# A Self-organized Adaptation of Spreading Factor for LoRa Radio Layer Based on Experimental Study

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**Abstract.** LoRa technology provides low power, long range and low data rate communication solution for sensor nodes on Internet of the Things (IoT) applications. In this work, we study experimentally the performance of LoRa radio for a device-to-device communication with different spreading factors. A measurement campaign is carried out under different scenarios such as outdoor, indoor, different altitudes, and different distances. In all scenarios, we measure Packet Delivery Ratio (PDR) and Signal to Noise Ratio (SNR). The results show that the distance between a transmitter and a receiver is not the only effective parameter determining the SNR but also environmental conditions and the altitude of a receiver impact on the SNR. We show also that the PDR depends on the applied spreading factor. Besides, we derive a mapping between the SNR to a proper spreading factor of the LoRa radio for different PDR requirements using our empirical results. Applying this mapping, we propose a self-organized algorithm that adapts the spreading factor in LoRa radio to achieve a required PDR. The results show that the proposed adaptive scheme adapts the LoRa radio to provide a given 80% PDR requirement between two LoRa nodes.

**Keywords:** LoRa nodes · Arduino · Self-organization · Experimental study

## 1 Introduction

LoRa is a technology developed for low power wide area networks. It can be applied mainly in Internet of the Things (IoT) such as smart homes, intelligent transportation systems [1], UAV based networks [2,3], or sensor networks. A LoRa network consists of LoRa devices that work based on the specifications of the physical layer which were patented by Semtech Corporation [4] and the MAC layer of LoRaWAN protocol [5].

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This experimental study focuses only on the LoRa physical layer. The LoRa physical layer uses the frequency range of 902–928 MHz in the United States, 863–870 MHz in Europe and the ISM band of 433 MHz and 169 MHz [4]. Its coverage rage is from 10 to 15 km in rural areas and up to 5 km in urban areas [6]. The radio modulation scheme used by LoRa is Chirp Spread Spectrum. Chirp spreading factor provides robustness against the channel degradation due to multipath, fading or interference [4]. By employing the orthogonal spreading factors, signal robustness can be increased depending on the coverage range and the transmission power. On the other side, data rate decreases when the robustness of the signal increases.

In this paper we present the results of our study on the LoRa physical layer and the experimental evaluations of its performance. For this purpose, we implemented a device-to-device communication between the RN2483 LoRa nodes from the Microchip [6]. The idea of device-to-device communication has been proposed in LTE networks [7], but it is applied to LoRa nodes for an experimental study in this paper. Three scenarios were considered for our experiments. In the first scenario, the receiver was placed about 15 m higher than the ground and the transmitter was located at different distances from 250 m up to 3000 m. The second scenario is similar to the first one, but the receiver was located on the ground. In the third scenario, the transmitter was located at a distance of 480 m from the receiver and was sending packets over 24 h. For each scenario three spreading factors (7, 9 and 12) were applied in the physical layer of LoRa nodes and the Packet Delivery Ratio(PDR) and Signal-to-Noise-Ratio (SNR) were measured.

Based on the experimental results, we derived a table that maps SNR to PDR for each Spreading Factor (SF). The mapping table can be used to decide the spreading factor according to the SNR of the received packets and a given PDR requirement. By utilizing the mapping table, we propose a self-organized algorithm which dynamically adapts the spreading factor over the time for a device-to-device communication between two LoRa nodes based the state of communication (SNR) and the PDR requirements. The results show that the proposed adaptive algorithm achieves a given requirement of 80% PDR in a communication between two LoRa nodes.

This paper is organized as follows. Section 2 presents related work. Section 3 describes the hardware specifications of LoRa nodes and scenarios for the experiments. In Sect. 4, the results of the measurement campaign are presented and analyzed. A self-organized algorithm to adapt the spreading factor in the LoRa nodes is proposed in Sect. 5. Finally, the conclusion and future work is presented in Sect. 6.

## 2 Existing Work

Since the release of the LoRa specifications version 1.0 in 2015 [8], some performance evaluations and experimental analyses have been carried out. In [9], the authors derived experimentally the minimum required Received Signal Strength

Indicators (RSSI) to receive a packet using spreading factors 7, 9 and 12 in the 868MHz frequency band. The experiment was conducted in the suburb of Paris using a LoRa gateway and an end-node. The authors transmitted packets from five different locations with a transmission power. The article did not provide any information about PDR during the experiment.

A similar experiment was described in [10]. This time, the authors took measurements in the city of Glasgow. The transmitter was moved through the streets up to a distance of 2.2 km from the receiver, while sending beacons. For every received beacon, the RSSI was measured. However, the paper did not provide any information about the applied spreading factor for the transmissions and the achieved PDR.

Authors in [11] assessed the QoS that a LoRa network can provide in the 868.1 MHz frequency band. In their experiment, the authors considered two scenarios. In the first scenario, the transmitter was mobile in a suburban scenario, while sending packets using the spreading factor 12. The packet was received by different receivers. In the second scenario, transmitter sent packets using spreading factors 7, 9 and 10 and eight receivers were located at a distance of 3 km to the transmitter. In both scenarios the authors measured Packet Error Rate (PER), RSSI and SNR.

In [12], another performance evaluation was done for LoRa in the 863–870 MHz frequency band. It was an indoor scenario in a 570 m x 320 m area. In their first experiment the transmitter sent packets using spreading factor 12 in different channels, while moving at the speed of 5 km/s. The results showed a PDR of 95%. In the second experiment, PER and RSSI for spreading factors 7, 8, 9 and 10 were measured using different distance to the receiver.

Authors in [13] presented a comprehensive experimental work where RSSI, SNR and PER were evaluated for the 868MHz frequency band. The author used a single measurement point for its experiment with a line of sight scenario, indoor and urban scenarios. In this work, the author presented the minimum SNR values for each spreading factor, which are required for receiving a packet. Additionally, it was suggested that further experiments should be carried out, in order to clarify more the relation between SNR and the spreading factor.

In this paper, we contribute with an experimental analysis of the LoRa performance applying spreading factors 7, 9 and 12 in the 433MHz frequency band that complements previous studies. Our scenarios focus on the impact of distance between a transmitter and a receiver, location of nodes and the impact of environmental conditions. Our goal is to experimentally define the spreading factor that should used based on the SNR of received packets and a given PDR requirement.

## 3 Experimental Setup

This section describes the hardware and static parameters that were used for the experimental study on LoRa radio layer. Then, we present three scenarios that we considered for our measurements. At the end of this section, we describe the scenario where our proposed adaptive SF algorithm was tested.

### 3.1 Hardware

The experiments were carried out using the Microchip's LoRa module RN2483. This module can operate in the 433 MHz and 868 MHz frequency bands. Its transmitter (TX) power can be configured up to +14 dB and it can use FSK, GFSK or the LoRa modulation scheme [6]. According to [6], the module RN2483 has a coverage up to 15 km in rural areas and up to 5 km in urban areas. The module RN2483 was connected to an Arduino board by using the cooking hacks multi-protocol shield for Arduino [14]. The complete node is presented in Fig. 1.

The configuration of the LoRa module RN2483 and packet generation is made by the Arduino. For the following experiments we used the LoRa radio layer and module was controlled using the radio commands presented in the module commands reference user's guide [15].

In our experiments, the transmissions were done at 433.375 MHz frequency with the highest possible TX power which is +14 dB. LoRa nodes used the LoRa modulation scheme and 4/8 coding rate in their physical layer.

**Fig. 1.** The LoRa node used in the experiments.

### 3.2 Scenarios

Our measurements took place in the city of Ilmenau, in Germany. The considered scenarios are as follows:

**Packet Delivery for Different TX/RX Distances with Receiver at 15 m Height.** The first scenario for the measurements is presented in the Fig. 2. In this scenario the receiver position is represented by the star and was located 15 m above the ground outside of a building. The black dots represent the transmitter location for each measurement. In each position, the transmitter sent 50 packets using each of spreading factors 7, 9 and 12. No ACKnowledgment (ACK) packet was used for this scenario. On the receiver side, the SNR value for each received packet and the total PDR for each SF were measured.

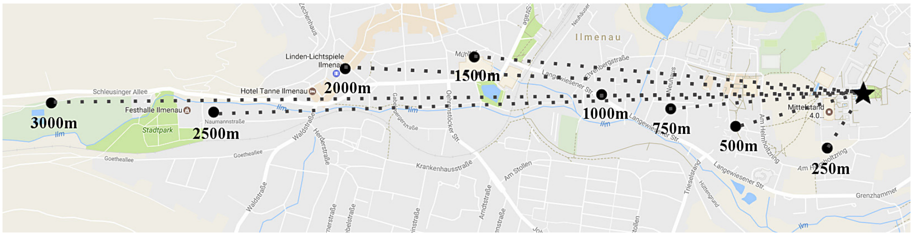
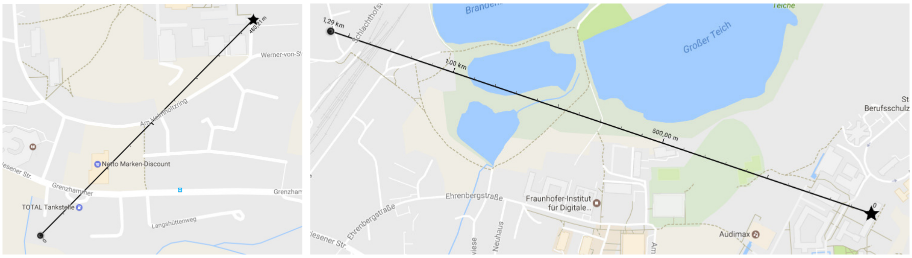


**Fig. 2.** Measurement points



(a) Scenario 24 hours

(b) Scenario adaptive

**Fig. 3.** Scenarios

**Packet Delivery for Different TX/RX Distances with Receiver at Ground Level.** In our second scenario, we put the receiver at the same place of the star in Fig. 2, but this time we located it on the ground level. For this experiment, 50 packets were transmitted at each one of the 8 black points in Fig. 2. For each transmission only SF12 was used.

**Packet Delivery over 24 h.** In the third scenario, the receiver and transmitter were located as Fig. 3(a). The receiver is represented by the star and the transmitter by the black point. The distance among receiver and transmitter was 480 m and it was fixed over the whole experiment. Every hour, the transmitter sent 100 packets using SF7, SF9 and SF12 and no ACK was used. On the receiver side, the SNR and PDR were measured.

**Test Scenario for the Proposed Adaptive SF Algorithm.** The proposed adaptive algorithm was tested using the scenario of Fig. 3(b). Again, the star represents the position of the receiver and the black point is the position of the transmitter. The distance between the receiver and transmitter was 1.3km. In this scenario, the transmitter sends groups of 10 packets and waits 5 s for the ACK. The receiver waits for the group of packets to arrive, measures the SNR and returns an ACK. The test was run continuously for one hour. PDR and average SNR were measured over the hour.

# 4 Results and Analysis

In this section, we present and analyze the results of the experiments described in Sect. 3.

## 4.1 Packet Delivery for Different TX/RX Distances

We measured the PDR and SNR of received packets in a device-to-device communication between two LoRa nodes in scenario 1. The nodes were placed in different distances from 250 m to 3000 m, as it is shown in Fig. 2. The receiver's location is marked by the star and we placed the transmitter in to the different 8 locations inside the city, that are marked by a black point in the Fig. 2. The height of receiver was about 15 m from the ground but the transmitter and receiver never had a Line of Sight (LoS) situation. During measurements, both nodes were kept stationary.

Our study in this section had two main objectives as follows:

- Study the impact of spreading factor and distance on PDR and SNR
- Study the impact of a receiver altitude

Next we describe in details each of studies.

**Study on the Impact of Spreading Factor and Distance.** To see the impact of different spreading factors in a communication between two LoRa nodes, we sent 50 packets applying spreading factors 7, 9 and 12 in each distance between the LoRa transmitter and receiver. Figures 4 and 5 illustrate the performance of LoRa nodes for the scenario 1. Figure 4 shows that SF9 and SF12 have similar PDR and SF7 is the least robust spreading factor. By the distance of 1000 m, all spreading factors have PDR of 80% or more. Beyond 1000 m, SF7 faces several fluctuations in PDR, but generally speaking, the distance only impacted SF7 while SF9 and SF12 can deliver all packets even in 3000 m. Figure 5 presents fluctuations in SNR of received packets for all spreading factors. These fluctuations show that the distance is not the main factor in SNR. The location of transmitter and obstacles between the nodes have a bigger impact than the distance. However, fluctuations in SNR impacts the PDR of the weakest spreading factor, but others can tolerate a high amount of degradation in SNR.

**Comparison Between Performance with Receiver on Ground Level and 15 m Height.** In our second scenario, we compared the PDR and SNR for two different heights of the receiver applying the most robust spreading factor which is SF12. This time, we repeated the first experiment but this time the receiver was at the ground level. Figures 6 and 7 demonstrate the PDR and SNR of received packets for two different altitudes of the receiver. By increasing the altitude of the receiver, the SNR increases dramatically and therefore PDR

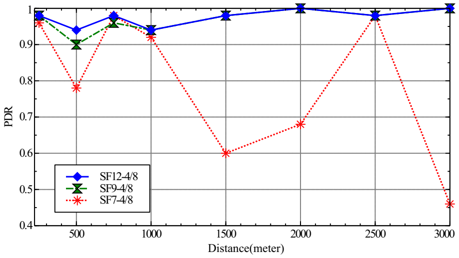


**Fig. 4.** Packet delivery ratio for different spreading factors and distances.

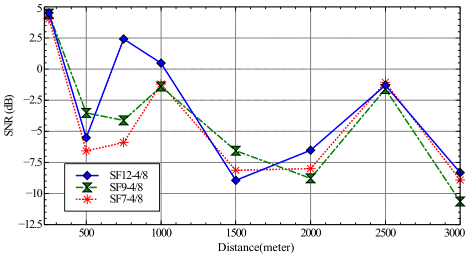


**Fig. 5.** Signal to noise ratio of different spreading factors and distances.

increases. The results show a big difference in PDR for most of the distances by elevating the location of a receiver for several meters from the ground even if there is no LoS transmission between two nodes. By locating the receiver in an altitude of 15 m from the ground, the PDR changes from 30% to 100% for 3000 m distance between the transmitter and receiver.

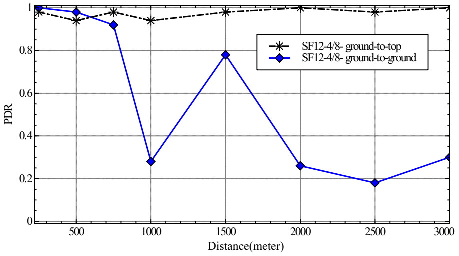


**Fig. 6.** Impact of different receiver altitudes on the packet delivery ratio.

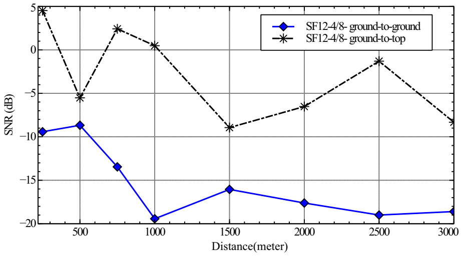


**Fig. 7.** Impact of different receiver altitudes on the signal to noise ratio.

## 4.2 Packet Delivery over 24 h

We study in this section the influence of environmental conditions in communication between two LoRa nodes. For this reason, we placed two LoRa nodes inside two different buildings as shown in Fig. 3(a) and kept them stationary for 24 h. Every hour, the transmitter sent 100 packets using SF7, 100 packets using SF9 and 100 packets using SF12. The distance between nodes, their location and the spreading factor was constant during the 24 h measurement. Therefore, any change on PDR and SNR may be caused by the weather conditions such as rain, humidity, temperature change or due to the noise and interference. Figure 8 shows the PDR for different repeats of our measurements with different spreading factors. SF12 was tolerant to the environmental changes and most of the

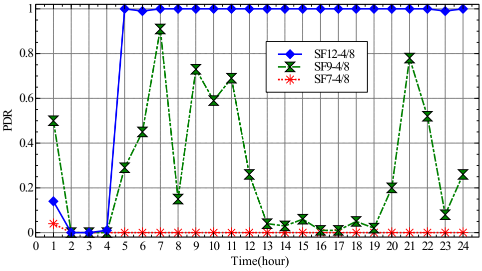


**Fig. 8.** Packet delivery ratio in 24 h with different spreading factors.

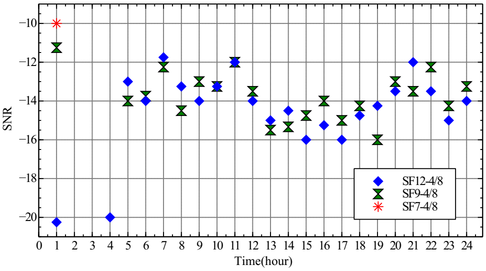


**Fig. 9.** Signal to noise ratio in 24 h with different spreading factors.

times was able to receive all packets. On the other hand, SF7 did not receive any packet mostly. SF9 shows a fluctuating behavior over time. However, it can receive about 80% of packets some times, but for several hours had a PDR of zero. In Fig. 9, we can see many changes in SNR for SF9 and SF12 in different times of a day. However, SF12 tolerated them, but SF9 lost many or all of the packets.

## 4.3 SNR Table

Based on our measurements in the mentioned experiments above, we derive a mapping between SNR and PDR for each spreading factor of LoRa. Table 1 illustrates the PDR for each spreading factor based on the average SNR of received packets. The mapping table provides us the spreading factor that should be applied in LoRa nodes for any PDR requirement having an average SNR in received packets. This table will be used in the next section to adapt the spreading factor for a given PDR requirement in a device-to-device LoRa communication.

**Table 1.** Mapping SNR to PDR for different spreading factors.

| Spreading factor | PDR (80–100)% | PDR (30–80)% | PDR $\leq$30% |
|---|---|---|---|
| SF7 | SNR $\geq -6.5$ | $-6.5 >$ SNR $\geq -9$ | $-9 >$ SNR $\geq -10.5$ |
| SF9 | SNR $\geq -12$ | $-12 >$ SNR $\geq -14$ | $-14 >$ SNR $\geq -16$ |
| SF12 | SNR $\geq -16$ | $-16 >$ SNR $\geq -17.5$ | $-17.5 >$ SNR $\geq -21$ |

## 5 Self-organized Spreading Factor Adaptation for Device-to-device Communication of LORA Nodes

In this section, we propose a self-organized algorithm which adapts the spreading factor in a device-to-device communication between two LoRa nodes to achieve a PDR requirement. The proposed scheme applies the mapping table between SNR and PDR for different spreading factors that was presented in Sect. 4.3. In the self-organized spreading factor adaptation scheme, LoRa nodes start their communication with the most robust spreading factor which is SF12. Then, when some packets have been received in the receiver, the average SNR is calculated in the LoRa receiver and based on the mapping table (Table 1), both nodes adapt their spreading factor to achieve the required PDR.

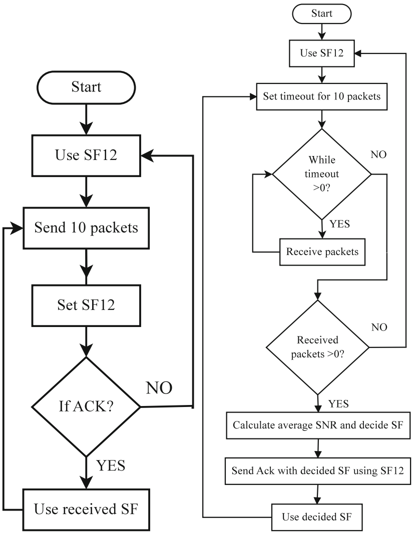
Having a static spreading factor during a communication may degrade PDR, as we showed in our 24 h measurements. As an example, LoRa nodes may be tuned to SF7 to have the fastest packet transmission, but the PDR can be very low in some scenarios (as we showed in our experimental results). However, if LoRa nodes are tuned to the most robust spreading factor to have the best PDR, they may loose the opportunity of using lower spreading factors and faster transmission of packets if there is a high SNR in received packets. Therefore, an adaptive scheme is a reasonable solution to define the spreading factor between two LoRa devices on-the-fly and based on the observations of nodes from the state of communication. Figure 10 shows the adaptive spreading factor algorithm in a LoRa transmitter and receiver pair. As mentioned, both nodes start with SF12 to do the adaptation based on the measurements from SNR of received packets on the receiver side. The reason that we chose SF12 is due to the high sensitivity of LoRa receivers in this spreading factor which can receive packets with a very low SNR (−21 dB as the minimum SNR for packet reception). If any other spreading factor is used for the start of adaptive scheme, the receiver may receive no message and the spreading factor adaptation fails in this case. Now, we describe steps in the algorithms in both transmitter and receiver sides. Steps in the transmitter side are as follows:

1. Set SF12: The transmitter tunes itself to SF12 to start the adaptation procedure.
2. Transmit data packets: 10 data packets are sent continuously without waiting for any acknowledgment.

3. Wait for ACK: After sending the packets, the transmitter waits at SF12 to receive an acknowledgment from the receiver. The ACK message is always sent in SF12 to increase the probability of its reception.
4. Tuning spreading factor: After reception of ACK, the transmitter tunes its spreading factor based the information in the ACK message.
   - If the ACK is not received during a time window, the spreading factor for data transmission will be set to SF12.
5. Goto the step 2.

In the receiver side, the algorithm has the following steps:

1. Set SF12: The receiver tunes itself to SF12 to start the adaptation procedure.
2. Receive, measure and make decision: By receiving data packets, the receiver measures the average SNR of the packets and decides about the spreading factor based on Table 1.
   - If the receiver does not receive any packet in a specific time window, it will choose SF12 as the next spreading factor.
3. Send ACK: The receiver sends an ACK to the transmitter and informs it about its decision for the spreading factor. The receiver uses always SF12 for transmission of ACK.
4. Tuning the spreading factor: The receiver tunes its spreading factor based on its decided spreading factor in step 2.
5. Goto the step 2.



(a) Transmitter (b) Receiver

**Fig. 10.** Adaptive algorithm in LoRa nodes.

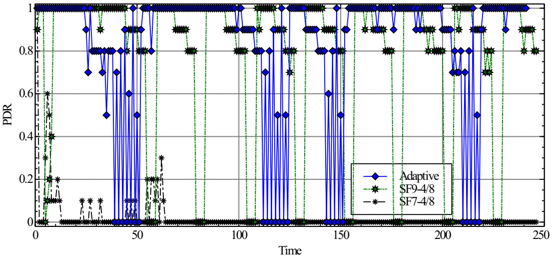


**Fig. 11.** Packet delivery ratio for different spreading factors and the adaptive approach.

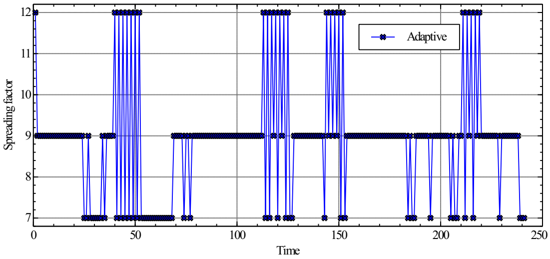


**Fig. 12.** Adaptation of spreading factor in the proposed approach.

Figure 11 shows the PDR for 3 different spreading factors in the scenario that was presented in Fig. 3(b). The nodes was placed outdoor in the second floor of two buildings inside the city but they had no LoS condition. The transmitter was transmitting data packets for 1 h using SF7, SF9, SF12 and the proposed adaptive algorithm of this paper. We set a requirement of 80% PDR for our transmission. As the PDR for SF12 was always 100%, we do not show the results for SF12 in the figure. As it can be seen in Fig. 11, SF7 can transmit a few or no packets in most of the time. SF9 was the best spreading factor for this scenario and it had more than 80% of PDR in most of the times. However, SF12 had always 100% PDR but due to its low throughput it is not the best choice is this scenario. Figure 12 demonstrates the changes in the spreading factor using the adaptive algorithm. We can see that the proposed algorithm adapts to SF9 which is the best spreading factor in this scenario. However, sometime the algorithm tries to use SF7 when the SNR increases, but when it does not receive any packet with SF7 it changes to SF12. Additionally, Fig. 11 shows that the proposed algorithm achieve an average PDR of 83%, which is a bit more than our initial requirement.

## 6 Conclusion

In this paper an experimental study on the LoRa radio layer was presented. We used the 433MHz frequency band and tested a device-to-device communication between two nodes using spreading factors 7, 9 and 12. During our experiments, we proved that, in non line of sight scenarios, the TX-RX distance is not a good parameter for configuring the spreading factor of the LoRa radio layer. Instead of that, SNR measurements gives better information for selecting the spreading factor. Based on our results, we derived a mapping table that allows us to decide which spreading factor should be used according to the SNR of received packets and a given PDR requirement. Based on this table, a self-organized algorithm for on-the-fly adaptation of the spreading factor in a transmitter and receiver was proposed. We validated experimentally our algorithm and showed its capability in achieving a required PDR. A study on the performance of the self-organized algorithm in a scenario with mobile LoRa devices is considered as a future work.

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