Performance Evaluation of IEEE 802.11g with Smart Antenna System in the Presence of Bluetooth Interference Environment

Shiann Shiuin Jeng, Chen Wan Tsung
Department of Electrical Engineering, National Dong Hwa University
No. 1, Sec. 2, Da Hsueh Rd., Shoufeng, Hualien, 97401, Taiwan
TEL:+886-3-8634065 Fax:+886-3-8634060
ssjeng@mail.ndhu.edu.tw, m9023008@mail.ndhu.edu.tw

Abstract

Due to the coexistence of the Bluetooth and IEEE 802.11g at the ISM band, the performance of the IEEE 802.11g is deteriorated by the Bluetooth interference. This paper evaluates the performance of a smart antenna system applied to an IEEE 802.11g system in the presence of Bluetooth interference environment. The proposed smart antenna system utilizes the spectral spatial smoothing which uses the multi-carrier transmission of an OFDM system to decorrelate the correlation of the received signals and span the signal space. The DOA estimation algorithms can use the signal space derived by spectral spatial smoothing to estimate the DOAs of the received signals and the DOA based beamforming algorithms generate the weighting vector to mitigate the multipath fading, increase the diversity gain, and suppress the co-channel interference of different devices. The simulation results show that the performance of the IEEE 802.11g with the proposed smart antenna system is much better than that without the proposed smart antenna system when the Bluetooth interference exists.

I. Introduction

The IEEE 802.11g system is one of the most popular wireless communication systems. It utilizes 2.4 GHz as the transmission band and adopts OFDM as baseband modulation scheme. The transmission data rate can be promoted up to 54 Mbps. IEEE 802.11g system also utilizes CSMA/CA (Carry Sensing Multiple Access/ Collision Avoidance) in the MAC (Medium Access Control) layer to solve the interference between different IEEE 802.11 systems [1]. Except for IEEE 802.11 series systems, Bluetooth is also a very popular wireless system. It utilizes the frequency hopping as the transmission scheme. In November 2003, Bluetooth SIG adopts the adaptive frequency hopping scheme in the new specification (version 1.2). The Link Manage Protocol (LMP) runs link judgment to avoid interference from other Bluetooth devices utilizing the same occupied bandwidth [2]. However, because both IEEE 802.11g and Bluetooth utilize the same 2.4 GHz ISM transmission band [1,2], the Bluetooth transmitted signals will interfere IEEE 802.11g system and the performance of IEEE 802.11g will be degraded. The CSMA/CA mechanism of the IEEE 802.11g can not avoid the interference from the Bluetooth. There are some references about the cancellation [5, 6] or the performance analysis [3, 4] of the coexistence of Bluetooth and IEEE 802.11g system on the single antenna condition. In order to eliminate the interference from Bluetooth system, this paper proposes a smart antenna system to promote the performance of the IEEE 802.11g system.

II. The proposed smart antenna system

Fig. 1 shows the environment of the 802.11g utilizing the proposed smart antenna system in the presence of Bluetooth interference and multipath signals. First, according to [7], if the transmitted signal is $s(t)$, then the spatial signature at different subcarrier frequency can be expressed as a $M \times P$ matrix, $A$, given by

$$A = [\tilde{a}^1, \tilde{a}^2, ..., \tilde{a}^P] = [\sum_{l=1}^{N} \tilde{a}^1_l (\theta_i, f_j) \tilde{a}^2_l (\theta_i, f_j) ... \sum_{l=1}^{N} \tilde{a}^P_l (\theta_i, f_j)]$$

(1)

where $\tilde{a}^i_l = \sum_{l=1}^{N} \tilde{a}_l (\theta_i, f_j)$ is the spatial signature of the $i$-th subcarrier $f_j$, and $\tilde{a}^i_l (\theta_i, f_j)$ can be represented as

$$\tilde{a}^i_l (\theta_i, f_j) = [\alpha^i_l, \alpha^i_l e^{j2\pi f_l \sin(\theta_i)}, ..., \alpha^i_l e^{j2\pi f_l \sin(\theta_i)^{M-1}}]$$

(2)

$P$ is the number of the subcarrier frequencies, $N_m$ is the number of the received paths, and $\alpha^i_l$ is the difference of
the amplitude and phase between the l-th multipath signal and the direct path at the i-th subcarrier, and M is the number of the receiving antenna elements. c is the speed of the propagation wave. D is the distance of adjacent antenna elements. In order to create a generation set of the signal space, the parameter P must be larger than the number of the antenna elements and the received paths. We also assume that N_m ≤ M. Equation (1) can be rewritten as

\[
A = \begin{bmatrix}
\sum_{l=1}^{N_l} a_l^0 & \sum_{l=1}^{N_l} a_l^1 e^{j2\pi \sin(\theta_l) D} & \cdots & \sum_{l=1}^{N_l} a_l^i e^{j2\pi \sin(\theta_l) D} \\
\sum_{l=1}^{N_l} a_l^1 e^{j2\pi \sin(\theta_l) D} & \sum_{l=1}^{N_l} a_l^2 e^{j2\pi \sin(\theta_l) D} & \cdots & \sum_{l=1}^{N_l} a_l^i e^{j2\pi \sin(\theta_l) D} \\
\vdots & \vdots & \ddots & \vdots \\
\sum_{l=1}^{N_l} a_l^i e^{j2\pi \sin(\theta_l) D} & \sum_{l=1}^{N_l} a_l^{i+1} e^{j2\pi \sin(\theta_l) D} & \cdots & \sum_{l=1}^{N_l} a_l^{m_i} e^{j2\pi \sin(\theta_l) D}
\end{bmatrix}
\]

(3)

In Equation (3), the rank of A is between 1 and M, that is

\[
1 \leq r \leq M
\]

(4)

where r is the rank of A. This analysis shows that A is of full rank and can be the generation set of the signal space of dimension M. Thus, the high resolution subspace based DOA estimation algorithms can be used to correctly estimate the DOAs of the received signals. In Equation (3), A can be represented as the sum of the antenna array response matrices A_1, ..., A_Nm of each path as illustrated by the equation

\[
A = A_1 + A_2 + \cdots + A_{N_m}
\]

(5)

The antenna array response matrix of the l-th multipath signal, A_l, is shown as

\[
A_l = \begin{bmatrix}
\alpha_l^1 & \alpha_l^2 & \cdots & \alpha_l^i \\
\alpha_l^{i+1} & \alpha_l^{i+2} & \cdots & \alpha_l^{m_i}
\end{bmatrix}
\]

(6)

In Equation (6), A_l is composed of antenna array response vectors and can be rewritten as

\[
A_l = [\tilde{a}_l^1(\theta_l, f_i) \quad \tilde{a}_l^2(\theta_l, f_i) \quad \cdots \quad \tilde{a}_l^i(\theta_l, f_i)]
\]

(7)

We rewrite \( \tilde{a}_l^i(\theta_l, f_i) \) as

\[
\tilde{a}_l^i(\theta_l, f_i) = \alpha_l e^{j2\pi f_i \sin(\theta_l) D / c}
\]

(8)

Consider the following matrix

\[
Z_l = \begin{bmatrix}
e^{j2\pi f_1 \sin(\theta_l) D / c} & e^{j2\pi f_1 \sin(\theta_l) D / c} & \cdots & e^{j2\pi f_1 \sin(\theta_l) D / c} \\
\vdots & \vdots & \ddots & \vdots \\
e^{j2\pi f_i \sin(\theta_l) D / c} & e^{j2\pi f_i \sin(\theta_l) D / c} & \cdots & e^{j2\pi f_i \sin(\theta_l) D / c}
\end{bmatrix}
\]

(9)

In Equation (9), \( Z_l \) is an \( M \times P \) Vandermonde matrix and the dimension of \( Z_l \) is \( M \) if \( M = P \). There are \( M \) independent column vectors of matrix \( Z_l \). However, multiplying scalars to column vectors in \( Z_l \) does not change the independence between all vectors and the rank of \( Z_l \). The column vectors of \( A_l \) are therefore the corresponding column vectors of \( Z_l \) multiplied with scalar \( \alpha_l^i \) and they are rank of \( M \). The matrix A is the sum of the matrices \( A_1, ..., A_Nm \) and the column vectors of A are the linear combination of the corresponding column vectors of \( A_1, ..., A_Nm \). Thus, the i-th column vector of A can be written as

\[
\tilde{\alpha}_i = \sum_{l=1}^{N_l} \tilde{a}_l(\theta_l, f_i) = \tilde{a}_l(\theta_l, f_i) + \tilde{a}_l(\theta_l, f_i) + \cdots + \tilde{a}_l(\theta_l, f_i)
\]

(10)

In equation (5) and (10), the matrices \( A_1, ..., A_Nm \) and their linear combination are of rank \( M \), and column vectors of \( A_1, ..., A_Nm \) is of dimension \( M \). Thus, the column vectors of A are also of dimension \( M \). According to the above analysis, \( \tilde{\alpha}_i \) in Equation (14) can be represented as

\[
\tilde{\alpha}_i = \sum_{l=1}^{N_l} \alpha_l b_l + \sum_{l=1}^{N_l} \alpha_l e^{j2\pi f_i \sin(\theta_l) D / c} b_l + \cdots + \sum_{l=1}^{N_l} \alpha_l e^{j2\pi f_i \sin(\theta_l) D / c} b_l
\]

(11)

where \( \tilde{b}_l = [0, 0, \cdots, 1, 0]^T \), that is, the i-th element equals 1 and the others elements equal 0. \( \mathbf{B} = [\tilde{b}_1, \tilde{b}_2, \cdots, \tilde{b}_M] \) forms the basis set of the full signal space.

All column vectors of A can be represented by the basis set \( \mathbf{B} \). Assume that a vector \( \tilde{\mathbf{v}} \) is the linear combination of the column vectors of A. Then, \( \tilde{\mathbf{v}} \) can be written as:

\[
\tilde{\mathbf{v}} = \beta_1 \tilde{\mathbf{a}}_1 + \beta_2 \tilde{\mathbf{a}}_2 + \cdots + \beta_{N_m} \tilde{\mathbf{a}}_{N_m}
\]

(12)

In Equation (12), the vector \( \tilde{\mathbf{v}} \) is composed of the basis. Clearly, any vector in the vector space \( \mathbf{V} \) of dimension M can be represented by the column vectors of
\( \mathbf{A} \) as long as suitable coefficients \( \beta_1 ... \beta_p \) are chosen. Equation (12) can be rewritten as
\[
\tilde{y}_l = \beta_1 \sum_{m=1}^{N} \mathbf{v}_m^T \mathbf{a}_l + \beta_2 \sum_{m=1}^{N} \mathbf{v}_m^T \mathbf{a}_l' + \ldots + \beta_p \sum_{m=1}^{N} \mathbf{v}_m^T \mathbf{a}_l'')
\]

For the linear combination of the array response vector, \( \mathbf{v}_m \) can be chosen as the uplink weighting vector. Thus, the main beam of the radiation pattern is pointed at the desired user and suppress interference from undesired users. In this work, Dominant DOA (DDOA) beamforming algorithm [11] is used to calculate the weighting vectors to get the desired signal and suppress the interference. Fig. 4 shows the radiation pattern of the Dominant DOA beamforming algorithm. After estimating the DOAs of the received signals, the DOA’s by TLS-ESPRIT, the DOA with the maximum amplitude, \( \mathbf{a}' \), is selected and its array response vector, \( \tilde{a}'(\theta_i, f_i) \), is chosen as the uplink weighting vector. Thus, the main beam of the radiation pattern will be pointed at the direction of the dominant path to promote the performance of the system. However, this method will not put the null on the direction of the undesired signals.

III. Simulation Results

1) Simulation model

Fig. 1 shows the simulation block diagram. The modulation utilized in the simulation is QPSK, and the transmission data rate used in this simulation is 12 Mbps. In order to save the simulation time, the convolution code is omitted. The other simulation parameters follow IEEE 802.11g specification. The number of IEEE 802.11g multipath signals is four, and the Bluetooth signal is one. Therefore, the number of DOAs is five and the distribution of DOA is Laplacian. The angle spread is 30° and the mean is 0°. The number of antenna array elements is eight, and the spatial signatures don’t change during the smart antenna system process. The parameters used in this simulation are shown in Table 1. The transmitted signal of the IEEE 802.11g can be represented as
\[
s(t) = s_{FSK} \sum_{i=1}^{N} c_i(t) \exp(2 \pi f_i (t - T_{Sym} - kT_F)) + n(t)
\]

where \( s_{FSK} \) is the window function, \( T_{Sym} \) is the guard interval, \( n(t) \) is the AWGN, \( \tilde{a}_l(\theta_i, f_i) \) is the l-th path antenna array response vector of IEEE 802.11g at the k-th subcarrier, \( \tilde{a}_l(\theta_i) \) is the antenna array response vector of Bluetooth signal. \( N_m \) is the number of the direct path and the multipath signal. First, the receiver acquires the spatial signature matrix, \( \mathbf{A} \), and utilizes the spatial signatures at different subcarriers to span the signal space, \( \mathbf{V}_S \). Then, the DOA estimation algorithm, TLS-ESPRIT, utilizes the signal space, \( \mathbf{V}_S \), to estimate the DOAs of received signals. Finally, the DDOA beamforming algorithm uses the DOAs, \( \{ \theta_i \} \), and the amplitude of multipath, \( \{ \tilde{a}_l \} \), to generate the weighting vectors \( \tilde{w} \) and derive the desired signal. The received signals after beamforming can be represented as
\[
s(t) = w_{FSK} \sum_{i=1}^{N} c_i(t) \exp(2 \pi f_i (t - T_{Sym} - kT_F)) + n(t)
\]
\[ \hat{s}(t) = \hat{w}^T \hat{x}(t) \]  
(17)

where \( \hat{w} \) is the weighting vector generated by the DOA-based beamforming algorithm illustrated in the previous section.

The channel model proposed in [12] is adopted in this simulation. The impulse response can be represented as

\[ c(t) = \sum_{l=0}^{\infty} \sum_{k=0}^{\infty} \beta_{kl} \exp(j \phi_{kl}) \delta(t - T_l - \tau_{kl}) \]  
(18)

where \( T_l \) is the arrival time of the \( l \)-th cluster; \( \tau_{kl} \) is the \( k \)-th received signal arriving at the receiver in the \( l \)-th cluster; \( \phi_{kl} \) is the phase of the received signals and is generated by normal distribution; \( \beta_{kl} \) is the power gain of the \( k \)-th multipath signal in the \( l \)-th cluster.

The amplitude of each received signal is generated from the Rayleigh distribution to model multipath fading [12]. The variance depends on the delay spread by each received signal. When the delay spread of the received signal is longer, the amplitude becomes smaller. The variance of each multipath signal can be represented as

\[ \sigma_{\text{RMS}}^2 = 1 - \exp\left(-T_s / \frac{T_{\text{RMS}}}{\text{RMS}}\right) \]  
(19)

\[ \sigma_{\text{RMS}}^2 = \sigma_0^2 \exp\left(-k T_s / \frac{T_{\text{RMS}}}{\text{RMS}}\right) \]  
(20)

\[ h_k = N\left(0, \frac{1}{2} \sigma_k^2\right) + jN\left(0, \frac{1}{2} \sigma_i^2\right) \]  
(21)

In the above equations, \( T_s \) is the sampling time; \( k \) is the index of the received signals; \( \sigma_0 \) is the reference variance to generate the variance of the \( k \)-th path, and \( \sigma_k \) is the variance of the \( k \)-th path. \( T_{\text{RMS}} \) is the root mean square delay time, and \( N(0, \frac{1}{2} \sigma_k^2) \) is the Gaussian distribution with mean and variance equal to 0 and \( \frac{1}{2} \sigma_k^2 \), respectively.

2) Simulation results

Fig. 2 shows the simulation results of the IEEE 802.11g signal transmitted over channels of various SIR without the proposed smart antenna system. The SIR definition in this simulation is defined as

\[ \text{SIR} = \frac{P_S}{P_I} \]  
(22)

Where \( P_S \) and \( P_I \) is the power of the IEEE 802.11g signals and Bluetooth signal respectively. In the simulation results, the performance of the IEEE 802.11g without the proposed smart antenna system is the worst of all cases. Besides, the curve of the IEEE 802.11g without the proposed smart antenna becomes flat at the value of 10 dB of SNR because increasing the SNR increases not only the signal power of IEEE 802.11g but also the interference power of Bluetooth. This will cause an error floor of BER. In Fig. 2, the simulation result shows that the curve of IEEE 802.11g using the proposed smart antenna system does not become flat when the SNR increases. The reason is that the proposed smart antenna system can eliminate the interference from the Bluetooth signal.

Fig. 3 shows the simulation results when the SIR is 20 dB. It shows that the performance of the IEEE 802.11g without the proposed smart antenna system is the worst among all of the cases. However, the curve of IEEE 802.11g without the proposed smart antenna system is closed to the curve of the multipath case due to the SIR increment when Bluetooth interference exists. After using the proposed smart antenna system, the performance of IEEE 802.11g with the proposed smart antenna system has the best results. The simulation results in Fig. 3 reveal that the SNR of the IEEE 802.11g with the proposed smart antenna system is about 1 dB, while the BER is 10^{-5}. However, if the BER of the IEEE 802.11g without the proposed smart antenna system achieves 10^{-3}, the BER is about 11 dB when the Bluetooth interference exists. Thus, the proposed smart antenna system can provide about a 10 dB gain when the SIR is 20 dB. Here, we also compare the improvement in Fig. 3 with that in Fig. 2. In Fig. 2, when the BER is 10^{-3}, the corresponding SNR of the IEEE 802.11 using the proposed smart antenna system is about 1.5 dB. However, no matter how large the SNR increases, due to the error floor caused by Bluetooth interference, the BER of the IEEE 802.11g without the proposed smart antenna system cannot achieve 10^{-3}. Thus, the larger the power of the interference, the more significant the improvement of the proposed smart antenna system becomes.

IV Conclusion

Due to the same transmission band occupied by both systems, Bluetooth signals interfere with those of the IEEE 802.11g signals and degrade its performance. Differing from other methods, this paper proposes a smart antenna system to eliminate the interference of the Bluetooth interference. The performance of the IEEE 802.11g system with the proposed smart antenna system is better than that without the proposed smart antenna system in different SIR cases. Aside from this, when the interference is high, using the proposed smart antenna system can provide greater improvement. Therefore, the proposed smart antenna system applied to the IEEE 802.11g system can eliminate interference from the Bluetooth system and improve the performance of the IEEE 802.11g system.

References

Higher Data Rate Extension in the 2.4 GHz


Table 1 parameters of IEEE 802.11g

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSD</td>
<td>48</td>
</tr>
<tr>
<td>NSP</td>
<td>4</td>
</tr>
<tr>
<td>NST</td>
<td>52 (= NSD+NSP)</td>
</tr>
<tr>
<td>△F</td>
<td>0.3125 MHz (= 20MHz/64)</td>
</tr>
<tr>
<td>TFFT</td>
<td>3.2µs (= 1/△F)</td>
</tr>
<tr>
<td>TPREAMBLE</td>
<td>16µs (= TSHORT+TLONG)</td>
</tr>
<tr>
<td>TSHORT</td>
<td>4.0µs (= TFFT/4)</td>
</tr>
<tr>
<td>TSYM</td>
<td>1.6µs (= TFFT/2)</td>
</tr>
<tr>
<td>TGI2</td>
<td>4µs (= TFFT/2)</td>
</tr>
<tr>
<td>TGI</td>
<td>8µs (= TFFT/4)</td>
</tr>
<tr>
<td>TGI0</td>
<td>8µs (= 2TFFT/4)</td>
</tr>
</tbody>
</table>

Fig. 1 the simulation block diagram

Fig. 2 the simulation results of DDOA beamforming algorithm when SIR is 0 dB.

Fig. 3 the simulation results of DDOA beamforming algorithm when SIR is 20 dB.