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Multiband-OFDM MIMO for UWB Communication Systems

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Abstract—Ultra Wideband (UWB) communication technology promises to satisfy need for high data rate applications over wireless. It can supports connection of multiple devices at very high data rates. Also due to its use of a high frequency bandwidth, UWB satisfy need for low cost, low power devices. Also the use of multiple-input multiple-output (MIMO) can satisfy the growing demand for higher data rates, so a combination of a MIMO system and an UWB OFDM is one possible solution for the growing demand for higher data rates. In this paper we discuss about a multiband OFDM UWB system with simple block and we show that we can improve the performance of system with such a simple system. Also we analyzed this system, and we show that MIMO multiband-OFDM system have less BER than OFDM UWB system.

Index Terms—Multiband Orthogonal Frequency Division Multiplexing (OFDM),ultrawideband (UWB), Wireless Personal Area Networks(WPANs), multiple-input multiple-output (MIMO).

I. Introduction

ULTRAWIDEBAND (UWB) is a technology that promises to satisfy need for low cost, low power and high speed digital wireless home networks. UWB is defined as any radio transmission that occupies a bandwidth of more than 20% of its center frequency, or nominally more than 500 MHz. In 1998, the Federal Communications Commission (FCC) has mandated that UWB radio transmission can legally operate in the range from 3.1 GHz to 10.6 GHz, at a transmit power of -41.3 dBm/MHz[1].UWB system has no carrier and it energy is below than the thermal noise of devices such as GPS, Bluetooth.Tabel1. shows the characteristics of the UWB OFDM standard vs. other technologies for short range Wireless Personal Area Networks(WPANs) , e.g. Bluetooth, IrDA, or medium range Wireless Local Area Networks (WLAN), e.g. 802.11a/b and Wireless Metropolitan Area Network (WMAN), e.g. WiMAX. Since UWB OFDM features up to 10 m connection range, the highest data rate (hundreds of Mbps vs. the few Mbps of Irda and Bluetooth and 54 Mbps of WLAN) at low output power (1 mW), it has the potentiality to enable wireless multimedia networking in home or SOHO (Small Office Home Office) scenarios. Moreover, UWB OFDM can allow wireless USB connections[9].

	Data Rate (Mb/s)	Output Power (mW)	Range (meters)	Frequency Band (GHz)
Bluetooth	1 – 2	100	100	2.4
IrDA	4	100 mW/sr	1 – 2	infrared
OFDM-UWB	100 500	1	10	3.1 10.6
IEEE 802.11a	54	40 – 800	20	5
IEEE 802.11b	11	200	100	2.4
IEEE 802.11g	54	65	50	2.4

Table1. UWB OFDM system main features vs. other wireless technologies.

Traditional UWB used single bands systems, but use of multiband with OFDM can improve traditional UWB systems. In multiband UWB schemes, the available spectrum divided into several bands, each having a minimum of 500 MHz of bandwidth, to comply with the FCC requirements [2].Using orthogonal frequency division multiplexing (OFDM) technique in each subbands to modulate the information, improve the robustness of the system with respect to multipath effects and interference. Current UWB systems can support more than 500 Mbps data transmission within 10m, which enables various new services and applications [3]. Multiple-input, multiple-output (MIMO) systems have been improved performance of wireless systems in terms of flexibility, reliability and throughput without requiring additional bandwidth or power. In this paper we want to study the performance of MIMO in UWB systems, where the available bandwidth is large and the SNR per degree of freedom is low.The rest of the paper is organized as follows. In Section II, we present our multiband UWB-MIMO system model, including the channel model, transmitter description, and receiver description. The analysis of MIMO multiband UWB system is presented in Section III. Section IV shows simulation results and finally Section V concludes the paper.

II. System Description

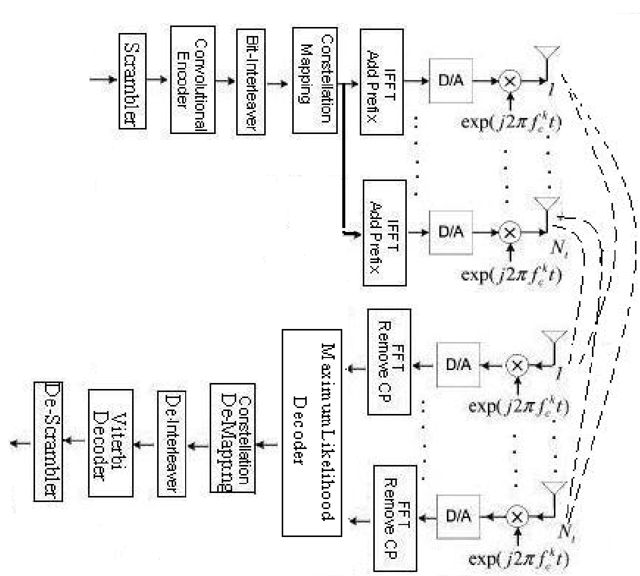


Fig. 1. Multiband UWB-MIMO system.

Fig.1 shows the block diagram of a Multiband UWB-MIMO system, which closely follows the IEEE 802.15.3a proposal. The available UWB spectrum of 7.5 GHz is divided into several subbands, each with bandwidth BW of at least 500 MHz. Each user utilizes one subband per transmission. For each user, signals from all transmit antennas share the same subband. Within each subband, OFDM modulation with N (=128) subcarriers is used at each transmit antenna. Different bit rates are achieved by using different channel coding, frequency spreading, or time spreading rates[1]. In the following we described transmitter, channel model and receiver of the system.

A. Transmitter

The binary data stream to be transmitted is first scrambled. The scrambled data bits are obtained using:

$$s_n = b_n \oplus x_n \tag{1}$$

In the next stage, the convolutional encoder adds patterns of redundancy to the
data in order to improve the signal-to-noise ratio (SNR) for more accurate detection at the receiver. A bit interleaver is used to prevent burst errors or losing consecutive data bits. Interleaving is performed on the coded bit stream so errors appear more randomly, and then converted into QPSK symbols. Each symbol is spread into two widely separated tones in the same OFDM block to exploit frequency diversity in UWB channels. At the OFDM a cyclic prefix of length T_{CP} and guard interval is T_{GI} added to the output of the IFFT processor, so the duration of an analog baseband OFDM signal is $T_{SYM} = T_{FFT} + T_{CP} + T_{GI}$. Fig.2. illustrates a time-frequency representation of multiband UWB symbols. In this figure three pulses are sent in three time slots.

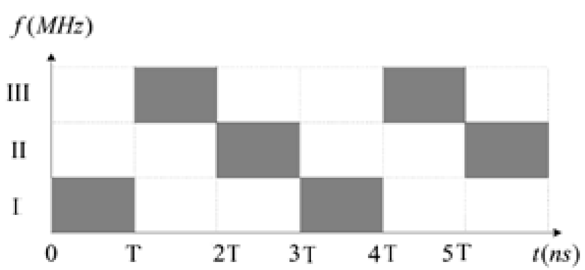


Fig. 2. Time-frequency representation of multiband UWB symbols

B. Channel Model

For our simulation we consider the channel model developed under IEEE 802.15 for UWB systems. Because in ad hoc networks and WPANs the terminal mobility is very limited so the channel impulse response(CIR) is assumed time invariant within the transmission of each packet. Also the CIR is a Saleh-Valenzuela model where multipath rays arrive in clusters with exponentially distributed cluster and it models the ray interarrival times as well as the average power of rays and clusters. Fading of the ray amplitudes is emulated by a log-normal random variable. Also, in Saleh-Valenzuela model,the CIR can be modeled by:

$$h(t) = \sum_{c=0}^{C} \sum_{l=0}^{L} \alpha(c,l)\delta(t - T_c - \tau_{c,l}) \tag{4}$$

Where $\alpha(c,l)$denotes the gain of lth multipath component in the cth cluster, and $\tau_{c,l}$ is the delay of the lth path in the cth cluster relative to the cluster arrival time [7].
Four channel models (CM1,CM2,CM3 and CM4) are specified in the IEEE 802.15.3.a,each model is based on transmission distance and line-of-sight (LOS) conditioning with different arrival rates and decay factors.CM1 is based on 0-4 m distance LOS condition ,CM2 involves the same distance but non-LOS,CM3 also operates on non-LOS but 4-10 m distance and CM4 is based on 4-10 m distance and an extreme non-LOS multipath channel condition.

C. Receiver

At the receiver, after OFDM demodulation discards the cyclic prefix and performs an N-point FFT a maximum-likelihood (ML) detection is jointly performed across all receive antennas, then we obtain a binary sequence which is input into the bit deinterleaver. ML decoder is the optimal detection and can achieve the best BER performance. However, its computational complexity grows exponentially with the number of transmit antennas M. Here we analysis the process of ML decoder. Assume $w_{k,l}$is statistically independent with respect to indices k and l, which is given by

$$\langle w^*_{k1,l1} w_{k2,l2} \rangle = \sigma_w^2 \delta_{k1k2} \delta_{l1l2} \tag{8}$$

σ_w^2 is the average power of the noise, and < > and * denote the ensemble average and complex conjugation, respectively. Let us consider ML decoder works based on the observation vector $\underline{y}$ over a relatively short K length of symbols. The probability density function of the received data matrix after OFDM demodulation $\underline{y}$ conditioned on the MIMO channel matrix $\underline{H}$ and transmitted symbol matrix $\underline{x}$ can be written as:

$$p\left(\underline{y}\middle|\underline{H}, \underline{x}\right) = \frac{1}{(2\pi\sigma_w^2)^{L\times K}} e^{-(1/2\sigma_w^2)\sum_{i=1}^{K}\left\|\underline{y_i} - \underline{H}\underline{x_i}\right\|^2} \tag{9}$$

So by maximizing $p\left(\underline{y}\middle|\underline{H}, \underline{x}\right)$ we can find ML estimation of $\underline{H}$ and $\underline{x}$.Equivalently,the joint ML estimation can be obtained by minimizing absolute power of the exponential function, Thus the decision rule can be stated as:

$$(\hat{x}, \hat{H}) = arg\,\min_{\underline{H},\underline{x}} \sum_{i=1}^{K} \left\|\underline{y_i} - \underline{H}\underline{x_i}\right\|^2 \tag{10}$$

After ML decoder the hard decision Viterbi decoding algorithm is utilized to decode the convolutional encoded sequence. After descrambling the output of previous stage, we obtain a binary sequence with a certain bit error probability. At last for one transmit antenna and one receive antenna we have $y_0,\ldots, y_{N-1}$ whose are related to the frequency response of the channel by

$$y_k = x_k H_k + w_k \qquad (2)$$

Where, H_k is the channel's frequency response in the kth subcarrier and w_k is the additive noise component in the kth subcarrier and x_k is the kth transmitted symbol. MIMO UWB systems can be modeled as:

$$\underline{y_k} = \underline{H} \,.\, x_k + \underline{w_k} \qquad (3)$$

Where $x_k = \begin{pmatrix} x_{1,k} \\ x_{2,k} \\ \vdots \\ x_{M,k} \end{pmatrix}$ is the transmitted symbols vector of the M transmitters $y_{l,k}$,$w_{l,k}$ are the received signal, and the additive noise component(with interference) at the kth tone, and $\underline{H}$ denotes the $L \times M$ MIMO channel's frequency response matrix ,For this system the same OFDM symbol is transmitted at different times or frequency bands.

III. Analysis of MIMO Systems

Here we discuss about three important factor in a communication system on especially in our of multiband-OFDM UWB system, and discuss how we can improve the performance of the system.

A. Channel capacity

According to Shannon limit on channel capacity, C, for a given channel, whose bandwidth is B and average SNR of SNR_0 at the receiver, then C is

$$C = B.\log_2(1 + SNR_0) \qquad (5)$$

Because UWB channels is wideband channels, the available transmitted power is spread over a large number of degrees of freedom and this makes the SNR per degree of freedom low[6]. Consequently according to above equation we can't increase C for UWB channels as desired. Because we have seen the emergence of high data rate so we need greater C, now, if we have L antennas at the receiver and M antennas at the transmitter (assumes that same signal transmitted by each antenna).The total transmitted power is divided up into the M transmitter branches and because we have L receiving antennas we assume that the noise level is L times greater than previous case, so we get approximately an ML-fold increase in the SNR as compared to the previous case. Thus the overall increase in SNR is approximately:

$$SNR \approx \frac{M^2.(transmitted\ signal\ power/M)}{L.channel\ noise} \qquad (6)$$

But in MIMO systems we send different signals in the same bandwidth so we have M channels, thus if again we use Shannon limit on channel capacity, C is

$$C = M.C_{single} \approx B.M.\log_2\left(1 + \tfrac{M}{L}.SNR_0\right) \qquad (7)$$

Thus, the channel capacity for MIMO system is higher than the simple case and we have a linear increase in capacity with the number of transmitting antennas.

B. Average Bit Error Rate(BER)

Another important thing in a communication system is BER. So here we consider BER of multiband-OFDM UWB system.

Writer of [8] evaluate bit error rate (BER) of the multiband-OFDM UWB:

BER_{uc} (Average uncoded BER) $=0.5 * (1 + \sqrt{\frac{SNR_0}{1+SNR_0}})$ (11)

Where SNR_0 is the signal-to-noise ratio at the receiver and BER_{uc} is BER before the convolutional decoder.

And Average coded BER (BER after the convolutional decoder) can be approximated by[8]:

$$BER_c \approx 7[4.BER_{uc}(1 - BER_{uc})]^{\frac{15}{2}} \qquad (12)$$

This BER is for one transmit antenna and one receive antenna, for MIMO systems it will be changed. For example for one transmit antenna and two receive antennas[8]:

$$BER_{uc} = 0.5 - 0.75\sqrt{\frac{SNR_0}{1+SNR_0}} + 0.25\left(\sqrt{\frac{SNR_0}{1+SNR_0}}\right)^3 \qquad (13)$$

With compression of these BER we find that this BER_{uc} is less than the previous BER_{uc} .

C. UWB Link Budget

Another important parameter in a communication system is lnk budget. Since The transmission power must not exceed -41.3 dBm/MHz, and it is a very small power, for comparison the light emitted by a candle (one candela) is equivalent to 18.4 mW.The light power (not heat) radiated by a candle is 200 times than that of a wireless USB transceiver that meets multiband OFDM specification[11]. So in UWB system link budget is very important.Table2 is the link budget that appears in multiband OFDM UWB specification[10].

Parameter	>110 Mbps	>200 Mbps	Unit
Throughput (Rb)	119.6	257.4	Mbps
Center frequency Fc	4.8	4.8	GHz
Path loss at 1 meter [L1=20Log(4PI*Fc/c)]	46.0	46.0	dB
Path loss at d meters [L2=20log(d)]	20.0	12.0	dB
Rx power (Pr =Pt-L1-L2)	-73.8	-65.9	dBm
Average noise power per bit [N=-174 +10*log(Rb)]	-93.2	-89.9	dBm
Rx Noise Figure Referred to the Antenna Terminal (Nf)	7.0	7.0	dB
Average noise power per bit (Pn=N+Nf)	-86.2	-82.9	dBm
Minimum Eb/No (S)	5.4	4.5	dB
Implementation Loss(I)	3.0	3.0	dB
Symbol Rate	13.0	19.5	MHz
Bits per symbol	11.5	16.5	
Raw Bit rate	149.5	321.8	Mbps
Code rate	0.8	0.8	
Pulse Tx power (Pt)	0.5	-1.3	dBm
Link Margin (M=Pr-Pn-S-I)	4.0	9.5	dB
Min. Rx Sensitivity Level (Pr-M)	-77.8	-75.4	dBm
Range	15.8	12.0	m

Table2. Link Budget from IEEE 802.15.3a Proposal

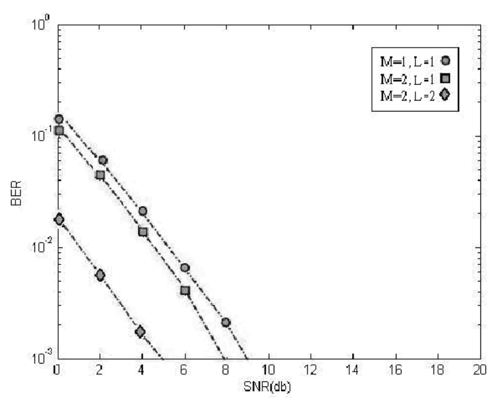
This table include path loss, link margin, data rate, range… The table demonstrates the fundamental trade off between data rate and range. Second column is for data rate greater than 200Mbps and the associated range of 12.0 meters, and first column for the lowest data rate of 110Mbps and a range of 15.8 meters. The signal attenuation during transmission is modeled by the path loss

$$p_L = 20\log(4\pi f_g / C) \tag{14}$$

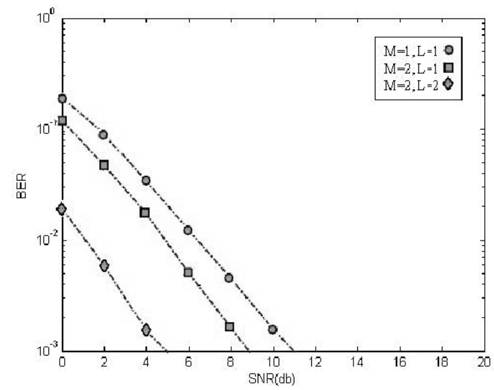
Where C is the speed of light, f_g is the geometric average of the upper and lower frequencies in terms of MHz of the transmission spectrum , and d is the transmission distance [8]. In practical the signal attenuation is compensated by the use of multiple-transmitter, multiple-receiver antenna.
So from above we conclude that, increasing the number of transmit and receive antennas, decrease the BER of the system and increase the capacity of it (data rate), and can help use of the power, thus this technique improve the transmission range of UWB devices.

IV. SIMULATION RESULTS

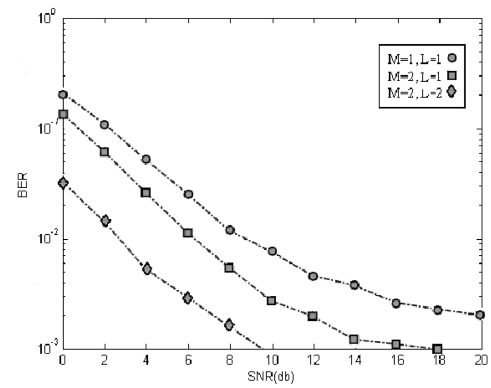
To show the performance of our system , we perform simulations for it. We implemented this system in the MATLAB. Our simulated system has N=128 subcarriers and the duration of OFDM symbols is 2 ns and bit rate is 160 Mbps. In the transmitter the output of IFFT block is real, so our simulation is in the baseband, also our system without channel estimation and obviously we can improve the performance of our system with channel estimation. Also this simulation is done for 500 OFDM symbols. In what follows, we present the average bit error rate (BER) curves of our system as functions of the average SNR per bit in db. The plots for this simulation under the four standard channel models with ISI and noise is shown in figure 3. In this figure, the curves with circles (‘○’), squares (‘□’) and diamond (‘◊’) show the performances of the system with single transmit and single receive antennas, two transmit and one receive antennas, and two transmit and two receive antennas, respectively.



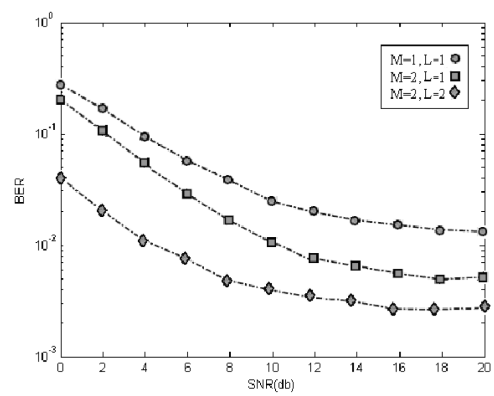
(a)



(b)



(c)



(d)

Fig. 3. BER vs. SNR plots for (a) CM1 (b) CM2 (c) CM3 (d)CM4

From this figure we can see the effect of channel (CM1, CM2, CM3, CM4) on two transmit and two receive antennas is less than others and we can see for the same conditions two transmit and two receive antennas has less BER than other systems. Also we can see the performance of our system is less than other systems for the same purpose, especially we compared this system with [1] and we found that it has a better performance.

V. CONCLUSION

UWB communication provides a new and exciting opportunity for high-bandwidth data communications. We discuss about a multiband OFDM UWB system with simple block and we show we can improve the performance of system with such a simple system. We show additional antennas at the transmitter and receiver can decrease BER of the system and increase data rate of it. Also we discuss about the channel capacity of the MIMO multiband OFDM UWB. We use maximum-likelihood decoder in the receiver and show it's equation for estimation of channel and symbol matrix. Also we discuss about UWB link budget and the importance of it in designation. Finally we show the results of our simulations and we show that according to our simulation, we can improve the performance of the multiband UWB system without complex block such as STF.

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