Scalability of LoRaWAN in an Urban Environment: A Simulation Study

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Abstract— **The Long-Range Wide Area Network (LoRaWAN) communication protocol can be adapted for the Internet of Things (IoT) due to its long geographical coverage, low energy consumption, high capacity, open business model, and low cost. Recently, both academia and industry are attracted to LoRaWAN because of its recent developments and applicability in the IoT environment. Mostly, the IoT concept involves massive end devices distributed over a wide topographical area, hence establishing a high density and large-scale environment. LoRaWAN makes use of six orthogonal spreading factors (SFs) in order to improve spectral efficiency and increase the capacity. In this paper, we focus on the LoRaWAN class A network end devices and the problem of network scalability under high-density urban environment by using both the confirmed and unconfirmed mode of communication. Simulation results show that the urban environment has a high impact on the distribution of SFs, thus leading to low network performance in terms of success ratio. We also observed that the use of acknowledgment limits the scalability of the LoRaWAN due to the duty cycle constraints. However, this study further reveals that elevating the antenna height can significantly improve the performance in an urban area.**

Keywords— ***LoRaWAN, Internet of Things, scalability, capacity, spreading factor***

I. INTRODUCTION

Long Range Wide Area Network (LoRaWAN) [1] describes the MAC protocol, whereas LoRa enables the physical layer for long-range communication by adapting the chirp-spreading spectrum (CSS) modulation. Owing to the use of CSS, in a LoRaWAN network, a single gateway (GW) can cover a large geographical area. The long-range, network lifetime, network capacity, and low cost make it suitable for the Internet of Things (IoT). The long-range and long battery life of end devices (EDs) is achievable by star topology.

In IoT, EDs serve different applications, thus have different requirements, i.e., packet length, delay, data rate (DR), reliability, throughput, etc. To improve the diversity of such applications, LoRaWAN supports three types of different classes; class A, B, and C. Class A devices are most energy-efficient and support bi-directional communication by using the ALOHA channel access mechanism, but these devices support only unicast communication. After each uplink transmission, each ED opens a receive window (RW) for downlink communication to receive an acknowledgment from a network server (NS). Class B devices are also battery powered and support bi-directional communication. These devices support unicast as well as multicast transmission; however, it has more RWs than class A. These devices are synchronized with a beacon from the GW. Lastly, the class C devices utilize more power compared to class A and B counterparts. Also, they listen all the time except in transmit time. In order to communicate with the GW, each ED uses a spreading factor (SF) and a corresponding DR, respectively, as shown in Table I.

Table 1. Assignment condition for the spreading factor in LoRaWAN

Data Rate	SF	Sensitivity	
		$GW_{(i)}^{SF}$	$ED_{(i)}^{SF}$
0	12	-142.5	-139.5
1	11	-140.0	-137.0
2	10	-137.5	-134.5
3	9	-135.0	-132.0
4	8	-132.5	-129.5
5	7	-130.0	-127.0

SF has a high influence on the packet success ratio. For example, leads to reception errors due to low signal to noise ratio (SNR) value. Misjudging the SF, e.g., assigning too higher SF, may cause unnecessary high Time-On-Air (ToA) [1]. LoRaWAN makes use of six orthogonal SFs in order to improve spectral efficiency and increase the capacity. Assignment of SF based on the GW sensitivity is shown in Table I [2]. This assignment should be determined to minimize the ToA and lower the probability of collisions in an urban area [2]. In this paper, we show the effects of SF assignment at both confirmed and unconfirmed mode by analyzing the success ratio and SF distribution impact in a high-density urban area.

The remaining of this paper is organized as follows: section II describes the related works. The network model and SF assignment to EDs are explained in section III. The simulation results and performance analysis are presented in section IV, whereas the last section concludes this paper.

II. RELATED WORK

This section presents the related works regarding SF assignment and analysis of LoRaWAN in both confirmed and unconfirmed mode.

The performance of LoRaWAN network with the only unconfirmed mode in an urban environment is presented in [2]. [2] shows an assignment of SF to each ED based on the GW sensitivity by analyzing the radio frequency power signal at the GW. As a result, it lowers the probability of collisions and

This work was supported by Institute of Information & communications Technology Planning & Evaluation (IITP) grant funded by the Korea government(MSIT) (2018-0-00691, Development of Autonomous Collaborative Swarm Intelligence Technologies for Disposable IoT Devices)

minimizes the ToA. Then, the GW is chosen based on the received power and SFs are allocated for the transmission. The GW is configured with 8 received paths with 3 channels in total. These receiving paths are assigned to each channel for uplink transmission. However, in this work, downlink transmission and confirmed mode are not considered.

Another approach, RS-LoRa MAC protocol, aims to improve the reliability and scalability of LoRaWAN under free space path loss model [3]. RS-LoRa works in two major steps; in the first step, the GW is responsible for scheduling EDs within its range by measuring the Received Signal Strength Indicator (RSSI) and SF for each channel. In the second step, each ED decides its SF, transmission power, and channel based on the information provided by the GW. This scheduling reduces the collision by carefully selecting an SF in order to improve network reliability, scalability, and capture effect.

In order to tackle the interference and capture effect, an error model is described in [1]. This model is used for determining the range between EDs and a GW as well as analyzing the interference among various concurrent communications. The algorithm considers three different methods for assigning an efficient SF: (i) a random assignment method which assigns SFs based on uniform distribution mechanism, (ii) a fixed assignment method which assigns the same SFs all the time during the simulation period, (iii) Packet Error Rate (PER) based which finds and allocates the lowest SF for which the PER falls under a certain threshold. The PER approach for finding a suitable SF performs better than both the random and fixed-based SF assignment methods and can play a vital role in enhancing the packet delivery ratio.

Another work shows the performance of LoRaWAN network by performing a system-level simulation on NS-3 when heterogeneous traffics are transferred for smart metering communication [4]. The simulation was performed under a single GW located at the densely populated area in combination with multiple buildings of some random heights and sizes. EDs are distributed uniformly on each floor in the building within a coverage range of 2500 m. The lowest SFs are assigned according to SNR of ED packets, thus it reduces the ToA for each ED and minimizes the chances of interference.

The SF control algorithm is presented by allocating SFs to interact with two types of collisions: (a) two packets with the same SF collide and (b) two packets with different SFs collide in [5]. Hoverer, it fails to provide a solution to the second type. The primary purpose of this research is to reduce PER, improve fairness, and the throughput between EDs. The algorithm sorts the EDs based on distance and path loss to form distinct groups, where each group uses a separate channel. EDs in each group get the same SF based on the distance. Then the sum of the received power and cumulative interference ratio (CIR) is computed. If CIR exceeds the highest received power then it passes the feasibility check. On the other hand, the lowest SF is assigned to each group if the CIR is lower than the threshold. The proposed scheme decreases the PER up to 42% overall.

An SF allocation scheme for massive LoRaWAN network aims to enhance the success ratio by considering the interference among the same SFs and channel [6]. To identify the interference caused by the collision of two packets, it determines the collision overlap time between the packets of the same SFs over the same channel. Then the SIR and received power are computed. If it exceeds the threshold, then the packets survived from interference. Otherwise, the packets are lost due to interference. However, it ignores any interference occurred due to the different SFs over the same channel, because these SFs are not perfectly orthogonal.

III. NETWORK MODEL

In this section, we describe the network model briefly. Where this paper follows the same simulation environment presented in [4]. The rest of this section describes the assumptions, propagation model, and SF assignment algorithm.

A. Assumptions

In this paper, class A network is considered, where N EDs are uniformly positioned around a single GW. Where the transmission is always initiated by an ED in the uplink direction on any available channel among the C, where $\mathrm{C}(\in Ch = \{868.1, 868.3, 868.5\}\ and\ \mathrm{C} = |Ch|)$ is the index assigned for the corresponding channel. Whereas, during the downlink transmission, the same SF and channel are considered for RW1 as for uplink and for the RW2 the SF12 and 869.525 MHz channel is used.

In this paper, the transmission success ratio is presented. The transmission success ratio in this paper is termed as the ratio of the number of packets successfully received to those transmitted by the EDs. It is defined as:

$$P_{SR} = \frac{Pkt_r}{Pkt_s}, \tag{1}$$

where Pkt_r is the total number of packets correctly received at the GW and Pkt_s is the total number of packets sent, however Pkt_s does not consider the retransmitted packets.

Furthermore, a packet is considered delivered in an unconfirmed mode if a GW correctly receives it. Whereas, a confirmed packet is measured delivered if a GW successfully receives a packet and the ED receives an acknowledgment in response from an NS.

B. Path loss model-Urban Area

The propagation loss for the urban environment where the buildings are of approximately uniform height can be presented in [7].

$$L = 40 \times (1 - 4 \times 10^{-3} \times h) \times \log_{10}(R) - 18 \times log_{10}(h) + 21 \times \log_{10}(f) + 80dB, \tag{2}$$

where R represents the distance in kilometer between ED and a GW, h is the antenna height of the GW in meters, and f describes the frequency in MHz [7].

As an example, with 868 MHz and antenna height of 15 m and 50 m the propagation loss is shown in equation (3).

$$L_{height15} = 120.5 + 37.6 \log_{10}(R), \qquad L_{height50} = 111.1 + 32.0 \log_{10}(R). \tag{3}$$

After the propagation loss (L) is computed, log-normally distributed shadowing ($LogF$) with a standard deviation of 10dB can be added [8]. This yield to the path loss (PL) equation:

$$PL_{urban} = L + LogF \quad (4)$$

Generally, this path loss model is applicable for $h \in [0 \sim 50]$ and for long distance, but not accurate for short coverage [7]. By substituting L in equation (4) with equation (3), it becomes:

$$\begin{aligned} PL_{urban}^{height15} &= 120.5 + 37.6\log_{10}(R) + LogF, \\ PL_{urban}^{height50} &= 111.1 + 32.0\log_{10}(R) + LogF. \end{aligned} \quad (5)$$

Furthermore, the path loss exponent (n) is a significant constraint and it severely impacts the system performance. Mostly, n is known prior, however, generally, that is not the case. Before designing and modeling a real environment, n should be carefully chosen for a given environment. In this paper, we have computed as $n = 3.76$ and 3.20 based on the height of the antenna for 15 and 50 m, respectively.

$$\begin{aligned} PL_{urban}^{height15} &= 120.5 + 10 \times n\, log_{10}(R) + LogF, \\ PL_{urban}^{height50} &= 111.1 + 10 \times n\, log_{10}(R) + LogF, \end{aligned} \quad (6)$$

C. *Assignment of spreading factors to end devices*

The SF assignment to EDs in this paper is mainly based on [2] [9]. SF is assigned during the initial deployment and this assignment is updated according to the GW sensitivity as described in Algorithm 1. When an ED is far away from the GW or its signal is highly attenuated, the received power will be low, consequently forcing the ED to use a higher SF. The algorithm calculates the power level that GW will receive from EDs. Then each ED picks the GW with the highest power and gets an SF based on that value. On the other hand, if the received power is less than the GW sensitivity, the algorithm assigns 12 for SF and it assumes that the EDs are out of range and cannot reach the GW.

Algorithm 1. SF assignment to EDs based on sensitivity [2]

```
INPUT: SF(i) = GW sensitivity to SF(i)
OUTPUT: Assignment of SF(i) to EDs
for N EDs
  Calculate the power (P) received by EDs
from the current GW
 if (P of ED ≥ GW sensitivity)
    ED_i ←SF(i) //Such that P> SF(i)
  else
    ED_i ←SF(0) //EDs out of range
 end
end
```

IV. Results and Analysis

This section presents the performance analysis of LoRaWAN under realistic channel model under the high-density urban area in terms of success ratio. The simulation analysis is based on NS-3, where N number of EDs communicate with a single GW within a radius of 7.5 km. In a 7.5 km radius, the GW and EDs can communicate above sensitivity by using SF 12, keeping in mind the propagation loss in maximum distance. In order to have a more realistic simulation, the entire area of radius 7.5 km features square shaped buildings. The dimensions and distance of the buildings are based on the Manhattan layout model along with correlated shadowing. During the initial deployment of EDs, if an ED is randomly assigned to a particular building, that ED will be considered as indoor and transmissions from that particular ED will suffer from high building penetration losses. The building parameters utilized in an urban environment are shown in Table II. During the transmission, each ED transmits a packet of 51 bytes with a transmitting power of 14dBm during the 600 seconds of simulation time by randomly selecting any channel for the uplink transmission from the available three channels. The rest of the simulation parameters are shown in Table III.

Table II. Building parameters utilized in urban environment

Parameter	Description	Value
Grid width and height	The number of objects laid out on a line	16 × 21
LengthX	The length of the wall of each building along the x-axis	400 m
LengthY	The length of the wall of each building along the y-axis	400 m
DeltaX	The x space between buildings	500 m
DeltaY	The y space between buildings	300 m
Height	The height of the building (roof top level)	6 m
NRoomsX	Number of rooms along the x-axis	2
NRoomsY	Number of rooms along the y-axis	4
Nfloors	Number of floors	2

Table III. Parameters utilized in simulation

Parameter	Value
Simulation time (s)	600
Application time (s)	600
GW radius (m)	7500
Number of GWs	1
Packet size (bytes)	51
Number of EDs	100-1000
Channels	3
Receive paths (total) at GW	8
Antenna height (m)	15, 50

Figs. 1 and 2 show the SF assignment in an urban and free space path loss, respectively. The GW is placed in the middle and the number of EDs uniformly distributed within a 7.5 km radius. The distribution of SF assignment is presented in Figs. 3 and 4. As it can be seen in Fig. 3, the distribution of SF is greatly affected by the high-density buildings. In this urban scenario, the SF 12 is mostly used, compared to the others. In Fig. 3, 53.2% of the devices are using SF12 when compared to the free space path loss channel conditions, where 41.6% of the EDs make use of SF 12 as presented in Fig. 4.

Fig. 5 shows the packet transmission success ratio for the confirmed (CON) and unconfirmed (UNC) mode of communication in the case of a single GW LoRaWAN network, where the antenna is placed at a height of 15 m. It is clear from Fig. 5 for the CON and UNC mode under the urban scenario that the packet success ratio is observed decreased by increasing the number of EDs, respectively. It is due to massive EDs trying to send the packets at the same time without knowing the other EDs are already sending their packets to GW, thus causes collisions and decreasing the packet transmission success ratio. Furthermore, the declining tendency of the success ratio is due to the high interference between SFs or the inaccessibility of reception paths at the GW [10]. In case of a high-density urban area, we observed in particular that, on average, 20% of the EDs could not connect to the central GW owing to the unfavorable channel that leads to high packet loss during the transmission. However, these unconnected EDs stay active while causing interference to surrounding EDs, limiting the scalability in terms of retransmissions and acknowledgments. To ensure reliability, the EDs keep on retransmitting the lost packets (i.e., up to maximum 8 retries limit), however the duty cycle restriction does not allow such transmission if the EDs reach maximum allowed time. In the case of UNC mode, the main reason for packet loss is a collision, where the GW is busy in receiving packets.

The maximum transmission success ratio is observed 69% and 63% for both the CON and UNC mode under an urban scenario with 100 EDs, respectively. On the other hand, the higher success ratio of 97% and 82% for both CON and UNC mode under the free space path loss scenario with 100 EDs is witnessed, respectively.

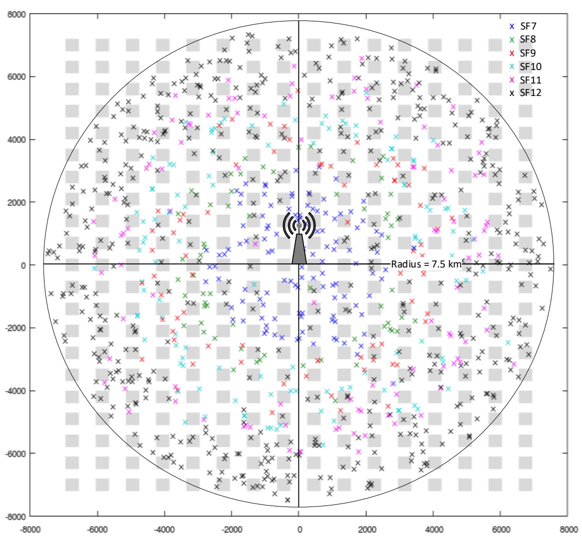

Figure 1. SF assignment in an urban area with N=1000.

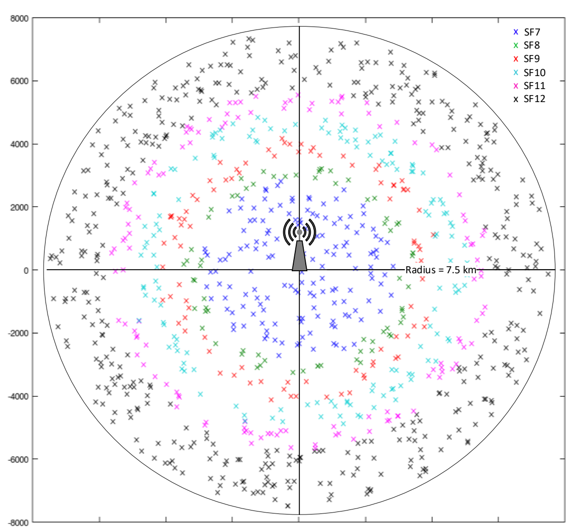

Figure 2. SF assignment in free space path loss with N=1000.

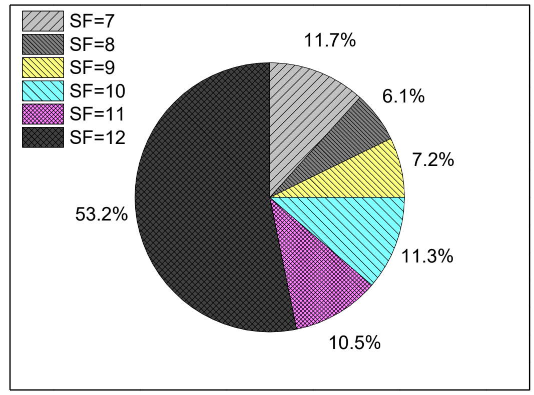

Figure 3. SF assignment ratio in an urban area with N=1000 (antenna height=15 m).

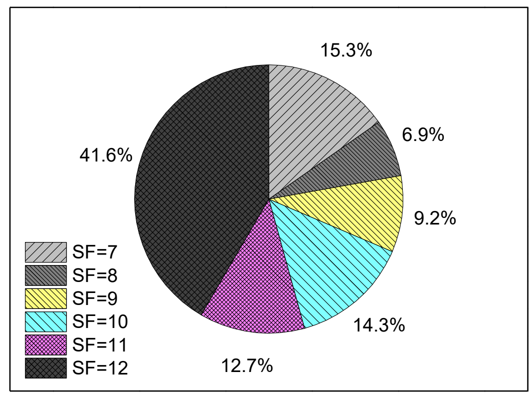

Figure 4. SF assignment ratio in free space path loss with N=1000 (antenna height=15 m).

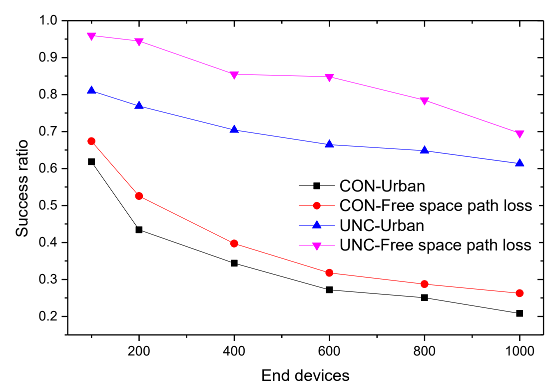

Figure 5. The transmission success ratio of LoRaWAN in urban and free space path loss situations with an antenna height of 15 m.

Another scenario for the transmission success ratio is presented in Fig. 6, where the antenna is placed at a height of 50 m. The SF assignment ratio for the same scenario is shown in Figs. 7 and 8. By increasing the height of the antenna, a significant improvement in success ratio is observed. These improvements on average are 33%, 43%, 21%, and 12% for CON-Urban, CON-Free space path loss, UNC-Urban, and UNC-Free space path loss situations, respectively. It is due to the fact that the signal strength is not greatly affected by the obstacles and penetration losses, thus resulting in more assignment to lower SF and an improved success ratio. Hence, it is evident from Figs. 6, 7, and 8 that antenna elevation has a massive impact on the performance [11].

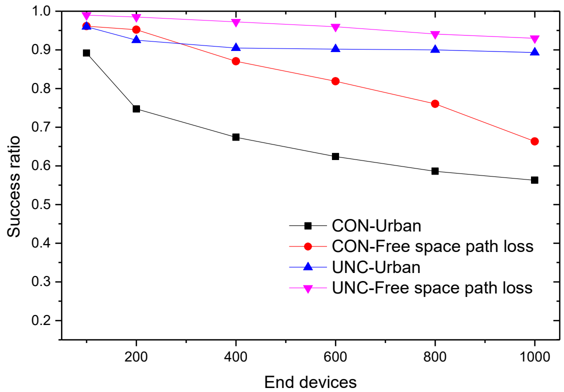

Figure 6. The transmission success ratio of LoRaWAN in urban and free space path loss situations with antenna height of 50 m.

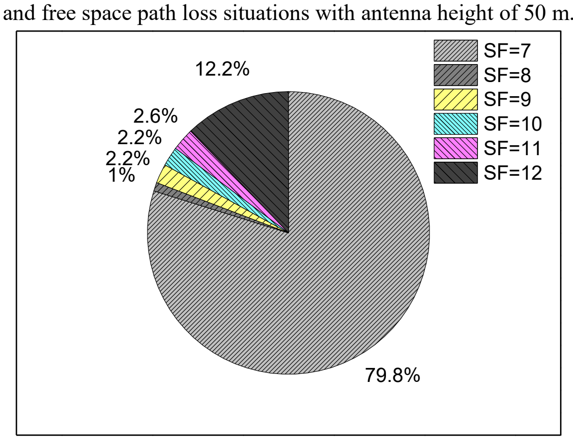

Figure 7. SF assignment ratio in an urban environment with N=1000 (antenna height=50 m).

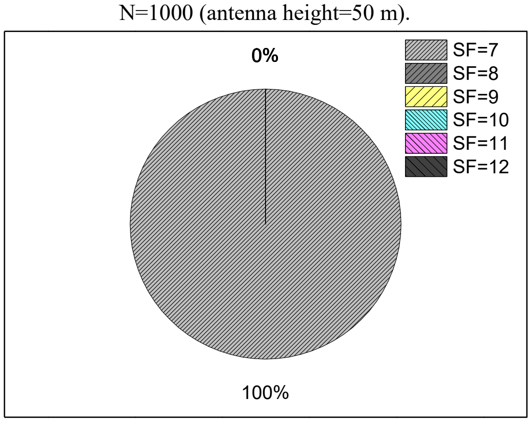

Figure 8. SF assignment ratio in free space path loss with N=1000 (antenna height=50 m).

V. Discussion and Conclusions

In a LoRaWAN network, thousands of EDs communicate with one or more GWs using different SFs. Due to the high-density urban environment, it suffers from high packet loss due to channel impairments, interference, and receiver saturation. In the existing literature, there is no appropriate study which presents the scalability analysis under high-density urban environment for both the CON and UNC mode of communication under the variation of antenna height. Therefore, this paper investigated the LoRaWAN for the massive IoT network in terms of scalability using CON and UNC mode in the presence of realistic and free space path loss.

From the analysis, we conclude that in general UNC mode performs better in a high-density urban environment in terms of transmission success ratio due to the absence of downlink communication as compared to the CON mode. Therefore, it is recommended to use the UNC mode when reliability is not required. We also observed that the duty cycle restriction limits the scalability of LoRaWAN in terms of retransmissions and acknowledgments. Further, it has the drawback of low reliability, substantial delay and potentially poor performance in terms of downlink traffic. LoRaWAN achieves better performance and satisfactory scalability under uplink transmission only. Moreover, to achieve better performance in a massive IoT environment under realistic channel conditions, the height of the antenna plays a vital role in achieving better performance in terms of success ratio.

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