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Diversity Techniques for Interference Mitigation between IEEE 802.11 WLANs and Bluetooth

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***Abstract*— Wireless LANs (for e.g., IEEE 802.11g) and Wireless Personal Access Networks (WPANs) operate in the same 2.4 GHz ISM frequency band. In this paper, we consider the techniques to mitigate the interference caused by WPANs (e.g., Bluetooth) on the IEEE 802.11 wireless LAN. In particular, we consider the downlink where an adjacent Bluetooth device interferes with a WLAN station. We show that a simple frequency diversity scheme makes the IEEE 802.11 WLAN robust to the narrow band interference caused by a Bluetooth device. We also propose an interference cancellation algorithm which estimates the interference and reconstructs the WLAN signal (which is interference free). We compare our scheme with that of the existing architecture. We show that our scheme offers a significant gain compared to the existing architecture. Other techniques like error control coding may also be used for interference mitigation. But, coding does not exploit the inherent frequency diversity gain that we show in this paper. Hence, the performance of our scheme would be much better than what one would expect with coding techniques.**

I. INTRODUCTION

In the era of 3G wireless, multimedia services requiring data rates of the order of Mbps are envisaged. Wireless Local Area Networks (WLANs), for example IEEE 802.11g, provide bit rates of 6, 9, 12, 18, 24, 36, 48 and 54 Mbps thus providing a promising solution to the high data rate multimedia applications. WLANs operate in the 2.4 GHz unlicensed spectrum and can co-exist with a cellular network. Thus, WLANs are being deployed in the hotspot areas, such as campuses, hotels and offices.

Also, the proliferation of mobile computing devices including laptops, personal digital assistants (PDAs), and wearable computers has created a demand for wireless personal area networks (WPANs). Both, WLANs and WPANs operate in the 2.4 GHz Industrial Scientific and Medical (ISM) band which extends from 2.4 to 2.483 GHz. This (unlicensed) ISM band is also used by other devices such as baby monitors, garage door openers, microwave ovens etc, creating interference to the WLAN device. Thus, WLANs suffer from a great deal of interference from the devices operating in the ISM band.

According to the IEEE 802.15 Working Group, interference between IEEE 802.11 and Bluetooth cause a severe degradation of the systems' throughput when the distance between the interfering devices is less than 2 m; a slightly less significant degradation is obtained when the distance ranges between 2 and 4 m [5]. In order to mitigate such an effect, the IEEE 802.15 Working Group has created the Task Group 2 (TG2), which is devoted to the development of *coexistence mechanisms* [7], i.e., techniques that allow 802.11 and Bluetooth to operate in a shared environment without significantly affecting the performance of each other [2].

The effect of Bluetooth interference on the coverage of IEEE 802.11g has been studied in [6]. Also, [6] assumes the knowledge of interference in the WLAN transmitter and *erases* the subchannels which suffer interference from Bluetooth transmission. The results in [6] show that as the number of erasures increases the impact of interference on coverage is less severe. [3] analyzes the effect of the interference between IEEE 802.11b WLANs and bluetooth, mainly through simulations. One of the important findings in [3] is that increasing WLAN transmission power to even fifty times the power of Bluetooth is not sufficient to reduce the WLAN packet loss. In [1], traffic scheduling techniques which mitigates interference between IEEE 802.11 WLANs and bluetooth are proposed. In this paper, we propose a frequency diversity based technique for IEEE 802.11g which do not require any information about the interfering Bluetooth device or any additional functional blocks in the physical layer of the WLAN system. We also propose a simple interference cancellation mechanism which filters out the interference from the received signals; thus providing a better estimation of transmitted symbols.

The rest of the paper is organized as follows. In Sec. II, we describe the bluetooth and the WLAN technologies. In Sec. III we present the system model and then analyze the performance of our system. Sec. IV provides the simulation study of IEEE 802.11 WLAN system with frequency diversity and in an interfering bluetooth network. The performance results are compared against the system employing error correcting codes. Sec. V concludes the paper.

II. SYSTEM BACKGROUND

A. Bluetooth

Bluetooth operates in the unlicensed ISM band between 2.4 and 2.480 GHz. The bandwidth of a Bluetooth link is 1 MHz. Thus, 79 RF channels are available for Bluetooth transmission (23 channels in some countries). The range for Bluetooth communication is 0-30 feet (10 meters) with a power consumption of 0dBm (1mW). However, by boosting the transmit power to 20 dBm, the range can be increased to 100 meters. The signal is modulated using binary Gaussian

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Frequency Shift Keying (GFSK). The Bluetooth radio system is optimized for mobility.

Since many devices using different physical layers operate in the ISM band, Bluetooth is highly susceptible to interference. Hence, Bluetooth uses Frequency Hop Spread Spectrum (FHSS) scheme to avoid interference. The frequency hopping rate is 1600 hops per second. Thus, the time slot between successive hops is 625 micro second. This trades bandwidth efficiency for reliability, integrity and security.

Bluetooth supports two kinds of links: Asynchronous Connectionless (ACL) links for data transmission and Synchronous Connection oriented (SCO) links for audio/voice transmission. The raw data rate of Bluetooth is 1 Mbps while the maximum effective rate on an asymmetric ACL link is 721 Kbps in either direction and 57.6 Kbps in the return direction. A symmetric ACL link allows data rates of 432.6 Kbps. Bluetooth also supports up to three 64Kbps SCO channels per device. These channels are guaranteed bandwidth for transmission.

Two or more Bluetooth devices can communicate on the same channel. In this case, they form a star topology, where there is a central master device and the peripheral slave devices. This adhoc configuration is called a piconet. All devices within a piconet share the same channel. There may be up to seven active slaves at a time within a piconet. Thus, each active device within a piconet is identifiable by a 3-bit active device address. Inactive slaves in unconnected modes may continue to reside within the piconet. A master is the only device that may initiate a Bluetooth communication link. However, once a link is established, the slave may request a master/slave switch to become the master. All communication occurs within the slave and the master. Slaves are not allowed to talk to each other directly. Slaves within a piconet must also synchronize their internal clocks and frequency hops with that of the master. A master device in a piconet transmits on even numbered slots and the slaves may transmit on odd numbered slots.

There are several piconets in a large Bluetooth network. Each piconet uses a different frequency hopping sequence. Multiple piconets with overlapping coverage areas form a scatternet. Each piconet may have only one master, but slaves may participate in different piconets on a time-division multiplex basis. A device may be a master in one piconet and a slave in another or a slave in more than one piconet.

B. *IEEE 802.11 WLAN*

IEEE 802.11 standards are defined in [4]. In [4], the physical (PHY) and medium access control (MAC) layers of IEEE 802.11 WLANs are defined.

The physical layer handles the transmission of data between nodes. It can use either direct sequence spread spectrum, frequency-hopping spread spectrum, or infrared (IR) pulse position modulation. IEEE 802.11g makes provisions for data rates of 6, 9, 12, 18, 24, 36, 48 and 54 Mbps and calls for operation in the 2.4 - 2.4835 GHz frequency band which is an unlicensed band for industrial, scientific, and medical (ISM) applications. WLAN standards like IEEE 802.11a, IEEE 802.11g use OFDM as the physical layer transmission with 1024, 256 or 64 subchannels.

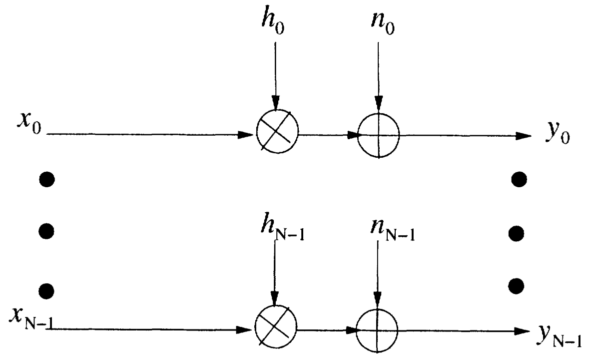

Fig. 1. OFDM System Model

WLANs using IR transmission operating in the 5 GHz band is generally considered to be more secure to eavesdropping, because IR transmissions require absolute line-of-sight links (no transmission is possible outside any simply connected space or around corners), as opposed to radio frequency transmissions, which can penetrate walls and be intercepted by third parties unknowingly. However, infrared transmissions can be adversely affected by sunlight, and the spread-spectrum protocol of 802.11 does provide some rudimentary security for typical data transfers.

III. SYSTEM MODEL AND ANALYSIS

The IEEE 802.11a and IEEE 802.11g WLAN systems use OFDM for transmission. The basic idea of OFDM is to divide the available spectrum (frequency selective channel) into several subchannels (subcarriers). By making all subchannels narrow band, they experience almost flat fading, which makes equalization very simple. For high spectral efficiency, the subchannels are chosen such that their frequency response are overlapping and orthogonal and hence the name OFDM. The orthogonality of all the subchannels can be completely maintained even if the signal passes through a time dispersive channel, by introducing cyclic prefix. This allows a OFDM system to be modelled as a set of N parallel Gaussian channels as shown in Fig. 1. We assume that the fading in all the N subchannels are independent.

Since the WLANs and Bluetooth operate in the same ISM band, the downlink signal corresponding to a WLAN device is severely interfered by a nearby Bluetooth device. In IEEE 802.11g, the number of subchannels, N is typically 64 and the OFDM signal occupies approximately 16 MHz of the 20 MHz bandwidth. Since the bandwidth of the Bluetooth signal is 1 MHz, one would expect the interference in approximately 4 of the subchannels. Here, in this study, we assume that the Bluetooth signals affect m OFDM subchannels (where m is assumed to be much smaller than $N/2$). In each of the OFDM subchannels, we use one of the following modultion schemes: BPSK, QPSK, 16-QAM or 64-QAM.

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A. Diversity Transmission Techniques

The key idea in maximizing the reliability of transmission in an interference channel is to replicate the signal in frequency or time. Typically, the wireless channel experience a block fading phenomenon and hence one cannot expect much from a time diversity transmission. Since $m \ll N/2$, a frequency diversity of order 2 can be used to mitigate the interference and also obtain a diversity gain. There are other approaches like coding, scheduling etc which aim at mitigating the interference. It is generally observed that diversity gain is more significant than the coding gain and hence diversity transmission is preferred over channel coding. Scheduling algorithms usually require information regarding the WLAN and Bluetooth network at a central device or at all devices. This would be difficult to achieve in many cases and hence scheduling may not always be possible. Thus, we look at the performance of frequency diversity techniques for interference mitigation.

Let x_i be the symbol transmitted in the ith subchannel. We assume that the ith subchannel undergoes Rayleigh fading, h_i. The received signal can be described as

$$y_i = h_i x_i + n_i + I_i, \; i = 0, 1, 2, \ldots, N-1 \qquad (1)$$

where n_i is the zero mean Additive White Gaussian Noise (AWGN) with variance σ^2 and I_i is the interference on the ith subchannel. It is to be noted that out of $I_0, I_1, \ldots I_{N-1}$ only m of them $(I_j, I_{j+1}, \ldots I_{j+m-1})$ are non-zero. Since we have a frequency diversity of order 2,

$$x_{\frac{N}{2}+i} = x_i \; i = 0, 1, 2, \ldots, N/2-1. \qquad (2)$$

Thus, of the two transmitted copies of x_i, at most one copy is corrupted by interference.

We assume that the receiver has perfect knowledge of the OFDM channel. We use Maximal Ratio Combiner (MRC) to combine the diversity signals from subchannels i and $N/2+i$. It is clear that $N/2-m$ x_i's do not suffer from interference and the output of MRC of these subchannels are given by

$$\begin{aligned} y_i^* &= h_i^* y_i + h_{\frac{N}{2}+i}^* y_{\frac{N}{2}+i} \\ &= \left(|h_i|^2 + |h_{\frac{N}{2}+i}|^2\right) x_i + Z_i \qquad (3) \end{aligned}$$

where $Z_i = h_i^* n_i + h_{\frac{N}{2}+i}^* n_{\frac{N}{2}+i}$. It is clear that $\mathrm{E}Z_i = 0$ and $\mathrm{Var}(Z_i) = \left(|h_i|^2 + |h_{\frac{N}{2}+i}|^2\right)\sigma^2$. Thus, the Signal to Noise ratio (SNR) of the subchannels which do not suffer from interference are given by $(|h_i|^2 + |h_{\frac{N}{2}+i}|^2)\mathrm{E}|x|^2/\sigma^2$.

It is to be noted that one of the copies of m x_i's suffer from interference. For these set of subchannels which are affected by interference, the combiner output is given as

$$\begin{aligned} y_i^* &= h_i^* y_i + h_{\frac{N}{2}+i}^* y_{\frac{N}{2}+i} \\ &= \left(|h_i|^2 + |h_{\frac{N}{2}+i}|^2\right) x_i + Z_i + \widetilde{I}_i \qquad (4) \end{aligned}$$

If I_i is assumed to be Gaussian then $\widetilde{I}_i$ is also Gaussian for a given channel state and the variance of $\widetilde{I}_i$ is given by $|h|^2 P_I$ where P_I is the interference power and $|h|^2$ is either $|h_i|^2$ or $|h_{\frac{N}{2}+i}|^2$. Without loss of generality, we assume that $|h|^2 = |h_i|^2$. Thus, the SNR of the subchannels that are affected by interference is given by $\frac{(|h_i|^2+|h_{\frac{N}{2}+i}|^2)\mathrm{E}|x|^2}{\sigma^2+\frac{|h_i|^2}{(|h_i|^2+|h_{\frac{N}{2}+i}|^2)}P_I}$.

The average symbol error rate of such a system is given by

$$\begin{aligned} P_s &= \frac{N-2m}{N} \int g\left(\frac{(\alpha_1+\alpha_2)\mathrm{E}|x|^2}{\sigma^2}\right) f(\alpha_1, \alpha_2) d\alpha_1 d\alpha_2 \\ &+ \frac{2m}{N} \int g\left(\frac{(\alpha_1+\alpha_2)\mathrm{E}|x|^2}{\sigma^2 + \frac{\alpha_1}{\alpha_1+\alpha_2} P_I}\right) f(\alpha_1, \alpha_2) d\alpha_1 d\alpha_2 \qquad (5) \end{aligned}$$

where $g(.)$ is the symbol error probability of a given SNR for a particular modulation scheme and $f(.,.)$ is the joint probability density function of the random variables $|h_i|^2$ and $|h_{N/2+i}|^2$. It is to be noted that the random variables $|h_i|^2$ and $|h_{N/2+i}|^2$ are independent and exponentially distributed with mean 1. From Eqn. 5, it is clear that with second order diversity, the interference power is scaled down by a fraction $\alpha_1/(\alpha_1+\alpha_2)$. By a similar analysis, one can show that an Lth order diversity mitigates the interference power by $\alpha_1/(\alpha_1+\ldots+\alpha_L)$ and boost the signal energy by $\alpha_1+\ldots+\alpha_L$.

The performance of the frequency diversity scheme stated above can be analyzed as follows. The average reduction in interference on L fold diversity is given by

$$\begin{aligned} &\int_0^\infty \cdots \int_0^\infty \frac{\alpha_1}{\alpha_1+\ldots+\alpha_L} e^{-\alpha_1} \ldots e^{-\alpha_L} \, d\alpha_1 \ldots d\alpha_L \\ &= \frac{1}{L} \qquad (6) \end{aligned}$$

Thus, on the average, the interference power is reduced by L times and the signal power is boosted by L times on Lth order frequency diversity.

B. Interference Cancellation

Here, we propose a model and a scheme for interference cancellation in a WLAN system. We follow the frequency diversity approach stated in the previous section. We assume that the WLAN receiver (Wireless station, in this case) knows the information about the channels which are prone to interference. The interference signals from the Bluetooth transmitter are in the same frequency band as some of the subchannels of IEEE 802.11g OFDM system. Also, as the symbol duration of 802.11g is much shorter than the symbol duration of Bluetooth transmission, we assume that the interference is approximately the same in all the m subchannels of 802.11g. This simplistic assumption allows us to derive a better receiver structure for interference cancellation. Even if the interference in each subchannel is different and follows some distribution, our conjecture is that the receiver structure proposed here will perform atleast as good as the conventional receiver (without interference cancellation).

In this scheme, we first estimate the transmitted symbol of a WLAN device from MRC techniques as shown above. We then subtract the estimated signal component in the received signal. Thus, we have the collection of the m samples (corresponding to the interference channels) which represent the AWGN and interference only. These m samples are averaged and the interference is estimated to be the average. We then subtract the interference from the corresponding m subchannels and estimate the transmitted symbols again.

Let the subchannels $j, j+1, \ldots, j+m-1$ be affected by interference from neighboring Bluetooth network. Without loss of generality, we assume that $j < N/2$. Thus, the received signal from the interference prone channel is given by

$$\begin{aligned} y_i &= h_i x_i + n_i + I \quad i = j, j+1, \ldots, j+m-1 \\ y_{\frac{N}{2}+i} &= h_{\frac{N}{2}+i} x_i + n_{\frac{N}{2}+i}. \end{aligned} \tag{7}$$

The received signals y_i and $y_{\frac{N}{2}+i}$ are then combined using MRC and the transmitted symbol, x_i is estimated. Let the estimate be $\widehat{x}_i$. Using these estimates $\widehat{x}_j, \widehat{x}_{j+1}, \ldots, \widehat{x}_{j+m-1}$, we estimate the interference I from the received signals $y_j, y_{j+1}, \ldots, y_{j+m-1}$.

$$\widehat{y}_i = y_i - h_i \widehat{x}_i \quad i = j, j+1, \ldots, j+m-1 \tag{8}$$

I is estimated as

$$\widehat{I} = \frac{\sum_{i=j}^{j+m-1} \widehat{y}_i}{m} \tag{9}$$

We then subtract this estimated interference from the corresponding y_i's and then estimate the transmitted symbols from the interference free signals.

$$\widetilde{y}_i = y_i - \widehat{I} \quad i = j, j+1, \ldots, j+m-1 \tag{10}$$

We then estimate x_i from $\widetilde{y}_i$ and $y_{N/2+i}$ for the subchannels $i = j, j+1, \ldots, j+m-1$.

IV. SIMULATION RESULTS

We compare the performance of the frequency diversity scheme with that of No Diversity Transmission (NDT). We consider a OFDM system with N = 64 subchannels. We assume that the Bluetooth interference affects m = 10 OFDM subchannels. The OFDM subchannels undergo independent Rayleigh fading. In Diversity Transmission (DT) scheme, 32 ($N/2$) BPSK symbols are transmitted in N=64 subchannels. Thus, subchannel i and $32 + i$ carry the same BPSK symbol. We assume that the interference power is 1 mW (worst case scenario) and it is the same in all the m = 10 interfering subchannels. The receiver does a MRC on the two diversity signals and the transmitted symbols are estimated. The symbol error rate is plotted in Fig. 2.

Fig. 2 also compares the performance of the DT scheme with that of NDT. In the NDT, the symbol rate is double that of DT. But the symbol error rate performance of NDT is very poor compared to that of DT. For example, to achieve a bit error rate (BER) of 10^{-3} DT requires SNR of 8 dB whereas NDT requires more than 18 dB. This number translates to a huge margin for packet loss probability. We also compare the performance of the DT and the NDT schemes under the 64-QAM constellation. Fig. 2 also shows that there is a huge saving in power as one goes from NDT to DT. To achieve a BER of 10^{-1} DT requires 12 dB whereas NDT requires 18 dB.

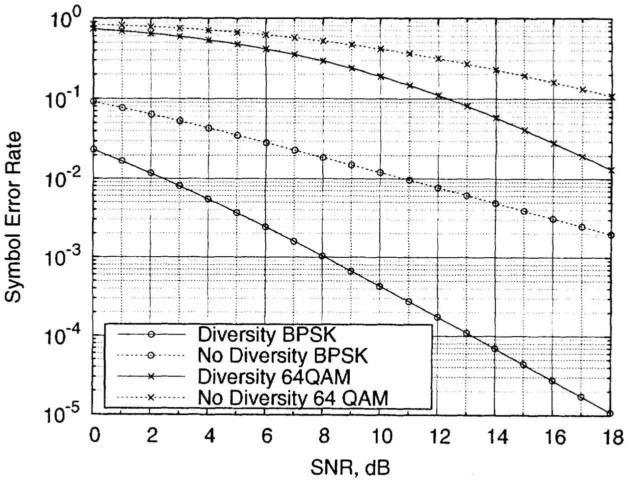

Fig. 2. Simulation Results

Since error control coding helps in combating errors, it could be used as a means of mitigating interference as well. One could explore the possibility of interference suppression in IEEE 802.11 WLAN systems using a rate 1/2 (and K = 7) convolution code with the generator polynomials 0x6d and 0x4f. A block (Rayleigh) fading channel is assumed and the length of the block is assumed to be one code block length (i.e., the channel is fixed for one code block transmission). The length of a code block is taken to be 2320 coded bits. One could study the transmission of BPSK symbols on the N = 64 subchannels. The receiver employs a 8-bit soft decision viterbi decoder. The BER performance of this system could be evaluated The performance of the coded system is believed to be poor than that of the system employing frequency diversity.

It is to be noted that the Bluetooth changes frequency at the rate of 1600 hops per second or the time between frequency hopping is 625 μs. This means that during some OFDM symbol transmission the interference signals hops from $j_1, j_1+1, \ldots, j_1+m-1$ to $j_2, j_2+1, \ldots, j_2+m-1$ thus affecting $2m$ OFDM subchannels. But, the total interference power is divided between $2m$ OFDM subchannels instead of m subchannels. The above analysis given in Eqn. 5 will then provide an upper bound on the symbol error rate by replacing m with $2m$.

V. CONCLUSION

In this paper, the problem of interference between IEEE 802.11 WLANs and Bluetooth operating in the same 2.4 GHz ISM band was considered. In particular, we considered IEEE 802.11g which uses OFDM for physical transmission. We provided two different techniques which mitigate interference from a Bluetooth device to a WLAN device. The first technique we analyzed was the frequency diversity transmission of order L which provides significant gain in the symbol error rate. We observed that an Lth order diversity suppresses interference power by an order L and boosts the signal power by L fold. We compared the performance of this scheme with that of no diversity transmission. This would translate into a huge margin for the packet error loss. In the second technique, we proposed an algorithm which estimates the interference and cancels out from the received signals. From the interference free signals, we estimate the transmitted symbols. The advantage of these techniques is that it is very easy to implement without affecting any other functional blocks. Also, we compared the frequency diversity technique with a system which does not have any diversity transmission. We found that the techniques proposed here offers a promising solution to the reliable transmission problem in interference channels. Also, the diversity and interference cancellation techniques proposed here could provide a much higher performance gain as compared to error control coding.

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