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Research on Multiband Impulse Radio UWB System based on PSWF in Multipath Fading Channel

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Abstract

This paper presents an architecture of Multiband Impulse Radio UWB (MB-IR-UWB) system based on Prolate Spheroidal Wave Function (PSWF) by binary time hopping pulse position modulation (TH-PPM) over multipath fading channel. In order to combat multipath fading, Rake receiver using maximal ratio combining (MRC) is applied to this system, which can successfully capture the unique multipath-rich property and multipath-clustering phenomenon of UWB channels. Through simulation, a comparison of system performance between different types of Rake receiver is analyzed. What's more, considered multipath delay spread, a data rate estimation of the communicating system is given. Finally we get the conclusion that increasing data rate is best-achieved by increasing the number of subband instead of decreasing the symbol repetition period.

Keywords*—Multiband Impulse Radio UWB; High data rate; multipath; Rake reception; performance analysis*

1. Introduction

Due to its high channel capacity, an ultra-wideband (UWB) system is an attractive solution for the implementation of very high data rate in short-range wireless networks [1]. However, conventional single-band UWB signal has a wide fixed spectrum, which made the receiver lack the flexibility to manage radio resources efficiently and restricted the improvement of the system transmission performance. In 2004, Stkphane Paquelet proposed the idea of multiband in [2-3], and proved that the method can effectively improve the transmission rate. Later in [4] Martin Mittelbach modified the model and concluded that extending the basic architecture to a multiband system could allow remarkable data rates in the order of several hundred Mbit/s up to almost a Gbit/s. Multiband Impulse Radio UWB (MB-IR-UWB) scheme divides the allocated UWB frequency range into several subbands and transmit information in multiband parallel band, which would not only expand the capacity of the system, but also improve the flexibility of spectrum utilization.

According to preceding researches, we know traditional MB-IR-UWB systems use band-pass filter to arrange for the spectrum, and use incoherent energy detection in the receiver, but the filter design is more complex and the system performance is worse than coherent reception. Based on the band-limited and orthogonal characteristics of PSWF [5], it can be equivalent to the ideal band-pass filter, thus the coherent demodulation can be applied to get better performance.

In UWB wireless communication, multipath propagation can cause frequency selective fading of received signals and influence signal detection. In order to implement an efficient

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system, it is vital to capture the behavior of UWB channels, which has been characterized by Saleh-Valenzuela (S-V) model [6]. The fine resolution of received multipath components in UWB systems allows the use of Rake receiver to combine natural channel diversity to improve system performance. In this paper, we apply Rake receiver into MB-IR-UWB system and use coherent reception to get a better performance.

In this paper, Section 2 makes a brief introduction of MB-IR-UWB architecture. The channel model specified by IEEE 802.15.3a, Rake receiver and system signal model is developed in Section 3. The simulation result and analysis of MR-IR-UWB transmission performance with different Rake receivers is presented and discussed in Section 4. Finally, Section 5 concludes this paper.

2. MB-IR-UWB System Overview

A block diagram of entire system model is depicted in Figure 1 and Figure 2. These two diagrams contain the major components of this architecture [7-8].

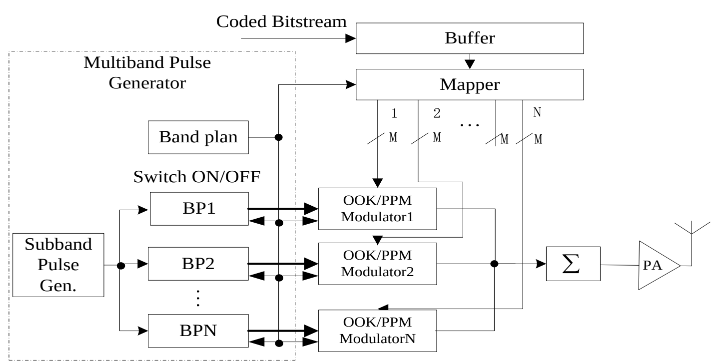

Figure 1. Multi-band Pulse Generator and MB-IR-UWB transmitter

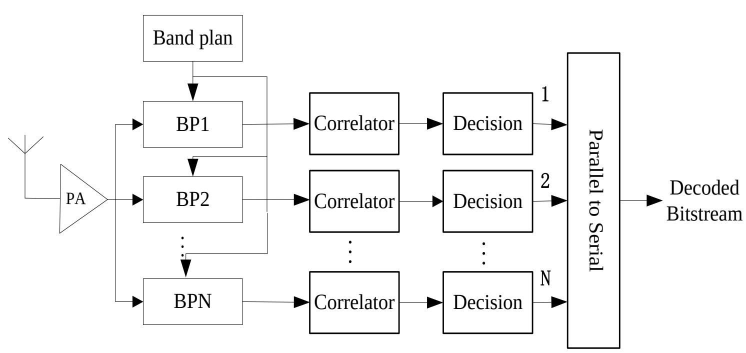

Figure 2. MB-IR-UWB receiver block diagram

The basic working method of MB-IR-UWB system is as follows. A mono-band pulse generator is to generate a number of pulses where each pulse occupies a specific frequency band. The relatively narrow-band pulses are referred to as subband or monoband pulses. Each subband pulse is modulated with different data according to a specific modulation scheme. Prior to modulation the coded bit stream is convert into a block of M N band bits that is partitioned into N band groups of M bits. After modulation, the N multi-band pulses are combined, amplified and transmitted via an UWB antenna. After experiencing a multi-path and thermal noise channel, on the receiver side, a coherent demodulation is considered, ensuring the optimum reception. At first, the received multi-band signal is decomposed by multiplying the orthogonal mono-band pulse to its subband and subsequent operations are performed per band. And then, make the received data parallel to serial conversion and make a soft or hard bit decision depending on the type of channel decoder. At last, we can get the original data. Theoretically multi-band technology can improve the system capacity N times (N is the sub-band number), but it is still far from this limit.

In our scheme we divide the UWB spectrum (from 3.1GHz to 7.5GHz) into several subbands, and then use the corresponding PSWF time domain impulse as the information carrier of MB-IR-UWB. The multiband spectrum allocation is given in Figure 3. In order to meet the requirements of ultra-wideband communications, the bandwidth of each band should be greater than or equal to 500MHz.

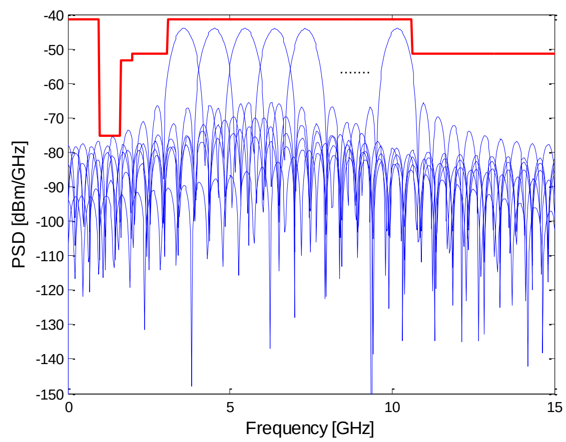

Figure 3. The multiband spectrum allocation diagram

3. Channel model and Rake receiver

3.1 Channel model

The channel model specified in the IEEE 802.15.3a standard [9] is based on the S-V model for indoor channels, modified so that multipath gains have a lognormal distribution rather than a Rayleigh distribution. In S-V model, the channel impulse response can be modeled by

$$h(t) = X\sum_{k=1}^{L}\sum_{k=1}^{K}\alpha_{l,k}\delta(t-T_l-\tau_{l,k}) \tag{1}$$

where X is the log-normal distributed amplitude gain of the channel, $\alpha_{l,k}$ denotes the gain of the *k*th multipath component in the *l*th cluster, T_l is the delay of the *l*th cluster, and $\tau_{l,k}$ is the delay of the *k*th path in the *l*th cluster relative to the cluster arrival time. The cluster arrivals and the path arrivals within each cluster can be modeled as Poisson distribution with rate Λ and rate $\lambda(\lambda > \Lambda)$, respectively.

$$\begin{aligned} p(T_l \mid T_{l-1}) &= \Lambda e^{-\Lambda(T_l - T_{l-1})} \\ p(\tau_{l,k} \mid \tau_{l,k-1}) &= \lambda e^{-\lambda(\tau_{l,k}-\tau_{l,k-1})} \end{aligned} \tag{2}$$

According to the cluster arrival and path arrival time within each cluster, there are four channel models specified in the IEEE for different propagation environments, that is CM1(LOS 0~4m), CM2(NLOS 0~4m), CM3(NLOS 4~10m) and CM4(Extreme NLOS 4~10m). The corresponding channel parameters is shown in Table 1.

Table 1. IEEE 802.15.3a channel parameters

	Λ /(ns^{-1})	λ /(ns^{-1})	T/ns	γ /ns
CM1	0.0233	2.5	7.1	4.3
CM2	0.4	0.5	5.5	6.7
CM3	0.0667	2.1	14	7.9
CM4	0.0667	2.1	24	12

3.2 Channel model

Rake receiver is a digital receiver that takes advantage of temporal diversity of a multipath channel in order to increase the average received signal to noise ratio (SNR) [10]. A typical Rake receiver with N_R parallel correlators is shown in Figure 4.

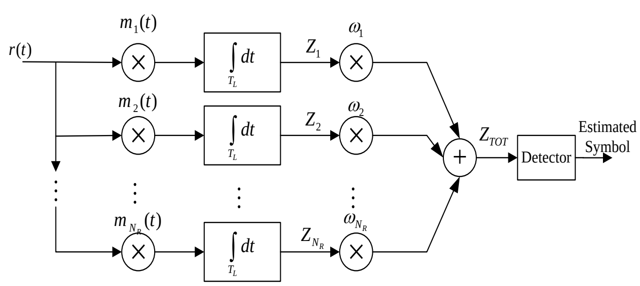

Figure 4. Rake receiver with N_R parallel correlators

The adoption of a Rake considerably increases the complexity of the receiver. This complexity increases with the number of multi-path components analyzed and combined before decision and can be reduced by decreasing the number of components processed by the receiver. In our system, three strategies for reducing the complexity of the Rake are presented and analyzed. The first strategy called All Rake (Arake) collects all the multi-path components, which is an ideal Rake receiver. The second strategy called Selective Rake (Srake) consists of selecting the L_S best components among the L_{TOT} available at the receiver input. The number of branches of the Rake is reduced but the receiver still must keep track of all the multi-path components to perform the selection. A third and simpler solution called Partial Rake (Prake) combines the first arriving L_P paths without operating any selection among all available multi-path components [11].

3.3 MB-IR-UWB system signal model

Consider a single-user MB-IR-UWB, both PAM and PPM modulations can be used for TH technique. Here, we use TH-PPM modulation in our system. It is assumed that the pulse repetition time is T_s and every N_s pulses are used to transmit one bit information. So the binary symbol rate $R_b = 1/N_sT_s$ bps. The transmitted signal can be expressed as:

$$S(t)=\sum_{i=0}^{N-1}s_i(t)=\sum_{i=0}^{N-1}\sum_{j=-\infty}^{+\infty}p_i(t-jT_s-c_jT_c-a_j\varepsilon)$$
$$i=0,1,\cdots N-1 \tag{3}$$

where $s_i(t)$ is transmitted signal of the ith band, $p_i(t)$ is the pulse waveform of the ith band, c_jT_c defines the jitter of the pulse with respect to the timing of the integer, $a_j\varepsilon$ is the time shift caused by PPM modulation.

The signal $S(t)$ is transmitted via a multipath channel $h(t)$.On the receiver side, the noise $n(t)$ is modeled as additive white Gaussian noise (AWGN) with the two-sided spectral density $N_0/2$.The received signal can be written as:

$$\begin{aligned} r(t) &= S(t)*h(t)+n(t) \\ &= X\sum_{k=1}^{L}\sum_{k=1}^{K}\alpha_{l,k}S(t-T_l-\tau_{l,k})+n(t) \\ &= X\sum_{k=1}^{L}\sum_{k=1}^{K}\sum_{i=0}^{N-1}\alpha_{l,k}s_i(t-T_l-\tau_{l,k})+n(t) \end{aligned} \tag{4}$$

As stated earlier, the pulses between each sub-band are orthogonal, we use Rake receiver to collect the multi-path components of the received signal. Then it goes into the correlators, multiplying correlation mask of each band, then into the decision unit for judgment. The correlation mask of the ith band is

$$v_{i,R}(t)=\sum_{k=1}^{N_R}w_kv_i(t-\tau_k) \tag{5}$$

where $v_i(t)=p_i(t-c_jT_c)-p_i(t-c_jT_c-\varepsilon)$, N_R is the number of Rake receiver branch, w_k is the weighted coefficient of the kth branch.

For each band is independent, separate judgments can be made in each branch. The detection is a standard hypothesis testing problem. While the decision variables

$$Z_i=\int_{\tau}^{\tau+T_s}r(t)v_{i,R}(t)dt>0 \tag{6}$$

it will be judged bit '0',othervise bit '1'. At last, make the data convert from parallel to serial and we can get the decoded bit stream.

4. Simulations and Performance Analysis

In this paper, we divide the UWB spectrum (from 3.1GHz to 7.5GHz) into several subbands, and then use the corresponding PSWF time domain impulse as the information carrier of MB-IR-UWB. The simulation parameters can be found in Table 2.

Table 2. MB-IR-UWB system simulation parameters

Parameter	Symbol	Value
Frequency bounds	f_{low}, f_{high}	3.1GHz,10.6GHz
Number subband	N_{sub}	15
Bandwidth of subband	B_{sub}	500MHz
Pulse type	-	PSWF
Pulse duration	T_m	6ns
Symbol repetition period	T_s	60ns
Modulation	-	TH-PPM
Receive type	-	coherent demodulation

4.1 Performance analysis with Rake receiver in multipath channel

The simulation was made under the assumption of perfect synchronization between transmitter and receiver. Rake receiver that employ maximal ratio combining (MRC) is considered, for it can guarantee that the receiver can get the biggest SNR.

Figure 5 presents the bit error rates (BER) curves of MB-IR-UWB in different channel environment with Arake receiver. It can be seen that in CM1 and CM2 channel model, the performance is almost the same. That is to say, the system performs well under the LOS conditions. But the worst is for CM4 channel model.

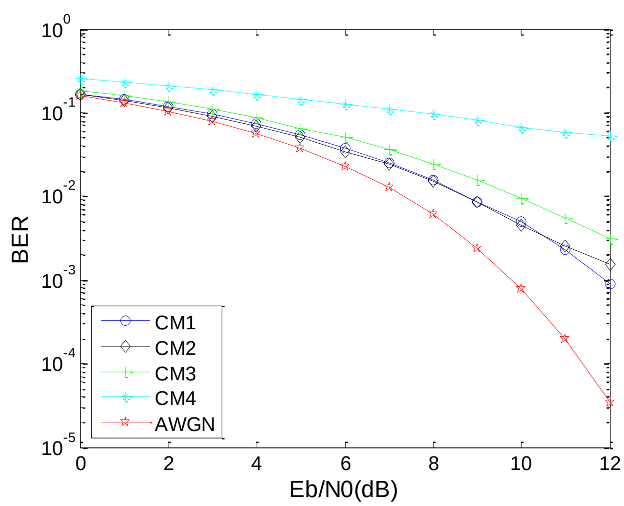

Figure 5. Performance comparison of MB-IR-UWB in different channel models

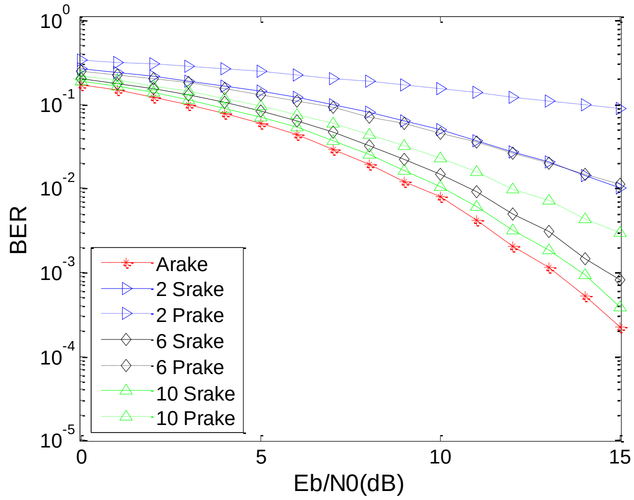

Figure 6. Performance comparison of MB-IR-UWB in multipath channel

It can be seen from Figure 6 that the BER curves of different Rake receivers with different fingers. As analyzed theoretically, we can get the best performance using the ideal Rake receiver, for it collected all the multi-path components. But it's difficult to realize because of its complexity. We can use Srake and Prake to reduce the complexity. Srake receiver has a better performance than Prake receiver in the same finger for it selects the best components at the receiver. From Figure 6 we can see that increasing the fingers of Prake and Srake, the system performance is getting better respectively. But the performance of 2 fingers Srake is nearly the same as 6 Prake. It means that the energy captured by the first six components and captured by the two best components are almost the same.

4.2 Analysis of MB-IR-UWB data rate in multipath channel

The transmitter generates a combined symbol with a repetition time T_s that is usually set larger than the channel delay spread T_d and the pulse duration T_m to avoid or alleviate inter-symbol interference (ISI). CM2 channel model is closest to the ultra-wideband actual transmission environment, so the following simulation is based on this model. In our simulation, we assumed T_s = 60ns. The following part will focus on analyzing the impact of different numbers of subband on data rate of MB-IR-UWB in multipath channel. The corresponding relation between different N_{sub} values and R_b is shown as Table 3.

Table 3. The transmission data rate without ISI for different subband(T_s=60ns)

N_{sub}	4	8	12	15
R_b/Mbps	66.7	133	200	250

From Table 3 it can be concluded easily that with the same T_s that guarantees no ISI, the data rate increases linearly by increasing the number of subband.

If we want to get a certain data rate, how will the number of subband affect the system performance? The interference between each subband can be ignored if N_{sub} is smaller than the limit N_{sub} =15.

Table 4. The transmission data rate for different subband in different T_s

N_{sub}	4	8	12
R_b/Mbps	200	200	200
T_s/ns	20	40	60

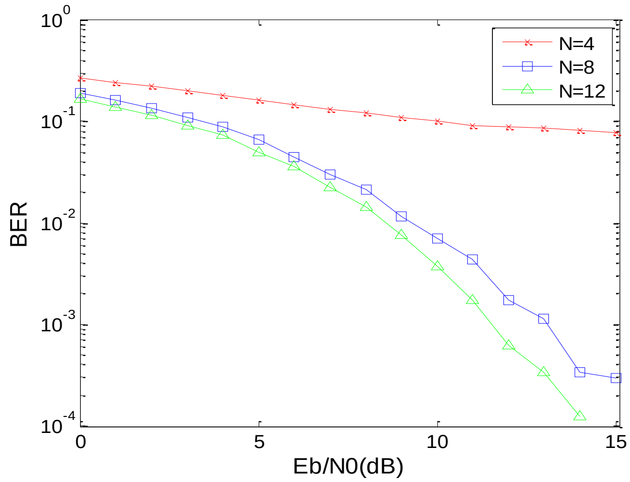

Figure 7. Performance of MB-IR-UWB with different numbers of subbands

The difference in BER curves of Figure 7 is primarily due to changes of the symbol period T_s since the channel delay spread is the most limiting factor for system performance. Suppose we want a high data rate, for N_{sub} = 4, it will result in smaller T_s. Thus the transmitted waveform for one symbol overlaps other symbols. One can conclude that increasing data rate is best-achieved by increasing the number of subbands instead of decreasing T_s. But more numbers of subbands will inevitably increase the complexity of the system. So in actual communication, we should make a balance between the performance and complexity to a best choice.

5. Conclusions

This paper takes the MB-IR-UWB communication system based on PSWF pulse as the research object, talks about the system performance in multipath channel with Rake receivers. In addition, the data transmission rate with different numbers of subbands is analyzed without ISI and with ISI. The simulation results show that the ideal Rake receiver has the optimal performance, but it is not a solution for a practical implementation because we have to take all the components of the transmitted signal into consideration. Therefore, depending on the complexity of the receiver we want to implement and the performance we want to achieve, the proper Rake receiver can be applied. At the same time, according to actual need for data rate, we can decide how many bands to choose.

Acknowledgements

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