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# Opportunities and Challenges of LoRa 2.4 GHz

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## Abstract

Internet of Things (IoT) technologies are increasingly used in our daily life. Among these technologies, LoRa is widely used for low power IoT data collection in wide areas. LoRa typically operates in sub-GHz bands which are region-specific, and thus has limited world-wide applications. The version of LoRa developed for the 2.4 GHz ISM band has spurred recent interest in the scientific community, as it enables the use of worldwide frequency channels. However, it requires the coexistence with numerous concurrent technologies within this 2.4 GHz band, and an evolution of the MAC and networking protocols for utilizing LoRaWAN connectivity. In this paper, we make the first experimental comparison between LoRa sub-GHz and LoRa 2.4 GHz in both indoor and outdoor scenarios. We show that LoRa 2.4 GHz can have a communication range of more than 2 km outdoor, and it can achieve a packet delivery rate of at least 0.98 for a distance of up to 39 meters indoor with the presence of obstacles. We also make an extensive discussion on the researches challenges that need to be addressed in order to fully take advantage of this new technology.

**Keywords:** LoRa 2.4 GHz, LoRaWAN, protocol design, protocol comparison.

## 1 Introduction

Low-Power Wide-Area Network (LPWAN) technologies [1] such as LoRa<sup>®</sup>, NB-IoT, and Ingenu, have gained global momentum. Industries and telecommunication operators around the world are deploying these new technologies for several reasons: (i) they answer the needs of a large variety of Internet of Things (IoT) applications that are meant to facilitate our lives, monitor our health or measure pollution in our cities, (ii) they can transmit data packets over several kilometers at low data rates (a few hundred bits per second), which helps to reduce the cost of deployment, (iii) the low-power consumption, the low cost of radio chips, and the overall low complexity of LPWAN architectures make the deployment and the maintenance easier.

LoRa [2] is one of the most representative LPWANs. It uses a spread spectrum technology on license-free sub-GHz bands (e.g., 868 MHz in Europe, 915 MHz in North America). Thus, parameters such as frequency channel, maximum duty-cycle, maximum transmission power, and medium access mechanism, differ from one geographical region to another, and have to be considered in hardware components and communication protocols design.

In an effort to overcome these problems, Semtech<sup>1</sup> proposed a new version of LoRa in the 2.4 GHz ISM

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<sup>1</sup>Semtech and LoRa are registered trademarks or service marks of Semtech Corporation or its affiliates.

band that has common technical specification, allowing it to have a worldwide coverage, with three main advantages: robustness thanks to the use of the LoRa modulation, the use of a common frequency band, and no duty-cycle limitations. This paper focuses on LoRa 2.4 GHz, as we believe it can bring a major evolution in the domain of the IoT by enabling worldwide applications such as global tracking. While the impact of a frequency change has been studied for other modulations, it is not yet known for LoRa, especially in the overcrowded 2.4 GHz spectrum that is used by Wi-Fi, Bluetooth, ZigBee, microwave ovens, and baby phones. Thus, protocol designers for LoRa 2.4 GHz have to face the difficult challenge of interference mitigation, coming from the potentially large number of LoRa 2.4 GHz devices, as well as from devices using other technologies. The goal of this paper is to present LoRa 2.4 GHz in details, to provide a comparison between LoRa sub-GHz and LoRa 2.4 GHz through an experimental performance evaluation, and to highlight the relevant challenges and research opportunities.

Section 2 presents the characteristics of LoRa 2.4 GHz. Section 3 highlights the main motivations and promotes its use. Section 4 presents a performance evaluation of LoRa 2.4 GHz in comparison with LoRa sub-GHz both in indoor and outdoor scenarios. Sections 5 and 6 make a discussion on the research challenges and opportunities brought by LoRa 2.4 GHz. Section 7 draws the main conclusions.

## 2 Crash Course on LoRa 2.4 GHz

We present here the core characteristics of LoRa 2.4 GHz, and the main differences with respect to LoRa sub-GHz.

Considering the physical layer, both technologies use the same chirp spread spectrum modulation where a signal is encoded using a sequence of chirps. A chirp is a linear frequency sweep over a given bandwidth and during a given time. Each chirp is either an up-chirp if the frequency sweep increases, or a down-chirp if it decreases (see Fig. 1). The starting

frequency of the chirp encodes the value of that chirp.

LoRa 2.4 GHz uses essentially the same parameters values as LoRa sub-GHz to achieve a trade-off between reliability and energy consumption (and by consequence data rate): Spreading Factor (SF), Bandwidth (BW) and Coding Rate (CR). By increasing the value of the SF, the chirp duration increases, and so does the energy consumption as it takes longer to transmit the same message. However, by increasing the SF, the reception sensitivity increases, which in turn increases the communication range. Considering the BW, an increased value decreases the chirp duration, thus being more energy efficient, but having the downside of reducing the reliability. Finally, the CR controls how many redundancy bits are added to the data in the payload. Table 1 summarizes the values of these parameters for both LoRa sub-GHz and LoRa 2.4 GHz. Note in LoRa 2.4 GHz, the introduction of SF5 and higher bandwidths that allow to significantly increase the data rate (up to 202kbps).

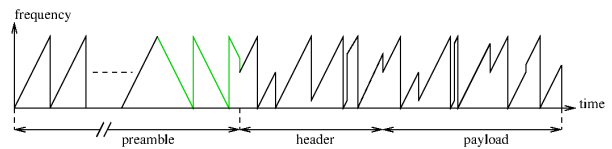


Figure 1: Example of an uplink LoRa frame. Up-chirps are represented in black, and down-chirps in green. The 2.25 down-chirps are used for time and frequency synchronization. In LoRa 2.4 GHz the preamble for SF5 and SF6 uses 12 up-chirps instead of 8. Due to the higher bandwidth, the receiver needs more time for the synchronization.

LoRa modulation has several advantages, regardless of the operating frequency band: (i) its design oriented towards robustness enables a very large link budget (about 168 dB and 144.5 dB with the Semtech SX1276 and SX1280 chip respectively), (ii) the SF parameter enables to trade-off communication range with data rate and energy consumption, (iii) the quasi-orthogonality of the SFs allows concurrent communications on different SFs, and (iv) it requires a low energy consumption (about 11.5 mA and 7 mA as reception current with the Semtech SX1276 and SX1280 chip respectively).

|                                       | LoRa sub-GHz                                      | LoRa 2.4 GHz  |
|---------------------------------------|---|---|
| SF                                    | 6 to 12   | 5 to 12   |
| BW (in kHz)                           | 125, 250, 500                                     | 203, 406, 812, 1625   |
| CR                                    | 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<br>Rx: 11.5 mA<br>SX1276 chip | Tx: 24 mA at 12.5 dBm<br>Rx: 7 mA for BW=812<br>SX1280 chip |
| Highest data rate / energy efficiency | SF7, BW=500, CR=4/5                               | SF5, BW=1625, CR=4/5  |
| Greatest comm. range                  | SF12, BW=125, CR=4/8                              | SF12, BW=203, CR=4/8  |
| Intermediate configurations           | SF8, BW=125, CR=4/5                               | SF7, BW=812, CR=4/5<br>SF11, BW=812, CR=4/5                 |

Table 1: LoRa parameters and characteristics. The configurations used in the experiments are highlighted.

However, LoRa 2.4 GHz also has some disadvantages and has to face several challenges as we discuss in Section 5. First, LoRa 2.4 GHz works in a widely used frequency band, alongside Wi-Fi and BLE. This leads to a huge possibility of interference between technologies. Second, LoRa 2.4 GHz has a lower communication range compared to LoRa sub-GHz, especially in indoor scenarios. This comes from the fact that the 2.4 GHz frequency band has a higher attenuation when penetrating into buildings or passing through walls and floors. Still, its communication range remains larger than other low power technologies that operate in the 2.4 GHz band.

Concerning the upper layers, everything is standardized for the sub-GHz bands by the LoRa Alliance® in the LoRaWAN® standard [3]. In a LoRaWAN network, end-devices communicate directly with all the gateways in their communication range, which then forward the received packets to a network server, before dispatching them to the appropriate application server. For the medium access, LoRaWAN uses an Aloha-based protocol, for which it defines three modes of operation that offer different trade-offs between energy consumption and communication latency. As it stands today, there is no

amendment to LoRaWAN for the specific use of LoRa 2.4 GHz, which can be seen as a disadvantage and as an opportunity at the same time.

## 3 Motivations for LoRa 2.4 GHz

Since LoRa sub-GHz and LoRa 2.4 GHz are very similar, the goal of this section is to highlight the main technical and scientific motivations for using LoRa 2.4 GHz compared to LoRa sub-GHz and to present the new applications that can now be supported, such as localization, object tracking, and worldwide transport.

### 3.1 New Applications for LoRa 2.4 GHz

*Global roaming and tracking applications:* The availability of a world-wide, single radio frequency band with shared configuration parameters eases the emergence of worldwide applications for LoRa 2.4 GHz. These applications can run anywhere, anytime, with

a single hardware and software, without the adaptations due to regulations on regional radio frequencies use. Examples include applications where the devices can operate in multiple regions where a maximum range of a few hundred meters is enough, in opposition to several kilometers as offered by LoRa sub-GHz. Such applications are global roaming and global tracking applications (e.g., maritime or air transport), where the location of the monitored objects (including goods, animals, and persons) is followed regularly.

The monitored objects can now seamlessly cross the boundaries of countries or regions, thus opening the path for worldwide interoperability for IoT devices and applications.

*High precision ranging:* The use of higher bandwidth in LoRa 2.4 GHz enables a highly accurate ranging mechanism up to 2 m. This enables in turn high accuracy localization, as well as new localization-based applications, including accurate object tracking [4]. Note that the accurate ranging feature is natively implemented in Semtech’s SX1280 chip.

### 3.2 Practical motivations for LoRa 2.4 GHz

*Single hardware and software:* LoRa 2.4 GHz enables and simplifies the use of the same hardware everywhere in the world. While LoRa sub-GHz chips can now deal with all sub-GHz ISM bands, the whole system still needs to have different RF optimizations and different firmwares, because of differences in the LoRaWAN standard depending on the region of deployment. LoRa 2.4 GHz constructors can design, manufacture, test, stock and sell a single system, which ultimately reduces the cost of the devices. Similarly, the software implementation of the network protocol becomes simpler and unique. Hardware and software certifications become easier to obtain for manufacturers, which reduces their capital expenditures. Also, the users can buy any LoRa 2.4 GHz chip and deploy it anywhere without having to take into consideration the deployment region beforehand.

*Smaller sensor size:* The wavelength for the 2.4 GHz ISM band is about a third of the wavelength

of the sub-GHz band, which means the antenna size of LoRa 2.4 GHz devices is significantly smaller than with LoRa sub-GHz. This reduces the overall size of the end-device, and allows a smaller and better integration of IoT devices, where miniaturization is a compelling requirement.

### 3.3 Technical and scientific motivations for LoRa 2.4 GHz

*Better channel usage:* LoRa 2.4 GHz does not have duty-cycle limitations, contrarily to some regional regulations for the sub-GHz band (e.g., 1% in Europe): a LoRa 2.4 GHz device can send data at any time, or ideally when the medium is free. If a LoRa 2.4 GHz network is deployed in an area where a channel is not used, a device can use it at its full extent.

*Lower impact of the overhead:* The increase in the data rate of LoRa 2.4 GHz enables the increase of the maximum payload size of packets, thus reducing the relative cost of the overhead caused by preambles and header.

*Lower latency:* LoRa 2.4 GHz can achieve low latency in packet transmission, as there is no duty-cycle limitation. The large latency of LoRa sub-GHz is one of its main drawbacks for some applications. With LoRa 2.4 GHz, it is possible to consider applications with a typical latency of up to tens of milliseconds.

*Higher data rate:* There is no duty-cycle limitation in the 2.4 GHz frequency band and a larger data rate can be obtained by LoRa 2.4 GHz compared to LoRa sub-GHz. When combining these two characteristics, it is possible to transmit multimedia content (such as sound or images) or to implement broadband IoT applications.

*Robustness to interference:* Given the high robustness of the LoRa modulation, it is likely that LoRa 2.4 GHz communications will be able to be demodulated even in the presence of interference from other technologies, under specific conditions [5].

## 4 Performance Evaluation of LoRa 2.4 GHz and Comparison with LoRa sub-GHz

While the performance of LoRa has been widely studied in the sub-GHz bands, its counterpart in the 2.4 GHz band has yet to undergo such scrutiny, as the corresponding hardware is still less mainstream. To the best of our knowledge, few works have investigated the performance of LoRa 2.4 GHz, out of which only one has studied its performance experimentally: Rander et al. observed a maximum communication range for reliable communication of 1700 m in an outdoor scenario [6]. Janssen et al. made an analytical evaluation of the maximum communication range, achieving a maximum of 133 km in a free space scenario, 74 m indoor, and 443 m in an urban scenario [7]. Also, Masek et al. compare the scaling of LoRaWAN in three frequency bands (868 MHz, 915 MHz and 2.4 GHz) using network simulation, achieving a success rate above 90% for 2000 end-nodes in the 2.4 GHz frequency band [8].

### 4.1 Experimental Setup

We investigate here the performance of LoRa 2.4 GHz and compare it to LoRa sub-GHz in both outdoor and indoor scenarios, under several configurations, as shown in Table 1. For all settings, we used a MAC payload of 20 bytes, and a transmission power of 13 dBm.

The experiments were carried out using Arduino UNOs with SX1276 radio chip for LoRa sub-GHz and Nucleo boards with SX1280 radio chip for LoRa 2.4 GHz, which we deployed on wooden poles at 1.5 m from the ground. Each experiment consists of 10 campaigns of 50 transmitted packets per configuration. Within a campaign, each end-device sends a packet every 2 seconds. We collected and analyzed three metrics: Packet Delivery Ratio (PDR), Received Signal Strength Indication (RSSI) and Signal to Noise Ratio (SNR). For lack of space, we focus here on the PDR results. The RSSI and SNR results are consistent with the trends observed here.

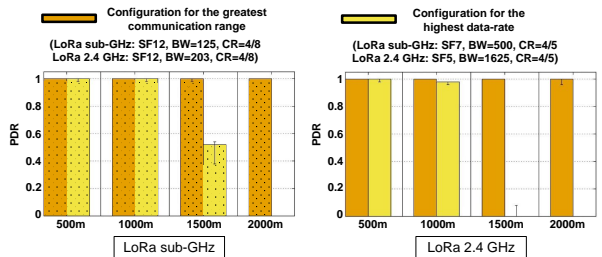


Figure 2: PDR of LoRa sub-GHz and LoRa 2.4 GHz in the outdoor scenario.

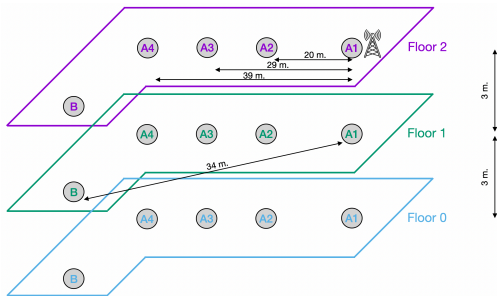


Figure 3: Building plan for indoor experiments.

### 4.2 Outdoor scenario

The outdoor evaluation was done in a line-of-sight scenario, along the Rhône river, near the city of Lyon (France). The gateways had fixed locations and end-devices were located between 0.5 km and 2 km from the gateways. It was not possible to do experiments farther away without losing line-of-sight.

Fig. 2 shows the average PDR for each distance, for LoRa sub-GHz and LoRa 2.4 GHz. The results show that for both frequency bands, for all distances, the greatest communication range configuration provides a PDR of 1, showing that the maximum range is not reached. For the highest data rate configuration, i.e., SF7 for LoRa sub-GHz and SF5 for LoRa 2.4 GHz, as expected, LoRa 2.4 GHz has a slightly lower communication range than LoRa sub-GHz: from 1500 m, the connectivity is lost for LoRa 2.4 GHz, while LoRa sub-GHz maintains a PDR of about 0.5. Still, this is sufficient for applications targeted by LoRa 2.4 GHz (e.g., international tracking).

### 4.3 Indoor scenario

The indoor evaluation took place in the building of the Telecommunications department at INSA Lyon, France, as it models a deployment in real conditions with multiple 802.11 access points. The gateways were located in the spot A1 of floor 2, at one end of a corridor. End-devices were either located along this corridor (spots A1 to A4) or in a different corridor (spot B). The same spots were used at floor 1 and floor 0 (see Fig. 3).

Fig. 4 shows the average PDR for each location and for each floor. The results show that the performance in an indoor scenario is directly impacted by the distance, obstacles and number of floors between gateways and end-devices, whatever the frequency band is. With LoRa sub-GHz, all spots are covered with a high PDR, dropping slightly to 0.85 in the worst case (spot B, floor 0). However, the results degrade quickly for LoRa 2.4 GHz. When gateways and end-devices are on the same floor (floor 2), the PDR of LoRa 2.4 GHz decreases with the distance, as expected. Still, the SF12 configurations guarantees excellent performance with a PDR of 1 for all the spots of floor 2. If we look at spot B in particular, the greatest communication range configuration for LoRa 2.4 GHz, is the only one that manages to maintain a connectivity with the gateway, regardless of the floor. The PDR degrades as we move further away: 0.6 at floor 1, and 0.5 at floor 0. This means that to cover a building of several floors with LoRa 2.4 GHz, several indoor gateways are required, which is useful for localization applications. Moreover, using LoRa 2.4 GHz permits to cover the same space as ZigBee or Bluetooth, but with less anchors/access points, which considerably lowers the cost and complexity of deployment. We can also note that the PDR for the spot A3 is lower than the PDR for the spot A4. This comes from the location of spot A3 which is slightly off from the line of sight.

## 5 Research Challenges

The development of LoRa 2.4 GHz brings numerous opportunities and research challenges that we discuss

below.

### 5.1 Technology Co-existence Challenges

The main challenge of LoRa 2.4 GHz is the coexistence with other radio technologies already occupying the 2.4 GHz ISM band such as Wi-Fi, Bluetooth, Bluetooth Low Energy (BLE), and ZigBee. This brings up a series of considerations that can make or break the success of LoRa 2.4 GHz.

*Channel allocation.* Semtech has proposed the use of LoRa 2.4 GHz in conjunction with a protocol emulating LoRaWAN with three mandatory channels. As we can see in Fig. 5, these channels are located in a part of the spectrum outside of Wi-Fi's most common channels, and between two consecutive BLE channels. However, is this the best choice? Why not setup the LoRa channel between two BLE data channels instead of between an advertising and a data one? Moreover, it is still possible for Wi-Fi channels to completely overlap LoRa 2.4 GHz channels.

*Interference mitigation.* Cross-technology interference can limit the performance of technologies working in the same frequency band and having overlapping channels. It is of uttermost importance to evaluate and characterize the type of interference of other technologies on LoRa 2.4 GHz and vice-versa, so that we can design appropriate interference avoidance mechanisms. For example, the LoRa transmission during a small Wi-Fi silent time.

*Demodulation.* Because the LoRa modulation is robust and largely different from the other modulations in the 2.4 GHz ISM band, it might be possible for a LoRa 2.4 GHz frame to be demodulated with a low SNR, even if a frame with a higher SNR is transmitted by another technology. In order to increase the PDR it will be very useful to design strategies that help recover LoRa signals in the presence of simultaneous cross-technology transmissions.

*Cross-technology transmission.* The coexistence of multiple technologies can also have some benefits. It is possible to modify the physical layer of a given technology to allow a transmitter to send frames that can be detected or decoded by the receiver of another

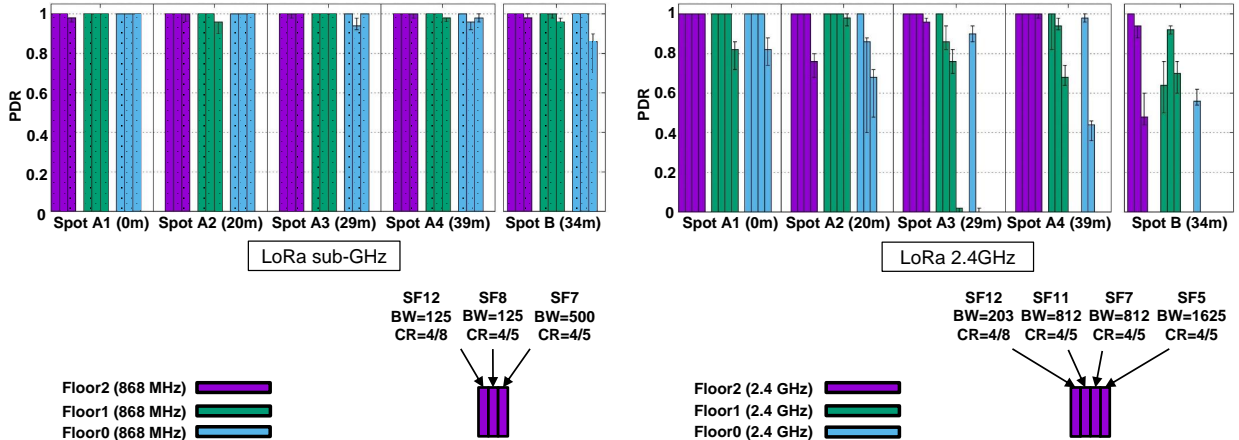


Figure 4: PDR of LoRa sub-GHz and LoRa 2.4 GHz in the indoor scenario.

technology. For instance, Li et al. propose to exploit the frequency hopping of BLE to emulate LoRa 2.4 GHz chirps [9]. Hence, BLE devices can notify LoRa 2.4 GHz devices of their presence. This type of exchanges can help devices from different technologies make informed decisions and thus improve their coexistence.

*Cognitive radio.* To leverage the complexity of the competition in the 2.4 GHz ISM band, cognitive radios [10] can be used to adapt the physical layer configuration of LoRa 2.4 GHz to the environment. For instance, the channels could be dynamically shifted to increase the SNR, and LoRa parameters (SF, BW, CR) could be adapted based on the information from previous packet transmissions. Dynamically adapting the length of the data frames also achieves a trade-off between survivability and detectability as short data packets tend to collide less than long data packets which in turn are typically easier to detect by other technologies.

## 5.2 Hardware Related Challenges

Another important challenge is related to the development of new hardware to support the efficient deployment of LoRa 2.4 GHz networks, as well as the software that goes with it.

*Complex radio front-ends.* Designing the radio

front-ends for LoRa 2.4 GHz is difficult for several reasons. First, LoRa 2.4 GHz uses much larger bandwidths (typically, 812 kHz or 1625 kHz) than LoRa sub-GHz (typically, 125 kHz). Second, the available bandwidth in the 2.4 GHz ISM band is 80 MHz, which is very large, and is not likely to be covered by a single low-cost front-end. A possible design of the LoRa 2.4 GHz gateway is to have several front-ends, each on a relatively small bandwidth (say 1 MHz), and followed by a base-band concentrator chip which can detect and demodulate multiple packets of different SFs and channels in parallel.

*Parallel reception.* Current LoRa 2.4 GHz gateways are based on the SX1280 chipset, and can only listen to three configurations (SF/BW/channel) at the same time. It is likely that in the future, gateways will have to be able to receive more transmissions in parallel, as it is already the case in LoRa sub-GHz with 8 parallel reception paths. Moreover, since downlink communications often limit the network capacity and can also have a negative impact on uplink communications (LoRa gateways cannot receive and transmit packets at the same time) [11], full-duplex solutions should be imagined.

*Multi-mode radios.* We believe that LoRa 2.4 GHz networks will not replace LoRa sub-GHz networks, but could complement the actual standard with additional flexibility: on the one hand, LoRa sub-GHz



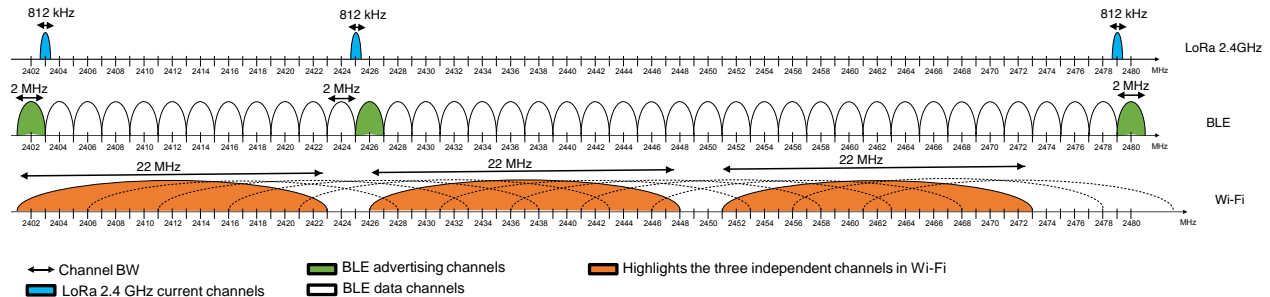


Figure 5: Frequency channels and bandwidth of LoRa 2.4 GHz, BLE, and Wi-Fi in the 2.4 GHz ISM band.

provides large coverage but uses regional parameters, and on the other hand, LoRa 2.4 GHz has higher throughput and a single world-wide setting. These two technologies are addressing different use-cases. Semtech recently launched a new LoRa radio chip (LR1120) that supports both LoRa sub-GHz and LoRa 2.4 GHz (and furthermore the Long-Range Frequency Hopping Spread Spectrum modulation that targets satellite communications). The collaborative scenarios between the two bands is still to be assessed according to applications and use cases; it will require the development of an appropriate software. How to share and take advantage of the information learned from using different settings? Will it need to run two MAC protocols in parallel?

*Relay nodes for LoRa 2.4 GHz.* While relays are already used in some LoRa sub-GHz networks, these are isolated scenarios (e.g., for underground communication). It is possible that relays will become common in LoRa 2.4 GHz as they will help reach devices far away from the gateways. This will add an extra degree of complexity to the topology. Note, that the use of relays can be extended to support D2D communications. Lumet et al. have already investigated the gain of using relays in a LoRa sub-GHz network, while keeping a low energy consumption, thus providing useful insights for LoRa 2.4 GHz around possible data aggregation techniques, lightweight relaying or even routing protocol [12].

## 6 Opportunities for LoRa 2.4 GHz

The success of LoRa was largely due to the open standardization efforts for LoRaWAN, resulting in the creation of a world-wide standard (with regional variations) supported by manufacturers and network operators across the globe. While the LoRa Alliance has not yet converged on a standard for the MAC and networking protocols in LoRa 2.4 GHz, this is of uttermost importance for the large adoption and the success of this technology. Designing this protocol as an extension of LoRaWAN might be easier to implement and faster to standardize, but might not be the optimal choice, as LoRa 2.4 GHz could benefit from the technical properties of the operating frequency band, as we highlight next:

*Optimized medium access mechanism.* LoRaWAN uses a simple protocol based on Aloha. In crowded radio environments, and without duty-cycle limitations, one can argue that better performance could be obtained with a clear channel assessment (CCA) or a listen before talk (LBT) mechanism, as such mechanisms have already proved beneficial in LoRa sub-GHz [13, 14]. Time-slotted approaches also yield less collisions and more robustness which could be of primary importance when considering reliable or low-latency applications [15]. The challenge is to find the best approach among all these possibilities.

*New features.* The new MAC and networking protocol for LoRa 2.4 GHz can include new features,

such as efficient mobility management and roaming, world-wide interoperability among end-devices and visiting LoRa-enabled networks. Grouped acknowledgements could spare gateway resources and improve network scalability, and a context-aware adaptive data rate (ADR) mechanism could take into account cross-technology interference (possibly through the use of a machine learning mechanism). For applications having severe constraints in term of energy consumption, an optional duty-cycle mechanism could be proposed. The maximum payload in the new MAC and networking protocol for LoRa 2.4 GHz has to be increased compared to LoRaWAN, as 51 bytes of typical payload (when using SF12) is hindering many applications. The ideal payload size is likely a trade-off between robustness and capacity. The new MAC and networking protocol for LoRa 2.4 GHz could also introduce a native fragmentation as well as the support of several quality of service requirements such as high throughput and low latency. These features would be a completely new addition to the LoRaWAN standard, and needs thorough discussions.

*Security.* The security provided by the LoRaWAN protocol is already high, and it does not seem that switching to the 2.4 GHz frequency band brings new security issues. There might still be some minor improvements made in the new MAC and networking protocol for LoRa 2.4 GHz: (i) the larger maximum payload size might allow the use of longer keys, (ii) the shorter time on air might enable more interactions when designing security protocols, and (iii) the increase of the data rate is likely to make the devices communicate more often than with LoRaWAN, thus requiring the introduction of revocation mechanisms for the various security keys that are used. Furthermore, due to the emergence of interoperable applications, and in order to support global roaming, new security functions should be designed to guarantee ubiquity and to provide trust for roaming devices.

*Localization.* Applications based on localization are important in the IoT [4]. A ranging feature is now native in LoRa 2.4 GHz and offers high accuracy of about 2 m. Based on multiple ranging among devices, localization algorithms can compute the location of a device. However, the new MAC and networking protocol for LoRa 2.4 GHz should state the

format of the packets and the timings at which they should be exchanged to avoid interfering with normal data transmission.

## 7 Conclusion

In this paper, we presented LoRa 2.4 GHz, a major evolution of LoRa sub-GHz in the 2.4 GHz ISM band, which opens a new era for IoT applications, including the support of low latency applications, world-wide roaming, global interoperability and broadband applications.

We propose a qualitative comparison between LoRa sub-GHz and LoRa 2.4 GHz, underlying the new SF5 and the new BW (812 kHz, 1625 kHz) available.

For the first time, we showed that LoRa 2.4 GHz can reach a distance of communication of at least 2 km in an outdoor scenario while maintaining a PDR of 1. We also showed that LoRa 2.4 GHz performance is suitable for several indoor IoT applications. While its performance degrades when compared to LoRa sub-GHz, it still offers the highest range among all technologies operating in the 2.4 GHz band (BLE, Zigbee, Wi-Fi). For complete coverage of a small multi-floors building, three or four gateways would be enough for LoRa 2.4 GHz, which is compatible with an accurate localization.

In our opinion, the experimental results obtained here are extremely useful for the scientific community to assess the real performance of LoRa 2.4 GHz technology, and to give engineers insights into the behavior of LoRa 2.4 GHz that will help them make more informed choices for LoRa 2.4 GHz network deployments.

To use of the 2.4 GHz ISM band, the first key technical challenge is the coexistence and interference management with other technologies. These challenges raise multiple research opportunities, such as using cognitive radios, or developing a new MAC protocol. Finally, in the future, energy-efficient relaying hardware and protocols will need to be developed to deal with the shorter radio range.

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