Co-existence of 802.11g WLANs with Bluetooth

K. K. Wong and T. O'Farrell

Institute of Integrated Information Systems

School of Electronic and Electrical Engineering

University of Leeds

Woodhouse Lane,

Leeds LS2 9JT,

U.K.

Email :- eenkkw@ecu-01.novell.leeds.ac.uk

Tel :- 0113 3432098

Co-existence of 802.11g WLANs with Bluetooth

K K Wong and T O'Farrell

University of Leeds, UK

Abstract: Orthogonal-frequency-division multiplexing (OFDM) based wireless local-area-networks (WLANs) will be implemented in the 2.4 GHz Industrial-Scientific-Medical (ISM) band. The advantages of OFDM WLANs are very high data rates, resilience to multipath and extended operating range. However, they will encounter interference from Bluetooth (BT) devices. In this paper, the co-existence issue of OFDM WLANs with BT devices is examined and the use of symbol erasures to ameliorate this interference source is proposed. Simulation results show that the combination of data rate reduction and symbol erasures helps to prevent irreducible packet error rate (PER) when the signal-to-interference ratio (SIR) is low. However, depending on the data rate, there is a threshold for the number of erasures beyond which further improvements in system performance is not obtained.

1 Introduction

OFDM (the modulation scheme used by IEEE 802.11a) has been adopted as the mandatory modulation in the IEEE 802.11g WLANs draft specification [1] for a further high-speed physical layer (PHY) extension to the 802.11b standard in the 2.4 GHz ISM band. This PHY offers a range of data rates from 6 up to 54 Mbit/s and allows for three non-overlapping channels in the 2.4 GHz band. Besides 802.11 WLANs, the ISM band also hosts numerous other devices, such as BT-enabled devices, cordless telephones and microwave ovens. The presence of these types of devices can degrade the performance of an OFDM WLANs.

BT uses frequency hopping to hop over the entire 2.4 GHz band, while 802.11g, on the other hand, uses OFDM and occupies approximately one third of the 2.4 GHz band. As a result, BT hops on to 802.11g transmissions. The impact of mutual interference depends on the utilization and proximity of both devices. With BT and 802.11g WLANs expecting rapid growth, collocation of the two technologies will become increasingly likely, especially in computing devices. Without further provision, they will interfere with each other. Previous investigations into co-existence issues have concentrated on 802.11b, including high-level analysis and simulations to investigate the impact of BT on 802.11b and vice-versa [2,3]. The IEEE 802.15.2 Task Group, in conjunction with the BT SIG, has been working on a "recommended practice" [4] that describes collaborative and non-collaborative co-existence techniques to allow 802.11g and BT to co-exist, such as collision avoidance and adaptive frequency hopping which operate at the system level. This paper evaluates the impact of the BT interference on an 802.11g OFDM PHY and studies the insertion of erasures, which operates purely at the PHY, as a method to mitigate the effects of such interference.

Section 2 provides descriptions of the OFDM signal and the parameters specified in the 802.11g specification. In Section 3, the modelling of the BT interference is presented. Section 4 explains the insertion of symbol erasures. In Section 5, results show that OFDM systems are able to withstand high levels of interference with the help of erasures, which would otherwise collapse the system PER performance. However, higher data rates that use a punctured binary convolutional code and more densely packed modulations do not benefit as much from the use of erasures. Finally, the conclusions are given in Section 6.

2 OFDM Modulation

An OFDM signal of duration T seconds consists of a set of N_{ST} complex exponential sub-carriers spaced in frequency by an integer multiple of $1/T$ such that the peak of its spectrum occurs at the zero energy frequency point of all the other sub-carriers. Hence the orthogonality of the sub-carriers is maintained although their spectra overlap. Phase shift keying (PSK) or quadrature amplitude modulation (QAM) is used to modulate the sub-carriers. In practice, the OFDM symbols can be generated efficiently using the Inverse Fast Fourier Transform (IFFT), transforming the spectrum (amplitude and phase) of the N_{ST} frequency-domain sub-carriers into a single discrete time waveform as shown in equation (1) [5] where c_i is the constellation point, k_i is the frequency multiplier for sub-carrier i and n is the sample number.

$$s(n) = \sum_{i=0}^{N_{ST}-1} c_i \exp(j2p \frac{k_i}{N} n) \qquad \text{for} \qquad 0 \le n \le L\text{-}1 \qquad (1)$$

The Fourier transform requires N samples, where $N \ge N_{ST}$ is a power of 2. However, the OFDM transmitter generates $L \ge N$ samples where the additional N-L samples contain a cyclic extension of the symbol forming a guard interval. The guard interval provides protection against inter-symbol interference whereas the cyclic extension in the guard interval eliminates inter-carrier interference as long as the multipath delay is smaller than the guard interval. At the receiver, the Fast Fourier Transform (FFT) is used to convert the received OFDM signal into the frequency domain before being demodulated and decoded.

In the 802.11g draft specification [1], the guard interval is set to 800 ns. In order to limit the amount of relative power spent on the guard interval to about 1 dB, the symbol duration is set to 4 µs, which determines the sub-carrier spacing at 312.5 KHz. The OFDM symbol is sampled at F_s = 20MHz, resulting in a symbol length $L = 80$ samples. For an FFT window length $N = 64$ samples, the guard interval is 16 samples. Out of the 64 possible sub-carriers N_{ST} = 52 are used, 48 sub-carriers are dedicated to data transport and 4 are pilot sub-carriers, which are introduced to make coherent detection robust against frequency offsets and phase noise. The remaining sub-carriers are zero-padded for the purpose of performing the FFT. For increased robustness against deep fades, channel coding is used supported by Gray code mapping of the data bits onto the constellation symbols and interleaving. The industry standard rate 1/2, constraint length 7 convolutional code [133, 171] is used as the fundamental channel coding. Optional coding rates of 2/3 and 3/4 are obtained through puncturing. Eight data rates, shown in Table 1, are defined combining the available symbol constellations and coding rates. Data rates using the 1/2 rate coding are mandatory while the rest are optional.

Data rate (Mbit/s)	Code Rate	Modulation	Data rate (Mbit/s)	Code Rate	Modulation
6	1/2	BPSK	24	1/2	16-QAM
9	3/4	BPSK	36	3/4	16-QAM
12	1/2	QPSK	48	2/3	64-QAM
18	3/4	QPSK	54	3/4	64-QAM

Table 1 : 802.11g coding rates and modulations for eight data rates.

3 The BT Impairment

BT provides relatively low data rates for supporting short-range (<10m), wireless personal area network (WPANs) applications in the 2.4 GHz ISM band using frequency-hopping spread spectrum techniques. BT's radio hops at a nominal rate of 1600 hops/s in a pseudo-random manner through a set of 79 1-MHz-wide channels available in this 83.5 MHz band [6]. The basic architectural unit in a BT system is the piconet, consisting of a master device and a maximum of seven active slave devices, which only communicate with the master. The master device determines the hopping sequence, the timing and the scheduling of all packets in the piconet. Time is divided into slots of 625 µs. The master starts its transmissions in even-numbered time slots only, and the slave starts its transmissions in odd-numbered slots only. For single-slot-packet transmission, the hop frequency changes every slot. Multi-slot-packets are restricted to 3 or 5 consecutive slots in which the hop frequency follows that of the first slot throughout the transmission. Both real-time, synchronous connection-oriented links for voice applications and asynchronous connection-less links for non-time critical data exchange are supported.

For a BT transmission to disrupt the 802.11g packets, there must be an overlap in frequency as well as time, as illustrated in Figure 1. The likelihood of interference depends on the bandwidth occupancy, the 802.11g packet length and the load factor of the interfering BT piconet. For a WLAN with a 20MHz channel, the BT signal appears as narrow-band interference. The probability that both the BT and 802.11g signals overlap in frequency is roughly 20/79 ≈ 25%. In the time domain, long 802.11g packets, such as 1000-byte packets, stand a higher chance of overlapping a number of BT time slots than 100-byte packets.

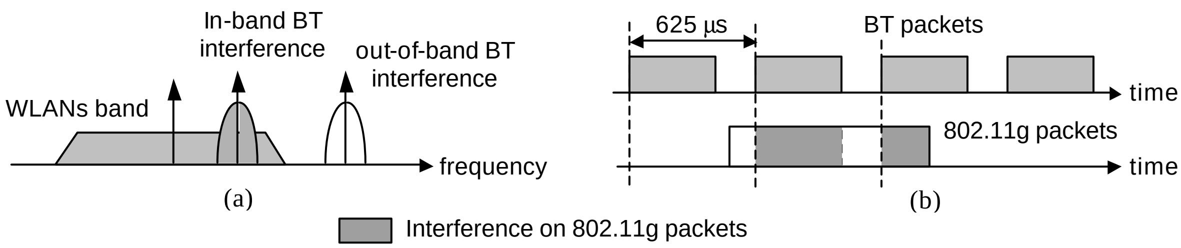

Figure 1 : Interference of BT signal on 802.11g signal (a) in frequency (b) in time.

3.1 BT Interference Model

The interference on each OFDM symbol with a duration of 4 µs is caused by four random BT data bits ∈ {+1, -1} at a rate of 1 Mb/s. The asynchronous transmission between the WLAN and the BT piconet is represented by a time offset, t_d, which is modelled as a uniformly distributed random variable between 0 and 625 µs. The start of transmission of the BT packets is taken as the reference time, $t = 0$ and the start of transmission of the WLAN packets is considered delayed by t_d from $t = 0$. Since BT only transmits for the first 366 µs of each time slot, only 366 random data bits are generated for each packet. The four BT data bits interfering the i-th OFDM symbol would be either '1' or '-1' if $(4i + t_d)$ modulo 625 is less than 366. The modulation is Gaussian Frequency Shift

Keying (GFSK) with a time-bandwidth product of 0.5 and modulation index, $m = 0.32$. The random data bits are convolved with a Gaussian pulse to form the modulating waveform $g(t)$ which causes a positive and negative frequency deviations from the centre frequency for a binary '1' and '-1', respectively. An expression for the passband GFSK signal is given in equation (2) [7] where P_{bt} is the average BT power, the random centre frequency, $f_{bt} = (2402 + k)$ MHz for $k = \{0, 1, 2, \ldots, 78\}$ and n is a continuous time dummy variable. The centre frequency, f_{bt} determines if the spectrum of the GFSK signal overlaps with that of the OFDM station. If interference occurs, the BT interference samples in the frequency domain are obtained from the frequency transform of $s(t)$ at the sub-carrier frequencies of the OFDM signal.

$$s(t) = \sqrt{2P_{bt}T_b^{-1}}\ \mathrm{Re}\left\{\exp\left[j\left(2pf_{bt}t + 2pm\int_{-\infty}^{t} g(n)dn\right)\right]\right\} \tag{2}$$

4 Symbol Erasures

The OFDM signal sees the BT signal as narrow band interference mainly affecting a small number of sub-carriers. The SIR level for each independent sub-carrier is determined instantaneously by the power of both the OFDM symbol and the BT signal transmitted over the bandwidth corresponding to that sub-carrier. Those data symbols corresponding to sub-carriers with low SIR will be replaced by erasures. This avoids a large bias to the path metrics in the Viterbi algorithm introduced by the corrupted data symbols. Besides that, the use of bit interleaving across the OFDM symbol helps to reduce the burst of errors generated by several adjacent corrupted data symbols. Since the power of the BT signal mostly concentrates around its centre frequency, the erasures would be inserted over those OFDM sub-carriers closest to the BT centre frequency. To simplify the simu lations, it is assumed that the receiver has knowledge of the BT interferer centre frequency. This could be learnt from an on-system BT receiver in the collaborative case or through channel measurements otherwise.

5 Results

The 802.11g WLANs PER vs E_b/N_0 performance has been evaluated in a multipath channel with one interfering BT piconet. The desired operating point is 1% PER. The BT interference is parameterised in terms of the SIR, which implicitly takes into account the distances between the access point and the BT transmitters from the wireless station. The BT interference assumes the transmission of single-time slot HV1 packets [6], which is a worst-case scenario since an HV1 link requires transmission in 100% of the time slots and a hop rate of 1600 hops/s. The impulse response of the exponentially decaying Rayleigh fading channel, h_i, expressed in equation (3) [8], is composed of complex samples with random uniformly distributed phases and Rayleigh distributed magnitudes with average power decaying exponentially where $N(0, s_k^2/2)$ is a zero mean Gaussian random variable with variance $s_k^2/2$, and s_0^2 is chosen such that $\sum s_k^2 = 1$ to ensure the same average received power.

$$h_i = N(0, s_k^2/2) + jN(0, s_k^2/2)\ ; \qquad s_k^2 = s_0^2 e^{-kT/t_{RMS}} \text{ and } s_0^2 = 1 - e^{-T/t_{RMS}} \tag{3}$$

The channel has been over sampled by 4 times the OFDM sample rate to ensure that the r.m.s. delay spread, t_{RMS}, of the generated c.i.r. closely approaches the desired value. To match an office environment, t_{RMS} is set to 100 ns. For this delay spread, the cyclic extension will protect the OFDM receiver from ISI introduced by the multipath channel. This multipath channel is equivalent to an independent flat Rayleigh fading channel for each OFDM sub-carrier. A single -tap equaliser is used to provide for phase correction.

The proximity of the BT device to the WLAN receiver has a tremendous effect on the degree of interference. Even though the WLAN has a higher transmit power (20mW) than the BT (0mW), the WLAN signal power drops considerably due to path loss during transmission to the receiver at a sufficient distance from the access point, and is likely to be drowned out by the BT signal. For a WLAN receiver at 10m from the access point with interference from a 1m-apart-BT device, the SIR is 0 dB. Figure 2 shows the simulation results for an 802.11g WLANs transmitting 100-byte packets at 24, 36, 48 and 54 Mbit/s with the number of erasures as a parameter. Without erasures, the BT interference completely corrupts the WLAN signal at an SIR = 0 dB, giving error floors at above 10% PER. To achieve the target PER, the SIR has to be raised to 15 dB for 24 Mbit/s and above 20 dB for higher data rates. This translates to limiting the WLANs coverage in order to maintain high SIR levels. The insertion of erasures significantly improves performance. For 24 Mbit/s, the SIR required is reduced from 15 dB to -7 dB when 9 erasures are used; for 36, 48 and 54 Mbit/s, the SIR needed is lowered by as much as 20 dB when up to 5 erasures are used. For the same number of erasures, the SIR required for 1% PER rises as the data rate increases.

However, too many erasures can cause negative effects when punctured convolutional codes and higher modulation orders (i.e. more compact signal constellation) are used. This effect is evident at 36, 48 and 54 Mbit/s modes where the convolutional code has been punctured to rates 3/4, 2/3 and 3/4, respectively; and the modulations are 16-QAM, 64-QAM and 64-QAM, respectively. For these three data rates, a maximum of 5 erasures gives sufficient amelioration as 7 erasures give similar performance, while 9 erasures result in a worse performance although with higher SIR levels. Since punctures are equivalent to erasure insertion, such a large number of erasures tend to leave paths unresolved within the Viterbi algorithm.

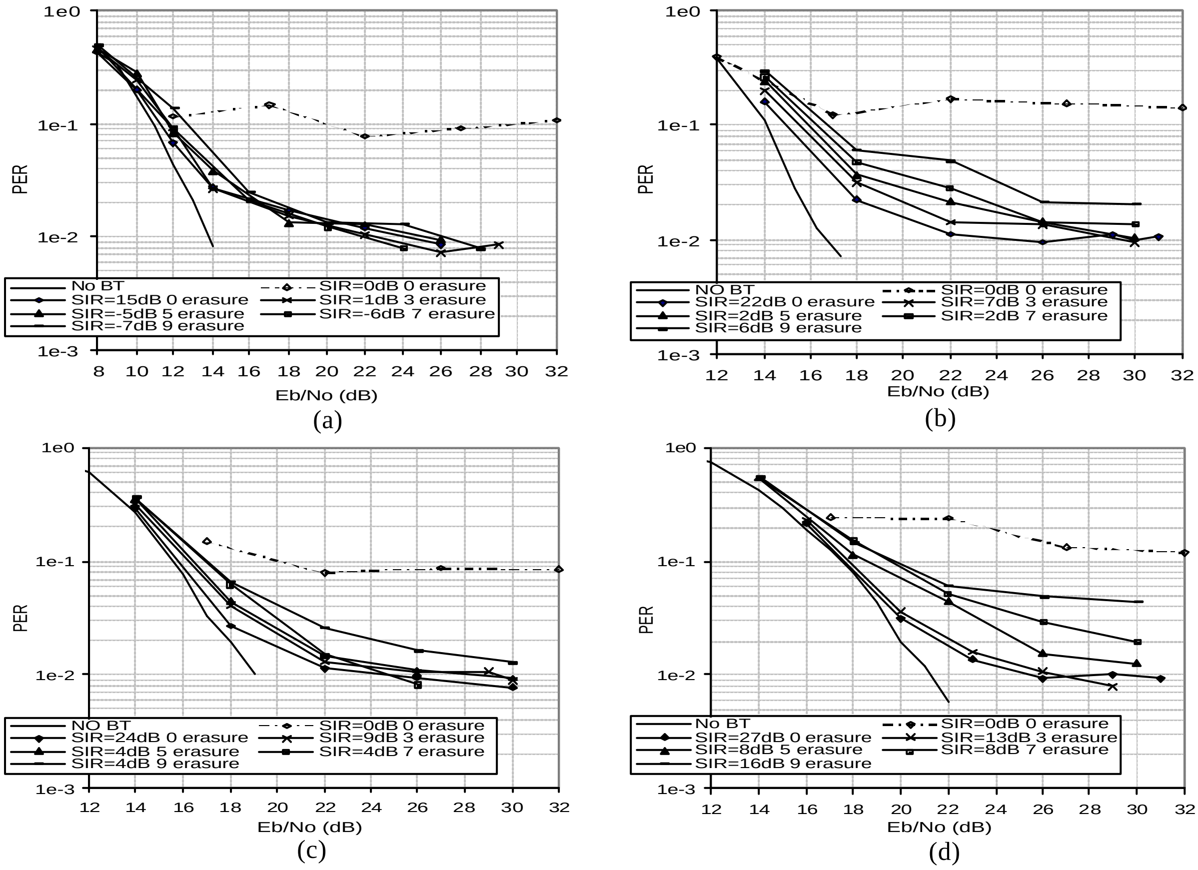

Figure 2 : Plots of PER vs E_b/N_o showing SIR required by 802.11g transmitting 100-byte packets in multipath channel with and without erasures to achieve target 1% PER at (a) 24 Mbit/s (b) 36Mbit/s (c) 48 Mbit/s and (d) 54 Mbit/s.

6 Conclusions

The results illustrate the impact of BT interference on the performance of a 2.4GHz OFDM WLAN. The results also demonstrate that erasure insertion can recover performance to satisfactory levels with a small loss in E_b/N_o as long as the OFDM receiver can track the interferer. Faster data rate modes combining code puncturing and higher order modulation will require a higher SIR level for operation. This might restrict the minimum distance between the transmitter and a potential interferer. Alternatively, a combination of data rate reduction and erasures insertion can be used when the target performance cannot be achieved. By lowering the data rate, the SNR level and the distance between modulation symbols increase. This solution might provide higher aggregate throughputs than remaining at the higher data rate and relying on retransmission procedure. The topic of rate adaptation in the presence of BT interference is the subject of further study by the authors.

References

[1] IEEE 802.11, Jan.2002, "Further Higher-Speed Physical Layer Extension in the 2.4GHz Band", IEEE Std. 802.11g/D2.8

[2] Kamerman, A., July 2000, "Coexistence Between Bluetooth and IEEE 802.11 CCK Solutions to Avoid Mutual Interference", IEEE 802.11-00/162

[3] Golmie, N., April 2001, "Bluetooth and 802.11 Interference: Simulation Model and System Results", IEEE 802.15-01/195R0.

[4] IEEE 802.15, March 2002, "Coexistence of Wireless Personal Area Networks with Other Wireless Devices Operating in Unlicensed Frequency Bands", IEEE P802.15.2/D04.

[5] Van Nee, R. and Prasad, R., 2000, "OFDM for wireless multimedia communications", Artech House, London, UK.

[6] Bluetooth SIG, Feb. 2001, "Specification of the Bluetooth System, Ver. 1.1B", http://www.bluetooth.com.

[7] Rappaport, T., 1996, "Wireless Communications Principles & Practice", Prentice Hall PTR, USA.

[8] Chayat, N., Sept. 1997, "Tentative criteria for comparison of modulation methods", IEEE P802.11-97/96