REDUCING BLUETOOTH INTERFERENCE WITH DIVERSITY TECHNIQUES IN IEEE 802.11B NETWORKS

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ABSTRACT
Lately different kinds of wireless networks have become more frequently used. If they occupy the same frequency band they are likely to interfere with each other. In this paper, we examine how spatial diversity can be exploited to suppress Bluetooth interference on a IEEE 802.11b network. Two dual antenna receivers, the maximum ratio combining (MRC) and the interference rejection combining (IRC) methods, have been evaluated and compared to the ordinary single antenna receiver. Simulation results show that adding spatial diversity yields a significant reduction in bit error rate (BER) and as a consequence the throughput is increased, especially for larger fragment sizes.

1. INTRODUCTION
Due to the rapid growth of wireless networks in the past few years, problems with different networks interfering with each other have risen. These problems become significant when networks occupy the same frequency band. A current example is the Bluetooth and the IEEE 802.11b networks, which due to the interference will begin to drop packets, resulting in a lowered throughput. As the demand of throughput is constantly increasing, it is of great importance that this problem is solved or reduced to its minimum.

Several papers addressing Wireless Local Area Networks (WLANs) (in this article, the notation WLAN is used for IEEE 802.11b networks) and Bluetooth coexistence problems have been published. In [1, 2, 3], analytical expressions for the probability of collision between a Bluetooth and a WLAN packet is presented. In [4, 5, 6], the transmission performance for WLAN is shown in terms of throughput. The calculations are based on probabilities of packet collision and show that the WLAN throughput drops rapidly as the Bluetooth network load is high. In [7, 8, 9], some ideas on how the two systems can coexist are discussed. For example, regulation of transmitting power levels and traffic scheduling are suggested.

In contrast to earlier work, the focus of this article is to study how WLAN receivers using spatial diversity can reduce the Bluetooth interference on IEEE 802.11b networks. It is found that, using dual antenna receivers employing MRC or IRC will result in a significant improvement of transmission throughput. We evaluate the differences in transmission performance for the IEEE 802.11b network in terms of BER and throughput.

2. SYSTEM OVERVIEW
Both IEEE 802.11b and Bluetooth are designed to cope with the interference from (a limited number of) other IEEE 802.11b or Bluetooth networks, respectively. Bluetooth networks are designed for short range, e.g., between a cellular and a mobile computer. On the other hand, IEEE 802.11b is designed for larger distances, e.g., in an open-plan office. Therefore, the two networks complement each other.

2.1. IEEE 802.11b System
The IEEE 802.11b [10] system uses the Industrial, Scientific and Medical (ISM) frequency band, which spans, according to the FCC(US) and ETSI(Europe), between 2.4 and 2.4835 GHz. The IEEE 802.11b standard is an extension of the IEEE 802.11 standard [11]. The data is transmitted at 1, 2, 5.5 or 11 Mbps. As we are concentrating on the IEEE 802.11b standard, only the DSSS physical layer is considered. It has a bandwidth of 22 MHz, thus three non-overlapping channels are available in the ISM band.

2.1.1. Medium Access Control Sublayer
The Medium Access Control (MAC) sublayer controls the reliability of the data delivery service, the channel allocation procedures and the encryption of the transmitted data. The transmitted frames, the MAC...
The transmitted packet, the so-called PLCP protocol data unit (PPDU), consists of a PLCP preamble, PLCP header and a PLCP service data unit (PSDU), which is equivalent to the MPDU. The IEEE 802.11b standard defines two types of preamble and header, a short and a long one. Only the long one is considered here. In this mode, both preamble and header are transmitted at 1 Mbps. The receiver uses the SYNC field in the PLCP preamble to acquire the signal and synchronize the demodulator. Here, we assume perfect synchronization at the receiver. The PSDU carries the payload and has a maximum length of 2346 bytes.

The modulation scheme for the 1 Mbps bit rate is differential phase shift keying (DPSK). The spreading code is a 11-bit Barker word at 11 Mchip/s and all stations use the same word. The bandwidth of the spread signal is 22 MHz. For the 11 Mbps bit rate, Complementary Code Keying (CCK) is used [11, pp. 43-45]. The length of the spreading code in CCK is 8 with a chipping rate of 11 Mchip/s and a symbol rate of 1.375 MSps. This makes the CCK spectrum occupy the same bandwidth as the lower bit rates.

### 2.2. Bluetooth System

The Bluetooth system [12] uses the ISM frequency band at 2.4 GHz, i.e., the same as the WLAN networks occupy. The data bits are modulated using Gaussian frequency shift keying and transmitted using frequency-hopping spread spectrum (FHSS). Bluetooth occupy 79 Mhz of the ISM band by using 79 different frequency channels, 1 Mhz wide each. The Bluetooth transmitter/receiver stays 625 $\mu$s, a time slot, in every frequency channel, i.e., the system changes channel 1600 times per second. The majority of Bluetooth applications transmit with a power level of 1 mW (significantly lower than the WLAN systems, which transmits with a power level of 100 mW) and at a data rate of 1 Mbps. The Bluetooth transmitter is only active 366 $\mu$s out of the 625 $\mu$s long time slot, thus giving a maximum payload size of 366 bits per time slot.

The standard defines several packet types. The ones used in the simulations are called DH1 and carry data information only. The maximum payload size is 366 bits. If the Bluetooth system is used for downloading data, e.g., email, the network load is 100% (i.e., every time-slot is occupied).

### 3. INTERFERENCE MODEL

As both the IEEE 802.11b and the Bluetooth systems are using the ISM frequency band, they may interfere with each other. IEEE 802.11b networks occupy a bandwidth of 22 MHz. The Bluetooth system with its FHSS scheme uses 79 Mhz of the available bandwidth. As a result, the probability that a Bluetooth time slot coincide in frequency with a WLAN packet is approximately 25%. This holds when the Bluetooth system is 100% loaded, which is the case considered in this work. The worst case is when three consecutive Bluetooth packets fall inside the WLAN bandwidth.
4. RECEIVER DESIGNS

A signal transmitted over a fading radio channel may be corrupted to such an extent that it is undetectable at the receiver. To improve the transmission performance we utilize techniques based on spatial diversity, which is an option in the WLAN standard. See [13] for a complete description of the receiver design.

4.1. Channel Model

In a system employing spatial diversity, the channels between the transmitter antenna and the receiver antennas can be modelled as

\[ h = [\alpha_1 e^{j\theta_1}, \ldots, \alpha_n e^{j\theta_n}]^T, \]

where \([:]^T\) denote transpose, \(\alpha_n\) are the channels attenuations (Rayleigh distributed), \(\theta_n\) are the channels phases, assumed to be uniformly distributed between \([0, 2\pi]\), and \(n\) is the number of receiving antennas. All channels are assumed to be time-invariant flat-fading and independent of each other. The received signal can be written as

\[ r(t) = h_1 s_{\text{wlan}}(t) + h_2 s_{\text{bt}}(t) + w(t), \]

where \(s_{\text{wlan}}\) is the WLAN signal, \(s_{\text{bt}}\) is the Bluetooth signal and \(w(t)\) is assumed to be additive white Gaussian noise (AWGN).

4.2. Single Antenna Receiver

The ordinary WLAN receiver has one antenna, and the received signal can therefore be modelled as

\[ r(t) = h_1 s_{\text{wlan}}(t) + h_2 s_{\text{bt}}(t) + w(t), \]

where \(h_1\) and \(h_2\) represents the one tap channel filters defined in (1). The channel is assumed to be known, yielding an estimate of the transmitted signal, \(s_{\text{wlan}}(t)\), as

\[ \hat{s}_{\text{wlan}}(t) = h_1^* r(t) = (|h_1|^2) s_{\text{wlan}}(t) + \frac{(h_1 h_2) s_{\text{bt}}(t) + h_1^* w(t)}{\hat{s}_{\text{bt}}}; \]

\[ = \alpha_1^2 s_{\text{wlan}}(t) + \hat{s}_{\text{bt}}(t) + \hat{w}(t), \]

where \((::)^*\) denotes the complex conjugate transpose. Obviously, the WLAN signal may be difficult to detect if the Bluetooth signal is much stronger than the WLAN signal.

4.3. Dual Antenna Receivers

In this study, two receiving antennas are used to introduce spatial diversity into the system. The following sections describe the two combining methods studied.

4.3.1. Maximum Ratio Combining

In maximum ratio combining, every available signal copy are used at the same time. The received signals are weighted with a gain factor proportional to their own SNR and then added coherently. Consider a system using two receiving antennas. The received signal is modelled as

\[ r(t) = h_1 s_{\text{wlan}}(t) + h_2 s_{\text{bt}}(t) + w(t), \]

where

\[ h_1 = [h_{11} h_{12}]^T, \quad h_2 = [h_{21} h_{22}]^T \]

represents the channels filters defined in (1) and,

\[ w(t) = [w_1(t) w_2(t)]^T \]

is assumed to be AWGN. Often, an acceptable simplification is to assume a known channel [13]. This yields the MRC estimate of \(s_{\text{wlan}}(t)\) as

\[ \hat{s}_{\text{wlan}}(t) = h_1^* r(t) = (|h_{11}|^2 + |h_{12}|^2) s_{\text{wlan}}(t) + \frac{(h_{11} h_{21} + h_{12} h_{22}) s_{\text{bt}}(t) + h_{11}^* w_1(t) + h_{12}^* w_2(t)}{\hat{s}_{\text{bt}}}; \]

\[ = (\alpha_1^2 + \alpha_2^2) s_{\text{wlan}}(t) + \hat{s}_{\text{bt}}(t) + \hat{w}(t). \]

Comparing (4) and (8), one can see that the WLAN signal is strengthened, making the WLAN signal easier to detect.

4.3.2. Interference Rejection Combining

Alternatively, one can estimate the channel coefficients, by exploiting a known training sequence. In the following, we model the received training signal as

\[ r(t) = H g(t) + w(t), \quad t = 1, \ldots, N \]

where \(g(t)\) is the known WLAN training sequence and where the additive noise \(w(t)\), representing both the background noise and the Bluetooth interference, is modelled as temporally white with some spatial color, i.e.,

\[ w(t) \sim \mathcal{CN}(0, Q) \]

\[ E[w(t) w^*(s)] = Q \delta_{t-s} \]

where \(Q\) is the spatial noise covariance matrix, and where \(H\) represents the unknown channel matrix. One method to estimate \(H\) and \(Q\) is found in [14, pp. 37-39], and reveals the following maximum-likelihood estimates

\[ \hat{H} = \hat{R}_{ry} \hat{R}_{yy}^{-1} \]
and

\[ \dot{Q} = \dot{R}_{rr} - \dot{R}_{ry} \dot{R}_{yy}^{-1} \dot{R}_{ry}, \]  

(12)

where

\[ \dot{R}_{rr} = \frac{1}{N} \sum_{t=1}^{N} r(t)r^*(t), \quad \dot{R}_{yy} = \frac{1}{N} \sum_{t=1}^{N} y(t)y^*(t), \]

\[ \dot{R}_{ry} = \frac{1}{N} \sum_{t=1}^{N} r(t)y^*(t). \]

It is possible to estimate the transmitted signal, \( s(t) \), using \( \hat{H} \) and \( \dot{Q} \), as

\[ \hat{s}(t) = \underset{s(t)}{\arg \min} |r(t) - \hat{H}s(t)|_Q^2 = (\hat{H}^* \dot{Q}^{-1} \hat{H})^{-1} \hat{H}^* \dot{Q}^{-1} r(t), \]

(13)

where \( \hat{s}(t) \) is the estimate of the transmitted signal and \( r(t) \) is the received signal.

5. SIMULATION SETUP

The WLAN system in this report is designed in Matlab according to the IEEE 802.11b standard [10]. The aim of the simulations is to investigate the increase in transmission performance in a WLAN network as the Bluetooth interference is reduced. The simulations look at the downlink.

The Bluetooth system is simulated as the worst case scenario, which means that the Bluetooth system uses single time slot packets of maximum payload size. Further, the Bluetooth frequency hop pattern is chosen randomly and we assume that no collision occur during WLAN ACK transmission. The Bluetooth signal is modulated as a frequency shift keying signal.

To get a measure on how severe the Bluetooth interference is, the decision device evaluate whether a logical “0” or a logical “1” was transmitted and counts the errors, this results in a BER. The throughput simulations are divided into two separate parts. The first one looks at every packet to decide if there were any bit error, i.e., a packet collision has occurred. The other simulation uses a probability measure to decide if a collision has occurred. The throughput measure is defined as

\[ \text{Throughput} = \frac{\text{Payload} \cdot \text{Number of packets}}{\text{Total transmission time}}, \]

(14)

where \text{Number of packets} is the total amount of transmitted packets, \text{Payload} is the number of data bits (excluding preamble and header) and \text{Total transmission time} is the total time elapsed to transmit the payload. The maximum packet length is, including preamble and header, 12192 bits long or \( t_{\text{wlan}} \approx 1283 \mu s \) [13]. The transmission time for a WLAN packet can be expressed as

\[ T_{\text{wlan}} = H_1 + \frac{\text{Payload}}{\text{Bit rate}} + \text{SIFS} + H_1 + \text{ACK}_1. \]

Further, the values in Table 1 are used. If a fragment is transmitted successfully (no bit error was detected), the transmission time is added to the Total transmission time. The transmission time, for the first fragment (in a continuous packet flow), is

\[ \text{time}_1 = B_t + \text{DIFS} + T_{\text{wlan}}, \]

(16)

where \( B_t \) is a randomly chosen backoff time. The contention time is represented by \( (B_t + \text{DIFS}) \). Each of the following fragments have a transmission time of, if no collision occurs,

\[ \text{time}_2 = \text{SIFS} + T_{\text{wlan}}. \]

(17)

If a packet collision has occurred, \( \text{time}_1 \) (now regarded as a time penalty), is added to the Total transmission time, and the packet is retransmitted. The probability simulations are based on the results in [4, 5, 6]. The throughput calculations uses a probability measure, which indicate if a packet collision has occurred. Howitt [1] presented a formula for calculating the probability that a IEEE 802.11b packet is either time coincident with \( n_r \) or \( n_r - 1 \) Bluetooth packets. The probabilities can be written as

\[ P_{n_r} = \frac{\tau_{bt} + t_{\text{wlan}} - (n_r - 1)T_{bt}}{T_{bt}} \]

(18)

\[ P_{n_r - 1} = 1 - P_{n_r}, \]

(19)

where

\[ n_r = \left\lceil \frac{t_{\text{wlan}} + \tau_{bt}}{T_{bt}} \right\rceil. \]

(20)

Here, \( \lceil \cdot \rceil \) is the ceiling function, \( \tau_{bt} \) is the active transmission time (366\mu s) and \( T_{bt} \) is the time slot (625\mu s). From [6], the probability of collision with \( n \) Bluetooth packets is

\[ P_{\text{coll}}(n) = 1 - (1 - P_{\text{coll}} \cdot BT_i)^n, \]

(21)
where $P_f$ is the probability of frequency overlap, 25%, between Bluetooth and WLAN, and where $BT_{l}$ denotes the Bluetooth network load factor. Finally, the overall probability of collision can be written as

$$P_{\text{tot}} = P_{n} \cdot P_{\text{coll}}(n) + P_{n-1} \cdot P_{\text{coll}}(n-1).$$ (22)

The throughput can now be calculated using equation (14) – (17), and the values in Table 1.

6. RESULTS

In this work we focus on how the WLAN throughput depends on the Bluetooth interference. This is the more interesting case, as Bluetooth is rather robust to interference from WLAN network due to its frequency hopping design.

Relating the received signal power to the noise power gives a quality measure of the communication link. We define the Signal-to-Noise Ratio (SNR) as

$$\text{SNR} = \frac{E_b}{N_0} = \frac{E_s/k}{N_0} = \frac{\|p(t)\|^2}{2kN_0}, \quad (23)$$

where $E_s$ is the average energy of one pulse and $k$ is the number of bits per symbol. The Signal-to-Interference Ratio (SIR) is a measure on how severe the Bluetooth interference is on the WLAN signal. The SIR is defined as

$$\text{SIR} = \frac{E_w}{E_I}, \quad (24)$$

where $E_w$ is the average signal energy of one WLAN symbol and $E_I$ is the average interference energy affecting one WLAN symbol. According to [8], the Bluetooth impact on WLAN is small when the SIR is above 10 dB, and we have accordingly concentrated on SIR below this value.

In Figure 1, the BER is plotted vs the SIR for SNR = 10 dB and a payload of 12000 bits. As can be seen from the figure the BER is much lower for the receiver employing MRC and IRC as compared to the receiver with one antenna. Also seen in the figure is that the IRC algorithm performs about 2–3 dB better than the MRC algorithm. Figure 2 shows the throughput for the same case. The increase in throughput due to spatial diversity is about 1–1.5 Mbps.

Further, Figure 3 and 4 shows the throughput for IEEE 802.11b as a function of different fragment sizes with a Bluetooth network load of 100%. As seen in the figures, the throughput drops rapidly with decreasing fragment sizes. The differences in the two figures can be explained by the fact that the simulations for Figure 3 are based on probabilities and do not count for SIR and SNR, which the simulations for Figure 4 do (they are conducted on bit level). As also seen from

Figure 1: Bit error rate for IEEE 802.11b.

Figure 2: IEEE 802.11b throughput.

Figure 4, the MRC and the IRC algorithms will even perform better with Bluetooth interference than the one antenna receiver will without the Bluetooth interferer. We refer the reader to [13] for further details and examples.

7. CONCLUSIONS

The performed BER simulations show that both the IRC and the MRC algorithms perform well in suppressing the Bluetooth interference. The diversity gain yields a high BER reduction, as compared to a receiver with one antenna. The throughput measure well illustrates the gain in transmission performance between the different receivers. Our simulations show that, the receiver employing two antennas and the IRC algorithm gives the highest throughput, typically
1–2 Mbps higher than the one antenna receiver.

The presented work show that utilizing spatial diversity with well chosen interference cancellation algorithms can efficiently reduce the impact of Bluetooth interference.

8. REFERENCES


