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An Investigation of the Coexistence of 802.11g WLAN and High Data Rate Bluetooth Enabled Consumer Electronic Devices in Indoor Home and Office Environments

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Abstract — *The anticipated proliferation of various wireless local area network (WLAN) enabled devices in the near future is likely to result in increased mutual interference in the 2.45GHz Industrial, Scientific and Medical (ISM) band. This work investigates the impact of standard Bluetooth and enhanced Bluetooth interference on 802.11g enabled consumer electronic devices and vice versa. Technical designs for Bluetooth, enhanced Bluetooth and 802.11g systems implemented in software are first presented. Issues involved in modelling the interferer(s) within typical indoor home and office environments are discussed in detail. Packet Error Rate (PER) vs. Carrier to Noise Ratio (CNR) plots for different Carrier to Interference Ratios (CIR) are presented. Techniques used to improve the performance of 802.11g and HDR Bluetooth systems in the presence of interference are discussed in detail as a conclusion to this paper.*

Index Terms — WLAN, 802.11g, Bluetooth and interference.

I. INTRODUCTION

There is growing concern for mutual interference between users of different consumer electronic devices such as personal digital assistants (PDAs), mobile telephones, and cordless TV and VCR systems following the avalanche of WLAN and WPAN systems appearing in the market. The once under-utilised ISM band is now becoming cluttered with WPAN systems and 802.11 compliant WLANs. Products include 802.11b [1] and 802.11g [2], Bluetooth [3] devices, Home RF and a plethora of other unlicensed systems. In order for interference to occur between these devices when operating in close proximity to one another, an overlap in both frequency and time is required. When these collisions occur, the data packet being transmitted may become corrupted. For data systems, this leads to packet retransmission. Consequently, interference results in a significant performance degradation in terms of data throughput for time-bounded and non time-bounded applications.

The continual roll-out of many new technologies in the ISM band requires critical measures to be undertaken if they are envisaged to coexist in harmony. Technical and market experts in recent years have expressed great concerns regarding interference (both mutual and cross interference) between WPAN and WLAN devices in the ISM band. The Coexistence Task Group (TG2) under the IEEE 802.15 committee has addressed the problem of cross interference from equipment employing different standards in the 2.4GHz band [4].

Initial attempts at modelling interference were purely based on mathematical models. These prior efforts did not consider the details of the WLAN physical (PHY); such as the different data transmission rates, modulation and channel coding schemes and the length of data packets sent. Issues such as the relative power levels of the interferers and the space/time varying characteristics of the wireless channel also need to be considered in addition to the aforementioned PHY details in order to achieve a realistic model of cross interference between different devices. In this paper, although the channel itself is modelled mathematically, the relative power levels of the interferers, packet lengths as well as the influence of forward error correction (FEC) schemes used in the packets are considered.

This paper presents novel research results that address the impact of enhanced Bluetooth enabled consumer electronic devices on 802.11g enabled devices and vice versa. Section II outlines key parameters and software design issues for Bluetooth 1.1 and the enhanced Bluetooth systems. In Section III the software simulation of an 802.11g signal is described. The level of interference is governed by factors such as the transmit power levels, the proximity of the devices relative to one another and also the duration of transmission (the packet size). The modelling of Bluetooth and 802.11g interferers (together with important assumptions made in the interference model) is discussed in Section IV. Section V presents and discusses results obtained from the above analysis. Section VI proposes ideas for interference mitigation and Section VII concludes the paper.

II. BLUETOOTH AND HDR BLUETOOTH

Bluetooth is an effort by a consortium of companies to design a royalty-free Wireless PAN technology. The aim is to develop a range of low cost and short-range radio transmission standards which, when fitted inside electronic devices, removes the need for physical cabling. The technology currently operates in the unlicensed 2.45GHz ISM band and utilises frequency hopping with terminals cycling through 79 1MHz hop channels (or 23 1MHz hop channels in Japan, France and Spain) at 1600 hops/s [5]. The current Bluetooth standard (Bluetooth 1.1) utilises Gaussian frequency shift keying (GFSK) modulation with a modulation index of 0.28 and a bandwidth-bit period (BT) of 0.5.

Since the roll-out of Bluetooth 1.1, two enhanced versions of Bluetooth have appeared and are being evaluated leading to

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possible standardisation. The first of these is Bluetooth 1.2, known as Medium Rate Bluetooth (MDR) which achieves up to 3Mb/s and the second is Bluetooth 2.0, known as High Data Rate (HDR) and aims to achieve up to 10Mb/s. The authors of this paper proposed an enhanced Bluetooth system (calling it High Data Rate Bluetooth) prior to the introduction of Bluetooth 1.2 and 2.0. Hence, 'enhanced Bluetooth' or 'high data rate Bluetooth' as referred to in this paper is analogous to Bluetooth 1.2 (MDR Bluetooth).

Phase shift keying methods have been proposed as likely modulation techniques to achieve data rates beyond 1Mb/s [6]. In Bluetooth 1.1, the receiver utilises non-linear differential phase detection is applied. When compared to phase-shift keying methods, the receiver design is low cost and workable in noisy environments. The use of GFSK enables the radios to tolerate a high degree of amplitude and phase distortion. A software simulation of the Bluetooth physical layer was implemented as part of this study. When the impulse response of a Gaussian filter is convolved with a single impulse, the response shown in Fig. 1(a) is obtained.

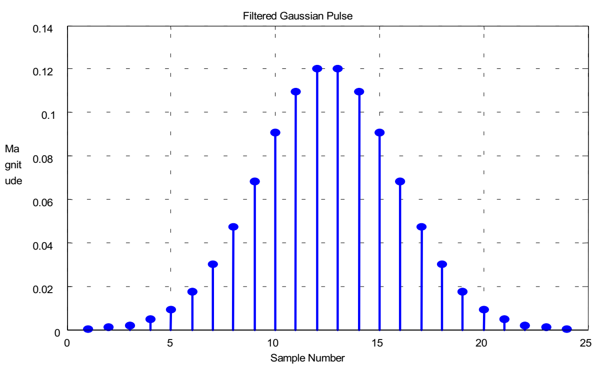

Fig. 1(a). Filtered Gaussian Pulse used for GFSK modulation in the current Bluetooth system. For simulation purposes, a 24-tap Gaussian filter was implemented

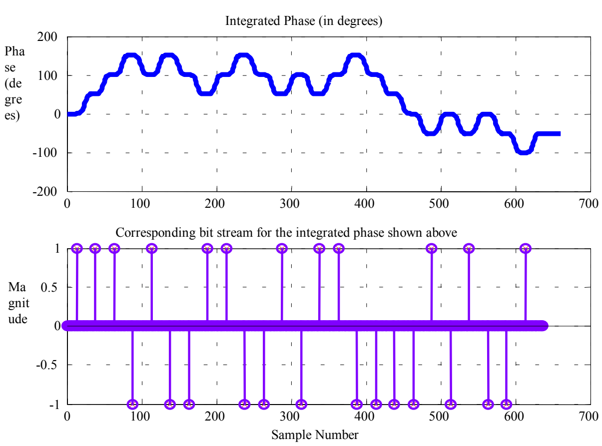

Fig. 1(b). Integrated phase response for a stream of GFSK symbols. The filtered waveform is integrated using a modulation index of 0.28. This produces a phase step of 50.4° for GFSK symbol 1 or -50.4° for GFSK symbol -1 per symbol period

Fig. 1(b) shows the integrated phase response for a stream of GFSK symbols. In practise, GFSK signals can be digitally produced by modulating the integrated phase as I and Q signals onto the 2.45 GHz carrier [7]. The transmitted signal S_T can be represented by the following relationship:

$$S_T(t) = A_m e^{j\theta_m(t)} \quad (1)$$

where A_m represents the amplitude of the transmitted signal and $\theta_m(t)$ the integrated phase given by:

$$\theta_m(t) = \pi h \sum_{-\infty}^{t} I_n g(\tau - nT) d\tau + \theta_0 \quad (2)$$

where I_n is mapped to ± 1 according to the binary data and θ_0 is the initial phase of the carrier.

One of the drawbacks with the current standard is its restricted bit-rate of less than 1Mb/s. Although this may seem adequate for low bit rate applications such as data modems, cordless telephones and low bit rate videophones, it is insufficient to support high bit rate VCR/TV quality digital video (2-12Mb/s). Previous research [6] has shown that high data rates can be achieved by employing coherent M-PSK modulation schemes in future Bluetooth enabled devices instead of the current GFSK scheme.

In software simulations involving M-PSK modulation, the mapped data stream is passed though a root-raised cosine filter (RRC) with a roll-off factor, α of 0.35. The amplitude and phase of the resulting signal can be represented as:

$$A_m(t) = \sqrt{I_{ch}(t)^2 + Q_{ch}(t)^2} \quad (3)$$

$$\theta_m(t) = arctan\left(Q_{ch}(t) / I_{ch}(t)\right) \quad (4)$$

where I_{ch} and Q_{ch} are the RRC filtered baseband I and Q samples. A Rayleigh fading channel is used to represent the worst possible narrowband fading scenario. Assuming the channel amplitude and phase is represented by A_c and θ_c respectively, the signal arriving at the receiver can be represented by the following equation:

$$S_R(t) = A_c A_m e^{\{j[\theta_m(t)+\theta_c]\}} + A_n e^{\{j\theta_n\}} \quad (5)$$

where A_n and θ_n are the amplitude and phase of the additive white Gaussian noise term.

TABLE I
ACL PACKETS DEFINED FOR BLUETOOTH AND ENHANCED BLUETOOTH AND THE TRANSMISSION TIME FOR SINGLE AND MULTI TIME SLOT PACKETS

ACL packet defined in Bluetooth	Symmetric Maximum Rate for GFSK (kb/s)	Symmetric Maximum Rate for QPSK (kb/s)	Symmetric Maximum Rate for 8PSK (kb/s)	Transmission time (µs) / packet
DM1	108.8	217.6	326.4	366
DM3	258.1	516.2	774.3	1616
DM5	286.7	573.4	860.1	2866
DH1	172.8	345.6	518.4	366
DH3	390.4	780.8	1171.2	1616
DH5	433.9	867.8	1301.7	2866

The Bluetooth radio system makes use of frequency hopping, where each Bluetooth packet is sent over a different quasi-static uncorrelated Rayleigh fading channel. For multi-slot transmissions, the entire 3 or 5 slot transmission is sent on the same hop frequency. In the current Bluetooth system, a slotted channel is used for transmission. User data is transmitted through packets – nominally covering a single time slot, but can be extended to up to five time slots. Each single time slot packet is transmitted on a different hop frequency whereas a single hop frequency is used for the entire span of a multi time slot packet. The hop frequency in the first time slot after a multi time slot packet shall use the frequency as determined by the current Bluetooth clock value. Although a single time slot is 625µs for single time slot transmission, the transmission time is only 366µs and rest of the time (259µs) is used for transient time-settling. Table I lists the data rates for data only (asynchronous connection-less, ACL) packets in Bluetooth using GFSK. In enhanced Bluetooth, the data rates increase by 2 and 3 times respectively for QPSK and 8PSK systems. The reader is referred to [8] for previous work carried out by the authors on statistical analysis of frequency hopping and information on the generation of Bluetooth hop patterns.

III. IEEE 802.11G WLAN SYSTEM

The 802.11g physical layer is based on the use of link adaptive coded orthogonal frequency division multiplexing (COFDM) [2], [10]-[12]. The OFDM modulation is implemented by means of an inverse fast Fourier transform (FFT). 48 data symbols and 4 pilots are transmitted in parallel in the form of one OFDM symbol. Various combinations of coding rate (for a forward error correction (FEC) convolutional code) and modulation scheme are specified in a similar manner to 802.11a to facilitate different 'modes' of transmission. FEC is typically facilitated in the receiver by means of a Viterbi decoding algorithm. Besides the COFDM modulation common to 802.11a and 802.11g, backwards compatibility with complementary code keying (CCK) direct sequence spread spectrum (DSSS) modulation as used in 802.11b is also mandated.

The backward compatibility of 802.11g with 802.11b is seen as crucial. 802.11b currently dominates the WLAN market under the 'Wi-Fi' brand name. The backwards compatibility of 802.11g makes it the obvious choice for evolution of this market by facilitating a smooth transition between standards. The benefits of backward compatibility in 802.11g are offset by additional overhead requirements. Previous work [11] performed by the authors shows that after taking into account the MAC overheads, the single user data throughput for 802.11g is less than 20Mb/s (assuming a packet size of 1500 bytes) when 802.11b backward compatibility is supported. Interestingly, the development of baseband OFDM chipsets for 802.11g may in turn accelerate the development of 802.11a devices, which will essentially differ from 802.11g only in terms of their RF components.

The analysis presented in this paper concentrates on the performance of the eight modes of 802.11g, which are equivalent to those of 802.11a. These eight modes are summarized in Table II. 802.11g supports variable size protocol service data units (PSDUs or packets). Table III summarizes the duration of transmission for packets of various payload size.

TABLE II
IEEE 802.11a/g TRANSMISSION MODES

	Modulation	Coding Rate	Nominal Data Rate, ($R_{Nominal}$)
1	BPSK	1/2	6 Mbits/s
2	BPSK	3/4	9 Mbits/s
3	QPSK	1/2	12 Mbits/s
4	QPSK	3/4	18 Mbits/s
5	16QAM	1/2	24 Mbits/s
6	16QAM	3/4	36 Mbits/s
7	64QAM	2/3	48 Mbits/s
8	64QAM	3/4	54 Mbits/s

TABLE III
PSDU DURATION AS A FUNCTION OF MODE AND PAYLOAD

Mode	Payload			
	256 bytes	*500 bytes*	*1000 bytes*	*2000 bytes*
1	348 µs	672 µs	1340µs	2672 µs
2	232 µs	448 µs	892 µs	1784 µs
3	176 µs	336 µs	672 µs	1336 µs
4	116 µs	224 µs	448 µs	892 µs
5	88 µs	168 µs	336 µs	668 µs
6	60 µs	112 µs	224 µs	448 µs
7	44 µs	84 µs	168 µs	336 µs
8	40 µs	76 µs	152 µs	300 µs

IV. THE INTERFERENCE MODEL

The results obtained from investigations that model cross interference between systems largely depend on the way the interferers are modelled. In order for a collision to occur in Bluetooth, or indeed 802.11g, their signals must coincide in both frequency and time. Since there are variable lengths of Bluetooth packets and 802.11g PSDUs, a simple mathematical relationship expressing the probabilities of packets coinciding in time between these two systems cannot be conveniently expressed. For the purposes of this paper, the main parameters that have been taken into consideration are the packet durations of the two systems, the Bluetooth frequency hop pattern and the relative strength of the interferer(s) on the system under investigation.

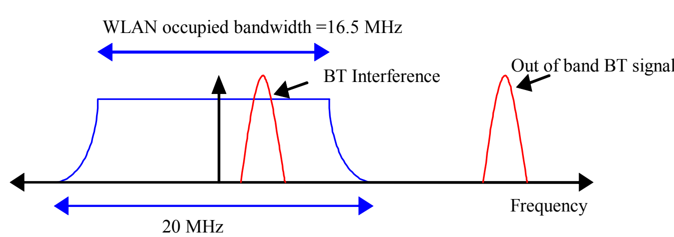

Fig. 2. Bluetooth interference on 802.11g WLANs and vice versa

Fig. 2 shows a frequency domain representation of part of the ISM band comprising 802.11g and Bluetooth signals. At any given time, the Bluetooth signal occupies 1 of the 79 different hop channels, each spaced 1MHz apart. The

Bluetooth signal acts as a narrowband jammer with a probability of spectral overlap given by 6.5/79≈20% (since the occupied bandwidth of 802.11g is 16.5 MHz, 52 (out of 64) usable subcarriers). It is worth noting that the number of times collisions occur will depend on the length of the duration of Bluetooth and 802.11g packets. If single time slot packets (occupying 625µs) are used in Bluetooth, then the use of 'long' 802.11g PSDUs (e.g. 2000 bytes in mode 1) will almost certainly result in a collision (either fully or partially) from a narrowband Bluetooth jammer. On the other hand, if a 'short' 802.11g PSDU (256 bytes) is sent then the probability of collision is much smaller. This occurs since a proportion of the 802.11g packets will be transmitted during the transient settling time between Bluetooth packets (299µs).

The probability of 802.11g PSDUs being completely transmitted within the time between Bluetooth packets depends on the proportion of time for which the Bluetooth transmitter is idle. Larger Bluetooth packets have less transient settling so the corresponding probability of collision for a given PSDU length will depend on the duration of the 802.11g PSDU. For multi time slot Bluetooth packets, the probability of collision with a 'long' 802.11g PSDU reduces. This occurs since the hopping rate of Bluetooth is effectively reduced given that the entire multi time slot Bluetooth packet is transmitted on the same frequency. Fig. 3 illustrates the different scenarios outlined above.

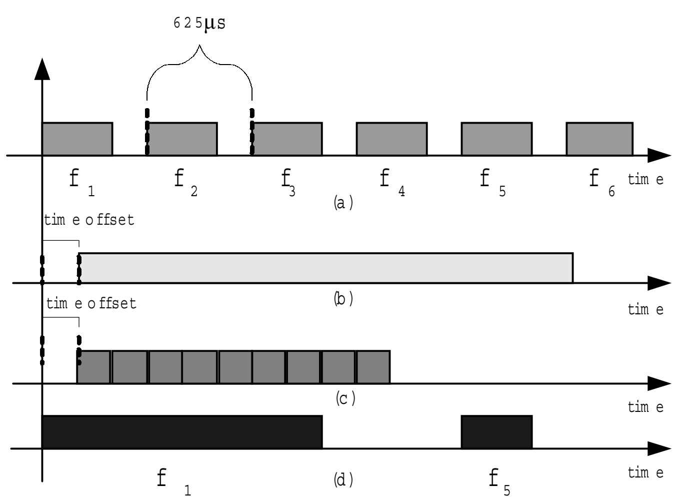

Fig. 3. Effect of packet size on the probability of collision: (a) Bluetooth 1 slot packets-different frequency *f* every 625 µs, (b) 'long' (2000 byte, mode 1) 802.11g packet, (c) 'short' (256 byte, mode 5) 802.11g packets and (d) Bluetooth multi-time slot packets (shown here 3 slot and single slot packets).

V. RESULTS AND DISCUSSION

A. *Standard Bluetooth interference on 802.11g system*

For the purposes of this paper, software simulation results for standard Bluetooth interference (using GFSK modulation) on various modes of 802.11g are presented. Since the transmit power level and the bandwidth used is the same, the results are equally valid for enhanced Bluetooth interference (employing QPSK and 8PSK) on 802.11g because we have assumed that in the high data rate Bluetooth that was implemented, the packet durations are identical. The only difference between the current Bluetooth system and the enhanced Bluetooth system simulated for this study lies in the modulation index (number of bits/symbol) and the type of detection process employed in the baseband structure of Bluetooth.

The issue of collision was fully modelled in the simulation, based on the 802.11g and Bluetooth packet durations and the overlap in frequencies as discussed above. A random time offset was introduced to emulate a typical real time scenario. A single Bluetooth interferer was assumed in this investigation. The effect of interference on the preamble used for channel estimation (as specified by the 802.11g standard) was considered in the simulation. The effect of interference on the pilot information transmitted throughout the PSDU was not considered. It was also assumed that the Bluetooth system was in connection mode and transmitting at a load factor of 100%. The ETSI 'channel model A' [9] for indoor home and office environments was used in this study.

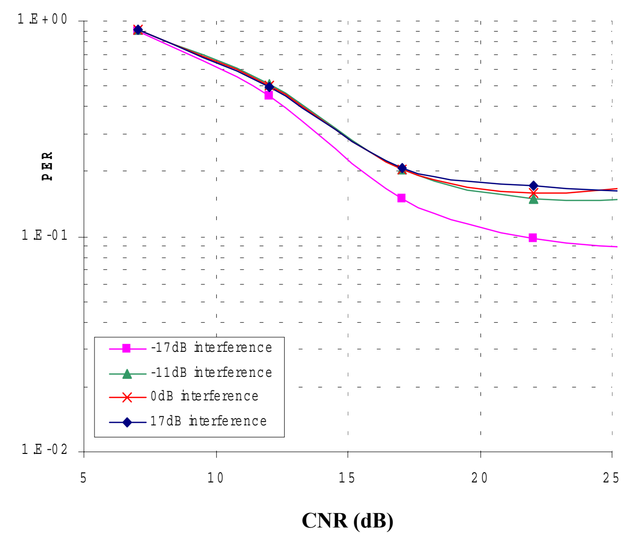

Fig. 4. PER performance of 802.11g with different values of Bluetooth interference for mode 5 with a PSDU size of 500 bytes

Fig. 4 shows the packet error rate (PER) performance of 802.11g with different values of Bluetooth interference for mode 5, using a PSDU size of 500 bytes. Note that when, for example, a carrier to interference ratio (CIR) of -11dB is quoted, although the Bluetooth signal power is 11dB less than the total 802.11g power, its power is 6dB higher than the power of the individual OFDM subcarriers [13]. This occurs because the power of the 802.11g signal is spread over 52 312.5 kHz subcarriers, whereas in Bluetooth the signal occupies a single narrow bandwidth. When the 1MHz Bluetooth interference is applied, only a few of the subcarriers are affected. For the results in Fig. 4, it was assumed that Bluetooth uses single slot packets (DM/DH1).

Fig. 5 shows that increased PSDU size results in a higher error floor. Note that performance also depends on the transmission mode. This error floor is due to two phenomena. Firstly, data on the subcarriers subjected to interference are corrupted. Secondly the channel state information for these subcarriers is also degraded due to interference on the preamble. The second phenomenon is the most important since it results in a biased metric for the soft decision Viterbi decoder. The corrupted subcarriers have very high reliability, since they have a lot of power. As a result of this biased reliability metric, the decoder cannot compensate for the few corrupted subcarriers and the errors propagate. For this reason, it can be seen from Fig.4 that this error floor occurs for a wide range of interference values. However, the Bluetooth interference affects only a small number of subcarriers. If the receiver has knowledge of the centre frequency of the Bluetooth interferer (through channel estimation or from a Bluetooth receiver) then it can inform the Viterbi decoder not to base its decisions on the corrupted subcarriers as it will be shown in Section VI.

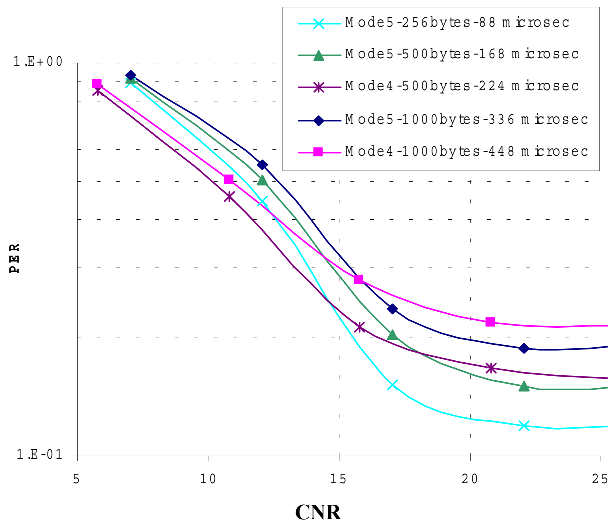

Fig. 5 The effect of PSDU size on PER performance given CIR = -11dB

If the duration of the 802.11g packet is similar to the Bluetooth packet duration then the error floor approximates the probability of the Bluetooth signal coinciding in frequency with the 802.11g signal, which is around 20%. If the duration of the 802.11g packet is much larger than the Bluetooth packet duration, the probability increases and depends upon the number of times the Bluetooth signal hops within the duration of the 802.11g signal. However, it will also depend upon the level of interference and the mode employed as well. If the duration of the 802.11g packet is much smaller than the Bluetooth packet duration, the error floor is reduced due to the period that the channel is not utilised by Bluetooth (289µs out of 625 µs in single time slot packets) This is shown in Fig. 5 for mode 5 (using 256 bytes), which has a packet duration of 88µs.

B. 802.11g interference on standard Bluetooth and enhanced Bluetooth

The analysis carried out for studying the effects of 802.11g interference on standard Bluetooth and enhanced Bluetooth is similar to that modelled in Section A. The simulations were performed for 16000 single Bluetooth time slots. Since each time slot is 625µs, this results in a total duration of 10 seconds. Single Bluetooth packets (DM1 and DH1) were transmitted (1600 hops/s so 800 packets in each direction per second). A single 802.11g signal (interferer) was assumed either throughout (or for some part) of the time frame of each transmitted Bluetooth packet (mode 5, 1000 byte, 802.11g packets assumed). The 802.11g signal was also assumed to occupy a bandwidth of 16.5MHz out of the total 79MHz available to Bluetooth.

The frequency hopping pattern (generated using a software implementation of the Bluetooth frequency hopping kernel) for the wanted Bluetooth signal was compared with the frequency occupied by the 802.11g signal to identify if spectral overlaps occurred. An overlap in frequency means that interference between the transmitted Bluetooth packet and the 802.11g signal is present. For simplicity, it was assumed that the wanted Bluetooth terminal remains in the connection state.

PER versus carrier to interference ratio (CIR) for standard Bluetooth and enhanced Bluetooth under different carrier to noise ratios (CNR) was analysed. The results are presented (shown in Fig. 6) for a carrier to noise ratio of 20dB, 30dB and 50dB. The authors have modelled the channel to approximate a worst case static fading channel with a Rayleigh fast fading distribution. The wanted Bluetooth piconet was set up in non-line of sight conditions but within close proximity to the 802.11g device.

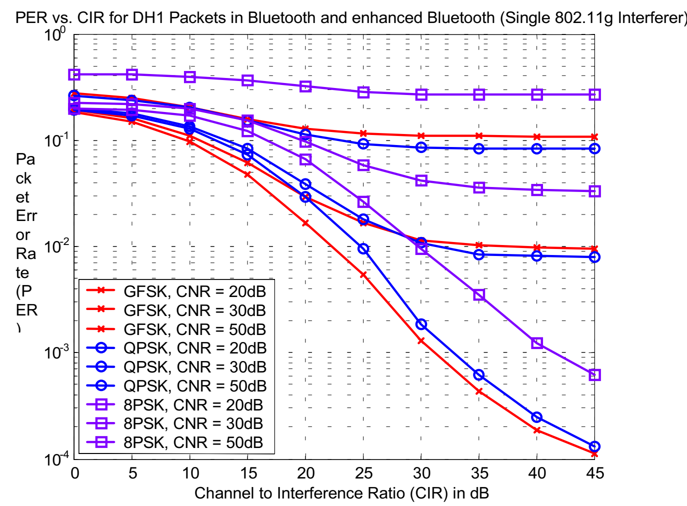

Fig. 6. PER performance of Bluetooth and enhanced Bluetooth using DH1 packets in the presence of a single 802.11g interferer (CNR values of 20dB, 30dB and 50dB)

From Fig. 6 it can be seen that the error floors present are high at low CNR values (20dB and 30dB). This is because the system is noise limited at low CNR values, even when the CIR values are high. At a CNR of 50dB, the performance at 1% PER for standard Bluetooth with and without an 802.11g interferer is 22.5dB and 30dB respectively. This clearly indicates that the impact of 802.11g interference on standard Bluetooth and enhanced Bluetooth affects the packet reliability quite severely. Another observation is that as the modulation level increases from GFSK to 8PSK, the general trend is for the PER value to increase. This is expected since as the modulation level increases, the number of bits per symbol increases and the Euclidean distance between symbols on the constellation diagram decreases. This effectively means that the symbols are more prone to interference. Within Bluetooth, even a single bit error will result in the entire packet being corrupted.

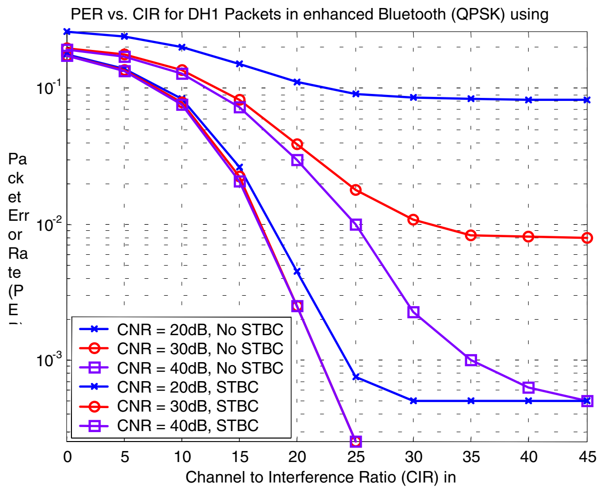

Fig. 7. PER performance of enhanced Bluetooth using DH1 and DM1 packets in the presence of a single 802.11g interferer (CNR values of 30dB and 40dB)

It is worth noting that DH1 packets do not incorporate forward error correction (FEC) and as such the performance in interference may be improve with the use of FEC. Fig. 7 shows the PER performance for enhanced Bluetooth at CNR values of 30dB and 40dB for DH1 (no FEC) and DM1 packets (with 2/3rd rate shortened (15,10) Hamming binary block code). Decoding is performed using a single error correction algorithm based on a parity check matrix [14]. Immediate observations reveal that the PER floor is lower for DM1 packets (relative to DH1). The presence of FEC in the DM1 packets provides greater protection against erroneous errors caused by interference. Although the error floor is still quite high, the performance improvement obtained at lower CIR values is encouraging, particularly at high CNR values (40dB). Observing Fig. 7, at a CNR of 40dB and a PER of 10%, the benefits of FEC in the DM1 packets results in a 5dB improvement in PER performance (assuming QPSK modulation). On the other hand, for 8PSK, the performance improvement is 12dB at a PER of 10%.

TABLE IV
COMPARISON OF PER ERROR FLOOR FOR DM1 AND DH1 PACKETS IN BLUETOOTH AND ENHANCED BLUETOOTH

CNR Value	Reduction in PER error floor (%) obtained from employing FEC coding in DM1 packets		
	GFSK	QPSK	8PSK
20dB	74	91	18
30dB	80	94	50
40dB	76	60	56

Table IV lists the reduction in the observed PER floor when FEC coding is employed in the DM1 packets. Two important observations can be made. Firstly, the above results show that in an interference dominated environment, the reduction in PER floor is dramatically improved. The benefits of employing a simple block code in Bluetooth and enhanced Bluetooth packets yields significant performance gains in terms of data throughput. The reduction becomes smaller as the CNR value increases. This occurs because although the channel conditions improve with increased CNR, the system performance is limited by the level of 802.11g interference present in the environment. Secondly, as the modulation level in enhanced Bluetooth increases from QPSK to 8PSK, the reduction in the error floor reduces. This is due to the symbols being more likely to corrupt as the Euclidian distance reduces.

Another important point to consider is the length of the transmitted Bluetooth packet. The PER performance of multi-time slot packets in Bluetooth and enhanced Bluetooth in the presence of a single 802.11g interferer was found to be identical to that of single time slot packets. This result arises since we assume a worse case scenario where the 802.11g signal is always present in the 16.5MHz bandwidth (i.e. a loading factor of 100%). In reality however, the performance of Bluetooth is highly dependent on the loading factor of 802.11g.

VI. PROPOSALS FOR INTERFERENCE MITIGATION

A. Recommendations for 802.11g systems

It is recommended that erasures are applied to corrupted subcarriers. This means that erased data are given a zero weight in the Viterbi convolutional decoding trellis. In [15], a number of erasures (up to 9) were introduced to improve performance under interference. The erasure process reduces the reliability metric for the given bit (i.e. one believed to be subject to interference) to zero. Erasure applies a binary weighting to the reliability metric (i.e. a 0 if interference is present and a 1 otherwise).

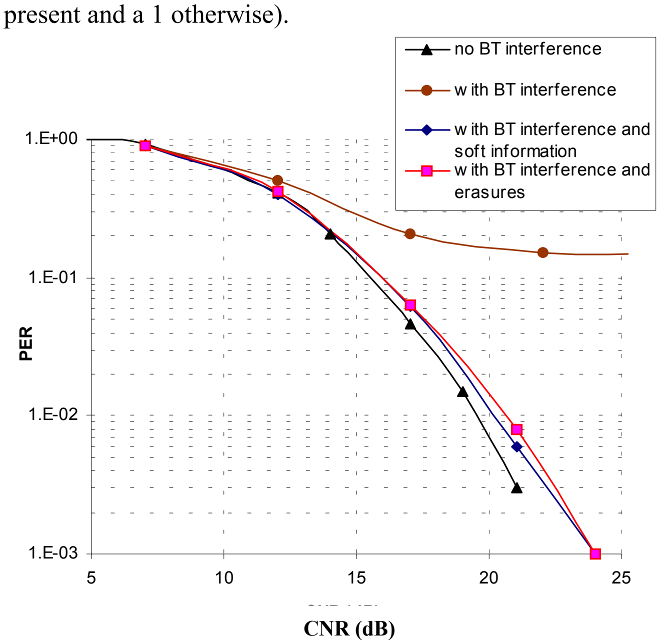

Fig. 8. PER performance of 802.11g packets in the presence of Bluetooth interference for mode 5 with a PSDU size of 500 bytes

In this paper, reliability metrics are soft weighted according to the amount of interference believed to be present. For example, if the sub-carriers at the centre of the Bluetooth interference suffer a 0dB CIR ratio then the interference on the two adjacent subcarriers is ~5 dB lower due to the shape of the Bluetooth signal spectrum. Similarly, the interference on the next most adjacent subcarriers is ~10 dB lower, etc. Hence, a soft metric can be used to weight the reliability metric for bits on a given sub-carrier according to the degree of interference they suffer. Typically, as identified in [15] only 9 sub-carriers at most will, at a given time, see significant interference from a single Bluetooth interferer.

Fig. 8 shows the PER performance of 802.11g for mode 5, PSDU size of 500 bytes, with -11dB CIR. In Fig. 8, two cases are simulated. For the first one, erasures are used for the three sub-carriers at the centre of the Bluetooth interference, but soft values (based on the CIR) were used for the other affected subcarriers. For the second case, 5 erasures were used. It can be seen that the performance is similar for both cases for this interference value. In both cases when the receiver, or more particularly the soft decision Viterbi decoder, has knowledge of the position of the corrupted subcarriers it can compensate for the few corrupted subcarriers. As can be seen from Fig. 8, performance is very close to a system without Bluetooth interference.

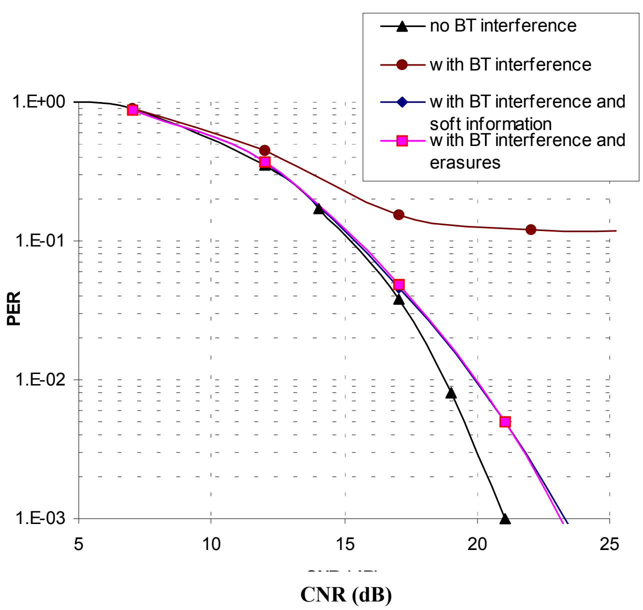

Fig. 9. PER performance of 802.11g packets in the presence of Bluetooth interference for mode 5 with a PSDU size of 256 bytes

Fig. 9 shows the PER performance of 802.11g with -11dB Bluetooth interference for mode 5, using a PSDU size of 256 bytes. It can be seen that the performance is better for smaller packet sizes. Fig. 10 shows the PER performance for mode 4, using a PSDU size of 500 bytes.

B. Recommendations for enhanced Bluetooth systems

From the above results, the strong impact of 802.11g interference on Bluetooth and enhanced Bluetooth systems has raised concerns over the coexistence of both technologies within close range of each other. The results show that with high error floors, the high PER values do not allow sufficient throughput for acceptable quality time-bounded applications, such as digital video and TV transmission. In [16], it was shown that by exploiting antenna diversity on Bluetooth and enhanced Bluetooth enabled devices using space time block codes (STBC) with maximum likelihood decoding, considerable performance improvement could be attained by mitigating interference between Bluetooth enabled devices.

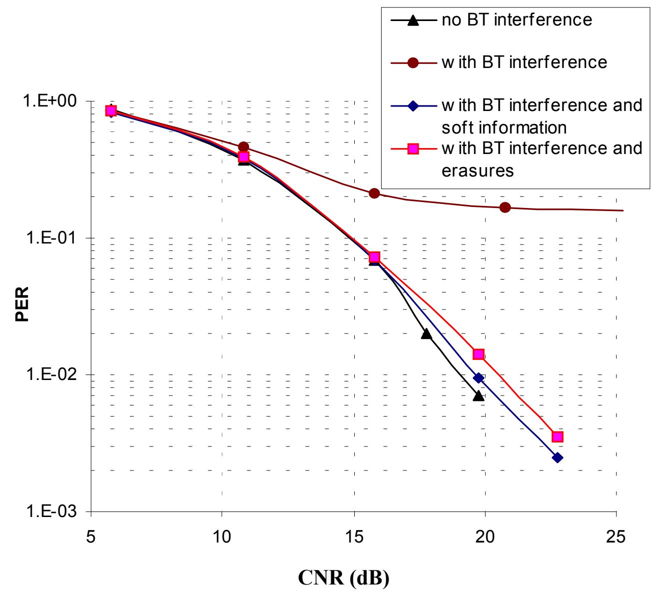

Fig.10. PER performance of 802.11g packets in the presence of Bluetooth interference for mode 4 with a PSDU size of 500 bytes

A simple space time block coding scheme was proposed by Alamouti in [17]. Fig. 11 shows a block diagram of the baseband representation of the space time block code incorporated into the Bluetooth software modem used in this investigation. The transmitter and receiver are each equipped with two antennas. A flat fading channel and perfect channel knowledge at the receiver is assumed. In the Alamouti scheme, it is assumed that fading is constant across two consecutive symbols. However, since the symbol period in Bluetooth is typically only a few microseconds, it has been assumed that the Doppler frequency of the channel is small enough such that the channels between the two transmit antennas and the two receive antennas remain static over the period of a single data packet transmission.

During the first symbol transmission period, two symbols c_1 and c_2 are transmitted simultaneously from the first and second antennas respectively. In the second transmission period, symbols $-c_2^*$ and c_1^* are transmit from the first and second antennas respectively. The received signal vector for receive antenna 1 and receive antenna 2 can thus be written as:

$$\underline{r}_1 = \underline{\underline{H}}_1 \underline{c} + \underline{\eta}_1 \quad \text{and} \quad \underline{r}_2 = \underline{\underline{H}}_2 \underline{c} + \underline{\eta}_2$$

$$\underline{\underline{H}}_1 = \begin{bmatrix} h_{11} & h_{21} \\ h_{21}^* & -h_{11}^* \end{bmatrix} \qquad \underline{\underline{H}}_2 = \begin{bmatrix} h_{12} & h_{22} \\ h_{22}^* & -h_{12}^* \end{bmatrix}$$

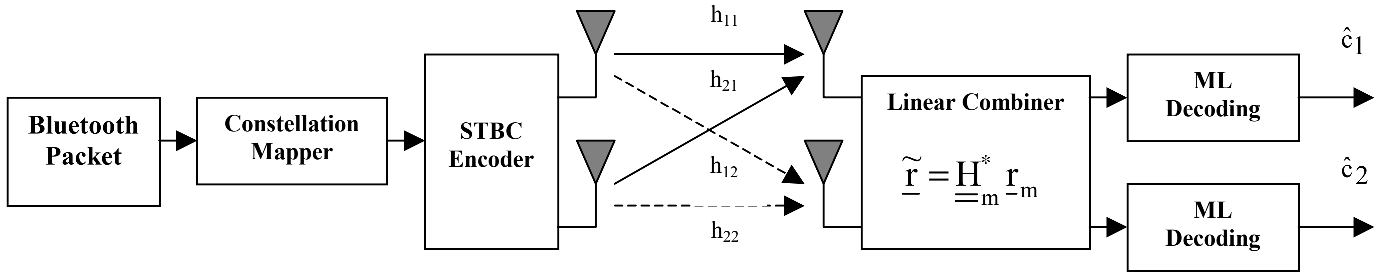

Fig. 11: Transmitter and receiver baseband representation of space time block codes for 2 transmit and 2 receive antennas

where $\underline{c} = [c_1 \quad c_2]^T$ represents the first two symbols, and $\underline{\eta}_1$ and $\underline{\eta}_2$ are vectors containing additive white Gaussian noise (AWGN) samples that are modelled as identically independently distributed Gaussian random variables with zero mean and power spectral density $N_o/2$ per dimension. The maximum likelihood (ML) decoding rule is:

$$\hat{c} = \arg \min_{\hat{\underline{c}} \in C} \sum_{m=1}^{2} \left\| \underline{r}_m - \underline{\underline{H}}_m \hat{\underline{c}} \right\|^2$$

where C is the complete set of possible transmitted symbols. Since the channels are orthogonal to each other, the above decoding rule can be further simplified by premultiplying the received signal vector $\underline{r}_m$ by $\underline{\underline{H}}^*_m$ [18].

Fig. 12 shows the PER performance for single time slot Bluetooth packets when STBC is employed. The results show that large performance improvements are obtained when antenna diversity is employed in Bluetooth enables devices. At low CNR values, the error floor is reduced dramatically. At CNR = 20dB and CIR = 20dB, the PER with and without antenna diversity is 0.5% and 10% respectively. These values can be used to analyse the improvements attained in terms of the necessary data throughputs required for a particular time-bounded or non-time bounded application.

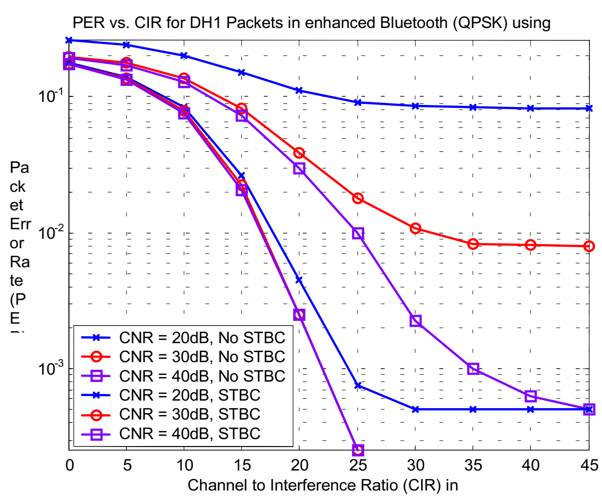

Fig.12: PER performance for enhanced Bluetooth (QPSK) with and without STBC in the presence of a single 802.11g interferer

The PER performance at high CNR (beyond approximately 30dB) using antenna diversity is limited by the amount of interference present in the environment. As the CIR value increases (beyond 25dB), from Fig. 12 it can be seen that reliable transmission can be achieved with negligible PER. This explains why the dotted curves for CNR = 30dB and 40dB (and 50dB although not shown in Fig.12) using antenna diversity are superimposed on top of each other.

Table V presents the data throughput performance achievable at CNR = 20dB and CNR = 30dB with and without antenna diversity for enhanced Bluetooth (using QPSK and 8PSK) in the presence of a single 802.11g interferer. The results are shown for CIR values of 20dB and 30dB respectively. The data throughput DT can be calculated using the following relationship:

$$DT = (1 - PER) \times \log_2 M \times DR \tag{6}$$

where M represents the constellation size (2 for BPSK, 4 for QPSK and 8 for 8PSK) and DR the maximum data rate (bits/s) for DM1 and DH5 packets. The results in Table V were computed using equation (6) from the PER values obtained from software simulations (Fig. 12 shows the PER results for QPSK).

TABLE V
DATA THROUGHPUT PERFORMANCE FOR SINGLE TIME SLOT PACKETS IN ENHANCED BLUETOOTH IN THE PRESENCE OF 802.11g INTERFERENCE

Modulation	Antenna Diversit y	CIR Value	Data Throughput (kb/s) CNR = 20dB	Data Throughput (kb/s) CNR = 30 dB
QPSK	**With STBC**	20 dB	344	345
		30 dB	345	345
	Without STBC	20 dB	307	332
		30 dB	316	341
8PSK	**With STBC**	20 dB	500	501
		30 dB	515	517
	Without STBC	20 dB	354	468
		30 dB	377	497

Immediate observations confirm that as the modulation level increases, the performance improves significantly by exploiting antenna diversity. From Table V it can be observed that for enhanced Bluetooth employing QPSK modulation, although the improvement in PER as suggested in Fig. 12 at CNR = 20dB and CIR = 20dB with antenna diversity is 20 times (i.e. 0.5% PER as opposed to 10% PER), the resulting gain in data throughput is not significant (i.e. 344kb/s with STBC and 307kb/s without STBC). Similarly, at high CIR values (beyond 30dB), the error floor reduces from a PER of 9% to 0.05%. Although the throughput is not improved significantly, the latency and jitter would be improved and this would be very useful for time bounded traffic.

The performance for enhanced Bluetooth employing 8PSK modulation and STBC however shows a significant improvement in achievable data throughput. This is because for higher level modulation schemes the use of STBC provides diversity to mitigate the crowding of symbols on the constellation diagram. Hence, the data throughput performance is higher for 8PSK compared to QPSK. The performance can be further improved by increasing the number of transmit or receive antennas; however this comes at the expense of increased cost and complexity for the Bluetooth enabled devices.

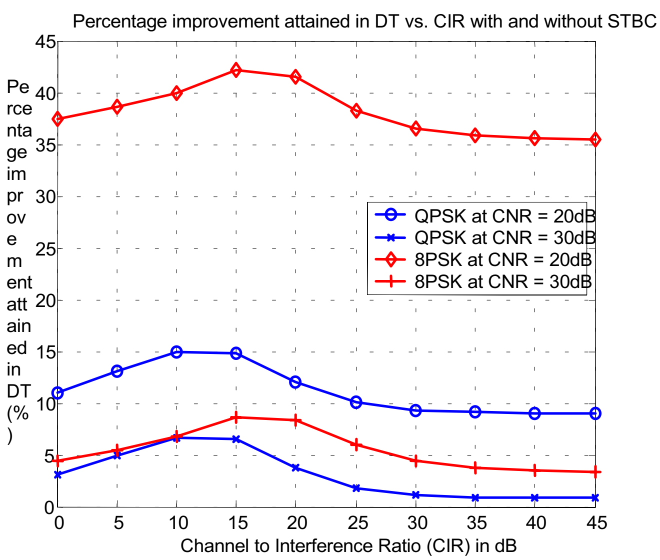

Fig.13: Percentage improvement in data throughput for enhanced Bluetooth using antenna diversity at CNR = 20dB and CNR =30dB

Fig. 13 shows the percentage improvement obtained when STBC is used to mitigate 802.11g at CNR values of 20dB and 30dB. It can be observed that firstly, as the CNR values increase, the improvement in performance reduces because the system is limited by the level of interference present. At low CNR values (20dB and below), as the modulation level increases, better data throughput performance is achieved. This can be accounted for by the fact that the number of samples per symbol is higher and the use of STBC makes the system more resilient to errors caused by interference (and hence an improvement in the PER performance).

One crucial point to consider in equation (6) is that the data throughput does not take into account the number of retransmissions. Obviously, retransmissions will only be practical in non-time bounded applications. If retransmissions were taken into consideration, although the PER appears unaffected, the effective data throughput would reduce. This issue is currently being investigated by the authors but is not discussed further in this paper.

VII. Conclusion

In this paper, the impact of Bluetooth interference on the 802.11g system and vice versa was investigated and methods suggested to mitigate these negative effects. If the Bluetooth device is located close or collocated (for example in a laptop) with the 802.11g device, interference will occur if the packets overlap in both time and frequency. The collision probability depends on the ratio of the 802.11g to Bluetooth packet duration and also on the ratio of the frequencies occupied by both systems.

Independent of the actual error floor value, it can be seen from the results that the degradation in performance of 802.11g is significant for the CIR values considered. Results presented here show that when soft weights corresponding to the CIR ratios are applied to the sub-band reliability metrics then performance is very close to that in the absence of interference. Multi-carrier modulation as used in 802.11g systems ensures that the interference is constrained to just a few symbols that correspond to the affected subcarriers. If the 802.11g receiver has knowledge of the position of the corrupted subcarriers, it is possible to prevent the interference from having a severe impact on system performance.

The results obtained for the impact of 802.11g interference on Bluetooth clearly highlight two main points of interest as far as Bluetooth enabled applications are concerned. The first point is packet reliability and the second is achievable throughput. High error floors are present in enhanced Bluetooth devices using QPSK modulation in the presence of 802.11g interferers. The PER performance subsequently improves when antenna diversity is exploited. This means that for time-bounded applications where packet reliability is of concern, STBC helps to mitigate the impact of 802.11g interferers by lowering the PER. On the other hand, the data throughput performance may not seem as catastrophic whether or not antenna diversity is exploited for lower modulation levels (QPSK). This is shown by the fact that the percentage improvement in data throughput is not significantly different with and without STBC. However, at higher modulation levels (8PSK), the improvement obtained in terms of PER and data throughput is comparable.

Coexistence strategies have been proposed for implementation in future Bluetooth enabled devices. Adaptive frequency hopping (AFH) is a technique that enables a Bluetooth device to reduce the number of channels it hops across, leaving some channels open for other devices such as 802.11g. AFH is a possible technique that may be implemented in future Bluetooth devices. Another method for Bluetooth interference mitigation is the exploitation of STBC, which was considered earlier in this paper. In practise, a two element antenna array in future Bluetooth devices is not unrealistic for many products. At the same time, owners and operators of 802.11g WLANs cannot rely on its effectiveness. In order to ensure robustness to Bluetooth interference, 802.11g needs its own method for mitigating interference effects. One such solution is considered in this paper. Thus, a method for 802.11g to mitigate Bluetooth interference without relying on co-operation from the Bluetooth device is available.

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REFERENCES

[1] IEEE Std. 802.11b-1999, Part11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Higher-Speed Physical Layer Extension in the2.4 GHz Band.

[2] IEEE Std. 802.11g/D1.1-2001, Part11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Further Higher-Speed Physical Layer Extension in the 2.4 GHz Band.

[3] The Bluetooth Std. Version 1.0b (http://www.bluetooth.com).

[4] http://grouper.ieee.org/groups/802/15/

[5] J.C. Haartsen , "BLUETOOTH^{TM} : A new radio interface providing ubiquitous connectivity", Proceedings of VTC 2000, Tokyo, Japan, 2000

[6] A.K. Arumugam, S.M.D. Armour, B.S. Lee, M.F. Tariq and A.R. Nix, "Consumer Electronics Application and Coverage Constraints using Bluetooth and Proposed Bluetooth Evolution Technologies", IEEE Transactions on Consumer Electronics, Vol.47, No. 3, August 2001.

[7] M.F. Tariq, P. Czerepinski, A. Nix, D. Bull, and N. Canagarajah, "Robust and Scalable Matching Pursuits Video Transmission Using the Bluetooth Air Interface Standard", IEEE Transactions on Consumer Electronics, vol.46, No.3, August.2000

[8] A.K. Arumugam, A.R. Nix, P.N. Fletcher, S.M.D. Armour and B.S. Lee, "Scenario Driven Evaluation and Interference Mitigation Proposals for Bluetooth and High Data Rate Bluetooth Enable Consumer Electronic Devices" IEEE Transactions on Consumer Electronics, vol.48, No.3, August 2002.

[9] J.Medbo, P. Schramm "Channel Models for HIPERLAN/2" ETSI/BRAN document no. 3ERI085B, 1998.

[10] A. Doufexi, S. Armour, P. Karlsson, M. Butler, A. Nix, D. Bull, J. McGeehan, "A Comparison of the HIPERLAN/2 and IEEE 802.11a Wireless LAN Standards," IEEE Communications Magazine, May 2002, Vol. 40, No. 5.

[11] A. Doufexi, S. Armour, B.S. Lee, A. Nix and D. Bull, "An Evaluation of the Performance of IEEE 802.11a and 802.11g Wireless Local Area Networks in a Corporate Office Environment", ICC 2003, Alaska, May 2003.

[12] A. Doufexi, A.K. Arumugam, S. Armour and A. Nix, "An Investigation of the Impact of Bluetooth Interference on the Performance of 802.11g Wireless Local Area Networks", Proceedings of VTC Spring 2003, Jeju, Korea, 2003.

[13] White Paper, Mobilian Corporation, "Adaptive Frequency Hopping: Good Enough?" (http://www.mobilian.com)

[14] A.J. Viterbi and J.K. Omura, "Principles of Digital Communication and Coding", by McGraw Hill Book Company © 1979.

[15] L.E. Aguado, K.K. Wong, T.O Farrell, "Coexistence Issues for 2.4 GHz OFDM WLANs", Proceedings of 3G 2002, London.

[16] A.K. Arumugam, P.N. Fletcher, A.R. Nix and S.M.D. Armour, " Interference Mitigation Proposals Exploiting Antenna Diversity using Space Time Block Codes for Bluetooth Enabled Devices", Proc. of VTC Fall 2002, Vancouver, BC, Canada.

[17] S. Alamouti, "Space Block Coding: A Simple Transmitter Diversity Scheme for Wireless Communications", IEEE JSAC, November 1998.

[18] A.F. Naguib and N. Seshadri, "Combined Interference Cancellation and ML Decoding of Space Time Block Coding", AT&T Labs Research, Building 103, Room C-288, 180 Park Avenue, Florham Park, NJ 07932, USA.

BIOGRAPHY

Arun Kumar Arumugam was born in Malaysia in 1977. He received his BEng degree in Electronic and Communications Eng. in 1999 from the University of Bristol. He is currently completing a PhD at the University of Bristol. He was awarded the Robinson Research Fellowship by the Institution of Electrical Engineers (IEE) UK in November 2000. His research interests are in enhancements of the Bluetooth technology and interference suppression techniques exploiting space-time block codes and antenna diversity for Bluetooth enabled devices. He is a member of the IEE and the IEEE

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Paul Fletcher received MEng and PhD degrees from the University of Newcastle-upon-Tyne (UK) in 1989 and 1993 respectively. He joined the low cost phased array antenna group QinetiQ Ltd. (formerly DERA) in 1993. He is currently a Visiting Industrial Fellow at the University of Bristol (UK). His research interests encompass mutual coupling compensation techniques, low sidelobe beamforming, adaptive beamforming, space-time signal processing, MIMO and spatial diversity techniques and iterative decoding. He has published over 65 journal and conference papers and holds four patents. He currently leads the space-time processing activities of the array antenna group for next generation wireless LAN and PANs within QinetiQ Ltd. He is a member of the IEE and IEEE.