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Performance analysis of LoRa in the 2.4 GHz ISM band: coexistence issues with Wi-Fi

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Abstract

Within realization of the visions of the Internet-of-Things (IoT), Low Power Wide Area Networks (LPWANs) are undoubtedly one of the fields that attract high interest from both academic and industrial fields. To ensure reliable data exchange between low power and low data rate devices across long distances, which are the main aims of LPWAs, it is necessary to utilize advanced wireless communication technologies. Emerging LPWA technologies, for instance Long-Range (LoRa) and SigFox, offer many benefits for IoT. These technologies have been primarily developed for sub-GHz frequency bands, but, in the future, their deployment is also considered in the 2.4 GHz industrial, scientific and medical (ISM) bands. However, these unlicensed ISM bands are also used by other technologies for Wireless Local Area Network (WLAN also denoted as Wi-Fi) connectivity and other services, and therefore, coexistence issues can occur here in the future. The main aim of this paper is to perform a performance analysis of the LoRa radio signals interfered by Wi-Fi, using interferers confirming to different IEEE 802.11 family standards, in the 2.4 GHz ISM band. For this purpose, an automated measurement setup and methodology on Physical (PHY) layer are proposed and used. In general, the evaluated results confirm theoretical assumptions on high robustness of LoRa against interferences. However, our results reveal that this robustness of LoRa is highly depending not only on the used LoRa system parameters, but also on the interferer properties and the assumed coexistence scenarios (co-channel, in-band and adjacent channel interferences).

Keywords Internet-of-Things · LPWAN · LoRa · Wi-Fi · Coexistence · Interference · RF measurement

1 Introduction

Nowadays, Low Power Wide Area Networks (LPWANs) and related wireless communication technologies are receiving a lot of attention mainly from the fields of industry, logistic and healthcare. These fields are closely connected with the Internet-of-Things (IoT) paradigm [1]. LPWA technologies, like LoRa, SigFox, Ingenu, Weightless-N and Dash, offer flexible sets to fulfill the main requirements of the IoT applications [2]. Low hardware and operational cost, low power, low data rate, reliable connection between numerous devices, long range communication and immunity against interference are the most important among them [3]. The common point of the mentioned LPWA technologies is that all of them utilize industrial, scientific and medical (ISM) radio frequency (RF) bands. In this work, our attention is devoted to the LoRa technology.

1.1 Brief introduction to LoRa

In this subsection, we provide a brief introduction to the LoRa technology. We focus only on its physical (PHY) layer technical specifications, which are directly related with this work. The basic features of LoRa are well documented and detailed information about this LPWA technology can be found in works [3–6].

LoRa, introduced in 2012, has its name derived from the capability of communicating with a very high link budget with low received power, which means long range communication is possible.

It has been developed for LPWANs utilizing of sub-GHz ISM bands. The specification is divided into two parts: The physical (PHY) layer, patented by company Semtech,[1] and

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upper layers (MAC), originating from LoRa Alliance.[2] The PHY layer is characterized by the following system parameters [3]: Code Rate (CR), modulation technique, Spreading Factor (SF), bandwidth (B_{LoRa}), carrier frequency and transmission power.

Forward Error Correction (FEC) is used to control the length of a LoRa frame and the robustness of data packets for various transmission conditions. The CR can be 4/5 (lowest robustness), 4/6, 4/7 or 4/8 (highest robustness).

Chirp spread spectrum (CSS) modulation [3] was adopted by the PHY layer of LoRa. It ensures high robustness against noises originated from multipath propagation interferences. Here, the value of SF plays a key role. The SF, defined as the ratio of chip and symbol rates, can be set between 6 and 12. The higher the SF, the higher the sensitivity of the receiver, and the longer the communication range and the time to send data. It is important to mention that the Gaussian Frequency-Shift Keying modulation (GFSK) with 50 kbps data rate can be used, when $B_{\text{LoRa}} = 150\,\text{kHz}$ [7].

The LoRa system dominantly supports three values of B_{LoRa}: 125 kHz, 250 kHz and 500 kHz. The higher is the used B_{LoRa}, the higher is the data bit rate, and the lower is the sensitivity of the receiver. The LoRa technology was primarily developed for ISM sub-GHz bands. Depending on the region, generally, it operates in the 433, 868 and 915 MHz bands [6].

The transmission power of the LoRa signal can be varied between -4 dBm and 20 dBm, in 1 dB steps. It is always depending on the region, where LoRa technology is used. In general, transmission power higher than 17 dBm can only be used on a 1% duty cycle [7].

1.2 Coexistence issues of LoRa: state-of-the-art

In recent years, study of the features of LoRa technology and its utilization in various application fields has reported in numerous works [6–13]. A dominant part of these works deals mainly with the introduction to the LoRa technology and with the study of the performance of LoRa system. However, exploring of the coexistence between LoRa and different wireless communication systems [14–20], especially in the non sub-GHz ISM bands, has received lower attention.

Poorter et al. in [14] present the state-of-the-art of emerging LPWA technologies in the sub-GHz bands. The authors stated that future research activities should focus more on a coordinated use of LPWA devices supporting the use of different wireless technologies.

Simulation-based analyses of coexistence scenarios between LoRa and SigFox networks, using CSS and ultra narrow band (UNB) techniques, were presented in [15]. The results showed gradual performance degradation of the interfered LoRa devices with their increasing distance from the base station.

Outputs of a measurement-based coexistence study of LoRa and SigFox systems in the 868-868.8 MHz ISM bands were published in [16] and [17]. The coverage and capacity of LPWA networks, influenced by interferences, were analyzed in different outdoor scenarios (e.g. industrial area, hospital complex) [16]. Results obtained at different link budget and time on air values, showed that both LoRa and SigFox technologies have a high resistance against interferences. However, their performance directly depends on the power level of the interfered and interfering signals and on the number of the used IoT devices. Further, susceptibility of LoRa to the inter-network interference issues (LoRa interferer, LoRa victim) were empirically studied by Mikhaylov et al. [18]. Based on the experimental results, it was derived that the LoRa signals with different data rates influence each other negatively (performance degradation) in a common RF channel. In addition, the payload size of the LoRa packet, depending on the power levels of the interacting RF signals, has a direct influence on the packet error rate (PER) value.

Interferences occurring at the coexistence between different sub-GHz technologies (LoRa, SigFox, Z-Wave and IO Home Control) were explored in [19]. For this purpose, a controllable measurement setup, containing a microcontroller, an attenuator, a combiner and a PC, was realized. From the viewpoint of LoRa, it was demonstrated that interferer signals from different sub-GHz systems affect different LoRa packet parts by different ways. Next, it was confirmed that the LoRa signal with a higher SF value has higher resistance against interferences. The main outputs of the work were presented in terms of packet loss ratio (PLR) versus signal-to-interference (SIR) ratio.

Interference issues between LoRa and IEEE 802.15.4g networks were investigated in [20]. In this complex work, authors explored the performance of LoRa influenced by IEEE 802.15.4g and vice versa in the 868 MHz ISM band. Packet reception rate (PRR) objective parameter was used for the evaluation. A set of experimental measurements were realized in an anechoic chamber. The obtained results revealed distinctly higher resistance of LoRa packets to interference than IEEE 802.15.4g ones. The lowest loss of LoRa packets, depending on the signal/interfering power levels and bandwidth values of LoRa, has observed for SF ≥ 9.

In current state-of-the-art, only several works focus on the utilization of LoRa in the 2.4 GHz band [21–23]. Vangelista and et al. [21] deal with possibilities of the using of LoRa in the 2.4 GHz band. Basic benchmark analysis of the LoRa technology in the 2.45 GHz band was presented in [22]. In this work, LoRa devices from the company EM Microelectronics were used. Authors of [22], according to the explored use cases, stated that the LoRa signal has a good resistance against echoes and fading occurring in the radio channel.

[2] LoRaWAN^{TM} Specifications, V1.0; LoRa Alliance.

The first application note devoted to the study of Wi-Fi immunity of LoRa in the 2.4 GHz ISM band was presented in [23]. A simple laboratory measurement setup was used to explore co-channel coexistence of LoRa and Wi-Fi for some selected LoRa system configurations and adjacent channel interference for one LoRa signal. First tests demonstrated that increasing the SF value and reducing the bandwidth results in higher interference immunity of LoRa against Wi-Fi. At adjacent channel interferences, this immunity can increase only starting at a certain frequency offset (frequency distance between the interacting RF signals).

1.3 Original contribution

From the above elaborated state-of-the-art is clear, that researchers' attention is dominantly focused on the coexistence issues of LPWANs in the sub-GHz bands. Outputs of some works also revealed disadvantages for massive utilization of LoRa in these RF bands due to strict requirements on the duty cycle and missing worldwide harmonization of the sub-GHz RF bands.

The Semtech company has already released two long range, low power transceivers,[3] which enable scalable data rate communication for point-to-point wireless links in the 2.4 GHz license-free RF band. Performance of LoRa-based communication in the 2.4 GHz ISM has been partly studied in [21,23–25]. The LoRa technology can complement other technologies, for instance IEEE 802.11 (Wi-Fi) or Bluetooth [26], used in these RF bands. However, the presence of LoRa in the 2.4 GHz RF band will increase the amount of unwanted cross-technology interferences. Thereby, a performance study of the LoRa system for such cases is important.

The main purpose of this work is to examine the influence of Wi-Fi on the performance of LoRa in the 2.4 GHz band. Our study takes into account various LoRa system configurations and different IEEE 802.11 technologies with various system settings as well as multiple coexistence scenarios. Thereby, it can significantly extend the first results published in this field by Semtech [23].

The main contribution of our work is summarized as follows:

- We present an automated laboratory measurement setup to measure the influence of Wi-Fi signals on LoRa communication on PHY level. We apply a general framework to evaluate the performance of LoRa as a dependence of Bit Error Ratio (BER) on carrier-to-interference (C/I) ratio. The proposed concept excels with simplicity, flexibility and easy reproducibility of the measurement for different scenarios.

[3] https://www.semtech.com/products/wireless-rf/24-ghz-transceivers.

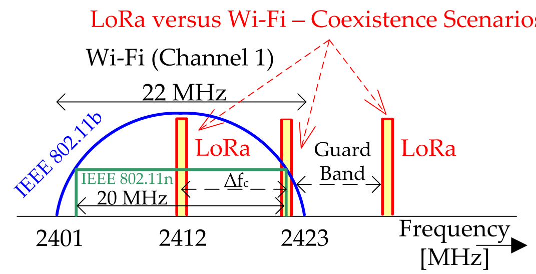


Fig. 1 Coexistence scenarios (co-channel, in-band and adjacent channel interferences) between LoRa and Wi-Fi in the 2.4 GHz ISM band. The symbol Δf_c marks the frequency offset between wanted (LoRa) and interfering (Wi-Fi) signal

- We provide an exemplary evaluation of the performance of LoRa influenced by co-channel, in-band and adjacent channel interferences. We show that different IEEE 802.11 technologies influence the LoRa signal in different ways.
- We compare the conclusion of our study with the state-of-the-art knowledge.

To the best of our knowledge, similar extensive performance study of the LoRa system in the 2.4 GHz band with an automated measurement setup has not been presented so far. The outputs of our study can be useful for the future development of effective cross-technology [27] interference mitigation techniques as well as for operators to effectively share unlicensed spectrum.

1.4 Organization of the paper

The rest of this paper is organized as follows. Coexistence scenarios between LoRa and Wi-Fi in the 2.4 GHz band are introduced in Sect. 2. The IEEE 802.11 technologies, considered in this work, are also briefly presented in this part. The proposed measurement setup and methodology, including the used LoRa/Wi-Fi system parameters, are described in Sect. 3. Evaluation of the obtained results and final conclusions are presented in Sects. 4 and 5, respectively.

2 Coexistence scenario

The 2.4 GHz RF band is one of the most utilized ISM bands. It is primarily used by IEEE 802.11-based Wireless Local Are Networks (WLANs), also known as Wi-Fi, and also by Bluetooth and ZigBee [28]. Possible occupancy of a part of 2.4 GHz RF band by LoRa is captured in Fig. 1. The main aim of this work is to explore the influence of Wi-Fi system on LoRa.

We focus on co-channel and in-band interferences. In the case of in-band interferences, we consider different carrier

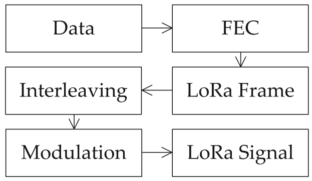


Fig. 2 Block diagram of the LoRa PHY simulator (TX part)

frequency offsets, marked as Δf_c, between Wi-Fi and LoRa RF signals (see Fig. 1). In addition, we will consider one case of adjacent coexistence scenario, where between the RF spectra there is a guard band (GB) [23] with a width of 250 kHz (shown also in Fig. 1).

In this work, the Wi-Fi RF signals are created according to IEEE 802.11b/n technologies [26,29]. The IEEE 802.11b specification is based on Direct Sequence Spread Spectrum (DSSS) and uses complementary code keying (CCK) modulation technique. It allows to achieve a data rate of 11 Mbit/s at 22 MHz bandwidth. IEEE 802.11n can be used in 2.4/5 GHz bands and is based on the Orthogonal Frequency Division Multiplexing (OFDM). It supports 20 and 40 MHz channel bandwidths and the maximum data rate can be 600 Mbit/s. More details can be found in [29].

3 Measurement setup and methodology

This section describes our proposed automated laboratory measurement setup and the adopted framework to evaluate coexistence scenarios between LoRa and Wi-Fi in the 2.4 GHz RF band.

3.1 Generation of the LoRa baseband signal

For the generation of the LoRa baseband signal we have created a MATLAB-based LoRa PHY simulator, which is based on [11]. Block diagram of the signal processing chain is depicted in Fig. 2.

Input data with a defined length are generated on a bit level and consequently a Hamming-based FEC code is applied. It is possible to select among four values of CR, according to $CR = 4/(4+n)$, where $n \in \{1, 2, 3, 4\}$. Here, it is possible to use a so called whitening block ensuring the break up the long sequences of zeros and ones. The employing of this block is optional [30,31] and hence, we do not use it in this simulator. Next, diagonal interleaving is used to increase the robustness of data against long-term interferences [32]. It is followed by applying of CCS modulation technique, where SF can be set according to the LoRa system specification [33]. Finally, the LoRa signal in the baseband is created.

3.2 Measurement setup

Block diagram of the realized measurement workplace is shown in Fig. 3. Its basic concept is inspired by works [20,34–37].

The LoRa baseband signal, according to the considered system parameters (see Table 1), is generated by the MATLAB-based simulator described above, running on a PC. Next, we used the Rohde&Schwarz (R&S) SMU200A two-path arbitrary RF signal generator, connected to PC via switch Netgear GS108T. It is utilized to RF modulate the LoRa baseband signal.

The IEEE 802.11b/n (Wi-Fi) interfering RF signal is also generated by the R&S SMU200A (see Table 2 for the system parameters). Both RF signals are combined in using a custom manufactured Wilkinson power combiner (the additional loss is $\approx$ 7 dB). The carrier frequency and power level of both RF signals can be varied according to considered coexistence scenarios. In this work, the power level of the LoRa and Wi-Fi RF signals are marked as C and I, respectively. To control the actual power level in the considered channel bandwidth and the actual value of Δf_c, the R&S FSQ spectrum analyzer is utilized.

To minimize the time needed for measurement and evaluation of the results, we automated the whole measurement. Both R&S devices are connected with our PC via switch. After setting the Internet Protocol (IP) addresses, netmask and gateway, it is possible to create a Local Area Network (LAN) for communication and data transfer between the R&S devices and PC. Thereby, data during the measurement are continuously collected by the PC. The measured data are then processed offline. More details can be found in [37].

3.3 Measurement methodology

The robustness of LoRa to the interfering Wi-Fi signals is evaluated in terms of BER depending on the values of C/I, where C/I (in dB) is calculated as $C/I = C - I$. In this work, we monitor BER values up to the threshold of 10^{-2}. According to [11], BER below this level is sufficient for a reliable LoRa-based communication. BER of the LoRa payload is determined from the comparison of non-interfered and interfered LoRa baseband signals in MATLAB. For this purpose, the I/Q data are measured. The R&S FSQ spectrum analyzer is set on the carrier frequency of LoRa signal and switched to zero span mode. After configuration of the FSQ analyzer [38], the I/Q data are captured and saved. In the next step, the I/Q data are exported to PC and processed in the RX part of the LoRa PHY simulator (inverse signal processing) to obtain the LoRa baseband signal (interfered).

To speed up the measurement, the radio duty cycle is disabled to ensure minimum time gap between transmission of LoRa packets [20]. Inspired by measurement methodology

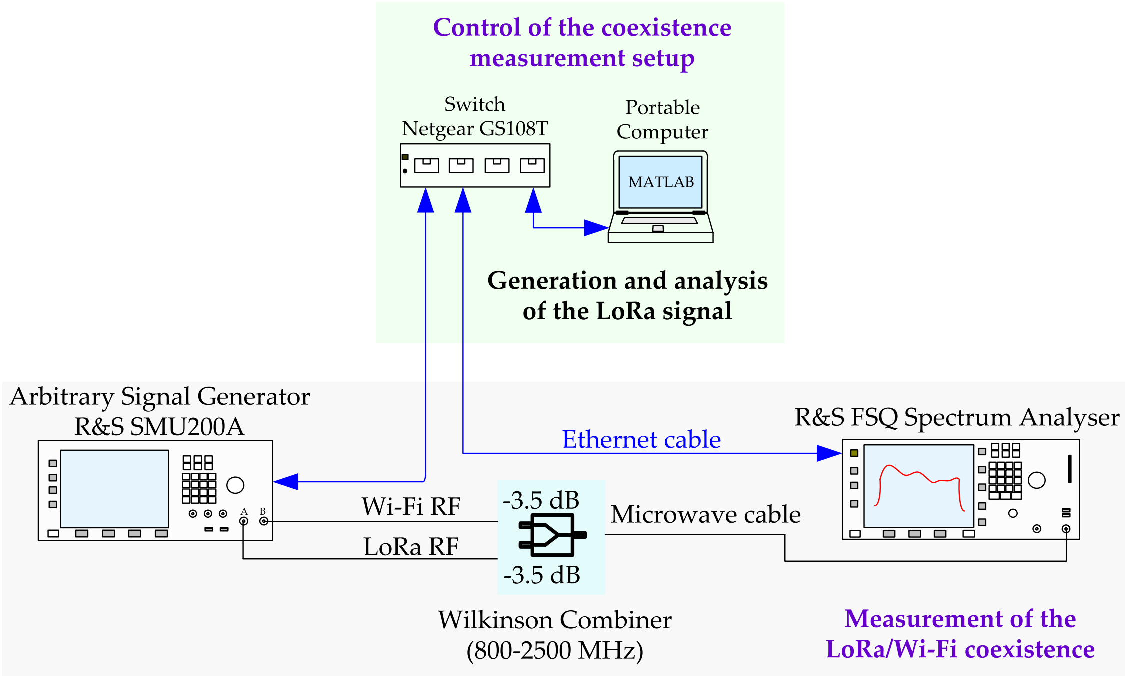


Fig. 3 Block diagram of the proposed LoRa/Wi-Fi coexistence measurement system

Table 1 The LoRa system parameters used in our study

	LoRa
Code rate	4/5
Modulation scheme	CSS
Spreading factor (SF)	6; 9; 12
Channel bandwidth (kHz)	150; 250; 500

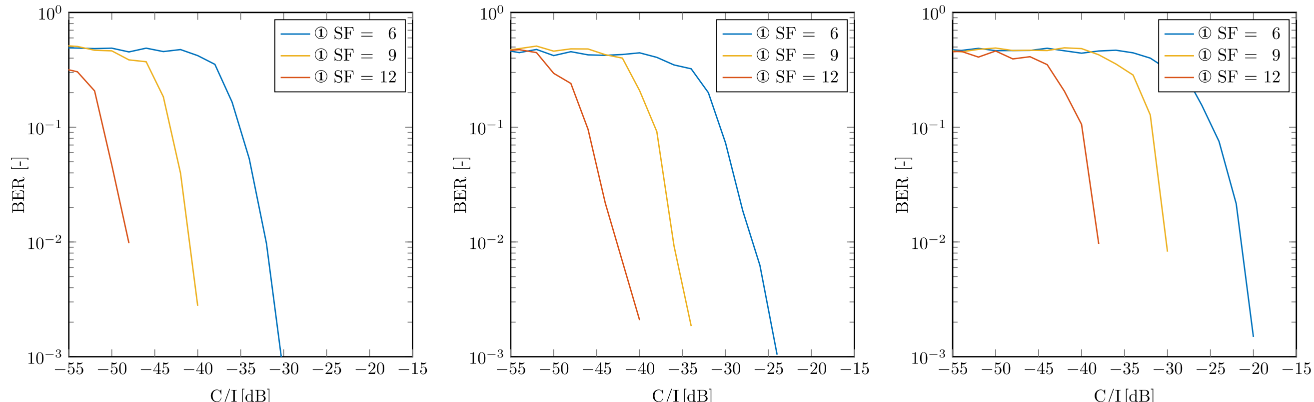
presented in [19], we set the TX power of LoRa signal to achieve −50 dBm average receive power at the RX side.

The following measurement methodology was adopted:

(1) The power level of the LoRa signal (measured at the receiver) is set to a defined value, which will be constant for all realized measurements. In this work, $C = -50$ dBm.
(2) The power level of the interfering IEEE 802.11b/g signal (I) is initially set below the value of C by 20 dB.
(3) The value of C/I is then gradually increasing with a step of 2 dB to evaluate the performance of LoRa under the influence of interfering Wi-Fi signal. During the measurement, the values of C and I are measured in the considered channel bandwidth by the R&S FSP3 spectrum analyzer.
(4) The values of C/I and BER for LoRa are calculated (offline), respectively.
(5) Steps from (1) to (5) are repeated for various LoRa and Wi-Fi system configurations, respectively, as well as for different Δf_c values.

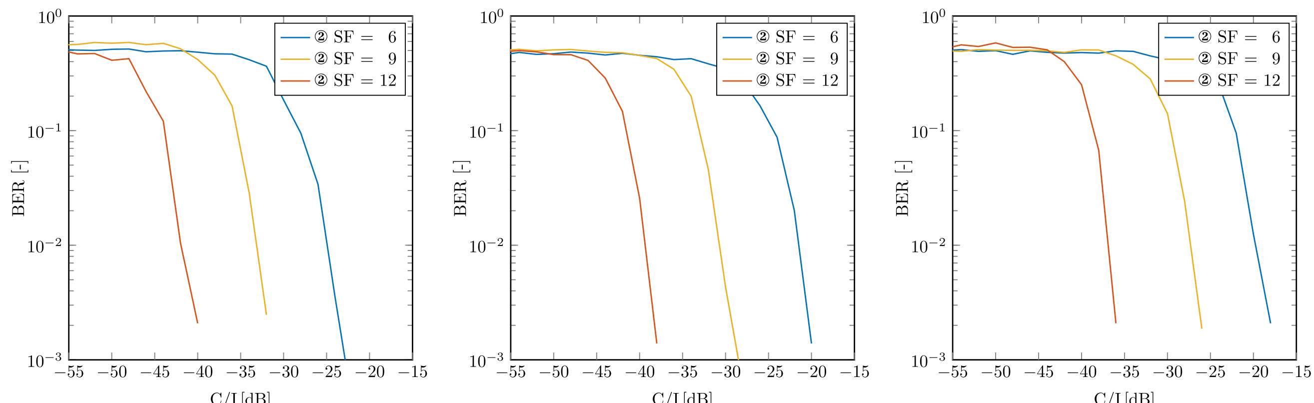
Table 2 The IEEE 802.11b/n system parameters used in our study

Setup	IEEE 802.11b		IEEE 802.11n			
	①	②	③	④	⑤	⑥
Code rate	1/2	1/2	3/4	3/4	3/4	3/4
Modulation scheme	DSSS	CCK	OFDM	OFDM	OFDM	OFDM
Modulation	DBPSK	DQPSK	QPSK	64QAM	QPSK	64QAM
FFT size	–	–	64	64	128	128
Guard interval (ns)	–	–	800	800	800	800
Channel bandwidth (MHz)	22	22	20	20	40	40
Data rate (Mbps)	1	11	19.5	65	40.5	135



(a) $B_{\text{LoRa}} = 125\,\text{kHz}$ **(b)** $B_{\text{LoRa}} = 250\,\text{kHz}$ **(c)** $B_{\text{LoRa}} = 500\,\text{kHz}$

Fig. 4 Co-channel interferences: evaluation of $BER = f(C/I)$ curves for different configurations of the LoRa system interfered by Wi-Fi using IEEE 802.11b technology (setup ①)



(a) $B_{\text{LoRa}} = 125\,\text{kHz}$ **(b)** $B_{\text{LoRa}} = 250\,\text{kHz}$ **(c)** $B_{\text{LoRa}} = 500\,\text{kHz}$

Fig. 5 Co-channel interferences: evaluation of $BER = f(C/I)$ curves for different configurations of the LoRa system interfered by Wi-Fi using IEEE 802.11b technology (setup ②)

The selected parameters (SF and B_{LoRa}) of LoRa system (see Table 1) and their combination represent the settings for LoRa signal with the lowest (low SF and high B_{LoRa}) and highest (high SF and low B_{LoRa}) resistance against interference [20]. Hence, results for other LoRa signal configurations will be within the borders defined by LoRa operation modes with the lowest and highest sensitivity.

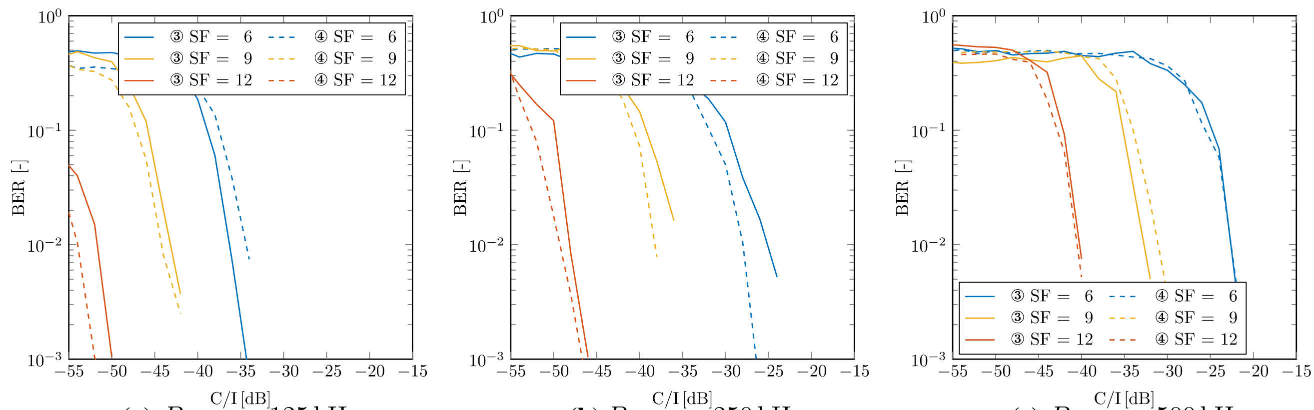
4 Results

This section deals with the analyzes of the results obtained from laboratory measurements. In the first part, the attention is devoted to co-channel coexistence scenarios, where both systems have the same 2412 MHz working frequency. In the second part, we focused on the in-band coexistence scenario. Here, we measured the Wi-Fi immunity of LoRa for various Δf_c. In addition, such immunity for LoRa was also measured for adjacent channel interference when $GB = 250$ kHz.

4.1 LoRa versus Wi-Fi: co-channel interference

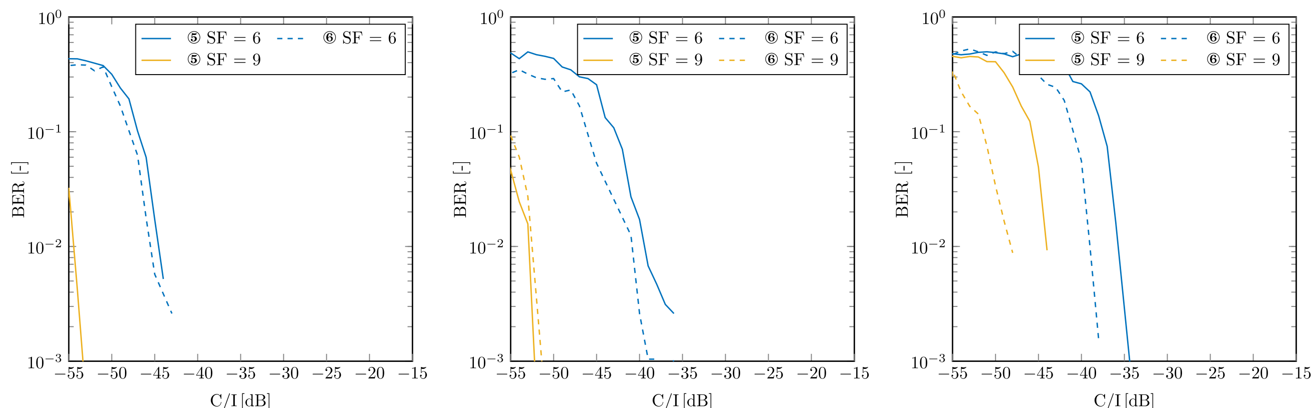
The performance of LoRa interfered by IEEE 802.11b (generated according to setup ① and ②), in the case of co-channel interference is demonstrated in Figs. 4 and 5, respectively. The trend of the BER curves meets with theory assumptions, i.e., the lower is the C/I, the higher is the BER. From the figures it is obvious that all C/I ratios have negative values. It means that the power level of the Wi-Fi signal, depending on the LoRa system configuration, can be approximately 20 dB to 45 dB higher than the measured power level of the LoRa signal at the input of the receiver. Such values prove high resistance of LoRa at co-channel coexistence scenarios.

The overall results, as expected, show that the LoRa signal with a configuration of high SF value and low B_{LoRa} have the highest resistance to co-channel interference. In the Fig. 5 can be seen that the IEEE 802.11b signal with higher data rate, using CCK modulation scheme, results in higher C/I requirements on LoRa to achieve the target BER values. There are visible differences between the required C/I ratios.



(a) $B_{\text{LoRa}} = 125\,\text{kHz}$ (b) $B_{\text{LoRa}} = 250\,\text{kHz}$ (c) $B_{\text{LoRa}} = 500\,\text{kHz}$

Fig. 6 Co-channel interference: evaluation of $BER = f(C/I)$ curves for different configurations of the LoRa system interfered by Wi-Fi using IEEE 802.11n technology. Solid and dashed lines are related to setup ③ and ④ (see Table 2)



(a) $B_{\text{LoRa}} = 125\,\text{kHz}$ (b) $B_{\text{LoRa}} = 250\,\text{kHz}$ (c) $B_{\text{LoRa}} = 500\,\text{kHz}$

Fig. 7 Co-channel interference: evaluation of $BER = f(C/I)$ curves for different configurations of the LoRa system interfered by Wi-Fi using IEEE 802.11n technology. Solid and dashed lines are related to setup ⑤ and ⑥ (see Table 2)

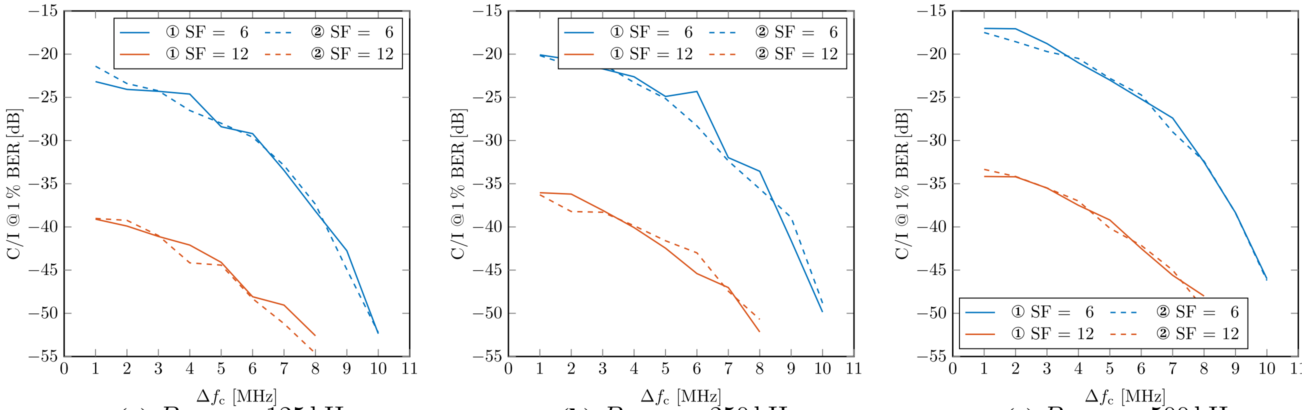
For instance, at the signal configuration $B_{\text{LoRa}} = 500\,\text{kHz}$ and SF $= 6$ (in this work, LoRa signal with the lowest resistance against interference), it is needed that C/I stays around $-20\,\text{dB}$ to achieve BER $= 10^{-2}$. In the case of $B_{\text{LoRa}} = 125\,\text{kHz}$ and SF $= 12$ (in this work, LoRa signal with the highest resistance against interference), however, the C/I equals to $-42\,\text{dB}$, see Fig. 5.

Results from the next measurements, where the IEEE 802.11n signal with different bandwidths and data rate was considered as interferer (see setup from ③ to ⑥ in Table 2), are depicted in Figs. 6 and 7. Compared to previous measurements, resilience of LoRa to IEEE 802.11n signal is higher than to IEEE 802.11b one. Once again, the LoRa signal with $B_{\text{LoRa}} = 125\,\text{kHz}$ and SF $= 12$ needs the lowest C/I values. In Fig. 7, as it is visible, the BER curves for some LoRa signal configurations in the considered C/I interval are missing, i.e. BER becomes negligible even when the interfering signal is stronger by 50 dB. Such a good performance of LoRa is caused by the spectrum shape of the interfering IEEE 802.11n RF signal [39,40]. The increase of traffic load in IEEE 802.11n up to 65 Mbps (setup ④) causes minor performance degradation of LoRa. In general, the required C/I values for the IEEE 802.11n with setup ④, compared to setup ③, are increased from 0.5 to 3.0 dB.

The curves in Fig. 7 where obtained at IEEE 802.11n interfering signal with channel bandwidth 40 MHz. Such a change in the interfering signal has notable effect on the C/I values needed for reliable LoRa communication. It is visible that LoRa signal has very high resistance against interference, mainly in the case of parameters $B_{\text{LoRa}} = 125\,\text{kHz}$ with SF > 9. Furthermore, for SF=12, independent of the value of B_{LoRa}, the BER curves for LoRa in the measured interval of C/I were not obtained. This can be explained by varying number of DC sub-carriers (IEEE 802.11n) that depends on the channel width [39,40].

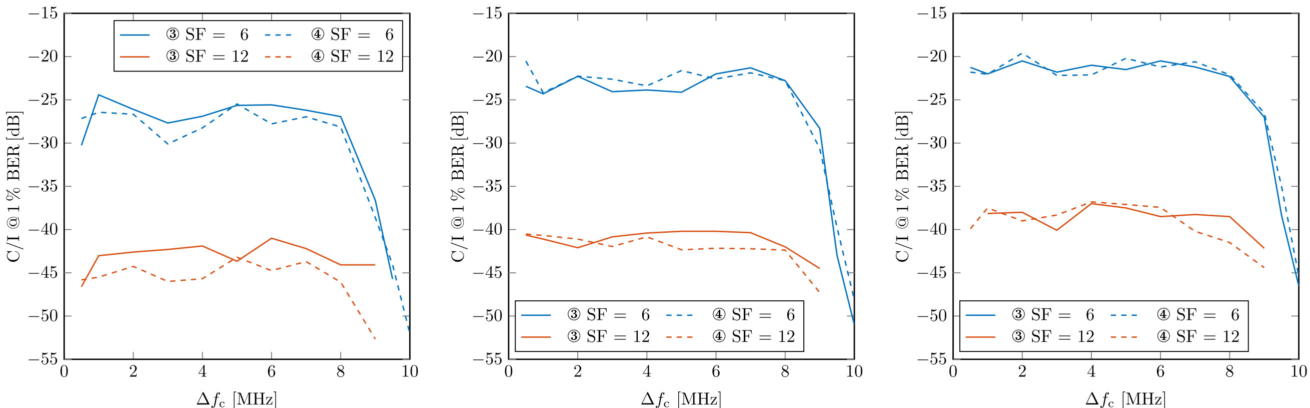
4.2 LoRa versus Wi-Fi: in-band interference

The measured resistance of LoRa against Wi-Fi in the case of in-band interference is depicted in Figs. 8, 9 and 10.



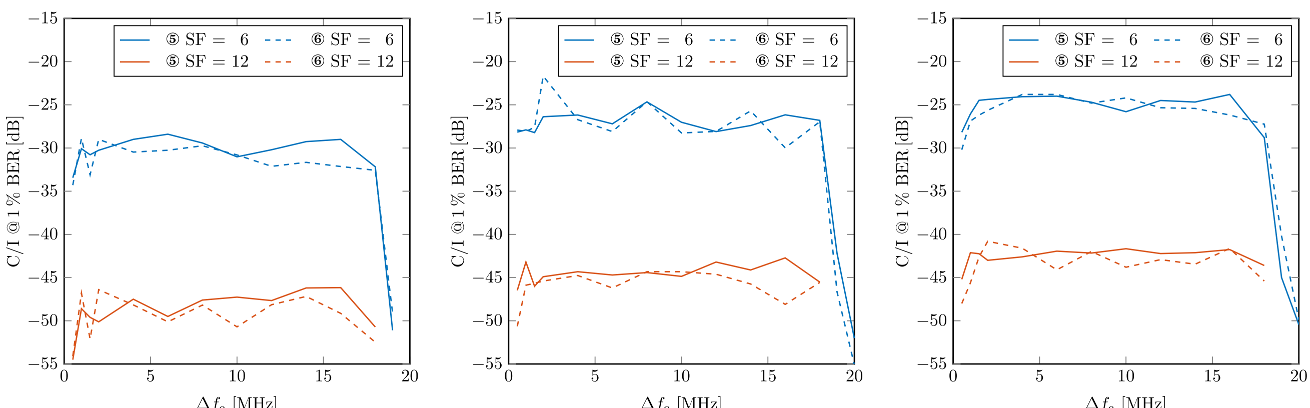
(a) $B_{\mathrm{LoRa}} = 125\,\mathrm{kHz}$ (b) $B_{\mathrm{LoRa}} = 250\,\mathrm{kHz}$ (c) $B_{\mathrm{LoRa}} = 500\,\mathrm{kHz}$

Fig. 8 In-band interferences: evaluation of C/I @ 1% BER = f(Δf_c) curves for different configurations of the LoRa system interfered by Wi-Fi using IEEE 802.11b technology. Solid and dashed lines are related to setup ① and ② (see Table 2)



(a) $B_{\mathrm{LoRa}} = 125\,\mathrm{kHz}$ (b) $B_{\mathrm{LoRa}} = 250\,\mathrm{kHz}$ (c) $B_{\mathrm{LoRa}} = 500\,\mathrm{kHz}$

Fig. 9 In-band interferences: evaluation of C/I @ 1% BER = f(Δf_c) curves for different configurations of the LoRa system interfered by Wi-Fi using IEEE 802.11n technology. Solid and dashed lines are related to setup ③ and ④ (see Table 2)



(a) $B_{\mathrm{LoRa}} = 125\,\mathrm{kHz}$ (b) $B_{\mathrm{LoRa}} = 250\,\mathrm{kHz}$ (c) $B_{\mathrm{LoRa}} = 500\,\mathrm{kHz}$

Fig. 10 In-band interferences: evaluation of C/I @ 1% BER = f(Δf_c) curves for different configurations of the LoRa system interfered by Wi-Fi using IEEE 802.11n technology. Solid and dashed lines are related to setup ⑤ and ⑥ (see Table 2)

Compared to previous study (co-channel coexistence), only a selected set of system configurations of LoRa were considered for easier interpretation of the results. Next, the results from measurements are evaluated as C/I @ 1% BER $= \mathrm{f}(\Delta \mathrm{f}_c)$, where the C/I values on the vertical axis indicate a situation when the threshold of 1% BER is achieved for the actual values of $\Delta \mathrm{f}_c$.

The results show that IEEE 802.11b/n signals have different influence on the performance of LoRa. In the case of IEEE 802.11b interfering signal it is clearly visible, that the higher is the value of $\Delta \mathrm{f}_c$, the lower is the required C/I value. The C/I difference between the LoRa signal with the lowest and highest resistance against noise from interference up to $\Delta \mathrm{f}_c = 6$ MHz is ≈ 20 dB.

The situation in the case of IEEE 802.11n interferer is different. The resistance of LoRa against the interfering OFDM-based Wi-Fi signal is practically on a constant level (see Figs. 9, 10). A rapid decrease in the C/I values can be depicted only at the highest $\Delta \mathrm{f}_c$ values. It is an interesting fact, that the difference between the lowest and strongest LoRa signal configurations in terms of C/I up to higher values of $\Delta \mathrm{f}_c$ is again around 20 dB. The IEEE 802.11n standard uses sub-carrier spacing of 312.5 kHz, hence, a single DC sub-carrier causes a gap (center frequency leakage) in the frequency domain of the IEEE 802.11n signal [39,40]. This explains lower C/I values needed at co-channel interference (see Fig. 6a) than in the case of in-band interference at $\Delta \mathrm{f}_c = 1$ MHz (see Fig. 9b).

4.3 LoRa versus Wi-Fi: coexistence at GB = 250 kHz

As the last case, we investigate the performance of LoRa-based communication, when a GB with a width of 250 kHz is assumed between Wi-Fi and LoRa RF spectra. Our experimental measurements showed that the LoRa communication at this condition is reliable in the considered C/I interval (BER was always below 10^{-2}). This is the reason why we do not present any figures in this part of our article.

4.4 Resilience of Lora to interference

In this part of our work, we briefly compare the outputs of our study with the state-of-the-art. As it was discussed in Sect. 1.2, previous studies, in general, revealed high robustness of the LoRa networks against other interfering signals corresponding to different communication technologies.

Compared to previously presented studies [18–20], the outputs of this work, in some cases, show similar behavior of the LoRa at the presence of interfering RF signals. To be more precise, as it was observed in [19,20], requirements on C/I ratios are higher for the LoRa signal were a configuration with lower SF and higher B_{LoRa} values are considered. Outputs of our work confirmed that this phenomenon is also valid for in-band coexistence scenarios and not only for co-channel ones. Next, it was demonstrated that the LoRa communication is more prone to Wi-Fi interferer utilizing DSSS/CCK modulation scheme, compared to OFDM-based Wi-Fi signal. Work of Orfandis et al. [20] partly showed similar behavior of LoRa against ZigBee against IEEE 802.15.4g network. However, our results revealed that the interfering Wi-Fi signal, depending on the used LoRa system configuration, can be notably higher than the actual LoRa receiving power.

In the case of in-band interferences, we can observe a slight reduction in Wi-Fi immunity of LoRa at lower values of $\Delta \mathrm{f}_c$ (see Figs. 9, 10). Similar behavior was observed in [23], but in this work only one signal configuration ($B_{\mathrm{LoRa}} =$ 200 kHz and SF = 12) for LoRa was considered. In the case of the OFDM-based Wi-Fi interfering signal with different channel bandwidths, our extended measurements showed that there is only a little difference between the required C/I values for the considered in-band coexistence scenarios (different $\Delta \mathrm{f}_c$ values). Outputs of our analyses revealed that there is a visible difference between the C/I values needed for LoRa signal with lowest and highest resistance against interference.

5 Conclusion

This paper dealt with the study of coexistence issues, which, in the future, can occur between the LoRa and WLAN systems in the 2.4 GHz ISM band. For this purpose, we proposed and realized a laboratory measurement setup allowing reproducible results in different measurement scenarios. The performance of the LoRa communication influenced by Wi-Fi transmission was evaluated in terms of BER depending on C/I ratios.

From the evaluation of the obtained laboratory measurements it was observed that:

- the immunity of LoRa to Wi-Fi at co-channel coexistence scenarios is high, especially with a combination of low B_{LoRa} and high SF values.
- In general, LoRa is less robust to CCK-based Wi-Fi interfering signal than to OFDM one due to spread noise-like power spectral density of the CCK-based Wi-Fi signal [23].
- In-band coexistence scenarios for LoRa, especially in the case of IEEE 802.11n interfering signal, result in increasing C/I values for LoRa.
- A very narrow GB (in our work we assumed 250 kHz) between Wi-Fi and LoRa RF spectra is enough to ensure error-less LoRa communication.

In the future, the study in this paper can be extended by performance analysis of LoRa using GFSK modulation and new supported values of B_{LoRa} [23,24], especially proposed to realize communication link in the 2.4 GHz ISM band. The coexistence scenarios between LoRa and other networks need to be explored (e.g. LTE or Bluetooth) under laboratory and real conditions, according to recommendation presented in [41]. An extensive investigation of possible interaction of LoRa and other emerging LPWA technologies, like Turbo-FSK [42], on the level of PHY (e.g. different system configurations) and MAC (e.g. network density, packet configuration, access approaches) layers is also among potential research topics. However, such research goes beyond the scope of this paper.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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