ATCZ175 INTEROP PROJECT

Interference Simulation of Bluetooth Low Energy

Version 1.1

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Abstract

Frequency utilization is hugely increasing in the communication systems, particularly in the ISM (Industrial, Scientific, and Medical radio) band. Consequently, interference seems to be a great impeding factor in the next wireless technologies including WiFi, Bluetooth, ZigBee, WiMax, and BLE (Bluetooth Low Energy). In simple words, as these technologies mostly work in the same frequency band, transmitted data signal of each system can be a source of interference for other ones. Moreover, even a same type adjacent system might cause interference with the desired signal. In this report, the interference effects on BLE systems are studied. First, the characteristics of BLE, particularly in the physical layer, are studied. Afterwards, the BLE system performance in the presence of different irritating signals is investigated. In particular, the BLE performance prone to two types of interfering signal, AWGN (Additive White Gaussian Noise) and GFSK (Gaussian Frequency Shift Keying) signals (another BLE system acts as interfering source), is investigated. The BER (Bit Error Rate) and PER (Packet Error Rate) parameters are used to assess the system performance.

1 Introduction to Bluetooth Low Energy

In this report, BLE is considered as the main system and its characteristics, mostly in the physical layer, are studied. In section 1.1, basic concepts of the BLE are discussed and properties of a BLE signal, specially in the basedband, are presented. Modulation and demodulation scheme of a BLE system are fully addressed in section 1.2. The resulted modulator and demodulator functions will play important rules in the further simulations of the BLE system. In section 1.3, a brief introduction to noise signal parameters is presented. To simulate noise, it is important to properly set the noise power in the given signal bandwidth. Occupied bandwidth is introduced and applied in determining the effective noise bandwidth. This method of adding noise to the signal at receiver node is frequently employed in the rest of the simulations. In section 1.5, modulator and demodulator functions are used to simulate effects of the noise power and frequency offset on the demodulation algorithm. Results are plotted in the contour format.

1.1 BLE Basic Concepts

There are two forms of Bluetooth wireless technology systems, classic Bluetooth and BLE [1]. BLE is a complenentary technology to classic bluetooth rather than a new version. Altough BLE uses lots of technologies from classic Bluetooth, it should be considered as differnet technology [2].

To move from classic Bluetooth to BLE, several basic concepts should be considered. In the design procedure, it is important to optimize the time period when a BLE device makes a connection. Reducing time, when a device transmits or receives information, directly leads to decrease in the energy consumption. Memory usage is also an effective parameter in the energy consumption. In BLE it is a goal to reduce the memory of system as much as possible. Asymmetric design, dedicating state to devices, client-server architecture, and modular architecture are other important design factors which are used in designing a BLE system [2]. The architecture of a BLE system is illustrated in Figure 1.

In this report, concentration is on the physical layer. The physical layer is simply the transmission and reception of the electromagnetic radiations. BLE uses GFSK modulation to transfer information. In section 1.2, the BLE modulation algorithm is fully addressed.

1.2 Modulation and Demodulation of BLE

As mentioned former, BLE uses GFSK [1] modulation. The Gaussian filter is used to optimize the transition between two bits. BLE often transmits at $1\,\mathrm{Mb/s}$ and uses one symbol to send each bit. The modulation index for BLE is between 0.45 and 0.55. In the following simulations, it is assumed to be 0.5 by default. The Gaussian filter is supposed to be such that *BT = 0.5*. Consequently, as T equals the bit period ($1\,\mu\mathrm{s}$) the B is determined as $0.5\,\mathrm{MHz}$. Frequency shift keying modulated signal is derived as

$$x_b(t) = e^{j2\pi \int_{-\infty}^{t} f_d(t)dt}\,, \tag{1}$$

where $f_d(t)$, output of Gaussian filter, represents the frequency deviation of the transmitted bits with given modulation parameters. $x_b(t)$ is called the equivalent baseband complex signal.

Figure 2 shows the frequency deviation of a GFSK modulated signal, transmitting a certain bit sequence. As it can be seen, for a BLE signal, the frequency deviation alters between $\pm 250\,\mathrm{kHz}$. Frequency deviation has great impact on system performance which is discussed in the next chapters. In the literature, several demodulation algorithms are used to recover the transmitted bits [3]. IaD (Integrate and Dump) demodulation and matched filter are two common methods. Before doing further study on demodulator algorithms, it is worthy to analyze noise in the BLE system.

1.3 Noise Analysis

BLE uses 40 radio channels, each has $2\,\mathrm{MHz}$ bandwidth, to transmit information. While each channel has $2\,\mathrm{MHz}$ bandwidth, The BLE uses narrower bandwidth to reduce leaking into the adjacent channels. In this report, an AWGN channel is used to model the noise in BLE systems.

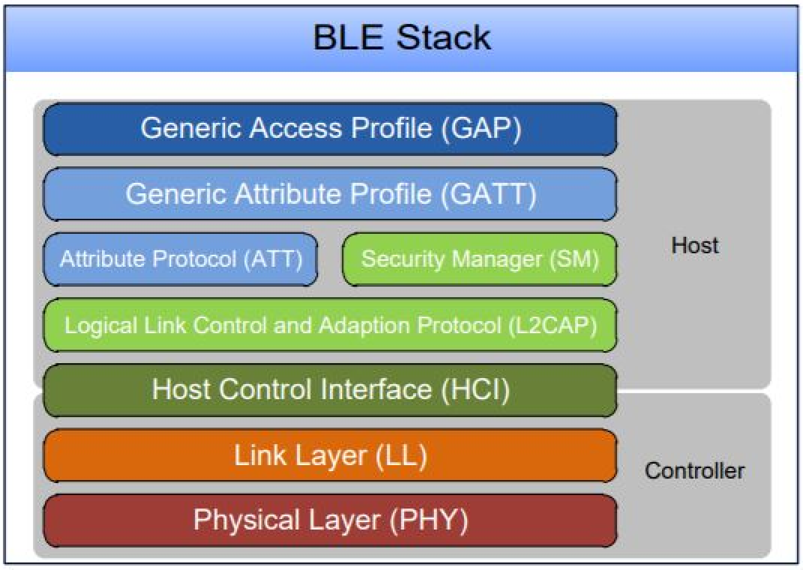

Figure 1: The Bluetooth Architecture [2]

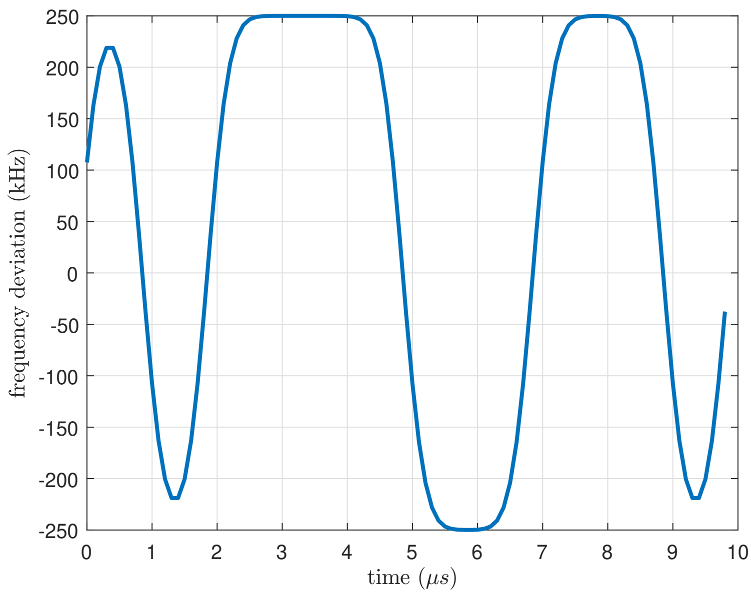

Figure 2: The frequency deviation of GFSK signal for a '1011100110' bit sequence

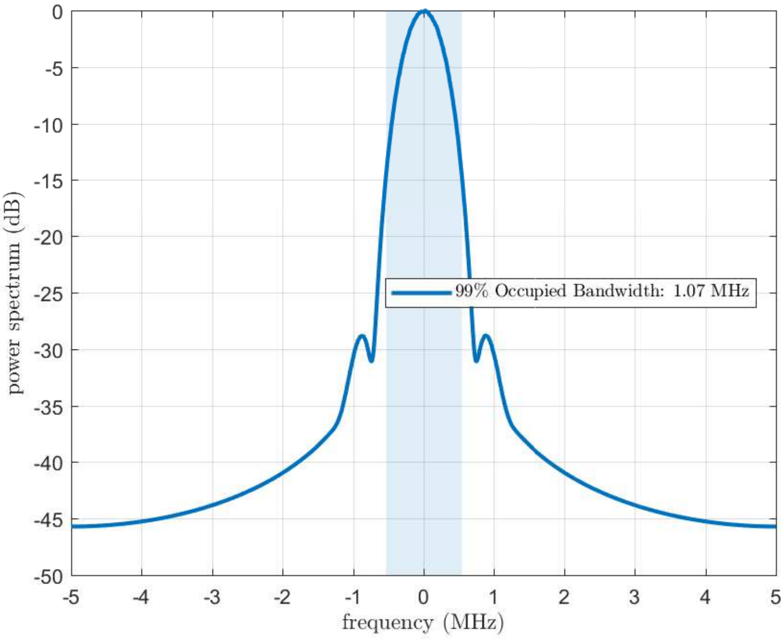

Figure 3: The frequency spectrum of a BLE signal

In defining the noise signal power in the BLE simulations, it is important to use the correct bandwidth definition. The occupied bandwidth (the bandwidth in which a specified percentage of the total mean power is located) is employed to set the noise power properly. For a random bit sequence, the spectrum of a GFSK modulated signal is illustrated in the Figure 3. As shown in this figure, the $99\,\%$ occupied bandwidth for the BLE signal is about $1.07\,\mathrm{MHz}$. If sampling frequency is f_s, then the noise power is uniformly distributed over the f_s or

$$N_0 = \frac{N}{f_s} \ , \tag{2}$$

where N_0 is the noise power spectral density and N is the noise power. Similarly, signal energy per bit can be derived by

$$E_b = \frac{S}{BW} \ , \tag{3}$$

where E_b is the signal energy per bit, S is the signal power, and BW is the signal occupied bandwidth. (2) and (3) result in:

$$\begin{aligned} \frac{E_b}{N_0}(dB) &= 10\log_{10}\left(\frac{\frac{S}{BW}}{\frac{N}{f_s}}\right) \\ &= 10\log(\frac{f_s}{BW}) + SNR(dB). \end{aligned} \tag{4}$$

In more explicit words, to properly define the noise power, the noise amplitude is multiplied by a factor of $\frac{f_s}{BW}$ in the simulations.

1.4 Demodulation Algorithms

Following, the performance of IaD and matched filter methods are assessed in the presence of different levels of noise power. To make a fair comparison, the ratio of the bit energy over noise power spectral density is used instead of SNR. The relation of these two parameters has been precisely explained in section 1.3. Figure 4 shows the comparison between two mentioned algorithms. For both algorithms, 10 number of samples are used for each symbol. A low pass filter with $2\,\mathrm{MHz}$ bandwidth is employed at the

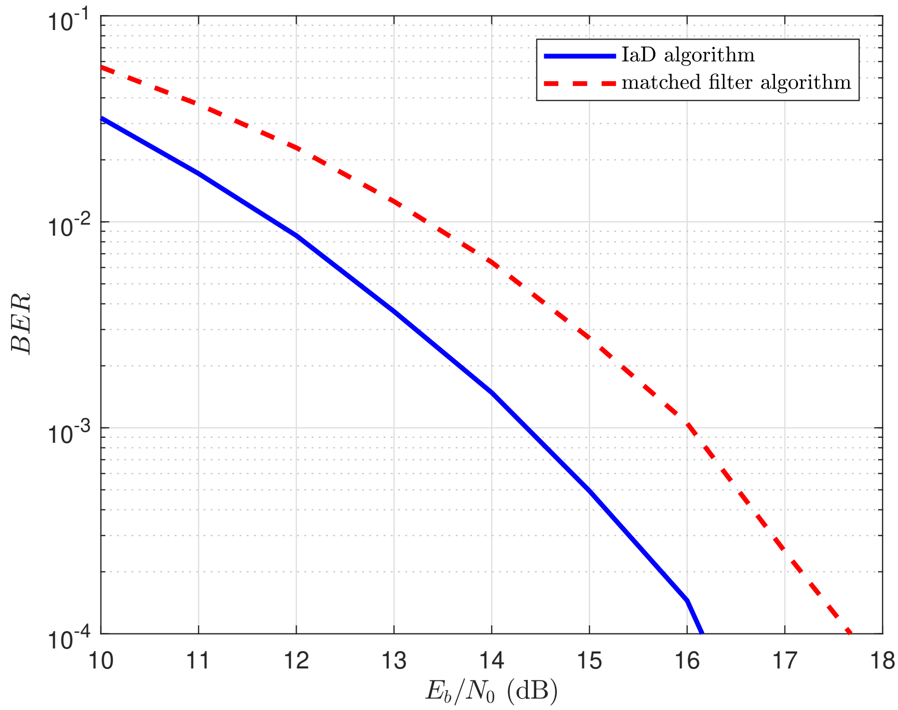

Figure 4: Comparison between IaD demodulator and matched filter demodulator

input of IaD demodulator. As it can be seen in this figure, IaD performs better. For example, to achieve BER less than $0.1\,\%$, the required E_b/N_0 is approximately 1.7 dB higher for matched filter algorithm compared to IaD.

1.5 Noise and Frequency Offset Effects on the Demodulator

A variety of parameters can degrade the performance of BLE systems. The level of noise power, presence of different types of interference, variation of frequency deviation throughout a packet, and offset shift in the frequency deviation due to the source imperfection are some examples of such irritating parameters. In this section, the effects of noise and frequency offset on the demodulator algorithm are investigated. Since matched filter algorithm is more robust to the frequency offset compared to the IaD, in the remaining simulations matched filter algorithm is used in the demodulator scheme.

1.5.1 Simulation Results

As mentioned in section 1.5, frequency offset of the source and noise are supposed to have a great impact on the demodulator algorithms. To apply frequency offset to the source, the frequency deviation (shown in Figure 2) would experience a shift in the y-axis. Different levels of noise power are realized based on what has been described in section 1.3. Figure 5 shows the BER curves of a GFSK demodulator versus SNR and frequency offset in the contour plot format. As shown in this figure, in the absence of frequency offset (frequency offset = 0), the required SNR for BER of $0.1\,\%$ is about $16\,\mathrm{dB}$. This is considerably smaller that the $21\,\mathrm{dB}$ reported in Bluetooth Core Specification [1]. As the absolute value of the frequency offset increases, the demodulator experiences a level of loss performance. For example, approximately $1\,\mathrm{dB}$ loss is expected for $\pm 150\,\mathrm{kHz}$ frequency offset in desired signal.

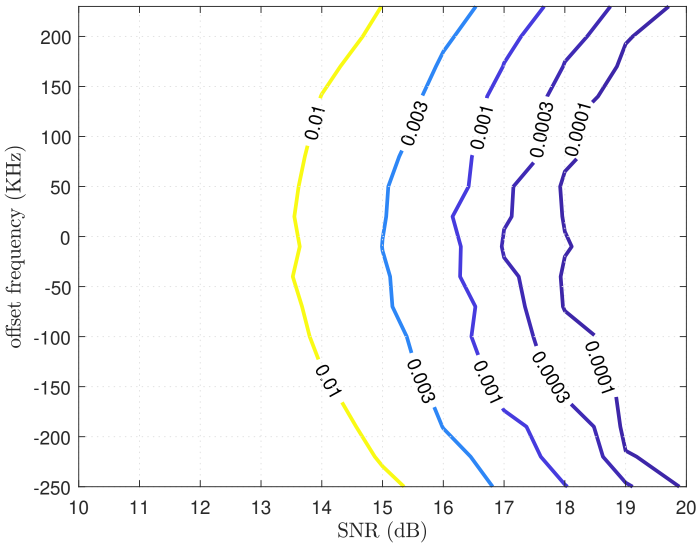

Figure 5: BER vs SNR and frequency offset

2 Interference Analysis

In this section, some consequences of the interference in BLE systems are presented. The performance of a BLE system in the presence of different interference signals is simulated to find the possibility of modeling the interference. It seems intuitive to model any type of interference source with an AWGN noise signal. However, such modeling needs to be precisely investigated. In this section comparison between two scenarios is presented. First case is that a GFSK signal acts as the interferer (co-channel interferer) and the second case is when the interferer is an AWGN source. The performance of system is evaluated for both cases based on BER of GFSK signals and also based on PER of short BLE packets.
In section 2.1, the situation that the interferer is a GFSK source is fully studied. Effects of different parameters of GFSK interfering signal on the BLE system performance are reported. In section 2.2, simulations are repeated for an AWGN noise source. Afterwards, comparison between two scenarios is made using BER and PER.

2.1 GFSK Signal as Interferer

In this section, the performance of a GFSK demodulator in the presence of different types of irritating signals is studied. The goal is to determine if it is possible to replace the known type interference signal with a noise source. To do that, it is assumed that the interference signal is a GFSK modulated signal as well as the desired signal. In other words, the desired and interference signal both are GFSK modulated. Different parameters of the interference signal such as delay, phase shift, and frequency offset, all related to the desired GFSK signal, may cause degradation in the GFSK demodulator performance. In the following, effects of these parameters are studied to determine if system performance is independent of the properties of interfering signal.

Figure 6 shows the BER contours of the GFSK demodulator versus different levels of the SIR (Signal to Interference Ratio) and also different values of the delay. It is worthy to note that this delay can be a fraction of the sampling frequency. It is clear from this figure that the bit coincidence between the desired signal and the interfering signal (delay over one bit) has a negligible impact on the demodulator performance. A further surprising result is that if the interfering signal is a GFSK modulated signal, the demodulator does not require a high SIR to achieve a BER of less than $0.1\,\%$. This is an important result which is described in the next section.

The next parameter to discuss is the phase shift in the interference signal. The effect of this parameter

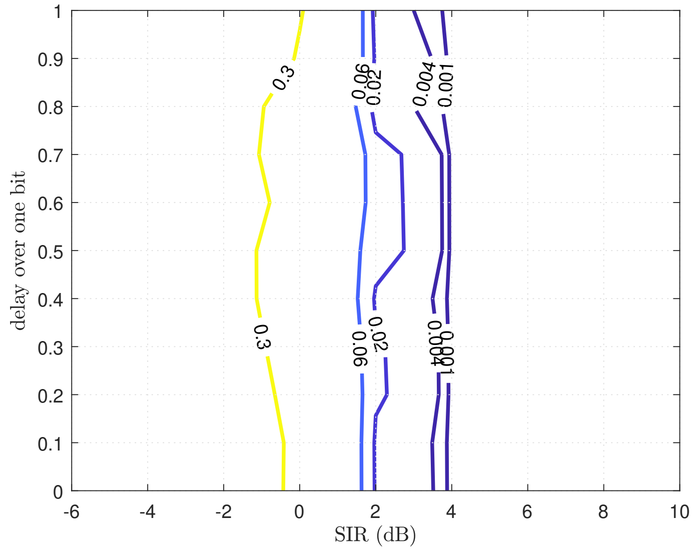

Figure 6: BER vs SIR and delay over one bit

is illustrated in the Figure 7. It can be clearly seen that the phase shift approximately has no effect on the demodularour performance.

The offset in the frequency deviation of a GFSK interference signal is another parameter which might degrade the performance of the GFSK demodulator. Figure 8 shows that unlike the phase shift and delay, frequency offset of interfering signal significantly changes the GFSK demodulator performance. For $SIR > 0$ region, BER performance is degraded as the frequency offset increases. This is due to the matched filter demodulator nature. The interfering signal frequency offset, added to desired signal frequency deviation, misleads the matched filter decision algorithm. The behavior of the graph for $SIR < 0$ region is controversy. However, the performance of the system in this region is beyond our interest.

2.2 Comparison between Noise and GFSK Signal as Interferer

Modeling different types of the interference signals is a matter of debate in the rest of this report. In the first step the possibility of replacing a GFSK interference signal with a Gaussian white noise signal is studied. Figure 9 compares the BER of a GFSK demodulator in the presence of GFSK interfering signal and white Gaussian noise source. This figure shows that for a Gaussian noise interferer an SIR greater than $16\,\mathrm{dB}$ is required to achieve BER less than $0.1\,\%$. This value for the GFSK signal interference is about $3\,\mathrm{dB}$. This shows that compared to the AWGN source, GFSK interfering signal has less effects on the demodulator algorithm.

It is also inspiring to make such comparison due to PER calculation. Two methods are used to derive PER in the presence of different interfering signals. First method is to simulate short BLE packets and expose them to the different levels of the interference. Then, to calculate the PER, the lost packets are counted. The second method is to derive PER analytically, using BER results. For a given packet of length l, the packet is considered as a lost packet if there is at least one error bit throughout the whole packet.

$$PER = 1 - (1 - BER)^l \tag{5}$$

Figure 10 shows the comparison between the noise and the GFSK signal interference effects on the system performance, using PER parameter. This figure shows that simulated PER values, for both cases (GFSK interfering signal and AWGN interfering signal), finely match with analytical formula. It is also clear that the BLE demodulator responds to the AWGN and GFSK interfering source in different ways.

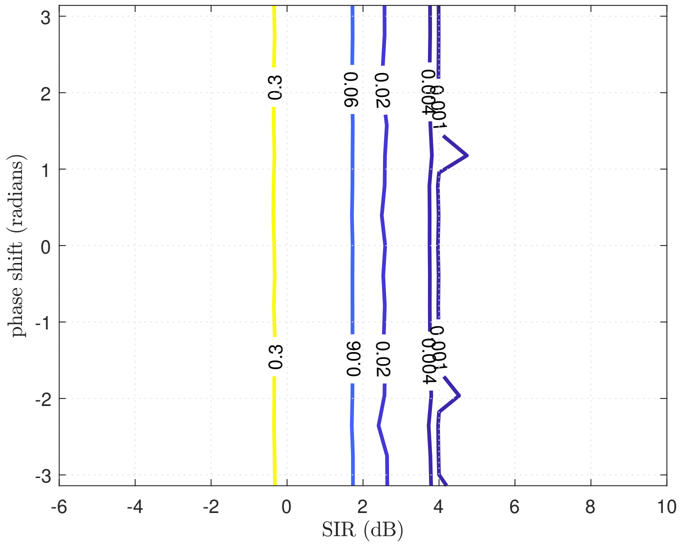

Figure 7: BER vs SIR and phase shift

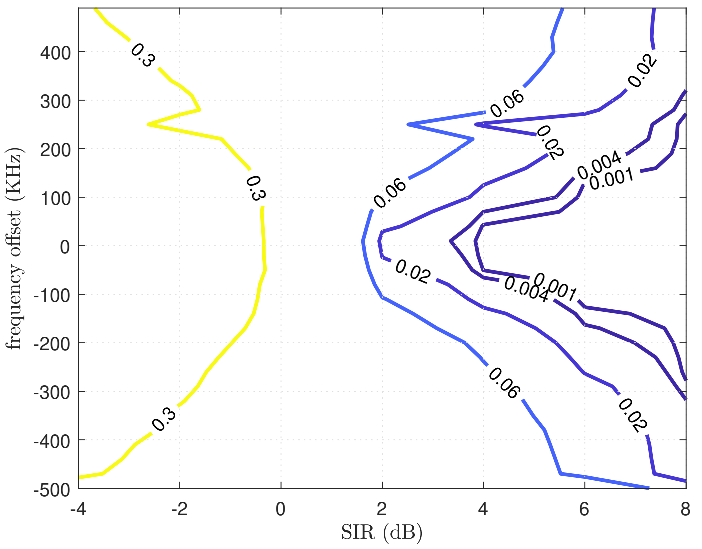

Figure 8: BER vs SIR and frequency offset

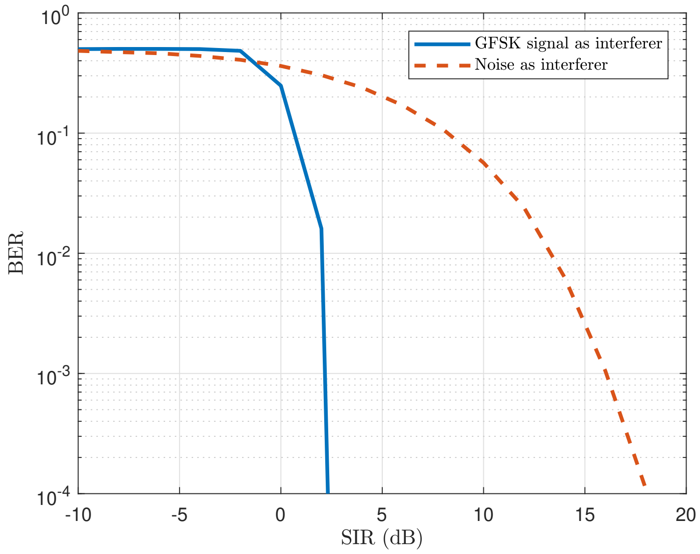

Figure 9: BER vs SIR for two case

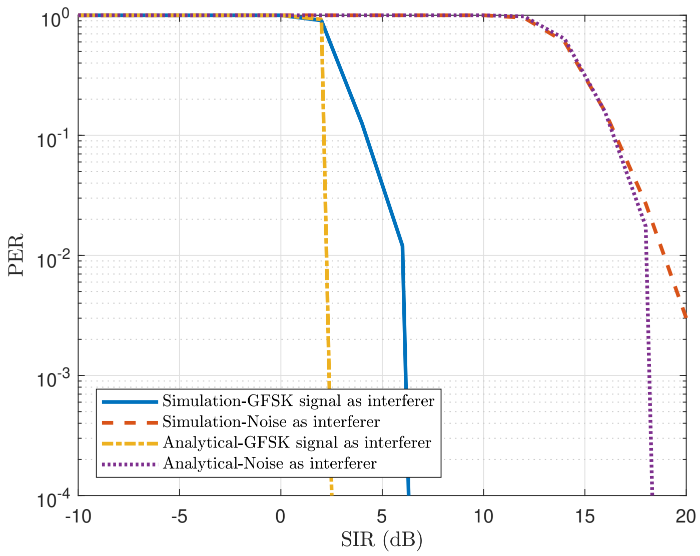

Figure 10: PER vs SIR

2.3 Conclusion

In this report, the performance of Bluetooth low energy in the presence of ISM band interference was analyzed. First, the BLE physical layer signal transmission was simulated. This includes modulation and demodulation for either random bit sequences (GFSK modulator and demodulator) or BLE packets (BLE modulator and demodulator). Afterwards, the performance of the demodulator versus noise and frequency offset was studied. To achieve a BER of $0.1\,\%$, the demodulator requires an SNR of about 16 dB. However, a performance loss is expected if frequency a offset exists. As an example, for a frequency offsets of $\pm 150\,\mathrm{kHz}$, a 1.1 dB loss occurs. Furthermore, analyses were performed for different types of interfering signals. For the case that a GFSK signal is the interferer, the demodulator performance was analyzed versus different parameters of the interfering signal. Unlike the phase shift and delay which have small effects, the frequency offset of the interfering signal can significantly degrade the demodulator performance. Simulations also showed that if a GFSK signal acts as the interferer, demodulator performance is slightly different from the situation that an AWGN signal is the interferer. A further step will be evaluating the BLE performance in the presence of other types of ISM band interferers such as WiFi packets. This will provide more reliable evidences to assess the possibility of modeling interference in the ISM band.

References

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[2] Robin Heydon. *Bluetooth low energy: the developer's handbook*, volume 1. Prentice Hall Upper Saddle River, NJ, 2013.

[3] Roel Schiphorst, Fokke Hoeksema, and Kees Slump. Bluetooth demodulation algorithms and their performance. In *2nd Karlsruhe Workshop on Software Radios*, volume 2, pages 99–106, 2002.

3 Revision History

Revision	Date	Author(s)	Description
1.1	March 5, 2019	Hamid Kavousi Ghafi	Some grammatical errors and typos are corrected. Figure 3 is modified to illustrate the occupied bandwidth. A brief interpretation for Figure 5 is presented.
1.0	November 19, 2018	Hamid Kavousi Ghafi	First version was released.