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Indoor Performance Evaluation of LoRa 2.4GHz

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Abstract—LoRa and LoRaWAN are one of the most common wireless technologies used today in the Internet of Things. If until now LoRa was strictly used in sub-GHz bands, a new version has been released for the 2.4 GHz band that does not have any duty cycle restrictions and that allows the use of higher data rates, which opens the door to the deployment of new applications (such as asset tracking or indoor localization). In this paper, we present the first extensive evaluation of LoRa 2.4 GHz in a typical indoor environment, both in the presence and lack of human and WiFi activities. We run an exhaustive evaluation of all 128 possible combinations of the different LoRa physical parameters (spreading factor, bandwidth and coding rate) and we show that despite the use of higher frequency, LoRa is capable of maintaining a good connectivity throughout the building, similar to what was observed in sub-GHz bands. Still, some configurations were clearly affected by the daily life activities in the building during the working hours of weekdays.

Index Terms—LoRa, 2.4 GHz, experiments, performance evaluation, indoor evaluation.

I. INTRODUCTION

The aim of Internet of Things (IoT) is to improve our daily lives. Typical applications include climate change monitoring, smart metering, asset tracking, intelligent building and smart cities. With the progress of technologies that offer long range wireless communication at low power and low cost, Low-Power Wide Area Networks (LPWANs) have become a frequent choice for users and network operators likewise.

LoRa [1] and LoRaWAN [2] are one of the most popular LPWAN technologies used today, as they offer a communication range for several kilometers, low deployment overhead, and minimal maintenance. LoRa operates on license-free sub-GHz bands around the globe, which makes it region-specific. Depending on the country, regulations for these sub-GHz bands (e.g. 868 MHz in Europe, 915 MHz in North America) specify different frequency channels, maximum transmission time, maximum transmission power, and different medium access mechanisms such as duty-cycle or listen-before-talk. These specificities can hinder the deployment of LoRa technology for applications needing regulation consistency.

To countermeasure these limitations, Semtech released a new version of LoRa operating in the 2.4 GHz ISM, which is worldwide available. Moreover, the lack of duty cycle and listen-before-talk constraints allow the use of new physical layer parameters that can increase the theoretical data rate up

to 253 kbps, which is more than 18 times the data rate of LoRa sub-GHz (computed for SF=7, BW=250kHz)¹. As such, LoRa 2.4 GHz makes easier the deployment of applications such as asset tracking, and food and medicines supply chain monitoring, where worldwide interoperability, high data rate, and no duty cycle limitations are required.

LoRa 2.4 GHz inherits the long range communication and robustness capabilities of LoRa sub-GHz, but this communication can be hindered by a slightly less good penetration through walls (as 2.4 GHz waves are shorter than the sub-GHz ones) and by the co-localization with other wireless technologies (such as WiFi and Bluetooth Low Energy). In this paper, we focus on evaluating the performance of LoRa 2.4 GHz in a typical indoor environment, by looking at the Packet Delivery Ratio (PDR), the Received Signal Strength Indication (RSSI), and the Signal-to-Noise Ratio (SNR). Our experiments take place in an office building, with other wireless technologies (typically WiFi and Bluetooth) operating in the same frequency. To our knowledge, **this is the first paper to provide a thorough evaluation of LoRa 2.4 GHz in an indoor environment.**

The remainder of the paper is organized as follows. Section II presents the characteristics of LoRa 2.4 GHz and the related state of the art. Section III presents the experimental setup, discusses the methodology, aimed to be repeatable and reproducible, and introduces the experimental protocol used to extensively evaluate LoRa 2.4 GHz. Section IV shows the experimental results, discussing in details the effects of all LoRa 2.4 GHz physical parameters on its performance. Finally, Section V concludes our work.

II. BACKGROUND ON LoRa 2.4 GHz

In this section, we first introduce LoRa 2.4 GHz before diving into the literature on LoRa 2.4 GHz.

A. Characteristics of LoRa 2.4 GHz

LoRa 2.4 GHz is based on Chirp Spread Spectrum (CSS) modulation, characterized by three physical parameters: spreading factor (SF), bandwidth (BW) and coding rate (CR), just like LoRa sub-GHz. The configuration used in a packet transmissions is a trade-off between data rate and robustness

¹The theoretical data rate is computed as $DR = \frac{SF}{2^{SF}} \cdot \frac{BW}{BW}$, where SF represents the spreading factor, and BW the bandwidth.

i.e. communication range, and depends on the application and on its requirements. The possible values of these three parameters are given in Table I. We can notice the appearance of two new values for the spreading factor (5 and 6) and new (and larger) bandwidths, which enable the increase in data rate.

TABLE I: Physical layer parameters for LoRa 2.4 GHz

Parameter	Values	Unit
Spreading Factor	5, 6, 7, 8, 9, 10, 11, 12	-
Bandwidth	203, 406, 812, 1625	kHz
Coding Rate	4/5, 4/6, 4/7, 4/8	-

Unlike the sub-GHz bands, the 2.4 GHz band shares a common base of frequency channels in all countries, and is not subject to duty-cycle regulations. Thus, LoRa 2.4 GHz can operate worldwide on the same set of parameters. This allows chipset constructors to design a single hardware and software, which enables a good interoperability.

B. State of the art on LoRa 2.4 GHz

While the performance of LoRa has been experimentally studied in the past by several works [3]–[5], this is not at all the case for LoRa 2.4 GHz. The research works related to LoRa 2.4 GHz focus rather on the study of its coexistence with other technologies from the 2.4 GHz band, like WiFi and Bluetooth, as they are intensively used indoors. Polak et al. address the coexistence between LoRa 2.4 GHz, LTE and Bluetooth technologies [6], [7], Chen et al. study the coexistence with WiFi [8], and Shi et al. show how ZigBee devices can use the variation of received power to retrieve data from distant LoRa end nodes [9]. Few works characterize the performance of LoRa 2.4 GHz, and only take a theoretical approach. For example, Janssen et al. make an evaluation by modeling the channel performance in terms of the data rate and the maximum link range, for different scenarios (indoor, outdoor and urban scenarios) [10].

Notice that even for LoRa sub-GHz, few works comprehensively evaluate the performance of all physical parameters such as [11], and to the best of our knowledge, none focuses on an indoor space such as an office building along an extended period of time. This is why the experimental study that we present in this paper is such important.

III. EXPERIMENTAL SETUP AND METHODOLOGY

The goal of this paper is to make an extensive performance evaluation of LoRa 2.4 GHz in an indoor environment, for which we designed and conducted two types of experiments:

- 1) **Exhaustive experiment.** This experiment was designed to evaluate how **all the physical layer parameters** (SF, BW, and CR) impact the communication of LoRa 2.4 GHz. We study all the possible combinations of these parameters (as presented in Table I), which results into a total of $8 \times 4 \times 4 = 128$ combinations. In order to reduce as possible all external interference, these experiments were run during the weekend, when almost no person was present in the building.

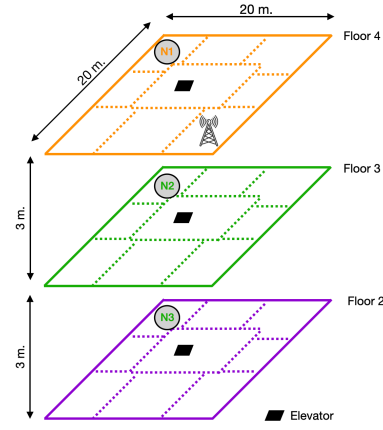


Fig. 1: Architecture of the building that presents the placement of the gateway and the three end nodes.

- 2) **Long-run experiment.** This experiment was designed to evaluate how **environment and daily life activities** (presence of people in the building, WiFi and Bluetooth usage, etc.) impact the communication of LoRa 2.4 GHz. These experiments were run on a subset of parameter combinations, over a one week period, which allowed us to see the day/night and weekday/weekend cycles.

We present next the experimental setup and the protocol that we designed to allow experiments to be reproducible ².

A. Experimental setup

All the experiments were performed in the Inria building in La Doua Campus, Lyon (France). As we can see in the plan from Fig. 1, the building is in a square shape of $20m \times 20m$ and has 4 floors, with the elevator situated in the middle. We placed the gateway on the 4th floor in one of the corners, and the end nodes across the building (one of each floor) in the opposite corner, to maximize the distance from the gateway (apx. 100m for the end node at the 4th floor). Unfortunately we do not have access to all the floors, so we could only situate three end nodes (on floors 2, 3, and 4).

The equipment used for these experiments consists of three end nodes, one gateway, and a computer that collects and logs all the data received by the gateway. All LoRa devices use the SX1280 radio chip from Semtech. Each end node is independently controlled using the STM32 NUCLEO-L476RG micro-controller, and the gateway is directly connected to the computer via USB.

Apart from the physical layer parameters used in the experiments (which are presented in Table I), we set the transmission power of end nodes to 10 dBm, and we fixed the center frequency at 2403 MHz. Each configuration is tested with $N = 50$ frames, each having a payload of 20 bytes. This short payload is intended to model common LoRa applications.

²Both the code and the data are available at <https://doi.org/10.5281/zenodo.7106073>. The code can be used according to the terms of the Revised BSD License.

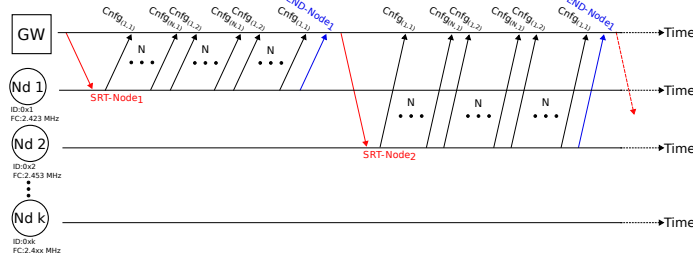


Fig. 2: Experimental protocol for one configuration cycle (three different parameter configurations). Red lines represent downlink frames, blue lines uplink frames with termination code and black lines represent test frames for each configuration.

B. Experimental protocol

In order to put in place such an exhaustive performance evaluation, we needed to design an experimental protocol that would automatize the experimental runs, and would be easily reproducible. Each end node has to run a certain number of configurations (e.g. 128 for the Exhaustive experiment), which have to be repeated several times (to minimize variations in observed data). Moreover, two or more end nodes should not transmit in the same time, in order to avoid collisions.

The designed protocol is presented in Fig. 2 and allows to individually test the communication link between each end node and the gateway, using a round-robin scheduling that has only one end node transmitting at a time. The gateway activates each end node sequentially by sending a downlink frame, denoted SRT-Node, with fixed physical parameters. This downlink contains the parameters for three configurations. For each configuration, the end node sends N test frames with the corresponding parameters. Once the series of three configurations is finished for an end node, it sends a END-Node message, and the gateway proceeds to the next end node. Once the round-robin on the three nodes finishes, the gateway moves on to the next three configurations and restarts the process. The configurations tested are organized by series of three as the gateway used cannot handle more configurations at a given time. Note that a timeout is included in the case either the SRT-Node downlink or the END-Node uplink are lost, to avoid dead times in the experiment, or de-synchronization with the gateway (the gateway and the end-nodes need to be on the same parameter configuration in order to communicate).

C. Evaluation metrics

To evaluate the performance of LoRa, we look at the reliability and at the quality of the communication link between an end node and the gateway by collecting and computing the following metrics:

- Packet Delivery Ratio (PDR), computed as the total number of frames received (and correctly decoded) by the gateway, divided by the total number of frames sent.
- Received signal strength indicator (RSSI), computed as the average signal strength of received frames by the gateway.
- Signal to noise ratio (SNR), computed as the average signal to noise ratio of received frames, by the gateway.

IV. EXPERIMENTAL RESULTS

In this section, we present and we discuss the results obtained from the two experiments.

A. Exhaustive experiment

The goal of this experiment is to evaluate how all the physical layer parameters (SF, BW, and CR) impact the communication of LoRa 2.4 GHz. All 128 configurations are tested for each of the three end nodes, according to Table I. The experiment ran for approximately 65 hours from Friday afternoon to Monday morning, with 3 repetitions for each configuration. During this experiment, the building was mostly empty and thus low interference from workers occurs, and as a consequence, there was also a low WiFi and Bluetooth activity.

Fig. 3 presents the mean PDR calculated for each configuration. We can notice that no matter the configuration that was used, the lowest PDR obtained was 70%. This means that **LoRa 2.4 GHz connectivity remains very good in an indoor environment**, and that depending on the building, one gateway can be enough for a complete LoRa 2.4 GHz coverage.

The PDR starts degrading when we use a combination of low SF (5, 6, 7) and high BW (812 and 1625 kHz), and we increase the distance from the gateway (2nd and 3rd floors). According to the SX1280 calculator [12], the data rate is 15.23 kb/s for configuration (6, 203 kHz, 4/5), while it is 6.98 kb/s for (11, 1625 kHz, 4/5). Although these two configurations yield a similar PDR, the use of a low SF and low BW yields a larger data rate (and hence a lower energy consumption), which means **it is better to decrease the SF and the BW, rather than to increase the SF and the BW**.

Another important finding is that **CR has no visible impact on the PDR**. This may be attributed to the lack of short burst interference during the period of time in which the experiment was performed. Still, it is consistent to what is observed in LoRa sub-GHz.

In order to see more clearly the impact of SF, BW and CR on the reliability of LoRa 2.4 GHz we plotted in Fig. 6 the PDR for the configurations with the largest data rate for the end node on floor 2, as this node is the furthest away from the gateway. Fig. 6(a) shows the PDR for the configurations with SF=5, BW=1625 kHz and all values of CR are shown. Again, the coding rate seems to have little impact on the PDR. Fig. 6(b) displays the PDR for the

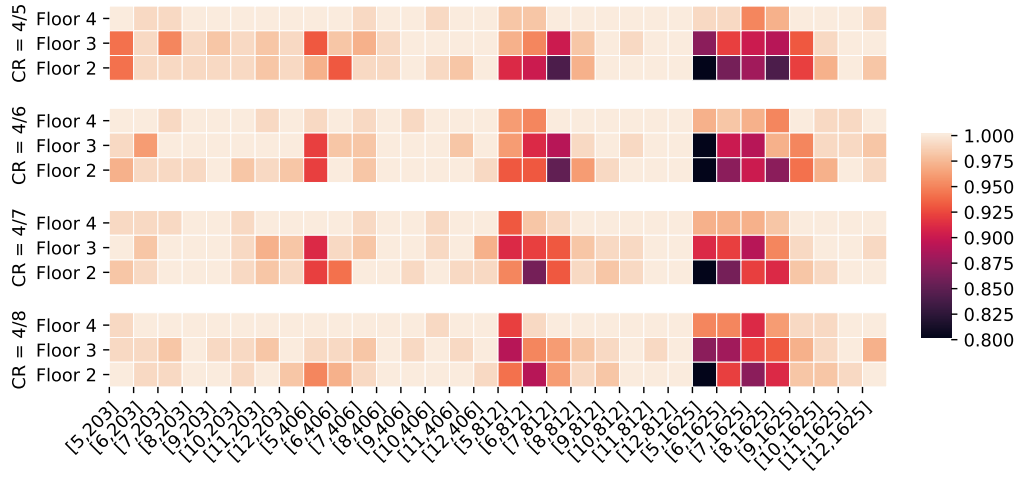


Fig. 3: Heatmap of the PDR for the three end nodes and all possible combinations of SF, BW and CR.

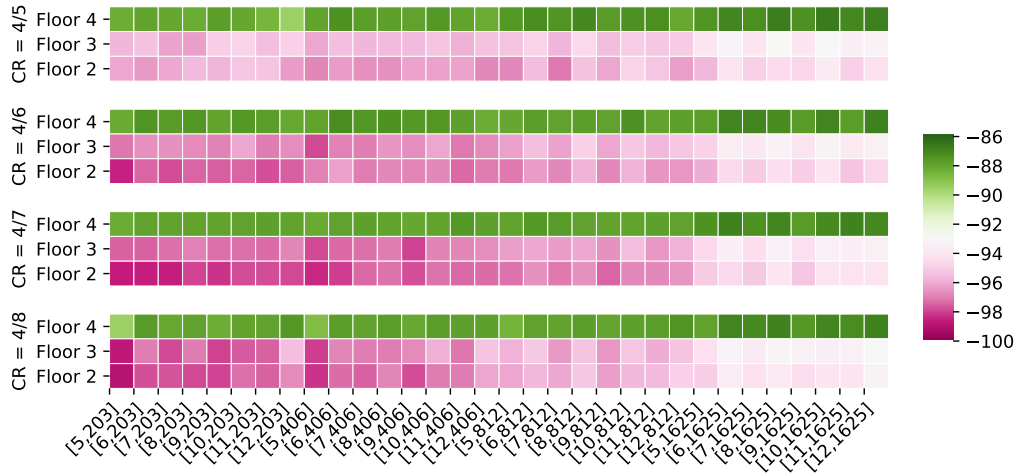


Fig. 4: Heatmap of the RSSI for the three end nodes and all possible combinations of SF, BW and CR.

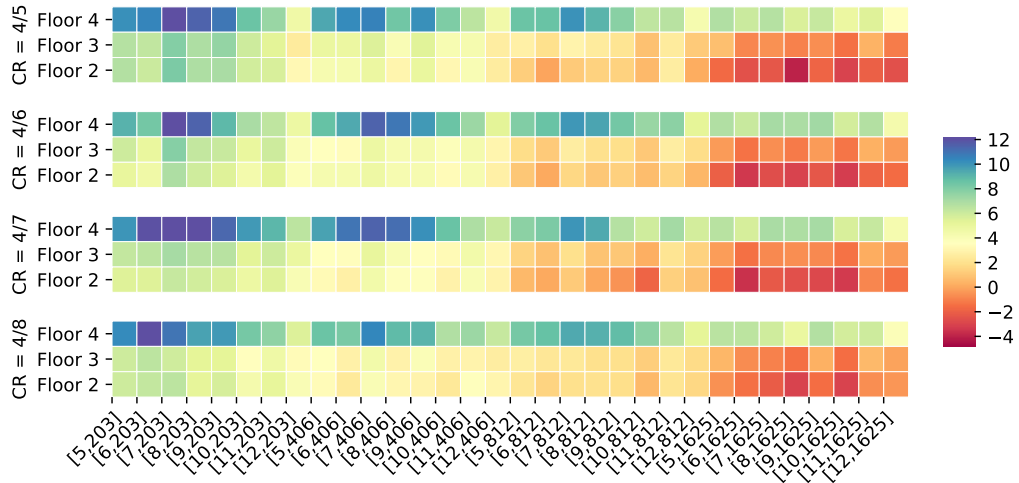


Fig. 5: Heatmap of the SNR for the three end nodes and all possible combinations of SF, BW and CR.

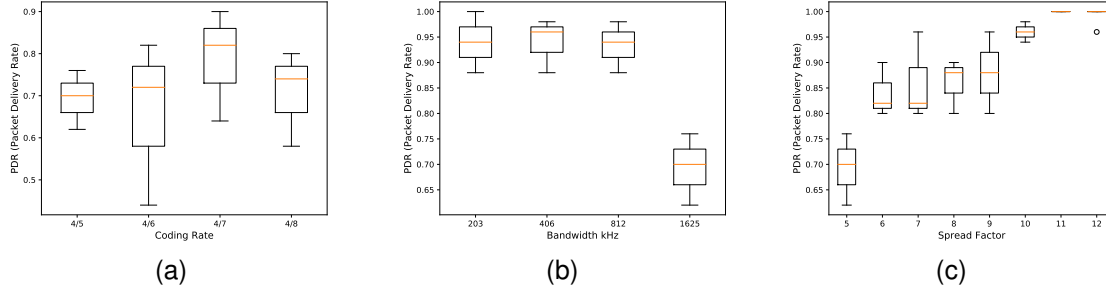


Fig. 6: PDR for the end node in floor 2 for high data rate configurations: (a) SF=5, BW=1625 kHz, all CRs, (b) SF=5, CR=4/5, all BWs, (c) CR=4/5, BW=1625 kHz, all SFs.

configurations with SF=5, CR=4/5 and all values of BW. The PDR has a clear relationship with the bandwidth, dropping considerably for BW=1625 kHz. This confirms our previous finding. Fig. 6(c) displays the PDR for the configurations with CR=4/5 and BW=1625 kHz, showing the direct relation between SF and PDR: **PDR increases with the increase in SF**, as the robustness of the modulation increases.

Fig. 4 presents the RSSI for each end node. Recall from Fig. 3 that the end node with the best performance in term of PDR was the one placed in the same floor as the gateway (that is, on floor 4), and the end node with the worst performance was the one placed in the second floor. This is reflected here in the RSSI, as the end node located in the same floor as the gateway has a RSSI of up to 10 dBm higher than the end nodes located in different floors from the gateway.

Fig. 5 presents the SNR for each end node, for all configurations. As expected, the SNR decreases as the distance between the end node and the gateway increases. For SF=12, the SNR decreases compared to the other SFs. This is especially noticeable for BW=203 kHz, as the SNR drops by almost 8 dBm from the maximum recorded value for that BW. **There is a clear relationship between the bandwidth and the SNR: the higher the bandwidth, the lower the SNR.**

B. Long-run experiment

In this second experiment, we study how the PDR varies over time, by studying the effect of daily activities on the communication performance of LoRa 2.4 GHz. As it would be too time consuming to run all 128 possible combinations of parameters, we decided to focus on a representative subset of six configurations, corresponding to two bandwidths (BW=203 kHz and BW=1625 kHz), three spreading factors (SF=5, SF=8 and SF=12), and a fixed CR of 4/5. This small number of configurations can run in about 30 minutes, allowing them to have a good granularity for the long-run experiment. The experiment started on Monday at 7:21pm, and ended the next Monday at 4:48pm, lasting one full week.

Fig. 7 presents the evolution of the PDR as a function of time, for the entire duration of the experiment. The results are divided for the two bandwidths used: BW=203 kHz is above, and BW=1625 kHz is below. The x-axis shows the hours for each day, and days are separated by a gray dashed line.

Let us first consider the case where BW=203 kHz. SF=5 and SF=8 show high PDR, with a good stability. The lowest PDR peaks (more noticeable for SF5) are on weekdays, except on Wednesday (a predilection day for people to work from home). This is likely due to human activity in the building. SF=12 shows an unexpected behavior, as it is the one with the poorest performance. We believe that this is related to the size of the frames for this configuration. Frames with SF=12 and BW=203 kHz have a very long time on air of 892.94 ms, which is the largest among all the configurations. Because of this, we suspect that collisions are occurring between LoRa 2.4 GHz frames and the WiFi frames. This is supported by the fact that the channel used here was centered at the 2.403 GHz frequency, which overlaps with the channel 1 (2.401–2.423 GHz frequency range) of the WiFi channels. After an investigation, we found out that it was the channel used for the WiFi networks in the building. As a reference, with SF=8 and BW=203 kHz, the time on air of frames is only 68.41 ms, which is almost 13 times lower than with SF=12. Hence, SF=8 might be only slightly impacted by WiFi, while **SF=12 is largely impacted by WiFi when BW=203 kHz.**

Let us now consider the case where BW=1625 kHz. The PDR results show a clear pattern of degradation in the times of the day in which there are activities in the building, that is during week days, between 8am and 7pm approximately. This degradation is clearly seen in the PDR for weekdays, which showed the lowest values of PDR for SF=5 and SF=8. This contrasts with the behavior of **the PDR during the weekend, in which little activity is registered in the building, thus resulting into a high PDR.** Compared to when BW=203 kHz, **SF12 has a steady performance during the long-run experiment with BW=1625 kHz.**

Overall, the best configuration for indoor in our experiment would be SF=8 and BW=203 kHz. This combination achieves a high robustness with a data rate of 5.08 Kb/s. Another candidate for a high robustness would be SF=12 and BW=1625 kHz, but data rate would be only 3.81 Kb/s.

V. CONCLUSIONS AND PERSPECTIVES

In this paper, we experimentally evaluated the performance of LoRa 2.4 GHz in a typical indoor environment. We proposed a protocol that automates experiments, and used it to

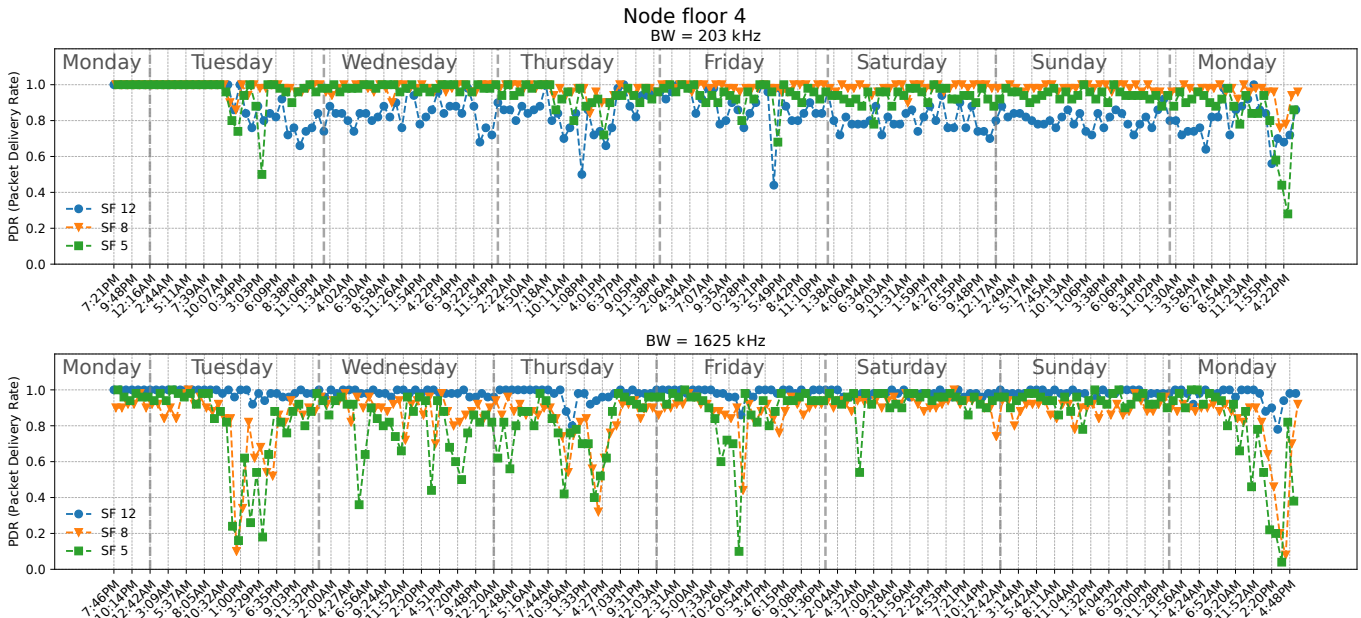


Fig. 7: Evolution of the PDR as a function of time, for six configurations (two BWs and three SFs), for the end node situated on the same floor as the gateway.

run two different experiments: an exhaustive experiment with all the 128 configurations of the three physical parameters of LoRa 2.4 GHz, and a long-run experiment that captures the sequence of weekdays and weekends.

Thanks to the Exhaustive experiment, we showed that the coding rate has very low impact on the PDR. We also showed that for a three-floor indoor deployment, when using the high data rate configuration, we can achieve a PDR of 66% for the furthest end node. When using the most reliable configuration, the PDR varies between 95% and 100%. This clearly shows LoRa's robustness and coverage capabilities even in the 2.4 GHz band.

Thanks to the Long-run experiment, we showed that the PDR is considerably affected by the activities during the hours of work of weekdays. These results can be explained by the fact that during the day, our experiment was interfered by other wireless technologies used in the building, such as WiFi. The use of SF=12 and BW=1625 kHz enables LoRa 2.4 GHz to keep a PDR close to 100%, even under a peak of activity in the building.

Overall, our main findings are that SF and BW have a significant impact on the PDR. SF=12 generally yields steady performance during the whole experiments. In order to achieve a high data rate with a robust link, it is better to use a low SF and a low BW, rather than to increase both SF and BW.

In the future, we will study the effect of WiFi on the indoor scenario more deeply, by testing the impact that different amounts of traffic have over the performance of LoRa 2.4 GHz. We will also perform outdoor experiments to expand the scenarios covered in this performance evaluation.

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