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Hate or Love in the 2.4 GHz ISM band: The Story of LoRa® and IEEE 802.11g

Gwendoline Hochet Derévianckine^{1,2}, Alexandre Guitton³, Oana Iova¹, Baozhu Ning², and Fabrice Valois¹

¹INSA Lyon, Inria, CITI, UR3720, 69621 Villeurbanne, France

²Semtech, Meylan, France

³Université Clermont-Auvergne, CNRS, Mines de Saint-Étienne, Clermont Auvergne-INP, LIMOS, 63000 Clermont-Ferrand, France

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Abstract

Long-Range (LoRa) is one of the main modulation techniques used for Low Power Wide Area Networks (LPWANs). Recently, it has been extended from the sub-GHz band to the 2.4 GHz Industrial, Scientific, and Medical (ISM) band, enabling the construction of a LPWAN that benefits from global interoperability without duty-cycle limitations. However, the coexistence of LoRa with the other wireless technologies of the 2.4 GHz ISM band is a challenging question. In this paper, we make the first performance evaluation of the interference between LoRa and Wireless Fidelity (Wi-Fi) transmissions, by analyzing multiple parameters: LoRa channel occupancy, deployment topology, LoRa physical layer parameters, and the frequency channels used. We also perform simulations to extend our experimental results to other configurations. The performance evaluation is achieved using a generic methodology that can be applied to other wireless technologies. Finally, we provide recommendations for the use and deployment of LoRa that will improve its coexistence with Wi-Fi.

1 Introduction

In the last decade, the Internet of Things (IoT) has gained global momentum. Smart cities, smart metering, and asset tracking are examples of possible applications [28]. Long-Range (LoRa) is one of the main technologies for the Low Power Wide Area Networks (LPWANs) that have flooded the market. Semtech released the LoRa technology that allows communication over long distances (several kilometers) with a low energy consumption, leading to an expected 10 years of battery life. LoRa communication is usually in the sub-GHz band, which

has various regional constraints around the world [18], particularly in terms of transmitting power and permissible channels. A few years ago, Semtech released a version of LoRa for the 2.4 GHz Industrial, Scientific, and Medical (ISM) band. The advantage of this frequency band is that a LoRa chip can be deployed everywhere in the world, as this spectrum has a large set of channels shared by all countries. In addition, the 2.4 GHz ISM band does not impose a duty-cycle, so LoRa can operate at higher data rates. LoRa in the 2.4 GHz ISM band opens the door to new IoT applications, such as accurate localization.

The 2.4 GHz ISM band is an ISM frequency band in the unlicensed spectrum. It is quite crowded already: mostly by Wireless Fidelity (Wi-Fi), but also by other wireless technologies such as Bluetooth (BT) and IEEE 802.15.4-based technologies.

While LoRa has been extensively studied in the sub-GHz band, there have been very few works on LoRa in the 2.4 GHz ISM band. As the 2.4 GHz ISM band is widely used by many wireless technologies, the development of LoRa in this band brings numerous research challenges, such as the coexistence between technologies, including cross-technology and cognitive radio approaches [8]. Thus, in this paper, one of the main questions is "How can LoRa and Wi-Fi coexist in the same frequency band?". Here, we consider the coexistence between two technologies as follows: we are interested in overlapping transmissions and how they survive to interference from each other.

In this work, we make the first performance evaluation of LoRa and Wi-Fi interfering transmissions in the 2.4 GHz ISM band. To study the coexistence of these two technologies, we compute and analyze the frame delivery ratio (FDR), the received signal strength indicator (RSSI), and the signal-to-noise ratio (SNR). We focus on Wi-Fi technology, among all technologies using the 2.4 GHz ISM band, for two reasons. First, Wi-Fi is the main and most known technology used in the 2.4 GHz ISM band. Second, Wi-Fi uses the entire channel bandwidth to transmit frames, which means a large period of interference for LoRa signals, as LoRa uses narrow bandwidths in comparison with Wi-Fi. We thus investigate several LoRa and Wi-Fi parameters (e.g., bandwidth, center frequency, topology) to characterize various periods of overlapping transmissions between these technologies. We designed our experiments to be repeatable and reproducible ¹, and so that each technology is the main source of interference for the other technology being evaluated. Our experimental coexistence study focuses on the physical layer of LoRa and Wi-Fi especially because LoRa has no MAC layer standardized yet in the 2.4 GHz ISM band. We focus on three aspects: (1) the characterization of the coexistence between LoRa and Wi-Fi including the impact of the LoRa occupancy channel rate and the center frequency of both technologies, (2) the use of specific PHY configurations for LoRa to improve the coexistence between LoRa and Wi-Fi, and (3) recommendations to choose a good channel for LoRa transmissions. We formalize the study of LoRa and Wi-Fi coexistence in the 2.4 GHz ISM band with the following research

¹Both the code and the data will be available upon acceptance of the paper. The code can be used according to the terms of the Revised BSD License.

questions:

RQ-1: How to study the coexistence of two wireless technologies using the same frequency?

RQ-2: How does Wi-Fi performance vary as a function of the LoRa occupancy channel rate?

RQ-3: How does the communication reliability of both technologies vary as a function of the frequency offset between LoRa and Wi-Fi center frequency channels?

RQ-4: How does the Wi-Fi communication reliability vary as a function of the used LoRa bandwidth and therefore of the time on air (ToA)?

RQ-5: How does the communication reliability of both technologies vary as a function of the Wi-Fi traffic rate?

RQ-6: Does the topology of the experiment, e.g., the distance between equipment using different wireless technologies, have an impact on the communication performance of both technologies?

RQ-1 to RQ-6 can be resumed into one general research question: **RQ-7:** What is the impact when there are LoRa and Wi-Fi overlapping transmissions on the reliability of both technologies' communication?

The results described in the next sections help us answer each research question through the subsequent contributions:

- We propose a methodology to evaluate the coexistence of LoRa and Wi-Fi in the 2.4 GHz ISM band. Our methodology can be applied to study the coexistence of LoRa with other wireless technologies.
- We make the first experimental evaluation of the coexistence between LoRa and Wi-Fi. We design and implement an experimental setup where we conceive a gateway-to-end-device communication synchronization to automatize our experiments. We then compute the FDR as a metric of connectivity when the medium is shared for both evaluated technologies. We also log and analyze the RSSI and the SNR to characterize the radio environment of our experiments. The results permit to characterize the coexistence and can also serve as a basis for future works to improve the coexistence between LoRa and Wi-Fi.
- We extend the experimental results through simulations based on our performance evaluation setup by testing more configurations and parameters than is possible on real hardware.
- We establish a list of recommendations, especially on the best LoRa configurations to improve both LoRa and Wi-Fi performance, and we propose how to choose the LoRa channel.

The rest of the paper is organized as follows: in Section 2, we give a short description of the 2.4 GHz ISM band, and the technical background of Wi-Fi and LoRa. In Section 3, we provide an overview of existing approaches for studying the coexistence between two wireless technologies. In Section 4, we present our methodology. In Section 5, we explain the resulting setup which allows us to

evaluate the coexistence of LoRa with any other wireless technology, and we also provide benchmark values for the evaluated technologies. In Section 6, we explain the results of our performance evaluation, and in Section 7, we discuss and highlight general recommendations for a good coexistence between LoRa and Wi-Fi, as well as several directions to investigate in the future. Finally, in Section 8, we conclude with the main lessons learned.

2 Technical background

In this section, we give a brief description of the 2.4 GHz ISM band, and the technical background of Wi-Fi and LoRa.

2.1 The 2.4 GHz ISM band

The ISM frequency bands are defined by the International Telecommunication Union (ITU) Radio Regulations (see article 5 from [17]) for non-communication purposes. Each country adapts the radio regulations article depending on national, or continental, limitations. For instance, in the United States the Federal Communications Commission (FCC) describes the rules of the ISM bands, and in particular, the allowed frequencies and transmission powers. In Europe, the European Telecommunications Standards Institute (ETSI) has the same role as the FCC.

Nowadays, one of the most popular device using the 2.4 GHz ISM band is the microwave oven. Other applications are cordless phones, garage door openers, and baby monitors. More recently, the IoT community has shown interest in using ISM bands with technologies such as Z-Wave [37] and LoRa. Even if the initial purpose of the ISM bands was not for communications usage, their unlicensed properties make them appealing for telecommunications applications.

The counterpart of using ISM bands is that the technologies must tolerate interference from (1) other users of the same technology, and (2) users of another technology in the same frequency band. The 2.4 GHz ISM band is now a congested frequency band (see Figure 1) mainly used by short-range wireless communications systems. One of the most attractive features of the 2.4 GHz ISM band is the lack of duty-cycle limits allowing higher data rates than in sub-GHz bands.

Figure 1 illustrates the characteristics and the coexistence challenges of the main wireless technologies using the 2.4 GHz ISM band: Bluetooth[®], BLE[®], IEEE 802.15.4, and IEEE 802.11g (the latest IEEE 802.11 standard designed for the 2.4 GHz ISM band only). We also represent the Semtech proposition for LoRa channels in the 2.4 GHz ISM band. These technologies are different in terms of frequency channels, bandwidth, and maximum transmission power, as described in Table 1. We notice that these five technologies overlap and thus are exposed to cross-technology interference.

In this work, we are interested in LoRa transmissions in the 2.4 GHz ISM band, which have very different properties from existing technologies that use

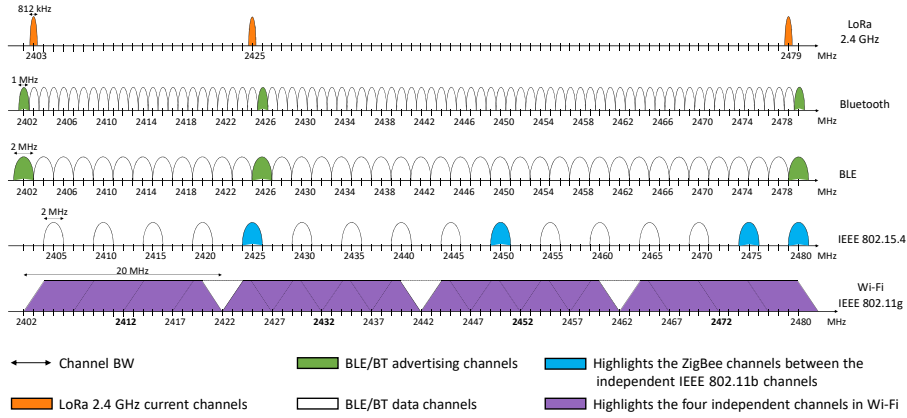


Figure 1: Spectrum occupancy of LoRa and the main wireless technologies using the 2.4 GHz ISM band.

| Technology | Number of channels | Overlapping channels? | Bandwidth (in kHz) | Maximum transmission power (in dBm) |
|---------------|--------------------|-----------------------|-----------------------|-------------------------------------|
| LoRa | 3 | No | 203, 406, 812 or 1625 | 13 |
| Bluetooth | 79 | No | 1000 | 20 |
| BLE | 40 | No | 2000 | 10 |
| IEEE 802.15.4 | 16 | No | 2000 | 18 |
| IEEE 802.11b | 13 | Yes | 22000 | 20 |
| IEEE 802.11g | 13 | Yes | 20000 | 20 |

Table 1: General characteristics of the main wireless technologies using the 2.4 GHz ISM band.

this frequency band. For example, Wi-Fi usually uses the 80 MHz band of the 2.4 GHz spectrum with 20 MHz bandwidth channels, while the largest available bandwidth for LoRa is 1625 kHz.

In this context, Semtech proposed three channels for LoRa [31], located 1 MHz away from the BLE advertising channels, and at the edge of the IEEE 802.11b independent channels. This channel allocation proposition (see Figure 1) means that the channel centered at 2403 MHz overlaps with the Wi-Fi channel 1 (centered at 2412 MHz), the channel centered at 2425 MHz is located outside of the most commonly used Wi-Fi channels (1, 6 and 11), and the last one centered at 2479 MHz, is the only one of the LoRa channels outside the Wi-Fi spectrum. As a LoRa channel is narrower than a Wi-Fi channel, the Wi-Fi can completely overlap various LoRa channels. Analyzing the occupancy of the 2.4 GHz ISM band is of uttermost importance to validate this choice of channels for LoRa, as well as to allow a fair usage for the original users of this frequency band.

2.2 Wi-Fi

The IEEE 802.11 set of standards defines the physical and the medium access control layers for wireless local area networks (WLANs). It is the basis for wireless network products using the Wi-Fi brand. Depending on the version of the standard, the modulation scheme, the channel bandwidth and the data rates change.

The IEEE 802.11 set of standards describes mechanisms that ensure the fair sharing of the medium and guarantee the radio link connectivity. Wi-Fi implements the following mechanisms: (1) the carrier sense multiple access with collision avoidance (CSMA/CA) that is used to access the medium, including listening to the channel to detect if it is free to transmit data, and to manage collision, (2) the modulation coding scheme (MCS) which ensures connectivity by adapting the transmission data rate and the redundancy of data frames; it can also change the modulation depending on the link budget, and (3) the acknowledgments (ACK) which provide reliability to Wi-Fi transmissions.²

In our daily life, most of the Wi-Fi access points (APs) are based on IEEE 802.11n (2009) [11], except for the new ones, which are based on the latest widely distributed IEEE 802.11 standard: the IEEE 802.11ax (2021) [12]. The IEEE 802.11n standard improves the IEEE 802.11g (2003) standard: (1) an additional bandwidth of 40 MHz is available, (2) the maximum theoretical data rate goes up to 150 Mbps, and (3) a multi-input multi-output (MIMO) feature, allowing four simultaneous flows, is implemented. In this work, we focus on the IEEE 802.11g standard. The IEEE 802.11g standard uses an orthogonal frequency-division multiplexing (OFDM) modulation scheme along with 20 MHz bandwidth channels, with data rates between 6 and 54 Mbps. The choice of IEEE 802.11g is a software constraint caused by the networking tool (`Scapy`) used to generate the Wi-Fi traffic. `Scapy` automatically selects the IEEE 802.11 standard from the IEEE 802.11 standards supported by the wireless card. In our case, the IEEE 802.11g standard with a 12 Mbps data rate was selected.

2.3 LoRa

LoRa [30] is a proprietary modulation scheme based on chirp spread spectrum (CSS). LoRa usually uses the sub-GHz bands (i.e., 433 MHz or 868 MHz frequency band in Europe). The upper layers are standardized in the LoRaWAN[®] standard [21]. LoRaWAN networks implement an adaptive data rate (ADR) mechanism, which is similar to the MCS mechanism implemented in Wi-Fi. It adapts the radio configuration (spreading factor and transmit power) based on the gateway link budget to ensure connectivity between an end-device and the gateway.

A LoRa signal is encoded using a sequence of chirps (see Figure 2) which are frequency sweeps over a given bandwidth. A chirp is either an up-chirp or a down-chirp, depending on whether its frequency increases or decreases. The

²Keep in mind that our experiments are focused solely on the physical layer, hence none of these mechanisms are active.

starting frequency of a chirp encodes the value of the chirp. A frame starts with a preamble in order to synchronize with the receiver. The preamble ends with 2.25 down-chirps which serve as the start of frame delimiter (SFD). The data are encoded in the following chirps. In Figure 2, we highlighted with a dotted rectangle the first chirp of the header. We highlight that apart from the chirps of the preamble all starting at frequency 0, each chirp of a LoRa frame is different. LoRa transmissions are either uplink or downlink. To demodulate the frame, the receiver synchronizes with the transmitter, and then it uses the highest peak of energy, resulting from the fast Fourier transform (FFT) of each chirp, to decode the data sent. The LoRa modulation and demodulation is proprietary, however, researchers have tried to analyze and describe the process through a mathematical description [33].

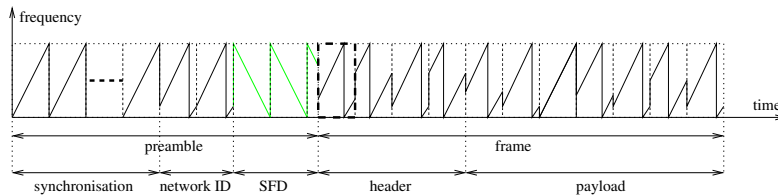


Figure 2: Example of an uplink LoRa frame. Up-chirps are represented in black, and down-chirps in green. The 2.25 down-chirps are used for time and frequency synchronization. [8]

LoRa transmissions are a trade-off between energy efficiency, and by consequence data rate, and reliability. This trade-off is controlled by the combination of three physical parameters: the spreading factor (SF), the bandwidth (BW), and the coding rate (CR). LoRa chipsets [32] support different SFs. A large value for SF gives more robustness, and a larger communication range, while a small value allows a higher data rate. In 2017, Semtech released a version of LoRa operating in the 2.4 GHz ISM band [32] that includes a smaller SF and larger bandwidths, which enables the data rate to be increased. We summarize the possible values of the LoRa parameters in Table 2.

| | LoRa sub-GHz | LoRa 2.4 GHz |
|--------------------|-----------------------------------------------------|---------------------------------------------------------------|
| Spreading Factor | 6 to 12 | 5 to 12 |
| Bandwidth (in kHz) | 125, 250, 500 | 203, 406, 812, 1625 |
| Coding Rate | 4/5, 4/6, 4/7, 4/8 | |
| Data rates | 183 bps - 62.5 kbps | 297 bps - 202 kbps |
| Link budget | 168 dB (SX1276 chip) | 144.5 dB (SX1280 chip) |
| Energy consumption | Tx: 28 mA at 13 dBm Rx: 11.5 mA (SX1276 chip) | Tx: 24 mA at 12.5 dBm Rx: 7 mA for BW=812 (SX1280 chip) |

Table 2: LoRa parameters and characteristics.

Presently, there is no MAC layer standardized for LoRa in the 2.4 GHz ISM band. Indeed, to the best of our knowledge, the LoRaWAN standard is currently

emulated above the physical layer of LoRa in the 2.4 GHz ISM band through an additional set of parameters [31].

3 Related work

Since there are several systems communicating in the same environment, the question of coexistence is raised. We define coexistence as how much a technology is robust to overlapping transmissions, i.e., interfering signals, from another technology. This problem has already been widely studied as several technologies use the 2.4 GHz ISM band to communicate, either using network simulations or real testbeds. However, the emergence of LoRa in this frequency band imposes more studies into eventual coexistence issues. In this section, we focus on the methodology applied to study the coexistence, rather than on the results obtained.

One of the most common devices using the 2.4 GHz ISM band is the microwave oven. At the end of the 1990s, Wi-Fi and Bluetooth started using the same frequency band, leading to the first coexistence issues, as both technologies use the entire frequency spectrum of the 2.4 GHz ISM band. As these technologies have been widely studied, we decided to apply a systematic literature review (SLR) process [23] to select the articles of our state of the art.

3.1 Systematic Literature Review

First, we searched five online databases (namely, IEEE Xplore, ACM Digital Library, Springer Link, Wiley Online Library, and ScienceDirect) for articles corresponding to the combination of keywords “LoRa” or “2.4 GHz” with “interference” or “coexistence”. We also added papers manually which correspond to Google Scholar alerts containing the words “LoRaWAN”, “LoRaWAN sub-GHz”, “IoT LoRaWAN”, “LoRa 2.4” or “interference 2.4”. These alerts were defined to keep abreast of recent papers published on these subjects. The inclusion criteria (the first two being mandatory) to select the potential papers of our state of the art were:

- studies in English language,
- studies that are peer-reviewed (i.e., no application notes, white papers, or papers from arXiv),
- studies that propose techniques to characterize the coexistence/interference between, at least, two technologies,
- studies that focus on LoRa coexistence/interference regardless of the frequency band,
- studies that focus on the 2.4 GHz ISM band coexistence/interference regardless of technology.

We obtained 285 papers. From our manual addition of papers, as well as from the search on five online databases, there was a possibility of having duplicated papers. The various databases that we interrogated to retrieve papers can reference the same papers depending on the journals or the conferences where articles are submitted. After removing the duplicates, we obtained 227 papers.

After that, we manually evaluated each article based on the title and the abstract. We excluded studies published before 2012 and studies that despite mentioning LoRa or the 2.4 GHz ISM band:

- are about intra-technology interference,
- are for other networks than WLANs and WMANs (e.g., WBANs, WPANs),
- focus on designing a hardware,
- focus on the impact of a specific feature of the devices e.g., localization accuracy,
- evaluate the occupancy of the band,
- are about improving the coexistence or mitigating interference,
- compare a licensed technology with an unlicensed technology e.g., LTE and Wi-Fi.

After the exclusion step, we reduced the number of articles to 39, which we classified depending on the rank of the conference / journal where the study was published according to CORE ³ and Scimago ⁴. We kept the works published in A+, A, and B conferences, as well as Q1 and Q2 journals. We also kept the non-ranked conferences / journals and evaluated the relevance of the studies.

In the last step, we performed a full-text evaluation on all papers. We thus read 35 articles. We kept the studies where (1) the evaluated metrics were linked with the performance of the evaluated technologies such as throughput, communication range, or packet error rate (PER), and (2) there was an implementation of the coexistence/interference evaluation i.e., we rejected the studies with only theoretical models, but we accepted studies combining theory with simulations or experiments. We ended our SLR process with 16 articles which are synthesized in Table 3, based on the methodology used to investigate the coexistence (i.e., network simulation or real experiments).

3.2 Methodology to study the coexistence

The methodologies to study the coexistence can be divided into three approaches: (1) theoretical, (2) simulations, and (3) experiments. These approaches generally characterized the coexistence in terms of percentage of occupation of a channel, bit error rate (BER), or FDR.

Theoretical approaches rely on a mathematical model, which is an abstraction of the real world. The environment and the behavior of technologies are

³<http://portal.core.edu.au/conf-ranks/>

⁴<https://www.scimagojr.com/>

| Ref | Simulations | | Experiments | |
|----------------------------------|------------------------------|----------------------------------|------------------------------------------|-------------------------|
| | discrete events e.g., NS3 | time-independent e.g., MATLAB | commercial off-the-shelf equipment | lab setup e.g., USRP |
| [6] [14] [15] [8] [19] [22] [25] | | | X | |
| [9] [29] | | X | | |
| [10] | X | | | |
| [13] [26] [27] | | | | X |
| [24] | | X | X | X |
| [34] [36] | X | | X | |

Table 3: State of the art classification.

represented through mathematical equations. While this approach gives insights on the coexistence, it cannot evaluate nor represent unexplained phenomenon present in a real deployment. For example, usually equations only consider one propagation path, whereas in the real world, a wireless communication is normally multi-path.

Simulations-based approaches face the same issues: we cannot implement a behavior that we are not aware of. Hence, we run simulations to confirm the results we are expecting. Theoretical and simulation approaches have the advantage of giving boundary results on the coexistence.

In our SLR process, the theoretical approaches were rejected unless they were combined with simulation validations. Some studies use mathematics to generate a loss model [10]. Some works perform real world measurements, like noise measurements, and use the collected data as the entry of the simulation model. This allows the authors to estimate the probability of losses or the probability of interference [34] [36]. Several studies start the coexistence study using equations or simulations and then run experiments to validate their hypothesis [22] [24]. Very often, when the coexistence study is simulation-based only, the interfering signal is not necessarily associated with a given technology. We rather evaluate an interferer signal such as singletone interference or wide-band noise interference under Gaussian or Rayleigh channels [29]. Simulations can also focus on varying one parameter of the interfering signal, such as the bandwidth [9].

The experimental approach is complementary to theoretical and simulation approaches. As experiments take place in the real world, they are subject to the variations of the environment but also to the potential constraints, limitations, and failures of the equipment.

One way of studying coexistence is to assess the frequency band occupancy. Irrespective of the technology, we focus on the degree of use of a frequency band, i.e., the percentage of time the channel is occupied and on what frequency. This enables us to identify the potential interference risks when a technology is about to be deployed in a given environment [19]. We can also reverse the previous approach: e.g., we evaluate the performance of a technology in terms of communication range, and we assume that the observed losses may be the result

of other technologies present in the environment. We thus obtain preliminary results that assess the relevance of studying coexistence or not [14] [8]. Using experiments to study the coexistence can take many forms. We can be interested in the instant at which the interference occurs on the interfered signal (preamble, payload, etc.), as well as in the power difference between the two interfering signals. A common approach is to study the impact of the frequency channel offset on performance [24] [26] [27]. Depending on the study, the impact on the performance of one technology on another is either one way [13], or mutual [22]. All these studies, based on experiments, evaluate various types of environments: controlled, e.g., anechoic chamber [15] [25], or real-world deployments, e.g., indoor [6].

3.3 Wi-Fi coexistence

The impact of Wi-Fi on other wireless technologies has already been widely studied. From real-world noise measurements Wi-Fi is identified as the main source of interference in a city center [36]. It has also been shown that interference between overlapping Wi-Fi and ZigBee channels, quickly deteriorates the BER when signal powers are different. For power imbalances of -17.3 to -16.9 dB, the ZigBee’s BER for an IEEE 802.11b interfering signal is 10^{-7} and 0.027 respectively [24]. The same occurs when Wi-Fi interferes with Bluetooth. The Bluetooth goodput drops from 1.2 Mbps to 0.59 Mbps when the transmitters of both technologies are collocated [6]. BLE has a shorter time on air than IEEE 802.15.4, making it less vulnerable to IEEE 802.11b interference. For example, when BLE and IEEE 802.15.4 use the same center frequency as the IEEE 802.11b channel, the packet error rate (PER) is 0.1 and 0.5 respectively [22].

Table 4 summarizes the studies, extracted from our SLR process, on the impact of Wi-Fi on other technologies of the 2.4 GHz ISM band. We conclude that Wi-Fi has a significant impact on the performance of other wireless technologies, while Wi-Fi seems unaffected. Our work aims to study whether Wi-Fi presents the same robustness to LoRa interference.

| Ref | Technology | Metric | Robustness |
|------|-------------------------------------|-------------------|--------------------------------------------|
| [6] | Wi-Fi over ZigBee/Bluetooth | FER Throughput | Wi-Fi +++ ZigBee - - Bluetooth - - - |
| [22] | IEEE 802.11b over BLE/IEEE 802.15.4 | PER | BLE - IEEE 802.15.4 - - - |
| [24] | IEEE 802.11b/g over ZigBee | BER | ZigBee - - - |
| [36] | Wi-Fi over IEEE 802.15.4 | PER | IEEE 802.15.4 - - - |

Table 4: Wi-Fi coexistence studies.

3.4 LoRa coexistence

LoRa robustness to interference has also been widely studied. Simulations works have demonstrated the sensitivity of LoRa to narrowband interference [9] and to

Rayleigh channel interference, but LoRa has a good resistance to Gaussian channel interference [29]. LoRa and SigFox are usually considered to be competitors, thus many studies focus on their performance [19] [34]. The probability of interference between LoRa and SigFox, for the same duty-cycle and in the worst case (-130 dBm of received signal strength), is 21% for LoRa using SF12, and 36% for SigFox [10]. The moment at which the interference occurs on the LoRa signal has a significant impact. A SigFox interference during the LoRa preamble leads to a packet loss ratio (PLR) of 28% [13]. Experiments also showed that LoRa is more robust to IEEE 802.15.4 interference than the contrary. For the same center frequency, LoRa packet reception rate (PRR) is around 60% while the IEEE 802.15.4 PRR is almost 0% [25].

The deployment of LoRa in the 2.4 GHz ISM band brings new coexistence challenges, particularly with Wi-Fi and Bluetooth. Studies showed that for an IEEE 802.11b co-channel interference i.e., the same center frequency, LoRa can achieve a BER of 10^{-2} with a carrier-to-interference (C/I) ratio equal to -42 dB using SF12/BW125 [26]. The robustness of LoRa to Bluetooth interference is highly dependent on the LoRa configuration (SF, BW) used. For an SF5/BW203 LoRa signal, the protection ratio (PR) is around -18 dB, and is approximately -25 dB for all SF with BW1625 [27]. From Table 5, we conclude that the modulation and the communication parameters (SF, BW, CR) used by LoRa are key factors of its robustness to external interference.

| Ref | Technology | Metric | Robustness |
|------|---------------------------------|-----------------------------|---------------------------------------------------------|
| [10] | LoRa and SigFox (mutual) | Probability of interference | LoRa + SigFox ++ |
| [13] | SigFox over LoRa | PLR | LoRa - |
| [25] | LoRa and IEEE 802.15.4 (mutual) | PRR | LoRa ++ IEEE 802.15.4 - |
| [26] | IEEE 802.11b/n over LoRa | BER | LoRa under IEEE 802.11b + LoRa under IEEE 802.11n ++ |
| [27] | Bluetooth over LoRa | PR | LoRa + |

Table 5: LoRa coexistence studies.

In comparison with the previously cited studies, our work makes the first study of the mutual effects of LoRa and Wi-Fi in the 2.4 GHz ISM band through real-life indoor experiments.

4 A new methodology for coexistence experiments

In this section, we present our original methodology to study the coexistence of LoRa and Wi-Fi in the 2.4 GHz ISM band, as well as the metrics and the networking tools used to setup our performance evaluation. We designed our experiments to be repeatable and reproducible: our experiments are automated and use commercial off-the-shelf (COTS) equipment. We provided the

official gateway ⁵ and end-device ⁶ public code. We did not provide the code we modify for our experiments as we are working on the development branch of the Semtech code which is not public. We made available the experimental data we collected, and the post-processing scripts ⁷. As the environment in which our experiments take place has an impact on the results, we design an experimental scenario using a minimal, easily transportable setup. This permits us to evaluate different environments at different times of the day.

4.1 Coexistence experiment design

We have shown in Section 3 that the few available studies on the robustness of LoRa to interference only consider how the interfering technology affects LoRa performance. Nowadays, Wi-Fi APs are deployed in every building and used by everyone at universities, in working offices, and in residential areas. We need to experimentally evaluate the feasibility of deploying LoRa in the 2.4 GHz ISM band where the coexistence with Wi-Fi might be challenging. In fact, if the impact of LoRa drastically degrades the reliability of Wi-Fi communication, it is likely that LoRa 2.4 GHz will not be used. For this reason, we decided to study the reciprocal impact of LoRa and Wi-Fi overlapping transmissions on each other. This aims to answer **RQ-7**: "What is the impact when there are LoRa and Wi-Fi overlapping transmissions on both technologies' communication reliability?" Before running our coexistence performance evaluation, we propose a methodology to answer **RQ-1**: "How to study the coexistence of two wireless technologies using the same frequency band?"

We design our experiments to have time periods where only one technology is transmitting without interference of the other technology and considering several LoRa configurations. The free-interference periods aim to setup a baseline for each technology we evaluate. This way we can compare the communication reliability in the presence and absence of interference and thus analyze how much interference prevents transmissions. Figure 3 shows the timeline we designed for our experiments, which enables us to automatize the experiments through the LoRa gateway-to-end-devices communication protocol, and Python scripts for Wi-Fi, described in Subsection 4.2.

We design the experiments with four phases: (1) only Wi-Fi is transmitting to have a benchmark for Wi-Fi performance, (2) LoRa starts transmitting and thus interferes with the Wi-Fi traffic, (3) Wi-Fi stops transmitting leaving LoRa transmitting alone, to have a benchmark for LoRa performance, and finally (4) Wi-Fi starts transmitting and interferes with the LoRa traffic. These phases allow us to compute the FDR of Wi-Fi alone, the FDR of Wi-Fi when LoRa is transmitting, the FDR of LoRa alone, and finally the FDR of LoRa when Wi-Fi is transmitting, for a given LoRa configuration at a given time. The duration of each phase is customizable. We conceived our experiment timeline

⁵https://github.com/Lora-net/gateway_2g4_hal

⁶<https://github.com/Lora-net/SWL2001/tree/master>

⁷Both the code and the data will be available upon acceptance of the paper. The code can be used according to the terms of the Revised BSD License.

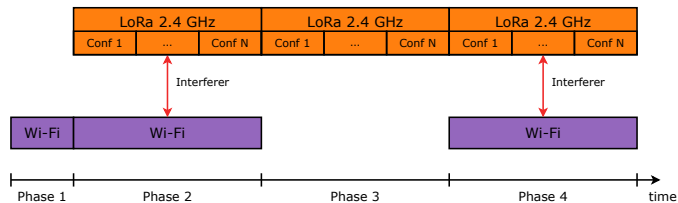


Figure 3: Experiment timeline in 4 phases: (1) Wi-Fi only, (2) Wi-Fi + LoRa, (3) LoRa only, and (4) LoRa + Wi-Fi.

to guarantee that: (1) a representative number of frames is sent per LoRa configuration to compute the FDR, and (2) each phase lasts the same period for each LoRa configuration. For example, if the duration of Phase 1 is two minutes, Phase 2 also lasts for two minutes per LoRa configuration. Each LoRa configuration has a different ToA depending on the combination of parameters used, in particular SF and BW values. Hence, to ensure the same duration for each LoRa configuration, we modify the number of frames, and the interval between two frames, during a period.

For a fair comparison of LoRa and Wi-Fi performance, we evaluate only the communications at the physical layer for both technologies. Indeed, as discussed in Subsection 2.3, no MAC layer is standardized for LoRa in the 2.4 GHz ISM band yet. On the Wi-Fi side, we do not consider the mechanisms ensuring the reliability of the communications mentioned in Subsection 2.2. This way, we focus on the transmissions of both technologies, evaluating only the impact of their configurations and modulations on their communication reliability. We consider our results as a lower bound since results represent the raw performance of LoRa and Wi-Fi in an overlapping transmission scenario considering the absence of interference mitigation mechanisms.

To evaluate the impact of the LoRa parameters on the performance of overlapping transmissions (**RQ-2**), we studied typical LoRa configurations, i.e., those providing the greatest communication range (SF12, BW 203) and the highest data rate (SF6, BW 1625), as well as intermediary configurations (SF9, BW 812). We refer to a configuration as a triple that contains (1) the number of bits encoded into a chirp, called the spreading factor, (2) the bandwidth, and (3) the coding rate, which is used in LoRa to increase the redundancy of bits in the frames, and thus add robustness.

We mentioned in Section 2 the bandwidth difference between LoRa and Wi-Fi: between 203 kHz and 1625 kHz for LoRa, and 20 MHz or 22 MHz for the IEEE 802.11g and IEEE 802.11b standards respectively. We vary the center frequency of the LoRa channel to change the overlap between LoRa and Wi-Fi to observe the impact of the chosen LoRa channel (**RQ-3** and **RQ-4**). Our timeline experiment represents the evaluation of various LoRa configurations for one LoRa center frequency. In our case, one experiment is composed of various repetitions of the timeline where we vary the LoRa channel and evaluate the

same LoRa and Wi-Fi configurations for each LoRa channel.

As the location of the LoRa and Wi-Fi equipment has an impact on the results, we designed the worst case topology (**RQ-6**) where the LoRa transmitter is next to the Wi-Fi receiver and conversely (see Figure 4). This is the worst case because each time the LoRa gateway receives a frame, there is a possibility that a Wi-Fi frame is transmitted simultaneously, meaning that our transmissions will suffer from the highest possible interference. LoRa frames are sent at the maximum transmit power (13 dBm). So if the LoRa end-device sends a frame and a Wi-Fi frame arrives at the receiver at the same moment, the Wi-Fi frame could be lost because of a degraded RSSI due to signal propagation losses and interference coming from the LoRa transmission.

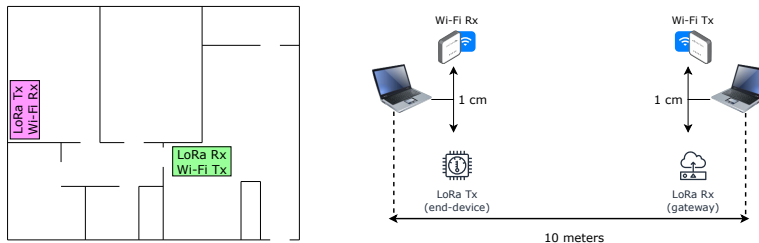


Figure 4: Architecture of the apartment (left). Experimental setup (right) composed of two laptops with wireless interfaces in monitor mode, one LoRa gateway, and one LoRa end-device. Transmitters and receivers of the same technology are approximately 10 meters away.

For simplicity, we will use Wi-Fi to refer to the IEEE 802.11g PHY layer for the rest of this article.

The characteristics of LoRa and Wi-Fi are very different. Thus, we must carefully choose the payload size to use in our experiments. LoRa typical applications have low data rates and send a small amount of data over long distances. We set the payload size to have a reasonable ToA and also to represent a common payload size that can be found in LoRa applications [3]. So, we use a 20 bytes payload, resulting in a ToA between 3 ms and 1054 ms depending on the LoRa configurations. Meanwhile, Wi-Fi typical applications have high data rates and send long data frames over short distances. The usual Wi-Fi payloads vary depending on the type of data sent. We scanned our environment with **Wireshark**, and observed a payload size between 190 and 350 bytes for beacon frames, and a payload size between 1200 and 1460 bytes for data frames. So, we decided to use 1400 bytes for the Wi-Fi payload size to cover a wide range of Wi-Fi applications.

Regarding the traffic model, we use a constant bit rate (CBR) for both LoRa and Wi-Fi. To be fair, and to compare the results of the different LoRa configurations, we use the same occupancy channel rate (see Equation 2) for each evaluated LoRa configuration. The typical Wi-Fi control traffic (e.g., beacon) is periodic. In our experiments, we reproduce the Wi-Fi traffic periodicity by

using 100 ms as it is the standard inter-beacon frame time. By default, a Wi-Fi transmitter retransmits up to 7 times a frame that is not being acknowledged by the receiver. As the ACK mechanism is not present at the PHY layer, it explains why our receiver logs contain 8 frames for each transmitted frame. The first frame is the original one and the seven following frames are tagged with a 1-bit value indicating that this is a retry transmission. So, a frame is transmitted exactly every $\frac{100 \text{ ms}}{8} = 12.5 \text{ ms}$. This ensures a period of coexistence between LoRa and Wi-Fi even for the shortest LoRa frames. The minimal interference period between LoRa and Wi-Fi original frame is 1 ms. The shortest LoRa frames last approximately 3 ms while the IEEE 802.11g frames last 1 ms.

$$\text{occupancy channel rate} = \frac{\text{time on air} \times \text{number of frames to sent for one LoRa configuration}}{\text{test duration of one LoRa configuration}}, \quad (1)$$

with time on air extracted from [32]

$$\text{time on air} = \frac{2^{SF}}{BW} \times N_{symbol}. \quad (2)$$

4.2 Coexistence gateway-to-end-devices communication protocol

To automatize the LoRa part of the experiments, we need a protocol between the gateway and the end-device to ensure that they are using the same configuration. The end-device has to run a certain number of configurations depending on the series of experiments, which must be repeated several times to average the possible variations in the results. The designed protocol is presented in Figure 5 and allows to initiate the communication link between the end-device and the gateway. The gateway activates the end-device by sending a downlink frame, denoted **SRT-Ed** (which stands for **START-End-device**). Then, the end-device sends N uplink data frames with the configured parameters. An end-device can run different configurations, one after the other. For example, End-device 1 in Figure 5 runs three different LoRa configurations. **Cnfg(i, j)** indicates that the end-device is sending the i -th frame of the j -th configuration. When the end-device finishes sending all the data frames for each configuration, it informs the gateway by sending a specific message: **END-Ed**. Then, the gateway can reconfigure itself and move to the next center frequency to be evaluated, or to the next set of configurations.

The automation of the Wi-Fi part consists of a timer in the Python scripts used to generate the frame transmissions because we considered a single Wi-Fi configuration. The timer is chosen to allow the synchronization of the four phases (see Figure 3).

The proposed protocol is scalable and can support multiple end-devices either to have parallel LoRa transmissions or by scheduling only one end-device transmitting at a given time.

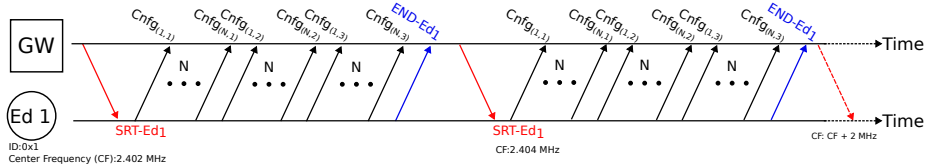


Figure 5: Protocol used between the LoRa gateway and end-devices. Red lines represent downlink end-device activation frames, blue lines represent uplink control frames, and black lines represent uplink data frames for each configuration.

4.3 Coexistence evaluation metrics

Our performance evaluation aims to characterize the coexistence between LoRa and Wi-Fi at the physical level. We are interested in the communication reliability achieved by a technology under interference, i.e., with overlapping transmissions, from another technology. We thus look at the number of frames lost and compute the FDR as a metric of reliability when the medium is shared for both evaluated technologies. We also log and analyze the RSSI and the SNR to characterize the radio environment of our experiments.

The **FDR** indicates the proportion of received frames to sent frames and is a commonly used metric for PHY layer performance evaluation. We do not evaluate any retransmission mechanism for LoRa or Wi-Fi. This metric gives insights on the robustness of a wireless link between two devices. Based on the FDR it is possible to evaluate the reliability and the communication range of a transmission between devices depending on the environment, on the configuration setup, and other physical parameters such as the antenna reception gain. We compute the FDR by logging frames at the transmitter and the receiver sides for both technologies. As our experiments take place in an open indoor environment, we cannot control all the Wi-Fi access points. Thus, even if we scan our environment, we do not know the volume of data transferred by other interfering traffic. For the Wi-Fi, we filter the source and destination MAC addresses to count only the frames we are generating. Note that, to compute the FDR we consider only the original Wi-Fi frames even if the "retry" frames also overlap with LoRa frames. Additionally, we do not evaluate any retransmission mechanism for LoRa or Wi-Fi, as we only considered the PHY layers of both technologies.

Usually, the **RSSI** is a metric that gives the signal strength of the radio link for each frame. Frame losses are likely to happen if the signal strength of the radio transmission is too low. However, according to the SX1280 datasheet [32] (LoRa chip for the 2.4 GHz ISM band), the RSSI is computed as the energy on the reception bandwidth and not the signal strength of frames received by the gateway. In our case, analyzing the RSSI variations can explain and complement the results obtained by computing the FDR. Generally, RSSI values vary between -30 dBm and -90 dBm for Wi-Fi, and between -20 dBm and -140 dBm for LoRa [32].

The **SNR** is a metric that allows to quantify interference and noise. We compute the SNR as the average signal-to-noise ratio of frames received by the gateway. Due to our topology where equipment of different technologies are collocated, we expect that analyzing the SNR will not provide any added value. Indeed, equipment of different technologies will experience a similar noise; so the SNR does not give us any additional information. However, we measure the SNR during our experiments and then analyze it to confirm or deny our assumption.

4.4 Networking Tools

To retrieve and compute these metrics, we use the following networking tools.

Scapy: This is a Python library that permits to forge and send IEEE 802.11 frames through the wireless interface of a computer. We specify the source and destination MAC addresses of the frames, the wireless interface to send the frames, the payload size, and the data payload to send. As far as we know, this Python library cannot change directly the IEEE 802.11 standard, or the MCS, used for the transmissions [2]. However, *Scapy* can be used to evaluate different versions of the IEEE 802.11 standards. In our configuration, depending on the wireless card of the laptop used to forge the *Scapy* frames, *Scapy* selects either the IEEE 802.11b or the IEEE 802.11g standard although our wireless interface supports more recent standards such as IEEE 802.11n and IEEE 802.11ac. Remember that for using *Scapy* the wireless interfaces have to support the monitor mode.

Tcpdump: When used in monitor mode, *Tcpdump* permits to observe the IEEE 802.11 headers of the Wi-Fi frames and the control frames (beacon, ACK). We use this command line utility program to monitor and log all the traffic sniffed through the wireless interface of the transmitter and the receiver. We are especially interested in the IEEE 802.11 traffic, which permits us to analyze our own Wi-Fi traffic. *Tcpdump* stores, information such as the source and destination MAC addresses, the IEEE 802.11 standard used to send the frame, the data rate, and the RSSI. By post-processing this information, we can compute the FDR and observe the RSSI variations over our experiments ⁸.

Netdownlink utility: The `netdownlink` utility is part of the gateway code owned by Semtech. When bound with the packet forwarder of the LoRa gateway, the `netdownlink` utility allows to save each frame received by the LoRa gateway into a CSV file. It retrieves information such as the LoRa configuration used to send the frame (SF, BW, CR), the RSSI, the SNR, the payload size, and the payload content. This log enables us to compute the FDR, and observe the RSSI, and the SNR, variations that can explain the frame losses.

We use two additional networking tools: *Wireshark* ⁹ and *Netspot* ¹⁰. *Wireshark* allows us to visualize the *Tcpdump* logs. We also confirm that the MCS used for the Wi-Fi traffic was fixed since the MCS field of the Wi-Fi

⁸<https://www.tcpdump.org/>

⁹<https://www.wireshark.org/>

¹⁰<https://www.netspotapp.com/>

frames was empty. `Netspot` allows us to visualize the Wi-Fi APs present in the environment of our coexistence as well as their RSSI (min, max, and average values).

5 Coexistence experimental description

In our experimental coexistence evaluation, we analyze a wide set of parameters that could impact LoRa and Wi-Fi communication reliability. The parameters to evaluate are chosen to answer the questions **RQ-2** to **RQ-6** on the performance in indoor environment of overlapping LoRa and Wi-Fi transmissions in the 2.4 GHz ISM band.

5.1 General description and parameters

To this end, we design and conduct two series of experiments:

1. **General experiment.** This experiment is designed to evaluate the impact of the LoRa traffic load and the LoRa channel on the performance of both technologies. In this series, we use three different combinations of SF, BW, and CR, for a LoRa occupancy channel rate of 10%.
2. **Bandwidth experiment.** This experiment is designed to evaluate the impact of a given BW on the LoRa and Wi-Fi performance. We focus on the BW for two reasons. First, the interference is spread over the entire BW of the interfered signal. So, we evaluate the impact of interference as a function of the BW of the interfered technology. Second, changing one parameter in a LoRa configuration modifies the time on air of a frame, and we are studying BW impact, and thus the ToA impact, on the performance of LoRa and Wi-Fi respectively. For that, we use fixed SF and CR values for a LoRa occupancy channel rate of 18%.

We evaluate a maximum occupancy channel rate of 18% because this is the limit when the LoRa configuration is SF6, BW 1625. The maximum occupancy channel rate corresponds to a number of frames sent over a given period with no inter-frame time, meaning that the only delay between transmitted frames comes from the hardware operation. The theoretical number of frames is computed according to the ToA of one frame and the inter-frame time (see Equation 4). Then we experimentally evaluate the effective duration to send the number of frames computed and adjust it until fitting the targeted phase duration. In this numerical example, we compute the number of frames to ensure a duration of ten minutes of continuous LoRa transmission.

$$\text{theoretical number of frames} = \frac{\text{test duration} \times \text{targeted occupancy channel rate}}{\text{time on air}} \quad (3)$$

$$= \frac{600000 \text{ ms} \times 0.18}{3.1 \text{ ms}} = 34838 \text{ frames.} \quad (4)$$

Both series were run at least three times, to smooth out variations that might arise from a change in the environment. We did not observe a significant difference between working days and weekends results so we ran our experiments irrespective of the day of the week. We start our coexistence study with the General experiment that evaluates a subset of LoRa configurations with SF, BW, and CR varying. We use the General experiment to evaluate the impact of the LoRa channel, and the topology of experiments, on the performance of Wi-Fi and LoRa. From the results obtained with the General experiment, we designed the Bandwidth experiment that only changes the ToA of the LoRa frames. We use the Bandwidth experiment to evaluate and compare the results obtained at different running times: by night and day. Changing the time of running our experiment allows us to evaluate how external wireless technologies usage in the environment of the experiments, Wi-Fi in our case, impacts the communications of the evaluated technologies. The duration of each experiment is about 6 hours.

We summarize the general parameters used for both series of experiments in Table 6. Table 7 focuses on the specificities of the LoRa parameters used in the Bandwidth experiments.

| Technology | Configuration number | PHY Configuration | Center frequency (in MHz) | Payload size (in bytes) | Time on Air (in ms) |
|------------|----------------------|--------------------|---------------------------|-------------------------|---------------------|
| Wi-Fi | / | 802.11g | 2412 (channel 1) | 1400 | 1 |
| LoRa | 1 | SF12, BW203, CR4/8 | 2402, 2404, | 20 | 1054 |
| | 2 | SF9, BW812, CR4/8 | 2406,2408, | | 38 |
| | 3 | SF6, BW1625, CR4/5 | 2410, 2412 | | 3 |

Table 6: Parameters of the General experiment.

| Configuration number | Spreading Factor | Bandwidth (in kHz) | Coding Rate | Time on Air (in ms) |
|----------------------|------------------|--------------------|-------------|---------------------|
| 2.a | 9 | 203 | 4/8 | 152 |
| 2.b | | | | 38 |
| 2.c | | | | 24 |
| 3.a | 6 | 1625 | | 32 |
| 3.b | | | | 8 |
| 3.c | | | | 4 |

Table 7: Parameters of the Bandwidth experiment for LoRa.

5.2 Coexistence scenario

We ran the experiments in an indoor environment as Wi-Fi and LoRa 2.4 GHz are not intended for long-range outdoor communications. We performed the experiments in a residential building representing a real interference case for LoRa, as one of the main applications of the IoT is smart home. We are interested in how the presence of residents in the building, and more precisely the

likelihood of external interference caused by people using devices in the 2.4 GHz ISM band impacts the LoRa transmissions (**RQ-6**).

All the experiments were performed in an apartment located on the fifth floor of a building in Lyon (France) in a dense area. As depicted in Figure 4, we collocate the LoRa gateway with the Wi-Fi transmitter, and the LoRa end-device with the Wi-Fi receiver, to evaluate the worst case topology. The LoRa equipment used for these experiments consists of one end-device sending uplinks and one gateway listening to uplink transmissions. Both LoRa devices use the SX1280 radio chip from Semtech [32]. The end-device is accessible using the STM32 NUCLEO-L476RG microcontroller. The gateway is connected via USB to the computer.

On the Wi-Fi side, we use two computers in monitor mode: one acts as the transmitter and the other as the receiver. The transmitter generates Wi-Fi traffic through *Scapy*, and both computers monitor and log the traffic. Having logs on both sides of the Wi-Fi communications allows us to compute the Wi-Fi FDR as the received frames over the sent frames. The Wi-Fi chipsets used by the computers are Intel Corporation Wireless 8265 / 8275 (rev 78) [16] for the transmitter, and Broadcom Corporation BCM4313 802.11bgn Wireless Network Adapter (rev 01) [5] for the receiver.

In Table 6, we detailed the LoRa configurations we evaluate in our coexistence performance evaluation. The LoRa configurations are referred to as configuration numbers 1, 2, and 3, respectively. Note that while LoRa allows the use of an SF of 5, our initial experiments highlight a hardware limitation: small inter-frame times led to gateway failure, causing the experiment to shut down. Indeed, the gateway has no time to demodulate incoming frames before switching to listening for new ones and eventually becomes blocked in a deadlock. Thus, we decided to use the smallest SF able to provide a stable operation, which is SF6. LoRa configurations 1, 2, and 3 are set up (i.e., number of frames and inter-frame time) to ensure a transmission time of five minutes per configuration, corresponding to 29, 791, and 9900 LoRa frames respectively.

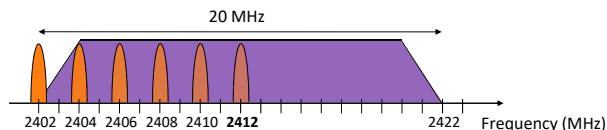


Figure 6: Evaluated LoRa channels and Wi-Fi channel.

On the Wi-Fi side, the computers are in monitor mode. The monitoring mode does not aim to generate traffic and thus does not permit to change the transmit power of the wireless interfaces of our laptop. Using *Netspot* we can estimate the RSSI of our Wi-Fi traffic by taking the average value of an AP generated with *Scapy*. The average RSSI value is -42 dBm. We chose the payload size within the MTU of Wi-Fi, and in accordance with the analysis of the wireless environment presented in Section 4.

In Figure 6 we visualize the narrow bandwidth properties of LoRa (203,

406, 812 or 1625 kHz) regarding the bandwidth of Wi-Fi (20 MHz). To answer the question **RQ-3** on the impact of the LoRa center frequency channel, we evaluate different center frequencies for LoRa transmissions, from 2402 MHz to 2412 MHz with a 2 MHz step. Since the Wi-Fi spectrum is symmetrical around the center frequency, for a given channel, transmitting LoRa frames with a fixed frequency in the first part of the Wi-Fi spectrum will give the same results as transmitting on the second part of the Wi-Fi spectrum. This assumption is true only if there is no wireless communication on the adjacent overlapped channels. Thus, we evaluate six LoRa channels to cover only the first lobe of Wi-Fi channel 1, which is centered at 2412 MHz with a bandwidth of 20 MHz. This choice allows us to avoid interference from Wi-Fi signals on channels 2 to 5, as Wi-Fi channels are separated by 5 MHz. With our setup, **Scapy** allows to use the IEEE 802.11g standard with a 12 Mbps data rate. As the physical layer of the IEEE 802.11n standard is an improvement of the IEEE 802.11g standard (see Subsection 2.2), our performance evaluation allows us to evaluate a popular Wi-Fi standard when LoRa is transmitting.

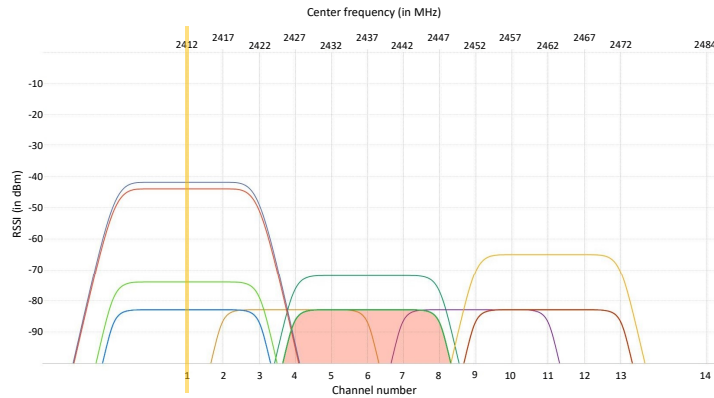


Figure 7: Capture of the **NetSpot** tool showing the distribution of the access points of the wireless environment where our experiments take place. The yellow vertical line highlights the Wi-Fi channel used in our experiments. Each access point is shown as a trapezoid with a different color.

In Figure 7, we can see the distribution of the APs in the environment where the experiments take place. Out of the ten APs visible on the figure, four are on channel 1, two on channel 6, and two on channel 11, which confirms that the default Wi-Fi deployments are generally on one of the three independent channels. In our experiment, we also evaluate the Wi-Fi channel 1. Regarding the Wi-Fi APs distribution, we observe that our transmissions will coexist with four other Wi-Fi networks that we considered as external interference. Three out of the four Wi-Fi APs are located in other apartments and have an average RSSI value between -72 dBm and -83 dBm. Due to propagation losses, transmissions coming from these networks might have little impact on our results. The last Wi-Fi AP is located inside the apartment and has an average RSSI value of -

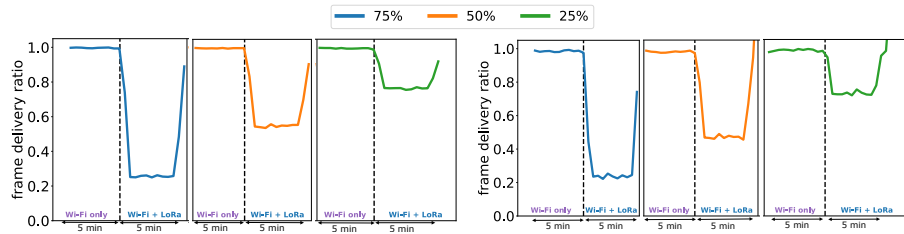
41 dBm. Still, during our experiments, we did not use this Wi-Fi AP, i.e., we did not generate data traffic, so the only traffic interfering with our transmissions is the control traffic. We make the assumption that if this control traffic has an impact on our results, it would be smoothed over the entire experiment and repetitions.

6 Experimental results

6.1 Impact of the LoRa occupancy channel rate

To answer the question "How does Wi-Fi performance vary as a function of the LoRa occupancy channel rate?" (**RQ-2**), we start with a first evaluation of the impact of LoRa transmissions on Wi-Fi performance. To this aim, we send LoRa frames centered at 2402 MHz during ten minutes for three different values of occupancy channel rate (75%, 50%, and 25%) representing various IoT applications with different traffic load. Note that there is no duty-cycle limits in the 2.4 GHz ISM band. So, using LoRa in the 2.4 GHz ISM band leads to the possibility of transmitting more often than in LoRa sub-GHz.

We do not evaluate the SF6 configuration, as to ensure a LoRa transmission of 10 minutes, the maximum occupancy rate reachable with SF6 and BW1625 is no more than 18% (see Equation 4).



(a) Wi-Fi FDR for different LoRa SF12 (b) Wi-Fi FDR for different LoRa SF9 occupancy rates

Figure 8: Wi-Fi FDR for several LoRa occupancy channel rates.

In Figure 8a, we can see the Wi-Fi FDR as a function of the occupancy rate using LoRa configuration 1, i.e., SF12/BW203. From these results, we can see that the LoRa occupancy channel rate has a direct impact on the Wi-Fi FDR. With a LoRa occupancy channel rate of 75%, the Wi-Fi FDR is around 25%. The same applies to a LoRa occupancy channel rate of 50% leading to a Wi-Fi FDR of around 50% and a LoRa occupancy channel rate of 25% leading to a Wi-Fi FDR of around 75%. In Figure 8b, we observe that the results obtained by the intermediate configuration (SF9) are almost identical to those of the greatest communication range (SF12). The Wi-Fi FDR decrease between the two configurations is approximately 5%. So the LoRa configuration has less impact on the Wi-Fi FDR than the LoRa occupancy channel rate.

As a LoRa SF12 signal is more robust than an SF9 signal, we thought we would see significant variations of the Wi-Fi FDR depending on the LoRa interfering signal configuration. In the next sections, we will further investigate these results.

Main take-away: This first evaluation provides an answer to the question "How does Wi-Fi performance vary as a function of the LoRa occupancy channel rate?" (**RQ-2**). The results show that the higher the occupancy channel rate, the lower the Wi-Fi FDR. The Wi-Fi FDR decrease is directly linked to the intensity of the LoRa traffic rather than to the LoRa configuration.

6.2 Impact of the LoRa center frequency

Depending on the center frequency of the LoRa channel, the LoRa channel is disjoint, partially overlapping, or fully overlapping with the spectrum of the Wi-Fi AP. This raises the research question "How does the communication reliability of both technologies vary as a function of the frequency offset between LoRa and Wi-Fi center frequency channels?" (**RQ-3**) we aim to answer in this Subsection.

Figure 9 shows the LoRa FDR for a range of center frequencies and for the three configurations detailed in Table 6. The trends observed in the results are the same for all the repetitions of the experiment. Hence, to ease the understanding of the results, in Figure 9 we display the results of only one experiment.

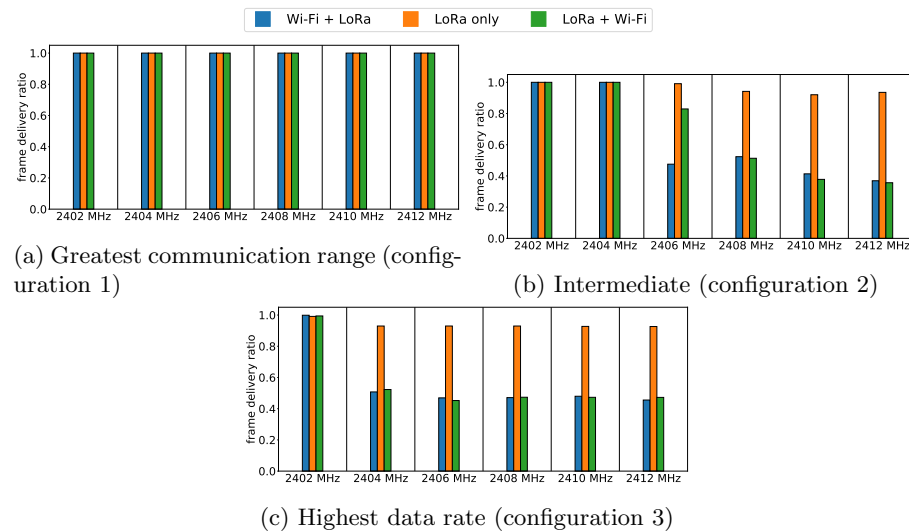


Figure 9: LoRa FDR depending on the center frequency.

We conclude from the results that the closer the center frequency of the LoRa channel is from the center frequency of the Wi-Fi channel, i.e., the biggest channel overlap, the higher the impact on the LoRa FDR. For example, for

configuration 2 (see Figure 9b), until 2404 MHz the FDR is 100%. Then the LoRa FDR decreases from 82% to 35% as we get closer to the Wi-Fi center frequency. When using a less robust LoRa configuration (e.g., small SF combined with high BW, such as configuration 3) the impact on LoRa performance appears sooner (at 2404 MHz). For the configuration providing the highest data rate (see Figure 9c), the results show that for all the tested center frequencies, except 2402 MHz, the LoRa FDR without interference is above 92% whereas under interference it decreases to a minimum of 45%. Finally, for the greatest communication range LoRa configuration (see Figure 9a), and thus the most robust configuration, the results indicate that the Wi-Fi has negligible impact on LoRa performance as we always received 100% of the transmitted frames. Indeed, LoRa is known to be able to demodulate a signal below the noise floor: as a high SF and a small BW increase the robustness such that the interference from the Wi-Fi frames is not sufficient to impact the received frames.

The analysis of the RSSI and the SNR for LoRa transmissions confirm that, due to our experiment topology, these two metrics are not sufficient to explain the frame losses experienced. Thus, we focus only on the FDR in the rest of this article.

Going back to the objective of this section, we analyze next the Wi-Fi FDR depending on the LoRa channel in Figure 10.

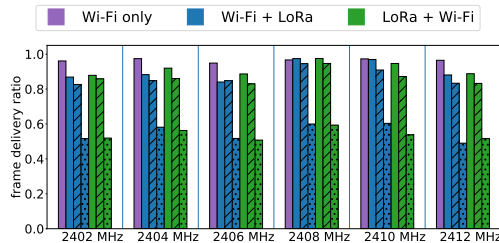


Figure 10: Wi-Fi FDR depending on LoRa center frequency. Blue and green bars correspond to the following LoRa configurations: empty bars for configuration 1, hatched bars for configuration 2, and spotted bars for configuration 3.

The results highlighted here show that the LoRa channel, used in overlapping transmission with Wi-Fi, has no significant impact on Wi-Fi performance. Indeed, the Wi-Fi FDR is on average 91%, 87%, and 55% for LoRa configuration 1, 2, and 3 respectively, and independently of the LoRa channel evaluated.

Take-away 1: The evaluation of the impact of the LoRa channel center frequency on LoRa and Wi-Fi performance answers the question "How does the communication reliability of both technologies vary as a function of the frequency offset between LoRa and Wi-Fi center frequency channels?" (RQ-3). We conclude that for Wi-Fi, the center frequency of the LoRa traffic has no significant impact on Wi-Fi performance as the FDR is similar for each LoRa configuration. For LoRa, the results show that the impact on the LoRa FDR increases by decreasing the frequency offset between LoRa and Wi-Fi center frequency chan-

nels.

Take-away 2: This result shows that LoRa channels have to be taken into account for future LoRa networks deployment to ensure a good coexistence with Wi-Fi. As the LoRa FDR under Wi-Fi interference is 100% for both LoRa channels at 2402 and 2404 MHz, we can validate the choice of these channels, at least for the greatest communication range and the intermediate configurations. We can also validate the 2403 MHz LoRa channel as a good option, as proposed by Semtech, as we validated channels on either side of this frequency.

6.3 Impact of the LoRa bandwidth

To answer the research question "How does the Wi-Fi communication reliability vary as a function of the used LoRa bandwidth and therefore of the ToA?" (RQ-4), we designed the Bandwidth experiment, and focus on the Wi-Fi performance we obtain through both experiments and simulations, as presented in Section 5. Since the LoRa greatest communication range does not experience frame losses (see Subsection 6.1), in this subsection, we focus on the intermediate and the highest data rate configurations.

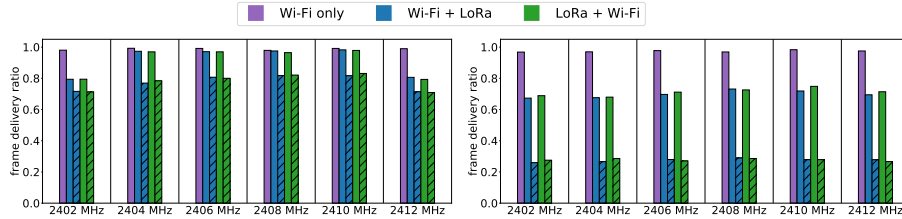
6.3.1 Experiment results

In this series of experiments, we fixed the LoRa occupancy channel rate to 18% to be able to evaluate the SF6 configuration because, as demonstrated in Equation 4, 18% is (almost) the maximum occupancy channel rate for LoRa using SF6 and BW1625.

Figure 11 shows the Wi-Fi FDR for the LoRa configurations 2.a, 2.c, 3.a and 3.c (see Table 7), i.e., SF9 and SF6 combined with the smallest and the highest available bandwidths. In each subfigure, the purple bar represents the Wi-Fi FDR without interference. It is still possible that external transmissions (from Wi-Fi APs in the environment) interfered with our Wi-Fi traffic. Then, for the two periods where we have overlapping LoRa and Wi-Fi transmissions, the Wi-Fi FDR is computed depending on the LoRa bandwidth used: the first blue and green bars correspond to BW203 kHz, while the second blue and green hatched bars correspond to BW1625 kHz.

Figure 11a shows that the LoRa bandwidth has an important impact on the Wi-Fi FDR. For example, for a LoRa traffic centered at 2410 MHz, using the configuration 2.a, i.e., SF9/BW203, the Wi-Fi FDR under interference is 98% for both periods of overlapping transmissions. In the same way, for LoRa using the configuration 2.c, i.e., SF9/BW1625, the Wi-Fi FDR is only 82%.

We also observe that for LoRa overlapping transmissions using a channel centered at 2402 MHz, the Wi-Fi FDR is lower than at the other center frequencies. We assume that there is possible interference from other wireless technologies, in particular Bluetooth/BLE, which uses the 2402 MHz frequency as the center frequency for one of their advertisement channels. We used a USRP to analyze this specific channel frequency and observed that nearby cellphones are constantly beaconing on the Bluetooth/BLE advertisement channels, thus



(a) Wi-Fi FDR for LoRa SF9, BW203 and (b) Wi-Fi FDR for LoRa SF6, BW203 and BW1625

Figure 11: Wi-Fi FDR for several LoRa bandwidths. Blue and green bars correspond to the following LoRa bandwidth: empty bars for BW 203 kHz, and hatched bars for BW 1625 kHz.

validating our hypothesis about possible interference. After validating our assumption on the behavior of Bluetooth equipment, we carried out the rest of the experiments with our Bluetooth devices switched off. The results in Figure 11a correspond to a series of experiments where BT devices were switched on. The Wi-Fi FDR for LoRa configurations 2.a and 2.c at 2402 MHz are 79% and 72% respectively, while the Wi-Fi FDR is on average 97% and 80% for the center frequencies from 2404 MHz to 2410 MHz. The results in Figure 11b, correspond to a series of experiments where BT devices were switched off. The results show that, regardless of the center frequency of the LoRa traffic, the Wi-Fi FDR under interference is on average 70% for LoRa configuration 3.a, and 28% for LoRa configuration 3.c, i.e., SF6, BW 203 and SF6, BW 1625 respectively. The Wi-Fi FDR difference between the two figures comes from the LoRa configurations. However, we see that when the BT devices are switched off, the Wi-Fi FDR for a LoRa channel centered at 2402 MHz is similar to the FDR obtained for the other center frequencies.

The result clearly shows that the LoRa bandwidth has a significant impact on the Wi-Fi FDR: we observe an FDR of under 100% during LoRa transmissions. Moreover, a low SF combined with a high BW has a higher impact on the Wi-Fi FDR than a large SF with a low BW, meaning that the Wi-Fi FDR decreases as a function of the LoRa time on air. Thus, to guarantee good Wi-Fi performance, it is best to use a small bandwidth with an SF of at least 9. The difference between the Wi-Fi performance when using SF9 or SF6 can be explained by the time on air of the frames. For the IEEE 802.11g 12 Mbps standard, a Wi-Fi frame lasts approximately 1 ms and is transmitted every 100 ms. For LoRa, an SF9/BW1625 frame lasts 24 ms and is transmitted every 106 ms, whereas an SF6/BW1625 frame lasts 4 ms and is transmitted every 24 ms. This means that approximately one over two Wi-Fi frames coexist with one LoRa SF9 frame, while a Wi-Fi frame coexists with a maximum of three LoRa SF6 frames. So Wi-Fi traffic is more likely to have interference from LoRa SF6 frames than LoRa SF9 frames.

The result highlighted here when the LoRa channel is used in overlapping

transmission with Wi-Fi, it has no significant impact on Wi-Fi performance. The Wi-Fi FDR retains the same value, except at 2402 MHz for the intermediate configuration, irrespective of the LoRa channel evaluated.

6.3.2 Simulation results

We extend the experimental results through simulations based on our performance evaluation setup by testing more configurations and parameters than is possible on real hardware. To quantify the impact of the LoRa ToA and the occupancy channel rate, on the Wi-Fi FDR, we used **MATLAB** simulations. These allow us to study various occupancy rates (1%, 10%, 18%, and 30%) for all possible LoRa spreading factors (from 5 to 12). These simulations compute the theoretical Wi-Fi FDR when the medium is shared with LoRa transmissions.

To compute the theoretical Wi-Fi FDR, we make the assumption that if a Wi-Fi frame overlaps with a LoRa transmission, the Wi-Fi frame would be lost independently of the arrival time of the LoRa frame. This way we give a lower bound FDR for Wi-Fi transmissions interfered by LoRa transmissions. We then compute the theoretical Wi-Fi FDR in Equation 5.

$$1 - \left(\frac{\text{Wi-Fi time on air}}{\text{LoRa time on air}} + 1 \right) \times \text{LoRa occupancy channel rate}. \quad (5)$$

This represents the probability that a Wi-Fi frame is not overlapping with any LoRa frame during the transmission. The results are shown in Figure 12 where each color corresponds to one LoRa occupancy channel rate, and each point of a given color corresponds to a LoRa configuration, from left to right, represented as a ToA in the simulations. We choose to evaluate a fixed BW of 1625 kHz to have the maximum frequency overlap between LoRa and Wi-Fi transmissions.

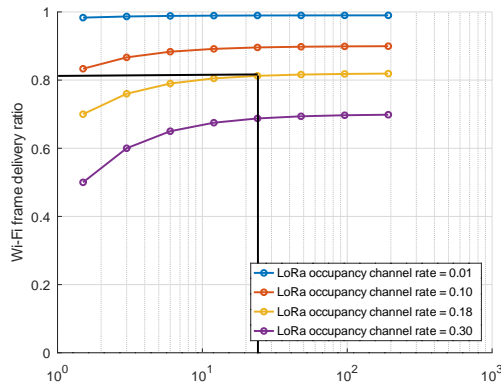


Figure 12: Simulated Wi-Fi FDR for several LoRa time on air of frames and channel occupancy rates. Black lines highlight the experimental Wi-Fi FDR for LoRa SF9, BW1625.

We observe that increasing the SF and thus the ToA of the LoRa frames also

increases the Wi-Fi FDR. This confirms that LoRa frames with a small ToA interfere more frequently Wi-Fi frames which decreases the Wi-Fi FDR. For a LoRa occupancy channel rate of 18% , as in our experiments, and for a LoRa ToA of 24 ms, which corresponds to the ToA of the intermediate configuration c, i.e., SF9/BW1625, the Wi-Fi FDR is 81%. In our experiments, we obtained a Wi-Fi FDR of 82%, which is consistent with the theoretical results.

Another way to increase the Wi-Fi FDR is to decrease the LoRa occupancy channel rate. In Figure 12, we see that for the LoRa configuration 2.c, the Wi-Fi FDR increases from 68% to 98%, by decreasing the occupancy channel rate from 30% to 1% respectively.

Main take-away: These results answer the question "How does the Wi-Fi communication reliability vary as a function of the used LoRa bandwidth and therefore of the ToA?" (RQ-4). The time on air of the LoRa frames has a significant impact on Wi-Fi performance. For a given LoRa occupancy channel rate, decreasing the SF and increasing the BW drastically decreases the Wi-Fi FDR until 28% using the highest data configuration. The theoretical results depicted in Figure 12 confirm these experimental results.

6.4 Impact of the environment

To fully validate the answers to the research questions **RQ-3** and **RQ-4**, we now explore the impact of the time of day when we run our experiments. To evaluate this, we perform several repetitions of our experiments: by night and by day. We do not observe a significant difference between working days and weekends results so we regroup all daytime experiments. We expect that during the night, the Wi-Fi activity is less present than during the day because, as our experiments take place in a private environment, there are fewer wireless networking activities, since people are sleeping. With low Wi-Fi activity, there is less interference, so we conjecture an improvement of LoRa performance. Some existing studies show that there are activity peaks in the early morning before people leave for work, at noon, and in the evening when people come back from work [1][4]. Since the pandemic, working remotely from home has become more popular, resulting in potential interference throughout the day.

We run the experiments and compute the results, for all the possible intermediate LoRa configurations detailed in Table 7. The concluding remarks on the results are the same, thus we present as an example the results for a bandwidth of 812 kHz, since this represents an intermediate LoRa configuration. Figures 13a and 13b show the LoRa FDR during night and daytime experiments, respectively. Each point corresponds to a measurement from one experiment, and the point's color indicates the type of transmission: blue and green represent overlapping transmissions, and orange represents LoRa interference-free transmissions. Each experiment lasts approximately 6 hours, corresponding to 348, 9492, and 118800 frames depending on the LoRa configuration used. This gives us a significant time to evaluate where variations in the wireless environment might happen. We conclude that for both technologies, the performance are similar. Regardless of the time of day when we run the experiments, we do

not observe a significant change of the FDR.

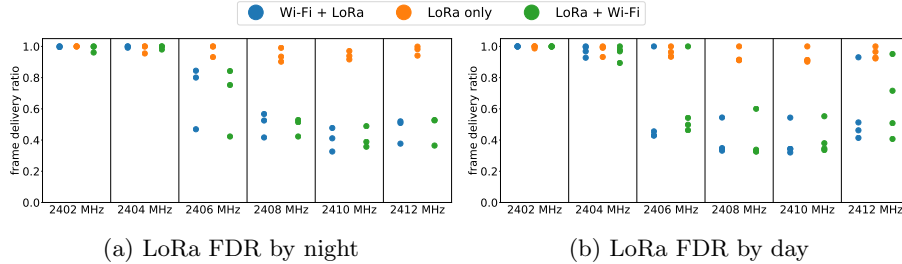


Figure 13: LoRa FDR for configuration 2.b, for several repetitions during night and daytime.

By comparing Figures 13a and 13b for LoRa channels centered at 2402 and 2404 MHz, we observe a slight amelioration of the FDR during the night. However, the lowest LoRa FDR on these channels by day, under interference, is 92% which is still very good. For the other center frequencies, we observe some variations between the different repetitions of the same experiment. We assume it comes from the environment of our experiment which can be different from one day to the next. Overall, by night the FDR varies from 32% to 56% with an average of 47%, whereas by day it varies from 32% to 54% with an average of 43%. The FDR variations follow the same trend.

In the same way, we analyze the Wi-Fi FDR by night and by day, when the LoRa transmissions use a SF9 combined with bandwidths of 203 and 812 kHz. It allows us to compare the low variation of the LoRa FDR with the Wi-Fi FDR. Figures 14a and 14b show the Wi-Fi FDR with colors coded as follows: blue and green represent overlapping transmissions, and purple represents Wi-Fi interference-free transmissions. Circles are for the first LoRa configuration evaluated, i.e., 2.a, and triangles correspond to the second LoRa configuration evaluated, i.e., 2.b.

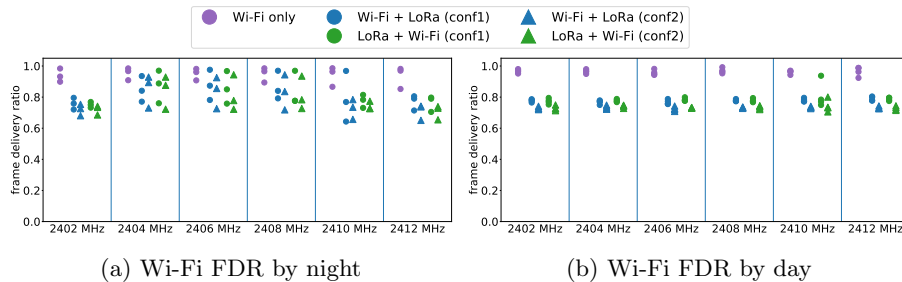


Figure 14: Wi-Fi FDR, for LoRa configurations 2.a and 2.b, for several repetitions during night and daytime.

The results show more variations of the Wi-Fi FDR by night (Figure 14a)

than by day (Figure 14b). Nevertheless, the average Wi-Fi FDR by night and by day for LoRa configuration 2.a, i.e., SF9, BW 203, is 78% whereas for the LoRa configuration 2.b, i.e., SF9, BW 812, the FDR is in average 73% by night and 72% by day. We conclude the same as for the results of Figure 13: we do not observe significant changes of the FDR between night and day experiments.

Main take-away: These results imply that in future deployments of LoRa, interference mitigation mechanisms have to be implemented to allow the coexistence of LoRa and Wi-Fi in the 2.4 GHz ISM band. The good coexistence of these two wireless technologies is not ensured even with LoRa applications sending frames only by night, as they would suffer from similar interference as during the day.

6.5 Impact of the Wi-Fi traffic rate

To answer the research question "How does the communication reliability of both technologies vary as a function of the Wi-Fi traffic rate?" (RQ-5) we repeated our coexistence experiment this time changing the traffic rate of Wi-Fi. We evaluated a traffic rate of 6 Mbps and 54 Mbps, additionally to the 12 Mbps traffic rate of the rest of our coexistence experiments, as these traffic rates are the lower and the higher possible value for the IEEE 802.11g standard. Remember that the wireless interface traffic rate can be modified directly in the hardware parameters but not through Scapy.

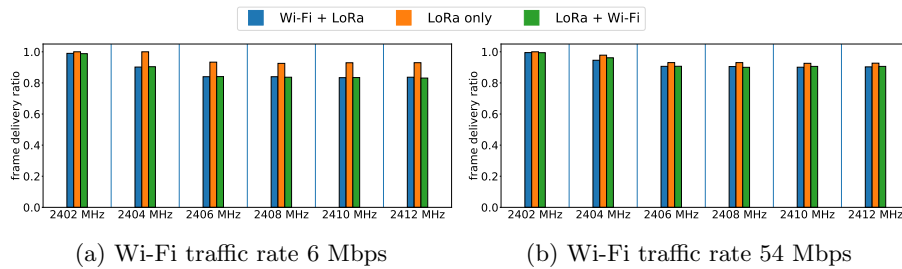


Figure 15: LoRa highest data rate configuration FDR depending on the Wi-Fi traffic rate.

Preliminary results indicate that the LoRa FDR is always 100% for the greatest communication range configuration irrespective of the Wi-Fi traffic rate. As LoRa intermediate and highest data rate configurations have similar FDR results, we present here only the results for the highest data rate configuration. In Figure 15a, we can see that the LoRa FDR reaches 85% on average when the Wi-Fi traffic rate decreases to 6 Mbps. This is almost double when compared to the 12 Mbps evaluation (LoRa FDR of 45% on average, as seen in Figure 9c). This might come from the fact that LoRa frames overlap less often with Wi-Fi frames at 6 Mbps than with Wi-Fi frames at 12 Mbps. When the Wi-Fi traffic rate increases to 54 Mbps, the ToA of a Wi-Fi frame decreases considerably

(200 μ s compared to 1 ms at 12 Mbps), having barely any impact on the LoRa FDR, as we can see in Figure 15b, where the average FDR is 90%.

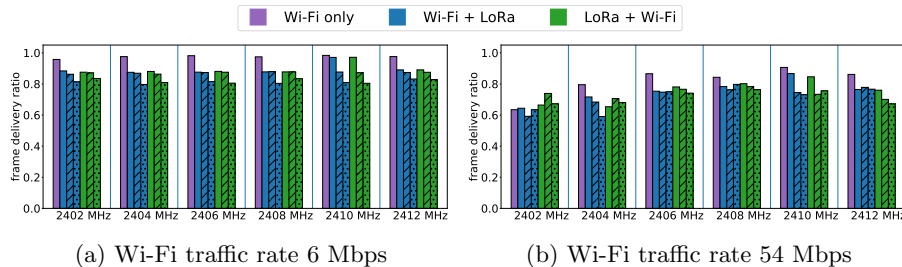


Figure 16: Wi-Fi FDR depending on the Wi-Fi traffic rate. Blue and green bars correspond to the following LoRa configurations: empty bars for configuration 1, hatched bars for configuration 2, and spotted bars for configuration 3.

In Figure 16 we can notice that the Wi-Fi FDR decreases with the increase in the traffic rate, regardless of the LoRa configuration. As with a high traffic rate Wi-Fi frames have a very short ToA, LoRa overlapping transmissions, as well as external interference, are very destructive and prevent receiving the Wi-Fi frames.

Main take-away: These results answer the question "How does the communication reliability of both technologies vary as a function of the Wi-Fi traffic rate?" (RQ-5). The results show that the higher the Wi-Fi traffic rate, the higher the LoRa FDR and the lower the Wi-Fi FDR.

6.6 Impact of the topology

The way we designed our experiments can have an impact on the LoRa and Wi-Fi performance we obtained. This raises the research question "Does the topology of the experiment, e.g., the distance between equipment using different wireless technologies, have an impact on the communication performance of both technologies?" (RQ-6). Hence, we study the impact of the topology. In addition to the worst case topology, where the transmitter of one technology is collocated with the receiver of the other technology evaluated, we consider another topology, called collocated transmitters topology, where both LoRa and Wi-Fi transmitters (and receiver) are collocated (i.e., one laptop with LoRa and Wi-Fi transmitters and another laptop with LoRa and Wi-Fi receivers).

Figures 17 and 18 show the FDR of LoRa and Wi-Fi for each topology. We compute the results for both technologies, for the three possible LoRa configurations: greatest communication range, intermediate, and highest data rate (see Table 6), and present the most relevant data.

For LoRa, the results show that collocating the transmitters of both technologies leads to better performance when there are overlapping transmissions between LoRa and Wi-Fi. This result makes sense as we initially designed

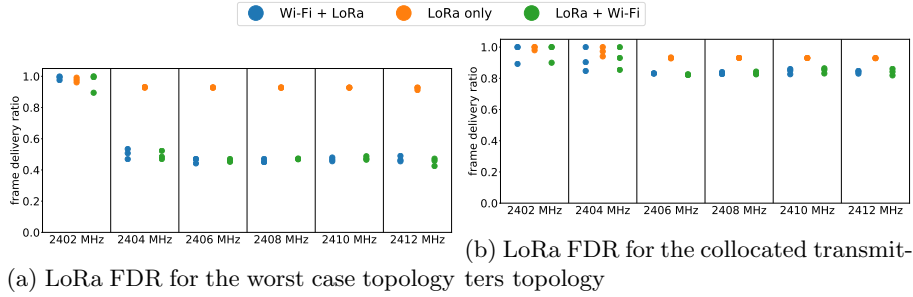


Figure 17: LoRa highest data rate configuration FDR for several repetitions and topologies.

our experiments to have the highest interference between the two technologies evaluated.

We note a significant LoRa FDR increase in Figure 17, when comparing the worst case and the collocated transmitters topologies, for the configuration that gives the highest data rate, and thus the smallest communication range. This configuration is also less robust to interference, so the gain obtained by changing the topology is outstanding. We observe that the FDR increases significantly for all centered frequencies when using the collocated transmitters topology. For example, for a LoRa traffic with Wi-Fi interference centered between 2404 MHz to 2412 MHz, the FDR in the worst case topology is on average 47%, whereas in the collocated transmitters topology, the FDR increases to 84%. This means that by simply changing the topology, the LoRa performance can be significantly improved.

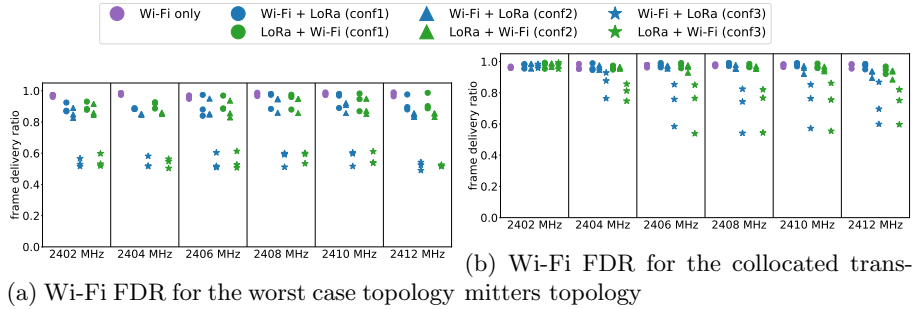


Figure 18: Wi-Fi FDR for several repetitions and topologies.

For Wi-Fi, the performance improvement is less noteworthy see Figure 18). In fact, the increase of the Wi-Fi FDR is only noticeable for a LoRa traffic centered at 2402 and 2404 MHz. We were expecting that the results of the worst case topology would show that moving away from the Wi-Fi center frequency channel, would increase the FDR. Our results demonstrate that this is

not the case because the topology of the experiments has more impact on the performance than the center frequency of the LoRa channel. The results of the collocated transmitters topology confirm the intuition and expectations we had when first experimenting with the worst case topology. For example, the results of Wi-Fi FDR, when the medium is shared with LoRa, centered at 2402 MHz, transmitting with the highest data rate configuration, depicted with blue and green triangles in Figure 18a, is on average 53%, and it increases up to 99% in the collocated transmitters topology.

Main take-away: The evaluation of the topology impact on LoRa and Wi-Fi performance responds to the question "Does the topology of the experiment, e.g., the distance between equipment using different wireless technologies, have an impact on the communication performance of both technologies?" (RQ-6). The results show that depending on the distance between LoRa and Wi-Fi transmitters and receivers, the communication of both technologies is increased. We can conclude that one way to improve the LoRa performance under Wi-Fi interference is to focus on the deployment, especially considering collocated transmitters topology. This is achieved by deploying LoRa gateways far away from Wi-Fi APs to reduce the interference between the transmitted and the received frames of both technologies. In other words, the network deployment of LoRa in the 2.4 GHz ISM band should consider the location of Wi-Fi devices, especially access points, working in the same area. Overall, the impact of LoRa on Wi-Fi for a given LoRa occupancy channel rate depends, from the higher to the lower impact, on (1) the LoRa configuration, (2) the LoRa topology deployment, and (3) the LoRa center frequency channel.

7 Discussions

7.1 General insights

The various experimental results presented in Section 6 allow us to provide an answer to the research questions **RQ-2** to **RQ-6** we raised at the beginning of this article. Gathering all the outcomes of our experiments provides an answer to the question "What is the impact when there are LoRa and Wi-Fi overlapping transmissions on both technologies' communication reliability?" (**RQ-7**). Our experimental results permit to highlight some technical principles that would be beneficial to deploy a LoRa network in a Wi-Fi environment in the 2.4 GHz ISM band, without implementing interference mitigation mechanisms [7] [20] [35]. The following recommendations aim to highlight good practices to ensure a fair coexistence between LoRa and Wi-Fi.

The first recommendation concerns the LoRa occupancy channel rate. As LoRa has no imposed duty-cycle in the 2.4 GHz ISM band, it can transmit as needed. We show in Subsection 6.1 that the higher the LoRa occupancy channel rate, the lower the Wi-Fi FDR (**RQ-2**). So, one way to ensure a fair coexistence between LoRa and Wi-Fi is to limit the LoRa occupancy channel rate, by configuring the inter-frames arrival time and the maximum number of frames to

send for a given period of time. Additionally, we show in Subsection 6.5 that using a low traffic rate of 6 Mbps for Wi-Fi transmissions provide a minimum FDR of about 80% for both LoRa and Wi-Fi, as decreasing the Wi-Fi traffic rate increases the robustness of Wi-Fi to overlapping transmissions (**RQ-5**).

The second recommendation is to use high SF values (9 to 12) combined with small bandwidths (203 to 812 kHz). Indeed, Subsection 6.3 shows that the choice of LoRa PHY parameters has an impact on Wi-Fi performance (**RQ-4**).

The third recommendation is to design a deployment where the LoRa end-devices are as far away as possible from the Wi-Fi transmitters, to have the lowest level of interference between LoRa and Wi-Fi (**RQ-6**). We underline this need in Subsection 6.6.

Finally, the fourth recommendation is to choose the LoRa channel center frequency farthest away from the Wi-Fi channel center frequency. In Subsection 6.2 we show that a close frequency would decrease both FDR (**RQ-3**). Thus, the Semtech proposal of a LoRa channel centered on 2403 MHz is a good option. The principle applies to the other LoRa channels (2425 and 2479 MHz) as they are neighbor to a BLE advertising channel and at the edge of a main Wi-Fi channel. However, we need further investigations to validate the proposed LoRa channels.

In our opinion, the best option to deploy a LoRa network in the presence of Wi-Fi, without implementing interference mitigation mechanisms, is to combine all these recommendations.

7.2 Future work

We presented the results of the worst case coexistence between LoRa and Wi-Fi in the 2.4 GHz ISM band following the scenario described in Section 5. Nevertheless, there are a number of extensions that would be interesting to investigate to have more insights on the coexistence of LoRa in this frequency band.

First of all, we evaluated only a single IEEE 802.11 standard and thus one data rate and one modulation. It could be interesting to study the latest widely distributed IEEE 802.11 standard: IEEE 802.11ax. The modulation in IEEE 802.11ax is similar as in IEEE 802.11g, but the IEEE 802.11ax standard allows higher data rates and other bandwidths. A coexistence study between LoRa and IEEE 802.11ax would give useful insights on a potential LoRa network deployment as the IEEE 802.11ax standard is currently deployed. This study requires access to a library to generate the IEEE 802.11ax traffic.

Another interesting study would be to repeat the same coexistence performance evaluation, this time implementing the Wi-Fi MAC layer. Indeed, Wi-Fi implements mechanisms such as the MCS and acknowledgments, to increase the robustness against interference. In our study, we only implemented the PHY layer of Wi-Fi because LoRa has no standardized MAC layer in the 2.4 GHz ISM band yet, and we wanted a coexistence study with the same conditions for both technologies. We expect the Wi-Fi results to be better when implementing MAC layer mechanisms as the MCS will decrease the data rate, if necessary, to ensure the connectivity of the transmission link. The acknowledgment mechanism also

certifies that the transmitted frames are well received, by retransmitting the frames if necessary.

Finally, the methodology presented in this article could be applied to evaluate the coexistence of LoRa with other wireless technologies operating in the 2.4 GHz ISM band, such as Bluetooth and BLE. We carried out a performance evaluation of LoRa with Wi-Fi as we believe that Wi-Fi is the most popular technology in indoor environments. However, we believe that it is of uttermost importance to also evaluate the coexistence between LoRa and Bluetooth, which is the second most used technology in this frequency band.

We also have several leads to explore to improve the coexistence between LoRa and Wi-Fi:

1. Choose the LoRa channels depending on the percentage of channel occupancy, obtained by a channel characterization (i.e., detecting a signal, its duration, periodicity, and associating it to a known wireless technology).
2. Use specific PHY configurations for LoRa transmissions depending on the target application and on the required trade-off between data rate and robustness.
3. Impose a duty-cycle to LoRa and therefore improve Wi-Fi performance, but not LoRa performance.
4. Use cognitive radio approaches which imply working on the implementation of MAC layer mechanisms.
5. Use a frequency hopping scheme to transmit LoRa frames depending on the percentage of channel occupancy which relies on the Wi-Fi traffic model (i.e., choosing the LoRa channels where Wi-Fi traffic is low).

8 Conclusion

In this article, we presented a methodology to study the coexistence of LoRa in the 2.4 GHz ISM band in an indoor environment. We also provided the first performance evaluation of LoRa and Wi-Fi overlapping transmissions. We showed that several implementation choices can have an impact on the resulting communication performance, such as the distance between LoRa transmitters and Wi-Fi receivers, the center frequency of the LoRa configurations, and the LoRa time on air used to transmit LoRa frames. Our main finding is that we can ensure a LoRa FDR of 100%, even with the configuration providing the highest data rate, by transmitting far from the center frequency of the Wi-Fi channel. In the same way, transmitting with LoRa centered at 2402 MHz, combined with a topology where the transmitters of both technologies are collocated, leads to a Wi-Fi FDR of 100% irrespective of the LoRa configurations that interferes with the Wi-Fi traffic. However, as Bluetooth uses 2402 MHz for advertising, we believe that 2403 MHz is a better option for the LoRa channel.

In our opinion, the experimental results presented here give useful insights to the scientific community, and to engineers, for future LoRa network deployments in the presence of Wi-Fi.

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