Performance Analysis of Bluetooth Network in the Presence of WI-FI System

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Abstract
Many wireless technologies used to build local or personal area network (WLANs or WPANs) operate in the 2.4 GHz ISM band. Due to mutual interference, the coexistence of such devices working at the same time in the same area can be troublesome. This paper reports the result of Bluetooth performance with 802.11b interference in term of BER of Bluetooth network. This study employed Agilent Advance Design system 2011 (ADS 2011) as methodology. The result revealed how Bluetooth network suffered degradation in terms of BER and the IEEE 802.11b interfering power and frequency offset. This study confirm previous finding. Further, the study recommends that the data rate of IEEE 802.11b should be taken into account in the performance evaluation of the Bluetooth network.
Keywords: Bluetooth, Performance, and WI-FI system

1.INTODUCTION
1.1 Introduction
In recent times, mobile devices such as Smartphone's are increasingly equipped with multiple network interfaces, which comprise Wi-Fi, Bluetooth and of course cellular interfaces. The 2.4GHZ Industrial, Scientific and Medical (ISM) band is poised for strong growth. Fueling this growth are two emerging wireless technologies; Wireless Local Area Networking (WLAN) and Wireless Personal Area Networking (WPAN). The WPAN is led by a short range wireless technology called Bluetooth which is designed principally for cable replacement applications **[1]**. Most Bluetooth implementations support a range of up to roughly 10 meters, and speeds of up to 700Kbps for data or asynchronous voice transmission. Bluetooth is ideal for applications such as wireless headsets, wireless synchronization of PDAs with computers, and wireless peripherals such as printers or keyboards. Coexistence between technologies has become a significant topic of analysis and discussion throughout the industry. WPAN and WLAN are complementary rather than competing technologies. Moreover, with both of them expecting rapid growth, Collocation of the IEEE 802.11b and Bluetooth devices will become increasingly likely**[18]**

The emergence of several radio technologies such as Bluetooth, and IEEE 802.11 operating in the 2.4 GHz unlicensed ISM frequency band may lead to signal interference and result in significant performance degradation when devices are co-located in the same environment. Thus, this framework will then be used to evaluate the impact of interference on the performance of Bluetooth and IEEE 802.11b. A simulation scenario is to be used in order to measure performance in terms of bit error rate and access delay.
Further, this study aims at Analysis of Bluetooth performance degradation with 802.11b interference in terms of BER of Bluetooth network.

2.1 Literature Review
2.2 BLUETOOTH TECHNOLOGY
In recent years with the massive rise in popularity of mobile and fixed electronic computing devices such as Personal Digital Assistant (PDAs), laptops, mobile phones, and other portable devices, there has been a growing demand for high speed digital wireless communication facilities. As the numbers of these devices increase and their use become so widespread, the use of cables to connect them become cumbersome and more and more inconvenient. Thus, the demand has arisen for a common digital wireless standard that will allow the connection of all kinds of electronic devices. It is this demand that has been the driving force for the development of Bluetooth **[3]**.

The Bluetooth wireless technology was developed by the Bluetooth Special Interest group which was founded in 1998 to define an industry-wide specification for connecting personal and business mobile devices. More than 1,400 companies are now members of the special Interest, signifying the industry's unprecedented acceptance of the Bluetooth wireless technology **[9]**.

Bluetooth is an open specification for a small factor, low cost, low power consumption, and robust wireless communication standard aimed at replacing cables between a wide range of electronic devices. It has been designed to provide short range, low power wireless connections and allow devices to form ad-hoc personal area networks (PANs) with other Bluetooth equipped devices away from fixed network infrastructures.

The Bluetooth wireless technology specification provides secure, radio based transmission of data and voice. It delivers opportunities for rapid, ad hoc, automatic wireless connections, even when devices are not within the line of sight. The Bluetooth wireless technology uses a globally available frequency range to ensure interoperability no matter where you travel **[3,9]**.

2.3 BLUETOOTH RADIO SYSTEM ARCHITECTURE

The 2.4-GHz Industrial Scientific and Medical (ISM) band in which Bluetooth operates is globally available for license free use. Bluetooth operates in ISM frequency band starting at 2.402 GHz and ending at 2.483 GHz in USA and Europe. 79 RF channels of 1MHz width are defined for Bluetooth technology **[2]**. The air interface is based on an antenna power of 1mW with an antenna gain of 1dB. Bluetooth signal is modulated using binary Gaussian Frequency Shift Keying (GFSK) modulation index of h=0.32 and a normalized bandwidth of $B_b\ T$ = 0.5 , where B_b is the 3dB Bandwidth of the transmitter's Gaussian low pass filter, and T is the bit period. The Bluetooth radio employs a frequency hopping scheme in which the carrier frequency is changed on a packet by packet basis. The raw data rate is defined at 1Mbits/s. Transmission occurs in packets that occupy an odd number of slots. Each packet is transmitted on a different hop frequency with a maximum frequency hopping rate of 1600hops/s **[9]**.The summary of the Bluetooth physical channel is presented in Table 2.1 below.

Table 2.1 Bluetooth radio parameters

Modulation	GFSK, h<0.35
RF band	ISM band, 2.4 GHz
Carrier Spacing	1 MHz
RF Carrier	23/79
Peak data rate	1 Mbit/s
Peak transmit power	≤ 20dBm

2.3.1 Multiple Access Scheme

Bluetooth is based on FH-CDMA (Frequency Hopping Code Division Multiple Access), FH-CDMA combines a number of properties which make it the best choice for ad hoc radio systems. On average the signal can be spread over a large frequency range, but simultaneously only a small bandwidth is occupied, avoiding most of the potential interference in the ISM band **[25]**. The hop carriers are orthogonal, and the interference on adjacent hops can effectively be suppressed by filtering. The hope sequences will not be orthogonal but narrowband and co-user interference is experienced as short interruptions in the communication, which can be overcome with measures at higher-layer protocol.

As mentioned earlier, Bluetooth is based on Frequency Hopping Code Division Multiple Access (FH-CDMA). In the 2.4GHz ISM hand, a set of 79 hop carriers have been defined at 1 MHz spacing. The channel is a hoping channel with a nominal hop dwell time of 625 μ s. A large number of pseudo-random hopping sequences is determined by the unit that controls the FH channel, which is called the master. The native clock of the master unit also define the phase in the hopping sequence. All other participants on the hopping channel are slaves **[1,10]**. They use the master identity to select the hopping sequence and add time offsets to their respective native clocks to synchronize or divide into slot. The minimum dwelt time of 625*us* corresponds to a single slot. To simplify implementation, full duplex communications is achieved by applying Time Division Duplex (TDU). This means that a unit alternately transmits and receives. Separation of transmission and reception in time effectively prevents crosstalk between the transmit and receive operations in the radio transceiver, which is essential if a chip implementation is desired. Since transmission and reception take place at different time slots, transmission and reception also take place at different hop carriers **[20]**.

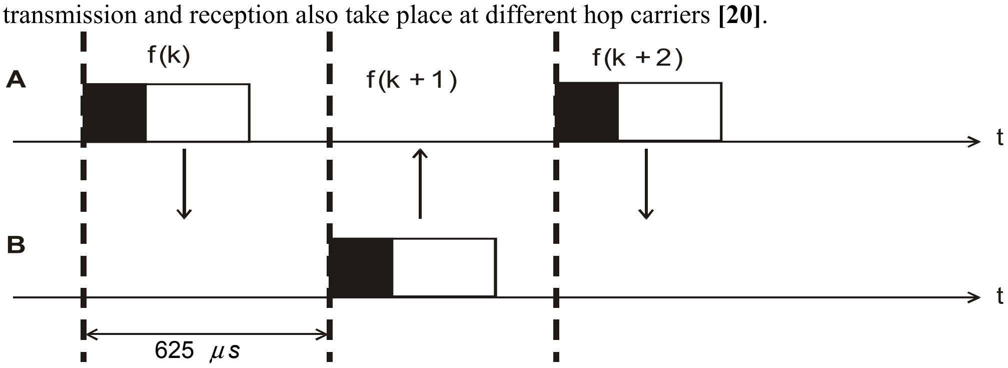

Figure 2.1 FH/TDD channel applied in Bluetooth

Figure 2.1 illustrates the FH/TDD channel applied in Bluetooth. Note that multiple ad hoc links will make use of different hopping channels with different hopping sequences and may have misaligned slot timing.

2.3.2 The Modulation Scheme

In the ISM band, the signal bandwidth of FH systems is limited to 1 MHz. For robustness a binary modulation scheme was chosen. With the above-mentioned bandwidth data rates are limited to about 1 Mbits/s. For FH system and support for busty a coherent detection scheme is most appropriate. Bluetooth uses Gaussian frequency Shift Keying (GFSK) modulation with a nominal modulation index of k=0.3. Logical ones are sent as positive frequency deviations, logical zeroes as negative frequency deviations. Demodulation can simply be accomplished by a limiting FM discriminator **[8,26]**.

This modulation scheme allows the implementation of low radio unit. The highest discriminator receiver consists of Intermediate Frequency (IF) filter, time limiter discriminator, an integrate and dump filter and the detector. The IF filter is responsible for removing noise and interference that are not in the same frequency band as the desired signal. A bandwidth 1 MHz is used since this provides a good compromise between noise and interference rejection. The limiter-discriminator essential takes the derivative of the noisy filtered IF signal. The derivatives are approximated by using finite impulse response (FIR) filters on the in-phase and quadrature samples. The integrate and dump filter, as its name implies, integrates over one bit period to obtain the phase. A decision is made for this bit. The process continues for the entire Bluetooth packet **[6]**.

2.3.3 Gaussian-Shaped Frequency Shift Keying (GFSK) Signal

The GFSK signal can be represented by

$$s(t,a) = A\cos(2\pi f_c t + \varphi(t,a)) \tag{2.1}$$

Where $A = \sqrt{\frac{2E_b}{T}}$, E_b is the energy per data bit, and f_c is the carrier frequency. *a* is the random input stream, comprised of the data bits α_i; $\varphi(t,\alpha)$ is the output phase deviation, given by

$$\varphi(t,\alpha) = 2\pi h_f \int_{\infty}^{t} \sum_{i=\infty}^{n} \alpha_i g(\tau - iT)\, d\tau \tag{2.2}$$

One of the key ideas in GFSK is that a single bit is transmitted over multiple symbols, which is done by using a pulse shaping filter with impulse response g(t) given by

$$g(t) = \frac{1}{2T}\left[\; Q\left(2\pi B_b \frac{t - \frac{T}{2}}{\sqrt{1n2}}\right) - Q\left(2\pi B_b \frac{t + \frac{T}{2}}{\sqrt{1n2}}\right)\right] \tag{2.3}$$

Where Q(t) is the standard Q-function $Q(t) = \int_{t}^{\infty} \frac{1}{\sqrt{2\pi}} e^{\frac{\tau^2}{2}} d\tau$.

By introducing controlled inter-symbol interference, the spectral occupancy of the signal is substantially reduced **[6,23]**.

Equation (2.2) can also be written as

$$\varphi(t,\alpha) = 2\pi h_f \sum_{i=n\ L+1}^{n} \alpha_i q(t - iT) + \pi h_f \sum_{i=\infty}^{n\ L} \alpha_i , \tag{2.4}$$

Where L is the g(t), and

$$q(t) = \int_{\infty}^{t} g(\tau)\, d\tau .$$

2.3.4 Frequency Hopping

Bluetooth uses a frequency hopping mechanism that sweeps 79 channels of the frequency band available at a maximum rate of 1600 hops/s depending on the packet size. Both master and slave devices are synchronized and follow the same random frequency hopping sequence. This frequency sequence is derived at the master and slave devices and depends on the master's clock and its Bluetooth address. The algorithm for generating the sequence works as follows. Given a window of 32 contiguous frequencies in the 2.4 -2.479 GHz range, a sequence of 32

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frequencies is chosen randomly. Once all 32 frequencies in that all have been visited once, a new window of 32 frequencies is selected. This new window includes 16 of the frequencies previously visited and 16 new frequencies **[12]**.

2.3.5 Medium Access

Two or more units communicating on the same channel form a piconet. Where one unit operates as a master and the others (a maximum of seven active at the same time) act as slaves. A channel is defined as a unique pseudo-random frequency hopping sequence derived from the master device's 48-bit address and its Bluetooth clock value. Slaves in the Piconet synchronize their timing and frequency hopping to the master upon connection establishment **[19]**.

In the connection mode, the master controls the access to the channel using a polling scheme where master and slave transmissions alternate. A slave packet always follows a master packet transmission.

There are two types of link connections that can be established between a master and a slave: the Synchronous Connection Oriented (SCO) which is typically for voice traffic and the Asynchronous Connectionless Link (ACI,) typically for bursty data transmissions. The SCO links are pre-allocated while ACL connections are controlled by the master unit using pulling mechanism **[14]**. Communication is enabled only between master and slave device as illustrated in Figure 2.2 .

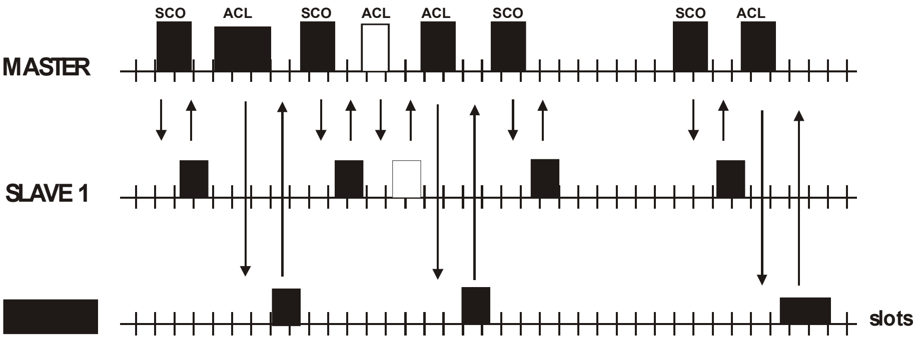

Figure 2.2 SCO and ACL links in a Piconet

The SCO link is a symmetric point to point connection between a master and a slave where the master sends an SCO packet in one transmitter (TX) slot at regular lime intervals, define by T_{sco} time slots. The slave responds with an SCO packet in the next T_x opportunity. T_{sco} is set either 2, 4 or 6 time slots for HV1, HV2 or HV3 packet formats respectively. All three formats of SCO packets are defined to carry 64 kbps of voice traffic and are never retransmitted in case of packet loss or error. The ACL link is an asymmetric point to point connection between a master and active slaves in the piconet. Several packet formats are defined for ACL, namely DM1, DM3 and DM5 packets that occupy 1, 3, and 5 time slots respectively **[4,16]**. An Automatic Repeat Request (ARQ) procedure is applied to ACL packets where packets are retransmitted in case of loss until a positive acknowledgement (ACK) is received at the source. The ACK is piggy-backed in the header of the returned packet where an ARQN bit is set to either 1 or 0 depending on whether the previous packet was successfully received or not. In addition, a sequence number (SLQN) bit is used in the packet header in older to provide a sequential ordering of data packets header in order to provide a sequential ordering of data packets in a stream and filter out retransmissions at the destination. Forward Error control (FEC) is used on some SCO and ACL packets in order to error and reduce number of ACL re transmission.

2.4 IEEE802.11b STANDARD

In 1990, the IEEE 802 Executive Committee established the 802.11 Working Group to create a wireless local area network (WLAN) standard. The standard specified an operating frequency in the 2.4GHz ISM (Industrial, Scientific, and Medical) band. Seven years later, the group approved IEEE 802.11 as the world's first WLAN standard with data rates of 1 and 2 Mbps. Afterwards the committee began work on another 802.11 extension that could satisfy future needs. Within 24 months, the working group approved two higher rate physical layer extensions to 802.11. The two extensions were designed to work with the existing 802.11 MAC layer (Medium Access Control), with one being the IEEE 802.11a 54Hz and the other IEEE 802.11b - 2.4GHz. Recently 802.11g was announced, which operates at 2.4 GHz and uses OFDM **[11]**. Table 2.2 compares the IEEE 802.1Ib and IEEE 802.1Ig standards with Bluetooth. This gives a better insight on these three technologies which operates in the same 2.4 GHZ ISM band.

Table 2.2 Comparison of IEEE 802.11b, IEEE 802,11g and Bluetooth technology

Standards	IEEE 802.11b	IEEE802.11g	Bluetooth
Time table	Standard in 1998	Standard in late year 2002	Standard in 2000
Frequency Band	2.4 GHz.	2.4 GHz	2.4 GHz
Modulation Techniques	Direct Sequence Spread Spectrum (BPSK,QPSK,CCK)	Direct Sequence Spread Spectrum (64-QAM OFDM)	Frequency Hopping (FH)
Data Rates	1,2,5.5, 11 Mbps	54 Mbps	1 or 2 Mbps
Coverage Distance	Up to 100 meter	Up to 100 meter	Up to 10 meter

3.1 Methodology

This section covers the concepts and methodologies of analyzing the Bluetooth network's performance with IEEE 802.11b coexistence using Agilent Advanced Design System 2011 (ADS 2011). In addition, the schematic of the test bench will be shown; this includes the sub networks used in Bluetooth transmitter and receiver as well. It will also cover briefly about ADS 2011 to give better insight on the procedure and method used to design the test bench.

3.2 DESIGN USING ADS 2011

To design the Bluetooth network with IEEE802.11b coexistence test bench, the libraries and components needed include:

- WLAN 802.11b Library
- Measurement components such as spectrum analyzer and Bit Error Rate Tester
- Filters, Modulator, Demodulator,
- Simulation license for Digital Signal processing and RF network

3.3 BLUETOOTH NETWORK'S PERFORMANCE WITH IEEE802.11b INTERFERENCE TEST BENCH

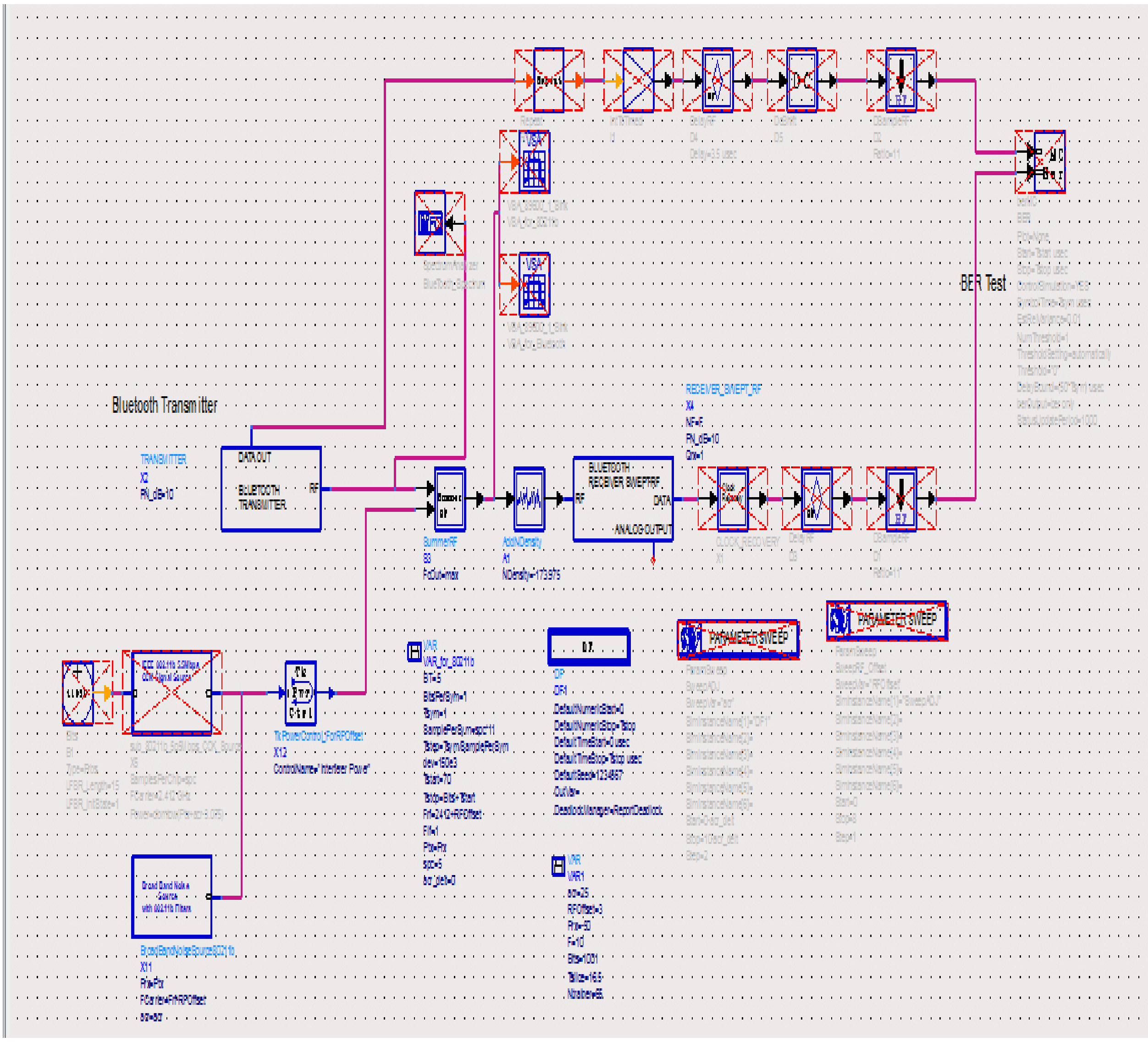

Figure3.1 The Bluetooth Network`s Performance with IEEE802.11b coexistence Test Bench

The test bench shown in Figure 3.1 above is used to simulate the BER of Bluetooth network in the presence of IEEE 802.11 b interfering signal. This test bench consists of Bluetooth signal source or Bluetooth transmitter, IEEE 802.1Ib with 5.5 Mbps data rate CCK signal source as the interfering source signal, Bluetooth receiver, RF signal combiner, measurements components such as spectrum analyzers, BER tester and other supporting components like DelayRF, DSampleRF and IntDumpTime. In this test bench, the Bluetooth signal source has two outputs. One output provides a pseudo-random bit stream while the other provides a Bluetooth RF signal modulated by the same pseudo-random bit stream bit pattern. The IEEE 802.11b interfering RF signal and the Bluetooth RF signal are added together by using the RF Signal Combiner (SummerRF component). This combined signal is then input to the Bluetooth receiver. In this test bench, the Bluetooth receiver uses models of amplifiers, mixers, filters and FM demodulator and a bit slicer . The AddNDensity component in this test bench is used to add White Gaussian Noise to the combined RF signal of Bluetooth and IEEE 802.1Ib before this signal is received by Bluetooth receiver. The Bluetooth receiver demodulates the combined RF signal, and outputs the resulting bit stream. This bit stream is compared to the pseudo-random bit stream from the Bluetooth signal source to determine the Bit Error Rate (BER) of the Bluetooth network. The BER of Bluetooth network is measured by using BER Tester which uses the Monte Carlo method for probability of error measurement. The measurement of BER is based on comparing test data to reference data waveforms, symbol by symbol.

In this simulation, 1001 bits of Bluetooth data packet is sent. The frequency offset between center frequency of

Bluetooth and IEEE 802.11b signal is 3MHz. However, the relative interference power of IEEE 802.11b varies from -2dB to 10dB while Bluetooth transmitting power remains constant for this simulation.

4. 1 Results and Discussion

This section discuses the results that were obtained from the simulation of the Bluetooth network with 802.11b coexistence test bench as discussed in previous section.

4.2 BLUETOOTH AND IEE802.11B SPECTRUM

The Bluetooth and IEEE 802.11b spectrum is shown in Figure 4.1. This figure shows how Bluetooth frequency hops into the IEEE 802.11b spectrum in the ISM band. From this figure, it is clearly shown that the frequency offset between center frequency of Bluetooth and IEEE 802.11b signal varies. The Bluetooth signal (marked red in Figure 4.1) hops from 2.41 GHz to 2.42 GHz in the 2.4 GHz ISM band in this simulation. The IEEE 802.11b WLAN uses 100mW power transmission and Bluetooth uses 1mW in practical. In this simulation, we assume the distance between Bluetooth network and IEEE 802.11b network is far enough so that Bluetooth signal is higher than interfering IEEE 802.11b WLAN signal.

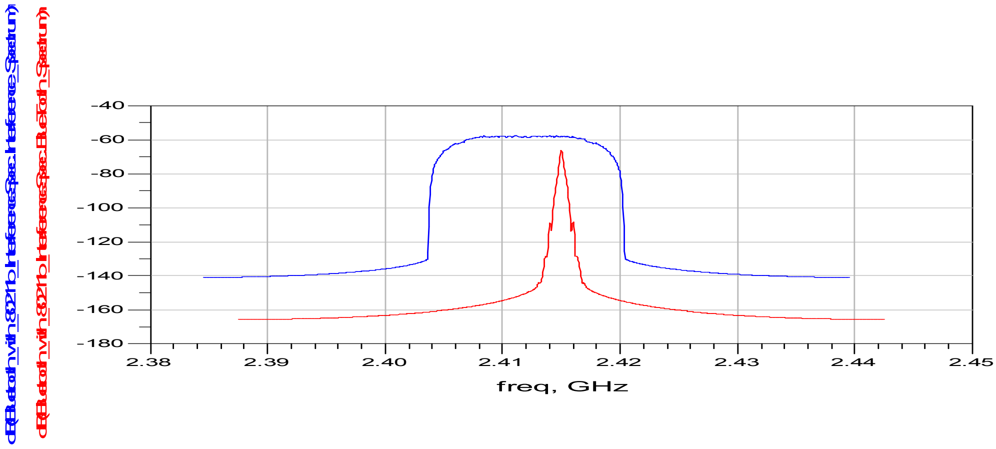

Figure 4.1 Bluetooth and IEEE802.11b WLAN Spectrum

4.3 PACKET ERROR RATE (PER)

The Bluetooth Network's Packet Error Rate (PER) can be calculated once the Bit Error Rate (BER) of the Bluetooth system is determined from this simulation. In this derivation, it is assumed that BER of the Bluetooth system is independent from bit to bit. This is a valid assumption for all cases in this thesis regardless of the frequency offset and relative interfering power of IEEE 802.11b signal **[22]**. The PER is derived in the following fashion: probability of correct reception of one bit can be calculated by:

Probability of 1 bit is received correctly= 1-BER (4.1)

Therefore,

Probability of correct reception of n bits= $\prod_{i=0}^{n}$ (1-BER, i) (4.2)

This formula can be further derived as

$P^n = (1\text{-}BER)^n$, where BER is independent (4.3)

and therefore, probability of incorrect reception of n bits can be derived as 1-pn or in short,

$PER=1-(1-BER)^{\text{number of bits in the packet}}$ (4.4)

4.3.1 Graph of Packet Error Rate Equation

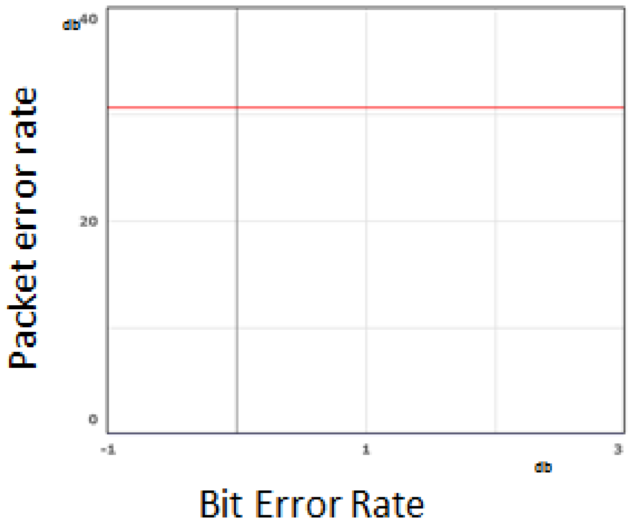

Figure 4.6 Graph of Packet Error Rate Vs Bit Error Rate

To analyze the performance of Bluetooth network in terms of PER, the threshold between acceptable and unacceptable performance is chosen to be a Bluetooth raw BER of 0.001. With Bluetooth packet lengths of 366 bits, this BER produces a raw packet error rate (PER) of approximately 30.66 percent. Network performance with 31 percent raw PER is worse than insignificantly degraded and better than complete network failure. The PER of the system is close related to the number of bits in the packet, which is clearly visible from the equation 4.4 and figure 4.6; the greater is a packet size of the Bluetooth, the greater is the PER of the system.

5. Summary, Conclusion and Recommendations

5.1 Summary

To summarize, a schematic for performance analysis of the Bluetooth network in the presence of the interfering IEEE 802.1Ib radio transmissions has been developed. This schematic design can be used to capture the performance impact of Bluetooth packet reception with the interference of the IEEE 802.1Ib signal when these two technologies collocated in the same area. The relationship of Bluetooth network's BER and the IEEE 802.11 b interfering power and frequency offset have also been determined. With regards to interference analysis between the Bluetooth System and IEEE 802.1Ib system, the dissertation can also be extended on simulation and performance analysis of the impact of the Bluetooth transmission on the IEEE 802.1Ib network which operates also in the same 2.4 GHz ISM band.

5.2 Conclusion

The result of the dissertation determined that when Bluetooth WPAN and IEEE 802.11b WLAN co-exist in the same location, the Bluetooth transmitter must have sufficient high of transmission power relatively to IEEE 802.11b transmission power so that the Bluetooth networks do not suffer network failure or severe error in data reception. However, since the Bluetooth has very low transmission power, approximately 1 mW for the operation over distance of up to 10m, compared to IEEE 802.1Ib WLAN which has 100mW of transmission power for operation within the range of 100m, therefore, the Bluetooth PAN must be located far enough from IEEE 802.1Ib WLAN environment so that the interference signal not degrade the Bluetooth network performance seriously.

5.3 Recommendations

To further improve the estimation of the Bluetooth network performance with the presence of the IEEE 802.11b WLAN system, the following recommendations are given so that they can be used for future improvement ;

i. IEEE 802.11b data rate (1, 2, 5.5 and 11 Mbps)

In this simulation, the IEEE 802.1lb with 5.5 Mbps data rate CCK signal source was used. But for IEEE 802.1lb standard, data rates defined are 1, 2, 5.5 and 11 Mbps which use different modulation type as discussed in the section two. So, the data rate of IEEE 802.11b should be taken into account in the performance evaluation of the Bluetooth network due to the interference from IEEE 802.1 lb signal.

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