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# An Investigation of the Impact of Bluetooth Interference on the Performance of 802.11g Wireless Local Area Networks

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**Abstract**—In recent years there has been considerable interest in the development of standards for Wireless Local Area Networks. In particular, IEEE’s 802.11 standard has now been extended to a family of WLAN standards. 802.11a and 802.11g both employ COFDM but operate in different frequency bands. The 802.11g physical layer standard specifies a link adaptive COFDM scheme for operation in the 2.4GHz ISM band. Operation in this ISM band will leave 802.11g vulnerable to interference from nearby Bluetooth devices. In this paper, the impact of Bluetooth interference upon the physical layer of 802.11g is investigated and methods to mitigate this impact are examined.

## I. INTRODUCTION

The original 802.11 standard specifies a common MAC layer and three Physical (PHY) layers [1]. Two of these PHYs facilitate communications in the 2.4GHz Industrial Scientific and Medical (ISM) bands using Direct Sequence (DS) and Frequency Hopped (FH) Spread Spectrum techniques. The third PHY facilitates communication over infra-red links. Data rates of up to 2 Mbits/s are facilitated by each of the PHYs.

The 802.11 standard has subsequently been expanded considerably. Whilst the MAC specification has remained largely unchanged until now (except for Quality of Service (QoS) enhancements under 802.11e [2]), several new PHY layer specifications have been added. The 802.11a PHY [3] facilitates link adaptive data rates of up to 54Mbits/s, employing COFDM (Coded Orthogonal Frequency Division Multiplexing) in the 5GHz Unlicensed National Information Infrastructure (UN-II) band. The 802.11b PHY [4] facilitates data rates of up to 11Mbits/s, employing Complementary Code Keying (CCK) and DS Spread Spectrum, also in the 2.4GHz ISM band. Also, a high rate extension to 802.11b in the 2.4GHz ISM band has been considered by 802.11g [5]. The selected solution is based upon the link adaptive COFDM modulation scheme of 802.11a with mandatory backward compatibility with 802.11b. Optional modes based on a CCK-COFDM hybrid and a Packet Binary Convolutional Code (PBCC) scheme were also included.

Operation in the 2.4GHz ISM band will leave 802.11g vulnerable to interference from a wide variety of sources. The anticipated proliferation of Bluetooth devices (also operating in the 2.4GHz ISM band) is likely to result in that technology becoming the most significant source of interference.

Bluetooth is a Wireless Personal Area Network (WPAN) technology [6]. It employs FH of a Gaussian Frequency Shift Keyed (GFSK) modulation to achieve symmetric data rates up to 434kbits/s in a 1MHz bandwidth. The extremely aggressive target pricing strategies of Bluetooth products are intended to ensure rapid proliferation to the point where it is the dominant near term WPAN technology.

The 2.4GHz ISM band provides 83.5MHz of spectrum. Note that this is not a global allocation but that national regulators are converging towards this common allocation. Allowing for guard bands, this facilitates 79 hop-channels for Bluetooth and 3 channels for 802.11g. Clearly, with Bluetooth devices currently designed to hop randomly over all 79 of the available hop frequencies, interference between a single Bluetooth piconet and a single 802.11g LAN can be expected to be significant, if they are co-located and operating near capacity. In this paper, the impact of an interfering Bluetooth signal on the packet error rate (PER) of the link adaptive 802.11g system is investigated. Additionally, the effect of different packet sizes for 802.11g and Bluetooth are examined.

## II. THE IEEE 802.11g WLAN STANDARD

The 802.11g physical layer is based on the use of link adaptive COFDM [5,7,8]. 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 Correcting (FEC) convolutional code) and modulation scheme are specified in order to facilitate different ‘modes’ of transmission. These different modes are defined in Table I.

Table I: IEEE 802.11g transmission modes

Mode	Modulation	Coding Rate	Nominal Data Rate, $R_{\text{Nominal}}$
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

FEC is typically facilitated in the receiver by means of a Viterbi decoding algorithm. In the context of COFDM this

Viterbi decoding strategy has the capability to exploit information on the reliability of the signal received on a given sub-band as well as on the signal itself. This serves to augment the performance of the FEC process. Typically, the reliability information is derived from the Channel State Information (CSI) generated from the channel estimator in the receiver.

Besides the COFDM modulation common to 802.11a and 802.11g, 802.11g also mandates backwards compatibility with the CCK DS-CDMA modulation of 802.11b. This compatibility of 802.11g with 802.11b is very important. 802.11b looks set to dominate the near term WLAN market under the ‘Wi-Fi™’ brand. The backwards compatibility of 802.11g makes it the obvious choice for evolution of this market by facilitating a smooth transition between standards. 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 benefits to 802.11g offered by backward compatibility are offset by additional overhead requirements.

The overheads introduced by the 802.11 MAC are mode dependent and also differ between 802.11a and 802.11g. Overheads are primarily due to the requirement to implement Distributed Inter-Frame Spaces (DIFS) and Short Inter-frame Spaces (SIFS) between data packet transmissions as well as ARQ signaling. The variation of overhead with mode is due to the fact that the DIFS and SIFS are of fixed duration whilst, for a given packet size, the packet duration is shorter for higher rate modes. The difference in overhead between 802.11a and 802.11g is due to the fact that different lengths are specified for the DIFS and SIFS in 802.11a and 802.11g. In order to inter-operate effectively with legacy 802.11b devices, 802.11g devices will be required to implement the DIFS, SIFS and ARQ in a manner common with 802.11b. If the backward compatibility with 802.11b devices were to be neglected, 802.11g devices could operate with the same MAC overhead as 802.11a devices. MAC efficiencies calculated on the basis of the ratio of the time used to transmit actual data relative to the total time occupied by the data and the various associated signaling overheads are shown in Table II for the eight modes of 802.11a and 802.11g using both the mandatory COFDM modulation and optional CCK-COFDM.

The efficiency values are given for the case of the Distributed Co-ordination Function both with and without RTS/CTS signaling and assume a packet size of 1500bytes. RTS/CTS can be used to prevent collisions between 802.11g devices and legacy 802.11b devices. Note that if CCK-COFDM modulation is employed, the RTS/CTS signaling is not needed to prevent collisions between 802.11g and legacy 802.11b devices since the 802.11b devices are capable of demodulating the CCK modulated 802.11g packet headers. However, the RTS/CTS signaling may still be required in order to deal with the hidden node problem. Given that the MAC efficiency is higher for the mandatory COFDM mode of transmission with RTS/CTS than for CCK-COFDM without RTS/CTS, the value of the optional CCK-COFDM mode is dubious. Hence this optional modulation scheme is not considered any further here.

From the information in Table I and Table II it can be seen that after the MAC overheads, 802.11g achieves a data rate less than 20Mbps even without the use of RTS/CTS or CCK-COFDM to prevent collisions with legacy 802.11b devices. The achievable data rate is even lower in cases where one of these collision prevention measures is employed.

Table II: MAC EFFICIENCY

Mode	Mac Efficiency, $\eta_{MAC}$					
	802.11a		802.11g OFDM		802.11g CCK-OFDM	
	With	Without	With	Without	With	Without
1	85%	90%	78%	81%	73%	76%
2	82%	87%	71%	74%	66%	68%
3	78%	84%	66%	69%	59%	62%
4	72%	79%	57%	61%	50%	52%
5	66%	74%	51%	54%	43%	45%
6	58%	66%	41%	44%	34%	36%
7	51%	60%	35%	37%	28%	29%
8	49%	57%	32%	35%	26%	27%

The impact of Bluetooth interference on 802.11b has been considered previously in [9]. The impact of Bluetooth on 802.11g when operating in its 802.11b backward compatibility mode can be expected to be very similar and will thus not be considered any further here. Instead, the analysis presented in this paper concentrates on the eight modes of 802.11g which are equivalent to those of 802.11a. Note that the CCK DS-CDMA backward compatibility mode offers no performance advantage over these modes. 802.11g supports variable size Protocol Service Data Units (PSDUs or packets). Table III summarizes the duration of transmission for packets of various payload sizes.

Table III: PSDU duration as a function of mode and payload

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

### III. THE BLUETOOTH PHYSICAL LAYER

Bluetooth aims to provide robust short range radio communication with low terminal cost, complexity and power consumption. The Bluetooth Physical layer [6] specifies the use of a single carrier GFSK modulation with a BT product of 0.5 and a modulation index between 0.28 and 0.35. A slot duration of 625 $\mu$ s is defined, as is a hopping rate of 1 hop per packet. Thus, each Bluetooth packet is transmitted on a different hop frequency to its predecessor. Packets may occupy 1, 3 or 5 slots. It is important to note that the system hops once per packet, not once per slot. Thus, multi-slot packets are transmitted entirely on one hop frequency. A

Bluetooth piconet will nominally occupy one of 79 hop frequencies for a slot period; either 625 $\mu$ s, 1875 $\mu$ s or 3125 $\mu$ s. It should be noted that a significant proportion of a slot time is reserved at the end of each packet to allow for hopping and radio turnaround. The result is that the period and percentage of time actually utilised is 366 $\mu$ s (59%), 1616 $\mu$ s (86%) and 2866 $\mu$ s (92%) for 1, 3 and 5 slot packets respectively.

#### IV. COLLISION PROBABILITY

For 802.11g to be subject to interference from Bluetooth (i.e. for a ‘collision’ to occur) their signals must coincide in both frequency and time [10].

The frequency domain occupation of the ISM band by 802.11g and Bluetooth is illustrated in Figure 1. The Bluetooth signal occupies 1 of 79 different hopping channels, each 1MHz wide, at any one time. For details on the hopping patterns employed, the reader is referred to [6]. For the purposes of this paper it is sufficient to understand that the hop patterns essentially achieve a uniform distribution across the available band. The 802.11g signal occupies a bandwidth of approximately 16.5MHz and is assumed fixed in frequency. The probability of the signals coinciding in the frequency domain is thus approximately 21%.

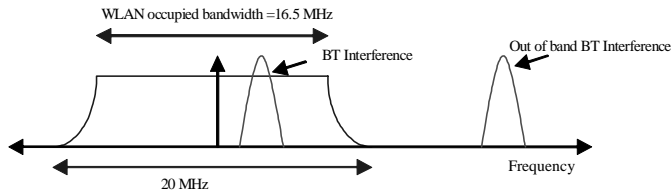


Figure 1: Bluetooth interference on 802.11g WLANs.

The probability of packets coinciding in time is a function of the lengths of the Bluetooth packets and 802.11g PSDUs and cannot be conveniently expressed mathematically. For the purposes of this paper, software simulation incorporating all the relevant parameters has been employed. However, some useful observations are presented below.

Figure 2 illustrates the time domain occupancy of the ISM band by Bluetooth (for 1 slot packets) and 802.11g (for PSDUs which are ‘long’ and ‘short’ relative to the Bluetooth packet).

Allowing for a time offset, five Bluetooth packets (each on a different frequency) will (at least partially) coincide in time with the ‘long’ 802.11g PSDU. As a result, collision is almost certain. This is true for any 802.11g PSDU length greater than 4 Bluetooth packet lengths. For longer Bluetooth packets, the probability of collision with a given length 802.11g PSDU reduces, since the hopping rate is effectively reduced.

For the case of the ‘short’ PSDU, it can be seen that the probability of collision will be less than the 21% probability of the signals coinciding in frequency. This is since some of the 802.11g packets will be transmitted during the redundant time between Bluetooth packets. The probability of 802.11g PSDUs being completely transmitted within the time between

Bluetooth packets depends upon the proportion of time for which Bluetooth is not transmitting. Since larger Bluetooth packets have less redundant transmission time, the corresponding probability of collision for a given PSDU length will be higher.

Note that in this paper a single 802.11g WLAN and a single Bluetooth piconet are assumed in all cases.

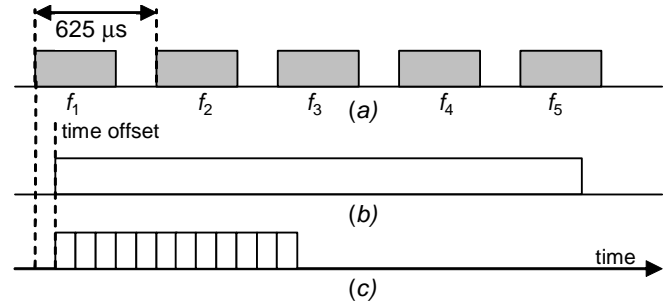


Figure 2: Effect of packet size in the probability of collision: (a) Bluetooth 1 slot packets-different frequency  $f$  every 625  $\mu$ s, (b) ‘long’ (2000 byte, mode 1) 802.11g packet, (c) ‘short’ (256 byte, mode 5) 802.11g packets.

#### V. PERFORMANCE RESULTS

The performance of the 802.11a transmission modes under interference free conditions has been simulated previously by the authors. These results, in combination with a discussion of the implications and overheads of the 802.11 Medium Access Control (MAC) have been published in [7,8].

In this section, simulation results for the performance of 802.11g under Bluetooth interference are presented. The issue of collision was fully modeled in the simulation, based on the 802.11g and Bluetooth packet durations, the Bluetooth signal characteristics and a random time offset. The effect of interference on the preamble used for channel estimation (as specified by the 802.11g standard) was considered in the simulation. The effects of interference on the pilot information transmitted throughout the PSDU were not considered.

Figure 3 shows the 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 (C/I) 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 [11]. This is because the power of 802.11g signal is spread along the 52 subcarriers, whereas the Bluetooth signal occupies a narrower bandwidth. When the 1MHz Bluetooth interference is applied, only a few of the subcarriers are affected. For the results in Figure 3, it was assumed that Bluetooth uses 1 slot packets. Figure 4 shows that increased PSDU size results in a higher error floor. Note that performance also depends on the transmission mode.

It can be observed that an error floor is present when interference occurs. 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 appear to have very high reliability, since they appear to 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 Figure 3 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 the channel estimation or from an on system Bluetooth receiver) then it can inform the Viterbi decoder not to base its decisions on the corrupted subcarriers.

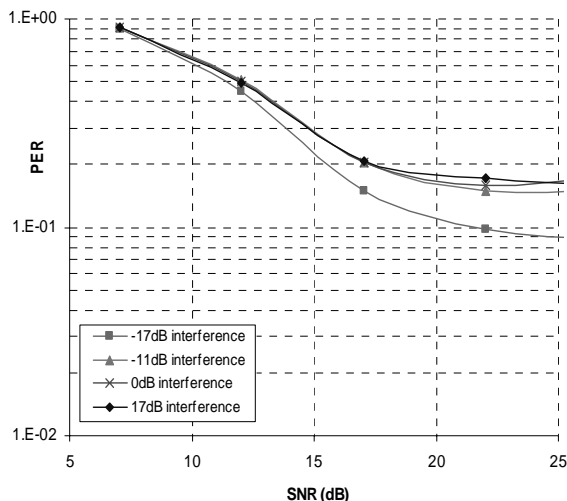


Figure 3: PER Performance of 802.11g with different values of Bluetooth interference for mode 5 with a PSDU size of 500 bytes.

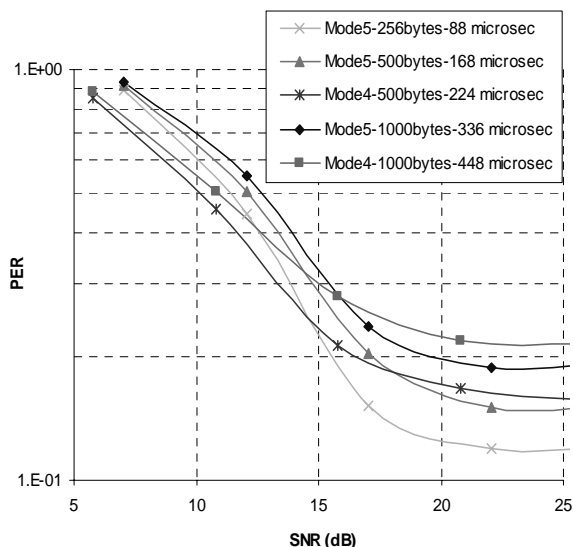


Figure 4: The effect of PSDU size on PER performance, C/I = -11dB.

In [10], 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 reliability metrics. Zero if interference is present, unity otherwise. 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 center of the Bluetooth interference suffers a 0dB C/I ratio, 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 [10] only 9 sub-carriers at most will at a given time see significant interference from a single Bluetooth interferer.

Figure 5 shows the PER performance of 802.11g for mode 5, PSDU size of 500 bytes, with -11dB C/I. In Figure 5, two cases have been simulated. For the first one, erasures were used for the three sub-carriers at the center of the Bluetooth interference but soft values (based on the C/I) 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 and more particularly the soft decision Viterbi decoder have knowledge of the position of the corrupted subcarriers it can compensate for the few corrupted subcarriers. As can be seen from Figure 5, performance is very close to a system without Bluetooth interference.

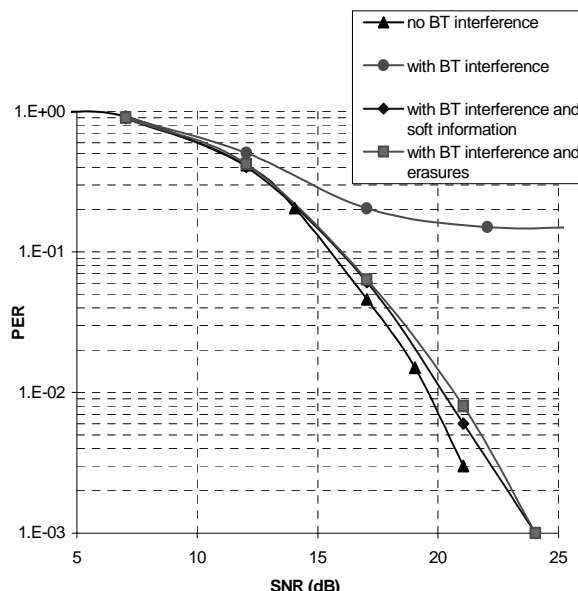


Figure 5: PER Performance of 802.11g with Bluetooth interference for mode 5 with a PSDU size of 500 bytes.

Figure 6 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. Figure 7 shows the PER performance for mode 4, using a PSDU size of 500 bytes.

If the duration of the 802.11g packet is similar to the Bluetooth packet duration 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, this probability is increased and depends upon the number of times that the Bluetooth signal will hop 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 (289 $\mu$ s out of 625  $\mu$ s in slot 1 packets) –see Figure 7, mode 5 with 256 bytes which has a packet duration of 88 $\mu$ s.

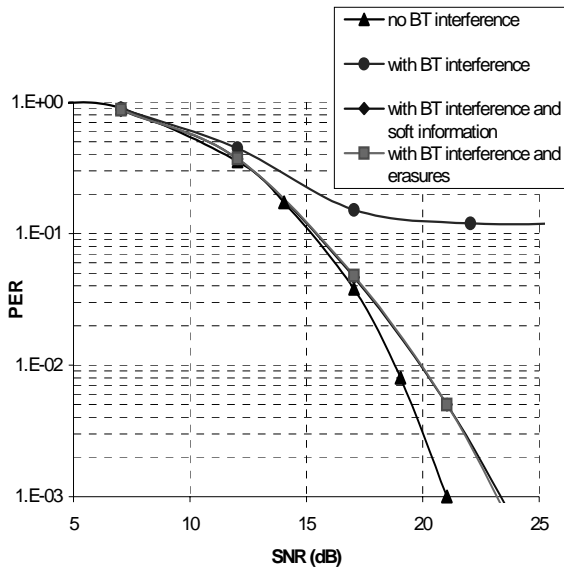


Figure 6: PER Performance of 802.11g with Bluetooth interference for mode 5 with a PSDU size of 256 bytes.

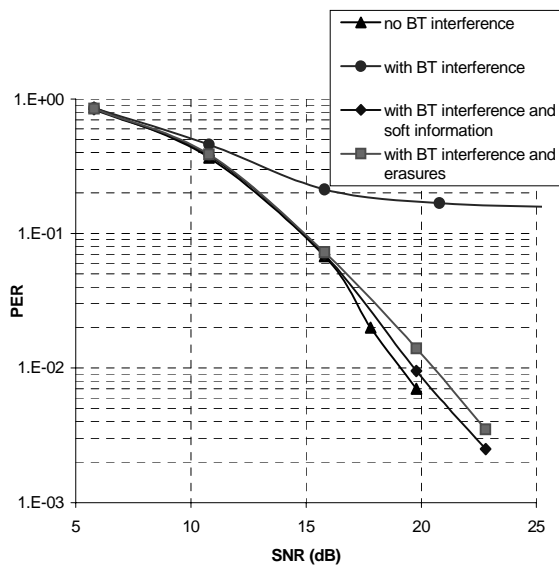


Figure 7: PER Performance of 802.11g with Bluetooth interference for mode 4 with a PSDU size of 500 bytes.

## VI. CONCLUSIONS

In this paper, the impact of Bluetooth interference upon the COFDM physical layer of 802.11g was investigated and methods to mitigate the impact of interference were examined. If the Bluetooth device is located close or collocated (for example in a laptop) with the 802.11g device, interference will occur. For a Bluetooth transmission to interfere with the 802.11g packets there must be an overlap both in frequency

and time. The collision probability depends on the ratio of 802.11g to Bluetooth packet duration and on ratio of frequencies occupied by two systems. Independent of the actual error floor value, it can be seen from the results that the degradation in the performance of 802.11g is significant for the C/I values considered.

Coexistence strategies have been proposed for implementation in Bluetooth. Adaptive Frequency Hopping (AFH) is a technique which enables a Bluetooth device to reduce the number of channels it hops across, leaving some channels open for other devices such as 802.11g.

However AFH is a technique which *may* be implemented in *future* Bluetooth devices. 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.

If the 802.11g receiver has knowledge of the position of the corrupted subcarriers, it is possible to prevent them having a severe impact on system performance. Results presented here show that when soft weights corresponding to C/I ratios are applied to the reliability metrics then performance is very close to that in the absence of interference. This is in part due to the COFDM physical layer of 802.11g. Multicarrier modulation ensures that interference is not spread among all symbols but is restricted only to the few symbols that correspond to the affected subcarriers. 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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