CHANNEL ESTIMATION IN 802.11G IN THE PRESENCE OF BLUETOOTH INTERFERENCE

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ABSTRACT

In this paper, we provide a model for the Bluetooth (BT) interference and propose interference mitigation techniques at the channel estimation stage in IEEE 802.11g Wireless Local Area Network (WLAN) receivers. BT signal has been modelled as a narrow band tonal interference. Estimation of the BT interference by the Estimation of Signal Parameters using Rotational Invariance Techniques (ESPRIT) algorithm is proposed. The structure of the 802.11g preamble is exploited to define the Difference Terms (DTs). The 802.11g signal is subtracted out in DTs and the ESPRIT algorithm efficiency is improved by operating on non-colored noise environment. The reconstructed interference signal is subtracted from the received time domain signal before getting the Least Square (LS) channel estimates. The proposed 'ESPRIT-LS' algorithm is shown to outperform the simple LS channel estimation algorithm in terms of channel estimation Mean Squared Error (MSE) and the Bit Error Rate (BER) for a range of interference power levels.

1. INTRODUCTION

The IEEE 802.11g [1] communication systems operating in the 2.4 GHz Industrial, Scientific and Medical (ISM) band experience unintentional interference from the BT systems [2]. Cooperative methods employed in the Medium Access Control (MAC) layer have been proposed [3] to avoid collision between the 802.11g and BT packets. Such methods reduce the bit rate of the WLAN system [4]. In [5] symbols on the 802.11g subcarriers with high levels of BT interference are replaced by erasures to avoid a large bias to the path metrics in the Viterbi algorithm while in [6], weighting the reliability metrics for the bits of a subcarrier according to the level of interference present on that subcarrier is suggested. In both cases it is assumed that the frequency band of the BT interference is known. In [7], a Radio Frequency Interference (RFI) (a narrow-band interference) cancellation scheme for Discrete Multi Tone (DMT) based Very High Speed Digital Subscriber Line (VDSL) systems is proposed. It measures the interference on a number of unused tones where the RFI is expected and then extrapolates and subtracts estimates of the interference on the modulated tones. This method relies on the availability of unused tones in the expected interference band. As explained later, it is not practical in the case of 802.11g systems.

In this paper, we model the BT interference and suggest interference mitigation techniques in the Physical layer (PHY) of 802.11g systems. We investigate the ESPRIT algorithm for estimation of the tonal BT interference. The ESPRIT algorithm performance degrades in the presence of colored noise [8]. To rectify the problem, we exploit the structure of the Long Training Field (LTF) of the 802.11g preamble to construct the DTs. The 802.11g signal is subtracted out in the DTs and, as a result, the ESPRIT algorithm operates in a white additive noise environment.

This paper is organized as follows. Section 2 gives relevant features of 802.11g and the BT systems. A BT interference model is proposed in this section, too. Section 3 describes interference estimation and mitigation techniques. Simulation results are presented in Section 4. Finally, conclusions are drawn in Section 5.

Throughout this paper, the time domain data are represented with lower-case, frequency-domain data with upper-case, vectors and matrices with bold face letters. The symbols $(\cdot)^T$, $(\cdot)^H$, and $(\cdot)^{-1}$ represent matrix transposition, Hermitian, and inversion, respectively.

2. SIGNAL MODELS

The signal bandwidth used in 802.11g system is 20 MHz. It uses Orthogonal Frequency Division Multiplexing (OFDM) with N=64 point Fast Fourier Transform (FFT). Therefore, the total duration of one OFDM symbol including a 16 point Cyclic Prefix (CP) is $((16+64)/20MHz)$ is $4\mu s$ [4]. An 802.11g PHY packet consists of the Physical Layer Convergence Protocol (PLCP) preamble, signal and data fields. The packet has variable lengths ranging from $40\mu s$ to $300\mu s$ depending upon the number of OFDM symbols used in the data field. The preamble consists of ten short training sequences used for timing and frequency synchronization and two long training sequences used for channel estimation. These two long training sequences, hereafter called the Long Training Field (LTF), consist of two cascaded identical OFDM symbols preceded by a CP of length P. This special structure, given in (2) is very useful for BT interference estimation as described in Section 3.

BT systems provides relatively low data rates for supporting short-range, Wireless Personal Area Networks (WPANs). Gaussian Frequency Shift Keying (GFSK) modulation is used with a modulation index of 0.28 and time-bandwidth product of 0.5 [6]. The BT packet transmission can be 1, 3 or 5 time slots long. It uses Fre-

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quency Hopping (FH) where each packet (single or multi time slot) is sent on one of 79 channels, each having a 1 MHz bandwidth. This FH feature makes it difficult to avail unused tones in 802.11g for BT interference estimation as in [7]. One time slot is 625 μs in which 366 μs is for data transmission and 259 μs is allocated for transient settling [6]. For a collision to occur, the 802.11g and BT packets must coincide both in time and frequency. A 2000 byte long 802.11g packet transmitted in 54 Mbps mode is about 300 μs [6]. Hence an entire 802.11g packet will be corrupted if the BT is transmitting in the 802.11g band. In this paper we only examine the effect of BT interference on channel estimation in 802.11g.

In [9] the BT interference for 802.11b WLANs has been modelled as a narrow band tone. The 1 MHz bandwidth of the BT signal is equivalent to about 3 consecutive bins of an 802.11g system. Therefore, we model the BT interference signal by adding 3 complex sinusoids at consecutive frequencies separated by one 802.11g bin width. Mathematically, the time domain BT interference signal $i(n)$ is given by

$$i(n) = \sum_{k=1}^{3} \alpha_k e^{j(\omega_k n + \varphi_k)}, \quad n = 0, 1, 2, \ldots \tag{1}$$

Here $\omega_k = 2\pi f_k$, α_k, and φ_k represent the angular frequency, amplitude and phases of the 3 tones, respectively. The phases φ_k's are independent random variables uniformly distributed between $[-\pi, \pi)$. Multiple sinusoids have also been used to model the narrow band interference in [10].

Let $X(k),\ k = 0, 1, \ldots, N-1$ be the training symbols to be used for channel estimation in 802.11g. An N-point Inverse DFT (IDFT) (implemented by IFFT) of $X(k)$ is performed. The last $P \geq 2(L-1)$ samples of the IDFT output are appended to its front where L is the length of the channel impulse response. Generation of the time domain LTF $x_l(n)$ is given in (2) at the top of the next page. This time domain signal is convolved with the multipath frequency selective slow fading channel $h(\tau),\ \tau = 0, \ldots, L-1$. In this paper, we consider Rayleigh fading channel in which the time domain channel taps are independent complex Gaussian random variables with an average power profile that decays exponentially with time [4]. The received signal is given by

$$\begin{aligned} r(n) &= \sum_{\tau=0}^{L-1} h(\tau) x_l(n-\tau) + v(n) + i(n), \\ &\quad n = 0, 1, \ldots, 2N + P - 1 \end{aligned} \tag{3}$$

Here $v(n)$ is the zero-mean complex Additive White Gaussian Noise (AWGN) with variance σ_v^2 and $i(n)$ is the BT interference signal. At the receiver first P samples of $r(n)$ are discarded and an N-point DFT of the next N samples is taken. In matrix notation, we can describe it as follows

$$\mathbf{Y} = \mathbf{X}\mathbf{H} + \mathbf{V} + \mathbf{I}$$

where $\mathbf{Y}$, $\mathbf{H}$, $\mathbf{V}$, and $\mathbf{I}$ are the $N \times 1$ vectors denoting the frequency domain received signal, the channel, the noise and the interference, respectively. $\mathbf{X}$ is a $N \times N$ diagonal matrix with the training symbols $X(k),\ k = 0, 1, \ldots, N-1$ at its diagonal. The Least Squares (LS) channel estimate is given by

$$\hat{\mathbf{H}}_{ls} = \mathbf{X}^{-1}\mathbf{Y}$$

Another LS estimate of the channel is obtained by repeating the above procedure for the second symbol in the LTF. The final channel estimate is the average of these two estimates. We refer to this method as 'LS' method in our simulations.

3. INTERFERENCE ESTIMATION AND MITIGATION

Assuming that BT interference starts at the beginning of the LTF. We can write (3) as

$$\begin{aligned} r(n) &= i(n) + [z(n) + v(n)] \\ &= i(n) + e(n), \qquad n = 0, 1, \ldots, \bar{N} - 1 \end{aligned} \tag{4}$$

where $\bar{N} = 2N + P$ is the length of the LTF and $e(n)$ represents the sum of the 802.11g signal $z(n)$ and the AWGN noise $v(n)$.

The 802.11g signal $z(n)$ itself is a sum of sinusoidal. We remove it from the received signal $r(n)$ in (4) and apply the ESPRIT algorithm on the resultant signal to estimate the BT interference signal parameters. In this way, we shall not estimate 802.11g subcarriers as BT interference tones.

Estimation and mitigation of a *single* tone interference using sub-space methods in an OFDM receiver has been proposed in [11]. Subspace methods degrade in the presence of colored noise [8]. The 802.11g signal $z(n)$ manifests itself as colored noise for the interference estimation due to the frequency selective nature of the multipath channel. We can rectify the problem by using the DTs defined in [11]. The 802.11g signal is removed in the DTs and it further enhances the BT interference estimation efficiency of the ESPRIT algorithm. We exploit the structure of the LTF and avail sufficient number of the DTs to estimate multiple sinusoidal BT interference at the channel estimation stage in 802.11g.

Due to the special structure of the LTF, we have

$$z(n) = z(n+N), \quad n = L-1, L, \ldots, P + N - 1$$

We then define the DTs as

$$\begin{aligned} d(n) &= r(n + L - 1 + N) - r(n + L - 1), \\ &\quad n = 0, 1, \ldots, \bar{N}_1 - 1 \end{aligned}$$

Here $\bar{N}_1 = P + N - L + 1$. we have in the sequel

$$\begin{aligned} d(n) &= \bar{i}(n) + \bar{v}(n) \\ &= \sum_{k=1}^{3} \alpha_k e^{j(\omega_k(n+L-1)+\varphi_k)}(e^{j\omega_k N} - 1) + \bar{v}(n), \\ &\quad n = 0, 1, \ldots, \bar{N}_1 - 1 \end{aligned} \tag{5}$$

Where $\bar{v}(n)$ is the zero mean complex AWGN with variance $2\sigma_v^2$. We see that the 802.11g signal has been subtracted out in (5).

$$x_l(n) = \begin{cases} x_l(N+n), & n = 0, \ldots, P-1 \\ \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k) e^{j\frac{2\pi k(n-P)}{N}}, & n = P, \ldots, P+N-1 \\ x_l(n-N) & n = P+N, \ldots, 2N+P-1 \end{cases} \tag{2}$$

The BT interference parameters estimation problem using the ESPRIT algorithm can be described as below. We define $\mathbf{d}_1 = [d(n), d(n-1), \ldots, d(n-m+1)]^T$, then the covariance matrix of $\mathbf{d}_1$ is given by

$$\hat{\mathbf{r}} \triangleq \frac{1}{(\bar{N}_1 - m + 1)} \sum_{n=m}^{\bar{N}_1} \mathbf{d}_1 \mathbf{d}_1^H$$

Here m is the number of lags used to estimate the covariance matrix $\hat{\mathbf{r}}$ and determines the complexity and accuracy of the ESPRIT algorithm. Let $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_m$ denote the eigenvalues of $\hat{\mathbf{r}}$, and $\hat{\mathbf{s}} = \{\mathbf{s}_1, \ldots, \mathbf{s}_3\}$ is an $m \times 3$ matrix of orthonormal eigenvectors of $\hat{\mathbf{r}}$ associated with $\{\lambda_1, \ldots \lambda_3\}$, We define

$$\begin{aligned} \hat{\mathbf{s}}_1 &= (I_{m-1} \quad 0\,)\,\hat{\mathbf{s}} \\ \hat{\mathbf{s}}_2 &= (0 \quad I_{m-1}\,)\,\hat{\mathbf{s}} \\ \hat{\mathbf{s}}_3 &= (\hat{\mathbf{s}}_1^H \hat{\mathbf{s}}_1)^{-1} (\hat{\mathbf{s}}_1^H \hat{\mathbf{s}}_2) \end{aligned}$$

If $\boldsymbol{\xi} = [\xi_1, \ldots, \xi_3]^T$ denote the eigenvalues of $\hat{\mathbf{s}}_3$, then the (angular) frequency estimates of the BT interference are given by [8],

$$\hat{\boldsymbol{\omega}} = -\arg(\boldsymbol{\xi}) \tag{6}$$

where $\hat{\boldsymbol{\omega}} = [\hat{\omega}_1, \ldots, \hat{\omega}_3]^T$.

To estimate the amplitude and the phase of the interference, we define

$$\begin{aligned} \hat{\boldsymbol{\alpha}} &= [\hat{\alpha}_1, \ldots, \hat{\alpha}_3]^T \\ \hat{\boldsymbol{\varphi}} &= [\hat{\varphi}_1, \ldots, \hat{\varphi}_3]^T \\ \hat{\beta}_k &= \hat{\alpha}_k e^{j\hat{\varphi}_k} \\ \hat{\boldsymbol{\beta}} &= [\hat{\beta}_1, \ldots, \hat{\beta}_3]^T \\ \mathbf{d} &= [d(0), d(1), \ldots, d(\bar{N}_1 - 1)]^T \\ \mathbf{b}_{\bar{N}_1 \times 3} &= [e^{j\omega_m(l+L-1)}(e^{j\omega_m N} - 1)] \end{aligned}$$

Here $\mathbf{b}$ is the $\bar{N}_1 \times 3$ matrix with $m = 1, 2, 3$, $l = 0, \ldots, \bar{N}_1 - 1$. After getting the estimate of $\boldsymbol{\omega}$ by the ESPRIT algorithm in (6), the least square estimate of $\boldsymbol{\beta}$ is given by [8]

$$\hat{\boldsymbol{\beta}} = (\mathbf{b}^H \mathbf{b})^{-1} \mathbf{b}^H \mathbf{d}|_{\boldsymbol{\omega} = \hat{\boldsymbol{\omega}}} \tag{7}$$

(7) gives the least square estimates of $\boldsymbol{\alpha}$ and $\boldsymbol{\varphi}$.

From the interference parameters estimates in (6) and (7), the interference signal $\hat{i}(n)$ is reconstructed using (1) and subtracted from (3) before taking the DFT at channel estimation stage. The LS estimates of the channel are then calculated from the DFT of the corrected signal. A second channel estimate is calculated by subtracting the constructed BT interference signal from the second symbol in the received LTF, taking the DFT and calculating the LS channel estimate. The final channel estimate is the average of these two estimates. This method is referred to as the 'ESPRIT-LS' in our simulations.

It should be noted that the DTs are useful only if the frequencies of the BT interference tones are non-coincident with 802.11g subcarriers. The normalized subcarrier frequencies of 802.11g signal are at $0, 1/N, \ldots, (N-1)/N$ respectively. If the frequencies of the interference tones are coincident with 802.11g subcarriers e.g., $f_1 = 27/N$, $f_2 = 28/N$, $f_3 = 29/N$, the term $(e^{j\omega_k N} - 1) = (e^{j2\pi f_k N} - 1) = 0$ for $k = 1, 2, 3$, and the BT interference signal is also subtracted out in (5). We are left with only the noise term in (5) and the DTs can not be used for BT interference parameters estimation. For such scenarios, we have suggested in [12], techniques based on interpolation to get the channel estimates on the BT interference subjected 802.11g subcarriers.

4. SIMULATION RESULTS

Channel estimation is performed using the LTF of the preamble corrupted by BT interference. Ten Thousand packets are transmitted and in each packet independent realization of data, channel, noise and interference are used. Signal and data fields of the packets contain 32 OFDM symbols. QPSK constellation is used and Gray coding is assumed. The channel has an rams delay spread of 50ns which gives L=11 taps. We normalize the channel in our simulations. The value of P used is 20. Perfect timing and frequency synchronization has been assumed at the end of the Short Training Field (STF) of the preamble. We set the non-coincident BT interference at $f_1 = 27.2/N, f_2 = 28.2/N, f_3 = 29.2/N$ in our simulations. We simulate different values of m and choose $m = 45$, which gives best results in terms of MSE and BER. We set $\sigma_x^2 = E\{|X(k)|^2\} = 1$. The Signal to Noise Ratio is defined as $SNR = 10\log(1/\sigma_v^2)$ where $\sigma_v^2 = E\{|v(n)|^2\}$ denotes the noise variance. The value of SNR=30 dB. Signal to (BT) Interference Ratio SIR is defined as $10\log(1/\alpha_2^2)$, α_2^2 is the middle interferer power. The right and left interferers powers are 5 dB lower than the middle one due to the shape of the BT signal spectrum [6]. We show the performance of the algorithms for SIR from -40 dB to 15 dB which implicitly takes into account the distance of the 802.11g receiver to the 802.11g and the BT transmitters.

In Figure 1, the MSE of the channel estimates is plotted against SIR. In Figure 2, we show the effect of channel estimates on the BER without adding the interference at the data detection stage. 'Ref.' plot shows the BER generated by using the actual channel values. The performance of the 'LS' method deteriorates at negative SIRs (high interference powers) and improves with the increase in SIR (decrease in interference power). The proposed 'ESPRIT-LS' method is robust to interference power levels and its channel estimates give BER curve

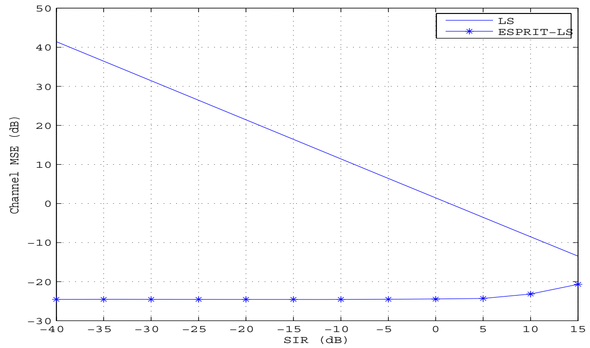

Figure 1: Channel estimate MSE vs SIR at SNR=30 dB.

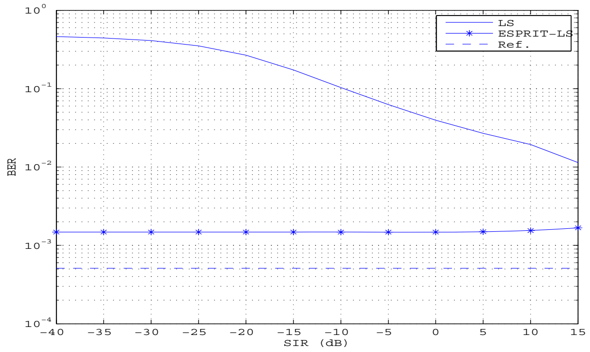

Figure 2: BER vs SIR at SNR=30 dB.

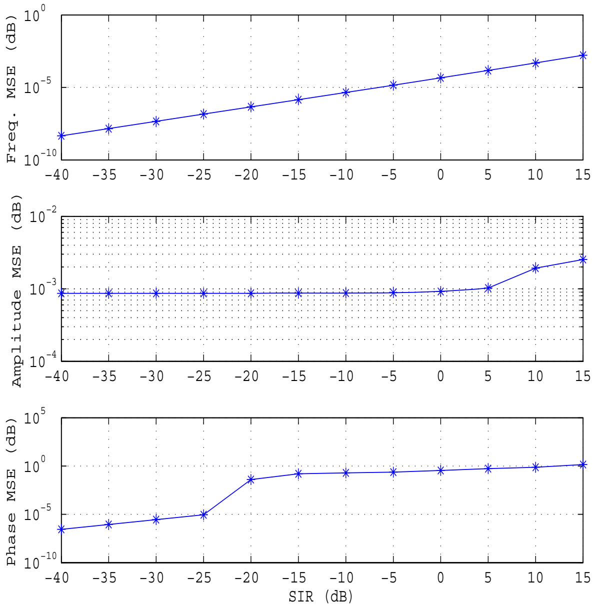

Figure 3: BT interference parameters Estimates MSE of the 'ESPRIT-LS' algorithm for the middle interference tone vs SIR at SNR=30 dB.

close to the 'Ref.' curve. Figure 3 shows MSE of the three (frequency, amplitude, and phase) parameters estimates for the middle interferer by the ESPRIT algorithm. We show results for the middle interferer only (the estimates for the right and the left interferer behaved similarly and are thus omitted in the interest of brevity).

5. CONCLUSIONS

In this paper, BT interference mitigation techniques for the channel estimation in IEEE 802.11g WLAN receivers were proposed. We have shown that the LTF of the 802.11g preamble is useful for BT interference parameters estimation. The simulation results show that the proposed 'ESPRIT-LS' method suppresses the BT interference successfully. Future work will look into BT interference mitigation in 802.11n WLANs.

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