Complex Complementary Sequence Real Orthogonal Spreading OFDM Scheme for HF Communication Link

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Abstract - The complementary *M*-ary orthogonal spreading with orthogonal frequency division multiplexing (CMOS-OFDM) is an efficient scheme for providing high bit error rate (BER) performance and low peak to mean envelop power ratio (PMEPR) in high frequency (HF) communications system. In the CMOS-OFDM, orthogonal spreading OFDM is implemented based on orthogonal complementary sequence pairs where there is an issue that one data symbol is transmitted through two OFDM symbols. In this paper, we present the *M*-ary orthogonal spreading OFDM scheme using complex complementary sequences which satisfy real domain orthogonality. The complementary real orthogonal spreading OFDM (CROS-OFDM) is restrict the PMEPR to 3dB and provides two times the bit rate of CMOS-OFDM. The CROS-OFDM scheme uses zero-center complementary sequences like the CMOS-OFDM and hence it is suitable to the HF OFDM and Wi-Fi system where the direct current subcarrier is not used. The simulation results show that the CROS-OFDM provides higher bit rate and BER performance.

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1. Introduction

For decades, the high frequency (HF) communications system that uses radio frequency band of 2-30MHz has been recognized as an important mean of long-haul wireless communications, but it is much affected by ionosphere and the performance is considered to be not reliable. Recently, with the multicarrier transmission and spread spectrum (SS) techniques being introduced to overcome the effect of HF fading channel, the HF communication has become a powerful complementary or alternative technology to satellite communications [1-3]. Orthogonal frequency division multiplexing (OFDM) has been widely applied to HF communications as an ideal technology to effectively overcome the frequency selective fading and narrow band interference. However, OFDM has a drawback of high peak to mean envelop power ratio (PMEPR) that decreases the power efficiency of HF OFDM transmitter [4,7].

The combination of SS and OFDM techniques is capable of simultaneously improving processing gain and multipath fading resistance where the works are focused on issues of increasing the data transmission speed and decreasing PMEPR [5-8]. In the SS-OFDM system, the best method for decreasing PMEPR is to use the complementary sequence as orthogonal spreading sequence. The Golay complementary sequences (GCS) have been widely used in radar signal design, synchronization and channel estimation, and were found an important application in OFDM systems to reduce PMEPR [9]. In [5], the authors studied construction of codebooks from GCS and showed that the PMEPR of OFDM waveform is at most 3dB when this GCS is spread over the frequency domain. In [6], as several important parameters of *M*-ary spread spectrum OFDM (MSS-OFDM), the cross-correlation function of spreading sequences, the number of spreading sequences and PMEPR are considered and then generation algorithm of multiple orthogonal sequence sets is presented with providing low PMEPR. The previous works does not reflect the practical requests of OFDM system such as HF OFDM and Wi-Fi which deactivate the direct current (DC) subcarrier.

In [7], the authors have proposed complementary M-ary orthogonal spreading OFDM (CMOS-OFDM) scheme where zero-center complementary pairs (ZCCP) for OFDM system deactivating DC subcarrier are designed. The authors also demonstrated that the PMEPR of the proposed OFDM waveform is at most 3dB and evaluated the performance of the CMOS-OFDM over the HF fading channel modelled by ITU-R F.1487 [10]. In the CMOS-OFDM scheme, the ZCCP corresponds to two OFDM symbols. In other words, a *K*-bit data symbol is mapped (spread) into two length-2^{K-1} complementary sequences forming a ZCCP, with each sequence being transmitted as one OFDM symbol. The CMOS-OFDM receiver concatenates received two adjacent OFDM symbols and demodulates the data bits by de-spreading it by ZCCPs. Therefore, the CMOS-OFDM reduces the bit rate by a factor of two compared with general MSS-OFDM.

In this paper, we propose complementary real orthogonal spreading OFDM (CROS-OFDM) scheme where the ZCCP is combined into a length-2^{K-1} complex complementary sequence and thus the bit rate is increased twice, with a data symbol being transmitted through an OFDM symbol. With the two sequences of each pair of the ZCCPs set corresponding to real and image, respectively, it is combined into a complex sequence. The two adjacent complex sequences form a complementary sequence pair (CSP) and all of the complex complementary sequences provide real domain orthogonality. Thus, the complementary orthogonal spreading can be implemented and the PMEPR is bound by 3dB.

The remainder of this paper is organized as follows. Section 2 illustrates the CROS-OFDM system model and formulates the real domain de-spreading detection process. In section 3, construction of real orthogonal complementary sequence set is presented and its properties are analyzed. In section 4, the simulation results for performance of the CROS-OFDM in HF channel is presented. Finally, section 5 concludes the paper.

2. CROS-OFDM system model

The CROS-OFDM system is an MSS-OFDM system that uses as spreading sequence the zero-center complementary sequence (ZCCS). As shown in Fig. 1, block diagram of the CROS-OFDM system is the same as CMOS-OFDM in [7] except that one complementary sequence is spread over one OFDM symbol in frequency domain. The *K*-bit data symbol input to CROS mapping block is mapped on a complementary sequence, resulting in time domain OFDM signal after frequency domain spreading and IFFT as follows

$$x[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X[k] e^{j\frac{2\pi}{N}nk}, 0 \le n \le N-1 \quad (1)$$

where N is the number of subcarriers and $X[k]$ is the OFDM symbol obtained by frequency domain spreading of ZCCS $\mathbf{S}_m$, that is

$$\{X[k]\}_{k=0}^{N-1} = \{S_m[L/2], S_m[L/2+1], S_m[L], 0, \cdots 0, S_m[0], S_m[1], S_m[L/2-1]\} \quad (2)$$

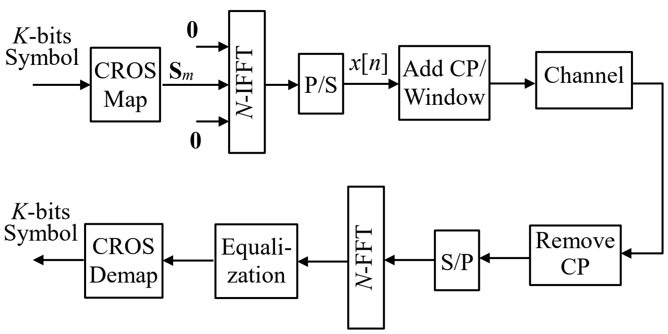

Fig. 1. Block diagram of CROS-OFDM system.

L+1 is length of the ZCCS and hence L is the number of active subcarriers of OFDM system. The output of IFFT is extended by cyclic prefix (CP) before passed through windowing with cyclic suffix (CS) and transmitted as time domain signal.

At the receiver, after the CP is removed from received OFDM signal, the time domain symbol is passed through FFT and frequency domain equalization, generating demodulated version of complementary sequence $\tilde{\mathbf{S}}_m$. In CROS de-mapping stage, the demodulated sequence $\tilde{\mathbf{S}}_m$ is input to $M = 2^K$ correlators and, based on real domain orthogonality of the complementary sequence set $S = \{\mathbf{S}_i\}_{i=0}^{M-1}$, K-bit data symbol corresponding to maximum real correlation value is selected as follows

$$\hat{m} = \arg \max_{i\in[0,M-1]} \mathrm{Re}\{\langle \mathbf{S}_i, \tilde{\mathbf{S}}_m\rangle\} \quad (3)$$

3. Real domain orthogonal complementary sequence set

In [7], given a CSPs set consisting of two CSPs of $[\mathbf{C}_{00}^{(0)}; \mathbf{C}_{01}^{(0)}]$ and $[\mathbf{C}_{10}^{(0)}; \mathbf{C}_{11}^{(0)}]$ which are mates of each other as follows,

$$C^{(0)} = \begin{pmatrix} \mathbf{C}_{00}^{(0)}; \mathbf{C}_{01}^{(0)} \\ \mathbf{C}_{10}^{(0)}; \mathbf{C}_{11}^{(0)} \end{pmatrix} \quad (4)$$

an iterative construction algorithm of ZCCPs set has been proposed according to following steps.

1) nth iterative extension of CSP set

$$C^{(n)} = \begin{pmatrix} \mathrm{e}_{00}C_L^{(n-1)}, \mathrm{e}_{01}C_R^{(n-1)}; \mathrm{e}_{02}C_L^{(n-1)}, \mathrm{e}_{03}C_R^{(n-1)} \\ \mathrm{e}_{10}C_L^{(n-1)}, \mathrm{e}_{11}C_R^{(n-1)}; \mathrm{e}_{12}C_L^{(n-1)}, \mathrm{e}_{13}C_R^{(n-1)} \end{pmatrix} \quad (5)$$

where the sequence set is expressed in matrix form and, $C_L^{(n-1)}$ and $C_R^{(n-1)}$ are left sequence set (LSS) and right sequence set (RSS), respectively. $\{\mathrm{e}_{ij}\}_{i\in[0,1],j\in[0,3]}$ satisfy following conditions.

$$\begin{cases} |e_{ij}| = 0,\ i \in [0,1], j \in [0,3] \\ \sum_{j=0}^{3} e_{0j}\, e_{1j}^* = 0 \\ e_{00}e_{01}^* + e_{02}e_{03}^* = 0 \\ e_{10}e_{11}^* + e_{12}e_{13}^* = 0 \end{cases} \quad (6)$$

2) Construction of ZCCPs set

Based on $C^{(n)}$, the ZCCPs set is constructed as follows

$$S^{(n)} = [I^{(0)}\{C_L^{(n)}\}; I^{(0)}\{C_R^{(n)}\}] \quad (7)$$

where $I^{(0)}$ denotes a central 0-inserting operation of an even length sequence. In the ZCCPs set $S^{(n)}$, length of each complementary sequence is $2^n L^{(0)} + 1$. $L^{(0)}$ is length of component sequence of CSPs set $C^{(0)}$.

For extension matrix $\mathbf{E} = [e_{ij}]$, if a condition

$$e_{i0}e_{i2}^* + e_{i1}e_{i3}^* = 0,\ i = 0,1 \quad (8)$$

is satisfied in addition to (6), the real orthogonal complementary sequence set can be constructed based on ZCCPs set $S^{(n)}$ as follows

$$S'^{(n)} = S_L^{(n)} + jS_R^{(n)} \quad (9)$$

where $S_L^{(n)}$ and $S_R^{(n)}$ are LSS and RSS of $S^{(n)}$, respectively. It can be illustrated that the set $S'^{(n)}$ is a set of complementary sequences through the following theorems.

Theorem 1: For two adjacent CSPs of $[\mathbf{C}_{m,0}^{(n)}; \mathbf{C}_{m,1}^{(n)}]$ and $[\mathbf{C}_{m+1,0}^{(n)}; \mathbf{C}_{m+1,1}^{(n)}]$ in CSPs set $C^{(n)}$ which are mates of each other, both $[\mathbf{C}_{m,0}^{(n)}; \mathbf{C}_{m+1,0}^{(n)}]$ and $[\mathbf{C}_{m,1}^{(n)}; \mathbf{C}_{m+1,1}^{(n)}]$ are CSPs which are mates of each other.

Proof: Without loss of generality, consider the case of m=0. If $C^{(0)} = \begin{bmatrix} + & + \\ + & - \end{bmatrix}$, the above fact is obvious. Now, suppose that following equations are satisfied for (n-1)th CSPs set $C^{(n-1)}$.

$$\begin{cases} \psi_{\mathbf{C}_{0,0}^{(n-1)}}(u) + \psi_{\mathbf{C}_{1,0}^{(n-1)}}(u) = 2L^{(n-1)}\delta(u) \\ \psi_{\mathbf{C}_{0,1}^{(n-1)}}(u) + \psi_{\mathbf{C}_{1,1}^{(n-1)}}(u) = 2L^{(n-1)}\delta(u) \\ \psi_{\mathbf{C}_{0,0}^{(n-1)},\mathbf{C}_{0,1}^{(n-1)}}(u) + \psi_{\mathbf{C}_{1,0}^{(n-1)},\mathbf{C}_{1,1}^{(n-1)}}(u) = 0 \end{cases} \quad (10)$$

where $L^{(n-1)}$ is length of component sequence of $C^{(n-1)}$ and $\psi_{\mathrm{A}}(u)$ and $\psi_{\mathrm{A,B}}(u)$ are auto-correlation function and cross-correlation function, respectively [4, 7]. Eq. (10) means that both $[\mathbf{C}_{0,0}^{(n-1)}; \mathbf{C}_{1,0}^{(n-1)}]$ and $[\mathbf{C}_{0,1}^{(n-1)}; \mathbf{C}_{1,1}^{(n-1)}]$ are CSPs and also mates of each other.

Next, for the CSPs set $C^{(n)}$ given in (5), we can write following equations.

$$\psi_{\mathbf{C}_{0,0}^{(n)}}(u) = \psi_{\mathbf{C}_{0,0}^{(n-1)}}(u) + \psi_{\mathbf{C}_{0,1}^{(n-1)}}(u) + e_{00}e_{01}^*\psi^*_{\mathbf{C}_{0,1}^{(n-1)},\mathbf{C}_{0,0}^{(n-1)}}\left(L^{(n-1)} - u\right), 0 \le u \le L^{(n)} - 1$$

$$\psi_{\mathbf{C}_{1,0}^{(n)}}(u) = \psi_{\mathbf{C}_{1,0}^{(n-1)}}(u) + \psi_{\mathbf{C}_{1,1}^{(n-1)}}(u) + e_{00}e_{01}^*\psi^*_{\mathbf{C}_{1,1}^{(n-1)},\mathbf{C}_{1,0}^{(n-1)}}\left(L^{(n-1)} - u\right), 0 \le u \le L^{(n)} - 1$$

Thus, using (10), the following relation is obtained.

$$\psi_{\mathbf{C}_{0,0}^{(n)}}(u) + \psi_{\mathbf{C}_{1,0}^{(n)}}(u) = 0,\ 1 \le u \le L^{(n)} - 1$$

Similarly, also the following relation is obtained.

$$\psi_{\mathbf{C}_{0,0}^{(n)}}(u) + \psi_{\mathbf{C}_{1,0}^{(n)}}(u) = 0,\ 1 \le |u| \le L^{(n)} - 1 \quad (11)$$

In the same way as the above, we can write following equation.

$$\psi_{\mathbf{C}_{0,1}^{(n)}}(u) + \psi_{\mathbf{C}_{1,1}^{(n)}}(u) = 0, 1 \le |u| \le L^{(n)} - 1 \quad (12)$$

As a result, (11) and (12) show that $[\mathbf{C}_{0,0}^{(n)}; \mathbf{C}_{1,0}^{(n)}]$ and $[\mathbf{C}_{0,1}^{(n)}; \mathbf{C}_{1,1}^{(n)}]$ are CSPs.

And then, the cross-correlation functions can be calculated as follows.

$$\psi_{\mathbf{C}_{0,0}^{(n)},\mathbf{C}_{0,1}^{(n)}}(u) = e_{00}e_{02}^*\psi_{\mathbf{C}_{0,0}^{(n-1)}}(u) + e_{01}e_{03}^*\psi_{\mathbf{C}_{0,1}^{(n-1)}}(u) + e_{00}e_{03}^*\psi^*_{\mathbf{C}_{0,1}^{(n-1)},\mathbf{C}_{0,0}^{(n-1)}}\left(L^{(n-1)} - u\right), 0 \le u \le L^{(n)} - 1$$

$$\psi_{\mathbf{C}_{1,0}^{(n)},\mathbf{C}_{1,1}^{(n)}}(u) = e_{00}e_{02}^{*}\psi_{\mathbf{C}_{1,0}^{(n-1)}}(u) + e_{01}e_{03}^{*}\psi_{\mathbf{C}_{1,1}^{(n-1)}}(u)$$
$$+e_{00}e_{03}^{*}\psi^{*}_{\mathbf{C}_{1,1}^{(n-1)},\mathbf{C}_{1,0}^{(n-1)}}\left(L^{(n-1)}-u\right), 0 \le u \le L^{(n)}-1$$

Using (8), sum of the two cross-correlation functions is expressed as

$$\psi_{\mathbf{C}_{0,0}^{(n)},\mathbf{C}_{0,1}^{(n)}}(u) + \psi_{\mathbf{C}_{1,0}^{(n)},\mathbf{C}_{1,1}^{(n)}}(u) = 0, 0 \le u \le L^{(n)}-1$$

Also, for $1-L^{(n)} \le u \le -1$, similar development can be performed and the sum of two cross-correlation functions is represented as follows.

$$\psi_{\mathbf{C}_{0,0}^{(n)},\mathbf{C}_{0,1}^{(n)}}(u) + \psi_{\mathbf{C}_{1,0}^{(n)},\mathbf{C}_{1,1}^{(n)}}(u) = 0, 0 \le |u| \le L^{(n)}-1 \quad (13)$$

From (13), we can see that the CSPs $[\mathbf{C}_{0,0}^{(n)};\mathbf{C}_{1,0}^{(n)}]$ and $[\mathbf{C}_{0,1}^{(n)};\mathbf{C}_{1,1}^{(n)}]$ are mates of each other. The Eq. (11-13) can be generalized for any even m. ■

Theorem 2: In the set $S'^{(n)}$ given in (9), for any even m, $[\mathbf{S'}_{m}^{(n)};\mathbf{S'}_{m+1}^{(n)}]$ is a CSP.
Proof: Again, without loss of generality, consider the case of m=0. Now, the auto-correlation functions of two sequences $\mathbf{S'}_{0}^{(n)} = \mathbf{S}_{0,0}^{(n)} + j\mathbf{S}_{0,1}^{(n)}$ and $\mathbf{S'}_{1}^{(n)} = \mathbf{S}_{1,0}^{(n)} + j\mathbf{S}_{1,1}^{(n)}$ are written as follows, respectively.

$$\psi_{\mathbf{S'}_{0}^{(n)}}(u) = \psi_{\mathbf{S}_{0,0}^{(n)}}(u) + \psi_{\mathbf{S}_{0,1}^{(n)}}(u)$$
$$+j\psi_{\mathbf{S}_{0,1}^{(n)},\mathbf{S}_{0,0}^{(n)}}(u) - j\psi_{\mathbf{S}_{0,0}^{(n)},\mathbf{S}_{0,1}^{(n)}}(u)$$
$$\psi_{\mathbf{S'}_{1}^{(n)}}(u) = \psi_{\mathbf{S}_{1,0}^{(n)}}(u) + \psi_{\mathbf{S}_{1,1}^{(n)}}(u)$$
$$+j\psi_{\mathbf{S}_{1,1}^{(n)},\mathbf{S}_{1,0}^{(n)}}(u) - j\psi_{\mathbf{S}_{1,0}^{(n)},\mathbf{S}_{1,1}^{(n)}}(u)$$

From the Theorem 1 of [7], $[\mathbf{S}_{0,0}^{(n)};\mathbf{S}_{0,1}^{(n)}]$ and $[\mathbf{S}_{1,0}^{(n)};\mathbf{S}_{1,1}^{(n)}]$ are CSPs and hence the sum of two auto-correlation functions is represented as follows.

$$\psi_{\mathbf{S'}_{0}^{(n)}}(u) + \psi_{\mathbf{S'}_{1}^{(n)}}(u) = j\psi_{\mathbf{S}_{0,1}^{(n)},\mathbf{S}_{0,0}^{(n)}}(u) - j\psi^{*}_{\mathbf{S}_{0,1}^{(n)},\mathbf{S}_{0,0}^{(n)}}(-u)$$
$$+j\psi_{\mathbf{S}_{1,1}^{(n)},\mathbf{S}_{1,0}^{(n)}}(u) - j\psi^{*}_{\mathbf{S}_{1,1}^{(n)},\mathbf{S}_{1,0}^{(n)}}(-u) \quad (14)$$

The cross-correlation functions in (14) are expressed as follows.

$$\psi_{\mathbf{S}_{0,1}^{(n)},\mathbf{S}_{0,0}^{(n)}}(u) = e_{02}e_{00}^{*}\psi_{\mathbf{C}_{0,0}^{(n-1)}}(u) + e_{03}e_{01}^{*}\psi_{\mathbf{C}_{0,1}^{(n-1)}}(u)$$
$$+e_{02}e_{01}^{*}\psi^{*}_{\mathbf{C}_{0,1}^{(n-1)},\mathbf{C}_{0,0}^{(n-1)}}(N/2+1-u) \quad (15)$$
$$\psi_{\mathbf{S}_{1,1}^{(n)},\mathbf{S}_{1,0}^{(n)}}(u) = e_{02}e_{00}^{*}\psi_{\mathbf{C}_{1,0}^{(n-1)}}(u) + e_{03}e_{01}^{*}\psi_{\mathbf{C}_{1,1}^{(n-1)}}(u)$$
$$+e_{02}e_{01}^{*}\psi^{*}_{\mathbf{C}_{1,1}^{(n-1)},\mathbf{C}_{1,0}^{(n-1)}}(N/2+1-u) \quad (16)$$

Substituting (15) and (16) into (14) and using the Theorem 1, (14) can be written as follows.

$$\psi_{\mathbf{S'}_{0}^{(n)}}(u) + \psi_{\mathbf{S'}_{1}^{(n)}}(u) = 0 \quad (17)$$

The Eq. (17) can be generalized for any even m. ■

From the Theorem 1 of [7], ZCCPs set $S^{(n)}$ is orthogonal CSPs set and therefore the set $S'^{(n)}$ satisfies real domain orthogonality, that is

$$\langle \mathbf{S'}_{m}^{(n)}, \mathbf{S'}_{k}^{(n)} \rangle = \langle \mathbf{S}_{m,0}^{(n)}, \mathbf{S}_{k,0}^{(n)} \rangle + \langle \mathbf{S}_{m,1}^{(n)}, \mathbf{S}_{k,1}^{(n)} \rangle$$
$$+j\langle \mathbf{S}_{m,1}^{(n)}, \mathbf{S}_{k,0}^{(n)} \rangle - j\langle \mathbf{S}_{m,0}^{(n)}, \mathbf{S}_{k,1}^{(n)} \rangle \quad (18)$$
$$\mathrm{Re}\{\langle \mathbf{S'}_{m}^{(n)}, \mathbf{S'}_{k}^{(n)} \rangle\} = 2L^{(n)}\delta(m-k) \quad (19)$$

4. Simulation results

Int this section, we set the parameters for MSS-OFDM system with HF channel and evaluate the performance of CROS-OFDM scheme through the simulations. The CROS-OFDM system simulation setup is chosen similar to [7]. Table 1 shows the simulation parameters. The transmission frame consists of two OFDM symbols where the first symbol is first sequence of the set $S'^{(5)}(64 \times 33)$, i.e., $\mathbf{S'}_{0}^{(5)}$ which serves as pilot for channel estimation and the second a complementary sequence corresponding to the data symbol. The CSPs set $C^{(5)}$ is constructed based on $C^{(0)} = \left[\begin{smallmatrix}+&+\\+&-\end{smallmatrix}\right]$ and $\mathbf{E} = \left[\begin{smallmatrix}+&+&-&+\\+&+&+&-\end{smallmatrix}\right]$ [7]. The channel is assumed constant during the transmission of a frame but changes over different frames. Also, it is supposed that perfect symbol timing and frequency synchronization of CROS-OFDM system is provided. The bit error rate (BER) performances are obtained by running 100000 frame transmission simulations for a given value of Eb/No.

Table 1. simulation parameters for CROS-OFDM system

Parameter	value
HF channel bandwidth	3kHz
Number of subcarriers	$N = 64$
Subcarrier spacing	$\Delta f = 64.0625$Hz
Number of active subcarriers	32
CP Length	16
CS Length	2
Symbol period	20ms
Sampling frequency	4.1kHz
Channel	ITU-R F.1487

In Fig. 2, the comparison between BER performances of CMOS-OFDM and CROS-OFDM for additive white Gaussian noise (AWGN) channel is shown where 'CROS-OFDM (350bps)' denotes the scheme that combines complementary sequence spreading of data symbol with binary phase shift keying (BPSK). That is, the first K bits of (K+1)-bit data is used in M-ary orthogonal spreading modulation and the rest 1 bit in BPSK of the orthogonal modulated OFDM symbol. In the 'CROS-OFDM (350bps)' scheme, with the number of data bits increasing by 1 bit, the symbol energy is remained equal and thus the BER versus Eb/No performance is higher than no BPSK.

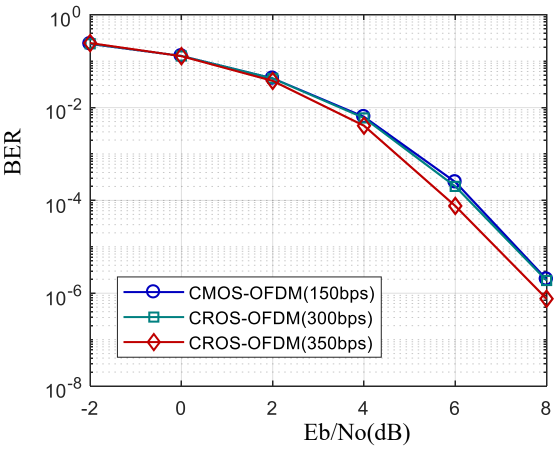

Fig. 2. Comparison of BER performance for AWGN channel

Fig. 3 shows the BER performances of BPSK-CROS-OFDM scheme for different HF channel models [10]. For the ITU-R F.1487 MD (mid-latitudes disturbed) channel model, the BER performance is obtained more badly. The reason is that the delay spread and doppler spread of the MD channel is large while the MD channel model reflects the disturbed condition of ionospheric layers.

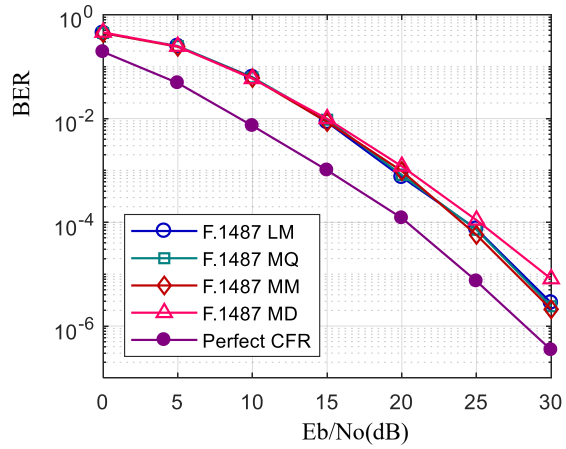

Fig. 3. BER performance of BPSK-CROS-OFDM scheme (bit rate 350bps, ITU-R F.1487 Rayleigh channel)

In Fig. 4, comparison of BER performance of the different HF OFDM schemes for ITU-R F.1487 MD channel model is shown. 'CMOS-OFDM (250bps)' scheme corresponds to the MSS-OFDM using only LSS of CSPs set $C^{(5)}$. Since 5 bits are mapped on one OFDM symbol, the bit rate is higher than 'CMOS-OFDM (150bps)', but the processing gain is smaller to degrade the BER performance. In CROS-OFDM scheme, the M-ary spreading modulation is performed using complex complementary sequence and hence the bit rate is twice higher compared to CMOS-OFDM and the OFDM symbol energy is also increased by a factor of 2. As a result, with the spectral efficiency being twice higher, the BER versus Eb/No performance is almost the same as CMOS-OFDM.

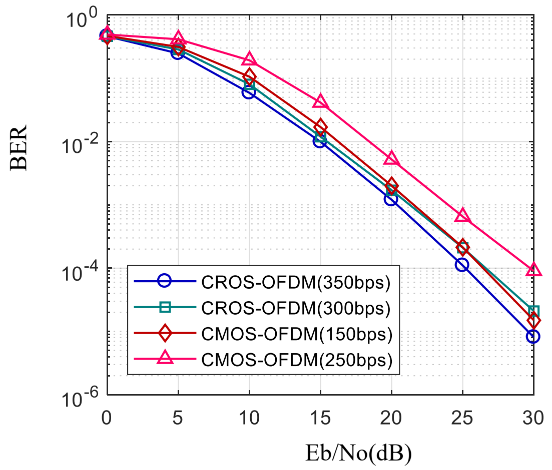

Fig. 4. BER performance of HF OFDM systems (ITU-R F.1487 MD Rayleigh channel)

5. Conclusions

The CMOS-OFDM scheme is an efficient MSS-OFDM scheme for providing high BER performance and low PMEPR in HF communications system that deactivates the DC subcarrier. In CMOS-OFDM, with a data symbol being transmitted through two OFDM symbols, the orthogonal spreading OFDM is performed using ZCCP. In this paper, we propose the CROS-OFDM scheme where OFDM is combined with *M*-ary orthogonal spreading modulation based on zero-center complex complementary sequences satisfying the real domain orthogonality. Since the CROS-OFDM scheme uses the ZCCSs, the PMEPR is restricted to 3dB while the bit rate can be increased by a factor of 2. The complex ZCCSs set obtained from ZCCPs set used in CMOS-OFDM provides the real domain orthogonality and therefore the de-spreading correlation have to be performed in real domain.

Data availability
Data is available to access and suitable to post.

Declarations
The authors declare that they have no competing interests.

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