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# On a testé pour vous : LoRa 2.4 GHz à l'intérieur.<sup>† ‡</sup>

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LoRa® est une modulation radio très utilisée pour l'Internet des Objets. Récemment, LoRa a été étendue à la bande de fréquences ISM 2.4 GHz, permettant ainsi de s'affranchir des limitations de cycle d'activité et d'atteindre de plus haut débits. Dans ce papier, nous présentons deux expérimentations de LoRa 2.4 GHz dans un environnement intérieur : la première expérimentation étudie de manière exhaustive 128 combinaisons de paramètres LoRa 2.4 GHz, et la deuxième expérimentation étudie les performances de LoRa 2.4 GHz en fonction des activités journalières dans des bureaux.

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## 1 Introduction

LoRa [2] is one of the most popular LPWAN (low-power wide area network) technology used today. Since LoRa operates on license-free sub-GHz bands that are region-specific (e.g., 868 MHz in Europe, 915 MHz in North America), parameters such as frequency channel, maximum transmission power, and medium access mechanism (duty cycle, listen-before-talk) differ from one geographical region to another, and have to be considered in hardware components and communication protocols design.

To countermeasure these limitations, Semtech released a new version of LoRa operating in the 2.4 GHz ISM band, which is available worldwide. Moreover, the lack of duty cycle and listen-before-talk constraints in this band 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. As such, LoRa 2.4 GHz is a strong candidate for applications such as asset tracking and supply chain monitoring, where worldwide interoperability and high data rate are required. Furthermore, the use of higher bandwidth in LoRa 2.4 GHz enables a highly accurate ranging mechanism up to 2 m, which can be used by localization-based applications for inventory and logistics purposes.

The main challenge of LoRa 2.4 GHz is the coexistence with other radio technologies already occupying the 2.4 GHz ISM band such as Wi-Fi, Bluetooth, Bluetooth Low Energy (BLE), and ZigBee, which triggered the work presented in this paper. Our contribution is a detailed performance evaluation of LoRa 2.4 GHz in a typical indoor environment in the presence of other wireless technologies.

## 2 Background on LoRa 2.4 GHz

LoRa is based on a Chirp Spread Spectrum (CSS) modulation, characterized by three physical parameters : spreading factor (SF), bandwidth (BW) and coding rate (CR). These parameters allow to trade-off data rate and energy consumption with communication range and robustness. Compared to LoRa sub-GHz, LoRa 2.4 GHz introduces SF 5, uses BW 203, 406, 812 and 1625 kHz, and keeps same CR values.

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

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<sup>‡</sup> Une version étendue de ces travaux est publiée dans [1].

and the maximum link range, for different scenarios (indoor, outdoor and urban scenarios) [3]. Even for LoRa sub-GHz, few works comprehensively evaluate the performance of all physical parameters [4], 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 important.

### 3 Experimental setup and methodology

The goal of this paper is to make an extensive performance evaluation of LoRa 2.4 GHz in a typical indoor environment in the presence of other wireless technologies (such as Wi-Fi and Bluetooth), and without disturbing people's daily activities. We designed two types of experiments : (1) an exhaustive experiment that will allow us to evaluate the impact of all physical layer parameters of LoRa 2.4 GHz (we tested all 8 values of SF, 4 values of BW and 4 values of CR), and (2) a long-run experiment that will allow us to evaluate the impact of daily life activities on the performance of LoRa 2.4 GHz. While the exhaustive experiment is run during the weekend to reduce external interference caused by humans working in the building, the long-run experiment is run without interruption for a whole week<sup>§</sup>.

All our experiments took place in the Inria building located in La Doua Campus, in Lyon. 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 corner, and the end nodes in the opposite corner, on floors 2, 3 and 4, in order to maximize the distance from the gateway (apx. 100m for the end node at the 4th floor). The end nodes use the SX1280 radio chip, controlled by an STM32 NUCLEO-L476 micro-controller, and the gateway is connected to a laptop via USB. The center frequency is set to 2403 MHz and the transmission power to 10 dBm. All configurations are tested with  $N = 50$  frames, with a payload of 20 bytes each. These values are intended to model common LoRa applications. We implemented a round robin technique in which the gateway schedules the transmissions of each end node so that we avoid collisions. The gateway also informs the end nodes about which configuration to use at a given time.

To evaluate the performance of LoRa, we collect the following metrics : (1) Packet Delivery Ratio (PDR), computed as the total number of frames correctly received by the gateway divided by the total number of frames sent, and (2) Signal to Noise Ratio (SNR), computed as the average signal to noise ratio of frames received by the gateway. The next sections present the results that we obtained.

### 4 Results for the exhaustive experiment

This experiment ran for approximately 65 hours from Friday afternoon to Monday morning, with 3 repetitions for each of the 128 configurations. During this experiment, the building was mostly empty and thus there were low interference from people or Wi-Fi.

We can see in Fig. 1 that no matter the configuration that was used, the PDR does not get below 70%. This means that **LoRa 2.4 GHz connectivity remains very good in an indoor environment**, and that one gateway can be enough to cover a three-floor building. The PDR starts degrading only with a combination of low SF (5, 6, 7) and high BW (812 and 1625 kHz) for the nodes situated further away from the gateway (on 2nd and 3rd floors), which is to be expected. We can also notice that we have similar PDR values for parameter combinations that yield different data rate (and energy consumption) values. For example, the configurations (6, 203 kHz, 4/5) and (11, 1625 kHz, 4/5). According to the SX1280 calculator [5], the data rate is 15.23 kb/s for the first configuration and only 6.98 kb/s for the second one. This shows that if we want to increase the network lifetime or the data rate, **it is better to decrease the SF and the BW, rather than to increase the SF and the BW**. Finally, 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.

In order to study the impact of each parameter individually (SF, BW, CR) on the reliability of LoRa 2.4 GHz, we need to isolate the results in which we fix two of these parameters, and we vary the third one. Let us focus for example on the end node on floor 2 and the configuration with the largest data rate<sup>¶</sup>.

<sup>§</sup>. Both 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.

<sup>¶</sup>. The figures are not shown here due to lack of space (check [1]), but the results can still be visible on Fig. 1

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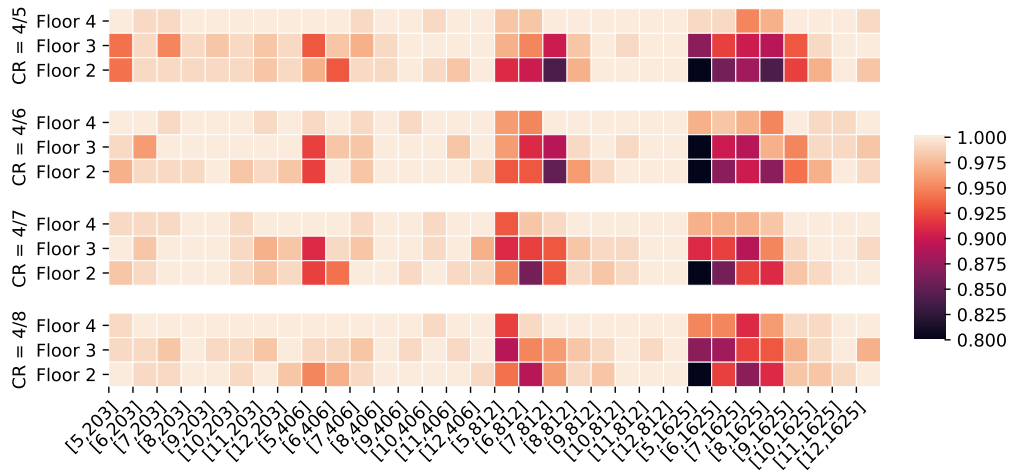


FIGURE 1 : Heatmap of the PDR for the three end nodes and all possible combinations of SF, BW and CR.

For the four configurations (5, 1625 kHz, \*), the coding rate has little impact on the PDR. For the four configurations (5, \*, 4/5), the PDR has a clear relationship with the bandwidth, dropping considerably for BW=1625 kHz. For the six configurations (\*, 1625 kHz, 4/5), we can observe that the PDR increases with the increase in SF, as the robustness of the modulation increases.

We also computed the SNR for each end node, for all configurations (the results can be found in [1]). 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.

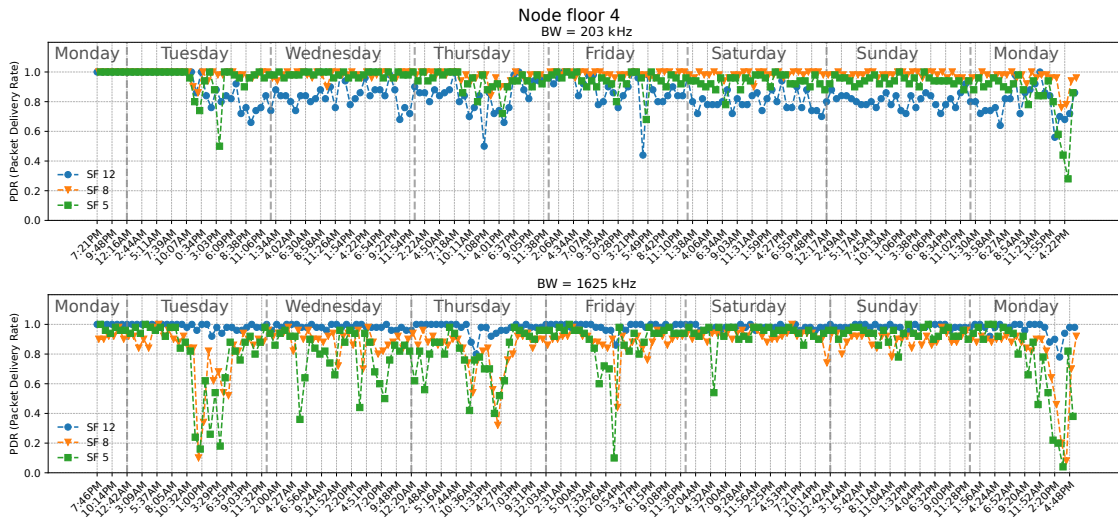
## 5 Results for the long-run experiment

In the second experiment, we studied the effect of daily activities on the communication performance of LoRa 2.4 GHz by studying how the PDR varies over time. 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. These values were chosen as they correspond to the smallest, intermediate, and highest data rate / robustness configurations. The test for each configuration runs in about 30 minutes, allowing us 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, thus lasting one full week.

Fig. 2 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, so we suspect that collisions are occurring between LoRa 2.4 GHz frames and the Wi-Fi frames. This is supported by the fact that the channel used here was centered at the 2.403 GHz frequency, which overlaps with channel 1 (2.401–2.423 GHz frequency range) of the Wi-Fi channels, which is used for the Wi-Fi network in the building. As a reference, with SF=8 and BW=203 kHz, the time on air of frames is only 68.41 ms (almost 13 times lower), hence, SF=8 might be only slightly impacted by Wi-Fi.

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. Compared to when BW=203 kHz, SF12



**FIGURE 2 :** 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.

has a steady performance during the long-run experiment with BW=1625 kHz.

Overall, the best configuration for indoor in our experiment is 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 is only 3.81 Kb/s.

## 6 Conclusions

In this paper, we experimentally evaluated the performance of LoRa 2.4 GHz in a typical indoor environment. We showed that the coding rate has very low impact on the PDR. We also showed that regardless of the configuration, it is still possible for LoRa 2.4 GHz to have good PDR throughout a three-floor building, with only one gateway deployed on site. For example, with 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 a long-run experiment lasting one week, we showed that the PDR is considerably affected by the activities during the working hours of weekdays. Still, the use of robust configurations (such as 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. Finally, 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.

## Références

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