PERFORMANCE ANALYSIS OF TWO HOPS AMPLIFY AND FORWARD RELAY BASED SYSTEM FOR OFDM AND SINGLE CARRIER COMMUNICATIONS

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ABSTRACT

This paper analyses the bit error rate (BER) and capacity behaviour of orthogonal frequency division multiplexing (OFDM) and cyclic prefix based single carrier (CP-SC) systems using amplify and forward relay (AF) with two hops wireless channel type 1 (Rayleigh-AF-UWB) and channel type 2 (Exponentially decaying multipath-AF-UWB). We consider Saleh-Venezuela [SV] channels-CM1, CM2, CM3 and CM4 for UWB standard. Our analysis show that BER performance is better in CP-SC system than OFDM system and CM1 UWB shows the best BER performance among other SV channel standards in our compound environment. On the other hand, OFDM system shows better capacity performance than CP-SC system and again CM1 UWB shows best performance. We also investigate the case that transmitter is located at indoor and therefore we check the BER, capacity performance, and find poor performance than transmitter located at outdoor.

KEYWORDS: *Bit error rate (BER), Ultra wide band (UWB), Orthogonal frequency division multiplexing (OFDM), Cyclic prefixed single carrier (CP-SC), Minimum mean square estimation (MMSE).*

I. INTRODUCTION

Ultra wide band (UWB) technology, aiming at providing high data rate at low power consumption has attracted enormous interest in recent years. Both multi carrier UWB employing orthogonal frequency division multiplexing (OFDM-UWB) and impulse based single carrier (SC) transmission have been proposed to IEEE 802.15.3a as a potential candidate for physical layer technology [1-2]. OFDM-UWB [3-4] has simple receiver structure where a one-tap frequency domain equalizer can sufficiently eliminate the multipath effects. Reference [5] investigated the channel estimation in ultra-wideband communications operating in a multipath environment and in the presence of multi-access interference. In [6], channel estimation and signal detection for UWB communications have been investigated with MMSE rake receiver at 7.5 GHz frequency. An efficient series is derived that can be used to calculate the probability of error in a binary symmetric channel with inter-symbol interference and additive white Gaussian noise [7].

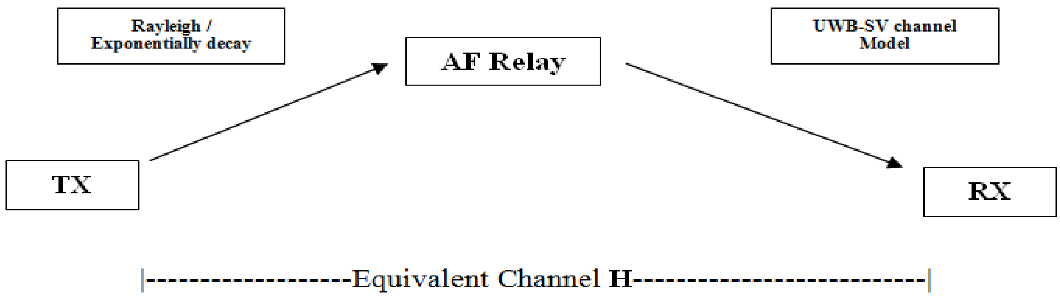

Figure 1: Channel model for the proposed system

A survey on frequency domain equalization (FDE) applied to single- carrier (SC) modulation is done in [8]. Similarities and differences of SC and OFDM systems and coexistence possibilities are discussed here. In [9], the minimization of uncoded BER for OFDM system with an orthogonal precoder is investigated. In [10], SC-FDE performs well with only small performance degradation, compared with perfect channel estimation. In [11], the CP-SC based UWB is proposed with minimum mean square estimation (MMSE) and in [12], the capacity of the CP-SC and OFDM based UWB has been proposed. Single carrier modulation with frequency domain equalization (SC-FDE) is a new and very interesting topic. In [11], we observed that the critical advantage of SC-FDE UWB over OFDM-UWB is low peak to average power ratio (PAPR). CP-SC with frequency domain equalization is very useful technique in broadband multipath fading environments for the cases where the channel is unknown at the transmitter and perfectly known at the receiver [12]. A useful outcome from [12] is that, the capacity of SC-FDE always poorer than that of OFDM in frequency selective channel under the assumption that the interference and noise are independent white Gaussian. We can further improve the capacity of CP-SC systems by introducing interference reduction techniques such as decision feedback approach and therefore SC-FDE is a very promising technology to meet the required high-speed data rate, low cost and low power UWB communication. Throughout the manuscript, we assume that, the cyclic prefix (CP) length is greater than the length of discrete time baseband channel impulse response, so the inter symbol interference (ISI) is eliminated [12].

We propose a compound channel with two hops combined by AF relay. For the case of continuous connectivity, sometime transmitter needs to transmit data through multiple hops. The first hop having 5-taps Rayleigh/ exponentially decaying multipath channel and the second hop has UWB SV [13] channel. We consider QPSK modulation scheme. For OFDM system consists of zero-forcing (ZF) equalizer and CP-SC system consists of MMSE equalizer. ZF equalizer has low complexity and the simplest for OFDM data detection. OFDM has peak to average power ratio (PAPR) issue and this leads the poor BER performance of OFDM systems than CP-SC systems. However due to multiple sub-channels in OFDM systems, capacity is higher in OFDM systems for both compound channel type 1 and channel type 2.

The manuscript is organized as follows. Section II presents the system model following the BER and capacity of both OFDM and CP-SC systems. Section III compares the BER performance and capacity performance of combined channel and related simulated results. In Section IV, we conclude the manuscript.

The notations used in this manuscript in the following sections are: $(\cdot)^H$ denotes Hermitian transpose, $(\cdot)^*$ denotes the complex conjugate. We use $\boldsymbol{I_N}$ for an $N \ x \ N$ identity matrix. $\delta(\cdot)$ is the Dirac delta function. E $(\cdot)$ denotes the statistical expectation.

II. SYSTEM MODEL

A. Channel Model

We consider the OFDM and CP-SC systems over proposed channel type 1 and 2 as explained in sec I. The first hop consists of Rayleigh/ exponentially decaying multipath channel and second hop has UWB SV [13] channel. A block of signals $(0 \leq k \leq N-1)$ is transmitted with block length of N. The QPSK signal can be expressed as $s_k = \pm\sqrt{E_s/2} \pm j\sqrt{E_s/2}$, where E_s is the symbol energy. The noise term of k-th sub-channel is, $e_k = x_k - s_k$, where x_k is the IFFT output of the k-th subcarrier with noise variance of σ_k^2.

A.1. *Channel at the First Hop*

The channel impulse response of the first hop Rayleigh / exponentially decaying multipath channel and its frequency response can be expressed, respectively, as

$$h(n) = \sum_{l=0}^{L-1} h_l\, \delta(n-l) \quad (1)$$

and

$$\boldsymbol{H_1} = \sum_{n=0}^{N-1} \sum_{l=0}^{L-1} h_l \delta(n-l)\, e^{-j2\pi kn/N} \quad (2)$$

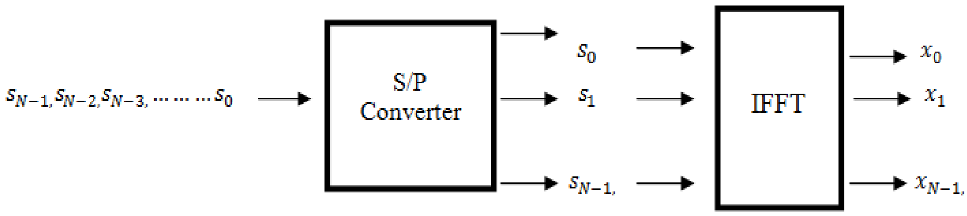

Figure 2: QPSK data generation

where, L is the total number of taps, $\delta(\cdot)$ is the Dirac delta function, h_l is the l -th tap's channel impulse response for $0 \le k \le N-1$.

A.2. *Channel at the Second Hop*

Channel impulse response of UWB-SV Channel model [13] is expressed as,

$$h(t) = \sum_{l=0}^{\infty} \sum_{k=0}^{\infty} \beta_{kl}\, e^{-j\theta_{kl}} \delta(t - T_l - \tau_{kl}) \quad (3)$$

$$h(nt) = \frac{1}{M} \sum_{l=0}^{\infty} \sum_{k=0}^{\infty} \beta_{kl}\, e^{-j\theta_{kl}} \delta(nt - T_l - \tau_{kl})$$

where M is the normalization factor. The frequency response of the second hop is expressed as,

$$\boldsymbol{H_2} = \frac{1}{M} \sum_{l=0}^{\infty} \sum_{k=0}^{\infty} \int_{-\infty}^{\infty} (\beta_{kl}\, \delta(nt - T_l - \tau_{kl}) e^{-j(\omega t - \theta_{kl})} dt) \quad (4)$$

where, l is the number of clusters, k is the number of rays, T_l is the delay of l-th cluster. τ_{kl} is the path delay of k-th ray of l-th cluster, β_{kl} is the path gain of k-th ray of l-th cluster. θ_{kl} is the phase angle of k-th ray of l-th cluster. θ_{kl} will be assumed a priori to be statistically independent random variable over $[0,2\pi]$ distribution. τ_{kl} forms a poisson arrival-time sequence with mean arrival rate of λ. β_{kl} associated with every τ_{kl} is then picked from some probability distribution whose moments are the function of τ_{kl} that eventually vanishes for large values of τ_{kl} [13].

The combined channel frequency response between transmitter and receiver is expressed as,

$$\boldsymbol{H} = G\boldsymbol{H_1 H_2} \quad (5)$$

We consider the first and second hop is having circulant matrix property. According to the circulant matrix property, the multiplication of two circulant matrix results a circulant matrix. Here $\boldsymbol{H}$ is having circulant matrix properties, $\boldsymbol{H} \in C^{NXN}$, amplification Factor G, $\boldsymbol{H^2} = \boldsymbol{HH^*}$ and $\sigma_N{}^2$ is the noise variance of the combined channel.

B. Data Transmission and Reception

In this section, we consider the transmission and reception of CP-SC and OFDM signals over our proposed channel type 1 and type 2. At the beginning of this transmission, we add the cyclic prefix in OFDM and CP-SC systems. After the insertion of CP in OFDM and single carrier systems, signals can be expressed, respectively, as

$$\boldsymbol{X} = \left[x_{N-N_g}, x_{N-N_{g-1}}, \dots\dots\dots\dots\dots\dots x_{N-1}, x_0, x_1, x_2, \dots\dots x_{N-1}\right] \tag{6}$$

and $$\boldsymbol{d} = [s_{N-N_g}, s_{N-N_{g-1}}, \dots\dots\dots\dots\dots\dots s_{N-1}, s_0, s_1, s_2 \dots\dots\dots s_{N-1}] \tag{7}$$

Here, N_g is the number of subcarriers for guard interval (length of cyclic prefix). The signal received via the relay can be expressed as,

$$\boldsymbol{Y} = \boldsymbol{HX} + \boldsymbol{n} \tag{8}$$

It is known that the circulant matrix $\boldsymbol{H}$ can be decomposed in [16] as, $\boldsymbol{H}$=$\boldsymbol{F^H DF}$ **,** then,

$$\boldsymbol{Y} = \boldsymbol{F^H DF}X + \boldsymbol{n} \tag{9}$$

where, $\boldsymbol{D}$ is the diagonal matrix and $\boldsymbol{F}$ is the FFT matrix which can be expressed as,

$$F_{l,k} = \frac{1}{\sqrt{N}} e^{-j2\pi lk/N}, \quad 0 \le l, k \le N-1 \tag{10}$$

The MMSE equalizer co-efficient for single carrier system can be expressed as (for k-th sub-carrier),

$$C_k = \frac{{H_k}^*}{|H_k|^2 + \sigma_k^2} \tag{11}$$

C. BER Performance

C.1. *BER Performance of OFDM System*

The signal is QPSK modulated; therefore, BER of k-th sub-channel can be expressed as,

$$BER\ (k)_{OFDM,ZF} = Q\left(\sqrt{E_s/\sigma_k^2}\right) \tag{12}$$

where, Q(n)= $\int_n^\infty e^{-t^2/2}\, dt/\sqrt{2\pi}$ and n$\geq$ 0 from [14]. Therefore,

$$E_s/\sigma_k^2 = \frac{E_s}{N_0/|H_k|^2} = \frac{E_s|H_k|^2}{N_0} \tag{13}$$

Taking the mean for total N sub-channels, the BER for OFDM system using ZF equalizer can be expressed as,

$$BER_{OFDM}^{ZF} = \frac{1}{N}\sum_{k=0}^{N-1} BER\ (k)_{OFDM,ZF} = \frac{1}{N}\sum_{k=0}^{N-1} Q\left(\sqrt{\frac{E_s|H_k|^2}{N_0}}\right) \tag{14}$$

C.2. *BER Performance of CP-SC System*

We know that the MMSE receiver is not ISI free and therefore the detection of bit x_0 will consist of the signal, noise and interference part [11] and the detected bit can be expressed as,

$$z_0 = \frac{1}{N}\sum_{k=0}^{N-1} \eta_k\, x_0 + \frac{1}{N}\sum_{l=1}^{N-1}\left(\sum_{k=0}^{N-1} \eta_k e^{-j2\pi lk/N}\right) x_l + \tilde{n} \tag{15}$$

where, $\tilde{n}$ is the noise part of the detected signal and can be expressed as,

$$\tilde{n} = \frac{1}{N}\sum_{l=1}^{N-1}\left(\sum_{k=0}^{N-1} C_k e^{-j2\pi lk/N}\right) n_l \quad (16)$$

Here n_l is the l-th noise element of the channel and $\tilde{n}$ is the real Gaussian noise after MMSE equalization and IFFT with variance,

$$\sigma^2{}_{\tilde{n}} = E[|\tilde{n}|^2] = \frac{1}{N}\sum_{l=1}^{N-1} |(\sum_{k=0}^{N-1} C_k e^{-\frac{j2\pi lk}{N}})|^2 \quad (17)$$

The second term of (15) is the interference part and mainly known as residual ISI (inter symbol interference) and can be expressed in short form as,

$$s_l = \sum_{k=0}^{N-1} \eta_k e^{-j2\pi lk/N} \quad (18)$$

Then, $$\boldsymbol{I} = \frac{1}{N}\sum_{l=1}^{N-1} s_l x_l \quad (19)$$

Finally, the error probability of the system using Gaussian Approximation can be expressed using the following equation,

$$BER_{CPSC}^{MMSE} = Q\left(\frac{\frac{1}{N}\sum_{k=0}^{N-1}\eta_k}{\sqrt{[E_s\sum_{l=1}^{N-1}|s_l|^2 + \sum_{l=1}^{N-1}\left|\sum_{k=0}^{N-1} C_k e^{-\frac{j2\pi lk}{N}}\right|^2]}}\right) \quad (20)$$

where, Q(·) is the Gaussian tail function [14]. η_k for k-th sub carrier is expressed by $\frac{|H_k|^2}{|H_k|^2+\sigma_k^2}$.

D. Capacity Performance

D.1. *Capacity Performance of OFDM System*

Let the received signal over the k-th subcarrier be given by,

$$y_k = H_k s_k + n_k \quad (21)$$

where H_k is defined in the previous sub section, $n_k \sim CN(0, \sigma_n^2)$ and the modulated symbol satisfies $E\{|S_k|^2\}$=1. Assume that the channel state information (CSI) is perfectly known at the receiver. The channel capacity over the k-th subcarrier can be expressed in [12] as,

$$c_k = \log_2(1 + \frac{|H_K|^2}{\sigma_n^2}) \quad (22)$$

Then the capacity carried by one OFDM symbol becomes,

$$C_{OFDM} = \sum_{k=0}^{N-1}\log_2(1 + \frac{|H_K|^2}{\sigma_n^2}) \quad (23)$$

D.2. *Capacity Performance of CP-SC System*

The received signal after the removal of CP in SC-CP system is expressed in [11] as,

$$\boldsymbol{y} = \boldsymbol{Hd} + \boldsymbol{n} \quad (24)$$

where, the transmission symbol has $E\{|d_k|^2\}= \boldsymbol{I}$ and $n \sim CN(0, \sigma_n^2\boldsymbol{I})$. We first apply FFT to the received signal, so that we have,

$$\widetilde{\boldsymbol{y}} = \boldsymbol{FHd} + \boldsymbol{Fn} = \boldsymbol{FHd} + \boldsymbol{z} \quad (25)$$

where, $z \sim CN(0, \sigma_n^2 \boldsymbol{I})$. After this, we apply FDE, where its k-th element is defined by using (12) and then IFFT. Through these operations, the received signal after FDE becomes,

$$\boldsymbol{r} = \boldsymbol{F^H}\tilde{\boldsymbol{y}} = \boldsymbol{F^H DFHd} + \boldsymbol{F^H DFn} \quad (26)$$

Let the k-th element of $\boldsymbol{r}$ be denoted by r_k which can be expressed as,

$$r_k = S_k + I_k + n_k \quad (27)$$

where, S_k, I_k, and n_k are the k-th element of data , interference and noise respectively. The signal-to-noise-and- interference ratio (SINR) is defined by in the following,

$$\lambda_k = \frac{E\{|S_k|^2\}}{E\{|I_k|^2\}+E\{|n_k|^2\}} \quad (28)$$

Therefore, the channel capacity of CP-SC systems can be expressed as,

$$C_{CP-SC} = \sum_{k=0}^{N-1} \log_2(1+\lambda_k) = \sum_{k=0}^{N-1} log_2(1+\frac{E\{|S_k|^2\}}{E\{|I_k|^2\}+E\{|n_k|^2\}}) \quad (29)$$

III. Simulated Performance of the Proposed System and Discussions

A. Channel Models

For simulating our proposed model, we consider MATLAB^{TM}simulation tool. The relay is mounted at the boundary between the indoor and outdoor channel. We consider the Saleh-Valnezuala [13] channel model for indoor communication according to IEEE 802.15.3a group (Nov. 2003) and the system parameters are given in the table 1.

Table 1: Indoor Channel Model from IEEE 802.15.3a group (Nov. 2003)

Parameters	Symbol	CM1	CM2	CM3	CM4
Cluster Arrival Rate	Λ [1/nsec]	0.0233	0.4	0.0667	0.0667
Ray Arrival Rate	λ [1/nsec]	2.5	0.5	2.1	2.1
Cluster Decay Factor	Γ	7.1	5.5	14.0	24.0
Ray Decay Factor	γ	4.3	6.7	7.9	12.0
Cluster Lognormal Fading Term	σ_1[dB]	3.3941	3.3941	3.3941	3.3941
Ray Lognormal Fading Term	σ_2[dB]	3.3941	3.3941	3.3941	3.3941
MERL, TR-2003-73	NP_{10dB}	12.5	15.3	24.9	41.2
SJSU, 12/13/2004	NP_{10dB} *	14.57	15.0	23.5	32.2

(*) Average over 200 channel realizations with T. Becker's Matlab model.

B. Performance Comparison between OFDM and CP-SC System Under Proposed Combined Channel

We consider QPSK modulation for data generation using MATLAB^{TM} simulation tool. The performances of zero forcing based OFDM and MMSE base CP-SC systems over combined channel are evaluated using the formulas derived in the previous section. We compared the results by varying UWB channels-CM1, CM2, CM3 and CM4 from [13] where the rms delay spread ranges from 5ns to 25ns. We take 10000 channel realizations. For both CP-SC and OFDM, we took 256 point FFT and CP length of 32. The system bandwidth in our case is 500 MHz and carrier frequency is 4GHz. We assume that perfect channel state information (CSI) is available at the receiver due to slow time varying nature of UWB channels.

C. BER Performance Analysis

We consider two different scenarios where the transmitter is located at outdoor and transmitter is located at indoor. We consider UWB channel for indoor communication and Rayleigh/ exponentially decaying multipath channel for outdoor communication.

1. Transmitter located at outdoor

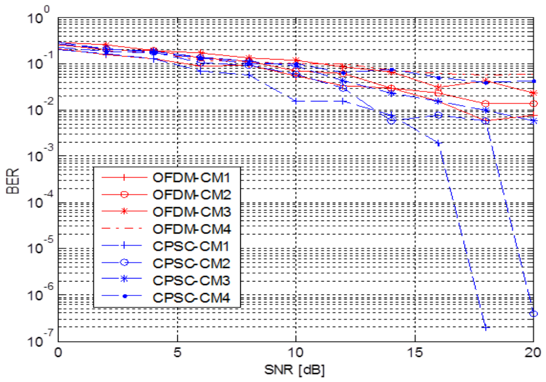

Figure 3. OFDM and CP-SC system for Rayleigh -AF-UWB channel

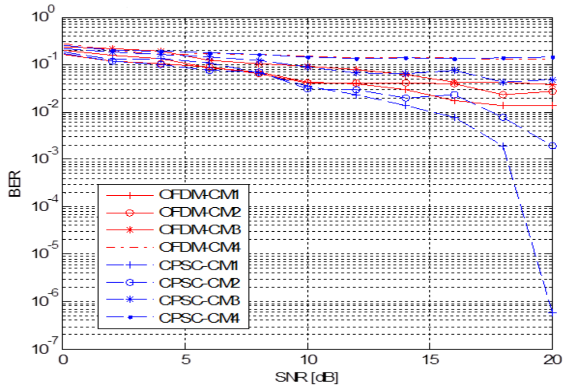

Figure 4. OFDM and CP-SC system for exponentially decaying multipath Channel

Figure 3 shows the BER performance comparison of OFDM and CP-SC systems for Rayleigh-AF-UWB channels. Here the BER performance of CP-SC based Rayleigh-AF-CM1 SV Channel [13] shows the best performance among others with BER of 10^{-7} at SNR of 18dB. Overall CP-SC systems show better BER performance than OFDM systems. As we know that the CP-SC system has minimum peak to average power ratio (PAPR), therefore the BER of Rayleigh-AF-UWB channel with CP-SC systems have better BER performance than OFDM based systems.

Figure 4 shows the BER performance comparison of OFDM and CP-SC systems for exponentially decaying multipath-AF-UWB channels. Here the BER performance of CP-SC based exponentially decaying multipath-AF-CM1 SV Channel [13] shows the best performance among others with BER of 10^{-6} at SNR of 20 dB. Overall CP-SC systems show better BER performance than OFDM systems. BER performance is identical with figure 3 but performance is poorer than Rayleigh-AF-UWB channels. The reason of poor BER performance of channel type 2 is mainly based on outdoor channel characteristics such as power delay profile (PDP) and robustness against echo and other noisy characteristics of the environment.

2. Transmitter located Indoor

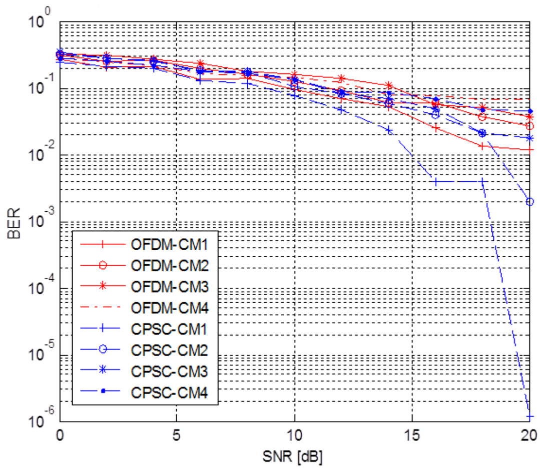

Figure5. OFDM and CP-SC system for UWB -AF- Rayleigh channel

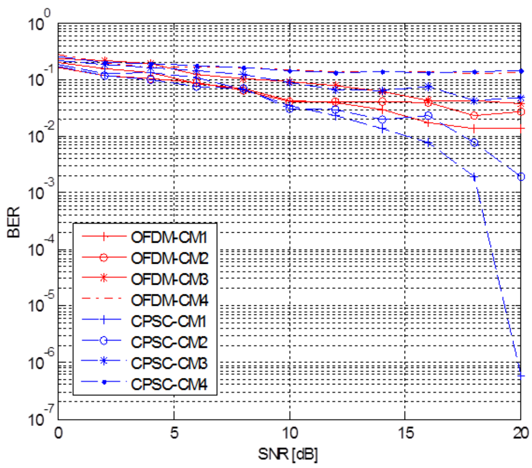

Figure 6. OFDM and CP-SC system for UWB -AF- exponentially decaying multipath channel

Figure 5 shows the BER performance comparison of OFDM and CP-SC systems for UWB-AF-Rayleigh channels. Here the BER performance of CP-SC based SV [13] CM1-AF-Rayleigh Channel shows the best performance among others with BER of 10^{-6} at SNR of 20 dB. Overall CP-SC systems show better BER performance than OFDM systems. However, the performance is lower as compared with Rayleigh-AF-UWB channels because the second hop (Rayleigh channel) has low transmission rate than UWB channels, less robustness against echo and more noisy environment around the receiver.

Figure 6 shows the BER performance comparison of OFDM and CP-SC systems for UWB-AF-exponentially decaying multipath channels. Here the BER performance of CP-SC based SV [13] CM1-AF- exponentially decaying multipath Channel shows the best performance among others with BER of 10^{-6} at SNR of 20 dB. One major outcome of this indoor-outdoor channel model is that we may use only SV [13] CM1 in the indoor environment for uplink purpose because of good BER performance in both Figure 5 and Figure 6. However, in Figure 3 and Figure 4, we can use CM1 and CM2 for outdoor-indoor proposed channel model.

D. Capacity Performance Analysis

1. Transmitter located at outdoor

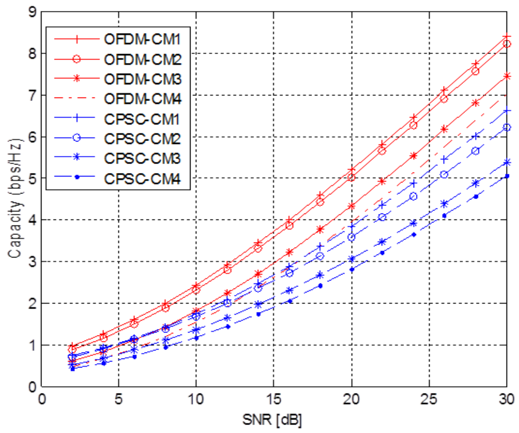

Figure 7. OFDM and CP-SC system for Rayleigh-AF-UWB channel

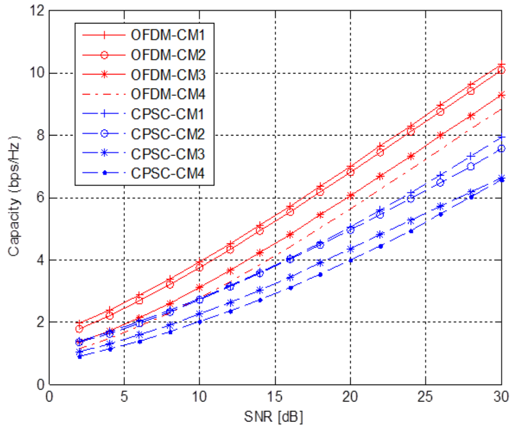

Figure 8. OFDM and CP-SC system for Exponentially decaying multipath-AF-UWB channel

Figure 7 shows the capacity performance comparison of OFDM and CP-SC systems for Rayleigh-AF-UWB channels. Here the capacity of OFDM based Rayleigh-AF-CM1 SV [13] channel shows the best capacity performance among others with capacity of 8.5bps/Hz at SNR of 30 dB. Overall OFDM systems show better performance than CP-SC systems (about 2bps/Hz). Due to multiple carriers, OFDM systems have better capacity than single carrier communication (CP-SC systems).

Figure 8 shows the capacity performance comparison of OFDM and CP-SC systems for exponentially decaying multipath-AF-UWB channels. The results are almost identical but the capacity of exponentially decaying multipath channel is almost 2bps/Hz better than Rayleigh-AF-UWB channels.

2. Transmitter located at indoor

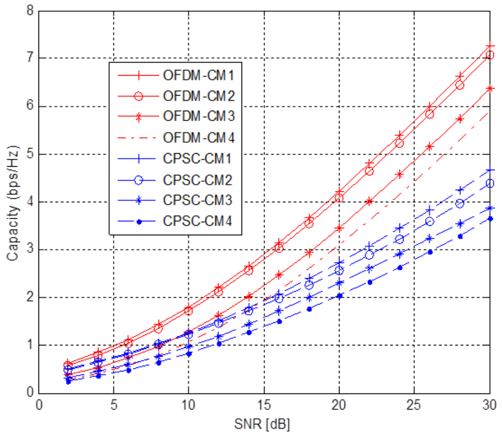

Figure 9. OFDM and CP-SC system for UWB -AF- Rayleigh channel

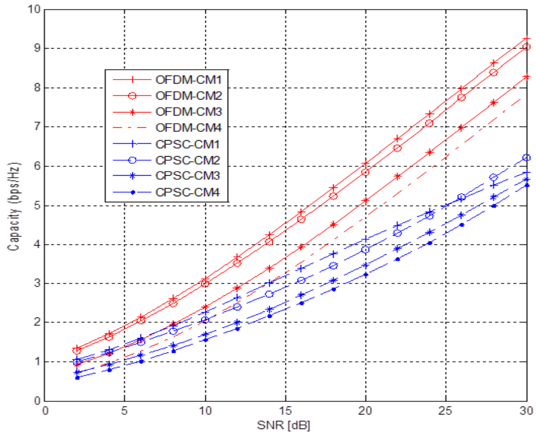

Figure 10. OFDM and CP-SC system for UWB -AF- Exponentially decaying multipath channel

Figure 9 shows the capacity performance comparison of OFDM and CP-SC systems for UWB-AF-Rayleigh channels. Here the capacity of OFDM based SV [13] CM1-AF-Rayleigh channel shows the best capacity performance among others with capacity of 7.2bps/Hz at SNR of 30dB. Overall OFDM systems show better performance than CP-SC systems (about 2.4bps/Hz). However, the capacity of this channel type is poorer than that of Rayleigh-AF-UWB channels (about 1.3bps/Hz). Figure 10 shows the capacity performance comparison of OFDM and CP-SC systems for UWB-AF-exponentially decaying multipath channels. Here the capacity of OFDM based SV [13] CM1-AF-exponentially decaying multipath channel shows the best capacity performance among others with capacity of 9.2bps/Hz at SNR of 30dB. However, the capacity of this channel type is poorer than that of exponentially decaying multipath-AF-UWB channels (about 0.9bps/Hz). We observe that the overall capacity of the indoor-outdoor channels is poorer than the outdoor-indoor channels as the second hop has poor transmission capacity and therefore a portion of the indoor capacity in the first hop (indoor) will be unused and it will create a bottleneck situation and overall capacity will degrade about 1bps/Hz.

IV. CONCLUSION

Based on the observed formulas, CP-SC systems show better BER performance than OFDM systems but we need to compensate with capacity, as the capacity of OFDM systems are showing better than CP-SC systems in our proposed model. We did not consider any kind of channel coding and therefore, we can further improve our system using channel coding and different types of relay and will make comparison between the outcomes. Furthermore, we can improve our system for more than two hops for enhancing the coverage. At the end, we examine the reverse link and find that for uplink case, we can use SV [13] CM1 channel with standard BER of 10^{-6} that will be a good option while applying our system for transceiver scenario. We can further improve our system using decision feedback for complete CSI information to the transmitter.

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