ICIC Express Letters
Part B: Applications
Volume **7**, Number **11**, November **2016**

ISSN 2185-2766
pp. 2389–2395

APPLICATION OF COMPLETE COMPLEMENTARY SEQUENCE IN MIMO SYSTEM TO COMBAT MULTIPATH INTERFERENCE

Libiao Jin, Yuchi Zhang and Shufeng Li*

School of Information Engineering
Communication University of China
No. 1, Dingfuzhuang East Street, Chaoyang District, Beijing 100024, P. R. China
*Corresponding author: lishufeng@cuc.edu.cn

Received April 2016; accepted July 2016

Abstract. *In this paper, we developed a novel architecture of spread spectrum system based on complete complementary sequences (CC-S) for multiple-input-multiple-output (MIMO) to combat multipath fading in wireless environment. In MIMO system, the bit error rate (BER) performance will deteriorate severely at a rapid pace in multipath fading wireless channels. Sets of sequences with complete complementary principle are well known because of their ability to obtain excellent correlation properties. This key advantage is also a kind of good combat multipath fading characteristic, and based on this method, we select the polyphase (quadri-phase for example) CC-S as the spread spectrum code to solve the problem above. We analyzed the BER performance of the system, and conducted extensive simulations to verify the analytical results. Simulation results indicate that using CC-S as spreading code of MIMO system can more effectively reduce BER in multipath Rayleigh fading channel than those traditional pseudo-random (PN) sequences.*

Keywords: MIMO, Complete complementary sequence, Spread spectrum, Multipath

1. Introduction.

MIMO techniques have become the crucial part of wireless broadband networks and space-time code (STC) has been applied broadly in communication systems to promote their performance and stability. MIMO systems improve its transmission rate greatly by utilizing space diversity, and then promote system performance. Among numerous proposals of STC designs, space-time block codes (STBC) [1] and space-time-trellis codes (STTC) [2] are considered to be the leading implementations. In order to enhance the STC performance, researchers make great effort for further research, such as the works on space-time complementary coding (STCC) using pairwise complementary code [3]. The existing schemes of traditional STC mostly focus on symbol level, but not much consideration is paid to multipath interference; when inter-symbol interference exists in wireless channel, system performance will degrade seriously. Moreover, traditional STC will lose the advantages in multipath fading channels on account of fading coefficients varying over symbol block. Various methods have been developed, such as adaptive equalization [4], and space-time error correcting codes [5], to solve the problem mentioned above. However, these designs only apply to slow fading and flat fading channels.

Non-ideal correlation properties are the main drawback of conventional spread-spectrum sequences (such as m-sequence, gold-sequence). In stark contrast to them, the CC-S has the optimal correlation properties. The CC-S was constructed from the original complementary sets of sequences [6]. And even for an asynchronous case, the orthogonality of the CC-S can be maintained. The perfect orthogonality property makes CC-S become an excellent method to combat multipath interference in wireless communication systems [7]. The CC-S has already been applied into fields such as MIMO radar system, and channel estimation [8].

In this paper, we propose a novel architecture based on CC-S for MIMO system to combat multipath fading. We utilize the chip-level STC to achieve the complete orthogonality for users among multiple antennas. By applying the CC-S to STC in the chip-level, the system may perform better than other systems using symbol-level codes. Given that the system is infancy in this paper, there are some possible study directions to be researched further in the future, such as massive MIMO system and 5G MIMO system using our proposed method.

2. **System Model.**

In this section, we design the system model, give the mathematics representation, and obtain the practical formulas through derivation in the section end.

The standard about perfect orthogonality property of CC-S can be described as that the auto-correlation function (ACF) must be zero for all shifts except the zero shift, and that the cross-correlation function (CCF) for any possible shifts must be zero as well [9]. Mathematical expressions can be given as follows. Suppose $\{A_n, B_n\}$ consists of N pairs of polyphase CC-S [10] that the length of them is L. And if $\{A_n, B_n\}$ meets the following correlation function definition equation, then they can be called as CC-S:

(i) For every $i = 1, 2, \ldots, N$,

$$R_{A_iA_i}(\tau) + R_{B_iB_i}(\tau) = \begin{cases} 2L & \tau = 0 \\ 0 & \tau \neq 0 \end{cases}, \tag{1}$$

(ii) For every $1 \leq i,\, j \leq N$, $i \neq j$,

$$R_{A_iA_j}(\tau) + R_{B_iB_j}(\tau) = 0 \quad \forall \tau. \tag{2}$$

(1) and (2) show the ACF and CCF of the CC-S, respectively. $R_{A_iA_i}(\tau)$ and $R_{B_iB_i}(\tau)$ describe the aperiodic ACF of A_i and B_i separately. And $R_{A_iA_j}(\tau)$ denotes the aperiodic CCF between A_i and A_j. Similarly, $R_{B_iB_j}(\tau)$ indicates the aperiodic CCF between B_i and B_j. Besides, τ represents the discrete time shift.

Figure 1 shows the architecture of simulation system from transmitter to receiver in detail. Because the presence of complex multipath fading effects, the transmission signal will abnormally alter to a serious consequence, so it is necessary to utilize training sequence to conduct channel estimation in frequency domain. We select channel estimation algorithm which takes use of the long training sequence in 802.11a [11] for simplicity. Specific way of composition of transmission frame is shown in Figure 2. In the transmitter, we set up 10000 frames per user, and every single frame consists of the pilot for one bit and 6 bits data symbols in total. At the receiver, we will conduct the channel estimation part after

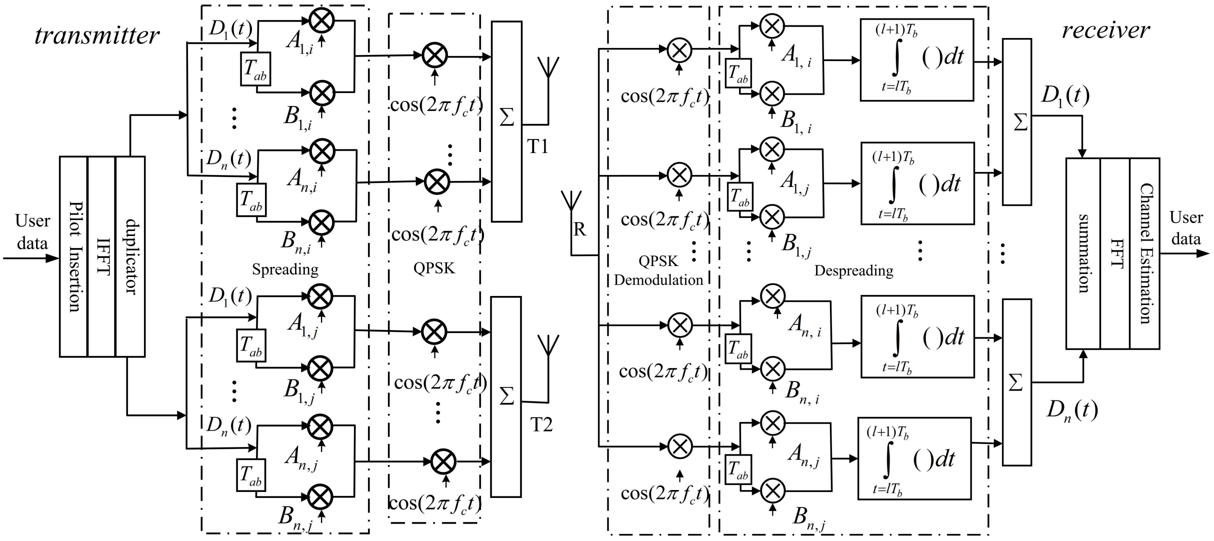

Figure 1. The architecture of simulation system

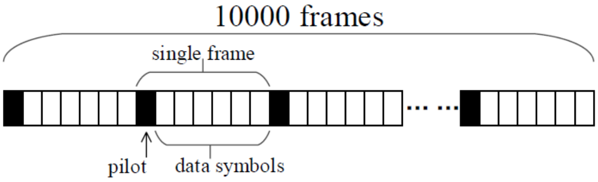

FIGURE 2. The pilot insertion type sketch in simulation model

signal via FFT (fast Fourier transform) [12] by obtaining the estimated distortion factor matrix, which is used to compensate for signal distortion.

Next, we provide the mathematics representation and deduce the practical formulas.

First, we give the definition of N pairs of polyphase complete complementary sequence $\{A_n, B_n\}$, which are given as follows

$$\begin{cases} A_n = \left(a_n^1, a_n^2, \ldots, a_n^L\right) \\ B_n = \left(b_n^1, b_n^2, \ldots, b_n^L\right) \end{cases}, \tag{3}$$

where $\{A_n, B_n\} \in (1, i, -1, -i)$ meet the complete orthogonality and they compose a set of CC-S. Then the baseband signal of the n-th user after spreading can be denoted by

$$S_n(t) = C_n(t)D_n(t), \tag{4}$$

where $C_n(t)$ represents the spreading sequence, which can be generated by using the method in [13], and it can be given by

$$\begin{aligned} C_n(t) &= A_{n,i}(t) + B_{n,i}(t - T_{ab}) + A_{n,j}(t) + B_{n,j}(t - T_{ab}) \\ &= \sum_{l=1}^{L} \left[a_{n,i}^l rect_c(t - lT_c) + b_{n,i}^l rect_c(t - T_{ab} - lT_c)\right] \\ &\quad + \sum_{l=1}^{L} \left[a_{n,j}^l rect_c(t - lT_c) + b_{n,j}^l rect_c(t - T_{ab} - lT_c)\right], \end{aligned} \tag{5}$$

where T_c is the subpulse time (chip period), and chip rate is R_c, $R_c = 1/T_c$. The length of sequence is L. For a given transmitting antennas $= 2$, $A_{n,i}$ and $B_{n,i}$ are transmitted in turn for the n-th user at the T_1 antenna, and $A_{n,j}$ and $B_{n,j}$ are transmitted in turn for the n-th user at the T_2 antenna. T_{ab} indicates the delay from $a_{n,i}$ to $b_{n,i}$. $rect_c(t)$ denotes the rectangle window function as follows

$$rect_c(t) = \begin{cases} 1 & 0 \le t \le T_c \\ 0 & else \end{cases}, \tag{6}$$

and $D_n(t)$ in (4) denotes the user data which is given by

$$D_n(t) = \sum_{n=1}^{N} d_n p(t) rect_d(t - nT_d), \tag{7}$$

where $T_d = LT_c$ demotes the pulse duration time, and symbol rate is R_d, $R_d = 1/T_d$. The original n-th user's data is denoted by d_n, and $p(t)$ refers to normalized energy

$$p(t) = \begin{cases} \sqrt{\dfrac{E_b}{LT_c}} & 0 \le t \le T \\ 0 & else \end{cases}, \tag{8}$$

where E_b represents signal energy per bit.

The transmitted equivalent signal of the n-th user $S_n(t)$ can be written as

$$S_n(t) = S_{n,T_1}(t) + S_{n,T_2}(t) = D_n(t)C_{n,i}(t) + D_n(t)C_{n,j}(t), \tag{9}$$

where $S_{n,T_1}(t)$ and $S_{n,T_2}(t)$ represent transmitted signals at antennas T_1 and T_2, respectively.

By plugging (5) into (9), we can obtain (10) and (11) as follows

$$\begin{aligned} S_{n,T_1}(t) &= D_n(t)C_{n,i}(t) = D_n(t)A_{n,i}(t) + D_n(t)B_{n,i}(t-T_{ab}) \\ &= p(t)\sum_{l=1}^{L}[d_n a^l_{n,i} rect_c(t-lT_c) + d_n b^l_{n,i} rect_c(t-T_{ab}-lT_c)] \\ &= s_{A_{n,i}}(t) + s_{B_{n,i}}(t-T_{ab}), \end{aligned} \tag{10}$$

$$\begin{aligned} S_{n,T_2}(t) &= D_n(t)C_{n,j}(t) = D_n(t)A_{n,j}(t) + D_n(t)B_{n,j}(t-T_{ab}) \\ &= p(t)\sum_{l=1}^{L}[d_n a^l_{n,j} rect_c(t-lT_c) + d_n b^l_{n,j} rect_c(t-T_{ab}-lT_c)] \\ &= s_{A_{n,j}}(t) + s_{B_{n,j}}(t-T_{ab}), \end{aligned} \tag{11}$$

combining (10) and (11), the transmitted equivalent signal can be derived to (12) as follows

$$S_n(t) = S_{n,T_1}(t) + S_{n,T_2}(t) = s_{A_{n,i}}(t) + s_{B_{n,i}}(t-T_{ab}) + s_{A_{n,j}}(t) + s_{B_{n,j}}(t-T_{ab}). \tag{12}$$

In the Rayleigh fading channel of baseband equivalence model, the channel impulse response between the transmitter antenna T_k and the receiver antenna R_k can be written as

$$H_{T_k,R_k}(t) = \sum_{m=1}^{M} h_{T_k,R_k,m} e^{j2\pi f_c t}\delta(t-\tau_m) = \sum_{m=1}^{M} h_{T_k,R_k,m}\cos(\theta_{T_k,R_k,m}), \tag{13}$$

where $h_{T_k,R_k,m}\cos(\theta_{T_k,R_k,m})$ is a complex Gaussian random variable and represents the fading channel complex attenuation factor; besides, $h_{T_k,R_k,m}$ obeys the Rayleigh distribution. The number of multipath between T_k and R_k is M, τ_m denotes multipath delay and $\theta_{T_k,R_k,m}$ indicates a uniformly distributed phase on the m-th path. f_c denotes the carrier frequency.

In the receiver end, signal of the n-th user received by the antenna R_k can be given

$$\begin{aligned} R_{n,R_k}(t) &= \sum_{m=1}^{M} h_{T_1,R_k,m}[s_{A_{n,i}}(t) + s_{B_{n,i}}(t-T_{ab})]\cos(\theta_{T_1,R_k,m}) \\ &\quad + \sum_{m=1}^{M} h_{T_2,R_k,m}[s_{A_{n,j}}(t) + s_{B_{n,j}}(t-T_{ab})]\cos(\theta_{T_2,R_k,m}) + v_n(t) \\ &= p(t)r_{n,R_k}(t), \end{aligned} \tag{14}$$

where the main signal part denotes the items from transmitter antennas T_1 and T_2, respectively; besides, $v_n(t)$ indicates the clutter sum of the noise and other additive disturbances. $r_{n,R_k}(t)$ represents received signal of R_k antenna.

The sum of signals after despreading can be represented by $Y_n(t)$ as follows

$$\begin{aligned} Y_n(t) &= p(t)\sum_{k=1}^{RK}\int_{\tau_m}^{\tau_m+T_b} C_{n,R_k}(t-\tau_m)r_{n,R_k}(t)dt \\ &= p(t)\sum_{k=1}^{RK}\int_{\tau_m}^{\tau_m+T_b} \frac{1}{2}[C_{n,i,R_k}(t-\tau_m) + C_{n,j,R_k}(t-\tau_m)]r_{n,R_k}(t)dt \end{aligned} \tag{15}$$

$$= \frac{1}{2}p(t)\sum_{k=1}^{RK}\int_{\tau_m}^{\tau_m+T_b}[A_{n,i}(t-\tau_m)+A_{n,j}(t-\tau_m)+B_{n,i}(t-T_{ab}-\tau_m)$$
$$+B_{n,j}(t-T_{ab}-\tau_m)]r_{n,R_k}(t)dt,$$

where RK is total number of the receiver antennas, T_b denotes per bit time, and the signal given by (15) can be decomposed into three parts: signal part, additive noise part, and the multipath interference part. The signal part is

$$D'_n(t) = p(t)L\sum_{k=1}^{K}h_{T_k,R_k,1}\cos\left(\theta_{T_k,R_k,1}\right). \tag{16}$$

The noise part is expressed by

$$v'_n(t) = p(t)\sum_{k=1}^{K}\int_{\tau_1}^{\tau_1+T_b}C_{n,R_k}(t-\tau_1)v(t)dt. \tag{17}$$

And the part of multipath interference can be given as

$$W(t) = \sum_{l=2}^{L}\sum_{T_k=1}^{TK}\sum_{R_k=1}^{RK}\int_{\tau_1}^{\tau_1+T_b}C_{n,R_k}(t-\tau_1)C_{n,T_k}(t-\tau_l)D_n(t-\tau_l)dt\times h_{T_k,R_k,l}\cos(\theta_{T_k,R_k,1}), \tag{18}$$

where TK is total number of the transmitter antennas.

And then, we can obtain the BER function as follows

$$BER = Q\left(\sqrt{\frac{\left[p(t)L\sum\limits_{k=1}^{K}h_{T_k,R_k,1}\cos\left(\theta_{T_k,R_k,1}\right)\right]^2}{\sigma_W^2+\sigma_v^2}}\right), \tag{19}$$

where σ_W^2 is the multipath interference variance and σ_v^2 is the noise variance. $Q(\cdot)$ is the Gaussian Q-function.

Figure 3 depicts the difference of spread spectrum mode between traditional PN code and CC-S for 2×1 or 2×2 MIMO system. Among these sketches, Figure 3(a) and Figure 3(c) describe 2×1 MIMO case, $h1$ and h11 represent the first path to receiver antenna from T_1 and T_2, respectively, then $h2$ and $h22$ signify the second path that has delay $= 20\times10^{-8}$s after the first one, and in addition, the average power of the second path is lower than the first one for 3dB. For the special spread spectrum case of CC-S, the operation of B is later for T_{ab} after the sequence A. Similarly, Figure 3(b) and Figure 3(d) depict 2×2 MIMO case. Especially like to point out that, $h3$ and $h33$ represent the cross-paths to unmatched receiver antenna from T_1 to R_1, as well as T_2 to R_2, and they have delay2 $= 30\times10^{-8}$s.

3. **Algorithm Analysis and Performance Comparison of Simulation.** We set up symbol rate for 250000bit/s and Doppler shift for 150Hz; besides, we take m-sequence as representative comparison in our simulation, because the generation method of CC-S is different from traditional PN sequence, so we select codes (10bits length of CC-S and 15bits length of m-sequence) with an approximate length to guarantee the simulation results rational and closer to reality.

In Figure 4(a) and Figure 4(b), we compare the simulation results of m-sequence and CC-S in 2×1 antennas MIMO system at different number of users. The channel we considered is flat Rayleigh fading channel. From the curves we can obtain easily that, the results of 10 users have higher BER than only 2 users in system, which is a rational fact

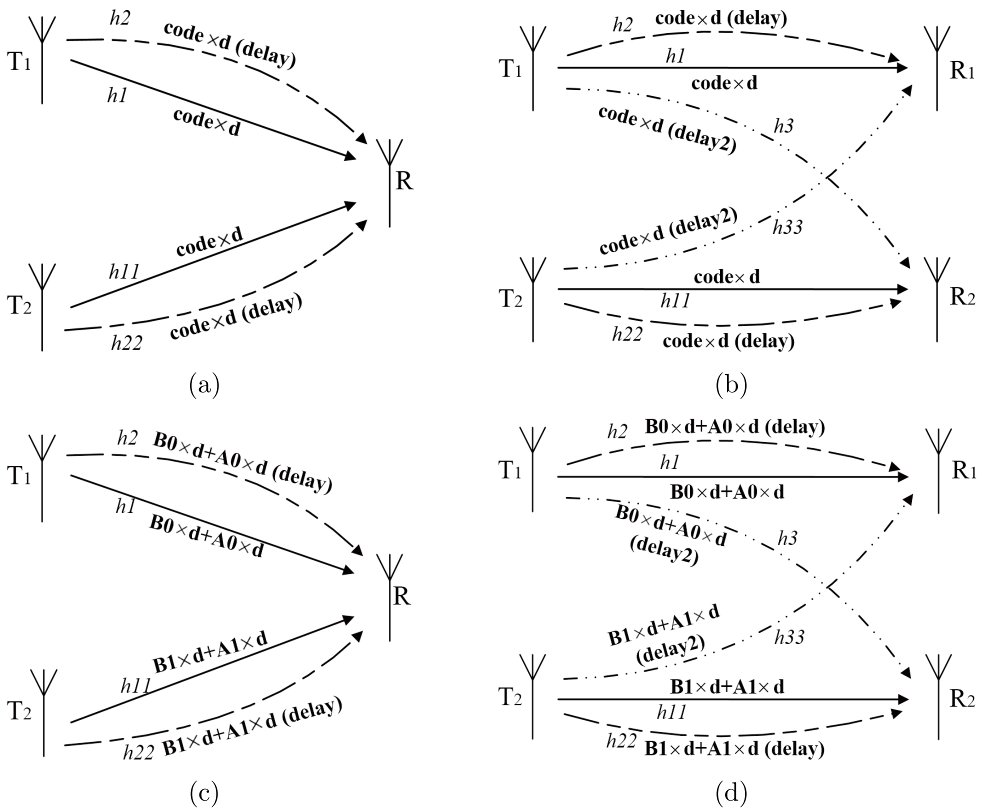

FIGURE 3. The sketch of multipath MIMO system

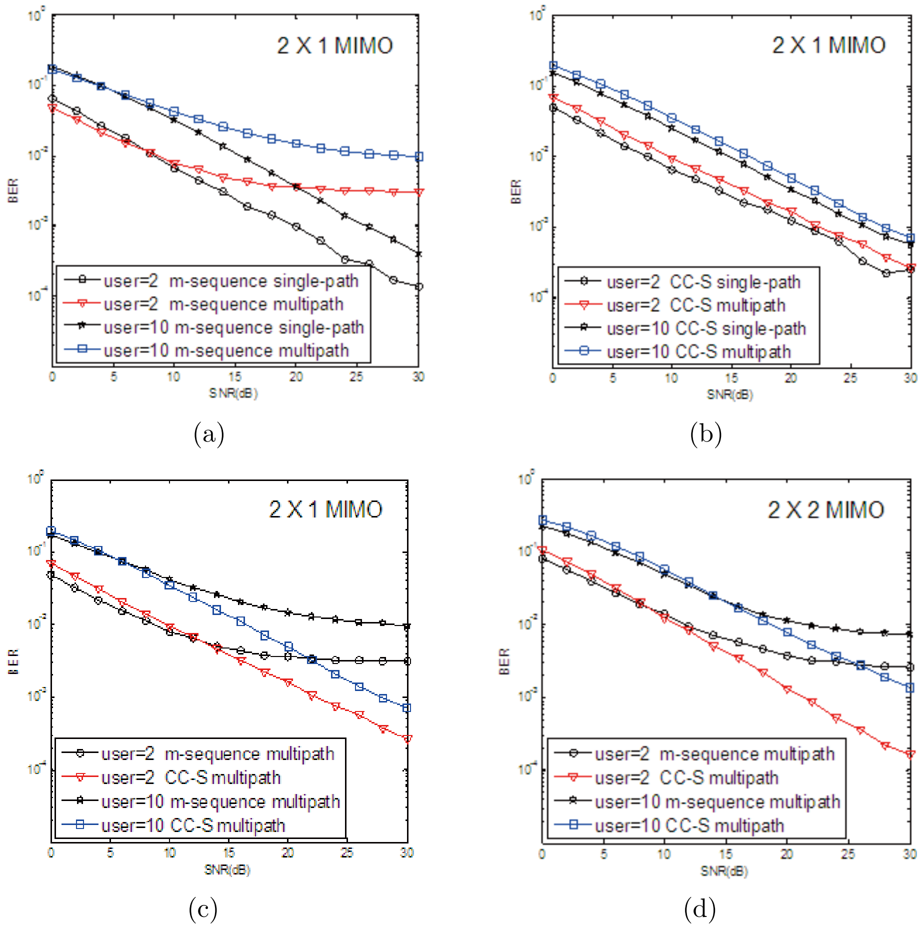

FIGURE 4. The BER performance simulation results

that the performance will deteriorate when the number of user increases because interchip interference exists. Compared with single-path channel, multipath channels have a worse BER performance naturally.

We compare the BER performance of multipath case between CC-S and m-sequence under 2×1 (Figure 4(c)) and 2×2 (Figure 4(d)) antennas systems separately. In Figure 4(c), it is obvious to find that m-sequence performance gradually degrades as the SNR increases. When SNR reaches 20dB, the BER declines stagnantly. However, on the other side, CC-S performs well with the SNR growing. The curves almost describe a linear relationship. This is because CC-S has a perfect orthogonality so it can combat the multipath interference effectively. Similarly with the 2×1 MIMO case, 2×2 MIMO system in Figure 4(d) has almost the same performance.

4. **Conclusions.** In this paper, we have designed a new architecture that utilizes spread spectrum method based on the CC-S to combat multipath fading interference in MIMO system. And we compared system performance in terms of BER through mathematics analysis and program simulation, to verify the theorized expectations. It is obvious in this paper that the method, which we proposed, outperforms typical traditional spreading code clearly, and CC-S can combat effectively the multipath fading in wireless MIMO system.

Acknowledgment. This work was supported by National Natural Science Foundation of China (NSFC): No. 61401407.

REFERENCES

[1] T. T. Lin and F. H. Hwang, A simple blind CFO estimate technique for a QO-STBC based MC-CDMA uplink system, *Digital Signal Processing*, vol.25, no.1, pp.62-71, 2014.

[2] L. K. Bansal, A. Trivedi and R. Gupta, Performance of STTC-MC-CDMA systems with imperfect channel estimation, *Wireless Personal Communications*, vol.75, no.1, pp.49-61, 2014.

[3] Y. L. Chang and L. Y. Oey, Analysis of STCC eddies using the Okubo-Weiss parameter on model and satellite data, *Ocean Dynamics*, vol.64, no.2, pp.259-271, 2013.

[4] M. R. Hueda, D. E. Crivelli and H. S. Carrer, *Adaptive Equalization in Coherent Fiber Optic Communication*, United States Patent 8457504, 2013.

[5] M. Lalam, K. Amis and D. Leroux, Space-time error correcting codes, *IEEE Trans. Wireless Communication*, vol.7, no.5, pp.1472-1476, 2008.

[6] S. F. Li, L. Q. Zhang, J. Chen et al., Construction of quadri-phase complete complementary pairs applied in MIMO radar systems, *The 9th International Conference on Signal Processing*, pp.2298-2301, 2008.

[7] S. Han, R. Venkatesan et al., A complete complementary coded MIMO system and its performance in multipath channels, *IEEE Wireless Communications Letters*, vol.3, no.2, pp.181-184, 2014.

[8] J. Tang, N. Zhang, Z. Ma et al., Construction of doppler resilient complete complementary code in MIMO radar, *IEEE Trans. Signal Processing*, vol.62, no.18, pp.4704-4712, 2014.

[9] S. Li, Y. Zhang and L. Jin, Spread spectrum communication system performance analysis based on the complete complementary sequence, *International Conference on Electronics Information and Emergency Communication*, pp.80-83, 2015.

[10] F. Zeng, X. Zeng et al., New polyphase complementary sequence sets for wireless communication systems, *International Journal of Hybrid Information Technology*, vol.7, pp.147-156, 2014.

[11] S. E. Alavi, I. S. Amiri, S. M. Idrus et al., All-optical OFDM generation for IEEE802.11a based on soliton carriers using microring resonators, *IEEE Photonics Journal*, vol.6, no.1, pp.162-166, 2014.

[12] C. Moffatt and A. Mattsson, Computationally efficient IFFT/FFT approximations for OFDM, *Military Communications Conference*, pp.1-7, 2007.

[13] S. F. Li, J. Chen and L. Q. Zhang, Optimisation of complete complementary codes in MIMO radar system, *Electronics Letters*, vol.46, no.16, pp.1157-1159, 2010.