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A novel OFDM directional modulation waveforms synthesis approach for multiple target sensing

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ABSTRACT

In this paper, a novel orthogonal frequency-division multiplexing directional modulation (OFDM-DM) waveform synthesis approach is presented for multiple radar target sensing in free space. The DM waveforms have demonstrated unique advantages in radar sensing. Unlike the conventional DM waveforms synthesis approach, the proposed method here can simultaneously deliver information to multiple targets at a high data rate and detect their azimuth angles. The desired OFDM-DM signals can be constructed using the inverse fast Fourier transform (IFFT) modules with no need to re-synthesize the array excitation vectors for different DM symbols. Simulation results are provided to prove the efficacy of the proposed approach.

Keywords: Directional modulation (DM), multiple target sensing, orthogonal frequency-division multiplexing (OFDM)

1. INTRODUCTION

Directional modulation (DM) has emerged as a cutting-edge technology in the physical layer of wireless communications. It is used to distort signal constellation points in unintended directions while preserving the integrity of the signals in the desired direction, as indicated in [1] and [2]. This unique capability has garnered significant attention and research. However, most existing studies have limited their scope to single carrier signal frameworks. It is until recently that the synthesis approach for multicarrier DM waveforms has been developed, as detailed in [3-5]. The approach described in [3] involves a multicarrier DM symbol synthesis method using a time-modulated array (TMA) transmitter, synthesizing DM symbols directly in the radio frequency (RF) domain instead of the baseband domain. This technique underwent further improvement in [4] to enhance the security performance. In [5], the concept of orthogonal frequency-division multiplexing directional modulation (OFDM-DM) was introduced, which offers a higher data rate in comparison to other DM strategies.

Joint Radar-Communication (JRC) systems have been developed to perform radar sensing and wireless communication functions using a single hardware platform with an optimized waveform. This JRC system can alleviate electromagnetic interference and improve spectral efficiency, thus, attracting great interest in this field [6-8]. However, the design of the JRC waveform faces a significant challenge. Fortunately, the DM waveforms can be used in JRC systems and have demonstrated a variety of advantages. For instance, DM waveforms can secure transmitted information and enable the estimation of the azimuth angle of the target, as demonstrated in [9] and [10]. When OFDM-DM signal is employed as the JRC waveform, it not only maintains the security of information at high data rates but also reduces sidelobe levels in radar range profiles, thereby, suppressing sidelobe interference, according to studies in [11] and [12].

In this paper, a novel OFDM-DM synthesis approach is proposed, which can secure the transmission of information to multiple directions while simultaneously sensing multiple targets.

The rest of the paper is organized as follows: Section 2 describes the principle of the proposed synthesis approach. This is followed by simulation results that demonstrate the effectiveness of this synthesis approach in Section 3. Finally, Section 4 concludes the paper.

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2. PROPOSED THE SYNTHESIS APPROACH

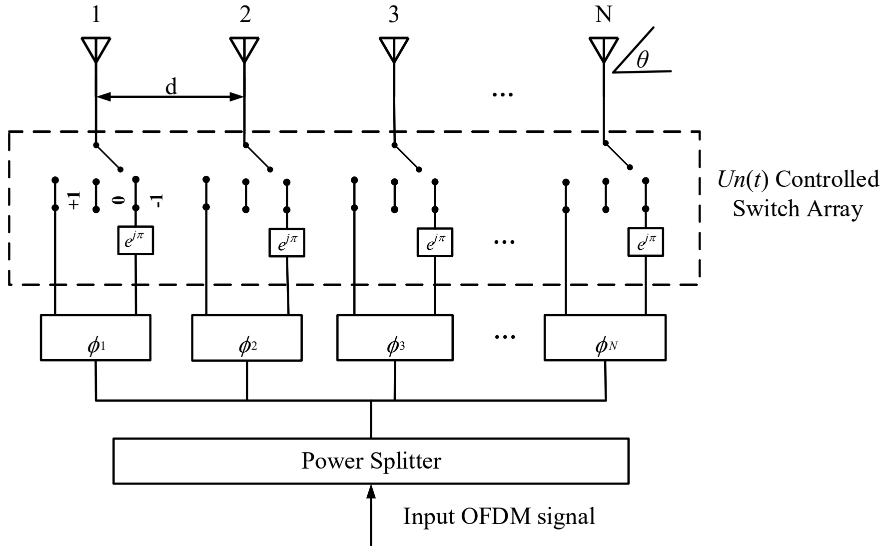

Figure 1. The transmitter architecture of the proposed OFDM DM scheme.

In Figure 1, the transmitter architecture, consisting of an *N*-element antenna array with identical inter-element spacing *d* to form multiple OFDM-DM beams, is depicted. At the transmitter, an input OFDM signal is initially split into *N* copies, which then processed through phase shifters, followed by a TMA array with three states, namely '+1', '−1', and '0'. Here, the RF switches can be carefully engineered, and the output signals will be emitted from the antenna elements. The radiated signals in the far-field space can be expressed as

$$F(\theta,t)=\frac{1}{\sqrt{N}}\sum_{n=1}^{N}\left(S(t)\cdot e^{j\phi_n}\cdot U_n(t)\cdot e^{j(n-1)\pi\cos\theta}\right). \tag{1}$$

Here, $S(t)$ denotes the transmitted OFDM signals, $U_n(t)$ represents the time domain function of the *n*th RF switch within the controlled TMA array, and ϕ_n signifies the phase delay in the *n*th antenna branch. Considering an individual OFDM symbol, $S(t)=\frac{1}{\sqrt{K}}\sum_{k=1}^{K}D_k\cdot e^{j2\pi\left[f_0+(k-1)f_p\right]t}$, where K is the total number of subcarriers, D_k the modulated data on the *k*th subcarrier, f_0 the frequency of the initial OFDM subcarrier, f_p the frequency spacing between successive subcarriers, which is related to the OFDM symbol period $T_p = 1/f_p$. After expanding $U_n(t)$ using Fourier series, the far-field pattern can be then depicted as delineated in equation (2),

$$F(\theta,t)=\left(\frac{1}{\sqrt{NK}}\cdot\sum_{K=1}^{K}D_k\cdot e^{j2\pi\left[f_0+(k-1)f_p\right]t}\right)$$

$$\cdot\sum_{m=-\infty}^{\infty}\left[\underbrace{e^{j2m\pi f_p t}\sum_{n=1}^{N}\left(\left(\frac{\sin\left(m\pi\Delta\tau_n^{(1)}\right)}{m\pi}-\frac{\sin\left(m\pi\Delta\tau_n^{(2)}\right)}{m\pi}e^{-jm\pi\left(\Delta\tau_n^{(1)}+\Delta\tau_n^{(2)}\right)}\right)\right.}_{V\left(m,N,\tau_n^{S1},\Delta\tau_n^{(1)},\Delta\tau_n^{(2)},\phi_n,t,\theta\right)}\right. \tag{2}$$

$$\left.\underbrace{\left.\cdot e^{-jm\pi\left(2\tau_n^{S1}+\Delta\tau_n^{(1)}\right)}\right)\cdot e^{j\left((n-1)\pi\cos\theta+\phi_n\right)}}\right],$$

where, m denotes the synthesized harmonic frequency index associated with the switching time function of $U_n(t)$. The variables $\Delta\tau_n^{(1)}$ and $\Delta\tau_n^{(2)}$ represent the normalized time durations for the switch states '+1' and '−1', respectively.

Furthermore, τ_n^{s1} designates the normalized time instants at which the switch is in the '+1'state. To facilitate the synthesis of multiple DM beams, for simplicity, we consider the generation of two DM beams directed along the directions of *α* and *β*, respectively. This synthesis procedure is translated into an optimization problem, outlined as follows,

$$\begin{aligned}
&\underset{m,\, N, \Delta\tau_n^{(1)}, \Delta\tau_n^{(2)}, \tau_n^{s1},\ \phi_n, \theta}{\text{minimize}} && V\left(m,\, N,\, \Delta\tau_n^{(1)}, \Delta\tau_n^{(2)}, \tau_n^{s1}, \phi_n, \theta\right) \\
&\text{subject to} && m \neq 0, \\
& && N > 1, N \in \mathrm{Z}^{+}, \\
& && 0 \le \Delta\tau_n^{(1)} \le 1, 0 \le \Delta\tau_n^{(2)} \le 1,\ \Delta\tau_n^{(1)} + \Delta\tau_n^{(2)} \le 1, \\
& && 0 \le \tau_n^{s1} \le 1, \\
& && 0 \le \phi_n \le 2\pi, \\
& && \theta = \{\alpha, \beta\}, \\
& && V\left(m = 0,\, N,\, \Delta\tau_n^{(1)}, \Delta\tau_n^{(2)}, \tau_n^{s1},\ \phi_n, \theta\right) \neq 0.
\end{aligned} \tag{3}$$

In (3), the variable *N* is typically a constant. When $m \neq 0$, along the directions *α* and *β*, the objective is for the function *V* $(\cdot)$ to be as close to zero as possible. Conversely, when $m = 0$, the function along *α* and *β* should also be optimized to be as close to $\left(\Delta\tau^{(1)} - \Delta\tau^{(2)}\right) \cdot \sqrt{N} \cdot S(t)$ as possible. Here, $\Delta\tau^{(1)}$ and $\Delta\tau^{(2)}$ respectively represent the values of $\Delta\tau_n^{(1)}$ and $\Delta\tau_n^{(2)}$ for each *n*, which are identical.

3. SIMULATION RESULTS

In this section, we illustrate the radiation patterns for a solution obtained via the Particle Swarm Optimization (PSO) algorithm and simulate its bit error rate (BER) to demonstrate secure transmission over various directions. In the simulation setup, we choose $N = 16$, $\alpha = 45°$ and $\beta = 60°$. Applying the PSO algorithm, a particular set of solutions for ($\Delta\tau_n^{(1)}$, $\Delta\tau_n^{(2)}$, τ_n^{s1}, ϕ_n) can be obtained, which are detailed in Table 1.

Table 1. An example set of solutions for ($\Delta\tau_n^{(1)}$, $\Delta\tau_n^{(2)}$, τ_n^{s1}, ϕ_n) with $N = 16$, $\alpha = 45°$ and $\beta = 60°$, obtained through the application of the PSO algorithm.

n	$\Delta\tau_n^{(1)}$	$\Delta\tau_n^{(2)}$	τ_n^{s1}	ϕ_n
1	0.576	0.038	0.220	0.752
2	0	0.437	0.490	2.055
3	0.476	0.016	0.561	2.059
4	0.056	0.568	0.719	2.816
5	0.227	0.328	0.419	1.564
6	0.342	0.372	0.564	2.840
7	0.358	0.140	0.555	2.596
8	0.467	0.041	0.235	2.931
9	0.580	0.052	0.729	0.154
10	0.510	0.033	0.368	0.357
11	0.060	0.650	0.748	0.096
12	0.629	0.020	0.946	1.415
13	0.276	0.554	0.386	1.814
14	0.326	0.446	0.625	1.291
15	0.282	0.298	0.663	1.490
16	0.235	0.501	0.430	2.485

Configuring the proposed array transmitter to align with Table 1, we can observe the resulting radiation patterns as depicted in Figure 2. It can be observed that the beamforming gains are prominent along the designated directions of 45° and 60° at $m = 0$, and near-null points are obtained for other beamforming gains at $m \neq 0$. Elsewhere, signals at $m = 0$ coexist with harmonic frequency components.

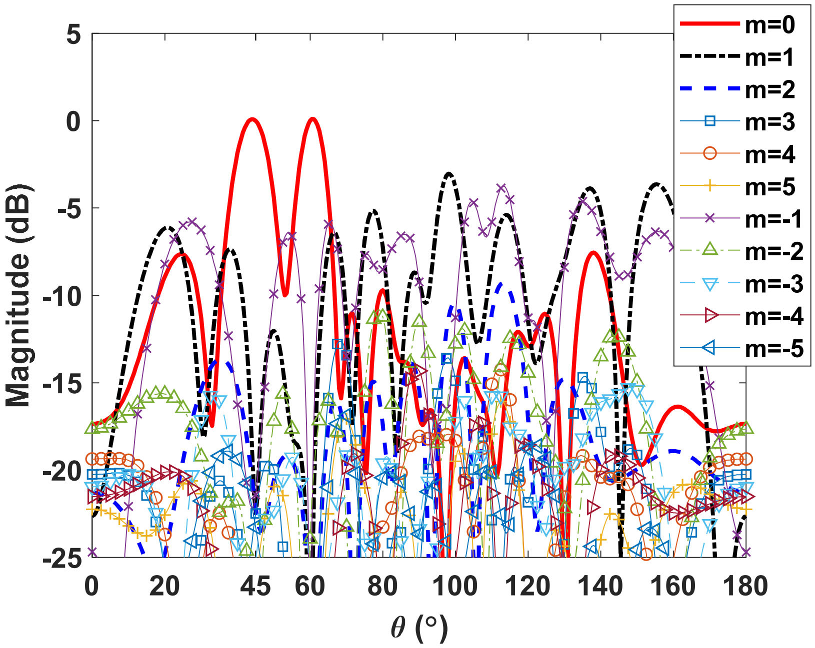

Figure 2. The array radiation patterns optimized from the parameters from Table 1.

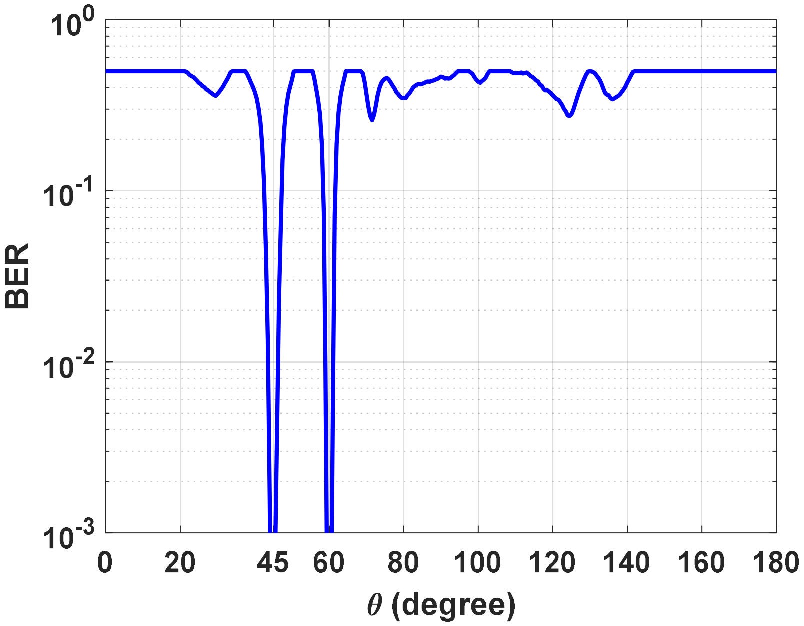

Figure 3. The BER simulation in the spatial domain at an SNR level of 23 dB.

In Figure 3, the BER in the spatial domain is illustrated at the signal-to-noise ratio (SNR) of 23 dB. A significant dip in BER values is discernible strictly in the directions of 45° and 60° , while low sidelobe levels in other directions suggest that the transmitted OFDM symbols are not leaked along other directions. Accordingly, the proposed DM synthesis approach effectively secures communication to multiple targets or users.

4. CONCLUSION

In this paper, we introduced a novel synthesis approach for OFDM-DM beams designed to secure the wireless communication of multiple users. Considering that DM beams serve the purpose of locating radar targets, our synthesized multiple OFDM-DM beams have the capacity to simultaneously establish communication links and track radar targets. This feature holds significant potential for JRC applications involving multiple targets. We will explore the radar performance of the proposed OFDM-DM beams in our future research.

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