WIRELESS & SENSING PRODUCTS

Application Note: Bluetooth® Immunity of LoRa® at 2.4 GHz

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1. Introduction

Invented by Ericsson in 1994, Bluetooth® is today managed by the Bluetooth® Special Interest Group (SIG) [1], which has more than 33,000 member companies. It is often considered the de-facto standard for short-range communications between both fixed and mobile computing devices, as well as Personal Area Networks (PANs). Bluetooth® is a wireless technology standard operating in the license-exempt 2.4 GHz band.

Thus any new technology deployed into this band must be robust against interference from incumbent Bluetooth®-connected devices and PANs. Given the recent expansion of LoRa® to the 2.4 GHz band, its coexistence with deployments of existing technologies in this frequency space is of significant importance.

For the purposes of this document we consider only the coexistence of a victim SX1280 LoRa® receiver with an interfering Bluetooth® 4.2 + Enhanced Data Rate (EDR) transmitter.

For further details of the immunity of a LoRa® receiver to IEEE 802.11 Wireless Local Area Networks (WLAN) operating in the same 2.4 GHz frequency-space, the reader's attention is drawn to Semtech Application Note AN1200.30 [2].

2. Bluetooth® 4.2 and Enhanced Data Rate

2.1 Physical Layer

The Bluetooth® 4.2 physical layer consists of both Basic Rate (BR) and Enhanced Data Rate (EDR) Physical Layer (PHY) modes. Both PHY modes operate on a 1 MHz channel raster as defined below:

$$f_{CH} = 2402 + k\ (MHz); k = 0,1,2..78$$

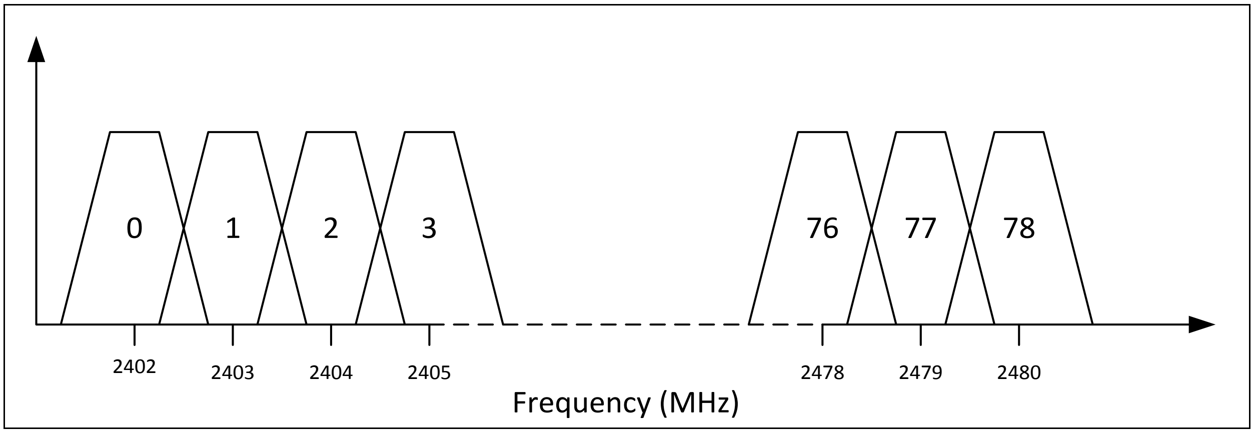

Figure 1: Bluetooth® 4.2 Channel Plan

Both BR and EDR modes of operation have a symbol rate equal to 1 MS/s. Similarly, frequency hopping at a nominal rate of 1600 hops/s and a Time Division Duplex (TDD) scheme for duplex transmission are defined for both modes.

2.2 Basic Rate

The mandatory basic rate PHY mode implements a Gaussian Frequency Shift Keying (GFSK) modulation scheme at 1 Mb/s with a modulation index, β, between 0.28 and 0.35. The bandwidth-symbol time product (BT) of the Gaussian filter is 0.5.

With the maximum conducted output power configured at a nominal 0 dBm, the 99% Occupied Bandwidth (OBW) power[1] and Power Spectral Density (PSD)[2] of the GFSK PHY modulation is illustrated in figures 2 and Figure 3, respectively.

[1] The measurement method described by ANSI C63:10 – 2013 is employed

[2] Measurement method AVGPSD-1 described in the April 5, 2017 revision FCC KDB document 558074 is employed

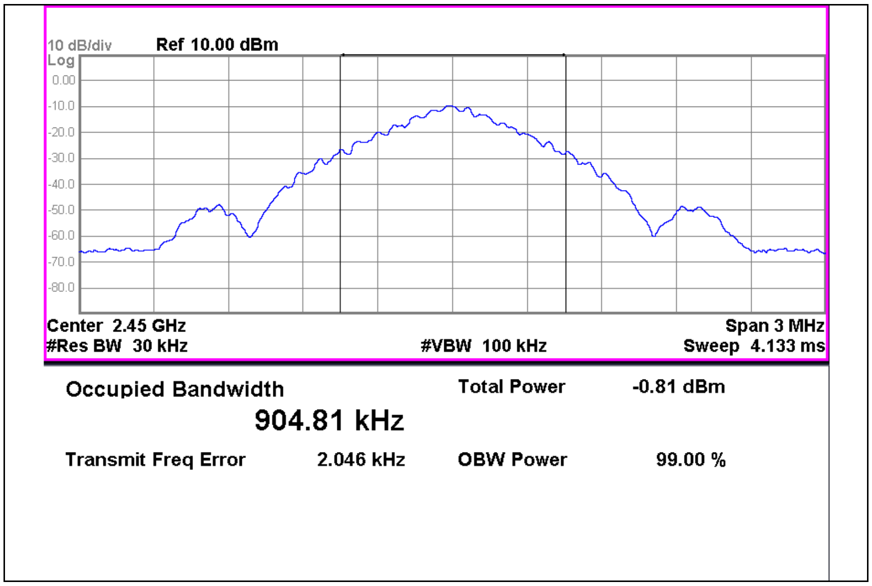

Figure 2: GFSK BR OBW Measurement

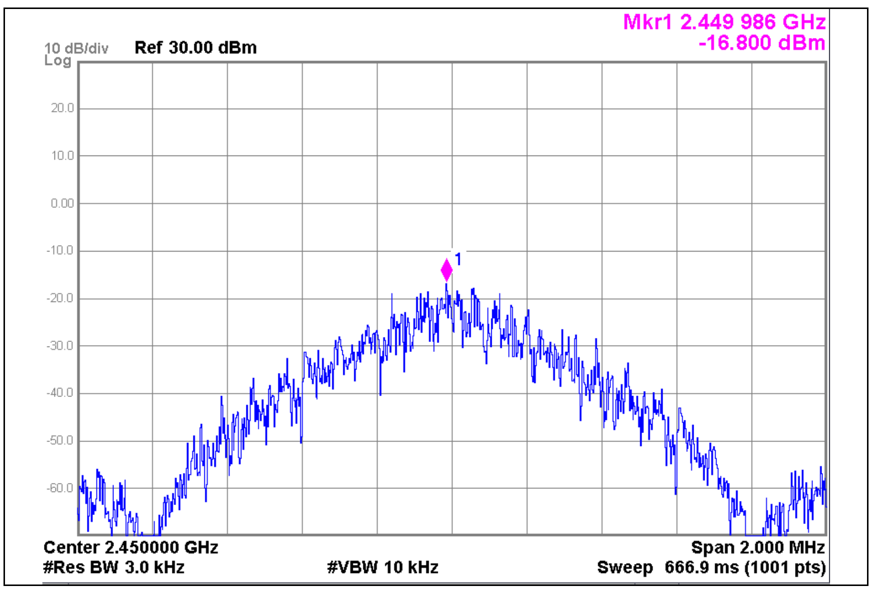

Figure 3: GFSK BR PSD Measurement

2.3 Enhanced Data Rate

The EDR PHY mode is implemented with two variants of PSK modulation; a π/4 Differential Quadrature Phase Shift Keying (π/4-DQPSK) mode at 2 Mb/s and an 8-Position Differential Phase Shift Keying (8-DPSK) mode at 3 Mb/s. For both EDR modulation schemes the modulated data is differentially encoded and a root-raised cosine pulse shaping filter of roll-off factor 0.4 is employed.

As with the BR mode, we note the OBW and PSD of both EDR PHYs with the maximum conducted output power again configured for both PHYs at a nominal 0 dBm.

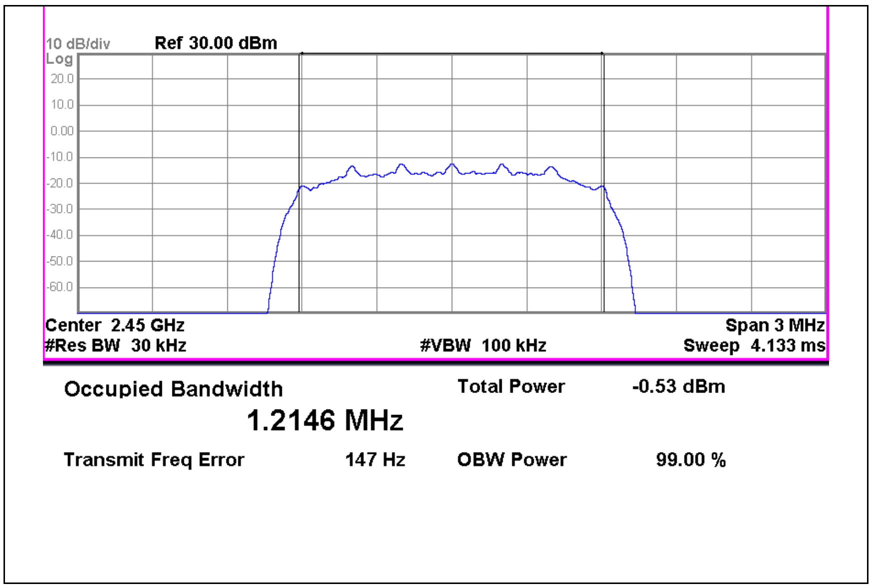

Figure 4: π/4-DQPSK EDR OBW Measurement

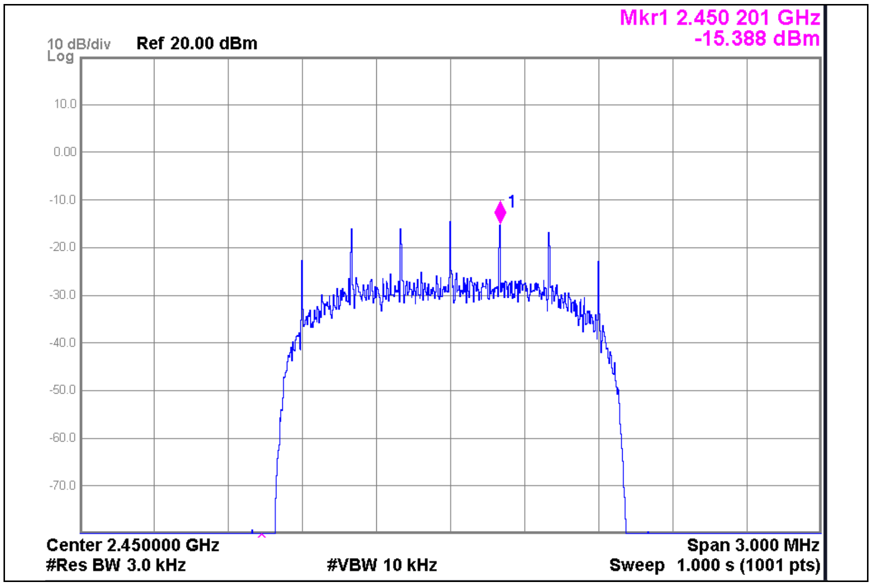

Figure 5: π/4-DQPSK PSD Measurement

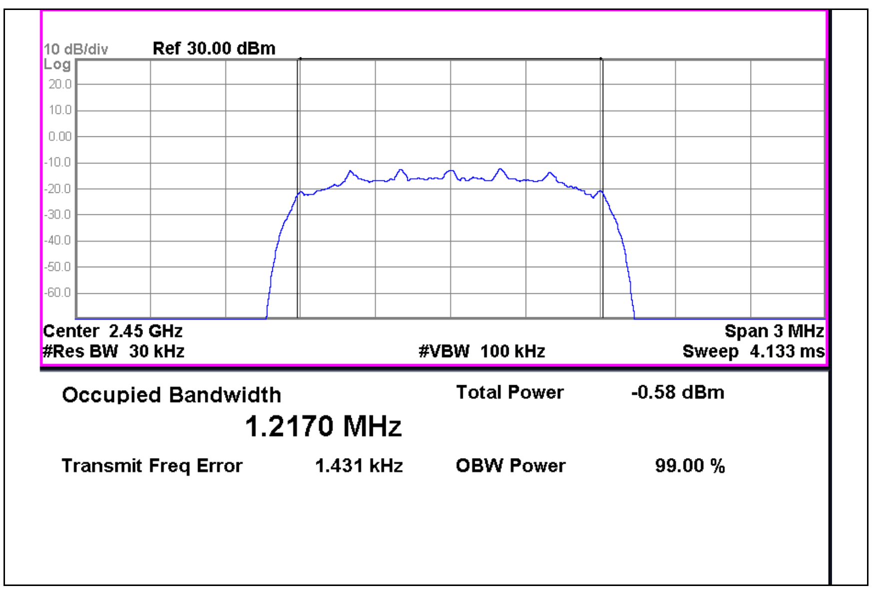

Figure 6: 8-DPSK EDR OBW Measurement

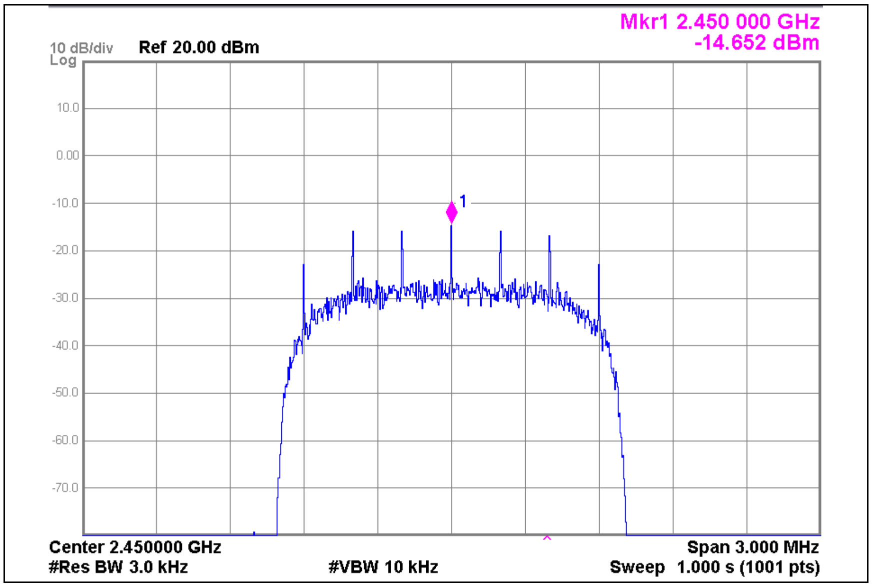

Figure 7: 8-DPSK EDR PSD Measurement

We observe that the OBW and PSD spectrums of both PSK PHY modes are similar enough that testing the immunity of the SX1280 LoRa® receiver to both EDR PHY modes for all test cases is not required.

2.4 Avoiding Bluetooth® Interference

Since Bluetooth® was developed as a short-range communications standard, where the application use case allows, simply providing for a degree of spatial separation by avoiding being in the same location as a Bluetooth®-enabled device is one of the most effective means of avoiding or reducing potential interference between the two radio systems.

However, for the purposes of this application note, we assume that we do not have full control over the location of the LoRa® receiver and thus we consider some of the characteristics of LoRa® modulation [3] that can be used to mitigate the effect of Bluetooth® interference.

Spread Spectrum Modulation

LoRa® is a spread spectrum modulation technique which provides inherent processing gain (as a function of Spreading Factor, SF) and enables the receiver to correctly recover the wanted data signal even when the Signal to Noise Ratio (SNR) of the channel is a negative value. In the presence of co-channel interferer this equates to the ability to receive wanted signal powers that are weaker than the interfering signal.

In addition, interfering signals are in-turn reduced by the process gain of the receiver. These are spread beyond the desired information bandwidth and can be easily removed by filtering.

Bandwidth Scalability

LoRa® modulation is bandwidth scalable and can consequently be used for both narrowband and wideband applications. Unlike existing narrowband or wideband modulation schemes, LoRa® can be easily adapted for either mode of operation with only a few simple configuration register changes.

A lower bandwidth signal reduces the impact of adjacent signals, reducing the probability of being the victim of interference. If we compare the narrower-bandwidth LoRa® signal with the typical 1 MHz wide bandwidth of a Bluetooth® 4.2 signal, we observe that the LoRa® signal occupies a fraction of the bandwidth of the Bluetooth® signal. We also observe that in the case of the Bluetooth® PSK PHY modes the power is spread across the entire channel. The power integrated across the narrower-band channel will therefore be a fraction of the total power. Consequently, in the case of co-channel interference, exposure to a narrow portion of the signal power means we receive a proportionately smaller fraction of the Bluetooth® signal power.

Forward Error Correction and Interleaving

Another benefit of LoRa® modulation is the implementation of Forward Error Correction (FEC) and interleaving. FEC allows the introduction of redundant information into the message which allows for a limited number of bits that are corrupted to be corrected and recovered.

Even with FEC sequential bit errors (i.e. neighboring corrupted bits) are the hardest to correct. For this reason interleaving is employed. This is a technique that redistributes the information in the packet so that, upon reconstruction, errors are less likely to be from adjacent bits.

3. Measurement Procedure

Since a Bluetooth® transmission will at any instant in time appear as either a co-channel, adjacent channel or in-band (blocking) interferer (or in the case of a collocated PAN network, all three), we consider a LoRa® receiver arbitrarily set to the 2450 MHz frequency and observe the impact of an interfering Bluetooth® transmission on the receiver selectivity as a function of frequency offset.

For the purposes of the analysis we set the wanted signal level to 6 dB above the nominal 10% Packet Error Rate (PER) sensitivity level for each LoRa® modem configuration and compare the selectivity against both Bluetooth® BR and EDR modes of operation.

A simplified block diagram of the experimental test setup is illustrated in Figure 8.

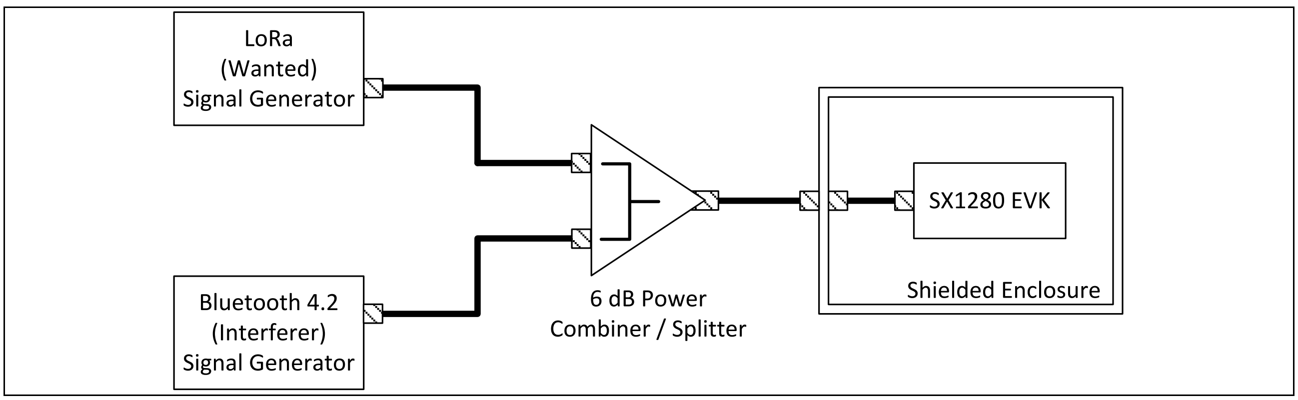

Figure 8: Bluetooth® Coexistence Experimental Setup

4. Measurement Results

We consider the case of a continuously modulated (100% duty-cycle) co-channel Bluetooth® interferer for the following LoRa® modem configurations:

- SF = 6; BW = 203 kHz; Payload = 20 bytes; CR = 4/5
- SF = 6; BW = 1625 kHz; Payload = 20 bytes; CR = 4/5
- SF = 12; BW = 203 kHz; Payload = 20 bytes; CR = 4/5
- SF = 12; BW = 1625 kHz; Payload = 20 bytes; CR = 4/5

In the absence of an interfering signal, the nominal 10% PER sensitivity level is identified for each modem configuration. The wanted signal is then increased by +6 dB and for each test case the interfering signal is increased until the indicated PER sensitivity level is again 10%. This value is then recorded.

4.1 Co-Channel Interference

The results of the LoRa® receiver co-channel rejection are tabulated in Table 1:

Table 1: Co-Channel Immunity

LoRa® Modem Configuration		Bluetooth® PHY Interferer Relative Amplitude [dB]		
SF	BW [kHz]	GFSK	π/4-DQPSK	8-DPSK
6	203	+7	+11	+10
6	1625	+6	+6	+5
12	203	+23	+27	+27
12	1625	+22	+21	+20

From the indicated results we observe the ability of the LoRa® modem to correctly demodulate a wanted signal below the power of a co-channel interferer, resulting in a positive co-channel rejection (CCR) ratio.

We also observe the impact of both LoRa® processing gain and received signal bandwidth. For a fixed signal bandwidth we note an increase in spreading factor results in an increase in CCR. Similarly, for a fixed processing gain we note a reduction in signal bandwidth similarly improves CCR.

4.2 In-Band Interference

We now consider the case of PHY interference as a function of frequency offset.

Since CCR is the dominant component for all linear interference mechanisms (e.g. Adjacent Channel Rejection (ACR) and Alternate Adjacent Channel Rejection (AACR)), we shall only consider the two extremes of the LoRa® modem configuration:

- SF = 6; BW = 1625 kHz; PL = 20; CR = 4/5
- SF = 12; BW = 203 kHz; PL = 20; CR = 4/5

Similarly we consider the impact of only the GMSK and π/4-DQPSK interference cases for both LoRa® modem configurations. The results obtained are illustrated in Figure 9.

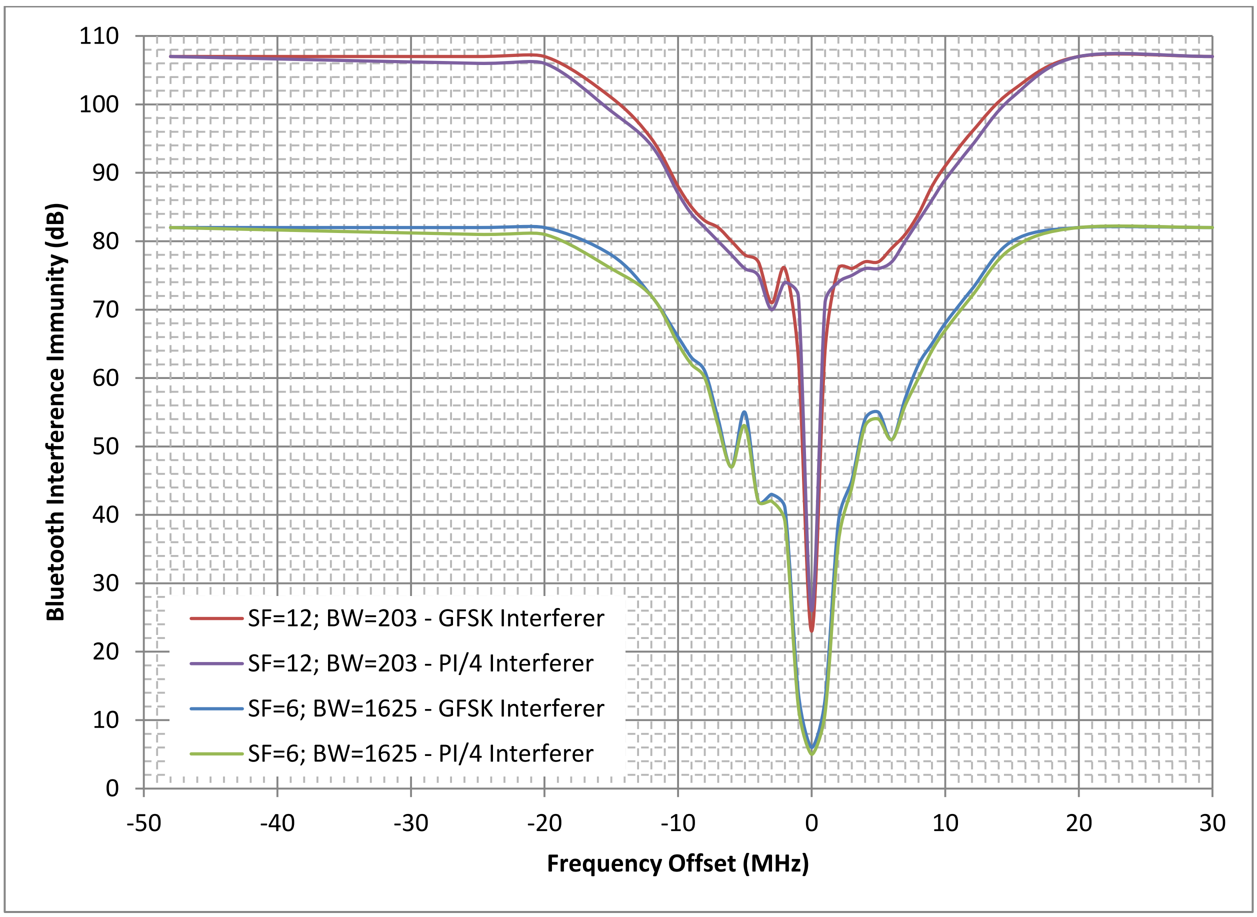

Figure 9: Bluetooth® Immunity as a Function of Frequency Offset

The results obtained are similar to those obtained for the CCR measurements. It can be seen that for a given frequency offset, Bluetooth® immunity is primarily a function of LoRa® modem processing gain and wanted signal bandwidth as opposed to the modulation of the interfering signal.

It should also be noted that as frequency offset increases beyond a few MHz, the interference mechanism changes from that of a linear interferer to a non-linear or blocking interferer. Here a small increase in interferer signal level of only 1 dB can lead to an increase in indicated PER from less than 10% to greater than 70%, as IC parameters (as opposed to those of the wanted modulation) start to dominate receiver selectivity.

From Figure 9 it can be seen that there is approximately 27 dB difference between the relative blocking immunity levels for the two modem cases. This mirrors the difference in sensitivity levels (typically -130 dBm for the case SF=12; BW = 203 kHz and -103 dBm for SF = 6, BW = 1625 kHz) and from this we can determine the absolute interference level at frequency offsets greater than 20 MHz is typically -16 dBm. A plot of absolute blocking immunity level is illustrated in Figure 10.

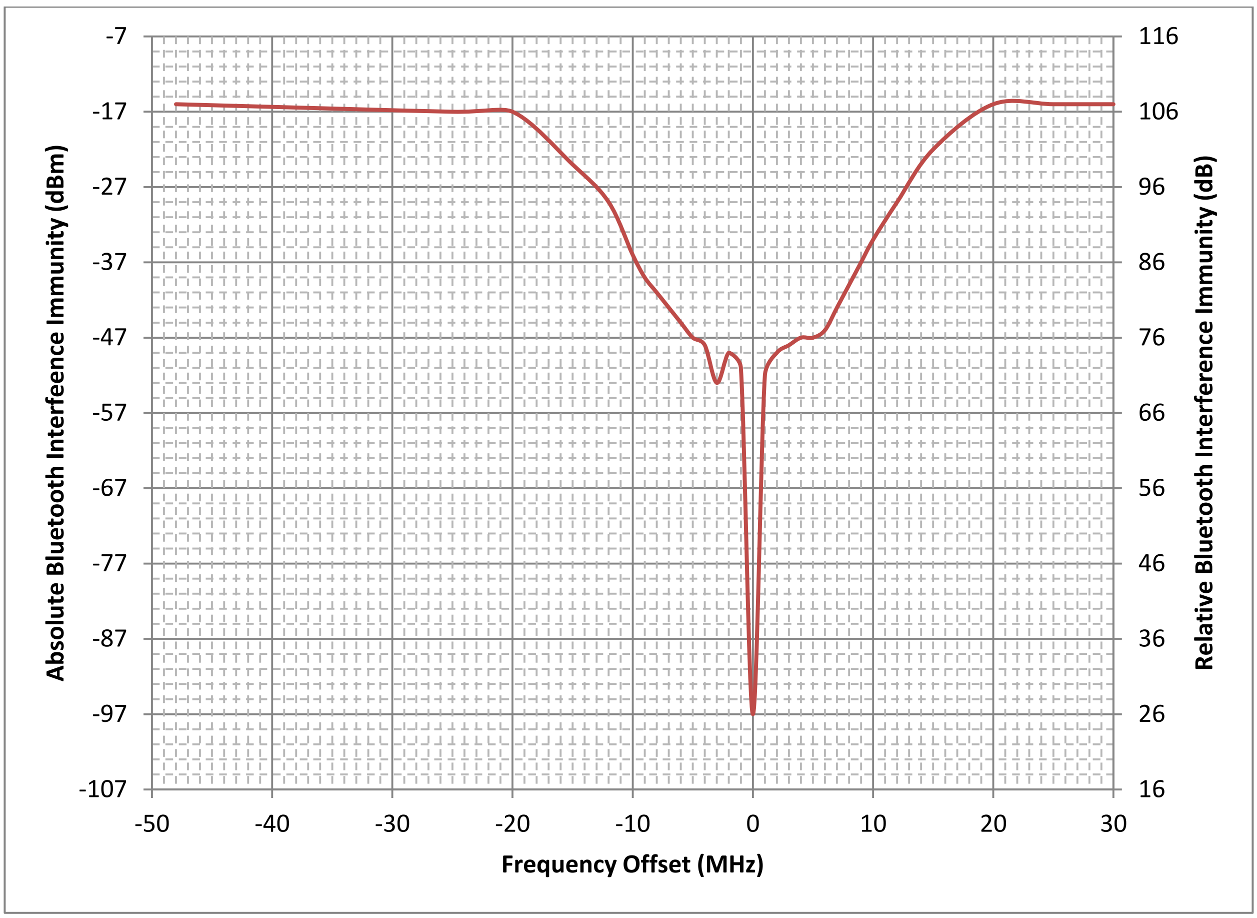

Figure 10: Absolute / Relative Immunity for a π/4-DQPSK Interferer (SF = 12, BW = 203 kHz)

4.3 AM Rejection

As has been previously noted, Bluetooth® implements both frequency hopping and a TDD mechanism. A frequency hopping interferer will appear as an Amplitude Modulation (AM) pulse to the victim receiver. The immunity of a receiver to this AM pulse, or AM rejection, is a measure of the receiver's second-order intercept (IP2) response.

To measure the AM rejection of the SX1280 LoRa® receiver, a Rohde & Schwarz SMBV100A VSG / Arb with option -K60 was used to generate representative Bluetooth® 4.2 test packets using the default setting of the generator.

The following packet types [4], [5] were used to analyze the AM rejection of the SX1280 LoRa® receiver.

Table 2: Bluetooth® 4.2 + EDR Test Packet Description

Transport Layer	Packet Type	Payload Length [Bytes]	Modulation		Duty Cycle [%]
			Access Code / Header	Payload	
ACL	DH1	17	GFSK	GFSK	28
eSCO	3-EV5	540	GFSK	8-DPSK	64

From the results illustrated in Figure 11 no noticeable degradation of the receiver selectivity is observed compared to the constant transmission case.

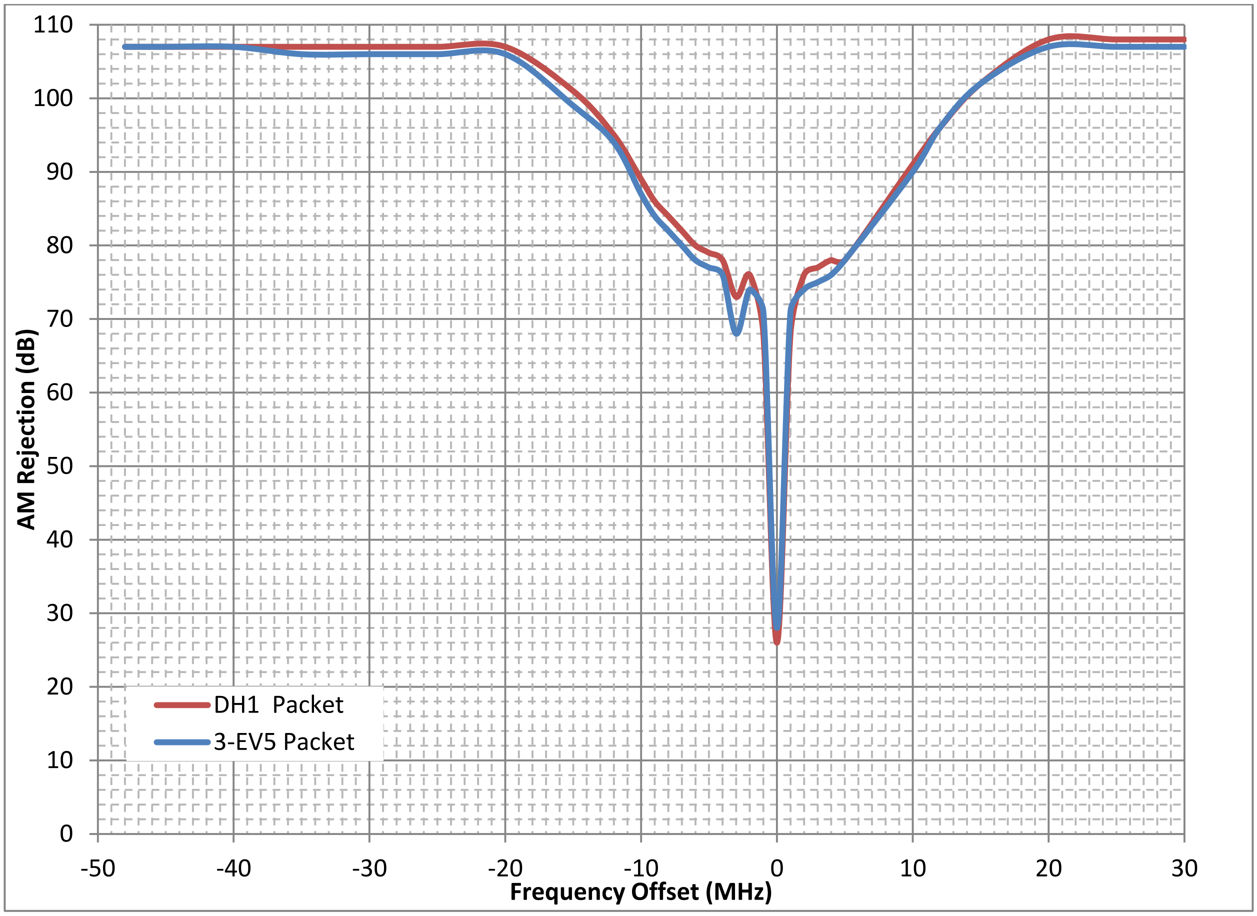

Figure 11: AM Rejection Response (SF = 12, BW = 203 kHz)

5. Conclusion

In-band Bluetooth® interference immunity in excess of 105 dB is possible using the LoRa® modem of the SX1280. From the results obtained it can be observed that for narrow-band LoRa® modes, the alternate adjacent Bluetooth® channel rejection ($k_{REL} = \pm 2$) exceeds 70 dB.

Since Bluetooth® implements frequency hopping it is impossible to avoid potential interference from collocated Bluetooth® devices or a Bluetooth® PAN. However as has been demonstrated in this application note, interference rejection has been shown to be a function of both SF and bandwidth employed.

In summary, this application note confirms that the main LoRa® interference mitigation techniques are:

- increasing spreading factor: this allows reception below what ever interfering noise power is seen within the modulation bandwidth
- reduction of the bandwidth: the reduction of the LoRa® system bandwidth reduces the interferer power integrated at the receiver input

6. Revision History

Version	Date	Modifications
1.0	April 2018	First Release

7. Glossary

8-DPSK	8-Position Differential Phase Shift Keying
AACR	Alternate Adjacent Channel Rejection
ACL	(Bluetooth) Asynchronous Connectionless Radio Link
ACR	Adjacent Chanel Rejection
AM	Amplitude Modulation
ANSI	American National Standards Institute
BR	(Bluetooth) Basic Rate Mode
BT	Bandwidth-Symbol Time Product
BW	Bandwidth
CCR	Co-Channel Rejection
CR	Forward Error Correction Redundancy Code Rate
EDR	(Bluetooth) Enhanced Data Rate Mode
eSCO	(Bluetooth) Enhanced Synchronous Connection Orientated Radio Link
FCC	Federal Communications Commission
FEC	Forward Error Correction
GFSK	Gaussian Frequency Shift Keying
IC	Integrated Circuit
IEEE	Institute of Electrical and Electronic Engineers
OBW	Occupied Bandwidth
PAN	Personal Area Network
PER	Packet Error Rate
PHY	Physical Layer
PSD	Power Spectral Density
SF	Spreading Factor (Modulation Processing Gain)SNR
SNR	Signal to Noise Ratio
TDD	Time Domain Duplex
VSG / Arb.	Vector Signal Generator / Arbitrary Waveform Generator
WLAN	Wireless Local Area Network
π/4-DQPSK	π/4 Differential Quadrature Phase Shift Keying

8. References

[1] Bluetooth® SIG
https://www.bluetooth.com/

[2] Semtech Application Note AN1200.30 "Wi-Fi Immunity of LoRa at 2.4 GHz"
https://www.semtech.com/uploads/documents/WiFi_Immunity_App_Notes.pdf

[3] Semtech Application Note AN1200.22 "LoRa Modulation Basics"
https://www.semtech.com/uploads/documents/an1200.22.pdf

[4] Bluetooth® Legacy Core Specifications
https://www.bluetooth.com/specifications/bluetooth-core-specification/legacy-specifications

[5] SMBV100A –k60 User Manual
https://cdn.rohde-schwarz.com/pws/dl_downloads/dl_common_library/dl_manuals/gb_1/s/digital_standards_for_signal_generators/SMBV_Bluetooth_EDR_UserManual_15.pdf

Important Notice

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