Empirical Study for IEEE 802.11 and Bluetooth Interoperability[1]

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Abstract

The IEEE 802.11 and Bluetooth (BT) wireless networks can provide complimentary services and they are likely to be installed within the same environments. Coexistence between the networks will be impaired, if the probability of packet collision between the networks is sufficiently large. This paper presents the results of an empirical study focused on evaluating one aspect of the probability of collision: determining the interference power at which packet retransmission is likely to be required. The results from this empirical study are used to substantiate analytical models for interference suppression versus carrier frequency offset. The empirical study and analytical model are used to provide insight into the impact of adjacent channel interference from the interfering wireless service.

1 Introduction

Wireless local and personal area networks provide complimentary services in the same unlicensed (UL) radio frequency band of operation. As the mutual benefits of utilizing these services become increasingly apparent, the likelihood of mutual interference may also increase. The IEEE 802.11 [1] and Bluetooth (BT) [2, 3] wireless networks can provide complimentary services and they are likely to be installed within the same environments. Coexistence between the networks will be impaired, if the probability of packet collision, $\Pr[C]$, between the networks is sufficiently large.

A packet collision, C, can be defined as the event that occurs when one or more interfering signal causes the desired service to retransmit a packet. Therefore, $\Pr[C]$ is dependent on the likelihood that the interfering service's packet is temporally and spectrally coincident with the desired service's packet as depicted in Figure 1. The evaluation of $\Pr[C]$ involves many factors including the radio signal propagation, network loading, relative distances, etc. The number of parameters involved with evaluating $\Pr[C]$, leads to the difficulty in using only empirical testing to characterize the coexistence issues between the wireless area networks (WANs). The study presented in this paper focuses on one aspect required for evaluating $\Pr[C]$: determining the interference power at which packet retransmission is likely to be required. The results from the empirical study were used to substantiate analytical models for interference suppression versus carrier frequency offset. The results are also useful in providing insight into the impact of adjacent channel interference from the interfering wireless service. In Section 2, a comparative analysis between analytical

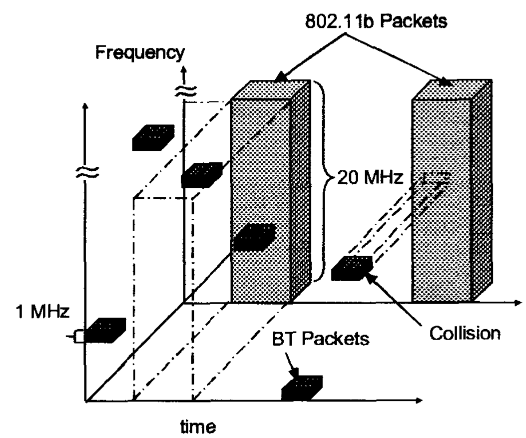

Figure 1 IEEE 802.11b and BT interoperability depicted.

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model and empirical results for studying the impact of BT interference on 802.11b is presented. In Section 3, corresponding comparative analysis is presented for studying the impact of 802.11b on BT and in Section 4 conclusions are presented.

2 Impact of BT on 802.11

2.1 Empirical Results

The goal of the empirical test was to obtain an estimate of the impact of BT interference under variations of the carrier frequency offset between the two WANs. For the tests, the BT interference signal was transmitting continuously on the same hop frequency, i.e., frequency hopping was not enabled. Therefore, based on Figure 1, the uncertainty associated with the timing and frequency coincidence of the two signals is removed; the only element remaining is the jamming suppression capability of the IEEE 802.11b. The measure of performance for the test was the expected packet error rate, $E[PER]$.

The setup used for the test is depicted in Figure 2. The IEEE 802.11b compliant Tx (Prism II) signal was attenuated such that the signal at the IEEE 802.11b Rx was approximately -40 dBm. The BT interference signal was generated using an HP ESG-D 4432 B digital signal generator. The signal's modulation was the same as per BT specification, but no packet structure was incorporated. The desired jamming to signal ratio (J/S) was obtained by setting an attenuator in the interference signal path. All devices were connected using low loss coaxial cables. For each trial, i.e., specific frequency offset, f_{offset}, and J/S, the number of packets used in evaluating the $E[PER]$ was based on the data rate of the IEEE 802.11b. For 11Mbps and 5.5 Mbps data rates, 10^6 packets were transmitted from the IEEE 802.11b Tx and for the 2 Mbps data rate, 0.5×10^6 packets were transmitted.

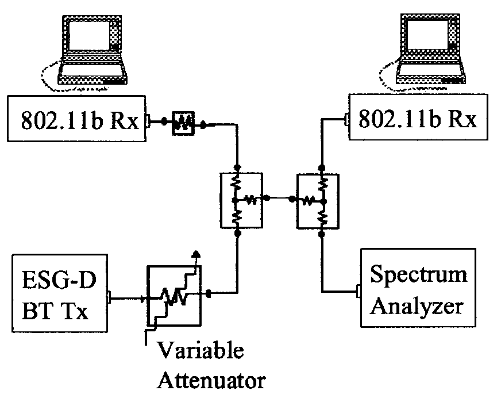

Figure 2 Setup for BT on 802.11b empirical test.

Figure 3 illustrates the results obtained for the 11 Mbps IEEE 802.11b data rate transmission under variations of both J/S and f_{offset}. In the graph, three regions are depicted. The bounds between each of the regions represent curves were the $E[PER]$ is constant, i.e., combinations of J/S and f_{offset} that result in either $E[PER]=0.03$ or $E[PER]=0.90$. As can be seen by the results depicted in the figure, a $J/S\approx-10$ dB was required to cause an increase in $E[PER]$ when the interference was in the passband of the 802.11 receiver, $f_{offset}\approx0$ Hz. This result corresponds to the same result reported by other empirical studies[4]. Also, as can be seen from the graph in Figure 3, a sharp transition region exists between the two boundaries. Typically, within 2 to 5 dB variations in J/S, the $E[PER]$ transitions from an acceptable *PER* level, $E[PER]\le0.08$, to an unacceptable *PER* level. Using this insight, Figure 4 depicts the empirical results for the jamming suppression versus f_{offset} based on a packet error rate threshold, $E[PER]=0.08$.

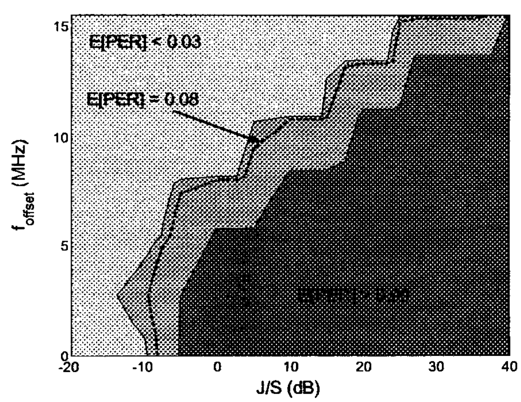

Figure 3 PER versus J/S versus f_{offset} for the 802.11b with BT interference.

2.2 Analytical Model & Comparison

An analytical model for the interference caused by a BT signal can be approximated based on the effects of a continuous wave (CW) tone on a direct sequence spread spectrum (DSSS) signal[5]. The model is based on letting $\gamma_{I/S}(f_{offset})$ represent the interference threshold, i.e., the

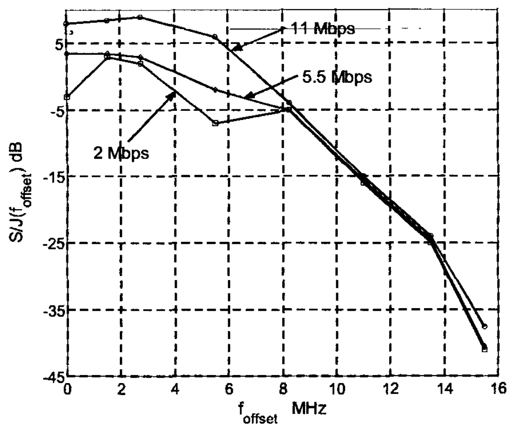

Figure 4 S/J versus f_{offset} for the 802.11b with BT interference. Based on determining interference level to cause $E[PER] = 0.08$.

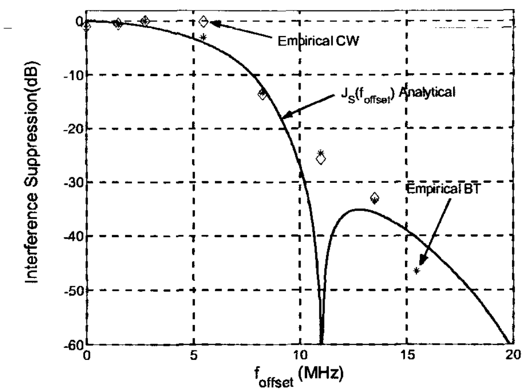

Figure 5 Interference suppression comparison, 'solid line': Analytical, '*': empirical results with BT interference, 'diamond': empirical results with CW interference.

value of J/S at which $E[PER]$ becomes significant. Using CW interference, the analytical model is given by

$$\gamma_{I/S}(f_{offset}) = \gamma_{I/S}(0) - J_S(f_{offset}) \text{ (dB)} \quad (1)$$

where

$$J_S(f_{offset}) = 10\log_{10}\left(\frac{\left|\text{sinc}(f_{offset}T_c)G(f_{offset})\right|^2}{|G(0)|^2}\right) \text{(dB)}. \quad (2)$$

The $\text{sinc}(\cdot)$ function results from the spreading of the CW tone at the 802.11b demodulator based on a chip period of T_c, and $G(f)$ is the Fourier transform of the chip pulse shaping filter, $g(t)$. For the 802.11b with 11 Mbps, a 5th order Butterworth filter with a cutoff frequency of 8.8 MHz was used for $g(t)$ [6]. Figure 5 depicts the graph of the jamming suppression as a function of carrier frequency offset, $J_S(f_{offset})$. Using $E[PER] = 0.08$ to estimate $\gamma_{I/S}(f_{offset})$ and using $\gamma_{I/S}(0) = -10$ dB, the corresponding $J_S(f_{offset})$ for the BT empirical results are depicted in Figure 5. An empirical study using CW tone interference was also investigated with the results depicted in the figure. As can be seen in the graph, good agreement was achieved with all three approaches.

3 Impact of 802.11b on BT

3.1 Empirical Results

The goal of the empirical test was similar to that specified above in Section 2.1, i.e., to measure the jamming suppression of BT in the presence of IEEE 802.11b interference.

The setup used for the test was similar to the one depicted in Figure 2, with the system under test and interference signals reversed. The BT Tx and Rx were from Ericsson Bluetooth starter kit compliant with version 1.1 of the BT specification. The BT Tx signal was attenuated such that the signal at the BT Rx was within the desired power level of the receiver. The IEEE 802.11b interference signal was generated using IEEE 802.11b compliant Tx (Prism II) with continuous transmission and the desired jamming to signal ratio (J/S) was obtained by setting an attenuator in the interference signal path. For each trial, i.e., specific f_{offset}, J/S, and BT packet type, the number of packets used in evaluating the $E[PER]$ was 10^3.

Figure 6 depicts the S/J versus f_{offset}. For the results depicted, the BT system was transmitting and receiving DH1 packets. Three graphs are presented based on different $E[PER]$ thresholds: maximum measured S/J such that $E[PER] > 0.20$, maximum measured S/J such that $E[PER] > 0.08$, and minimum measured S/J such that $E[PER]$ is the same as the case with no interference (residual $E[PER]$).

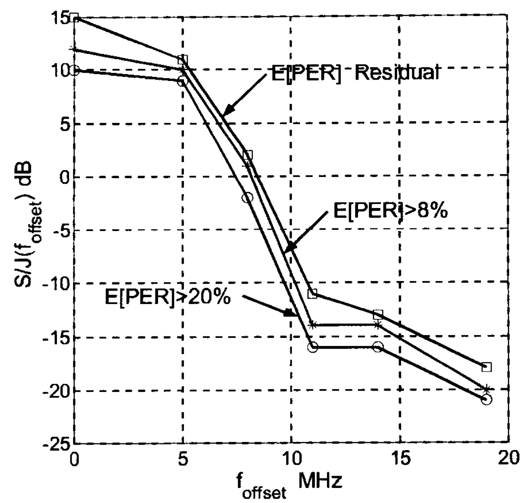

Figure 6 S/J versus f_{offset} for the BT DH1 packet with IEEE 802.11b interference.

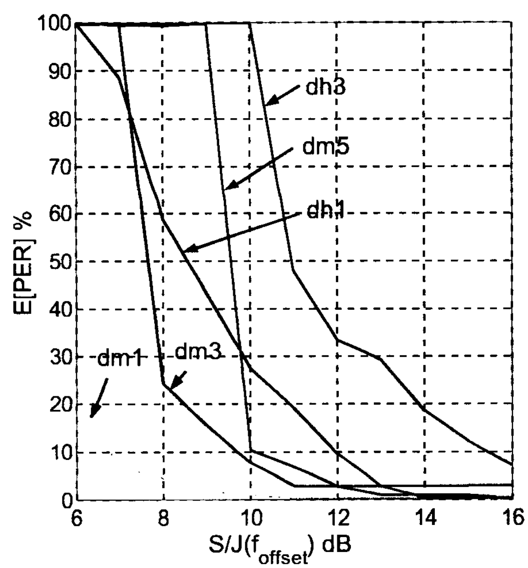

Figure 7 $E[PER]$ for various BT packet types versus S/J with $f_{offset} = 0$ Hz.

Figure 7 depicts $E[PER]$ for five of the possible BT packet types versus S/J. These tests were based on $f_{offset} = 0$ Hz.

Figure 8 depicts the residual bit error rate (BER) versus S/J for five of the BT packet types. Again the test was conducted with $f_{offset} = 0$ Hz. The residual BER is a measure of the number of bits received in error assuming the packet was received, i.e., the BT header was decoded correctly without error.

The BT specification [2] requires residual BER to be $< 0.1\%$ and the PER to be $< 8\%$. Table 1 summarizes the S/J required for each of the packet types evaluated to meet these two requirements, based on the empirical results with IEEE 802.11b interference with $f_{offset} = 0$ Hz.

Table 1 S/J required to meet PER and residual BER (RBER) constraints

BT Packet Type	S/J where $E[PER] > 0.08$	S/J where RBER > 0.001
DH1	12	11
DH3	10	10
DM1	7	7
DM3	9	8
DM5	15	6

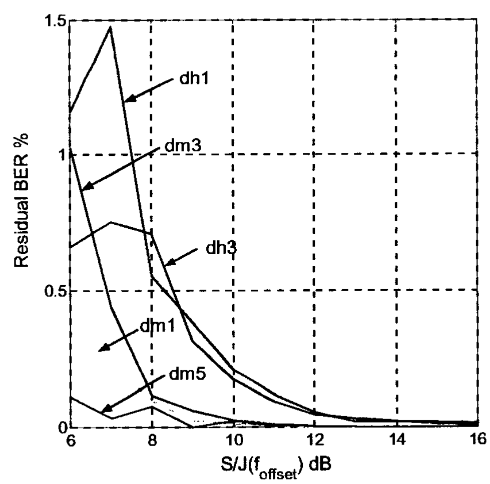

Figure 8 Residual BER for various BT packet types versus S/J with $f_{offset} = 0$ Hz.

3.2 Analytical Model & Comparison

An analytical model for the interference caused by an IEEE 802.11b on a BT signal is developed in this section. Utilizing (1), determining the portion of the 802.11b energy within the passband of the BT Gaussian filter provides

$$J_S(f_{offset}) = 10\log_{10}\left(\frac{\int_0^\infty G_S(f)\left|H_{BT}(f - f_{offset})\right|^2 df}{\int_0^\infty G_S(f)\left|H_{BT}(f)\right|^2 df}\right) \text{ (dB)} \quad (3)$$

where $H_{BT}(f)$ is the frequency response of the BT Gaussian filter with $B \times T = 0.5$ and $G_S(f)$ is the power spectral density (PSD) of the 802.11b transmit signal, $s(t)$. The transmit signal is modeled by

$$s(t) = f_{PA}(g_{OBO}(h_{802}(t) * x(t))) \quad (4)$$

where $x(t)$ is an 11 MHz chip rate QPSK signal and $h_{802}(t)$ is a 5th order Butterworth filter with cutoff frequency of 8.8 MHz. The function $f_{PA}(\cdot)$, in conjunction with g_{OBO}, models the effects of the 802.11b transmit power amplifier[7], where g_{OBO} is the output backoff from full saturation and

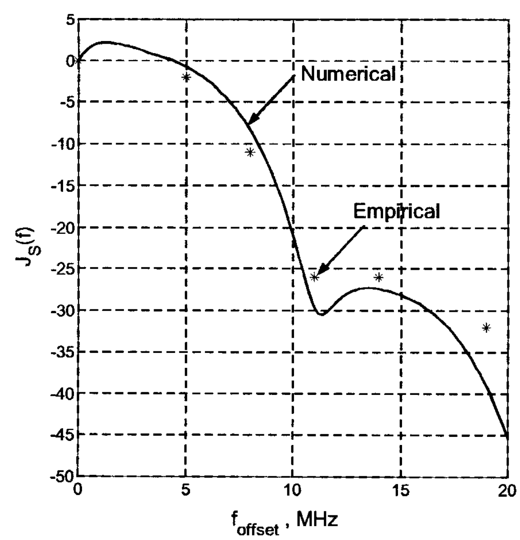

Figure 9 Interference suppression comparison between analytical model and dh1 empirical results.

$$f_{PA}(Ae^{j\phi}) = \left(\frac{A}{\left(1 + A^{2p}\right)^{1/2p}}\right)e^{j\phi}. \quad (5)$$

Figure 9 depicts a graph of $J_S(f_{offset})$, based on substituting into (3) a numerical estimation of the PSD based on (4) and (5). Empirical results are overlaid on the graph for the DH1 BT packet measurements, $E[PER] > 0.08$, from Figure 6.

4 Conclusions

In this paper, empirical results were presented based on controlled experiments to measure the effects of interference, IEEE 802.11b and BT, cochannel and adjacent channel on BT and IEEE 802.11b respectively. Analytical models of jamming suppression for both WLANs were derived and compared to the empirical results. In both cases, good agreement was obtained between the analytical models and empirical data. These results form one component in analyzing the $\Pr[C]$ and have been integrated with stochastic models to evaluate the impact of BT on IEEE 802.11b [8, 9] and the impact of IEEE 802.11b on BT [10].

5 References

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