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Three-state time-modulated array-enabled directional modulation for secure orthogonal frequency-division multiplexing wireless transmission

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Abstract
Recent works have shown that by using time-modulated arrays (TMAs), directional modulation (DM) physical-layer secured transmitters for orthogonal frequency-division multiplexing (OFDM) wireless data transfer can be constructed. In this paper, three-state TMAs are introduced for OFDM DM systems which allow more flexible manipulation of the injected orthogonal artificial noise and hence improve security. In particular, this paper presents for the first time both static and dynamic three-state time-modulated OFDM DM systems. Simulated bit error rate (BER) spatial distributions are shown for various system configurations in order to illustrate representative examples of secrecy performance enhancement that can be achieved by the proposed transmitter arrangement.

1 | INTRODUCTION

Directional modulation (DM) technology, originally associated with physical-layer secure wireless communications in free space, has been rapidly developing in recent years [1–17]. Unlike the classical cryptographic method, in which the mathematical encryption and decryption are applied at higher protocol layers, in DM systems the digitally encoded information is projected into a pre-specified spatial direction while radiation in all other directions is distorted, thereby gaining fundamental information theoretical security [1, 2]. DM originated from the concept of near-field direct antenna modulation (NFDAM) that was first introduced in [3], wherein the genuine information and the scrambled waveforms were respectively sent along the desired and undesired directions by way of changing the near-field electromagnetic boundary conditions hence its far-field radiation patterns at the transmission symbol rate. This DM method with pattern-reconfigurable array elements was further studied and demonstrated in [4, 5]. On the other hand, DM architectures constructed by reconfiguring array excitations at the radio frequency (RF) frontends were proposed in [6–8], with the DM essence revealed later in [2]. Meanwhile, the orthogonal vector concept was first described, and then employed for DM synthesis to achieve multiple independent secure beam transmissions in [9, 10]. In order to achieve secure wireless communications in practical scenarios, synthesis-free DM architectures which enable the DM functionality by purposely designing the DM transmitter hardware were presented.
The positive properties of the previously reported On-Off time-modulated OFDM DM are well preserved in our scheme. In other words, the proposed OFDM DM systems here enjoy single RF-chain, inverse fast Fourier transform (IFFT) compatibility and are DM synthesis-free [17];

- Unlike earlier schemes the distribution (in spatial domain or in null-space of the legitimate channels) of the orthogonal artificial noise can be fully manipulated;
- Narrower bit error rate (BER) main beam and suppressed BER sidelobes can be achieved in the static OFDM DM system variant through injecting more interference power, which can be further enhanced in the dynamic counterpart.

The paper is organised as follows. In Section 2, the three-state time-modulated OFDM DM transmitter architecture and the associated system assumptions are firstly described, followed by elaboration of its design principle. In Section 3, the BER simulations of the proposed OFDM DM systems are presented and compared with those in the previously reported On-Off time-modulated OFDM DM systems. Finally, Section 4 concludes the paper.

2 | PROPOSED THREE-STATE TIME-MODULATED OFDM DM TRANSMITTER

2.1 | Three-state time-modulated OFDM DM transmitter architecture

The proposed architecture of the three-state time-modulated OFDM DM transmitter is illustrated using a one-dimensional (1D) N-element linear array in Figure 1. Here, a 1-to-N power splitter is used to divide the input standard OFDM signals into N identical copies. Then each signal copy goes through a corresponding phase shifter $\phi_n$ followed by a single-pole triple-throw (SP3T) RF switch, setting its excitation as ‘On’, ‘Off’ and ‘Flipping’, represented as ‘1’, ‘0’ and ‘$-1$’ respectively. It is assumed that the array elements are uniformly spaced, see $d$ in Figure 1, and $d = \lambda_0/2$ where $\lambda_0$ is the wavelength corresponding to the lowest OFDM sub-carrier $f_0$. The active element patterns of each element in the array are assumed to be isotropic and identical in our analysis. The input OFDM signal $S(t)$ here can be written mathematically as

$$S(t) = \frac{1}{\sqrt{K}} \sum_{k=1}^{K} D_k \cdot e^{j2\pi f_0 t} e^{j2\pi (k-1)f_0 t}.$$  

where $D_k$ denotes the complex modulated symbol applied upon the $k$th sub-carrier (out of a total of $K$ subcarriers) and $f_0$ is the sub-carrier frequency spacing. The factor $1/\sqrt{K}$ is included for power normalisation. It is noted that here only one single OFDM symbol transmission period is considered since the
The far-field radiation patterns of the proposed OFDM TMA in free space can thus be expressed as:

\[
E(\theta, \phi) = \frac{1}{\sqrt{N}} \sum_{n=1}^{N} (S(t) \cdot e^{j\phi_n} \cdot U_n(t) \cdot e^{j(\omega_n t + \phi)}) \cos \theta, \quad (2)
\]

where \(\theta\) is the spatial direction, \(\phi \in [0, \pi]\), and \(S(t)\) is the phase delay in the \(n\)th antenna branch used for beam steering, designed as in (3) to steer the main radiation beam along the legitimate user's direction \(\theta_0\). Here, the legitimate user refers to the user/receiver that the transmitter intends to convey the information to. In the DM system context, the legitimate user is the receiver that locates along the desired secure communication direction \(\theta_0\).

\[
\phi_n = -(n-1)\pi \cos \theta_0 \quad (3)
\]

\(U_n(t)\) in (2) refers to the periodic sequence function in the time domain of the \(n\)th SP3T RF switch, see three cases in Figure 2. \(T_p\) is the OFDM symbol period and \(f_p = 1/T_p\). \(U_n(t)\) in one period can be expressed as in (4).

\[
U_n(t) = \begin{cases} 
1 & t_n^1 \leq t \leq t_n^2 \text{ when } t_n^1 > t_n^2, \text{ or } \\
0 & t_n^1 \leq t \leq t_n^0 \text{ and } t_n^0 \leq t \leq T_p \text{ when } t_n^1 < t_n^0 \\
-1 & t_n^2 \leq t \leq t_n^3 \text{ when } t_n^2 > t_n^3, \text{ or } \\
0 & t_n^2 \leq t \leq t_n^1 \text{ and } t_n^1 \leq t \leq T_p \text{ when } t_n^2 < t_n^1 \\
0 & \text{otherwise}
\end{cases} \quad (4)
\]

Here, \((t_n^0, t_n^1)\) and \((t_n^2, t_n^3)\) represent the switch (On, Off) time instants for the positive and negative cycles respectively, as seen in Figure 2, and we define

\[
\Delta t_n^{(1)} = t_n^1 - t_n^0 \text{ when } t_n^1 > t_n^0, \text{ or } \\
\Delta t_n^{(2)} = t_n^2 - t_n^1 \text{ when } t_n^2 > t_n^1, \text{ or } \\
\Delta t_n^{(3)} = t_n^2 + \Delta t_n^{(1)} + \delta \text{ when } t_n^1 < t_n^3, \delta \in [0, T_p) \\
\Delta t_n^{(4)} = t_n^1 + \Delta t_n^{(1)} + \delta - T_p \text{ when } t_n^1 < t_n^3, \delta \in [0, T_p) \quad (5)
\]

### 2.2 Operating principle of the proposed three-state OFDM DM system

Here, the design principle of the proposed OFDM DM is first introduced, then the static and dynamic variants are described. The periodic function \(U_n(t)\) can be represented by the Fourier series as

\[
U_n(t) = \sum_{m=-\infty}^{\infty} C_{mn} e^{j2\pi m n t / T_p} \quad (6)
\]

In (6), \(C_{mn}\) is the \(m\)th Fourier coefficient for the \(n\)th time sequence function, which can be expressed as

\[
C_{mn} = \frac{1}{T_p} \int_{0}^{T_p} U_n(t) e^{-j2\pi m n t / T_p} dt
\]

\[
= \frac{1}{T_p} \left( \int_{t_n^1}^{t_n^2} e^{-j2\pi m n t / T_p} dt - \int_{t_n^3}^{T_p} e^{-j2\pi m n t / T_p} dt \right) \quad \text{when } t_n^2 > t_n^1, t_n^3 > t_n^0
\]

\[
= \frac{1}{T_p} \left( \int_{t_n^1}^{t_n^2} e^{-j2\pi m n t / T_p} dt + \int_{t_n^3}^{t_n^0} e^{-j2\pi m n t / T_p} dt - \int_{t_n^3}^{T_p} e^{-j2\pi m n t / T_p} dt \right) \quad \text{when } t_n^1 < t_n^3, t_n^1 < t_n^0
\]

\[
= \frac{\sin \left( \frac{m\pi f_p \Delta t_n^{(1)}}{m\pi} \right) e^{-j\pi f_p (\Delta t_n^{(1)} + \delta)}}{m\pi} - \frac{\sin \left( \frac{m\pi f_p \Delta t_n^{(2)}}{m\pi} \right) e^{-j\pi f_p (\Delta t_n^{(2)} + \delta)}}{m\pi} \quad (7)
\]
Defining
\[
\begin{aligned}
\mathbf{1} \Delta t_{x} = t_{x}^{(1)} / T_{p} \\
\mathbf{2} \Delta t_{x} = t_{x}^{(2)} / T_{p} \\
\mathbf{3} \mathbf{4} \Delta t_{x} = \Delta t_{x}^{(1)} / T_{p} \Delta t_{x}^{(2)} = \Delta t_{x}^{(2)} / T_{p}
\end{aligned}
\]
(7) can be re-written as
\[
S_{cmn} \begin{cases} 
\sin \left( \frac{m \pi \Delta t_{x}}{m \pi} \right) - \sin \left( \frac{m \pi \Delta t_{x}}{n \pi} \right) e^{-j \pi \left( \Delta t_{x}^{(1)} + \Delta t_{x}^{(2)} + 2p \right)} \\
\sin \left( \frac{m \pi \Delta t_{x}}{m \pi} \right) - \sin \left( \frac{m \pi \Delta t_{x}}{n \pi} \right) e^{-j \pi \left( \Delta t_{x}^{(1)} + \Delta t_{x}^{(2)} + 2p \right)} 
\end{cases}
\]
(9)

Substituting (1), (3), (6) and (9) into (2), we get
\[
E\left( \theta, \tau \right) = \left( \frac{1}{\sqrt{NK}} \right) \sum_{k=1}^{K} D_{k} \cdot e^{j(\tau + (k-1) \tau) / \tau} \cdot V(\mathbf{1}, \mathbf{2}, \mathbf{3}, \mathbf{4})
\]
(10)

In order to secure the pre-selected direction $\theta_{0}$, the following conditions have to be met in order to guarantee the orthogonality in subcarrier domain, that is, $n$, and in spatial domain, that is, $\theta$, between the artificial noise and genuine information $S(\theta)$.
\[
V\left( m = 0, N, \tau_{0}^{(1)}, \Delta t_{x}^{(1)}, \Delta t_{x}^{(2)}, \rho, \tau, \theta = \theta_{0} \right) \neq 0 \quad (11)
\]
\[
V\left( m \neq 0, N, \tau_{0}^{(1)}, \Delta t_{x}^{(1)}, \Delta t_{x}^{(2)}, \rho, \tau, \theta = \theta_{0} \right) = 0. \quad (12)
\]

Considering (11), (12), a practical solution set is shown in (13).
\[
\begin{aligned}
\Delta t_{x} \neq \Delta t_{x}^{(2)} \\
\tau_{0} \in \left\{ \frac{w-1}{N} \mid w = 1, 2, ..., N \right\} \\
\tau_{0} \neq \tau_{0}^{(1)}, \Delta t_{x}^{(1)}, \Delta t_{x}^{(2)} = \Delta t_{x}^{(2)} \text{, when } p \neq q
\end{aligned}
\]
(13)

The first condition in (13) is to guarantee (11) and the remaining two ensure that the condition in (12) is met.

When $\theta \neq \theta_{0}$ the transmitted signal waveforms that fall into the $x$th ($x = 1, 2, ..., K$) OFDM sub-carrier can be expressed as
\[
E_{x}(\theta, \tau) = \left( \frac{1}{\sqrt{NK}} \right) \sum_{k=1}^{K} D_{k} \cdot e^{j(\tau + (k-1) \tau) / \tau} \cdot V\left( m = x - k \cdot N, \tau_{0}^{(1)}, \Delta t_{x}^{(1)}, \Delta t_{x}^{(2)}, \rho, \tau, \theta \right). \quad (14)
\]

The signal waveforms are distorted by the random data $D_{k}$ that are modulated onto all the sub-carriers, that is, $k = 1, 2, ..., K$. These are synthesised artificial noise that is injected in all other directions. While when (13) is satisfied and $\Delta t_{x}^{(1)}, \Delta t_{x}^{(2)}$ are set to be independent of $n$, denoted as $\Delta t_{x}^{(1)}, \Delta t_{x}^{(2)}$, the received OFDM signals along the pre-selected $\theta_{0}$ can be derived as
\[
E\left( \theta_{0}, \tau \right) = \left( \Delta t_{x}^{(1)} - \Delta t_{x}^{(2)} \right) \cdot \sqrt{N} \cdot S(\theta) \quad (15)
\]

From (15), it can be observed that the transmit beamforming gain is determined by $N \cdot \left| \Delta t_{x}^{(1)} - \Delta t_{x}^{(2)} \right|^{2}$, where $\left| \cdot \right|$ denotes the absolute value operator.

Based on the proposed three-state TMA concept, the static and dynamic OFDM DM array syntheses are now described.

- To construct static OFDM DM transmitters, both $\Delta t_{x}^{(1)}$ and $\Delta t_{x}^{(2)}$ are kept constant for each OFDM symbol. The difference between the proposed three-state time-modulated OFDM DM and the previous On–Off counterpart is now highlighted. In the On–Off time-modulated OFDM DM system, when the transmission gain for the legitimate user is defined, that is, proportionate to the duration of the ‘On’ state, the power of the generated artificial noise along
other directions cannot be changed. Whereas in the proposed three-state time-modulated OFDM DM system, the gain for the legitimate user, seen in (15), is governed by \( |\Delta \tau(1) - \Delta \tau(2)|^2 \) and the power of the injected orthogonal artificial noise is determined by \((\Delta \tau(1))^2 + (\Delta \tau(2))^2 - |\Delta \tau(1) - \Delta \tau(2)|^2 = 2(\Delta \tau(1)\Delta \tau(2))(\sigma)^2\). In other words, compared with the previous On–Off system, an extra degree of freedom is available to decouple the power of the genuine information projected along \( \hat{\theta}_0 \) and the artificial noise projected in all other directions.

- Security can be further enhanced by dynamically assigning different \( \Delta \tau(1) \) and \( \Delta \tau(2) \) for each OFDM symbol, subject to keeping \( |\Delta \tau(1) - \Delta \tau(2)| \) as a constant. In such a fashion the distribution of the artificial noise in the spatial domain can be further randomised, resulting in, what is by definition, a dynamic OFDM DM array.
- The properties of the static and dynamic three-state time-modulated OFDM DM transmitters will be discussed using the BER simulation metrics presented in Section 3.

### 3 SIMULATION RESULTS

In order to show the effect that the generated orthogonal (in the spatial domain) artificial noise has on the proposed three-state time-modulated OFDM DM transmitters, comparison examples depicting \( 1/\sqrt{N} \cdot \left| \Gamma (\rho, \theta, \tau, \Delta) \right| \) in dB, denoted as \( \Gamma_{\text{on}} \), are given in Figure 3 for various parameters that satisfy (13). In the examples in Figure 3, it is assumed that the linear transmit array has \( N = 7 \) equally spaced \( (\lambda_0/2) \) elements and the desired communication direction \( \hat{\theta}_0 \) equals \( 60^\circ \) in both the proposed three-state DM systems and the On–Off time-modulated OFDM DM systems [17]. It is noted that \( \hat{\theta}_0 \) is defined as the desired secure transmission direction, which can be selected among all spatial directions from \( 0^\circ \) to \( 180^\circ \). Here we select \( \hat{\theta}_0 = 60^\circ \) only as an example to show the security benefit of our proposed DM system in the paper. In Figure 3, the ‘proposed DM’ refers to the proposed static OFDM DM system with \( \rho = 0 \). Since \( \Gamma_{\text{on}} \) along directions other than \( \hat{\theta}_0 \) is non-zero for any integer \( m \), the received \( x \)th sub-carrier by potential eavesdroppers is a summation of \( K \) terms with each magnitude of \((1/\sqrt{K})D_k \Gamma_{\text{on}} \), subject to \( k + m = x \). Here for better illustration, \( \Gamma_{\text{on}} \) is depicted with \( m = \{-2, -1, 0, 1, 2\} \) for the received third sub-carrier \( (\kappa = 3) \) which is the vector summation of the five terms with magnitudes of \( (1/\sqrt{5})D_1 \Gamma_{\text{on}}, (1/\sqrt{5})D_2 \Gamma_{\text{on}}, (1/\sqrt{5})D_3 \Gamma_{\text{on}}, (1/\sqrt{5})D_4 \Gamma_{\text{on}} \) and \( (1/\sqrt{5})D_5 \Gamma_{\text{on}} \). For fair comparison, the determinants of achievable gain \( |\Delta \tau(1) - \Delta \tau(2)| \cdot \sqrt{N} \) here and \( |\Delta \tau| \cdot \sqrt{N} \) in the On–Off time-modulated OFDM DM systems [17] are set to be identical, that is, \( |\Delta \tau(1) - \Delta \tau(2)| = |\Delta \tau| = 2/7 \). Here \( |\Delta \tau| \) is the normalised ‘On’ period. In the examples in Figure 3a, it can be observed that more artificial noise power can be injected in the proposed static OFDM DM systems, as compared with that in the On–Off time-modulated OFDM DM systems. Meanwhile, the proposed OFDM DM system upon setting \( \Delta \tau(1) = 4/7 \), \( \Delta \tau(2) = 2/7 \) enjoys more injected artificial noise power than the system with setting \( \Delta \tau(1) = 3/7 \), \( \Delta \tau(2) = 1/7 \), as can be observed in Figure 3b. Hence in the proposed static OFDM DM systems, the injected artificial noise can be flexibly manipulated by way of selecting \( \Delta \tau(1) \) and \( \Delta \tau(2) \).

To validate the efficacy of the proposed OFDM DM transmitters, the BER simulation results of the proposed static OFDM DM are depicted and compared with that in the On–Off time-modulated OFDM DM systems (see Figure 4). For comparison purposes, the BER simulation results of the non-DM systems are also shown (the gain along \( \hat{\theta}_0 \) is normalised to be identical). Here, it is assumed that \( K = 64 \) and each OFDM sub-carrier is binary phase shift keying (BPSK) or quadrature phase shift keying (QPSK) modulated. In all the BER simulations in this paper, we first generate a large number of modulated symbols for transmission, saying \( 10^7 \), and free space transmission is assumed. Thus, the symbol streams are added with additive white Gaussian noise (AWGN) at the

![FIGURE 3](https://example.com/figure3.png)
FIGURE 4 Comparison of simulated BER in the proposed static three-state time-modulated OFDM DM arrays, the On–Off counterpart and the non-DM arrays. $E_b/N_0$ along $\theta_0$ of 60° is set to be 35 dB. Here, $N = 7$, $K = 64$, $\rho = 0$ and $G_{\theta_0}$ refers to the achievable gain along direction $\theta_0$. It is assumed that each sub-carrier is (a) BPSK, (b) QPSK and (c) BPSK and QPSK respectively modulated. BER, bit error rate; BPSK, binary phase shift keying; QPSK, quadrature phase shift keying.

FIGURE 5 Comparison of simulated BER spatial distributions in the proposed static three-state time-modulated OFDM DM arrays and the On–Off counterpart both with BPSK-modulated schemes. $E_b/N_0$ along $\theta_0$ of 60° is set to 15 dB.

**CONCLUSION**

In this paper, we propose the three-state TMA as a route to the construction of static and dynamic OFDM DM transmitters. With the advantage that by switching ‘On’ and ‘Flipping’ time period parameters the designer can flexibly decouple the power associated with genuine information being transmitted and the other benchmark systems. Thus, it will not change the security performance comparison and the conclusion of this paper. In each BER simulation, a known preamble (or pilot sequence) is appended, which is correlated at the receiver end for synchronisation. After the synchronisation, the minimum Euclidean distance to ideal constellation symbols in the IQ space is used as demodulation criteria. This Monte Carlo simulation is used throughout in the paper for BER analysis. In Figures 4a and 4b, it can be observed that the information can be securely conveyed only along the spatial direction around 60°, and the proposed three-state OFDM DM systems can achieve narrower BER main beam and suppressed BER sidelobes compared with the On–Off time-modulated OFDM DM systems. In contrast, the confidential information is vulnerable to interception in non-DM systems (see Figure 4c). In Figure 5, the compared BER results of On–Off TMA and three-state TMA BPSK modulated DM schemes are depicted at $E_b/N_0$ of 15 dB. It can be observed that lower BER sidelobes can be achieved for both On–Off and three-state TMA DM schemes at level of 15 dB. Along the spatial direction around 60°, the proposed three-state OFDM DM systems can still achieve narrower BER main beam compared with its counterparts.

In addition, the results show that the dynamic three-state time-modulated OFDM DM system is able to further narrow BER main beam and suppress sidelobes especially at high $E_b/N_0$ (along $\theta_0$) scenarios, that is, see the BER simulations in Figure 6 where $E_b/N_0$ is increased to 50 dB.
power of injected orthogonal artificial noise. This enables narrowing of the BER main beam and suppression of BER sidelobe levels while keeping the gain for legitimate users constant. It is noted that adding more states does not necessarily contribute to better OFDM-DM systems. Some aspects should be carefully analysed before reaching a conclusion. For example, more states usually associated with higher insertion loss, which will negatively contribute to the system performance. And more states inevitably provide the system more design flexibility but, in the meantime, they increase the design complexity. Those trade-offs are interesting topics for future research.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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