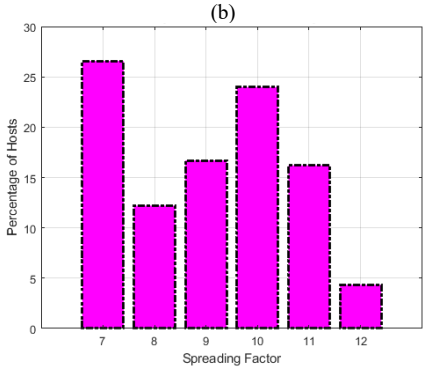
Fig. 7 displays hosts per spreading factor. It shows that using multiple GWs with the right deployment increases the number of hosts utilizing the lowest SFs, which has many advantages leading to improved network performance. Lower SFs offer higher data rates than higher SFs, beneficial for applications requiring low-latency or real-time communication. Additionally, shorter transmission periods at lower SFs typically result in lower power consumption. Lower SFs might also perform better in noisy environments due to better signal differentiation by the receiver, which usually has greater sensitivity to these factors. Furthermore, lower SFs are generally more resistant to multi-path fading effects, enhancing overall network reliability, especially in densely populated urban areas. Thus, using multiple GWs allows EDs to operate at lower SFs, resulting in a reliable, secure, and stable network.



(a)



(b)



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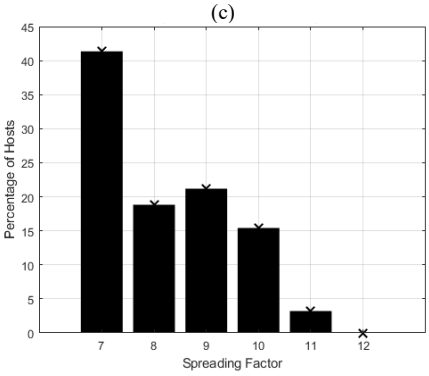
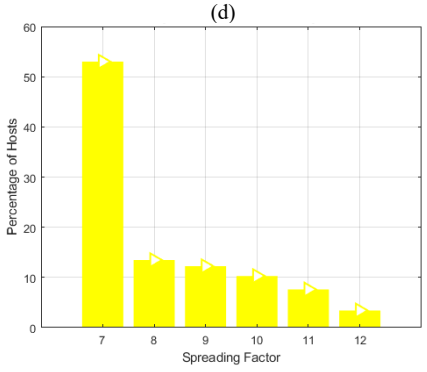
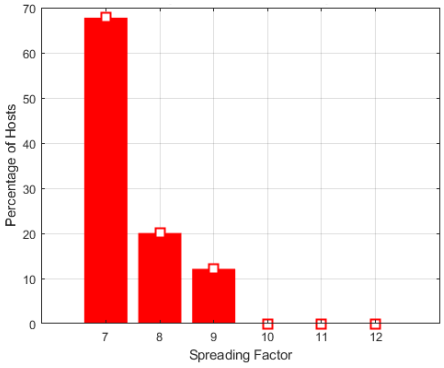


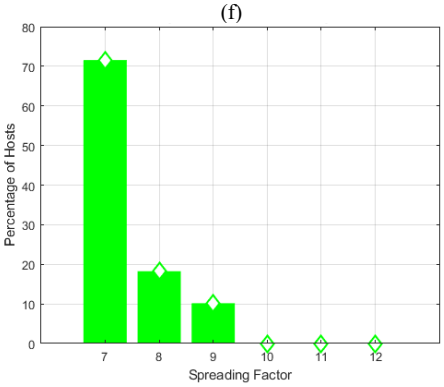
(d)



(e)



(f)



(g)

Fig. 7. Hosts per spreading factor for Multi-GW deployments. (a) 1 Gateway; (b) 2 Gateways; (c) 4 Gateways; (d) 5 Gateways; (e) 8 Gateways; (f) 9 Gateways; (g) 11 Gateways.

VII. Conclusion

This paper presents a simulation model designed to analyze the placement of multiple GWs and its impact on overall network performance. Our study found that strategic deployment of GWs significantly enhances network efficiency leading to fewer bottlenecks and more reliable connectivity for the users or devices within the network. Analyzing success rate, success probability, and host distribution across spreading factors, as depicted in the preceding graphs and detailed in the results section, illuminates the advantages of having a multiple GW simulation model for LoRa LPWAN. The developed model allows researchers to test and evaluate different network configurations before real world implementation and thus provides insights that can guide the actual deployment of the network infrastructure.

VIII. Limitations and Future Work

The developed OMNeT++ simulation model for multi-GW LoRa LPWANs serves as a valuable tool for assessing network performance and understanding key aspects of LoRa functionality. It enables comparative analysis by generating results that can be aligned with existing literature, allowing us to explore differences with similar studies. However, it also reveals challenges, such as the complexities of deploying heterogeneous network hosts, which can impact overall system efficiency, and the difficulties of strategically positioning gateways in real-world scenarios. By using mathematical optimization for ideal gateway placements and incorporating these

distributions into the simulation model, we can evaluate network performance under realistic conditions with numerous end devices. Additionally, we plan to utilize machine learning algorithms to further optimize gateway placements based on results from our simulation. The simulator will be crucial for generating synthetic datasets that facilitate the development and testing of these algorithms.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS

Minar El-Aasser implemented the initial simulation framework for LoRa Gateways, developing realistic living scenarios and conducting preliminary testing and troubleshooting under Tallal El-Shabrawy's supervision. Alaa Amar enhanced the simulation by integrating multiple gateways, designed and executed experiments to collect data, analyzed results, and wrote the paper under Minar El-Aasser's supervision. All authors had approved the final version.

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