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Implementation of DSTFCs in MIMO MB-IR-UWB System

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Abstract

This paper implements differential space-time-frequency codes (DSTFCS) to multiple-input multiple-output (MIMO), multi-band impulse radio ultra-wideband (MB-IR-UWB) system. Four scenarios of the system operating mode have been put forward and combination of DSTFCs and the system has been studied in this paper. Through simulation, a comparison of BER performance among different scenarios and channel statements is analyzed. In addition, considered inter-symbol interference (ISI), the simulation on system with ISI and without ISI is given. Finally the conclusion that scenario 3 is more suitable to the proposed MIMO MB-IR-UWB system for it being less sensitive to ISI has been drawn.

Keywords: *MB-IR-UWB;MIMO;DSTFCs;ISI*

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 0. The frequency band used by conventional single-band UWB system is up to 7.5GHz, however, the wide fixed spectrum made the receiver lack the flexibility to manage radio resources efficiently. In 2004, the idea of multi-band impulse radio UWB (MB-IR-UWB) was proposed by Stkphane Paquelet in-[2-[2], and proved improving transmission rate effectively. In 2006, [3] modified the model and pointed that MB-IR-UWB system could increase the data rate up to 1Gbit/s compared to the basic architecture. [4] solved the issue that in conventional multiband system the design of band-pass filter is complex and the orthogonal characteristics is far worse than the ideal band-pass filter by introducing PSWF into MB-IR-UWB system for its band-limited and orthogonal characteristics. [5] proved the implementation of PSWF in MB-IR-UWB system and pointed that multiband technology has the potential to expend the capacity of the system and improve the flexibility of spectrum utilization. [7] introduced equalization technique including time reversal (TR) equalization and frequency domain equalization (FDE) to the MIMO MB-IR-UWB system to eliminate interferences.

The multiple-input multiple-output (MIMO) technique has been introduced into MB-IR-UWB system in [7] to further improve the system performance. Combined with space-time-frequency codes (STFCs) the system performance including data rate, system capacity, bit error performance or the form of maximum achievable communication range may be improved significantly [8]. For the low complexity of coding and independent linear decoding processing of Alamouti algorithm, in [10-11] Lindskog-Paulraj proposed the space-time-frequency block coding (STFBC) which could be regarded as a promotion of Alamouti STC in single-carrier system over frequency-selective channels. [11] Le Chung Tran and Alfred Mertins researched the design criteria of STFC and analyzed the

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implementation and performance in MB-OFDM UWB communication. To achieve a reduction of decoding complexity, [13] proposed a linear decoding algorithm with Givens rotation algorithm and eliminates interference terms. [14] proposed an adaptive subcarrier allocation algorithm for VBLAST-OFDM downlink.

In 2013, [7] proposed unitary differential space-time-frequency codes (DSTFCs) for MB-OFDM UWB communication and presented that the proposed DSTFCs can significantly improve the bit error performance without channel state information (CSI) of conventional differential MB-OFDM system at high signal-to-noise ratios (SNR).

In this paper, more attention is paid to the system performance on DSTFCs in MIMO MB-IR-UWB system over the multipath channel.

The paper is organized as follows. Section 2 briefly reviews the mathematical model of the MIMO MB-IR-UWB system, including system model and signal model. In Section 3, DSTFCs models for the system are introduced and decoding metrics are derived. The simulation results and analysis of the system performance is presented and discussed in Section 4. Finally, conclusions are drawn in Section 5.

Notations: Throughout the paper, the signals transmitted in the proposed system are all real and the channel parameters are all assumed to be real.

2. STFC MIMO MB-IR-UWB System Model

The proposed STFC MIMO MB-IR-UWB system consisting of Nt Tx antennas and Nr Rx antennas is depicted in Figure 1. And the 7.5GHz frequency band is divided into L independent subband using PSWF [5].

2.1. MIMO MB-IR-UWB System Overview

The basic system working method is as follows. The bit stream generated by information source go through the STFC encoder after converting into NtL groups which occupy L bands of Nt antennas, and the parallel coded bit streams are fed to a repeated coder, modulator of PAM/PPM respectively. After it, the NtL bit stream is modulated by a pulse generator which generates a number of pulses where each pulse occupies a specific frequency band. The NtL pulses are combined, amplified and transmitted via UWB antenna. Transmitting through the multipath and thermal noise channel the signal received is equalized to eliminate distortion of wireless channel and then a coherent demodulation is considered ensuring the optimum reception. For coherent detection, channel coefficients are assumed to be known at the receiver. After multiplying the orthogonal mono-band pulse to its subband, STFC decoding is designed and subsequent operations are to make the data parallel to serial conversion and make a soft or hard bit decision.

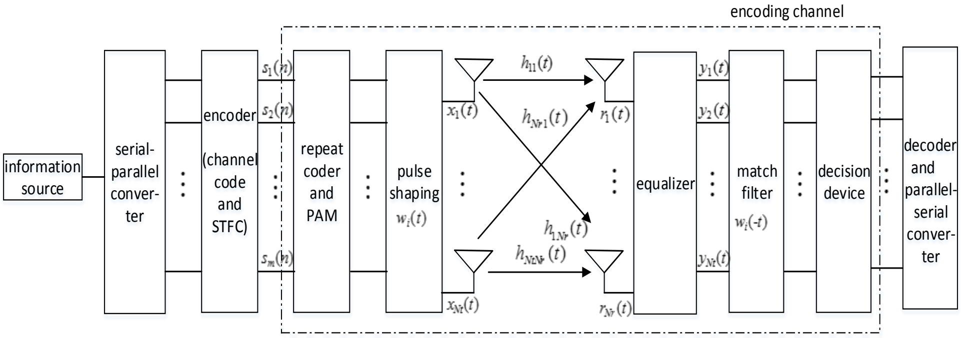

Figure 1. The Schematic Diagram for MIMO MB-IR-UWB System

2.2. System Model

The transmitted STFC block is denoted as a matrix $s_t = \{\bar{s}_{t,m}\}_{T\times Nt}$, where T is the number of MB-IR symbol time slots required to transmit the whole STFC block. The code matrix s_t can be structured as Alamouti space-time codes in conventional wireless STBC MIMO, but the elements in $\bar{s}_{t,m}$ is defined as a column vector $\bar{s}_{t,m} = \left[s_{t,m,1}, s_{t,m,2}, \ldots, s_{t,m,L}\right]^T$. The encoding channel can be denoted as $h(t) = \begin{bmatrix} h_{11}(t) & \ldots & h_{1Nr}(t) \\ \ldots & & \ldots \\ h_{Nt1}(t) & \ldots & h_{NtNr}(t) \end{bmatrix}_{Nt\times Nr}$, and the noise matrix can be presented as $n(t)$ which is considered to independent Gaussian RV, the signal received $r(t)$ can be expressed as the following form

$$r(t) = s_t * h(t) + n(t) \tag{1}$$

To guarantee the orthogonality of the code matrix we can rewrite $r(t)$, s_t, $h(t)$ and $n(t)$ in (2) in the following forms [7]

$$\begin{cases} R_t = \left\{diag\left(\bar{r}_{t,n}\right)\right\}_{TL\times NrL} \\ S_t = \left\{diag\left(\bar{s}_{t,m}\right)\right\}_{TL\times NtL} \\ S_t = \left\{diag\left(\bar{s}_{t,m}\right)\right\}_{TL\times NtL} \\ N_t = \left\{diag\left(\bar{n}_{t,n}\right)\right\}_{TL\times NrL} \end{cases} \tag{2}$$

Then the Eq (1) can be rewritten with matrix multiplication as follows

$$R_t = S_t \cdot H_t + N_t \tag{3}$$

2.3. Signal Model

It is assumed that the symbol repetition time is T_s, so the general transmitted signal $x(t)$ at the mth transmit antenna of the system can be expressed as follows

$$x_m(t) = \sum_{l=1}^{L} \sum_{d=-\infty}^{\infty} s_{m,l}(d)\, w_{m,l}(t - dT_s), m = 1, 2, \ldots, Nt \tag{4}$$

Where $s_{m,l}(d)$ is the symbol modulated by the lth subband at mth antenna. L is the number of subband. $w_{m,l}(t)$ is the pulse waveform of the lth band with energy normalized.

Therefore, the general transmitted signal $x(t)$ can be expressed by Eq (5)

$$x(t) = \sum_{d=-\infty}^{\infty} s(d)\, w(t - dT_s) \tag{5}$$

3. DSTFCs in MIMO MB-IR-UWB System

Space-time-frequency block codes (STFBC) is considered in the system for its orthogonal characteristics and simple form.

3.1. DSTFC for MIMO MB-IR-UWB System

We consider the application of the Alamouti STFC

$$s_t = 1/\sqrt{2}\begin{bmatrix} \bar{s}_{t,1} & \bar{s}_{t,2} \\ -\bar{s}_{t,2} & \bar{s}_{t,1} \end{bmatrix} \tag{6}$$

Where the symbol $\bar{s}_{t,m} = \left[s_{t,m,1}, s_{t,m,2}, \ldots, s_{t,m,L} \right]$ is a column vector of L real symbols corresponding to L subband, for $m = 1, 2$. Channel statement in the system is assumed to be constant during K consecutive transmitted STFBC blocks.

As Eq(2) the STFC can be rewritten as follows

$$S_t = 1/\sqrt{2}\begin{bmatrix} diag\left(\bar{s}_{t,1}\right) & diag\left(\bar{s}_{t,2}\right) \\ -diag\left(\bar{s}_{t,2}\right) & diag\left(\bar{s}_{t,1}\right) \end{bmatrix} \tag{7}$$

The STFC could also be represented in the following form,

$$S_t = \frac{1}{\sqrt{2}}\sum_{m=1}^{Nt}\sum_{l=1}^{L} X_{t,m,l}s_{t,m,l} \tag{8}$$

where the weighting matrices $X_{t,m,l}$ are real, orthogonal matrices.

And the transmission model can be expressed as Eq(3).

The Alamouti STFC can work accurately in quasi-static channel [8] and as the assumption mention before the channel model is a typical quasi-static channel. The assumption is in fact almost the case. In practical, the UWB channel can be seen as a quasi-static channel.

If we consider DSTFC the differential Alamouti STFC, the proposed system initializes the transmission with an identity matrix C_0. The subsequent code matrices will be generated according to the principle as following form

$$C_t = S_t C_{t-1} \tag{9}$$

We assume that the normalized power of each symbol is unitary, so S_t and C_t are unitary matrices of size $2L$, *i.e.*

$$S_t S_t^T = I_{2L} \quad ,C_t C_t^T = I_{2L} \tag{10}$$

C_t would replace the S_t being transmitted, so the transmission model can be rewritten as follows

$$R_t = C_t \cdot H_t + N_t \tag{11}$$

DSTFC could also work well in UWB channel as a promotion of Alamouti STFC without CSI.

3.2. Maximum Likelihood(ML) Decoding for STFC in MIMO MB-IR-UWB System

For Alamouti STFC, the ML decoding metric can be denoted as follows

$$\begin{aligned} \hat{S}_t &= \arg\min_{s_t} tr\left[\left(R_t - S_t H_t\right)^T\left(R_t - S_t H_t\right)\right] \\ &= \arg\min_{s_t} tr\left[H_t^T S_t^T S_t H_t - \left(H_t^T S_t^T R_t + R_t^T S_t H_t\right)\right] \end{aligned} \tag{12}$$

As we can see in Eq (12), each of the two symbols can be decoded independently, and CSI is needed in ML decoding of Alamouti STFC.

For DSTFC, to formulate the ML decoding metric, we define $D_{m,l}$ in the following form

$$\begin{aligned} D_{m,l} &= tr\left(R_{t-1}R_t^T X_{t,m,l}\right) \\ &= tr\left[\left(C_{t-1}H_{t-1} + N_{t-1}\right)\left(C_t H_t + N_t\right)^T X_{t,m,l}\right] \\ &= tr\left[\left(C_{t-1}H_{t-1} + N_{t-1}\right)\left(H_t^T C_t^T + N_t^T\right) X_{t,m,l}\right] \\ &= tr\left(C_{t-1}H_{t-1}H_t^T C_t^T X_{t,m,l} + N\right) \\ &= tr\left(C_{t-1}H_{t-1}H_t^T C_{t-1}^T S_t^T X_{t,m,l} + N\right) \end{aligned} \tag{13}$$

Where $N = (N_{t-1}H_t^T C_t^T + N_{t-1}N_t^T + C_{t-1}H_{t-1}N_t^T)X_{t,m,l}$. As we assumed in Section Ⅲ-A, channel statement is constant during consecutive blocks, so we can denote $H_t = H_{t-1}$. Eq (12) can be rewritten as follows

$$\begin{aligned} D_{m,l} &= tr\left(C_{t-1}H_t H_t^T C_{t-1}^T S_t^T X_{t,m,l} + N\right) \\ &= tr\left(H_t H_t^T S_t^T X_{t,m,l} + N\right) \\ &= tr\left(H_t H_t^T S_t^T X_{t,m,l}\right) + tr\left(N\right) \\ &= tr\left(H_t H_t^T s_{t,m,l}^T X_{t,m,l}^T X_{t,m,l}\right) + tr\left(N\right) \end{aligned} \tag{14}$$

The ML decoding metric for DSTFC can be derived as follows

$$\begin{aligned} \hat{s}_{t,m,l} &= \arg\min\left|D_{m,l} - \tfrac{1}{\sqrt{2}} tr\left(H_t H_t^T X_{t,m,l}^T X_{t,m,l}\right) s_{t,m,l}\right|^2 \\ &= \arg\min\begin{pmatrix} \left|D_{m,l}\right|^2 + \frac{1}{2}\left[tr\left(H_t H_t^T X_{t,m,l}^T X_{t,m,l}\right)\right]^2 \\ -\sqrt{2}\, tr\left(H_t H_t^T X_{t,m,l}^T X_{t,m,l}\right) D_{m,l} s_{t,m,l} \end{pmatrix} \end{aligned} \tag{15}$$

For certain t, m and l $tr\left(H_t H_t^T X_{t,m,l}^T X_{t,m,l}\right)$ is constant. So, the equivalent ML decoding metric is

$$\hat{s}_{t,m,l} = \arg\max\left(D_{m,l} s_{t,m,l}\right) \tag{16}$$

Similar to Eq (12), we can draw that the DSTFC symbol can also be separately decoded. However, compared to Eq (12), no CSI is required for the decoding process in DSTFC.

The decoding process of STFBC is completely linear, thus relatively simple.

4. Simulation Results

To examine the performance of the proposed STFC MIMO MB-IR-UWB system, we ran several Monte-Carlo simulations, each with 1024 STFC symbols. The transmitting power is assumed to be unitary, which means the transmitting power always keeps constant no matter how the number of transmitting antenna and band varies. In simulations, SNR is defined to be the signal-to-noise ratio (dB) per symbols, *i.e.*, E_b/N_0. Maximal ratio combining (MRC) is used when the number of receive antenna Rx is over one. To avoid ISI of the system a string of guard symbols is added to make sure the symbol duration T_s longer than the channel delay spread T_g. We denote $T_s = n_h T_w$, where T_w is the pulse duration. The corresponding parameters of the four channel models specified in the IEEE is shown in Table 1. The relationship between the number of subband N_{sub} and the symbol duration T_s is shown in Table 2 [5]. Table 3 shows parameters of the simulations.

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

Table 2. The Symbol Duration Ts Without ISI for Different Subband

Nsub	4	8	12
Ts/ns	20	40	60

Table 3. Simultion Parameters

Parameter	Symbol	Value
Frequency bounds	B	3.1~10.6GHz
Number subband	L	15
Bandwidth of subband	w	500MHz
Number of transmit antennas	Nt	2
Number of receive antennas	Nr	2
Pulse type	-	PSWF
Pulse duration	T_w	3ns
Symbol repetition period without ISI	T_s	42ns
Duration of guard symbol without ISI	$(nh-1)T_w$	38ns
Symbol repetition period with ISI	T_s	9ns
Duration of guard symbol with ISI	$(nh-1)T_w$	6ns
Modulation	-	PAM
Channel model	-	IEEE 802.15.3a

Consider thus four scenarios of MIMO MB-IR-UWB system.

Scenario 1: conventional MIMO IR-UWB system, transmit antennas share the same band.

Scenario 2: directly use of the conventional MIMO MB-IR-UWB system, each transmit antenna transfers a single band pulse which is orthogonal to others.

Scenario 3: each transmit antenna transfers several different subband pulse and every antenna occupies different frequency band. In this scenario, case 2 presents the case of transferring 2 subband pulse each antenna and case3 and case 4 can be done in the same manner.

Scenario 4: one transmit antenna transfers several different subband pulse and the others transfer the same subband pulse. In this scenario, case 2 presents the case of transferring 2 subband pulse each antenna and case3 and case 4 can be analogized in the same principle.

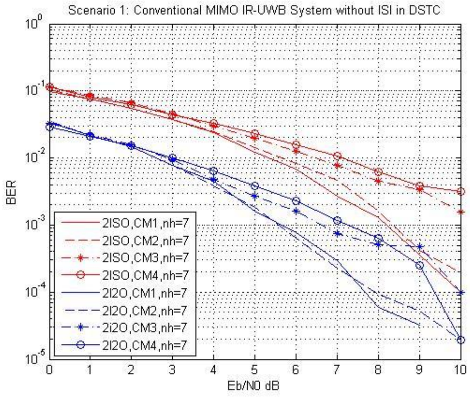

Figure 2. The BER Performance of Scenario 1 in DSTC

The BER performance of conventional MIMO IR-UWB system applying DSTC is demonstrated in Figure 2. As we can see from Figure 2, for 2ISO IR-UWB system (2 Tx, 1Rx antennas) the bit error ratios (BER) over CM1 and CM2 (10^{-4} at 10dB) outperforms CM3 and CM4 (10^{-3} at 10dB). The same result is shown in MIMO IR-UWB system, however, an improvement of about 2dB at BER=10^{-4} could be achieved compared to 2ISO over CM1 and CM2, and over 3dB at BER=10^{-3} could be achieved over CM3 and CM4. Compared to channel statement the number of transmit and receive antennas has greater influence on BER performance of conventional IR-UWB system.

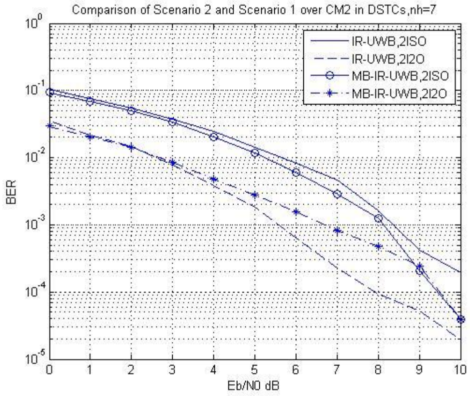

Figure 3. Comparison of Scenario 1 and Scenario 2 without ISI over CM2 in DSTFC

The BER performance of scenario 2 is demonstrated in Figure 3. As is shown in the figure, if we transfer only one subband pulse in one antenna the MB-IR-UWB system cannot work as well as the conventional IR-UWB system especially at high Eb/N0. The conventional MIMO IR-UWB system outperforms MB-IR-UWB about 3dB at BER=10^{-4}.

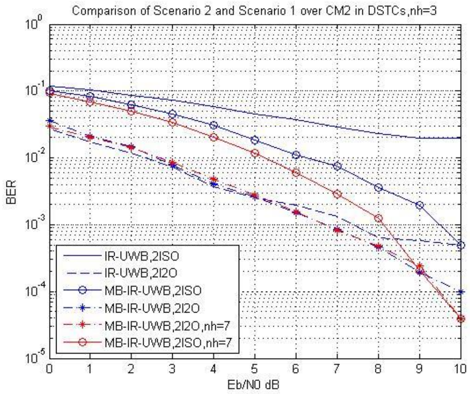

Figure 4. Comparison of Scenario 1 and Scenario 2 with ISI over CM2 in DSTFC

In the case of the system existing ISI, Figure 4 has presented that MB-IR-UWB system can work as normal with 2 Tx and 2 Rx antennas. On the other hand, the conventional IR-UWB system is badly influenced by ISI and in the case of 2ISO BER cannot reach 10^{-2} at 10dB.

The MB-IR-UWB system using DSTFCs works more robust in the case of existing ISI.

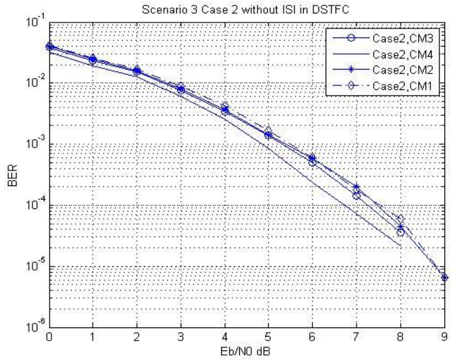

Figure 5. BER performance of Scenario 3 case2 in DSTFC without ISI

The BER performance of scenario 3 case 2 which can achieve 10^{-5} at 9dB is demonstrated in Figure 5. Channel statement has little influence on BER performance as we can draw from the figure.

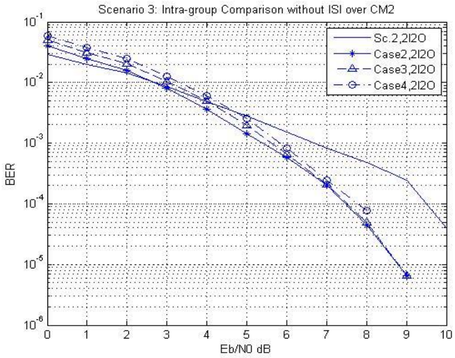

Figure 6. Intra-Group Comparison over CM2 in DSTFC Without ISI

As is shown in Figure 6, in scenario 3 the BER performance cannot keep increasing with the number of subband used. Over 2dB gain can be achieved by case 2 compared to scenario 2. However, the BER performance of case 3 and case 4 are almost the same as case 2. It means that in the case of no ISI existing in the system, case 2 should be the optimal choice in scenario 3.

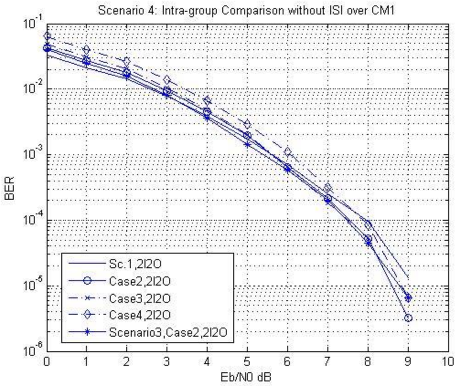

Figure 7. Intra-Group Comparison over CM1 in DSTFC without ISI

The BER performance of scenario 4 is demonstrated in Figure 7. There is no improvement in BER performance between scenario 4 and scenario 1 and among case 2, case 3 and case 4 of scenario 4. However, the BER performance of scenario 4 is almost equal to scenario 3 reaching 10^{-5} at 8.5dB. From the above, we can find that a boundary of BER performance exists and for a system in DSTFC without ISI, scenario 1: conventional MIMO IR-UWB is suggested.

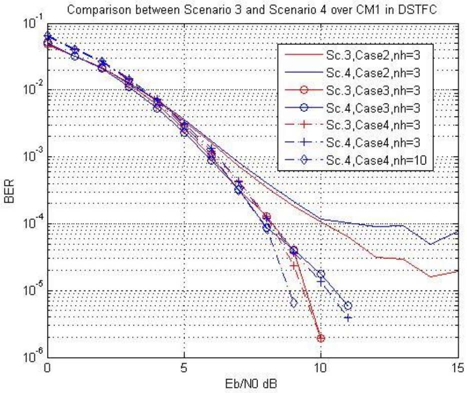

Figure 8. Comparison Between Scenario 3 and Scenario 4 over CM1 in DSTFC with ISI

Figure 8 demonstrates the BER performance of scenario 4 in DSTFC with ISI. Things have changed in this case, as we can see from the figure scenario 3 could improve the BER performance at high Eb/N0 compared to scenario 4. In case 2, scenario 4 can achieve 10^{-4} BER while scenario 3 can achieve 10^{-5} at 15dB. For case 3 and case 4 of scenario 3, 2dB improvement can be gained at BER=10^{-5} compared to scenario 4. The boundary of BER performance in this case is same as the one in system without ISI. As a result, we suggest that, in a system which cannot avoid ISI using DSTFCs, case 3 in scenario 3 is optimal.

The reason why the case 3 in scenario 3 is optimal to the system is that the ability of avoiding the interferences form other channels and frequency bands of the case is the strongest. The case make full use of the frequency source without any overlap, which makes sure the orthogonality between each antenna and frequency and that can help cancel most of the interference brought by multi-channel and multi-band.

5. Conclusions

This paper takes implement of DSTFCs in MIMO MB-IR-UWB system as the research object, discusses the BER performance in 4 scenarios of the system without ISI and with ISI. The simulation results show that, in a system which can avoid ISI combined with DSTFCs, MIMO IR-UWB system could be the most economic choice, while in a system which cannot avoid ISI completely combined with DSTFCs, case 3 in scenario 3 could be optimal. We can also draw a conclusion that scenario 3 is more suitable to the proposed MB-IR-UWB system for it being less sensitive to ISI, which could guide our future research.

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