Downlink Spreading Factor Selection in LoRaWAN

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Abstract

LoRaWAN is one of the most commonly used Internet of Things protocols for applications that require low cost, low power, and long range communications. It has been proved that – mainly due to regional radio duty cycle restrictions – the protocol does not scale well in presence of confirmed (downlink) traffic. To support downlink traffic, LoRaWAN employs two receive windows, RX1 and RX2, whereas a number of channels are assigned to each of those windows. The protocol uses a fixed Spreading Factor (SF) – a LoRa PHY modulation parameter – in RX2, while the SF of the uplink is employed in RX1. Since the SF of RX1 cannot be changed, selecting a low or a high value of SF in RX2 is of critical importance for the duty cycle resources of the gateways. On one hand, selecting high SF values, the time resources of the gateways may get depleted fast leading to low capacity because the transmission time increases with higher SF values. On the other hand, lower SF values reduce reachability due to the worse sensitivity which causes retransmissions, and thus, lower capacity. In this paper, a study of the total theoretical downlink capacity is provided giving useful insights of the protocol behavior as the number of uplinks increases, especially for congested network scenarios. An exhaustive SF selection solution is also presented to compute the maximum downlink capacity. It is shown that the RX2 SF which provides the best capacity may imply fairness compromises for part of the devices. Extensive simulations are employed to confirm the theoretical findings in scenarios with a single and multiple gateways. Experiments conducted on a test-bed for selected scenarios also confirm the theoretical findings.

Keywords: Internet of Things, LoRa, LoRaWAN, Downlink, Capacity, Fairness, Testbed, Simulations

1. Introduction

LoRaWAN stands as a prominent protocol within the realm of Low-Power Wide Area Networks (LPWANs) in the Internet of Things (IoT) domain. It constitutes an open standard devised by the LoRa Alliance, facilitating seamless communication between devices equipped with LoRa technology and servers. Its applications span various domains, including asset tracking, smart agriculture, and environmental monitoring [1].

LoRa utilizes a proprietary spread spectrum modulation technique, renowned for its impressive reach (exceeding 10 km in line-of-sight scenarios) and exceptional resistance to interference from other technologies and Doppler effects. Its key attribute lies in its ability to balance data rate and sensitivity by adjusting a modulation parameter known as the SF. A higher SF results in longer range (greater sensitivity) but slower data transmission. In the sub-GHz ISM spectrum, SF typically ranges from 7 to 12.

LoRa serves as the physical layer for LoRaWAN, which, in turn, furnishes the requisite mechanisms at the MAC (Medium Access Control) and link layers. These mechanisms support network registration, data encryption, acknowledgments, localization, and other services for a group of end-devices. The LoRaWAN architecture comprises three layers: end-devices (EDs), gateways (GWs), and back-end servers. For simplicity, the individual servers (Network Server, Join Server, and Application Server) are collectively referred to as the Network Server (NS). EDs can transmit their data to the NS via one or more GWs within their communication range (uplinks). Subsequently, the NS can send acknowledgments and network commands to the EDs through the GWs (downlinks). An acknowledgment is dispatched only if the ED specifically requests it during the corresponding uplink. Communication between the GWs and EDs employs LoRaWAN, while communication between the GWs and NS employs non-LoRaWAN networks.

LoRa-enabled commercial devices must adhere to strict radio duty cycle regulations within the sub-GHz ISM spectrum, as stipulated by local spectrum authorities. In regions like Europe, the spectrum is divided into bands, each further segmented into channels. Most bands impose a total duty cycle of 1

LoRaWAN classifies EDs into three modes of operation: Class A, B, and C [2]. Class A caters to energy-constrained devices that only power on when transmitting or receiving data. The MAC layer for Class A operates on an Aloha-based protocol, meaning that transmissions occur without employing collision avoidance mechanisms. Class B utilizes synchronization beacons generated

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by gateways to enable multiple EDs to open receive windows at specified times. Lastly, Class C presumes that end-devices have a constant radio presence, implying unlimited power resources. Class A is the most prevalent mode in LoRaWAN, while Class B and C are typically used for over-the-air firmware updates.

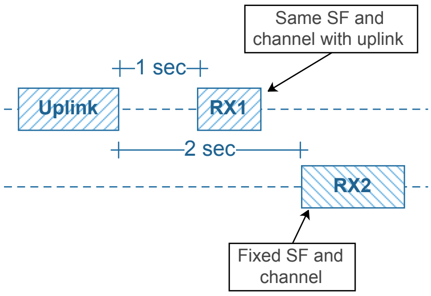

Figure 1: Default downlink scheme after an uplink transmission in Class A.

As depicted in Figure 1, in Class A mode of operation, the devices open one or two receive windows (i.e., RX1 and RX2) to receive an acknowledgment by a gateway after a confirmed uplink transmission. These windows open one and two seconds after the uplink transmission (default values). RX2 opens only if the device does not receive the acknowledgment in RX1. The SF and the channel in RX1 is the same with the uplink transmission while in RX2 both these settings are fixed. Uplink transmissions (at least in the EU868 spectrum) use bands with 1% radio duty cycle while a single 10% duty cycle channel is used for RX2. Successive transmissions of the same device are performed over a different channel, so the RX1 channel varies over time while RX2 remains always fixed.

It is known in the research community that downlink performance heavily worsens uplink performance of LoRaWAN. The GWs run out of time resources very quickly in presence of confirmed traffic, leading to non-acknowledged transmissions and, thus, to retransmissions which increase the number of collisions in the uplink. The proper selection of the RX2 SF plays a critical role for the network performance because it affects the amount of available time resources of the GWs. On one hand, a high RX2 SF value (e.g., the default one of SF12) causes a high increase in the packet airtime and, thus, it diminishes quickly the time resources that each gateway has available within an hour, leading to a low downlink capacity. On the other hand, a low RX2 SF value may lead to under-utilization of the RX2 channel (i.e., low capacity) because of the low number of EDs that are able to reach a GW. EDs that cannot reach the GWs with such a low SF have less chances to get an acknowledgement which leads to retransmissions and more traffic in the network. Hence, it is important to find a SF value for RX2 that balances underutilization and extensive use resources.

To this extent, the contributions of this paper are summarized as follows:

- A model for the LoRaWAN downlink capacity based on the most common frequency plan in the sub-GHz ISM spectrum is provided.
- An algorithm to calculate the theoretically best SF in RX2 that maximizes the total capacity given a number of uplinks is also introduced.
- It is shown theoretically (and confirmed by simulations and experiments) that the best SF in terms of capacity may lead to unfairness issues among EDs.

2. Related Research

Due to the high number of LoRa and LoRaWAN configuration parameters, a lot of research effort has been devoted to find good parameter settings or to discover their effect on the behavior of the protocol. Typical examples of such studies are the ones mentioned below.

In one of the first studies, Bor and Utz [3] stress that there are 6720 possible transmission parameter combinations and study the effect of some of them on the LoRa link performance. Nevertheless, only a few of those combinations can be used in LoRaWAN, such as combinations between the SF, the transmit power, and the coding rate. The vast majority of the rest of the studies deal with the Adaptive Data Rate (ADR) mechanism of LoRaWAN. ADR mechanism controls two LoRa transmission settings after registration: the data rate (thus the SF) and the transmit power. Since the purpose of the ADR is to use the most reliable settings that lead to the least energy consumption – even though those setting may not imply perfect reliability configurations – many researchers have come with their own proposal to achieve better capacity (i.e., less collisions) even if sometimes the energy consumption has to be compromised. The reader may refer to the following publications about transmit power and SF configuration settings [4, 5, 6, 7, 8]. Machine learning approaches have been employed as well to find optimal configuration settings between the uplink SF, the coding rate, and the transmit power [9, 10].

As regards to the downlink performance of LoRaWAN, many studies have confirmed the negative effect of confirmed traffic on the uplink performance and proposed solutions that mitigate the problem. The reader may also refer to recent surveys on the topic [11, 12, 13]. In some of these studies, the authors observed that the major problem is that many downlink packets cannot be transmitted in the first or second receive window due to the duty cycle restrictions [14, 15]. As a consequence, this large number of non-acknowledged packets causes re-transmissions and extra load to the network. To this extent, re-transmission attempts should be adaptive and according to the application requirement [16]. Mikhaylov et al. [17] stress that, besides the aforementioned effect, the downlink traffic compromises the performance of uplink due to interference between uplink and downlink on the same channel in RX1.

However, due to the fixed number of bands and channels in the current frequency plans of the providers, the downlink capacity cannot go beyond a limit [13]. To that extend, how additional channels can improve the performance by considering a new radio band with 10% duty cycle dedicated to downlink traffic to increase the total capacity in the EU868 spectrum is investigated [18].

Despite its high effect on the downlink performance of the protocol, the RX2 SF selection problem has not been studied in any of the aforementioned works. All these works consider the protocol's default value (i.e., SF12) or the TTN[1] setting for EU868 (i.e., SF9) without investigating the effect on the performance in terms of capacity, energy consumption, and fairness.

3. Spreading Factor Selection in RX2

In this section, we model the downlink capacity problem in LoRaWAN given a number of uplinks U and one gateway. The model is then extended to multiple gateways. For the sake of simplicity, the analysis is based on the uniform deployment of EDs but it can be adapted to any other node distribution model as well.

3.1. SF selection and Capacity

Let us denote with N the maximum total number of transmissions in RX1 and RX2 in T period of time, where $T \geq 3600$s. We denote with N_1 the number of transmissions in RX1, and with N_2 the number of transmissions in RX2. Assuming a TTN network operating at the EU868 spectrum, with 8 uplink channels spread in 2 bands with 1% duty cycle each, and 1 downlink channel with 10% duty cycle, the total available downlink time C in T is calculated as follows:

$$C = C_1 + C_2 = \frac{1+1}{100}T + \frac{10}{100}T, \qquad (1)$$

where C_1 and C_2 are the time resources in RX1 and RX2, respectively.

The total transmission time M that $N_1 + N_2$ downlink transmissions occupy in T can be calculated as follows:

$$M = N_1 \sum_{i=1}^{N_1} \frac{t_i^{SF_i}}{N_1} + N_2 t_i^{RX2SF}, \qquad (2)$$

where SF_i is the SF used in RX1's i-th transmission, $RX2SF$ is the SF of RX2, and t_i is the transmission time (i.e., airtime) of a transmission i for a given SF. The airtime is calculated as follows [19]:

$$\tau_i = (n_p + 4.25)\frac{2^{SF_i}}{BW} + \left(8 + \max(\lceil \tfrac{8PL - 4SF_i + 28 + 16 - 10H}{4(SF_i - 2DE)} \rceil (CR+4), 0)\right)\frac{2^{SF_i}}{BW}, \qquad (3)$$

where n_p represents the count of programmed preamble symbols, BW denotes the channel bandwidth, CR signifies the coding rate, PL stands for the packet payload, and H takes on a value of 0 when the header is enabled, and 1 when there is no header present. Additionally, DE equals 1 when the low data rate optimization is activated, and 0 when it is disabled.

It is important to highlight that EDs typically refrain from altering the CR setting (usually set to the default value of 1) due to the extended airtime associated with higher values. Furthermore, the channel bandwidth remains constant (typically 125 kHz in EU868, except for SF7 with a channel bandwidth of 250 kHz, which is seldom used in practical scenarios[2]).

Because $M \leq C$, given Eq.(1, 2), it holds that:

$$\sum_{i=1}^{N_1} t_i^{SF_i} + (N - N_1)t_i^{RX2SF} \leq \frac{12}{100}T. \qquad (4)$$

It also holds for each receive window and band that:

$$\sum_{i=1}^{N_{1A}} t_i^{SF_i} \leq \frac{1}{100}T, \qquad (5)$$

$$\sum_{i=1}^{N_{1B}} t_i^{SF_i} \leq \frac{1}{100}T, \text{ and} \qquad (6)$$

$$N_2 t_i^{RX2SF} \leq \frac{10}{100}T, \qquad (7)$$

where N_{1A} and N_{1B} are the number of transmissions for the channels that belong to the first and the second available band, respectively. Since the selection of the channel is random, we can assume that $N_{1A} = N_{1B}$, so Eq.(5) and (6) can be combined as follows:

$$\sum_{i=1}^{N_1} t_i^{SF_i} \leq \frac{2}{100}T. \qquad (8)$$

From Eq.(7) and (8), it is easy to understand that the higher the average SF in RX1 and the higher the SF in RX2, the less transmissions can be accommodated in either of these windows for some T. Since the average SF in RX1 cannot be controlled (it depends on deployment characteristics and the ADR mechanism), N_1 is fixed and upper bounded by $\lfloor C_1 / t_{SF_{avg}} \rfloor$, where SF_{avg} is the average SF of the transmissions. If an equal number of transmissions per ED is generated, SF_{avg} can be easily calculated based on the distribution of the EDs in the field. If the EDs transmit packets with a different rate, the distribution of SFs in that rate is required to calculate SF_{avg}. Nevertheless, the NS can learn this information assuming that not many EDs join and leave the network in T.

Having N_1 fixed, the total possible accommodated number of downlink transmissions is maximized by minimizing

[1]The Things Network (TTN), https://www.thethingsnetwork.org/, is the largest global LoRaWAN network.

[2]refer to https://www.thethingsnetwork.org/docs/lorawan/frequency-plans/

t^{RX2SF}. However, the higher the $RX2SF$ value, the more EDs can be reached in RX2 (i.e., higher N_2) but the less the achievable capacity because of the higher t^{RX2SF}. The opposite holds, when $RX2SF$ is low: the lower the reachability caused by selecting low $RX2SF$ values, the higher the number of transmissions that cannot be acknowledged in RX2.

Algorithm 1: Exhaustive RX2SF selection.

```
input: C_2, CR, PL, BW, U
maxN_2 ← 0;
RX2SF ← 0;
for N_2 = 1; N_2 ≤ U; N_2 += 1 do
    for SF = 7; SF < 13; SF+ = 1 do
        t_SF = airtime(SF, CR, PL, BW);
        perc = sfperc(SF);
        if t_SF · ⌊N_2 · perc⌋ > C_2 then
            continue;
        end
        if t_SF · ⌊N_2 · perc⌋ > maxN_2 then
            maxN_2 ← t_SF · ⌊N_2 · perc⌋;
            RX2SF ← SF;
        end
    end
end
return (maxN_2, RX2SF);
```

Let us denote with γ the percentage of uplinks that cannot be served in RX2 because of the low reachability (γ=0 when $RX2SF$=12). Let us also consider the scenario of Figure 2 consisting of an increasing number of uplinks U [3] initiated by uniformly distributed EDs. Given the number of uplinks, we are interested in maximizing the number of acknowledged transmissions selecting the best $RX2SF$ value without violating Eq. (7).

Algorithm 1 is used to select the theoretically best $RX2SF$ value by maximizing the RX2 capacity (i.e., N_2). The algorithm uses exhaustive search by evaluating all possible SFs with a gradually increasing number of uplinks. It also makes use of `sfperc()`, a function that computes the percentage of transmissions that correspond to a given SF according to the distribution model of the EDs. For example, assuming equal number of transmissions per ED, `sfperc` can be easily calculated as a function of the area that each SF ring covers given the distributions of the EDs on the plane. In that case, the number of EDs per SF is $\frac{A_f}{A}N$ for any f in [7..12], where A_f is the area of the SF ring and A all the area as it is defined by the SF12 range (see [18] for more details). The function can be changed accordingly for other ED distributions on the plane that affect the average uplink SF. The worst case

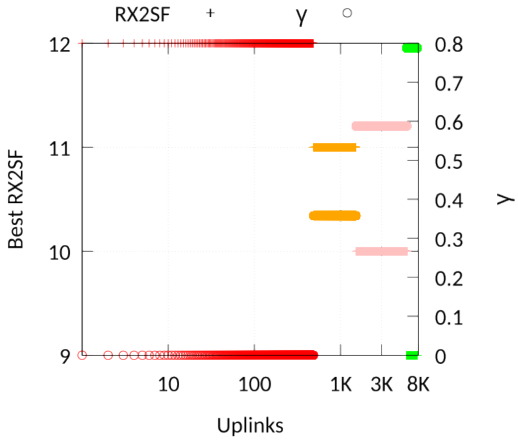

Figure 2: Best RX2SF and γ values for an increasing number of uplinks. γ is the percentage of uplinks that cannot be acknowledged in RX2. Results based on simulation settings of Section 4 with T=3600sec. (A raster version of the figure is presented to avoid slow rendering times due to the massive number of points).

runtime appears when SF=7 so the complexity bounded by $6\lceil\frac{C_2}{airtime(7,CR,PL,BW)}\rceil$, where `airtime()` is given by Eq. (3) for a given coding rate, a payload (PL), and a channel bandwidth. The downlink header in LoRaWAN is limited to 13 Bytes (EU868) unless MAC commands are included which may vary from 7 to 15 bytes. So the total number of bytes can reach 28. This means that considering again the worst case scenario, the total number of iterations is upper bounded by $\frac{6C_2}{0.482667}$ where 0.482667s is the minimum possible downlink airtime.

Coming back to the scenario of Figure 2, we can observe that as the number of confirmed uplinks is getting higher (e.g., by an increasing number of EDs), the best SF in RX2 is decreasing. The opposite holds for γ. This happens because as more uplinks are added in, the network becomes more saturated, thus, a lower $RX2SF$ is selected to increase the number of acknowledged transmissions (due to the lower airtime) even though non-acknowledged uplinks due to the non-reachability increase at the same time. Because only a subset of the uplink transmissions can be acknowledged in RX2 (i.e., those with uplink SF less than or equal to $RX2SF$[4]), the percentage of transmissions that cannot be served in RX2 will be retransmitted in the near future causing additional load to the system. This means that, in a saturated network, a large number of non-acknowledged transmissions are accumulated over time – up to some extent due to the max allowed number of retransmissions – causing reduced delivery ratio and low fairness. The higher the value of γ, the lower the fairness, because of the lower probability of an uplink with SF higher than $RX2SF$ to be acknowledged. Indeed, an uplink with SF lower than or equal to $RX2SF$ can be acknowledged in either RX1 or RX2 but an uplink with SF

[3]Note that the maximum capacity (i.e., total airtime) of decoded uplinks cannot exceed $T-C_1-C_2$. So the maximum possible number of decoded uplinks U_{max} is $\lfloor\frac{T-C_1-C_2}{\text{avg\_uplink\_airtime}}\rfloor$. avg_uplink_airtime can easily be calculated if all EDs transmit data with the same rate or it can be estimated based on past session experience.

[4]assuming link symmetry, otherwise EDs with uplink SFs $RX2SF+1$ may be reached as well

higher than $RX2SF$ can be acknowledged only in RX1. The fact that RX2 has 5 times the downlink resources of RX1 causes a huge fairness gap between the two aforementioned types of uplinks.

3.2. The case of multiple gateways

In the case of multiple gateways, we need to distinguish two sub-cases; multiple GWs deployment at one position and at multiple positions. It is very common among network providers to deploy multiple GWs at one position (e.g., at the roof of a building) to limit the deployment and maintenance costs but also deal with the half-duplex nature of LoRa transceivers[5]. In this case, the model does not change considerably because the average uplink SF remains the same. For instance, Eq.(1) which expresses the maximum downlink capacity can be written as kC, where k is the number of deployed GWs.

The sub-case where the GWs are deployed at different positions is more complicated because not all EDs can reach the same number of GWs, thus, cannot share the same capacity. Nevertheless, this sub-case is much more efficient in terms of performance because it considerably reduces the average SF in the network. This is translated to a higher number of uplinks that can be decoded by all GWs (i.e., U_{max}), but also to a lower average airtime in RX1, thus, to a higher capacity in RX1. The maximum downlink capacity can be written as $k_{avg}C_1 + k'_{avg}$, where k_{avg} and k'_{avg} is the average number of GWs that each ED can reach in RX1 and RX2, respectively. However, the coordinates of the EDs must be either known to compute k_{avg} which cannot happen in reality or estimations can be made based on previous experience.

In both sub-cases, the overall capacity is proportional to the number of GWs so the same behavior with a single GW is expected in terms of downlink capacity and fairness. The simulations presented in the next section confirm this statement.

4. Evaluation & Discussion of the Results

In this section, a series of simulations and experiments are conducted to confirm the theoretical findings of Section 3. The findings that are evaluated and confirmed are (a) the trade-off between RX2 SF and reachability (i.e., fairness) as $RX2SF$ decreases, (b) the best SF value for RX2, and (c) the same findings for multiple gateways.

For this purpose, we employed the LoRaWAN-SIM simulator[6], a tool that has seen recent use in various research papers. The simulation results are categorized into three subsections, each dedicated to one of the specific findings mentioned earlier.

Table 1: Simulation Parameters

Parameter	Value
Simulation time	10000s
End-Devices / Distribution	10 – 1000 / Uniform
Gateways	1 and 3
Terrain radius	1500m (1 GW) or 2500m (3 GWs)
EDs/GWs position	Random
Spreading Factors	7 – 12
Channel bandwidth	125 KHz
Preamble symbols	8
Coding Rate	4/5
SFs for RX 1/2	SF7–12 ADR-based / SF7–12 fixed
Uplink/Downlink channels	8 / 8+1 (TTN EU868)
Payload size	Randomly selected [SF7-8:222, SF9:115, SF10-12:51] Bytes [21] (overall average $\approx$ 40 Bytes)
Path loss model	$\overline{L_{pl}}(d_0) = 110$dBm, $d_0 = 40$m, $\gamma = 2.08$, $\sigma_{dBm} = 3.57$
Receiver sensitivities	Typical Semtech SX1276
Tx power	2, 7, 14 dBm (ADR adjustable)
Max current consumption (Tx, Rx, Idle, Sleep)	75, 45, 30, 0 mA
Voltage	3.3 V
Packet rate	1pkt every [2..15min] randomly selected with Gaussian mean $\simeq$5min
Retransmissions	8

In the initial subsection, we present the Packet Delivery Ratio (PDR), energy consumption, and downlink unfairness, all of which vary with the number of EDs. PDR is defined as the ratio between the number of acknowledged packets and the total number of uniquely transmitted packets. Note that packets successfully delivered to the NS without acknowledgment or where the acknowledgment is not received by the ED are not counted in the PDR. Packets are considered dropped if the corresponding uplinks fail to receive acknowledgment after a maximum number of retransmissions. Energy consumption is assessed by considering the transmission, reception, and idle power usage over time.

Unfairness, on the other hand, is characterized as the standard deviation of the actual ratio between the number of successfully acknowledged packets and the number of uplink packets received by the NS. The greater the deviation of an ED's ratio from the average ratio across all EDs, the higher the unfairness associated with that particular ED.

We have chosen a specific range for the ED population to provide clarity regarding the behavior of the $RX2SF$ selection. All the results presented in the figures are the averages of 50 runs, each with different ED and GW positions. We have also included 95% confidence intervals in each figure. It is worth noting that the SF and transmit power of the EDs are adjusted using the ADR mechanism following the initial transmission.

For a comprehensive overview of our simulation parameters and settings, please refer to Table 1.

[5] For example, using a 16-channel concentrator such as the Kerlink iBST [20]

[6] https://github.com/deltazita/LoRaWAN-SIM (v2022.10.4)

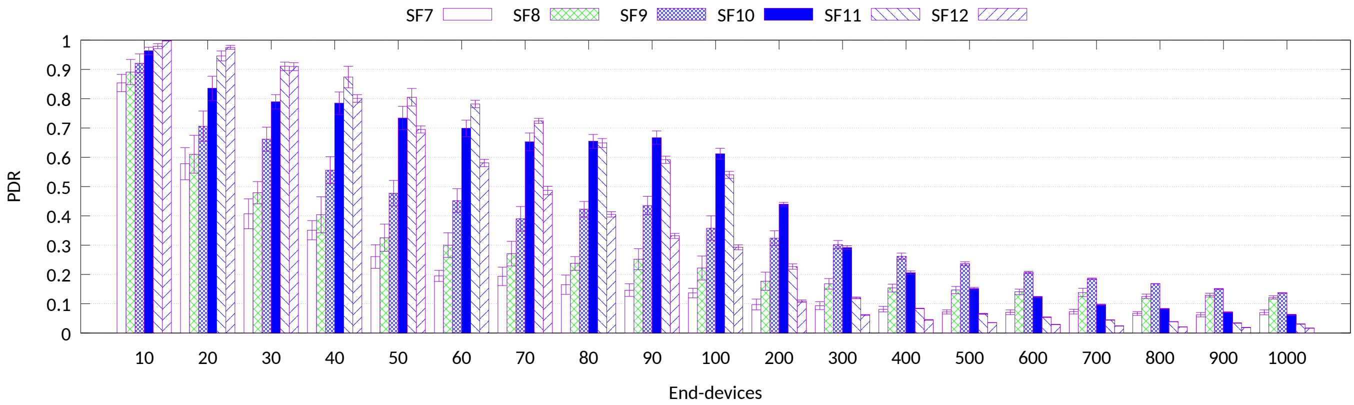

Figure 3: Packet Delivery Ratio for variable number of EDs.

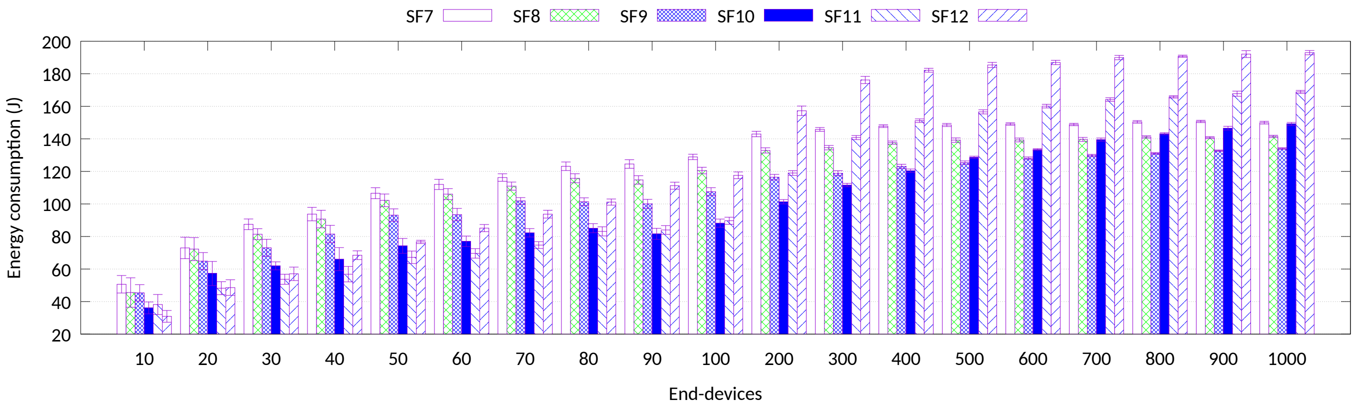

Figure 4: Energy consumption for variable number of EDs.

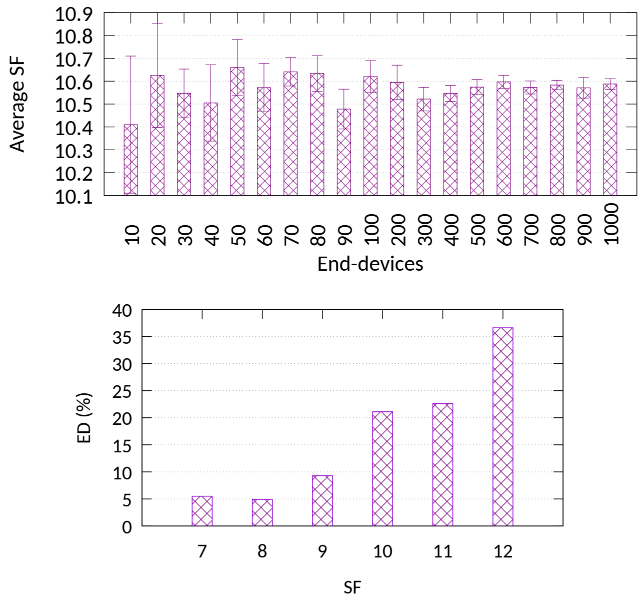

Figure 5: Average SF among all EDs (upper) and indicative SF distribution (lower).

4.1. Packet delivery ratio, Energy consumption, and Fairness

Figure 3 presents the PDR for a scenario with variable number of EDs and all available RX2 SFs. The average uplink SF in this scenario is 10.5 (regardless the number of EDs – see Figure 5). A number of interesting observations can be made as follows. First of all, it is straightforward that the best value of SF decreases with more congested networks. SF12 is the best option for a very low number of EDs (thus, low traffic) but the best SF gradually converges to the value of 9. The same behavior was captured by the theoretical model. In terms of energy consumption (see Figure 4), high SFs present the best performance for low traffic scenarios because they cause less retransmissions. The opposite holds for low SFs because of the large γ values.

Finally, as it can be observed from Figure 6, higher SFs provide the best fairness while the opposite holds for low SFs. As it was stressed in the theoretical analysis, low SFs cause a high number of non-acknowledged uplinks in RX2, reducing the overall chances those uplinks have to get acknowledged in one of the two receive windows. SF12 gives the best result at the expense of a much higher energy consumption and lower reliability in presence of high traffic. SF9 and 10 exhibit a good balance between energy consumption, fairness, and high PDR.

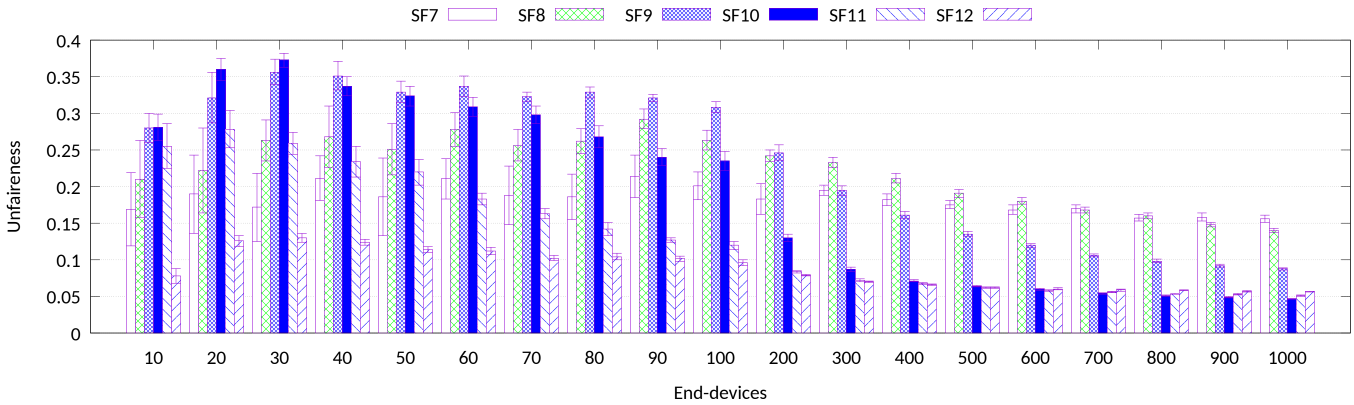

Figure 6: Unfairness for variable number of EDs.

Table 2: Experiments settings

Parameter	Value
Experiment time	2h
End-Devices	10 (TTGO SX1276)
Gateways	1
EDs position	Stationary (Randomly selected)
Spreading Factor per ED	7x1, 8x2, 9x2, 10x2, 11x2, 12x1
Channel bandwidth	125 KHz
Preamble symbols	8
Coding Rate	4/5
SFs for RX 1/2	SF7–12 / SF7, 9, 12
Uplink/Downlink channels	1 / 1+1
Payload size	50 Bytes
Tx power	14 dBm
Packet rate	1pkt every [30, 60, 120]s
Retransmissions	1

4.2. *Best SF for a given number of EDs*

Figure 7 exhibits the comparison between the best RX2 SF value as this was computed by the model and the best value derived by simulations. The results show that there is a quite good consensus between the model and the simulations. Excluding the case of 70 EDs, there is only one unit difference which can be justified by the slightly lower achievable capacity in simulations due to the downlink and uplink collisions in RX1 [17]. This is not the case for high traffic scenarios because the total number of uplinks exceeds the maximum possible (i.e., $Cup > T - C_1 - C_2$), so U_{max} is used as an input in the algorithm.

4.3. *Multiple gateways*

In the last set of simulations, a scenario with 3 GWs is examined. The positions of the GWs are random and the average uplink SF is 9.1, a much lower SF-scenario compared to the previous single GW case. As we can see from Figure 8, the behavior of the best RX2 SF is the same as with the single GW scenario. The two cases differ only in absolute values because of the higher downlink capacity and the lower average uplink SF. As we can observe from the bottom figure, fairness follows the same trend as well.

Table 3: Packet Delivery Ratio and Unfairness for different RX2 SFs and packet intervals (s).

Packet	**PDR**			**Unfairness**			**Model's**	**Exp.**
Interval	**7**	**9**	**12**	**7**	**9**	**12**	**Best SF**	**PDR**
120	0.36	0.66	**0.87**	0.24	0.329	0.056	12	0.87
60	0.26	0.57	**0.61**	0.262	0.381	0.089	11	0.78
30	0.19	**0.51**	0.44	0.269	0.299	0.065	10	0.58

4.4. *Testbed experiments*

A testbed consisting of 1 gateway and 10 EDs, as the one presented in Figure 10, was employed [22]. Due to the low number of devices a duty cycle higher than 1% and a single uplink channel were used in order to generate more traffic, and thus, emulate the presence of a higher number of devices in the network. The average uplink SF in the network was 9.5 and the average RSS was -91 dBm. Due to the enormous amount of time required to run all combinations of SFs, three RX2 SFs (7, 9, and 12) and three packet rates (1 packet every 120, 60, and 30 seconds) were selected. Each scenario was repeated 10 times and the average results in terms of PDR and unfairness are presented. The average standard deviation of the PDR among all measurements was only 0.045. The rest of the settings used in the experiments are summarized in Table 2.

Table 3 presents the experiments' results. As it can be observed, as more traffic is generated, SF9 gradually gives better results in terms of PDR compared to the other two SFs. However, SF12 always exhibits the best fairness. These results confirm the theoretical and simulation findings presented in the previous subsections. Moreover, the last two columns of the table indicate the model's best RX2 SF (the one that provides the best capacity) and the corresponding PDR as it was measured by the experiments with that SF. The results coincide with the theoretical values because (a) for a packet interval of 120 seconds, the theoretical best RX2 SF was 12, the same as with the experiment results since SF11 exhibited a PDR of 0.78; (b) for a packet interval of 60 seconds, the model's best SF was 11 while the experiments gave a PDR of 0.61 with SF12 and a PDR of 0.71 with SF10; and finally, (c) with a

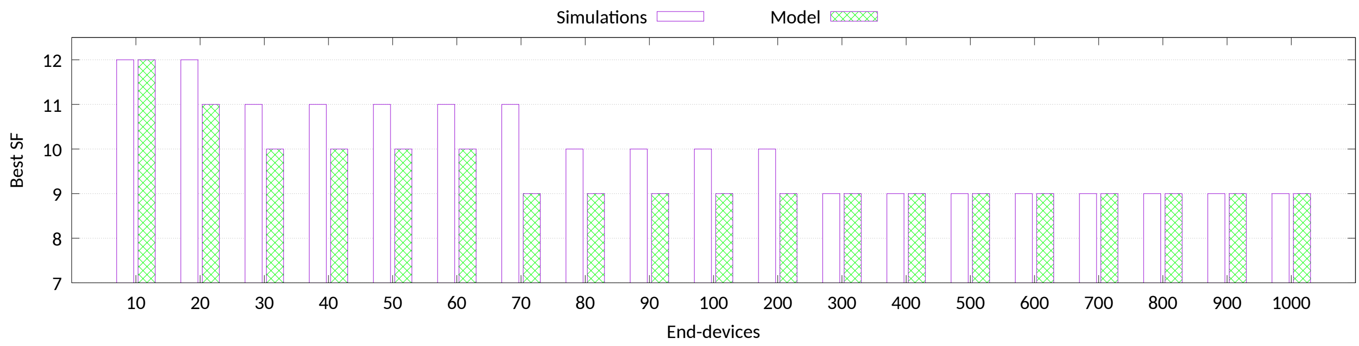

Figure 7: Model's best and best simulated RX2 SF for variable number of EDs.

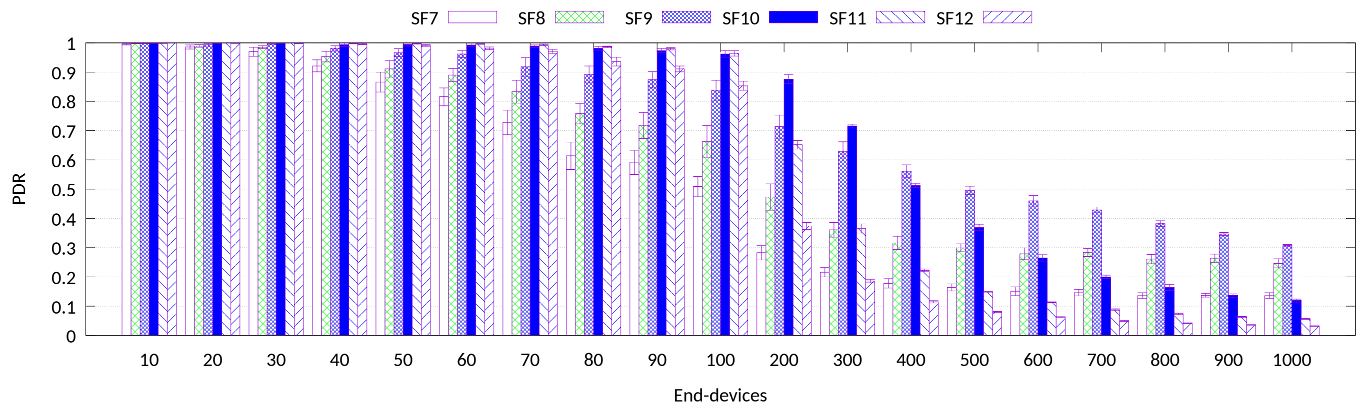

Figure 8: [3 gateways] Packet Delivery Ratio for variable number of EDs.

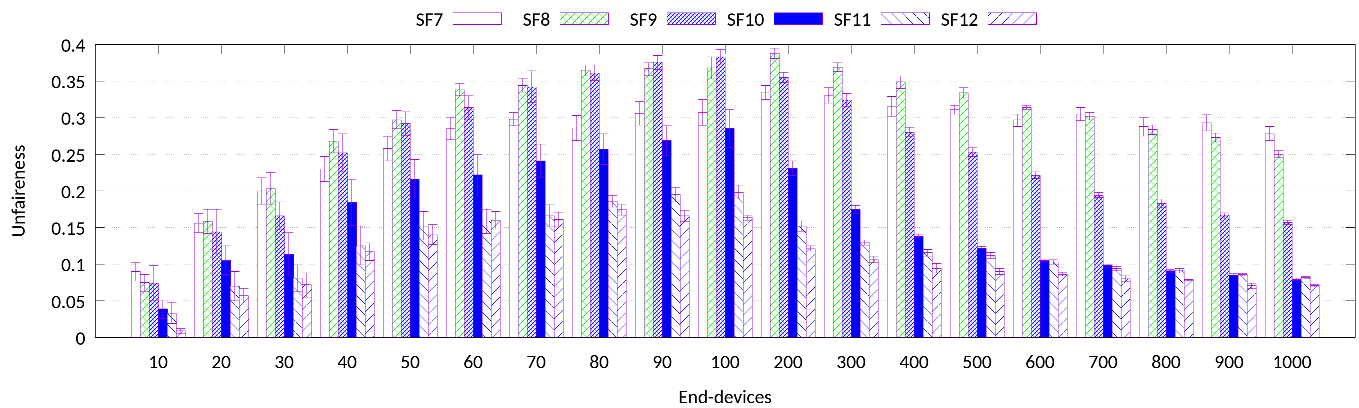

Figure 9: [3 gateways] Unfairness for variable number of EDs (the lower, the better).

Figure 10: Custom built of a TTGO SX1276 LoRa end-device.

packet interval of 30 seconds, the model's best SF was 10, while the experiments achieved a PDR of 0.51 with SF9, 0.57 with SF10, and 0.47 with SF11.

5. Conclusion & Future Work

The effect of RX2 SF on the network performance as well as the setting that theoretically maximizes the downlink capacity have been discussed in this paper. It has been found theoretically and confirmed through simulations that as the network gets more congested, the best found RX2 SF value decreases. It is also shown that lower RX2 SFs gradually increase the number of non-acknowledged packets and lead to a fairness problem. The discussion has been extended to the scenario of multiple gateways where the same behavior has been observed. The findings of this paper can be used by network providers to improve their networks downlink performance.

The effect of the maximum retransmissions and the presence of non-confirmed traffic on the selection of the RX2 SF will be studied in the future. Moreover, the joint optimization problem of finding the optimal number of gateways and the RX2 SF to achieve a certain capacity level will be examined.

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