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Adaptive algorithm for spreading factor selection in LoRaWAN networks with multiple gateways

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ABSTRACT

Recently, LoRaWAN has been considered a promising technology for large-scale IoT applications owing to its ability to achieve low power and long range communications. However, LoRaWAN is limited using Aloha random access scheme. When in dense scenarios, such scheme leads to a high number of collisions, thus severely impacts the reliability and scalability of LoRaWAN. In this paper, we investigate the impact of scalability and densification of nodes and gateways on the system reliability taking into account the capture effect. We propose an optimization problem to derive the node distribution at different spreading factors (SF) in LoRaWAN networks with multiple gateways. We then introduce an adaptive algorithm that enables to easily implement SF optimization by adjusting the signal-to-noise ratio thresholds. Moreover, the performance of the proposed algorithm is compared with the performance of legacy LoRaWAN and relevant algorithms from the state-of-the-art. Simulation results show that the proposed algorithm significantly outperforms the state-of-the-art algorithms, and improves the throughput and packet delivery ratio of the network.

1. Introduction

Internet of Things (IoT) paradigm is rapidly growing in our everyday life to connect a massive number of low-cost devices. According to Cisco, it is expected that the share of Low power wide area (LPWA) connections will grow to 1.9 billion by 2023 [1]. IoT devices will be used in a wide range of applications including smart homes, smart cities, smart agriculture, etc. These applications require low-rate, long-range and low-energy usage [2,3]. Low power wide area networks (LPWAN) have been therefore designed to meet such requirements and to support large-scale deployments. Nowadays, many LPWAN technologies exist such as SigFox, LoRaWAN, NB-IoT, Weightless, etc. An overview and comparison of these emerging LPWAN technologies have been presented in [4,5]. In particular, LoRaWAN [6] is one of these emerging LPWAN that has been widely investigated by the research and industrial communities.

1.1. Motivation and related work

LoRaWAN is based on pure Aloha channel access technique, where nodes transmit without any coordination on a randomly selected channel. Using such scheme in dense scenarios increases number of collisions and hence decreases the reliability and scalability of the network. The adaptive data rate (ADR) used by LoRaWAN controls uplink transmission parameters of LoRa nodes. The nodes will then increase their SF to reach the gateway or decrease their SF based on down-link messages from the network server. In this work, we will assess the shortcomings of ADR and demonstrate how such scheme fails to mitigate collisions at large scale.

Recently, a large number of studies have focused on capabilities and limitations of LoRaWAN. Theoretical evaluation of the capacity and scalability has been performed in [7–9]. The performance of LoRaWAN has been also analyzed and modeled for a single cell using stochastic geometry in [10]. The results show that the coverage probability drops exponentially as the number of end-devices increases due to interfering signals using the same spreading sequence. Mathematical model of packet error rate in LoRaWAN channel access taking into account acknowledged mode and retransmission policy has been presented in [11]. Numerous experimental tests have been also carried out in various indoor and outdoor environments to access the performance and coverage of LoRaWAN in real deployment [12–15].

Moreover, recent works have been conducted to manage allocation of resources (spreading factor, channel, transmit power) in order to address LoRaWAN issues [16–19]. In [16], an optimal SF distribution has been presented to minimize the collision probability. A power

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and SF control scheme has been then proposed to efficiently optimize the packet error rate (PER) fairness inside a LoRaWAN network by allocating distant users to different channels. Simulations show that PER can be decreased up to 50% for edge nodes in a moderate contention scenario. Furthermore, two algorithms to optimize SF allocation beyond the basic ADR strategy have been investigated in [17]. The first, named EXPLORA-SF, equally distributes SFs to covered nodes, constrained by their received signal strength indicator (RSSI) values and relevant thresholds. The second, named EXPLORA-AT, provides a balanced distribution of the channel load among the covered nodes to guarantee a time-on-air equalization and therefore fairness. In [19], the authors propose a novel MAC layer called RS-LoRa. They introduce a two-step lightweight scheduling, where the gateway first specifies allowed transmission powers and SFs on each channel. At a second step, each node uses information carried by beacons to determine its channel, transmission power and select randomly one of allowed SFs. In a single gateway scenario, they reduce PER by nearly 20% when number of nodes is 1000. In [18], the authors proposed an algorithm that schedules SFs, frequency channels, and time slots for wireless links connecting class B devices and gateways. The authors of [20] consider allocation of SFs in a single LoRaWAN cell in order to maximize the system packet success probability by assigning SFs to devices based on their distance to the gateway and SF sensitivities. Other works have focused on satisfying heterogeneous QoS requirements by assigning different modulation and coding schemes (MCS) to devices [21].

Another important feature of LoRaWAN gateways is related to the capture effect [22]. Under some conditions, the gateway may correctly receive a packet even if it collides with other ones. The capture probability depends on the interference from transmissions using the same SF (co-SF interference) or different SFs (inter-SF interference) [23]. The scalability and throughput of LoRaWAN deployments based on the capture effect and collision models have been evaluated in [24]. The obtained results illustrate the substantial impact of collisions on capture probability and thereby on LoRaWAN scalability. An analysis of the scalability of LoRaWAN taking into account multiple demodulating paths and capture effect have been reported in [25]. The authors show that the presence of multiple demodulation paths introduces a significant change in the analysis and performance of LoRa random access schemes. However, most literature algorithms are limited to single gateway deployments [16–18,20] and as in [18] and [19], they require signaling (beacons) from gateways to synchronize nodes, and then they are not suitable to be used with class A devices. Consequently, in the perspective of deploying and managing large scale IoT networks, an adaptive SF selection algorithm is required. The algorithm should take into account the capture effect in a multi-gateways network and support all class devices of LoRaWAN specification.

1.2. Contribution

In this paper, we first analyze the impact of a massive number of nodes, their distribution on large area sizes, and the densification of gateways on LoRaWAN performance, namely on the total throughput and packet delivery ratio. We then formulate an optimization problem that maximizes the network throughput taking into account the capture effect in order to derive an optimal distribution of nodes over SFs. Based on this distribution, a SF allocation algorithm is presented that adjusts signal-to-noise (SNR) ratio thresholds to satisfy the maximum throughput. Compared to state-of-the-art, the proposed algorithm does not involve any change or additional synchronization process compared to current LoRaWAN specification especially for class A. In fact, the network server simply notifies the nodes about new SFs in their receiving windows. Additionally, the performance of our proposed algorithm is evaluated and compared with legacy LoRaWaN and relevant algorithms from the state-of-the-art. The results show that the proposed algorithm significantly improves the throughput and packet delivery ratio of the network.

Table 1
Data rate, sensitivity and SNR thresholds of different SFs for 868 MHz band, bandwidth 125 kHz, Coding rate 4/5.

SF	Data rate [kbps]	Sensitivity [dBm]	Required SNR [dB]
7	5.458	−123	−7.5
8	3.125	−126	−10
9	1.757	−129	−12.5
10	0.976	−132	−15
11	0.537	−134.5	−17.5
12	0.293	−137	−20

The remainder of this paper is structured as follows. Section 2 briefly describes LoRa and LoRaWAN technology. The optimization problem and adaptive algorithm for SF selection are presented in Section 3. In Section 4, network settings are described and the performance of the proposed algorithm is evaluated and compared with Aloha scheme and other state-of-the-art algorithms. Finally, the conclusions are drawn in Section 5.

2. LoRa and LoRaWAN overview

This section briefly presents features of LoRa and LoRaWAN technologies that are pertinent to our work.

LoRa is a physical layer technology developed by Semtech [26]. It modulates signals using a chirp spread spectrum (CSS) technique that spreads a narrow-band signal over a wider channel bandwidth. This technique makes the signal robust to interference due to the processing gain of the spread spectrum technique. As a result, the maximum power budget for LoRa operating in 868 MHz band can exceed 150 dB (the receiver can decode transmissions 19.5 dB below noise floor), thus enabling long communication ranges.

LoRa is characterized by various configured parameters: SF, bandwidth, transmission power, and coding rate. The bandwidth can be 125 kHz, 250 kHz, and 500 kHz. SF refers to the number of bits encoded per symbol. LoRa supports multiple SFs ranging from 7 to 12. Table 1 gives the variation of data rate, sensitivity and SNR thresholds of different SFs for 868 MHz band. Note that for SNR values lower than -20 dB, a node is considered out of network coverage. The selection of SF is a trade-off between coverage range and data rate. The higher the SF, larger the coverage and lower the data rate is. We note also the different SFs are quasi-orthogonal [27], which enable simultaneous receptions of packets with different SFs. The transmit power is configured according to the region and transmission band. For example in Europe, the maximum transmit power is 14 dBm. In order to improve the robustness of the link, LoRa integrates forward error correction to perform error detection and correction. Coding rate can be set to 4/5, 2/3, 4/7 and 1/2.

LoRaWAN is the upper layer protocol developed by LoRa Alliance [6]. LoRaWAN network is a star topology consisting of four entities: nodes, gateways, a network server and an application server as illustrated in Fig. 1. Nodes communicate with gateways using single-hop LoRa communication. The gateway simply relays received messages to a central network server via an IP backbone. The central network server manages the network access and functionality and is responsible for routing messages between nodes and LoRaWAN application.

LoRaWAN uses pure Aloha as a channel access technique, where nodes transmit without any coordination on a randomly chosen channel, with a duty cycle limitation that depends on the region, *e.g.* 1% in Europe. Also LoRaWAN supports multiple frequency channels *e.g.* 433, 868 or 915 MHz industrial, scientific and medical (ISM) bands, depending on the region in which it is deployed [28]. In Europe, 868 MHz band with bandwidth settings of 125 kHz and 250 kHz are used.[2]

[2] Lebanon also follows this regulation.

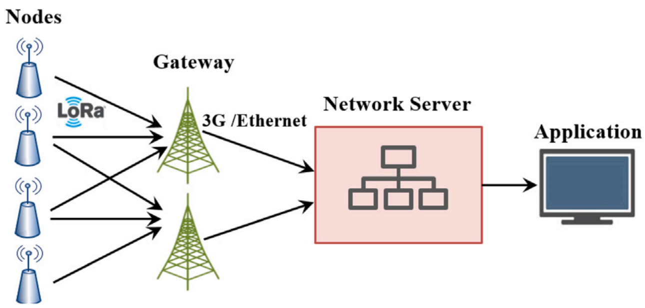

Fig. 1. LoRaWAN architecture.

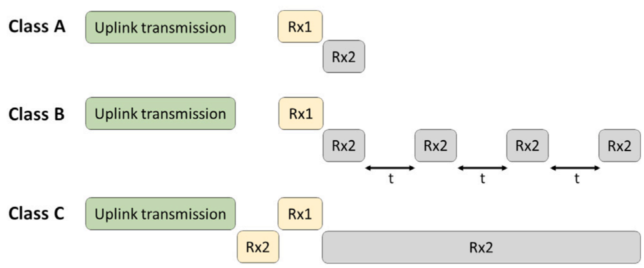

Fig. 2. LoRaWAN classes.

LoRaWAN defines three different classes of nodes with different capabilities and power requirements as illustrated in Fig. 2. Class A supports basic bidirectional communications, where each uplink transmission is followed by two short receive windows Rx1 and Rx2 where the network server can send MAC commands to nodes so as to control transmission parameters such as spreading factor, power and bandwidth. Rx1 uses same SF as the original uplink, while Rx2 uses SF 12 and is opened only if downlink message is not received during Rx1. Class B extends Class A by adding extra receive windows at scheduled times. The nodes are synchronized by periodic broadcast of beacons from gateways. Finally, nodes of Class C are permanently listening to the channel with continuously open reception windows.

Furthermore, LoRaWAN specification supports an adaptive data rate (ADR) mechanism for optimizing data rates, airtime and energy consumption in the network. In this mechanism, the data rate is changed according to channel conditions either at the node side or by the network server. In case of bad radio conditions, the data rate is lowered (*i.e.,* SF is increased) by a node in low coverage. Meanwhile in good radio conditions, the server increases the data rate (*i.e.,* SF is reduced) or reduces the transmit power of a node in order to maximize the battery lifetime and optimize overall network capacity. The network server determines an appropriate data rate based upon the strength of uplink signals received by gateways. Note also that ADR should be enabled whenever a node has sufficiently stable radio conditions.

LoRaWAN is also subject to intrinsic types of interference: co-SF interference due to collisions of packets with same SF, and inter-SF interference due to collisions with different SFs [23,24,29]. Usually a collision occurs when two or more signals are received at an overlapped time by a gateway. The gateway can then drop all received packets or it can decode the strongest packet thanks to the capture effect. The capture probability is a function of co-SF interference and inter-SF interference. The inter-SF interference can be mitigated by considering a protection margin in the received signal. In this work, we assume a protection margin of 10 dB in SNR computation. Therefore, we consider perfect orthogonality among different SFs, so that only packets of same SF within a common channel are vulnerable to collisions.

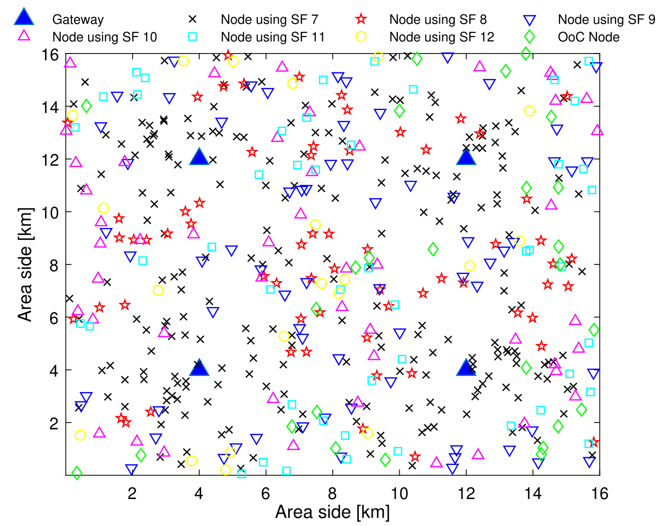

Fig. 3. Node distribution in a 4 gateways LoRaWAN network.

Table 2
Example of node distribution at different SFs, N_t=500 nodes.

SF	7	8	9	10	11	12
Number of nodes	227	67	64	49	47	20
N_s	474	247	180	116	67	20

3. Adaptive algorithm for LoRaWAN

In this section, we first describe the system model and assumptions used to adapt the transmission in a LoRaWAN network with multiple gateways. The optimization problem is then introduced to derive an optimal SF selection in order to maximize the throughput. We then extend this optimization problem to take into account the capture effect. An adaptive algorithm is next devised to implement SF selection on the nodes. This algorithm simply adjusts SNR thresholds and notifies nodes about selected SFs in their receiving windows.

3.1. System model

Let us consider a LoRaWAN network with N_t nodes and r gateways. Transmit attempts are done according to a Poisson distribution with mean arrival rate of λ packets per second. Class A nodes are considered with unconfirmed messages, even though each node opens two receive windows Rx1 and Rx2 after each uplink. All nodes are assumed to have same λ and same packet length l. Let T_s be the time to transmit a packet of l bytes on SF s. Then, given a duty cycle limitation of $d = 1\%$, the packet generation rate for each node operating on SF s must verify $\lambda T_s \leq d$. We denote by N_c the number of covered nodes, and N_s the number of nodes that use $SF \geq s$ according to Table 1. Fig. 3 represents an example of node distribution in LoRaWAN network of four gateways with $N_t = 500$ nodes in a square area with side 10 km. The distribution of nodes at different SF and the corresponding N_s values are presented in Table 2. For instance, when SF 9, $N_s = 180$. This corresponds to the sum of nodes at SF 9, 10, 11 and 12. Note that we have 26 OoC (Out of Coverage) nodes, since their SNR values are less than -20 dB, then $N_c = 474$ nodes.

Table 3 lists various variables and parameters included in our model.

3.2. Optimization problem for SF selection

Let p_s be the optimal ratio of nodes that can use SF $s \in \Omega = \{7, 8, 9, 10, 11, 12\}$. The minimum SF 7 is denoted later by S_{min}, and the

Table 3
System model parameters.

Parameters	Description
λ	Packet generation rate
T_s	Time to transmit a packet on SF s
l	Packet length in Bytes
d	Duty cycle
N_t	Total number of nodes
N_c	Number of covered nodes
N_s	Number of nodes using $SF \geq s$
p_s	Optimal ratio of nodes that can use SF s
G_s	Traffic load on spreading factor s
S	Total throughput

maximum SF 12 is denoted by S_{max}. Considering Aloha random access, the channel traffic load or the average number of packets transmitted per packet time T_s on SF s is given by:

$$G_s = \lambda.p_s.N_c.T_s. \tag{1}$$

According to Poisson distribution, the probability of having k transmissions during two packet-times is expressed as follows:

$$P(k \text{ transmissions}) = \frac{(2G)^k \exp(-2G)}{k!}. \tag{2}$$

Therefore, the probability of successful transmission ($k = 0$) is $\exp(-2G)$. Aloha throughput on each SF can be expressed as the traffic load multiplied by the probability of success: $G_s \exp(-2G_s)$. Since all SFs are supposed to be orthogonal, the total throughput (S) of LoRaWAN network is hence computed as the sum of throughput over the range of SF from S_{min} to S_{max}:

$$S = \sum_{s=S_{min}}^{S_{max}} G_s \exp(-2G_s). \tag{3}$$

The optimization problem of spreading factor selection consists in finding the optimal node distribution for each SF and therefore in computing their ratios p_s. We can write the optimization problem as follows:

$$(\mathcal{P}): \quad \max_{p_s} \sum_{s=S_{min}}^{S_{max}} \log\left(G_s \exp(-2G_s)\right) = \max_{p_s} \sum_{s=S_{min}}^{S_{max}} \log\left(G_s\right) - 2\sum_{s=S_{min}}^{S_{max}} G_s \tag{4a}$$

$$\text{subject to} \quad \sum_{s=S_{min}}^{S_{max}} p_s \leq 1, \tag{4b}$$

$$\sum_{i=s}^{S_{max}} p_i \geq \frac{N_s}{N_c}, \forall s \in \Omega. \tag{4c}$$

In this problem ($\mathcal{P}$), we apply the logarithm utility function (log) to ensure a proportional fair throughput. The utility maximization objective is subject to constraint (4b) ensuring that the sum of ratios does not exceed 1, and constraints (4c) to ensure that the number of nodes selecting SF s and above does not exceed the maximum number N_s. The objective function is non-linear and convex, and the constraints are linear. Therefore, problem $\mathcal{P}$ is a non-linear convex optimization problem that can be solved very efficiently using solvers such as CVX [30].

3.3. Optimization problem with capture effect

Generally, a packet collision occurs when two or more radio signals overlap in time at a receiver. However, in case of capture effect, the stronger of two or more simultaneous signals can be correctly received despite the presence of interfering signals. We assume that a packet is successfully received by a gateway if the corresponding received signal power is higher than the maximum interferer by a predefined capture margin Δ (Δ equals 3 dB or 6 dB in practice).

The authors in [22] and [31] demonstrate that if a receiver is used with uniformly deployed nodes, the probability K that the relative signal strength values being greater than or equal to some value Δ is given by:

$$K = \frac{10^{-\Delta/10\alpha}}{2}, \tag{5}$$

where α is the environment propagation coefficient. For example, $\alpha = 2$ in free space environment.

Let us denote by $P_{cap}(n, \Delta)$, the probability of successful capture, which corresponds to the probability of successful transmission of one packet when n collisions occur. With n transmitters, the probability that one of the packets in a collision is captured over all of the others is K^{n-1}. For simplicity, assuming same and independent capture probability for all r gateways, the possibility of capture at any of r receivers when n transmitters collide can be expressed as [31]:

$$(1 - P_{cap}(n, \Delta))^r = \left(1 - \frac{K^{n-1}}{n}\right)^r. \tag{6}$$

Having D_s nodes using SF s, the probability of successful transmission, denoted by P_{succ}, can be represented by a Poisson random variable with the addition of the capture probability:

$$P_{succ} = \sum_{n=2}^{D_s} \frac{(2G_s)^n}{n!} \exp(-2G_s)(1 - (1 - P_{cap}(n, \Delta))^r). \tag{7}$$

The total throughput (S) of LoRaWAN network is then given by:

$$S = \sum_{s=S_{min}}^{S_{max}} G_s \exp(-2G_s) + G_s P_{succ}. \tag{8}$$

Let

$$P' = \sum_{n=2}^{D_s} \frac{(2G_s)^n}{n!}(1 - (1 - P_{cap}(n, \Delta))^r). \tag{9}$$

Then, we can rewrite (S) as follows:

$$S = \sum_{s=S_{min}}^{S_{max}} G_s \exp(-2G_s)(1 + P'). \tag{10}$$

Therefore, the objective function expression given by Eq. (4a) can be modified to take capture effect as follows:

$$(\mathcal{P}_n): \max_{p_s} \sum_{s=S_{min}}^{S_{max}} \log\left(G_s \exp(-2G_s)(1 + P')\right). \tag{11a}$$

The new objective function of problem ($\mathcal{P}_n$) is non-convex and the problem cannot be solved directly. To overcome this limitation, we fit this function on another convex one, in order to obtain convex optimization problem. Given the number of covered nodes N_c, number r of receivers, environment propagation coefficient α, packet length l and packet generation rate λ, we perform a convex envelop fitting to the expression $(1 + P')$ for each SF s as follows:

$$(1 + P') \approx a_s.(p_s.N_c + b_s)^{c_s}.\exp(d_s.p_s.N_c), \tag{12}$$

where a_s, b_s, c_s and d_s are constant values selected for each SF to obtain a suitable fit of $(1 + P')$ expression using least square method. These values should be computed for every N_c, r, α and λ.

Using the approximation in expression (12), the objective function can be written as follows:

$$(\mathcal{P}_n): \quad \max_{p_s} \sum_{s=S_{min}}^{S_{max}} \log\left(G_s\right) - 2\sum_{s=S_{min}}^{S_{max}} G_s + \sum_{s=S_{min}}^{S_{max}} \log\left(a_s\right) + \sum_{s=S_{min}}^{S_{max}} c_s \log\left((p_s.N_c + b_s)\right) + \sum_{s=S_{min}}^{S_{max}} (d_s.p_s.N_c) \tag{13a}$$

Now ($\mathcal{P}_n$) with constraints (4b) and (4c) becomes a convex optimization problem.

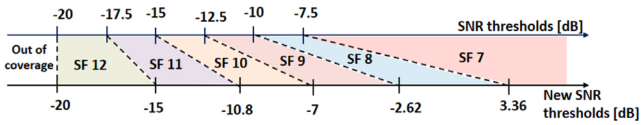

Fig. 4. Adjusting SNR thresholds example.

3.4. Adaptive algorithm

After finding the optimal distribution of nodes among SF, using ($\mathcal{P}$) or ($\mathcal{P}_n$), the adaptive algorithm searches to adjust SNR threshold for each SF that satisfy the optimal distribution as presented in Algorithm 1. First, the network server sorts received SNR from all nodes in the network from highest value to lowest one (Line 3). Next, for each SF s, we calculate the optimal number of nodes opt_n_s (Line 5). The SNR threshold SNR_s is adjusted to the lowest SNR value in the set of nodes opt_n_s (Line 7). Fig. 4 gives an example to show how the required SNR values are adjusted to achieve the optimal node distribution. For example, SNR threshold (−7.5 dB) in case of SF 7 could be adjust to 3.36 dB to redistribute nodes over higher SFs.

The network server can therefore notify each node about its new SF in one of the receiving windows, using DataRate bits of LinkADRReq command for example. Since, we have six SF, then we only need three bits to encode this information. The proposed algorithm schedule nodes in an implicit and simple way without any radical change in LoRaWAN specification. It can be effectively applied for all classes including class A, since no beacon is required, contrary to the work in [16–18].

Algorithm 1: SNR threshold selection algorithm

Input: Number of covered nodes N_c, Received SNR for node i, SNR_i, $i \in [1, N_c]$, p_s optimal ratio of nodes that can use SF s given by ($\mathcal{P}$) or ($\mathcal{P}_n$), $s \in [S_{min}, S_{max}]$
Output: Adjusted SNR threshold for SF s, SNR_s, $s \in [S_{min}, S_{max}]$

1 p_{temp} : temporary variable for node distribution
2 opt_n_s: optimal number of nodes that can use SF s
3 Sort SNR_i in decreasing order for all i
/* Distribute nodes among SF */
4 **for** $s = S_{min}: S_{max}$ **do**
5 $\quad opt\_n_s \Leftarrow round(N_c.p_s)$
6 $\quad p_{temp} \Leftarrow 0$
7 $\quad$**if** $p_{temp} < p_s$ **then**
$\quad\quad$/* Set the SNR_s threshold to the lowest SNR in the set of nodes */
8 $\quad\quad p_{temp} \Leftarrow p_{temp} + 1$
9 $\quad\quad SNR_s \Leftarrow SNR_{temp}$
10 $\quad$**end**
11 **end**

4. Simulation results

This section describes the simulation scenario and various parameter settings considered for assessing the performance of the proposed algorithm. First, the performance of legacy LoRaWAN with Aloha scheme, multiple gateways and different area sizes is presented. Then, the performance of our proposed algorithm for SF selection without and with the capture effect is evaluated and compared with legacy LoRaWAN, and relevant algorithms from the state-of-the-art:

- Legacy LoRaWAN: each node is assigned the lowest SF that fulfills SNR requirements according to Table 1,
- EXPLORA-SF [17]: equally distributes covered nodes among SFs,
- EXPLORA-AT [17]: derives a distribution of covered nodes that equalizes the time on air,

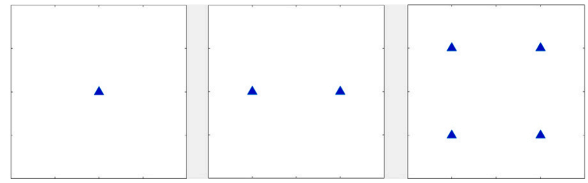

Fig. 5. LoRaWAN gateway positions.

Table 4
Time on Air and λ for different SFs, l = 50 bytes.

SF	Time on air [s]	λ [packets/h]
7	0.1245	289.1139
8	0.2097	171.6614
9	0.3801	94.7097
10	0.6816	52.8189
11	1.206	29.8542
12	2.254	15.9685

- Optimal SF distribution with unconstrained power control [16]: distributes covered nodes in order that the ratio of nodes at each SF verifies $p_s = \frac{s}{2^s} / \sum_{i=7}^{12} \frac{i}{2^i}$. This algorithm is denoted by optimal SF distribution algorithm in rest of the paper.

4.1. Simulation setup

We consider different LoRaWAN scenarios where the total number of nodes N_t equals 3000 nodes of class A are uniformly distributed on a square area with variable side around various number of gateways. The variable area side ranges from 2 to 16 km and the number of gateways varies between 1, 2 and 4 regularly positioned, as shown in Fig. 5, in order to study the impact of network densification. Having a payload length of l = 50 bytes, the variation of the time on air and maximum packet generation rate λ as function of SF is given in Table 4. For SF 12, a packet generation rate of 15 packets/h is obtained with a higher time on air of 2.254 s.

In our work, without loss of generality we consider a single available channel from the 3 default channels at 868 MHz band. Therefore, we assume that all nodes generate uplink messages periodically with the same packet generation rate of 5 packets/h, which corresponds to the maximum traffic intensity λ at highest SF 12 divided by the number of channels. The typical urban environment Okumura–Hata is considered as a path-loss model. The shadow fading is modeled by a lognormal distribution with zero mean and 8 dB standard deviation. The simulation parameters are listed in Table 5. All simulations have been performed using MATLAB simulator. The performance metrics used in the evaluation are presented hereafter.

- The percentage of covered nodes per SF corresponding to number of nodes transmitting at a SF according to Table 1 over total number of nodes in the network.
- The total throughput without and with capture effect computed as in Eqs. (3) and (10), respectively.
- The total packet delivery ratio without and with capture effect expressed by Eqs. (14) and (15), respectively.

$$\frac{\sum_{s=S_{min}}^{S_{max}} p_s.N_c.\exp(-2G_s)}{N_t} \tag{14}$$

$$\frac{\sum_{s=S_{min}}^{S_{max}} p_s.N_c.\exp(-2G_s)(1+P')}{N_t} \tag{15}$$

Table 5
Simulation parameters.

Parameter	Value
Number of nodes N_t	3000
Number of gateways	1, 2 and 4
Network Layout	Square, side [2-16] km
Path loss model	Okumura–Hata Urban
Spreading Factor SF	$s \in \Omega = \{7, 8, 9, 10, 11, 12\}$
Tx Power	14 dBm
Carrier Frequency	868 MHz
Bandwidth	125 kHz
Coding Rate	4/5
ED/GW antenna	3 dBi omnidirectional
Gateway height	30 m
Node height	1.5 m
Packet generation rate λ	5 packets/h
Packet Length	50 Bytes
Capture margin Δ	6 dB

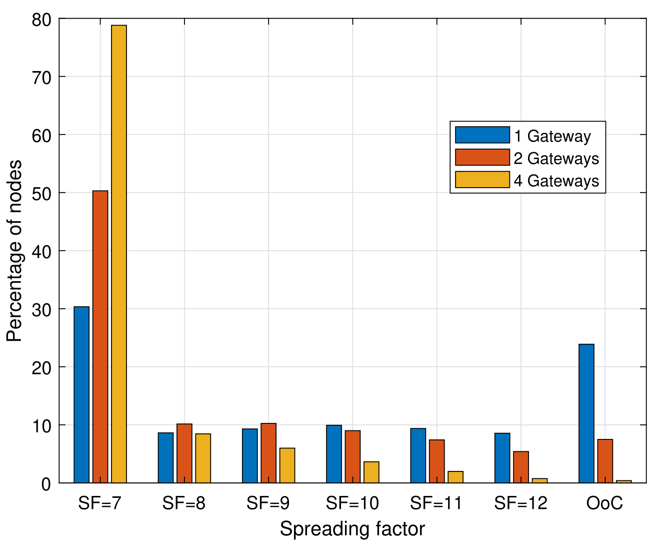

Fig. 6. Percentage of nodes at each SF for area side 10 km, LoRaWAN with Aloha Access, No capture effect.

4.2. Performance of LoRaWAN with Aloha access

We first evaluate LoRaWAN network performance with Aloha access scheme considering different area sizes on three scenarios with one, two, and four gateways. Next, we investigate the impact of increasing the area size on the distribution of nodes at different SFs. In addition, we study the impact of gateway densification taking into account the capture effect.

Fig. 6 illustrates the distribution of nodes among different SF for area side 10 km in three scenarios using Aloha access scheme without capture effect. On the one hand, it can be seen that in the case of one gateway, the percentage of out of coverage (OoC) nodes is equal to 25%. This high value decreases to 9% with two gateways and becomes negligible with 4 gateways. This shows the impact of gateway densification in solving the coverage problem in large areas. On the other hand, the percentage of nodes at SF 7 is equal to 30%, 50%, 78% in the case of one, two, and four gateways, respectively. Meanwhile, the distribution of nodes at other SFs is below 10% in all cases. The increase of node distribution at SF7 is mainly due to the best coverage and highest received power achieved when using multiple gateways. However, such distribution increases dramatically the number of collisions due to the large number of nodes transmitting using SF 7.

Fig. 7 shows the total packet delivery ratio in three scenarios with variable area sides considering the capture effect. The results show that for an area side between 2 and 4 km, the total packet delivery ratio is below 50% in all scenarios. This can be explained by the increase in the collision probability when a large majority of nodes transmits at SF 7, resulting in a significant degradation of the network performance. For an area side 4 and 6 km, the total packet delivery ratio is better when we use one gateway, since nodes are distributed over others SFs. For an area side 10 km, using 2 or 4 gateways have approximately the same impact on the total packet delivery ratio. For an area side greater than 10 km, using 4 gateways is more efficient. The impact of gateway densification and area side on the total throughput in aforementioned scenarios is also investigated as shown in Fig. 8. The results show that increasing area size up to 8 km and 10 km increases the throughput in case of one and 2 gateways, respectively. It can be also observed that for low area side, the throughput achieved in case of one gateway is higher than that of 2 and 4 gateways. This is to be expected as the higher number of gateways results in severe collision due to the increase of packets transmitted at same SF 7.

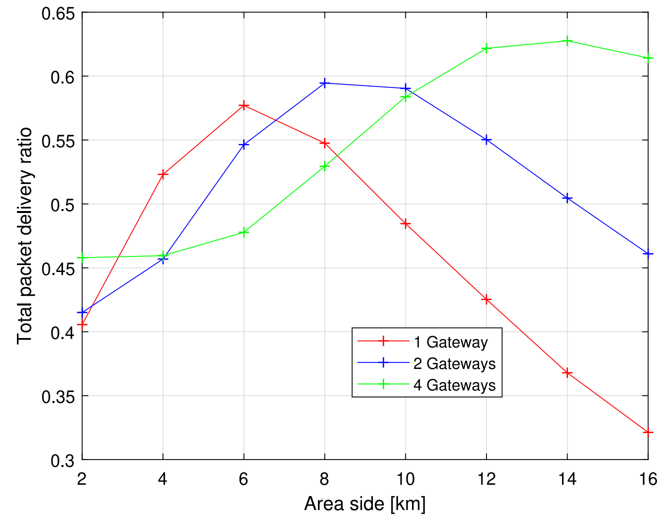

Fig. 7. Total packet delivery ratio of LoRaWAN with Aloha Access and capture effect.

In general, we can conclude from these results that while the gateway densification solves the coverage problem and increases the scalability of the network, it can severely reduce the total packet delivery ratio in some situations and decreases the throughput. This is where our algorithm improves the performance of a LoRaWAN deployment by distributing nodes in a optimized and adaptive way among SF in order to maximize the network reliability.

4.3. Fitting evaluation

In this section, we evaluate the accuracy of the fitting method used to approximate the expression $(1+P')$ according to Eq. (12). The values of a_s, b_s, c_s and d_s are found for given values of α, l and λ in three studied scenarios using least square fitting method. Then, these values are used to approximate $(1 + P')$ and to calculate an approximation of the total throughput in Eq. (10). A comparison of the approximate throughput and the theoretical throughput is depicted in Fig. 8 for Aloha access scheme with capture effect. The results reveal a perfect fit between the approximate and exact throughput curves with less that 0.05% difference. These results justify the efficiency and accuracy of using the curve fitting method to solve the optimization problem.

4.4. Performance of our proposed algorithm

In the following, the performance of our proposed algorithm without and with capture effect is evaluated and compared with legacy LoRaWAN and relevant algorithms from state-of-the-art.

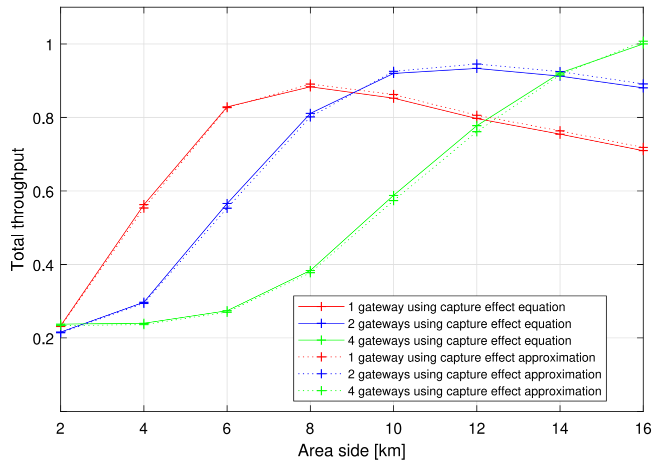

Fig. 8. Total throughput of LoRaWAN with Aloha Access and capture effect.

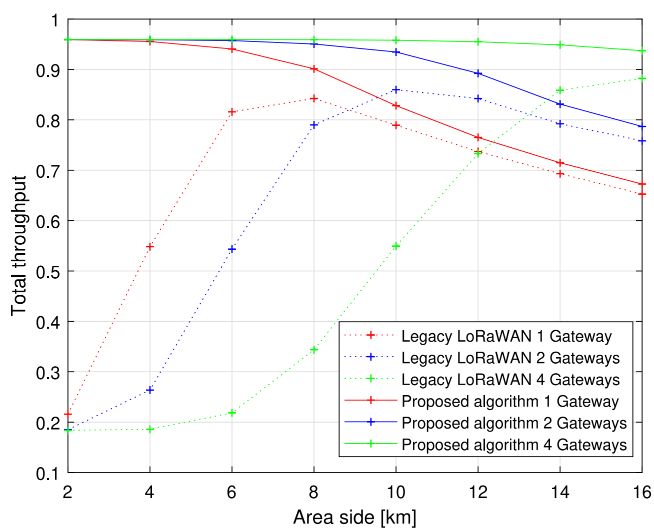

Fig. 9. Total throughput of proposed algorithm and legacy LoRaWAN without capture effect.

Fig. 9 illustrates the total throughput of our proposed algorithm and legacy LoRaWAN with one, two, and four gateways given various area sizes, without the capture effect. We can see that the proposed algorithm achieves higher total throughput in all cases compared to legacy LoRaWAN. More interestingly, the throughput is significantly improved for low area side where the collision problem is the most critical. For instance, the total throughput increases by about 80% (from 0.18 to 0.96) for an area size of 2 km in the 2 and 4 gateways scenarios, respectively. The reason of this improvement is the reduction of the collision resulted from the distribution of nodes in our proposed algorithm on available SFs, so that the throughput is maximized.

In Fig. 10 the packet delivery ratio of Legacy LoRaWAN and the proposed algorithm is compared in 4 gateways scenario given various area sizes, without considering the capture effect. The results indicate that the proposed algorithm achieves a significant improvement of total packet delivery ratio especially for area side below 10 km, e.g., for an area size of 2 km, the total packet delivery ratio is improved by more than 70% compared to legacy LoRaWAN.

Globally, we can see from these results the efficiency of our proposed algorithm for SF selection to mitigate the problem of collision, thereby improving the total throughput and the packet delivery ratio of LoRaWAN network. Provided that in realistic scenarios, the gateway may correctly receive a packet even if it collides with other ones, the

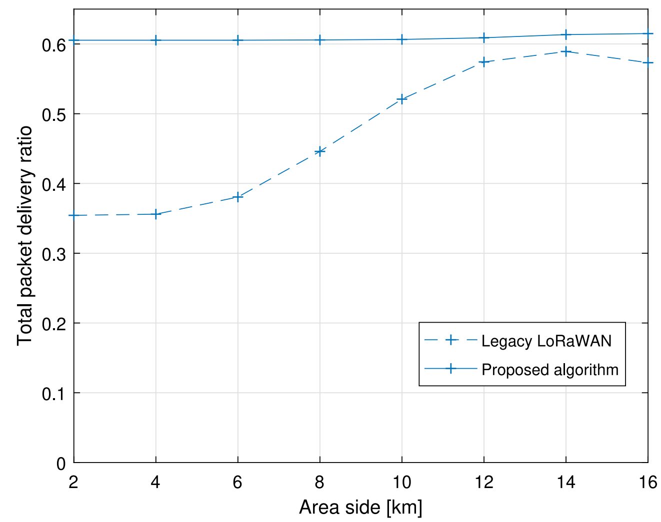

Fig. 10. Total packet delivery ratio of proposed algorithm and legacy LoRaWAN with 4 gateways, without capture effect.

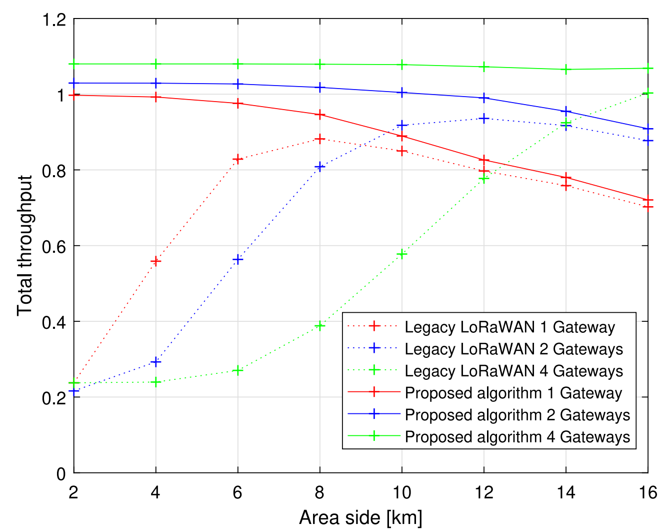

Fig. 11. Total throughput of proposed algorithm and legacy LoRaWAN with capture effect.

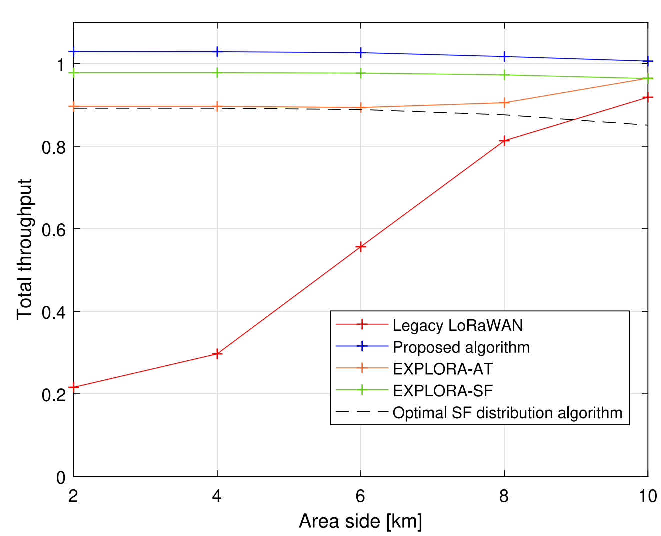

Fig. 12. Total throughput comparison in the case of 2 gateways with capture effect.

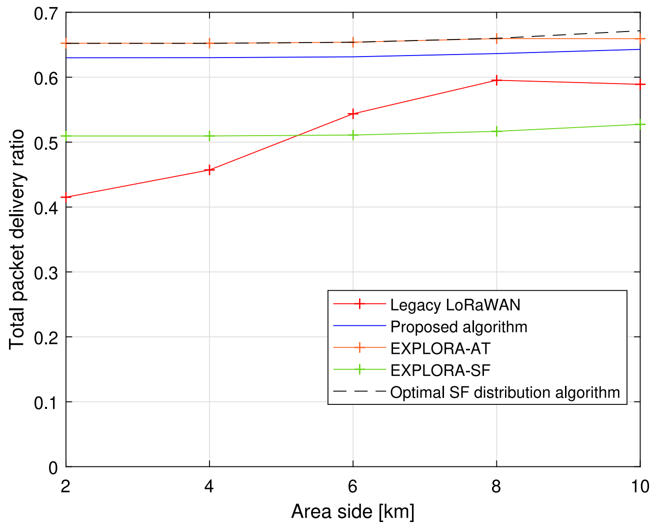

Fig. 13. Total packet delivery ratio comparison in the case of 2 gateways with capture effect.

performance of the proposed algorithm with capture effect is further evaluated. Fig. 11 shows the total throughput of the proposed algorithm considering the capture effect, given various area sizes. The results show similar behaviors as in the case presented earlier, where the total throughput is improved compared to legacy LoRaWAN. For an area side of 2 km, the improvement in all cases is about 80%. It is worth noting the impact of capture effect in achieving higher throughput compared to Fig. 9. For instance, in case 4 gateways, a throughput improvement of 12% is achieved. Moreover, it can be seen the benefit of using multiple gateways on improving network throughput. This is because the capture effect increases the probability of successful reception of collide packets and therefore increases the total throughput of the network. Figs. 12 and 13 present the total throughput and total packet delivery ratio comparisons between legacy LoRaWAN, our proposed algorithm and other proposed algorithms from the state-of-the-art namely, EXPLORA-SF, EXPLORA-AT [17] and optimal SF distribution algorithm [16], given 2 gateways scenario. It can be seen that our proposed algorithm achieves higher throughput compared to legacy LoRaWAN and other algorithms from the state-of-the-art, for all area sides. We notice also that for an area side of 10 km, Legacy LoRaWAN outperforms the optimal SF distribution algorithm. Meanwhile, the total throughput of EXPLORA-SF algorithm is higher than that of EXPLORA-AT. In Fig. 13, the results show that the proposed algorithm achieves higher packet delivery ratio compared to legacy LoRaWAN and EXPLORA-SF algorithm. However, EXPLORA-AT and optimal SF distribution algorithms slightly improve the total packet delivery ratio compared to our proposed algorithm, e.g 3.4% in a 2 gateway scenario at the expense of lower achieved throughput. For instance, the throughput improvement of the proposed algorithm is about 14% compared to optimal SF distribution EXPLORA-AT algorithms. The small degradation of packet delivery ratio is related to the objective function of the optimization problem that aims to maximize the throughput of the network by distributing nodes among different SFs. We can conclude that our proposed algorithm achieves a balanced distribution of nodes among different SFs which results in a best total throughput, and a good total packet delivery ratio.

5. Conclusion

In this paper, the impact of nodes scalability and gateways densification on the performance of LoRaWAN networks was first evaluated taking into account the capture effect. The results show that the densification of gateways increases the number of covered nodes and then the scalability of the network, but increases collisions in small areas. In order to reduce collision, an optimization problem that maximizes the network throughput was next proposed to calculate the optimal distribution of nodes over SFs. Based on this distribution, an adaptive SF algorithm was presented to adjust the SNR thresholds. Moreover, the performance of our proposed algorithm is evaluated and compared with legacy LoRaWaN and relevant algorithms from the state-of-the-art. Simulation results showed an improvement of total throughput and total packet delivery ratio compared to legacy LoRaWAN and other state-of-the-art algorithms. Going forward, others aspects such as power control and channel selection could be added to the proposed optimization problem in order to improve the performance of LoRaWAN network with multiple gateways.

CRediT authorship contribution statement

Ali Loubany: Conception and design of study, Acquisition of data, Writing Matlab code, Analysis and interpretation of data, Writing - original draft. **Samer Lahoud:** Conception and design of study, Analysis and interpretation of data, Writing - review & editing. **Rida El Chall:** Conception and design of study, Analysis and interpretation of data, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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