Performance Comparison of MQAM OFDM Based WLAN System in Presence of Bluetooth Interference with AWGN and Rayleigh Fading Channel

Minakshmi Roy, H.S. Jamadagni

Abstract— **Wireless local area networks (WLAN) operating in 2.4GHZ ISM band are often subjected to interference from narrowband signal like Bluetooth, Zigbee etc. A system designer should consider the interference effect on WLAN for getting the best performance. Bit error rate (BER) of BPSK-OFDM based WLAN in presence of Bluetooth (BT) interference using rectangular BT spectrum is given in some previous work [19]. But it is seen actual BT spectrum is non rectangular. So when Bluetooth's interference power will be high with respect to WLAN's power BER or symbol error rate (SER) of WLAN obtained using rectangular BT spectrum will not match with actual values of BER or SER in presence of Bluetooth interference. The reason is leakage effect in other sub carriers with respect to the sub carriers where Bluetooth has actually hopped is not considered in case of rectangular BT spectrum. In this paper we propose a interference model to find the power of Bluetooth (BT) interference for each sub-carrier of an OFDM based WLAN. Then using sub carrier power to interference power ratio symbol error rate (SER) for each WLAN sub-carrier is obtained in AWGN and Rayleigh fading channel. Finally average SER for the MQAM-OFDM based WLAN in presence of Bluetooth interference is given. Comparisons of BER or SER using the proposed model with the model of rectangular BT spectrum [19] are given.. From the results it is seen that SER or BER curves using proposed model is closely matching with the actual SER or BER curves.**

Index Terms—**Performance, WLAN, Bluetooth, ISM band, OFDM, IEE802.11g. Performance, SER, AWGN, Rayleigh Fading Channel, SIR, SINR etc**

I. INTRODUCTION

WLAN based on IEEE802.11g standard, very popular because of its number of attractive features like high throughput of 54Mbps, immunity to ISI (intersymbol interference) and ICI(inter carrier interference) etc. IEEE802.11g is a wireless standard, designed for replacement of Ethernet, uses OFDM as modulation and operates in the ISM (Industrial, Scientific, Medical)band of 2.4GHz. It can operate in the range of 100m. Bluetooth is also one of the most popular wireless standards for short range (typically 10m) communication; supports 1Mbps data rate, uses GFSK modulation and operates in 2.4GHz wireless band.

As both the systems operate in the same ISM band interference is inevitable when they operate near to each other at same time. So performance of WLAN in terms SER or BER is definitely worse in presence of Bluetooth. From literature [8,14-19] performance of WLAN in presence of Zigbee, Bluetooth can be found. It is seen most of results are based on experiments. We propose a theoretical model to find the power of Bluetooth interference in each OFDM sub-carrier which will give sub-carrier to interference power ratio and using the sub-carrier to interference power ratio performance of OFDM based WLAN in terms of SER is obtained by averaging the SER of all the sub-carriers. In the previous work [19] it is seen that BT spectrum is modeled as shown in figure2 . But it is seen that BT spectrum is not actually rectangular. For that reason when noise power is high or interference power is low SER obtained using rectangular BT spectrum will not much differ from actual SER. But for the case when interference power is high (signal to interference ratio is less than 20dB particularly for 16QAM or 64QAM OFDM system) SER obtained using rectangular BT spectrum will be less than the actual SER. In the proposed model the spectrum of BT is modeled as shown in figure2 (actual BT spectrum) and for that reason SER obtained using the proposed model is almost matching with the actual SER.

The paper is organized as follows: In section I introduction is given. In section II overview of OFDM and Bluetooth system is given. In section III interference model and analytical SER is given. In section IV simulation results are given. Section V summarizes and concludes the paper

II. OVERVIEW OF OFDM AND BT

In OFDM system information data are coded and modulated using convolution code of certain code rate and any of the MQAM modulation technique respectively. For 54Mbps data rate OFDM signal coding rate, 3/4 and 64QAM modulations is used. The discrete time model of OFDM system block is shown in figure1. The operation of OFDM system is briefly described below [1-4]:

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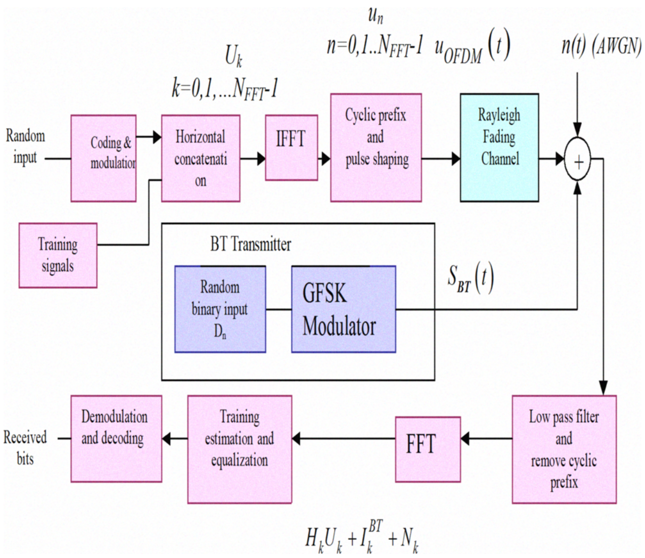

Figure 1. Bluetooth interference in WLAN

Let complex QAM signal of length N_{FFT} before and after the IFFT block be $\mathbf{U}=\left[U_0,U_1,.....U_{N_{FFT}-1}\right]^T$, $\mathbf{u}=\left[u_0,u_1,.....u_{N_{FFT}-1}\right]^T$ respectively. $\boldsymbol{F},\boldsymbol{F}^H$ are $N_{FFT}\times N_{FFT}$ FFT and IFFT matrix respectively.

$$\mathbf{u}=\boldsymbol{F}^H\boldsymbol{U} \tag{1}$$

After inserting cyclic prefix by premultiplying with matrix $\boldsymbol{I}_{CP}$ of dimension $(Ncp+N_{FFT})\times N_{FFT}$, the transmitted vector is passed through the channel. Then cyclic prefix is removed in the receiver by premultiplying with cyclic prefix-remove matrix of $\boldsymbol{R}_{CP}$ of dimension $N_{FFT}\times(Ncp+N_{FFT})$. After that FFT operation is performed on received data. Let $\mathbf{Y}=\left[Y_0,Y_1,.....Y_{N_{FFT}-1}\right]^T$ be $N_{FFT}\times 1$ received matrix after removing cyclic prefix by and performing FFT operation by premultiplying with matrix F.

$$Y_k=\boldsymbol{F}\boldsymbol{R}_{cp}\boldsymbol{H}\boldsymbol{I}_{cp}\boldsymbol{F}^H U_k+N_k \tag{2}$$

where H is the equivalent channel transfer function matrix and N_k is additive white gaussian noise (AWGN). Now inner matrix $\tilde{\boldsymbol{H}}=\boldsymbol{RcpHIcp}$ is a circulant matrix and from the properties of circulant matrix it can be shown:

$$\boldsymbol{F}\tilde{\boldsymbol{H}}\boldsymbol{F}^H=diag\left\{H\left(e^{j0}\right),H\left(e^{j2\pi/N_{FFT}}\right),...,H\left(e^{j2\pi(N_{FFT}-1)/N_{FFT}}\right)\right\} \tag{3}$$

Thus use of cyclic prefix maintains the orthogonally of the carrier which is just weighted by a factor of the channel transfer function. As a result demodulated output after FFT is given by:

$$Y_k=H_kU_k+N_k \tag{4}$$

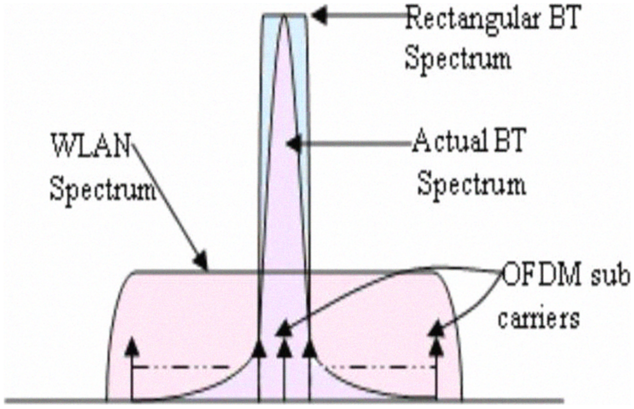

Figure 2. WLAN and Bluetooth Spectrum

Where Y_k corresponds to k^{th} carrier and in matrix form eq (4) can be rewritten as:

$$\boldsymbol{Y}=\boldsymbol{H}\boldsymbol{U}+\boldsymbol{N} \tag{5}$$

Where, $\boldsymbol{H}=diag[H_0,H_1,....,H_{N_{FFT}-1}]$, $\boldsymbol{N}=[N_0,N_1,...,N_{N_{FFT}-1}]^T$

The above diagram shows the interference model of BT in WLAN. Bluetooth signal is modulated by Binary Gaussian frequency shift keying (GFSK). The signal is transmitted using frequency hopping. It hops in any of the 79 frequency band of 1 MHz in the ISM band between 2.402-2.483GHz Each packet is transmitted at different hop frequency with maximum hopping rate of 1600 hops/s. The above diagram also shows the difference between actual non-rectangular BT spectrum and rectangular BT spectrum. It can be clearly noticed from the diagram that when the interferer (BT) power is high number of sub-carriers affected by BT interference will increase which will increase the SER or BER of the OFDM system. But using rectangular BT spectrum the number of sub-carriers affected will remain same for high or low value of BT power. So using the non rectangular BT spectrum which is marked as actual spectrum in the figure2 more accurate value of SER or BER for OFDM system, particularly for lower value of signal to interference ratio (SIR), can be obtained.

III. INTERFERENCE MODEL

The GFSK modulated signal can be written as [9,10,20,22]:

$$S_{BT}(t,\boldsymbol{D})=\left(A\cos\left(2\pi\left(f_c+f_l\right)t+\Phi\left(t;\boldsymbol{D}\right)\right)\right) \tag{6}$$

and its low pass equivalent waveform is written as:

$$S_{BT}(t,\boldsymbol{D})=\mathrm{Re}\left(Ae^{\left(j\left(2\pi f_l t+\Phi\left(t;\boldsymbol{D}\right)\right)\right)}\right) \tag{7}$$

Where, $A=\sqrt{2E_b/T_{BT}}$, E_b is the energy per data bit, T_{BT} is the symbol period and f_c, f_l denotes the carrier and hopping frequency of the BT signal respectively and $l\in\{0,1..78\}$. $\Phi(t,\boldsymbol{D})$ denotes time varying phase of the

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BT signal which can be expressed in the interval $nT_{BT} \leq t \leq (n+1)\, T_{BT}$ as:

$$\Phi(t,\boldsymbol{D}) = 2\pi h \sum_{i=n-L1+1}^{n} D_i q(t - iT_{BT}) + \pi h \sum_{i=-\infty}^{n-L1} D_i \qquad (8)$$

$$= 2\pi h D_n q(t - iT_{BT}) + \theta_n \qquad (9)$$

Where, $q(t) = \int_{-\infty}^{t} g(\tau)\,d\tau$, $g(\tau)$ is the shaping pulse which is obtained by filtering a rectangular pulse with Gaussian filer and L1 is the length of $g(\tau)$ and D_n Є {+1,-1} denotes random data input and h is modulation index. In eq (9) θ_n denotes the accumulation (memory) of all the symbols up to time $(n-1)T_{BT}$ and first part of eq (9) is dependent on the data bit D_n at time instant $nT_{BT.}$ Now from eq (7) and using eq (8) complex valued data at the output of the GFSK modulator is written as:

$$S_{BT}^{c}(t,\boldsymbol{D}) = Ae^{(j(2\pi f_l t + \theta_n))}\left(\cos(2\pi h D_n q(t - nT_{BT})) + j\sin(2\pi h D_n q(t - nT_{BT}))\right) \quad (10)$$

As D_n is +1or -1 and $\cos(x)=\cos(-x)$,sin(x)=-sin(-x);
So eq(10) can be rewritten as :

$$S_{BT}^{c}(t,\boldsymbol{D}) = Ae^{(j(2\pi f_l t + \theta_n))}\left(\cos(2\pi h q(t - nT_{BT})) + jD_n\sin(2\pi h q(t - nT_{BT}))\right) \quad (11)$$

Let $Ae^{(j(2\pi f_l t))}\cos(2\pi h q(t - nT_{BT})) = P(t)$,

$jAe^{(j(2\pi f_l t))}\sin(2\pi h q(t - nT_{BT})) = Q(t)$

Then eq (11) becomes

$$S_{BT}^{c}(t,\boldsymbol{D}) = \left(y_{1n}P(t) + y_{2n}Q(t)\right)e^{j\theta_n} \qquad (12)$$

Where $y_{1n}=1;\ y_{2n} = D_n$

If there are N samples for one BT symbol period, then in matrix form eq(12) is written as:

$$\boldsymbol{S}_{BT_{n,l}}^{c} = \begin{bmatrix} P(nT_{BT}, f_l) & Q(nT_{BT}, f_l) \\ P(nT_{BT}+T_S, f_l) & Q(nT_{BT}+T_S, f_l) \\ . & \\ . & \\ P(nT_{BT}+(N-1)T_S, f_l) & Q(nT_{BT}+(N-1)T_S, f_l) \end{bmatrix} \begin{bmatrix} 1 \\ D_n \end{bmatrix} e^{j\theta_n} \qquad (13)$$

$$= \boldsymbol{B}_{PQ_{n,l}} \boldsymbol{Y}_n e^{j\theta_n} \qquad (14)$$

Where subscript l is given to denote the dependence on l^{th} hopping frequency of Bluetooth.

Where $\boldsymbol{Y}_n = \begin{bmatrix} 1 \\ D_n \end{bmatrix}$,

$$\boldsymbol{B}_{PQ_{n,l}} = \begin{bmatrix} P(nT_{BT}, f_l) & Q(nT_{BT}, f_l) \\ P(nT_{BT}+T_S, f_l) & Q(nT_{BT}+T_S, f_l) \\ . & \\ . & \\ P(nT_{BT}+(N-1)T_S, f_l) & Q(nT_{BT}+(N-1)T_S, f_l) \end{bmatrix}$$

Similarly samples corresponding to next BT symbol (after GFSK modulation) can be written as:

$$\boldsymbol{S}_{BT_{n+1,l}}^{c} = \boldsymbol{B}_{PQ_{n+1,l}} \boldsymbol{Y}_{n+1} e^{j\theta_{n+1}} \qquad (15)$$

$$= \boldsymbol{B}_{PQ_{n+1,l}} \boldsymbol{Y}_{n+1} e^{j(\theta_n + \phi_{S_n})} \qquad (16)$$

$$= \boldsymbol{B1}_{PQ_{n+1,l}} \boldsymbol{Y}_{n+1} e^{j\theta_n} \qquad (17)$$

Where $\boldsymbol{B1}_{PQ_{n+1,l}} = \boldsymbol{B}_{PQ_{n+1,l}} e^{j\phi_{S_n}}$ (18)

Where ϕ_{S_n} is the phase difference of the phase θ_{n+1} of Nth sample of the vector $\boldsymbol{S}_{BT_n}^{c}$ and the initial phase θ_n.

Let $\boldsymbol{S}_{BT_n}^{c^p}$ denote the vectors of GFSK modulated BT samples corresponding to one OFDM symbol period. Where superscript p denotes the number of BT signal in one OFDM symbol period According IEEE802.11g standard [11] one OFDM symbol period T_{OFDM}=4μs and one BT symbol period T_{BT}=1μs. So in one OFDM symbol period there will be 4 BT symbols or the value of p corresponding to one OFDM symbol interval is 4. $\boldsymbol{S}_{BT_n}^{c4}$ has N1=N*4 data samples and $\boldsymbol{B}_{PQ_n}^{4}$ is a N1×8 deterministic matrix and $\boldsymbol{Y}_n^{p}$ is a 8×1 matrix of unknown random data and phase. If $\boldsymbol{S}_{BT_n}^{c^4}$ is a matrix of the samples of the 4 BT modulated symbol then

$$\boldsymbol{S}_{BT_{n,l}}^{c4} = \begin{bmatrix} \boldsymbol{S}_{BT_{n,l}}^{c} \\ \boldsymbol{S}_{BT_{n+1,l}}^{c} \\ . \\ . \\ \boldsymbol{S}_{BT_{n+3,l}}^{c} \end{bmatrix} = \begin{bmatrix} \boldsymbol{B}_{PQ_{n,l}} & & & \\ & \boldsymbol{B1}_{PQ_{n+1,l}} & & \\ . & . & & \\ . & & & \\ & & & \boldsymbol{B1}_{PQ_{n+3,l}} \end{bmatrix} \begin{bmatrix} \boldsymbol{Y}_n \\ \boldsymbol{Y}_{n+1} \\ . \\ . \\ \boldsymbol{Y}_{n+3} \end{bmatrix} e^{j\theta_n} \qquad (19)$$

or

$$\boldsymbol{S}_{BT_{n,l}}^{c^4} = \boldsymbol{B}_{PQ_{n,l}}^{4} \boldsymbol{Y}_{n,l}^{4} e^{j\theta_n} \qquad (20)$$

Where, $\boldsymbol{B}^{4}_{PQ_{n,l}} = \begin{bmatrix} \boldsymbol{B}_{PQ_{n,l}} & & & \\ & \boldsymbol{B1}_{PQ_{n+1,l}} & & \\ \cdot & & \cdot & \\ \cdot & & & \\ & & & \boldsymbol{B1}_{PQ_{n+3,l}} \end{bmatrix}$

and $\boldsymbol{Y}^{4}_{n} = \begin{bmatrix} 1 & D_n & 1 & D_{n+1} & 1 & D_{n+2} & 1 & D_{n+3} \end{bmatrix}^T$

Clearly is $\boldsymbol{Y}^{4}_{n}$ depending upon transmitted set of binary data:

$$x_j = \{D_n D_{n+1} D_{n+2} D_{n+3}\} \in \{-1-1-1-1, -1-1-11, \ldots, 1111\} = \{x_0, x_1, \ldots, x_{15}\}$$

Where $j \in \{0, 1, \ldots, 15\}$.

So eq(20) can be rewritten as:

$$\boldsymbol{S}^{c^4}_{BT_{n,l,j}} = \boldsymbol{B}^{4}_{PQ_n} \boldsymbol{Y}^{4}_{n,j} e^{j\theta_n} \quad (21)$$

Where subscript j is given to denote the dependence on particular data input vector x_j.

The received BT data vector $\boldsymbol{S}^{c4}_{BT_n}$ in OFDM receiver is passed through a low pass filter of impulse response $h_{lpf}(t)$. Let T_s^{OFDM} and T_s be the sampling time of the OFDM and BT signal respectively. Then the filtered BT samples in OFDM system is [21]:

$$i(n,l,j) = \sum_{i=0}^{N1-1} h_{lpf}\left(nT_s^{OFDM} - iT_s\right) S^{c^4}_{BT_{n,l,j}}(i) \quad (22)$$

After removal of cyclic prefix of length L in OFDM receiver, which is done by premultiplying by cyclic prefix remove matrix $\boldsymbol{R}_{cp} = \left[\mathbf{0}_{N_{FFT} \times L} \, \mathbf{I}_{N_{FFT} \times N_{FFT}}\right]$. Where $\mathbf{0}$ is a null matrix and $\mathbf{I}$ is an identity matrix and the time domain vector $\mathbf{i}$ of interference become $\mathbf{i}^{\mathrm{N_{FFT}}}$ which can be written in matrix form as :

$$\mathbf{i}^{\mathrm{N_{FFT}}}_{\mathbf{n,l,j}} = \boldsymbol{R}_{cp} \mathbf{h}_{\mathbf{lpf}} \boldsymbol{S}^{c^4}_{BT_{n,l,j}} = \mathbf{h1} \boldsymbol{B}^{4}_{PQ_{n,l}} \boldsymbol{Y}^{4}_{n,j} e^{j\theta_n} \quad (23)$$

Where,

$$\mathbf{i}^{\mathrm{N_{FFT}}}_{\mathbf{n,l,j}} = \begin{bmatrix} i_{0,l,j} & i_{1,l,j} & \cdot\cdot & i_{N_{FFT}-1,l,j} \end{bmatrix}^T, \quad \mathbf{h1} = \boldsymbol{R}_{cp} \mathbf{h}_{\mathbf{lpf}}$$

The matrix $\mathbf{h1}$ is a of dimension $N_{FFT} \times N1$. According to IEEE802.11g standard for OFDM system $N_{FFT}=64$ and cyclic prefix is ¼th of the symbol duration. So L=16 is taken in our simulation. After performing FFT on $\mathbf{i}^{\mathrm{N_{FFT}}}_{\mathbf{n,l,j}}$ interference on the kth sub-carrier is given by:

$$I^{BT}_{k,l,j} = \sum_{n=0}^{N_{FFT}-1} i_{n,l,j} e^{-j\frac{kn}{N_{FFT}}} \quad (24)$$

In matrix form the above equation is written as:

$$\boldsymbol{I}^{BT}_{k,l,j} = \boldsymbol{F}_k \mathbf{i}^{\mathrm{N_{FFT}}}_{\mathbf{n,l,j}} = \boldsymbol{F}_k \mathbf{h1} \boldsymbol{S}^{c4}_{BT_{n,l,j}} = \boldsymbol{F}_k \mathbf{h1} \boldsymbol{B}^{4}_{PQ_{n,l}} \boldsymbol{Y}^{4}_{n,j} e^{j\theta_n} \quad (25)$$

Where $\boldsymbol{I}^{BT}_{k,l,j} = \left(I^{BT}_{0,l,j}, I^{BT}_{1,l,j}, \ldots I^{BT}_{N-1,l,j}\right)^T$

$\boldsymbol{F}$ is the FFT transform matrix. Let $\boldsymbol{V}_{k,l} = \boldsymbol{F}_k \mathbf{h1} \boldsymbol{B}^{4}_{PQ_n}$, So from eq (25), the vector of interference on kth sub-carrier of an OFDM symbol is given by:

$$\boldsymbol{I}^{BT}_{k,l,j} = \boldsymbol{V}_{k,l} \boldsymbol{Y}^{4}_{n,j} e^{j\theta_n} \quad (26)$$

The magnitude, of the interference I^{BT}_k for the kth sub-carrier is independent on the initial phase θ_n, and depend on the magnitude of the product of the matrix $\boldsymbol{V}_{k,l}$ and matrix $\boldsymbol{Y}^{4}_{n,j}$ So for the particular hopping frequency f_l magnitude or power of the BT interferer on kth WLAN sub-carrier will depend upon the data input vector

A. SER in AWGN

According to the equation (2) it is seen that for IEEE802.11g or OFDM system k^{th} sub-carrier is obtained after performing FFT operation to received signal. From equation (4) demodulated output *Yk* after FFT operation in presence of Bluetooth interference is given by:

$$Y_k = H_k U_k + I^{BT}_{l,k,j} + N_k \quad (27)$$

Where U_k is the QAM modulated input signal and *Nk* is AWGN noise, H_k is the transfer function of the combined impulse response of the transmitter pulse shaping filter and receiver low pass filter and $I_{l,k,j}$ is interference from Bluetooth on k^{th} carrier when Bluetooth has hopped in l^{th} channel for jth combination data vector x_j. The effective SINR (signal to interference + noise ratio) in AWGN channel is given by [5,6]:

$$SINR_{l,k,j} = P_s / (P_{I_{l,k,j}} + P_N) \quad (28)$$

Where, P_s is power of OFDM sub-carrier. $P_{I_{l,k,j}}$ is the BT interference power for the k^{th} OFDM sub-carrier, for the jth combination data vector x_j, for l^{th} hopping frequency of BT. P_N is the noise(AWGN) power.

$SER_{l,k,j}$ is obtained from the following equation:

$$SER_{l,k,j}^{AWGN}=4\left(1-\frac{1}{\sqrt{M}}\right)Q\left(\sqrt{\frac{3SINR_{l,k,j}}{(M-1)}}\right)-4\left(1-\frac{1}{\sqrt{M}}\right)^2Q\left(\sqrt{\frac{3SINR_{l,k,j}}{(M-1)}}\right)^2 \quad (29)$$

B. SER in flat Rayleigh fading channel

If the received signal is Rayleigh faded by α then SINR is given by: $SINR_{l,k,j}=\alpha^2P_s/(P_{I_{l,k,j}}+P_N)$ where pdf of α is given by[5,6]:

$$p(\alpha)=\frac{2\alpha}{\Omega}e^{-\frac{\alpha^2}{\Omega}}$$

If SER for rectangular MQAM is approximated by: $SER\approx\beta Q\left(\sqrt{\eta SINR}\right)$.The parameters β and η depend on the constellation shape. SER for rayleigh fading channel is expressed as[5,6]:
Therefore,

$$SER_{l,k,j}^{fading}=\int_0^\infty\beta Q\left(\sqrt{\eta SINR_{l,k,j}\,|\,\alpha}\right)\frac{2\alpha}{\Omega}e^{-\frac{\alpha^2}{\Omega}}d\alpha \quad (30)$$

Analytical evaluation of (30) leads to a solution in the form:

$$SER_{l,k,j}^{fading}=2\left(\frac{\sqrt{M}-1}{\sqrt{M}}\right)\left(1-\sqrt{\frac{1.5SINR_{l,k,j}}{M-1+1.5SINR_{l,k,j}}}\right)-$$
$$\left(\frac{\sqrt{M}-1}{\sqrt{M}}\right)^2\left(1-\sqrt{\frac{1.5SINR_{l,k,j}}{M-1+1.5SINR_{l,k,j}}}\left(\frac{4}{\pi}\right)\tan^{-1}\sqrt{\frac{M-1+1.5SINR_{l,k,j}}{1.5SINR_{l,k,j}}}\right) \quad (31)$$

C. Average SER

As there are 16 different combination of the input data vector ***x*** of the Bluetooth, average error probability of a particular OFDM sub-carrier is obtained by averaging the error probability over all the 16 possible combinations of Bluetooth data vector ***x***. Again to get the average symbol error for OFDM signal SER should be averaged over the SER of all the OFDM sub-carrier. Bluetooth is hopping at L different hopping frequency where some frequencies are inside WLAN frequency band and some frequencies are outside WLAN frequency band. So average symbol error rate over AWGN or Rayleigh fading channel is given by:

$$SER^{AWGN}=\frac{\sum_{l=0}^{L-1}\sum_{k=0}^{N_{rmnull}-1}\sum_{j=0}^{15}SER_{l,k,j}^{AWGN}}{16LN_{rmnull}} \quad (32)$$

$$SER^{fading}=\frac{\sum_{l=0}^{L-1}\sum_{k=0}^{N_{rmnull}-1}\sum_{j=0}^{15}SER_{l,k,j}^{fading}}{16LN_{rmnull}} \quad (33)$$

Where L is total no frequencies in which Bluetooth is hopping and N_{rmnull} is the total no of sub-carriers in OFDM system after removing null sub-carriers.

IV. SIMULATION RESULTS

PHY layer of model of both WLAN and BT are used in simulation. First SER of MQAM-WLAN without BT is obtained. For OFDM based WLAN we have taken total 64 sub-carriers out of which 12 are null carriers. Frequency spacing of each sub-carrier is .3125KHz. For BT system transmitted binary data bits are passed through a Gaussian filter and filtered signal is FSK modulated by shifting the signal frequency to any of the 79 hopping frequencies. Bandwidth and modulation index of the GFSK modulated BT signals is taken 1MHz and 0.3 respectively. We have also given the comparison of the SER from the above proposed model and with the SER using rectangular BT spectrum [19] for BPSK-OFDM, 16QAM-OFDM, 64QAM-OFDM. We have given the results for SER performance of 16QAM and 64QAM OFDM based WLANs in presence of BT interference. In all our simulation results SIR is ratio of total OFDM power of all sub-carriers with interferer (BT) power. SNR is the ratio of total OFDM power with additive white Gaussian noise.

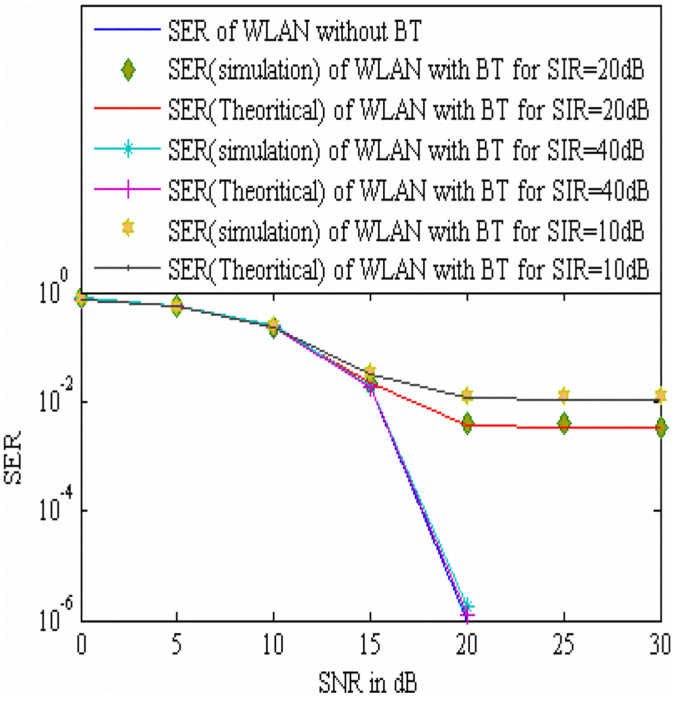

Figure 3. SER (symbol error rate) of uncoded 16QAM-OFDM with and without Bluetooth in AWGN

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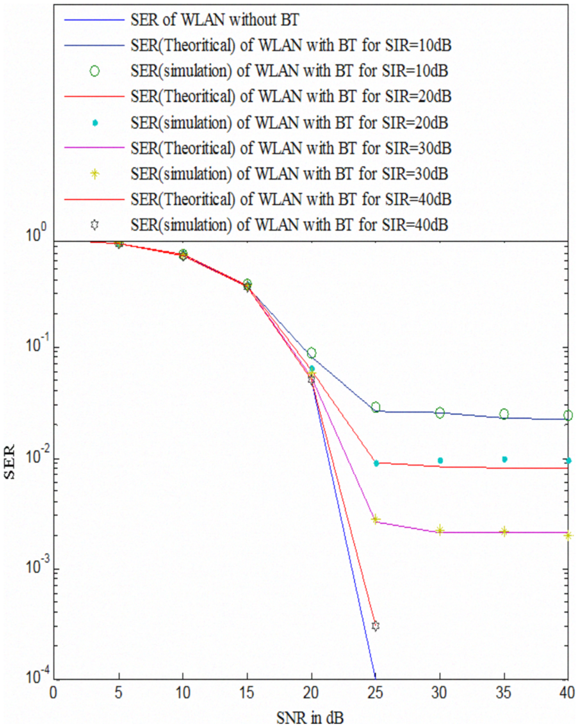

Figure 4. SER (symbol error rate) of uncoded 64QAM-OFDM with and without Bluetooth in AWGN

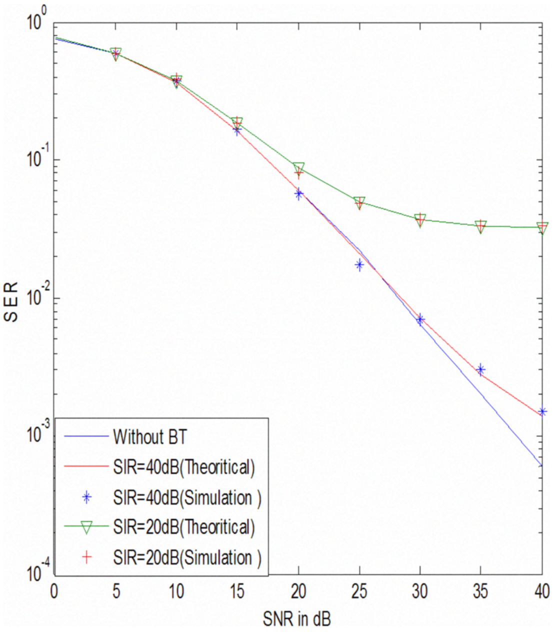

Figure 5. SER (symbol error rate) of 16QAM OFDM system in presence of Bluetooth interference (operating in same frequency of WLAN) in Rayleigh fading channel

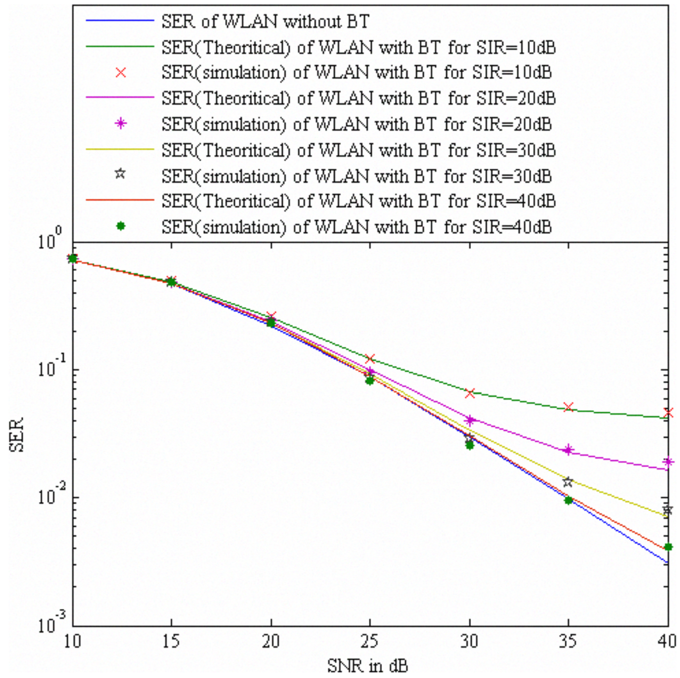

Figure 6. Symbol Error rate of uncoded 64QAM-OFDM with and without Bluetooth in Rayleigh Fading channel

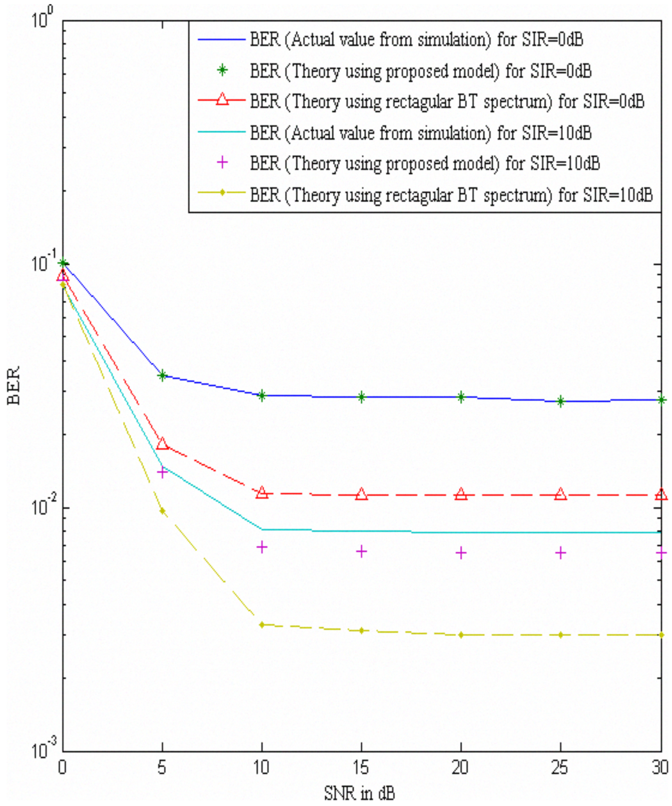

Figure 7. Comparison of BER of BPSK-OFDM using BT spectrum from above proposed model with rectangular BT spectrum when Bluetooth is operating at same frequency of WLAN with AWGN

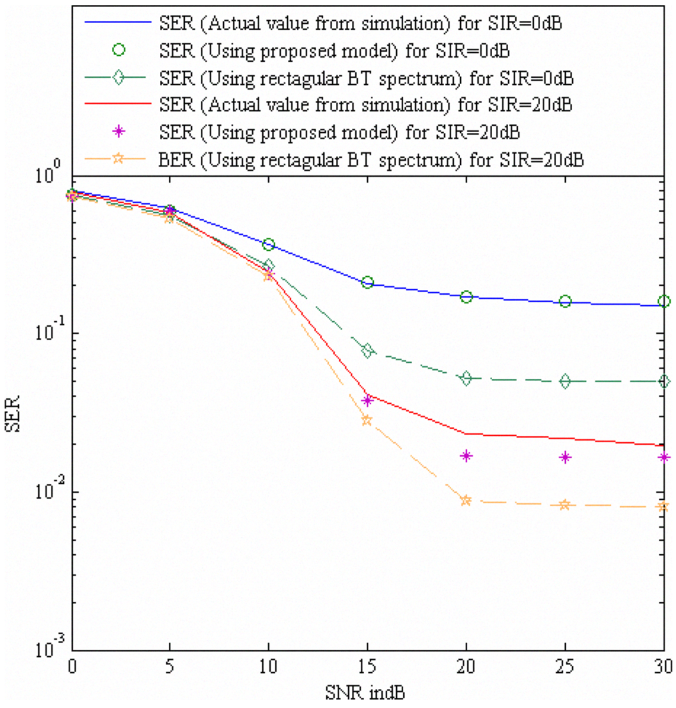

Figure 8. Comparison of SER of 16QAM-OFDM using BT spectrum from above proposed model with rectangular BT spectrum when Bluetooth is operating at same frequency of WLAN with AWGN

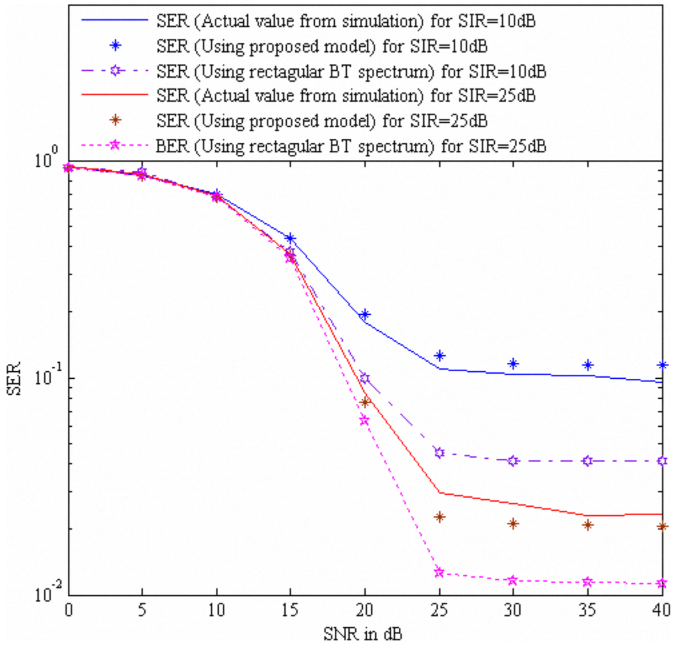

Figure 9. Comparison of SER of 64QAM-OFDM using BT spectrum from above proposed model with rectangular BT spectrum when Bluetooth is operating at same frequency of WLAN with AWGN

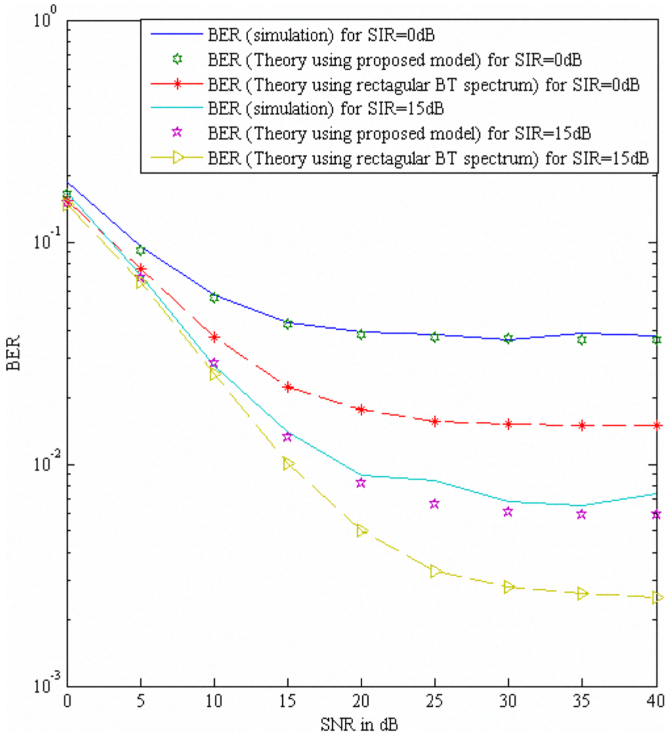

Figure 10. Comparison of BER of BPSK-OFDM using BT spectrum from above proposed model with rectangular BT spectrum when Bluetooth is operating at same frequency of WLAN with Rayleigh Fading Channel

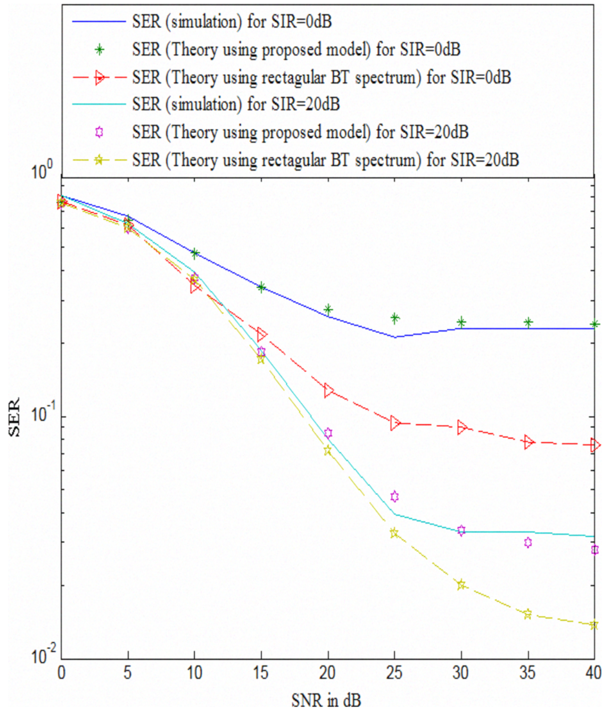

Figure 11. Comparison of SER of 16QAM-OFDM using BT spectrum from above proposed model with rectangular BT spectrum when Bluetooth is operating at same frequency of WLAN with Rayleigh Fading Channel

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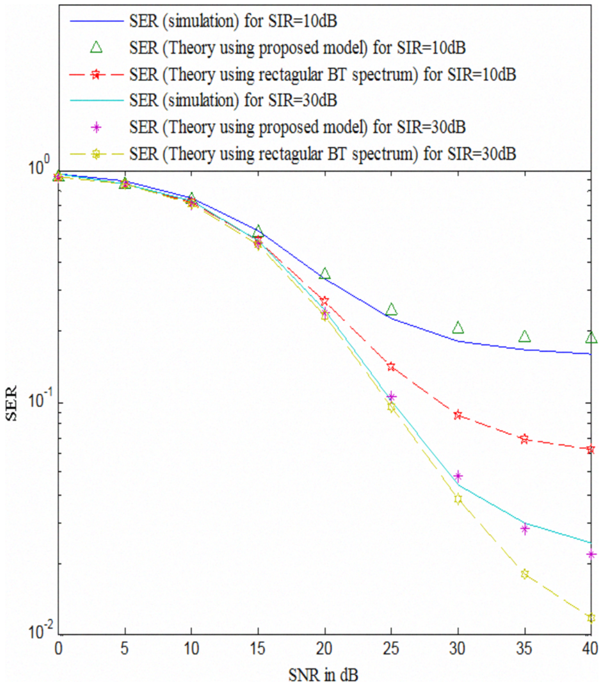

Figure 12. Comparison of SER of 64QAM-OFDM using BT spectrum from above proposed model with rectangular BT spectrum when Bluetooth is operating at same frequency of WLAN with Rayleigh Fading Channel

From the simulation results of figure 3-12 it is seen SER values obtained from our proposed model match with actual SER values obtained from simulation. While SER values obtained using rectangular BT spectrum is lower than the actual value. The reason behind this is that actual BT spectrum is not exactly rectangular. So not only the 3 sub-carriers falling inside the 1MHz BT band are affected but also some adjacent sub-carriers outside the BT band are also affected for lower value of SIR. Actual average SER value is higher than the SER values obtained using rectangular BT spectrum. It is seen theoretical SER curves which are obtained from eq (32), (33) and using eq(29),(31) match with our actual simulation results. The table below gives the comparison of the SER values obtained from simulation, theory using proposed non-rectangular BT spectrum and using rectangular BT spectrum for BPSK-OFDM, 16QAM-OFDM, 64QAM-OFDM system.

TABLE1

Modulation Type	SNR in dB	SIR in dB	SER		
			From Simulation	From Theory (Using non-rectangular BT spectrum)	From Theory (Using rectangular BT spectrum)
BPSK-OFDM	20	10	.007	.0065	.003
16QAM-OFDM	30	20	.02	.019	.008
64QAM-OFDM	20	10	.17	.19	.098

V. CONCLUSION

The paper proposes to use non rectangular BT spectrum to evaluate the WLAN performance in presence of BT interference. It also gives a convenient method for extracting the non-rectangular BT spectrum using which interference power present in each sub-carrier of the OFDM based WLAN can be obtained. SER curves shows that SER obtained from using eq(32),(33) exactly matches the SER from simulations.

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