Performance of multi-band OFDM UWB communication systems in presence of IEEE802.11n WLAN interference for different antenna scheme configurations

Ehab M. Shaheen

Electronic Warfare Department,
Military Technical College,
Cairo, Egypt
Email: ehab.m.shaheen@mtc.edu.eg

Abstract: Multi-band orthogonal frequency division multiplexing ultra-wideband (MB OFDM UWB) communication system has been a leading proposal in the IEEE 802.15.3a standard and has been adopted in the ECMA standard for wireless personal area networks. In this paper, the performance of the MB-OFDM UWB communication system in the Saleh-Valenzuela multi-path UWB channel model using different antenna scheme configurations has been analytically evaluated. The analytical evaluation has been investigated for the three antenna scheme configurations which are the single input multiple output (SIMO), the multiple input single output (MISO), and the multiple input multiple output (MIMO). The issue of existence of high power inband interference signal such as the IEEE802.11n has been also analytically evaluated. A practical link budget analysis is considered. It was shown that the performance of the desired MB-OFDM UWB SIMO/MISO/MIMO communication system can severely deteriorated due to presence of such high power inband interference signal. The obtained analytical results are validated with the aid of extensive simulation results.

Keywords: MB-OFDM UWB; SIMO/MISO/MIMO schemes; IEEE802.11n interference; Saleh-Valenzuela channel model.

Reference to this paper should be made as follows: Shaheen, E.M. (2019) 'Performance of multi-band OFDM UWB communication systems in presence of IEEE802.11n WLAN interference for different antenna scheme configurations', *Int. J. Ultra Wideband Communications and Systems*, Vol. 4, No. 1, pp.41–48.

Biographical notes: Ehab M. Shaheen received his BSc and MSc in Electrical Engineering both from Military Technical College, Cairo, Egypt in 1995 and 2000, respectively. In 2010, he received his PhD from Carleton University, Ottawa, Canada. His doctoral thesis focused on performance analysis of UWB communication systems in the presence of interference and noisy environments. He currently works as an Associate Professor in Electronic Warfare Department in Military Technical College. He currently focuses on UWB and mobile broad-band wireless access technologies. Also, his current research interests include ultra-wideband (UWB) radio communications, IEEE physical layer standards, MIMO systems, spread-spectrum communications, and digital communications over fading channels.

1 Introduction

Ultra-wideband (UWB) provides a promising solution to satisfying the urging need for high data rate, very low cost and very low power consumption indoor and home networking applications (Siriwongpairat and Liu, 2008).

In February 2002, the US Federal Communications Commission (FCC) agency had issued UWB rulings that provided the first radiation limitations for UWB transmission and permitted the operation of UWB devices on an unlicensed basis (FCC, 2002).

There are two main approaches to implementing this kind of radio system. The first one is known as the impulse radio (IR) UWB in which a very narrow pulse (on the order of several tens of picoseconds) is used to carry out the information data without any carriers. The second approach is the multi-band orthogonal frequency division multiplexing (MB-OFDM) UWB in which the information data is multiplexed into sub-frequency bands with each sub-band having 528 MHz bandwidth (for the entire band 3.1 GHz to 10.6 GHz). This information data is transmitted by the aid of OFDM technology (ECMA-368, 2008).

According to the FCC ruling, UWB should operate at a transmission power of at most –41.3 dBm/MHz to avoid interfering with existing narrow-band communication systems (FCC, 2002). Yet, one can expect major performance degradation to the UWB communication system due to presence of other high power radio systems that operate in the same frequency band (such as the Wi-Fi OFDM based IEEE802.11a/n).

The coexistence issue between UWB communication system and other operating services had been studied extensively in recent years. In Li et al. (2010) the coexistence issue between UWB with both impulse radio and multiband modulation and IEEE802.11n system, using physical layer modelling strategy had been investigated. In Kumbhani et al. (2013) the performance of impulse radio UWB communication system had been investigated in presence of coexisting narrowband systems and how to mitigate its impact using wavelet packet transform. A comparative study to the performance of both the MB-OFDM UWB and direct sequence UWB systems was presented in the presence of interference modelled as the forth-coming 4G and the 100 MHz interference locating at IEEE802.11a band in additive white Gaussian noise channel model in Viittala et al. (2006). In Shaheen et al. (2015) a closed form expression for the bit error rate (BER) performance of the single input single output (SISO) MB-OFDM UWB communication system in presence of interference modelled as IEEE802.11n was analytically analysed. It was proven that the range performance of the SISO MB-OFDM UWB communication system is severely deteriorated due to the presence of such interference.

To this end, the work presented in this paper can be considered a continuation to the work presented in Shaheen et al. (2015). The main objectives of this paper can be summarised as follows:

- The paper investigates theoretically the performance of MB-OFDM UWB communication system for different antenna configuration schemes in the Saleh-Valenzuela (S-V) channel model in presence of IEEE802.11n which adopts OFDM as core technology.
- Three antenna scheme configurations which are the single input multiple output (SIMO), the multiple input single output (MISO), and the multiple input multiple output (MIMO) have been adapted.
- Closed form expressions of the BER performance of the SIMO/MISO/MIMO MB-OFDM UWB communication systems are evaluated and compared with the SISO results obtained in Shaheen et al. (2015) in presence of the same interference model.
- The derived analytical results had been validated by the aid of extensive simulation results.

The rest of this paper is organised as following. Section 2 presents the both the desired MB-OFDM UWB communication system model and the interference system model. In Section 3 the channel models for the desired and interference signal is depicted. Section 4 derives analytically the performance of the desired SIMO/MISO/MIMO MB-OFDM UWB communication system in presence of interference. A practical link budget analysis is depicted in Section 5. Simulation and analytical results are presented and verified in Section 6 before drawing the conclusions in Section 7.

2 Desired signal and interference system models

The MB-OFDM UWB transmitted signal can be written as

$$S_{MB}(t)=\sum_{i=\infty}^{\infty}\sum_{k=0}^{N_m-1}x_{k,i}\cdot\varphi_k\left(t-iT_m\right)\exp\left(j2\pi f_m t\right) \tag{1}$$

where N_m, T_m and f_m, are the number of sub-carriers, the OFDM symbol duration, and the carrier frequency respectively. The transmitted QPSK symbols are denoted by $x_{k,i}$ where k and i represent the sub-carrier index and the MB-OFDM symbol index, respectively.

The basis function for sub-carrier q can be written as

$$\varphi_q(t)=\frac{1}{\sqrt{D_m}\exp\left[j2\pi B_m q\left(t-g_m\right)\right]} \tag{2}$$

where $D_m = T_m - g_m$ is the data-carrying part of the OFDM symbol, g_m is the durations of the cyclic prefix, W_m is the bandwidth of transmission and $B_m=\dfrac{W_m}{N_m}$ is the bandwidth per subcarrier.

The remaining N symbols after removing the guard interval and after passing through the FFT process can be written as (Siriwongpairat and Liu, 2008):

$$y[m]=H[m]\times[m]+n[m] \tag{3}$$

where $x[m]$ is the transmitted data symbol in the m^{th} subcarrier, $n[m]$ is the additive noise component in the mt$^{\text{h}}$ subcarrier, and $H[m]$ is the channel frequency response in the m^{th} subcarrier it can be written as

$$H[m]=\sum_{n=0}^{K-1}h(n)e^{\left(\frac{-j2\pi mn}{N}\right)} \quad m=0,1,\ldots,N-1 \tag{4}$$

Thus, $x[m]$ can be estimated as

$$\hat{x}[m]=\frac{y[m]}{H[m]} \tag{5}$$

Without loss of generality, through this work the one transmitted two received (1Tx2Rx), two received one transmitted (2Tx1Rx), and two transmitted two received antenna schemes will be used to represents the SIMO, MISO, and MIMO schemes respectively. Yet, it can be generalised to any number of transmitting and receiving antennas.

2.1 1Tx2Rx MB-OFDM UWB system

In this configuration the transmitted signal is received by two antennas as depicted in Figure 1. The received signal can be written as

$$\begin{bmatrix} y_1[m] \\ y_2[m] \end{bmatrix}=\begin{bmatrix} H_{11}[m] \\ H_{21}[m] \end{bmatrix}\cdot[x[m]]+\begin{bmatrix} w_1[m] \\ w_2[m] \end{bmatrix} \tag{6}$$

At the receiver side, the transmitted symbol can be estimated from the output of the maximal ratio combiner, where it can be written as (Foerster, 2003):

$$\hat{x}[m] = H_{11}^{*}[m] y_1[m] + H_{21}^{*}[m] y_2[m] \tag{7}$$

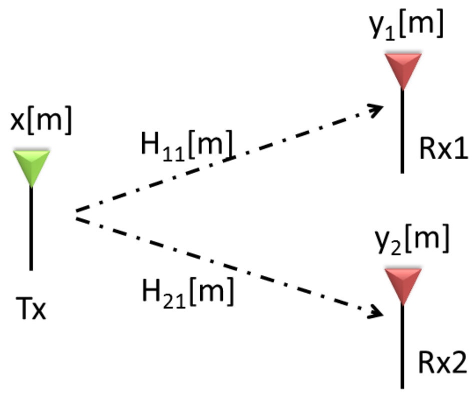


Figure 1 SIMO OFDM antenna system model (1Tx2Rx) (see online version for colours)

2.2 2Tx1Rx MB-OFDM UWB system

The 2Tx1Rx antenna MISO scheme is depicted in Figure 2. This antenna configuration adapts the Alamouti transmit-diversity scheme.

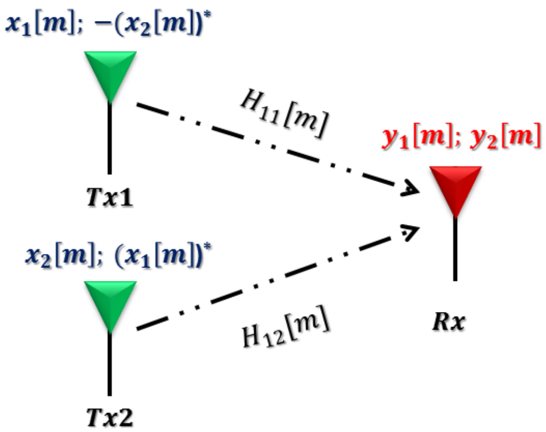


Figure 2 MISO OFDM antenna system model (2Tx1Rx) (see online version for colours)

At block time i, the symbols $x_1[m]$ and $x_2[m]$ are transmitted by the first and second transmit antennas, respectively; at block time $i + 1$, the symbols $-(x_2[m])^*$ and $(x_1[m])^*$ are transmitted by the first and second transmit antennas, respectively. Consequently, the received data from two consecutive blocks are

$$\begin{bmatrix} y_1[m] \\ (y_2[m])^* \end{bmatrix} = \begin{bmatrix} H_{11}[m] & H_{12}[m] \\ H_{12}^{*}[m] & -H_{11}^{*}[m] \end{bmatrix} \cdot \begin{bmatrix} x_1[m] \\ x_2[m] \end{bmatrix} + \begin{bmatrix} w_1[m] \\ (w_2[m])^* \end{bmatrix} \tag{8}$$

In the receiver side both $x_1[m]$ and $x_2[m]$ can be estimated as (Foerster, 2003):

$$\hat{x}_1[m] = H_{11}^{*}[m] \cdot y_1[m] \cdot H_{12}[m] \cdot (y_2[m])^* \tag{9}$$

$$\hat{x}_2[m] = H_{12}^{*}[m] \cdot y_1[m] \cdot H_{11}[m] \cdot (y_2[m])^* \tag{10}$$

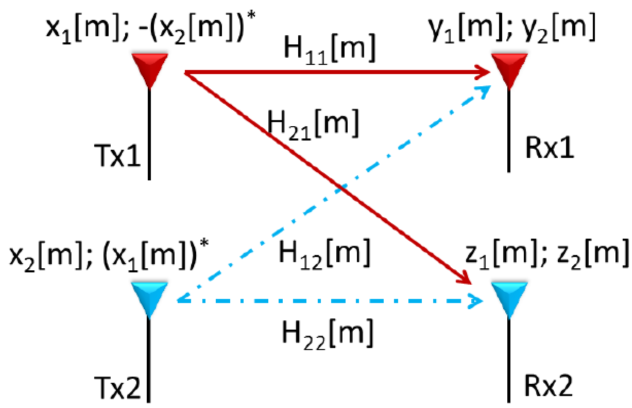
2.3 x2Rx MB-OFDM UWB system

The 2Tx2Rx antenna scheme is depicted in Figure 3. Using the Alamouti transmit-diversity scheme, one can get

$$\begin{bmatrix} y_1[m] \\ (y_2[m])^* \end{bmatrix} = \begin{bmatrix} H_{11}[m] & H_{12}[m] \\ H_{12}^{*}[m] & -H_{11}^{*}[m] \end{bmatrix} \cdot \begin{bmatrix} x_1[m] \\ x_2[m] \end{bmatrix} + \begin{bmatrix} w_1[m] \\ (w_2[m])^* \end{bmatrix} \tag{11}$$

$$\begin{bmatrix} z_1[m] \\ (z_2[m])^* \end{bmatrix} = \begin{bmatrix} H_{21}[m] & H_{12}[m] \\ H_{22}^{*}[m] & -H_{11}^{*}[m] \end{bmatrix} \cdot \begin{bmatrix} x_1[m] \\ x_2[m] \end{bmatrix} + \begin{bmatrix} w_1[m] \\ (w_2[m])^* \end{bmatrix} \tag{12}$$

Figure 3 MIMO OFDM antenna system model (2Tx2Rx) (see online version for colours)



In the receiver side both $x_1[m]$ and $x_2[m]$ can be estimated as (Foerster, 2003):

$$\begin{aligned} \hat{x}_1[m] &= H_{11}^{*}[m] \cdot y_1[m] + H_{12}[m] \cdot (y_2[m])^* \\ &\quad + H_{21}^{*}[m] \cdot z_1[m] + H_{22}[m] \cdot (z_2[m])^* \end{aligned} \tag{13}$$

$$\begin{aligned} \hat{x}_2[m] &= H_{12}^{*}[m] \cdot y_1[m] + H_{11}[m] \cdot (y_2[m])^* \\ &\quad + H_{22}^{*}[m] \cdot z_1[m] + H_{21}[m] \cdot (z_2[m])^* \end{aligned} \tag{14}$$

A classical complete IEEE802.11n physical layer model mainly includes three parts: transmitter, channel, and receiver. Data source, coding (decoding), interleaving (de-interleaving), modulator (demodulator), framing, channel estimator, and equaliser are the indispensable components. The structures of IEEE802.11n symbols and frames, and the algorithms of the function models are exactly specified in IEEE P802.11n/D3.00 (2007).

A general IEEE802.11n OFDM-based signal can be written as

$$I(t) = \mathrm{Re}\left\{ \sum_{i=-\infty}^{\infty} \sum_{n=1}^{N} a_n^i x(t - iT_s) \exp\left(j2\pi f_n (t-\tau) + \theta\right) \right\} \tag{15}$$

where a_n^i are the complex symbols for the nth subcarrier, N is the number of sub-carriers, T_s is the OFDM symbol duration, $x(t)$ is the IEEE802.11n transmitted pulse waveform and $f_n = f_0 + \Delta f[n - 1 - (N - 1) / 2]$ are the subcarrier frequencies equally spaced by Δf and centred at f_0. Since we assume that the interferer is asynchronous with respect to the desired signal, τ is modelled as a random time delay, and θ as a random variable uniformly distributed in $[0, 2\pi)$.

3 Desired and interference channel models

3.1 Channel model

The channel model of the desired MISO MB-OFDM UWB signal is the modified version of the Saleh-Valenzuela multi-path channel model (Saleh and Valenzuela, 1987), where it had been recognised that multi-path components tend to arrive in clusters of rays.

The time impulse response of the UWB channel is given by (Foerster, 2003):

$$h_s(t) = \sum_{l=0}^{L}\sum_{k=0}^{K} a_{k,l}\delta\left(t - T_l - \tau_{k,l}\right) \tag{16}$$

where l is the cluster index, and k is the ray index within a cluster, where the total number of clusters and rays are denoted by L and K respectively. $a_{k,l}$ is the multi-path fading coefficient of the of the k^{th} ray within the l^{th} cluster, $\delta(.)$ is the Kronecker delta,and the arrival time of the l^{th} cluster is denoted by T_l and that of the k^{th} ray within the l^{th} cluster is represented by $\tau_{k,l}$. Finally, X is the log-normal shadowing characterised by the following $20\log10(X)\alpha$ Normal $(0, \sigma_x^2)$.

3.2 802.11n interference channel model

The discrete-time version of the MIMO channel can be written as

$$H_{Total}(t) = \sum_{l=0}^{L} \mathbf{H}_{\mathbf{l}}\delta\left(t - \tau_l\right) \tag{17}$$

and the output of the MIMO channel can be written as

$$y(t) = \sum_{l=0}^{L} \mathbf{H}_{\mathbf{l}} x\left(t - \tau_l\right) \tag{18}$$

where $x(t)$ is the input vector of all transmitting antennas at time t, y(t) is the output vector of all receiving antennas at time t and $\mathbf{H}_{\mathbf{l}}$ is a MIMO channel coefficients with tap index l and delay τ.

4 Performance analysis

4.1 SISO scheme

Assuming that the baseband transmitted pulse is $\varphi(t)$ and T_s is the symbol time. Then, the discrete time based impulse response can be written as

$$h(n) = X\sum_{l=0}^{L}\sum_{k=0}^{K} a_{k,l}\varphi\left(nT_s - T_l - \tau_{k,l}\right)e^{-j2\pi f_c\left(T_l + \tau_{k,l}\right)} \tag{19}$$

$$H[m] = \sum_{n=-\infty}^{\infty}\sum_{l=0}^{L}\sum_{k=0}^{K} Xa_{k,l}\varphi\left(nT_s - T_l - \tau_{k,l}\right)e^{-j2\pi f_c\left(T_l + \tau_{k,l}\right)}e^{-j\frac{2\pi mn}{N}} \tag{20}$$

$$E\left\{|H(m)|^2\right\} = E\left\{|X|^2\right\}E\left\{\left|\sum_{l=0}^{L}\sum_{k=0}^{K} a_{k,l}e^{-j2\pi f_c\left(T_l + \tau_{k,l}\right)}\right|^2 \sum_{n=-\infty}^{\infty}\left|\varphi\left(nT_s - T_l - \tau_{k,l}\right)e^{-j\frac{2\pi mn}{N}}\right|^2\right. \tag{21}$$

From sampling theorem

$$\sum_{n=-\infty}^{\infty}\varphi\left(nT_s - T_l - \tau_{k,l}\right)e^{-j\frac{2\pi mn}{N}} = \begin{cases} \exp\left(-j\dfrac{2\pi m\left(\vartheta T_s T_l + \tau_{k,l}\right)}{NT_s}\right) & 0 \le m \le \dfrac{N}{2} - 1 \\ \exp\left(-j\dfrac{2\pi(m-N)\left(\vartheta T_s T_l + \tau_{k,l}\right)}{NT_s}\right) & \dfrac{N}{2} \le m \le N - 1 \end{cases}$$

Then, $E\{|H(m)|^2\}$ can be simply estimated as

$$E\left\{|H(m)^2|\right\} = E\{X^2\}E\left\{\sum_{l=0}^{L}\sum_{k=0}^{K}\left|a_{k,l}\right|^2\right\} \tag{22}$$

It can be assumed that for each realisation, the total energy contained in the terms $a_{k,l}$ is normalised to unity, i.e., $\sum_{l=0}^{L}\sum_{k=0}^{K}|a_{k,l}|^2 = 1$. Then

$$E\left\{|H(m)|^2\right\} = E\{x^2\} \tag{23}$$

where

$$E\{X^2\} = \frac{1}{\sqrt{2\pi\sigma_x^2}}\int_{-\infty}^{\infty}\left(10^{x/20}\right)^2\exp\left(-\frac{x^2}{2\sigma_x^2}\right)dx = \frac{\int_{-\infty}^{\infty}\exp\left[-\dfrac{\left(x - \dfrac{\sigma_x^2\ln(10)}{10}\right)^2 + \dfrac{\sigma_x^2\ln^2(10)}{200}}{2\sigma_x^2}\right]}{\sqrt{2\pi\sigma_x^2}} \tag{24}$$

$$E\left\{|H(m)|^2\right\} = \exp\left(\frac{\sigma_x^2\ln^2(10)}{200}\right) \tag{25}$$

For $\sigma_x = 3$, $E\{|H(m)|^2\} = 1.269$.

Now the bit error rate performance before the convolutional decoder can be written as (Tse and Viswanath, 2005):

$$P_e = E\left\{Q\left(\sqrt{2|h|^2 \cdot SNR}\right)\right\} \tag{26}$$

where SNR is the signal to noise power ratio, $SNR = \dfrac{E_b}{N_0}$, E_b is the average received energy per bit, N_0 is the single sided power spectral density of the additive white Gaussian noise, h is circularly Gaussian distributed with $E\{|h|^2\} = 1$, and $Q(.)$ is the complementary cumulative distribution function of the standard normal distribution.

The BER performance for the SISO scheme without the in-band interference signal can be further simplified as [see Tse and Viswanath (2005, pp.52–56) for derivation]

$$P_e^N = \frac{1}{2}\left(1 - \sqrt{\frac{SNR}{1+SNR}}\right) \tag{27}$$

4.2 SIMO/MISO/MIMO schemes

For the SIMO 1Tx2Rx antenna scheme, the estimated symbol can be rewritten as

$$\begin{aligned}\hat{x}[m] &= H_{11}^*[m]\left[H_{11}(m)x(m) + w_1(m)\right] \\ &\quad + H_{21}^*[m]\left[H_{21}(m)x(m) + w_2(m)\right] \\ &= \left[\left|H_{11}(m)\right|^2 + \left|H_{21}(m)\right|^2\right]x(m) \\ &\quad + H_{11}^*[m]w_1(m) + H_{21}^*[m]w_2(m)\end{aligned} \tag{28}$$

$$BER_{1Tx2Rx} = E\left\{Q\left(\sqrt{2\left(\left|h_{11}(m)\right|^2 + \left|h_{21}(m)\right|^2\right)\cdot SNR_1}\right)\right\} \tag{29}$$

where $SNR_1 = \frac{\hat{E}_b}{N_0}$ and $\hat{E}_b$ is the energy per bit in $x[k]$, then

$$BER_{1Tx2Rx} = E\left\{Q\left(\sqrt{2\left(\left|h_{11}(m)\right|^2 + \left|h_{21}(m)\right|^2\right)\cdot SNR_2}\right)\right\} \tag{30}$$

where $SNR_2 = \frac{\hat{E}_b \cdot E\{|H[k]|^2\}}{N_o}$ and the term $(\hat{E}_b \cdot E\{|H[k]|^2\})$ represents the average received energy per bit per antenna.

Finally it can be written as

$$BER_{1Tx2Rx} = E\left\{Q\sqrt{2\left(\left|h_{11}(m)\right|^2 + \left|h_{21}(m)\right|^2\right)\cdot SNR}\right\} \tag{31}$$

where SNR is the signal to noise power ratio will be derived in the next section.

Similarly the BER for the 12Tx1Rx scheme can be evaluated as

$$BER_{2Tx1Rx} = E\left\{Q\sqrt{2\left(\left|h_{11}(m)\right|^2 + \left|h_{12}(m)\right|^2\right)\cdot SNR}\right\} \tag{32}$$

The BER for the 2Tx2Rx scheme can be evaluated as

$$BER_{2Tx2Rx} = E\left\{Q\sqrt{\left(H[m]\right)\cdot SNR}\right\} \tag{33}$$

where $H(m)$ can be written as

$$H[m] = \left|h_{11}(m)\right|^2 + \left|h_{12}(m)\right|^2 + \left|h_{21}(m)\right|^2 + \left|h_{22}(m)\right|^2 \tag{34}$$

As, $h_{lj}[m]$ are statistically independent and circularly Gaussian distributed with $E\{|h_{lj}[k]|^2\} = 1$. Moreover, the sum $\sum_{l,j} |h_{l,j}|^2$ is chi-square distributed, with the probability density function given by

$$f(x) = \frac{x^{B-1}}{(B-1)!}\cdot e^{-x} \tag{35}$$

where B is the number of $|h_{lj}[M]|^2$ terms in the sum.

The average BER can be explicitly computed to be

$$BER = \int_0^\infty Q\left(\sqrt{x\cdot SNR}\right)\cdot f(x)dx \tag{36}$$

Finally the BER for the three antenna schemes including the impact of interference can be written as

$$BER_{2Tx1Rx} = \frac{1}{2} - \frac{3}{4}(\beta) + \frac{1}{4}(\beta)^3 \tag{37}$$

$$BER_{2Tx1Rx} = \frac{1}{2} - \frac{3}{4}(\gamma) + \frac{1}{4}(\gamma)^3 \tag{38}$$

$$\begin{aligned}&BER_{2Tx1Rx} \\ &= \left(\frac{1-\gamma}{2}\right)^4 \left[1 + 2(1+\gamma) + 2.5(1+\gamma)^2 + 2.5(1+\gamma)^3\right]\end{aligned} \tag{39}$$

where $\beta = \sqrt{\frac{SINR}{1+SINR}}, \gamma = \sqrt{\frac{0.5SINR}{1+0.5SINR}}$ and $SINR$ is the signal to interference to noise power ratio.

To this end, one can easily drives the BER for another combination of MIMO scheme.

For first generation devices, the MB-OFDM hops over three bands with equal average usage (Siriwongpairat and Liu, 2008).

Assuming that the interferer exists in one of those bands, the average BER performance of the MB-OFDM UWB system in the presence of the NBI signal can be rewritten as

$$P_e = \frac{1}{3}\cdot P_e^{n,i} + \frac{2}{3}\cdot P_e^n \tag{40}$$

where P_e^n and $P_e^{n,i}$ are the BER in absence and presence of interference respectively.

5 Link budget analysis

In this section; the dependence of the BER on the UWB transmission distance d_{uwb} in presence of interference is analysed. It has been seen that from equation (27) that the BER performance of the MB-OFDM UWB system depends on the SNR term.

This BER probability can be rewritten to include the impact of interference as follows

$$SINR = \left[(SNR)^{-1} + \left(\frac{SIR}{\delta}\right)^{-1}\right]^{-1} \tag{41}$$

where SIR is the signal to interference power ratio, and δ is the in-band interferer signal bandwidth to the UWB signal bandwidth.

Since the transmission power cannot exceed the specified –41.25 dBm/MHz, the average transmitted power should satisfy

$$P_x^t \leq -41.25 + 10\log_{10}\left(F_H - F_L\right) \tag{42}$$

where F_H and F_L are the higher and lower frequencies in terms of mega-hertz of the transmission spectrum, respectively.

The signal attenuation during transmission is modelled by the path loss

$$P_L = 20\log_{10}\left(\frac{4\pi F_{ga} d_{uwb}}{C}\right) \tag{43}$$

where F_{ga} is the geometric average of F_H and F_L i.e., $F_{ga} = \sqrt{F_H \cdot F_L}$ and d_{uwb} is the distance between the UWB transmitter and receiver.

At the receiver side, the average noise power per bit (in dBm) can be computed using the formula

$$P_n = -174 + 10\log_{10} R_b \tag{44}$$

where R_b is the data rate in bits per second, and –174 comes from kT calculated at room temperature as the thermal noise power per hertz, where k = 1.38 × 10–23 J/K is the Boltzmann's constant, and T is the temperature in Kelvin.

According to Batra et al. (2004) it was assumed that the noise figure of the antenna and the receiver RF chain is 6.6 dB, and the implementation loss in the digital baseband is 2.5 dB, then we have

$$\begin{aligned} SNR = {} & P_x^t - P_L - P_n - 6.6 - 2.5 \\ & + 10\log_{10}\left(E\left\{|H(m)|^2\right\}\right) \text{(dB)} \end{aligned} \tag{45}$$

where the term $10\log_{10}(E\{|H(m)|^2\})$ represents the fading gain that is captured by the S-V channel models.

The path loss model with shadow fading added used for indoor propagation, can generally be written as follows (Erceg et al., 2004):

$$L(d_i) = L_{FS}(d_i) + \vartheta_\sigma \quad (d_i \geq d_{BP}) \tag{46}$$

$$L(d_i) = L_{FS}(d_{BP}) + 35\log_{10}\left(\frac{d_i}{d_{BP}}\right) + \vartheta_\sigma \tag{47}$$

where the first equation gives the pass loss (in dB) for distances less than d_{BP} [line of sight (LOS) case], known as the break-point distance, and the second equation gives the pass loss beyond distance d_{BP} NLOS case), where ϑ_σ is a Gaussian random variable with a zero mean and with standard deviation (in dB). The term $L_{FS}(.)$ refers to the free space path loss equation.

This expression applies to distances less than d_{BP} and has a slope of 2 (in dB scale).

The expression for the system loss with free space propagation can be written as (Perahia and Stacey, 2008):

$$L_{FS}(d) = -10\log_{10}\left(\frac{G_t G_r \lambda^2}{(4\pi d)^2}\right) \tag{48}$$

where G_t and G_r are the transmitter and receiver antenna gains respectively, d is the distance between them, in metres [known as T-R separation (Perahia and Stacey, 2008)], and λ is the wavelength of the transmitted carrier frequency.

Note that the TGn channel models A to C represent small environments (0 to 30 ns delay spread), and models D to F represent larger environments (50 to 150 ns delay spread).

6 Analytic and simulation results

In this section, the performance of the MB-OFDM UWB communication system is investigated numerically in the presence of the IEEE802.11n OFDM based interference signal and validated with the aid of simulation for different number of antenna schemes.

Following the link budget presented in Shaheen et al. (2015), the following parameters are used: the upper frequency, F_H = 6.072 GHz, the lower frequency, F_L = 5.016 GHz, the data rate, R_b = 110 Mb/s and the transmission power = –10.3 dBm in the S-V channel models. The simulated interference signal is the 2 × 2 IEEE802.11n signal with transmitted power = 15 dBm, the centre frequency of the interference signal f_i = 5.54 GHz, and its bandwidth = 40 MHz. The numerical and simulation results for the interferer are satisfied under the TGn 'D channel model' (Typical office) with a root mean square delay spread = 50 ns, d_{BP} = 10 m (Perahia and Stacey, 2008).

Figure 4 depicts the BER performance of 1Tx2Rx scheme at different SIR values (–10, –20 and –30 dB). It can be seen that the performance of this scheme is completely deteriorated due to presence of high inband interference signal such as the IEEE802.11n WLAN signal. It can be seen that for a SIR value = –30 dB a distance degradation is expected to reach up to 25 m at BER = 10^{-1}.

Figure 4 BER performance for 1Tx2Rx MB OFDM UWB system for different SIR values (see online version for colours)

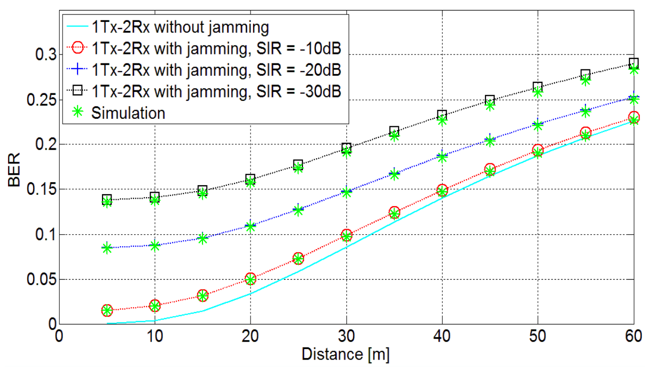


Figure 5 BER performance for both SISO and MISO (2Tx1Rx) MB OFDM UWB system in absence of interference (see online version for colours)

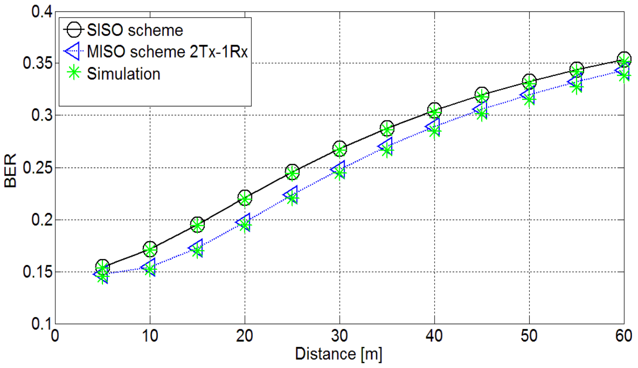


Figure 5 depicts both SISO scheme and MISO (2Tx1Rx) scheme in absence of interference. It can be seen that as expected the BER performance is enhanced by increasing the number of transmitted antennas.

Figure 6 BER performance for both SISO and MISO MB OFDM UWB system in presence of interference, SIR = –10dB (see online version for colours)

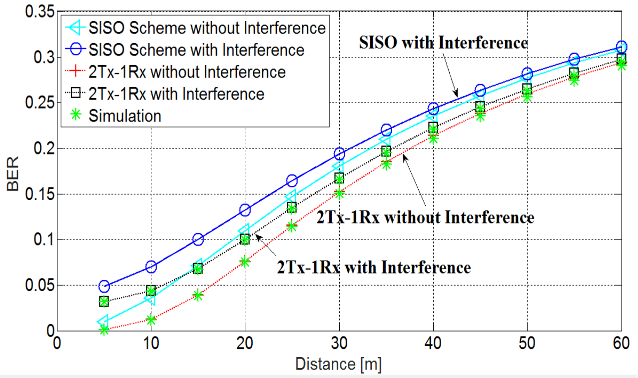


Figure 6 depicts the impact of presence of the IEEE802.11n interference on the BER performance of both the SISO and MISO (2Tx1Rx) schemes. It can be seen that at $BER = 0.05$, a degradation in the MB-OFDM UWB coverage distance could reach up to 5 m at $SIR = -10$dB.

Figure 7 BER performance of MISO (2Tx1Rx) MB OFDM UWB system in presence of interference for different SIR values (see online version for colours)

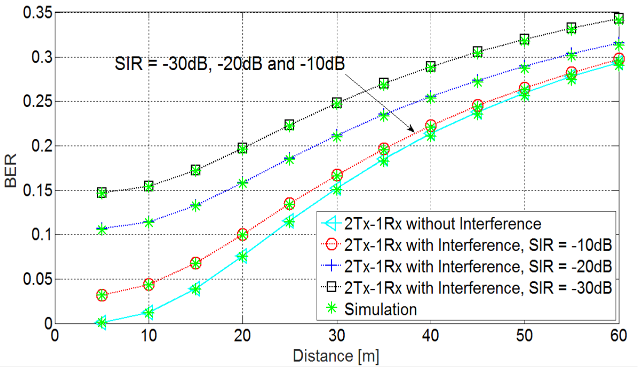


Figure 7 depicts the impact of presence of the IEEE802.11n interference at different SIR values on the considered scheme. It can be seen that the BER performance of the MISO (2Tx1Rx) scheme is severely deteriorated due to presence of high power in band interference.

Figure 8 BER performance of 2Tx1Rx MB OFDM UWB system in presence of interference for different data rate values, SIR = –30dB (see online version for colours)

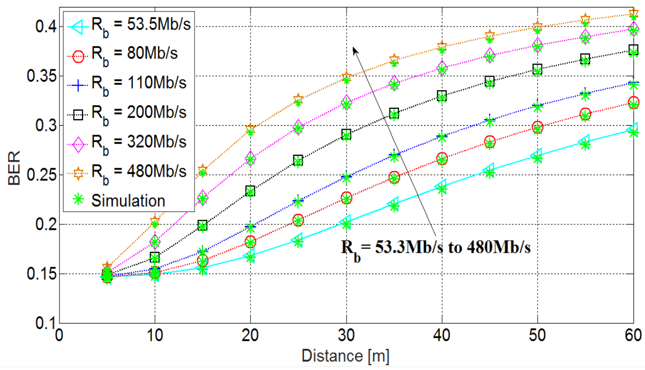


Figure 8 depicts the impact of varying the data rate of the 2Tx1Rx MB-OFDM-UWB system from 53.3 Mb/s to 48 0Mb/s in presence of the IEEE802.11n interference at $SIR = -30$dB. It can be seen that increasing the data rate in presence of high power inband interference signal will degrade the quality of service of the desired system at certain coverage distance. From all the previous figures it also can be seen that the simulation results are in a good match with the derived theoretical results.

Figure 9 BER performance of MIMO 2Tx2Rx MB OFDM UWB system in presence of interference for different SIR values (see online version for colours)

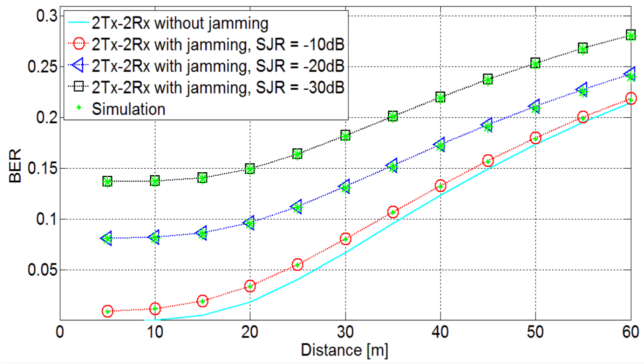


Figure 9 depicts the BER performance of the 2Tx2Rx MB-OFDM UWB MIMO scheme in presence of interference for different SIR values (–10 dB, –20 dB and –30 dB). It can be seen that increasing the number of transmitting and receiving antennas improve the transmission range of the MB-OFDM UWB communication systems. Yet, the presence of high inband interference signal such as the IEEE802.11n WLAN operating services may cause a harmful effect on the performance of the UWB systems.

7 Conclusions

Nowadays, the implementation of MIMO scheme is the key element to meet the exponentially increasing demand on the limited resources in mobile communications especially increasing the data rate.

To this end, in this paper, the BER performances of the SIMO (1Tx2Rx), MISO (2Tx1Rx), and the MIMO (2Tx2Rx) MB-OFDM UWB communication system were analytically investigated in the S-V multi-path UWB channel model. The scenario of presence of high power inband interference was also investigated. The interference was modelled as the MIMO (2Tx2Rx) IEEE802.11n Wi-Fi OFDM based signal.

A practical link budget analysis was also analytically investigated. It was shown that the transmission range limit of the MB-OFDM UWB communication system was improved due to increasing the number of transmitting and receiving antennas. Yet, the presence of such high power inband interference signal can severely deteriorate the performance and in turn the transmission ranges of the desired system.

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