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# Performance Analysis of MC-CDMA Based UWB System for Beyond 4G

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### Abstract

In this paper, we analyze the impact of system imperfections on the overall performance of the MC-CDMA based Ultra-Wide-Band (UWB) system. A new expression of the signal-to-interference-noise ratio (SINR) for UWB Multicarrier Code division multiple access (MC-CDMA) system over a Rayleigh fading channel with imperfect power control condition are derived and investigated. The performance of MC-CDMA based UWB system over the frequency-selective multipath fading channel is examined with varying the number of users, K, the signal-to-interference-noise-ratio (SINR) per bit, $E_{\mathrm{b}}/N_0$. From the simulation results, we have seen that the SINR performance is affected by these parameters. The result of the analysis will provide relevant information to design the physical layer protocol for high speed UWB 4G communications system.

## 1 Introduction

The development of short range and high speed communication system plays a key strategic role in the field of Wireless Personal Area Networks (WPAN) [1],

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Body Area Network (BAN) [2] and Wireless Vehicular Network (WVN) [3]. This has inspired the development of the transmission system Ultra-Wide-Band (UWB) because of its potential uses for 4G and beyond. The principal benefits of this definition are the adjustable distribution of duration. UWB works in the wireless indoor environment where the channel suffers from frequency-selective fading [4]. In order to improve the efficiency of the Multi-Band OFDM (Orthogonal Frequency Division Multiplex) solution proposed by the Multi-Band OFDM Alliance (MBOA), incorporating a spreading portion in the frequency domain is a good solution because it enables resource allocation and also offers better robustness against channel frequency selectivity and narrow-band interference. DS-CDMA must therefore use many rake fingers which increase the complexity of the system. Since MC-CDMA does not need a RAKE receiver, it is simpler than DS-CDMA and shows great potential for use with UWB (WLAN, WPAN) applications because it can be concluded that slow channels differ in time [5]. This has prompted research into MC-CDMA systems that allow variable data rates [6, 7, 8]. In the meantime, MC-CDMA has emerged as a strong alternative to traditional direct sequence CDMA (DS-CDMA) in mobile wireless communications [9, 10, 11] and showed superior performance in multi-path fading to single carrier CDMA. MC DS-CDMA is recommended for use in UWB communications [12]. Ultra Wideband Transmission based on MC-CDMA is presented considering ideal condition in [5]. In MC-CDMA systems, transmitted data bits are serial-to-parallel converted to a number of parallel branches [13, 14]. Each bit on each branch is DS-SS (Direct Sequence-Spread Spectrum) modulated and transmitted with a number of orthogonal and overlapping carriers. The structures of MC-CDMA based UWB transmitter and receiver are illustrated in Figures 1 and 2, respectively.

The channel model of the UWB communication in indoor application is characterized by stochastic tapped-delay-line model [15].

The rest of the paper is organized as follows: Section 2 discusses the system model of the proposed MC-CDMA based UWB system. The SINR and BER of the proposed system is derived in Section 3. Section 4 presents the simulation result of the proposed system. We conclude our paper in Section 5.

## 2 MC-CDMA Based UWB System Model

The proposed MC-CDMA based UWB system is considered to have a total number of users, $K$, and each sub-band has $N$ subcarriers. In addition,

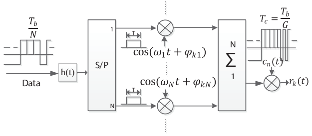

Figure 1: Transmitter of a MC-CDMA based UWB system.

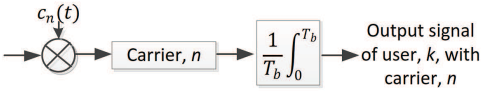

Figure 2: Receiver of a MC-CDMA based UWB system.

the chip rate and the bit rate of message signals are assumed to be set so that the processing gain, $G$, is determined by the chip rate ratio and the bit rate. Under these assumptions, the received signal $r_k(t)$, including the multipath interference (MPI), multiple access interference (MAI) narrow-band interference (NBI) and noise, is modeled as

$$r_k(t) = \sum_{m=1}^{K} r_{m,k}(t) + v(t), (k-1)T \leq t < kTr_k(t) \leq t < kT, \tag{2.1}$$

where $T$ is the length of the data bit, $k$ is the time index and $v(t)$ is the double-sided Gaussian spectral density additive of $N_0/2$. In Equation 2.1, the received signal from the $n$-th sub-band using the $i$-th subcarrier, $r_{ni,k}(t)$, is given by

$$r_{m,k}(t) = \alpha_{ni}(t)\sqrt{P_{ni}(t).}a_{ni}(t)\sum_{g=1}^{G} c_{ng,k}.h(t - gT_c - kT).\cos\left(2\pi\left(f_c + \frac{z_i}{Tc}\right)t\right)$$

The transmitted power of the $n$-th sub-band using the $i$-th subcarrier is denoted by $P_{ni}(t)$, $a_{ni}(t) \in \{-1, +1\}$, is a data bit, $c_{jg,k} \in \{-1, +1\}$ is the $g$-th component of a signature sequence with chip duration $T_c$ and $h(t)$ represents a pulse of duration $T_c$. The $f_c$ is a center frequency and $z_i$ stands for the $i$-th subcarrier that has an integer value for $1 \leqslant Z_i \leqslant N$. Each data is transmitted through a different frequency band, modulated by a different subcarrier, and experiences different fading. $\alpha_{ni}(t)$ is the component of fading envelope for the $n$-th sub-band using $i$-th subcarrier and has a Rayleigh distribution [16]. The fading envelope $\alpha_{ni}(t)$ is actually time varying, but here it is assumed that the fading changes with a rate much slower than the bit rate so that $\alpha_{ni}(t)$ can be considered as having constant value during a bit duration.

## 3 System Analysis

Let the correlation between the signals of the $n$-th sub-band with carrier $z_i$ and the signals of the $m$-th sub-band with $z_j$ be $R_{ij}^{nm}$. Then the output of the matched filter for the $n$-th sub-band using the $i$-th subcarrier is

$$U_{ni} = \alpha_{ni}\sqrt{P_{ni}} + \sum_{m=1,m\neq n}^{K} R_{ii}^{nn} + \sum_{j=1,j\neq i}^{N} R_{ij}^{nn} + \sum_{m=1,m\neq n}^{K}\sum_{j=1,j\neq i}^{N} R_{ij}^{nm} + \text{Noise} = \text{D} + \text{I} + \text{Z}.$$

The decision statistic consists of the contribution from the desired signal, interference (MPI, MAI, NBI of the UWB system) and noise.

## 3.1 Desired signal, D

In equation 3.2, the first term, which represents the desired signal, is obtained as

$$\begin{aligned} R_n^{nn} &= \alpha_{nt}.\sqrt{P_{ni}}.\frac{1}{T_b}\int_0^{T_b} c_n(t).c_n(t).\cos\left(\frac{2\pi(z_i - z_i)t}{T_C}\right)dt \\ &= \alpha_{nt}\sqrt{P_{ni}}.\frac{1}{T_b}\int_0^{T_b} c_n(t).c_n(t) = \alpha_{nt}\sqrt{P_{ni}} \end{aligned} \tag{3.2}$$

The desired power is easily obtained as

$$E[D^2] = E[\alpha_{ni}^2]P_{ni} = P_{ni,rv} \tag{3.3}$$

## 3.2 Interference Term, I

The second term in equation 3.2 is the interference from the different sub-bands with the same carrier and the cross correlation between the $n$-th sub-band with the $i$-th subcarrier and the $m$-th sub-band with the same subcarrier is

$$\begin{aligned} R_{ii}^{nm} &= \alpha_{mi}\sqrt{P_{mi}}\frac{1}{T_b}\int_0^{T_b} c_n(t).c_m(t).\cos\left(\frac{2\pi(z_i - z_i)t}{T_C}\right)dt \\ &= R_{ii}^{nm} = \alpha_{mi}\sqrt{P_{mi}}\frac{1}{T_b}\int_0^{T_b} c_n(t).c_m(t).dt \end{aligned} \tag{3.4}$$

The third term in equation 3.2 comes from the same sub-band with the different carriers and the cross correlation between the $n$-th sub-band with the $i$-th subcarrier and the $n$-th sub-band with the $j$-th subcarrier is zero due to the orthogonality of subcarriers in a sub-bands.

$$\begin{aligned} R_{ij}^{nn} &= \alpha_{nj}\sqrt{P_{nj}}\frac{1}{T_b}\int_0^{T_b} c_n(t).c_n(t).\cos\left(\frac{2\pi(z_i - z_j)t}{T_C}\right)dt \\ &= \alpha_{nj}\sqrt{P_{nj}}\frac{1}{T_b}\int_0^{T_b} \cos\left(\frac{2\pi(z_i - z_j)t}{T_C}\right)dt \end{aligned} \tag{3.5}$$

The fourth term in equation 3.2 comes from different sub-bands with different carriers and the cross correlation between the $n$-th sub-band with the $i$-th subcarrier and the $m$-th sub-band with the $j$-th subcarrier is zero due to the orthogonality of subcarriers.

$$\begin{aligned} R_{ij}^{nm} &= \alpha_{mj}\sqrt{P_{mj}}\frac{1}{T_b}\int_0^{T_b} c_n(t).c_m(t).\cos\left(\frac{2\pi(z_i-z_j)t}{T_C}\right)dt \\ &= \alpha_{mj}\sqrt{P_{mj}}\frac{1}{T_b}\int_0^{T_b} .\cos\left(\frac{2\pi(z_i-z_j)t}{T_C}\right)dt \end{aligned} \tag{3.6}$$

Total other-user interference is obtained by calculating the variance of $U_{ni}$ without noise. Other-user Interference

$$Var[U_{ni}] = Var\left[\sum_{m=1,m\neq n}^{K} R_{ii}^{nm}\right] \tag{3.7}$$

Since the first, the third and the fourth terms in the equation **??** are constant, the corresponding variances are zero. Let $Y = \sum_{m=1,m\neq n}^{K} R_{ii}^{nm}$, then the value of $Y$ is

$$\begin{aligned} Y = \sum_{m=1,m\neq n}^{K} \alpha_{mi}\sqrt{P_{mi}}\frac{1}{T_b}\int_0^{T_b} c_n(t).c_m(t)dt \\ = \frac{1}{T_b}\sum_{m=1,m\neq n}^{K}\alpha_{mi}\sqrt{P_{mi}}\sum_{s=1}^{G}c_n^s c_m^s\int_{sT_c}^{(s+1)T_c} \\ h(t-sT_c)h(t-(s+1)T_c)dt \\ = \frac{T_c}{T_b}\sum_{m=1,m\neq n}^{K}\alpha_{mi}\sqrt{P_{mi}}\sum_{S=1}^{G}c_n^s c_m^s \\ = \frac{T_c}{T_b}\sum_{m=1,m\neq n}^{K}\alpha_{mi}\sqrt{P_{mi}}\left[c_n^1c_m^1+...+c_n^Gc_m^G\right] \\ = \frac{T_c}{T_b}[\alpha_{1i}\sqrt{P_{1i}}\left(c_n^1c_1^1+...+c_n^Gc_1^G\right)+......+\alpha_{n-1,i}\sqrt{P_{n-1,i}}\left(c_n^1c_{n-1}^1+...+c_n^Gc_{n-1}^G\right) \\ +\alpha_{n+1,i}\sqrt{P_{n+1,i}}\left(c_n^1c_{n+1}^1+...+c_n^Gc_{n+1}^G\right)+......+\alpha_{Ki}\sqrt{P_{Ki}}\left(c_n^1c_K^1+...+c_n^Gc_K^G\right)], \end{aligned} \tag{3.8}$$

where $c_n^G$ is the $g$-th component of the $n$-th sub-band's signature sequence. Then

$$E\left[Y^2\right] = \left(\frac{T_c}{T_b}\right)^2 E[\alpha_{1i}^2P_{1i}\left(c_n^1c_1^1+....+c_n^Gc_1^G\right)^2+....$$

$$+\alpha^2_{n-1,i}, P_{n-1,i}\Bigg(c_n^1 c_{n-1}^1 + .... + c_n^G c_{n-1}^G\Bigg)^2$$

$$+\alpha^2_{n+1,i}P_{n+1,i}\Bigg(c_n^1 c_{n+1}^1 + .... + c_n^G c_{n+1}^G\Bigg)^2 + ...$$

$$+\alpha^2_{Ki}P_{Ki}\Bigg(c_n^1 c_k^1 + .... + c_n^G c_K^G\Bigg)^2]$$

$$= \left(\frac{T_c}{T_b}\right)^2 E\left[\sum_{l\neq n}^{K} \alpha^2_{li}P_{li}\left\{\left(c_n^1 c_l^1 + ... + c_n^G c_l^G\right)^2\right\}\right]$$

$$= \left(\frac{T_c}{T_b}\right)^2 E\left[\sum_{m=1,m\neq n}^{K} \alpha^2_{mi}P_{mi}\left\{\Bigg(c_n^1 c_m^1) + ... + (c_n^G c_m^G\Bigg)^2\right\}\right]$$

$$= \left(\frac{T_c}{T_b}\right)^2 E\left[\sum_{m=1,m\neq n}^{K} \alpha^2_{mi}P_{mi}G\right]$$

$$= \left(\frac{T_c}{T_b}\right)^2 G \sum_{m=1,m\neq n}^{K} E\left[\alpha^2_{mi}\right]P_{mi}$$

$$= \left(\frac{T_c}{T_b}\right)^2 G \sum_{m=1,m\neq n}^{K} P_{mi,rv}$$

$$= \frac{1}{G}\sum_{m=1,m\neq n}^{K} P_{mi,rv}. \tag{3.9}$$

Finally, the variance of $Y$ is

$$Var[Y] = E[Y^2] - (E[Y])^2 = \frac{1}{G}\sum_{m=1,m\neq n}^{K} P_{mi,rv}. \tag{3.10}$$

Thus MAI power

$$\sigma^2_{MAI} = \frac{1}{G}\sum_{m=1,m\neq n}^{K} P_{mi,rv}. \tag{3.11}$$

### 3.3 Noise term, Z

From Equation 3.2

$$Z = \int_0^{Tb} n(t)c_1(t)cos\omega_n tdt \tag{3.12}$$

$$E[Z^2] = \frac{1}{T_b}\int_0^{Tb} n^2(t){c_1}^2(t)cos^2\omega_n tdt \approx \frac{N_0}{4T} \tag{3.13}$$

$$Var[Z] = E[Z^2] = {\sigma^2}_N = \frac{N_0T_b}{4} \tag{3.14}$$

From equations 3.3, 3.11 and 3.14, the received SINR of the $n$-th sub-band using the $i$-th subcarrier is

$$\begin{aligned}\text{SINR}_{ni} &= \frac{D}{\sigma^2_{MAI} + \sigma^2_N} = \frac{P_{ni,rv}}{\left(\frac{1}{G}\sum_{m=1,m\neq n}^{K} P_{mi,rv} + \frac{N_0}{4T_b}\right)} \\ &= \frac{1}{\left(\frac{1}{GP_{ni,rv}}\sum_{m=1,m\neq n}^{K} P_{mi,rv} + \frac{N_0}{4P_{ni,rv}T_b}\right)}\end{aligned} \tag{3.15}$$

In case of imperfect power control, the set of power level for the K-1 interfering users are not constant, but a random variable. The received amplitude $P_k$ of the k-th user can be modeled as a random variable with uniform distribution around the nominal value of the received power level $P_0$. The *pdf* of $P_k$ can be assumed as [110],

$$f(P_k) = \frac{1}{2V},\ P_0 - V \leq P_k < P_0 + V, \tag{3.16}$$

where V is the maximum variation range of the received signal with respect to the mean value $P_0$. Here,

$$E[P_k] = \int_{P_0-V}^{P_0+V} P_k f(P_k)dP_k = P_0 \tag{3.17}$$

$$\text{SINR}_n = \sum_{i=1}^{N}\text{SINR}_{ni} = \frac{P_0}{P_k}\frac{N}{\left(\frac{1}{G}K + \frac{N_0}{4E_b}\right)}, \tag{3.18}$$

where energy per bit $E_b = PT_b$. For Binary Phase-Shift Keying (BPSK) modulation scheme, over any channel bit error rate (BER) is expressed by the well-known relation [17]

$$\text{BER} = Q(\sqrt{\text{SINR}}) = Q\left(\sqrt{\frac{P_0}{P_k}\frac{N}{\left(\frac{1}{G}K + \frac{N_0}{4E_b}\right)}}\right). \tag{3.19}$$

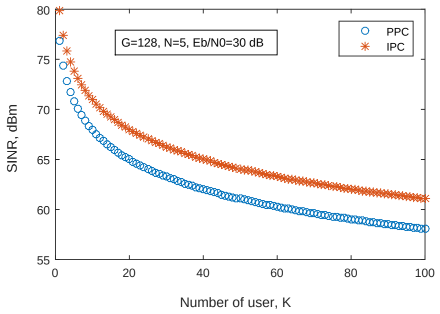

Figure 3: SINR versus the number of users for MC-CDMA based UWB system with imperfect power control.

# 4 Results

SINR in case of imperfect power control of MC-CDMA based UWB system has been plotted in Figures 3 and 4 versus the number of users K and the SNR per bit $E_b/N_0$ respectively. Here, $P_0/P_k = 1$ corresponds to the perfect power control (PPC) condition and $P_0/P_k = 2$ is an imperfect power control (IPC) condition where the maximum variation of the received amplitude $P_0$ is twice to the mean value of the received amplitude $P_k$. In Figure 3, SINR is plotted versus the number of simultaneously active users, K, using G=128, N=5 and $E_b/N_0$=30 dB to draw the two curves considering PPC and IPC condition. From Figure 3, it is observed that keeping all other parameter constant, if the number of simultaneously active user is increased, the SINR decreases. The cause behind this trend of SINR can explain easily. As the number of user increases, the interference among the users increase which in tern increase the MAI power and consequently, the SINR decreases. The variation of SINR versus $E_b/N_0$ using G=128, N=5, K=5 is shown in Figure 4 and observed that keeping all other parameters constant, if the ratio $E_b/N_0$ is increased, the SINR increase almost linearly upto a certain value. After that certain value of $E_b/N_0$, the SINR becomes almost independent of $E_b/N_0$. It can be explained as below. For lower value of $E_b/N_0$, the interference power caused by multiple users is negligible compared to the noise power. Consequently, for the lower value of $E_b/N_0$, SINR is linearly related with $E_b/N_0$. But after a certain value of $E_b/N_0$, the noise power becomes less significant compared to that MAI power. Hence the SINR becomes almost independent of $E_b/N_0$. Next the BER performance of the proposed MC-CDMA based UWB system is compared with the theoretical performance in Figure 5. As observed,

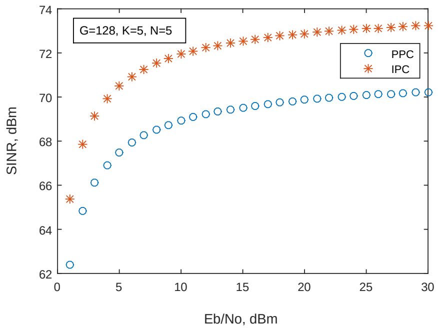

Figure 4: SINR versus $E_b/N_0$ for MC-CDMA based UWB system with imperfect power control.

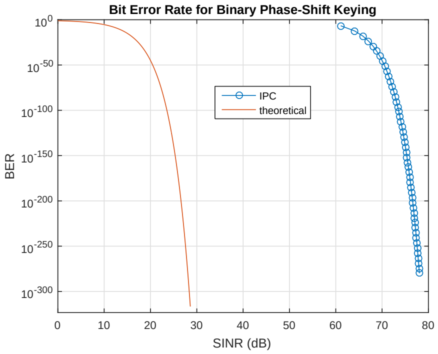

Figure 5: BER versus SINR for MC-CDMA based UWB system.

in imperfect power control condition the BER performance degrades almost three fold compare to its theoretical values.

## 5 Conclusion

In this paper, the expression of SINR and BER of MC-CDMA based UWB communication system over a frequency selective multipath Rayleigh fading channel is evaluated. An imperfect power control condition has been used to evaluate the SINR and BER performance for the MC-CDMA system and observed that its performance degrades almost three fold compared to its theoretical values. MC-CDMA seems like a promising method for supporting variable data rates for a large number of users in UWB communication systems for 4G and beyond.

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