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Low-PMEPR rotatable pilot sequences for MIMO-OFDM systems

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Dear editor,

The multiple-input multiple-output orthogonal frequency division multiplexing (MIMO-OFDM) is the core of many advanced Wi-Fi standards, such as Wi-Fi 4, 5, and 6, to increase the throughput. Operating at the 5-GHz band and considering the phase tracking of the very high throughput long training field (VHT-LTF) sequences, MIMO-OFDM receivers are far more efficient in Wi-Fi 5 and 6 compared to Wi-Fi 4. Unfortunately, the traditional preamble sequences are poor candidates for VHT-LTF sequences in Wi-Fi 5 and 6 because their peak-to-mean envelope power ratios (PMEPRs) may increase because of the phase rotation in pilot tones for the phase tracking [1,2]. Hence, new sequences with low PMEPRs under some specific rotatable index sets should be considered. According to the design requirement of preamble sequences used in the phase tracking method proposed in [3] and applied in Wi-Fi 5 and 6, we propose a novel class of sequence sets called rotatable sequence sets (RSSs). This study presents several direct or general constructions of low-PMEPR RSSs with different sizes based on generalized Boolean functions and complementary sequence sets.

Construction 1: low-PMEPR training sequences for q-th rotatable pilots. Let $m \geqslant 2$ be an integer and q be a positive and even integer. Let

$$f(\boldsymbol{x}) = \frac{q}{2}\sum_{k=1}^{m-1} x_{\pi(k)}x_{\pi(k+1)} + \sum_{k=1}^{m} c_k x_k + c,$$

where $\boldsymbol{x} \in \mathbb{Z}_2^m, c_k, c \in \mathbb{Z}_q$. Let π be a permutation of $\{1, 2, \ldots, m\}$.

(1) Let $a(\boldsymbol{x}) = f(\boldsymbol{x})$. For the q-th rotatable index set $\Gamma_k = \{i : i_k = 1\}$, $1 \leqslant k \leqslant m$, $0 \leqslant i \leqslant 2^m - 1$, where i_k is the k-th element of the binary representation of index i and $|\Gamma_k| = 2^{m-1}$, $\mathcal{A}_{\Gamma_k}$ is a $(q, \Gamma_k, 2^m, 2)$-RSS for all $k = 1, 2, \ldots, m$.

(2) Let $a(\boldsymbol{x}) = f(\boldsymbol{x}) + \lambda x_{\pi(t)}x_{\pi(t+1)}$, where $\lambda \in \mathbb{Z}_q$ and $1 \leqslant t \leqslant m-1$. For the q-th rotatable index set $\Gamma_t = \{i : i_{\pi(t)}i_{\pi(t+1)} = 1\}$, $1 \leqslant t \leqslant m-1$, $0 \leqslant i \leqslant 2^m - 1$, where i_t is the t-th element of the binary representation of index i and $|\Gamma_t| = 2^{m-2}$, $\mathcal{A}_{\Gamma_t}$ is a $(q, \Gamma_t, 2^m, 4)$-RSS for all $t = 1, 2, \ldots, m-1$.

(3) Let $a(\boldsymbol{x}) = f(\boldsymbol{x}) + \lambda x_{\pi(m)} \prod_{k\in\mathcal{S}} x_{\pi(k)}$, where $\lambda \in \mathbb{Z}_q$ and $\mathcal{S} = \{s_1, s_2, \ldots, s_{r-1}\}$ is any subset of $\{1, 2, \ldots, m-1\}$ with $|\mathcal{S}| = r-1$. For the q-th rotatable index set $\Gamma = \{i : i_{\pi(m)} \prod_{k\in\mathcal{S}} i_{\pi(k)} = 1\}$, $0 \leqslant i \leqslant 2^m - 1$, where i_k is the k-th element of the binary representation of index i and $|\Gamma| = 2^{m-r}$, $\mathcal{A}_\Gamma$ is a $(q, \Gamma, 2^m, 2^r)$-RSS.

The details on RSSs and Construction 1 can be found in Appendixes A and B, respectively.

Note that the upper bound on the PMEPR of RSSs in Construction 1 increases as the size of the RSS decreases. The following results give general methods for generating low-PMEPR RSSs with small rotatable index sets.

Construction 2: general RSS construction methods for small 4-th rotatable index sets with low PMEPRs. Consider $q = 4$ and let $(\boldsymbol{a}, \boldsymbol{b})$ be a Golay complementary pair (GCP) of length L with $(\boldsymbol{c}, \boldsymbol{d})$ its Golay mate and these sequences have the same energy. Let $\boldsymbol{e} = \Im(\boldsymbol{a}, 0, \xi_q)$ and $\boldsymbol{h} = \Im(\boldsymbol{a}, L, \xi_q)$. In addition, let $\boldsymbol{w} = (\boldsymbol{a} \parallel \boldsymbol{c})$ be a sequence of length $2L$ and $\boldsymbol{k} = \Im(\boldsymbol{w}, L, \xi_q)$. Then we have the following results:

(1) For the 4-th rotatable index set $\Gamma = \{0\}$, $\mathcal{E}_\Gamma$ is a $(4, \Gamma, L+1, 4)$-RSS.

(2) For the 4-th rotatable index set $\Gamma = \{L\}$, $\mathcal{H}_\Gamma$ is a $(4, \Gamma, L+1, 4)$-RSS.

(3) For the 4-th rotatable index set $\Gamma = \{L\}$, $\mathcal{K}_\Gamma$ is a $(4, \Gamma, 2L+1, 4)$-RSS.

(4) For the 4-th rotatable index set $\Gamma = \{0, L+1\}$ and $\boldsymbol{m} = \Im(\boldsymbol{e}, L+1, \xi_4)$, $\mathcal{M}_\Gamma$ is a $(4, \Gamma, L+2, 4)$-RSS.

The details on Construction 2 can be found in Appendix C.

The rotatable index sets in Construction 2 are very small and may not be sufficient for the phase tracking. The following result shows two general methods for generating RSSs from given complementary sequence sets (CSSs), which can be used to obtain new RSSs with larger sequence lengths and rotatable index sets.

Construction 3: general methods for constructing q-th

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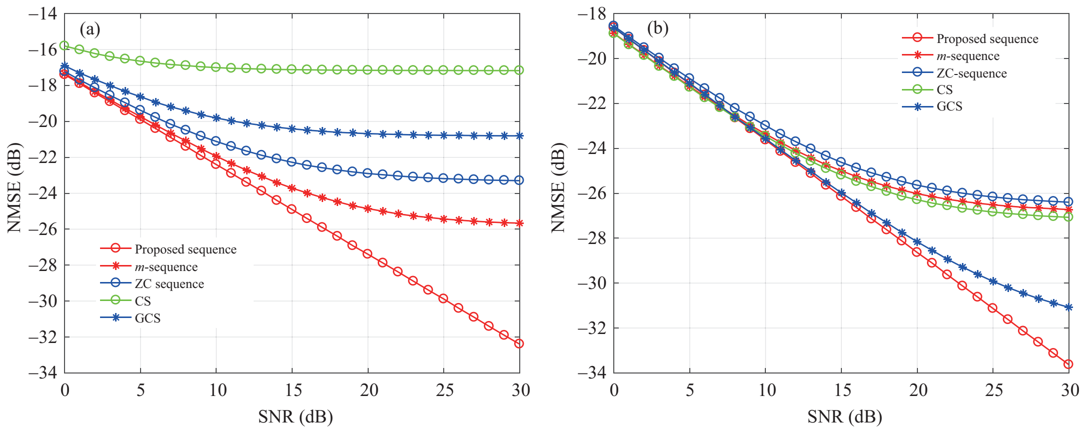

Figure 1 (Color online) NMSE comparison for various SNRs. (a) Number of subcarriers is 64, $\Gamma = \{i : i_2 i_5 = 1\}$, and the saturation voltage is 0.646; (b) number of subcarriers is 128, $\Gamma = \{i : i_1 i_2 i_7 = 1\}$, and the saturation voltage is 0.784.

RSSs from CSSs. For positive integers M, N with $M = 2N$, let $\mathcal{S} = \{\boldsymbol{s}_1, \boldsymbol{s}_2, \ldots, \boldsymbol{s}_M\}$ be a CSS of length L, where the sequences have the same energy. Consider M q-th rotatable index sets $\Gamma_m = \{\{t_1^m, t_2^m, \ldots, t_{d_m}^m\} : 1 \leqslant t_i^m \leqslant L\}$, $1 \leqslant m \leqslant M$, where d_m is the size of Γ_m. If for any $p \in \mathbb{Z}_q$, $\mathcal{S}_p = \{\boldsymbol{s}_{1,p}^{\Gamma_1}, \boldsymbol{s}_{2,p}^{\Gamma_2}, \ldots, \boldsymbol{s}_{M,p}^{\Gamma_M}\}$ is also a CSS, then we have the following results:

(1) Let $\mathcal{S}^k = \{\boldsymbol{s}_1^k, \boldsymbol{s}_2^k, \ldots, \boldsymbol{s}_M^k\}$, where $\boldsymbol{s}_{2n-1}^k = \boldsymbol{s}_{2n-1}^{k-1} \lozenge \boldsymbol{s}_{2n}^{k-1}$, $\boldsymbol{s}_{2n}^k = \boldsymbol{s}_{2n-1}^{k-1} \lozenge - \boldsymbol{s}_{2n}^{k-1}$, $\boldsymbol{s}_m^0 = \boldsymbol{s}_m$, $1 \leqslant m \leqslant M$, and $\boldsymbol{a} = \boldsymbol{s}_1^k$. Then $\mathcal{A}_{\Gamma^k}$ is a $(q, \Gamma_1^k, 2^k L, M)$-RSS, where "$\lozenge$" denotes the bit-interleaved operation, $\Gamma_1^k = \Gamma_2^k = (2\Gamma_1^{k-1} - 1) \bigcup (2\Gamma_2^{k-1})$, $\Gamma_1^0 = \Gamma_1, \Gamma_2^0 = \Gamma_2$, and $k \geqslant 1$.

(2) Let $\mathcal{S}^k = \{\boldsymbol{s}_1^k, \boldsymbol{s}_2^k, \ldots, \boldsymbol{s}_M^k\}$, where $\boldsymbol{s}_{2n-1}^k = (\boldsymbol{s}_{2n-1}^{k-1} \parallel \boldsymbol{s}_{2n}^{k-1})$, $\boldsymbol{s}_{2n}^k = (\boldsymbol{s}_{2n-1}^{k-1} \parallel -\boldsymbol{s}_{2n}^{k-1})$, $\boldsymbol{s}_m^0 = \boldsymbol{s}_m$, $1 \leqslant m \leqslant M$, and $\boldsymbol{a} = \boldsymbol{s}_1^k$. Then $\mathcal{A}_{\Gamma_1^k}$ is a $(q, \Gamma_1^k, 2^k L, M)$-RSS, where $\Gamma_1^k = \Gamma_2^k = \Gamma_1^{k-1} \bigcup (2^{k-1} L + \Gamma_2^{k-1})$, $\Gamma_1^0 = \Gamma_1, \Gamma_2^0 = \Gamma_2$, and $k \geqslant 1$.

The details on Construction 3 can be found in Appendix D.

Simulation result. We consider the channel estimation performances under the least squares estimator of the binary proposed sequences, complementary sequences (CSs) [4], Golay complementary sequences (GCSs) [5], Zadoff-Chu (ZC) sequences, and m-sequences, where the elements in the rotatable index sets have been rotated by 180° as the preamble sequences for MIMO-OFDM systems over frequency-selective channels with 5 taps and a soft limiter power amplifier, where the oversampling rate is 8, and the length of the cyclic prefix equals the number of subcarriers. In Figure 1, we evaluate the channel estimation normalized mean squared error (NMSE) performances of the rotated proposed sequences, rotated CSs, rotated GCSs, rotated ZC sequences, and rotated m-sequences of lengths 64 and 128 when the signal-to-noise ratio (SNR) runs over $\{0, 1, \ldots, 30\}$ dB, and the number of transmit antennas is 8. As shown, our proposed sequences considerably outperform the other sequences under the least squares estimator. This result is obtained because the peak signal powers of those sequences exceed the limited power of the soft limiter power amplifier due to the rotation of some elements, which distorts these signals, while our rotated proposed sequences are unaffected by the power amplifier. The PMEPRs and code rates of the proposed sequences are compared with those of the well-known ZC sequences and m-sequences in Appendix E.

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Supporting information Appendixes A–E. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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