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Time-modulated OFDM Directional Modulation Transmitters
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Abstract—In this paper directional modulation (DM) transmitters, designed for orthogonal frequency-division multiplexing (OFDM) wireless data transfer are proposed using time-modulated arrays (TMAs). It is shown that by properly designing the switch controlling time sequences the proposed time-modulated OFDM DM systems exhibit promising features, such as (i) requires only one radio frequency (RF) chain, (ii) the conventional efficient OFDM signal construction approach, i.e., by using inverse fast Fourier transform (IFFT) modules, can be adopted, (iii) it is ‘DM synthesis-free’, meaning that there is no need to re-synthesize the array excitation vectors for different secure communication directions, different modulation schemes, and different DM power efficiencies; and (iv) the trade-off between secrecy performance and power efficiency can be flexibly adjusted.

Index Terms—Directional Modulation (DM), orthogonal frequency-division multiplexing (OFDM), physical-layer wireless security, time-modulated array (TMA)

I. INTRODUCTION

Directional Modulation (DM), as a promising physical-layer secure wireless communication technique, has been rapidly developed in recent years [1]–[5]. It has the key property of transmitting digitally modulated signals whose waveforms are well preserved only along a pre-selected direction along which legitimate users locate in free space. Its evolution began with a type of architectures consisting of re-configurable, operating at the transmitted symbol rates, radio frequency (RF) components, [1], [2], [6], which have the ability of changing far-field radiation patterns, resulting in signal waveform distortions in unwanted directions. Later, digital baseband DM solutions were proposed, [3], [4], [7], which facilitate the synthesis of the DM transmitter array excitation vectors. More recent efforts were directed at practical field applications. This resulted in ‘synthesis-free’ DM architectures, such as Fourier beamforming network enabled DM [8], antenna subset modulation arrays [9], [10], retrodirective DM arrays [5], and mode-pattern circular DM arrays [11]. Here the term ‘synthesis-free’ refers to the fact that no calculation of the DM array excitation vectors is required, as the DM functionality is directly enabled through carefully constructed DM transmitter hardware.

It needs to be pointed out that most of the previous DM works only consider single carrier signals. Since multi-carrier modulation schemes, like orthogonal frequency-division multiplexing (OFDM), have been widely adopted in the modern wireless communication systems, such as IEEE 802.11 and LTE, it is worth investigating the multi-carrier DM systems, incidentally mentioned as the future work in the review paper [12].

One approach to extending the single-carrier DM to multi-carrier DM is to synthesize multiple single-carrier DM transmitters and vectorially combine the resultant array excitations that can then be used for multi-carrier DM. In this category, a special arrangement of applying the frequency diverse array (FDA) concept onto the DM was first introduced in [13]. However, this strategy is associated with a number of issues, namely: (i) it requires multiple RF chains, the number of which equals the number of array antenna elements. This multi-RF-chain structure is not preferred as it significantly increases the system complexity and cost, especially when higher operation frequencies are used; (ii) as the synthesized DM excitation signals at each antenna port are not OFDM signals, they cannot be efficiently constructed using IFFT modules; and (iii) the synthesis process needs to be re-run when the number of signal carriers, the modulation types, and the desired secure communication directions change, i.e., the approach is not ‘synthesis-free’.

Different to the afore-mentioned approach, in this paper, we exploit the unique property of time-modulated arrays (TMAs) to construct OFDM DM transmitters, which overcome the problems associated with the method presented earlier.

TMA is a technique wherein by introducing a fourth dimension, time, as an additional degree of freedom for the array design, i.e., connecting and disconnecting the antenna elements from the feeding network in time domain, the radiation pattern can be further manipulated [14]. The approach has been primarily exploited for array radiation pattern synthesis with suppressed sidelobes by shifting the signal energy projected along sidelobe directions out of the system operating frequency bands [15], [16]. Until recently, this ability of shifting the frequency of radiated signals has been found useful for a number of applications, such as direction finding [17] and space division multiple access [18]. In this paper we use this spatial frequency expansion characteristic of the TMA to secure broadcasted OFDM signals by enabling DM functionality, i.e., constructing OFDM DM transmitters. To achieve the DM functionality, namely preserving OFDM signal waveforms along selected spatial directions while distorting them in all other directions, which is equivalent to enabling the orthogonality between the information signals and the artificial interference, not only in spatial domain but also in frequency domain, the switching waveforms controlling the connection and disconnection of the array elements have to be carefully designed.

The contributions of the research presented in this paper are summarized as follows;

• The architecture of an OFDM DM transmitter, constructed using TMAs, is presented. It features single RF-chain, IFFT compatible, DM ‘synthesis-free’, and adaptable performance, which have never been studied in previous reported works;
• The required time-domain switch functions are analytically derived and validated through simulations;
• The tradeoff between array energy efficiency and secrecy performance is revealed and quantitatively investigated.

Readers who are following DM developments may be aware of a number of recent DM works, which claim that the FDA concept (and its variants such as non-linear frequency increments and random subcarrier selections) can be incorporated into DM transmitters, achieving free-space wireless security in range-domain, e.g. the random-subcarrier-selection-based OFDM DM transmitters in [19] and some of the references therein. However, in those works one important factor was overlooked, which is that ‘FDA range-angle dependent beamforming patterns are also functions of time’. This
means that the secure reception regions (normally defined as the locations where the reception bit error rates (BERs) are below a specified threshold), erroneously claimed in those works as being fixed in angle and range domains, propagate in range as time elapses. For example take the scheme in [19] as an example, here the authors formulated the received signals acquired by the legitimate and eavesdropper receivers in (11) and (12), respectively, in [19]. It can be observed that the authors assumed that two receivers sample the signals at the same time instant, i.e., using the same viable ‘τ’ for both receivers. This leads, as shown through simulation results, to the pencil peak of signal to interference and noise ratio (SINR) in 2-D angle-range domain. However as the authors here pointed out that the FDA radiation patterns are also time variant, meaning that the legitimate and eavesdropper receivers do not necessarily sample signals at the same time instant. In fact, in (12) when \( \theta_k = \theta_d \), i.e., along the same spatial direction, if the eavesdropper receiver delays (or advances) signal samplings by \( (R_e - R_0)/c \) when \( R_e > R_0 \), or \( (R_0 - R_e)/c \), when \( R_e = R_0 \), (12) becomes (11). Here ‘c’ refers to the speed of light. This clearly indicates that the secure reception region propagates in range as time elapses. This suggests that it is impossible for any FDA enhanced DM systems to achieve free space wireless security in range domain.

It is noted in this paper that for any free space DM transmissions, the knowledge of directions of legitimate receivers needs to be acquired by the DM transmitter in advance before initiating secure transmissions. This information can be obtained by using direction of arrival (DOA) algorithms [20], or by using analogue retrodirective technologies as in [5]. This aspect is beyond the scope of this paper, thus, it will not be discussed further.

This paper is organized as follows, in Section II the architecture of the proposed time-modulated OFDM DM transmitter is presented, and the design principle is investigated. Simulation results, validating the trade-offs between the energy efficiency and secrecy performance, are provided in Section III. Finally, conclusions are drawn in Section IV.

II. PROPOSED TIME-MODULATED OFDM DM TRANSMITTER

The architecture of the proposed time-modulated OFDM DM transmitter is illustrated in Fig. 1. Apart from the input signal being OFDM modulated, it is a standard TMA system consisting of an N-element linear antenna array. It is assumed that all the antenna elements have identical isotropic active element patterns, and they are uniformly half-wavelength (\( \lambda_0/2 \)) spaced. Here wavelength \( \lambda_0 \) is associated with the frequency of the first OFDM sub-carrier \( f_0 \). The OFDM signals can be constructed using conventional IFFT modules in digital baseband, and up-converted using a single RF chain. The signals are then split into \( N \) copies with identical power. It is explained here that all OFDM subcarriers are power divided together, meaning that the power of each subcarrier in each antenna branch \( n \) is always identical, i.e. no power allocation among subcarriers. The power dividing ratio for each antenna branch, however, can be non-uniform, e.g. tapered array excitation magnitude for radiation sidelobe controls.

Before being fed into their respective antenna elements, each OFDM signal copy is phase delayed and then ‘on-off’ manipulated in time domain by an RF single-pole-single-throw switch. Phase shifters steer the desired free space communication direction as in the classical phased beam-steering arrays. In order to enable the DM functionality for the OFDM signal transmission, the ‘on-off’ switching functions for each antenna branch need to be carefully selected. The method for doing this is now mathematically elaborated.

An OFDM signal can be written as

\[
S(l,t) = \frac{1}{\sqrt{K}} \sum_{k=1}^{K} D_k \cdot e^{j2\pi [f_k t + (l-1) f_c]} ,
\]

where \( K \) is the total number of the OFDM sub-carriers, and the frequency spacing between consecutive sub-carriers is denoted as \( f_s \). \( D_k \), normalized to be unit power, refers to the \( k \)-th complex modulated symbol applied upon the \( k \)-th sub-carrier. Unless otherwise specified, subscript ‘l’ is dropped hereafter in this paper, as in most cases we only consider one transmission OFDM symbol period, and the following analysis is independent to the symbol transmitted. Thus, \( D_k \) is a constant with respect to time, though being randomly selected from the adopted digital modulation constellation sets. Due to the same reason, \( S(l,t) \) is referred to as \( S(t) \) hereafter. The coefficient \( l/\sqrt{K} \) is added in (1) for power normalization.

After being processed with the phased TMA shown in Fig. 1, the OFMA signal radiated into the half-space, \( \theta \epsilon [0, \pi] \), can be expressed as

\[
R(\theta, t) = \sum_{n=1}^{N} \left( \frac{1}{\sqrt{N}} \sum_{k=1}^{K} S(t) \cdot e^{j\phi_n} \cdot U_n(t) \cdot e^{j(f_s t - n\lambda_0 \cos \theta)} \right).
\]

Here \( \phi_n \) is the phase delay in the \( n \)-th antenna branch, seen in Fig. 1. When the desired secure communication direction in free space is \( \theta_l \), the value \( \phi_n \) is set to be that in (3), the same as that in classical phased beam-steering arrays.

\[
\phi_n = -(n-1)\lambda_0 \cos \theta_l
\]

It is noted here that when a multipath channel is considered, the term \( e^{j(f_s t - n\lambda_0 \cos \theta)} \) in (2) should be replaced with the channel coefficient between the \( n \)-th transmit element and any observation point in the radiation field. While the \( \phi_n \) in (3) is set to the value that cancels out the phase of the channel between the \( n \)-th element and the legitimate receiver. The following analyses are thus applicable to multipath propagation scenarios.

\[ U_n(t) \] in (2) is a square waveform, controlling the ‘on-off’ of the \( n \)-th RF switch in time-domain, see the illustrations in Fig. 2. \( U_n(t) \) of 1 (or 0) represents on/close (or off/open) of the RF switch. \( T_s \) denotes the repetition time period of the waveform, and it is set to be \( 1/f_s \), identical for all switches in the \( N \) branches. For the \( n \)-th switch, \( t_n^0 \) and \( t_n^f \) refer to the ‘turn-on’ and ‘turn-off’ time instants, respectively. The ‘on’ time period is denoted as \( \Delta t_n \). For the examples in Fig. 2, \( \Delta t_n = t_n^f - t_n^0 \)

Fig. 1. Architecture of the proposed time-modulated OFDM DM transmitter.
when \( t'_n > t'_o \), or \( \Delta t_n = T_p + t'_o - t'_n \) when \( t'_o < t'_n \).

\( U_n(t) \) can be expanded in the form of Fourier series, as

\[
U_n(t) = \sum_{m=-\infty}^{\infty} c_{mn} e^{j2\pi n f_j t},
\]

where

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

In order for this to happen, comparing (1) and (6), the following conditions have to be met,

\[
\begin{align*}
\left\{ V\left(m \neq 0, N, t'_n, \Delta t_n, t, \theta = \theta_0\right) = 0 \right. \\
\left\{ V\left(m = 0, N, t'_n, \Delta t_n, t, \theta = \theta_0\right) \neq 0 \right.
\end{align*}
\]

Let us consider (7) first, which can be written as

\[
\sum_{n=1}^{N} \left| \Delta t_n \cdot \text{sinc}(m \pi \Delta t_n) \cdot e^{-j m \pi (2\pi t'_n + \Delta t_n)} \right| = 0 \quad (m \in \mathbb{Z}, m \neq 0).
\]

There exist infinite solutions to (9). As \( \Delta t_n \) determines how much energy is preserved in the fundamental frequency component radiated by the \( n^{th} \) element in the TMA, seen in (5) when \( m \) is set to 0, we choose to make \( \Delta t_n \) identical for each \( n \), so that the energy efficiency of the entire TMA can be uniquely tuned by setting different \( \Delta t \). This facilitates the illustrations of the tradeoff between array energy efficiency and secrecy performance, which will be studied in Section III. This choice results in the solution sets shown in (10).

\[
\begin{align*}
\left\{ \tau'_n, \Delta t_n \in \left\{ \frac{w-1}{N} \right\} \quad w = 1, 2, \ldots, N \right. \\
\left\{ \tau'_p \neq \tau'_q, \Delta t_p = \Delta t_q \quad \text{when} \quad p \neq q \right.
\end{align*}
\]

The condition in (8) can be simplified as

\[
\sum_{n=1}^{N} \Delta t_n \neq 0.
\]

Since \( \Delta t_n \in (0, 1] \), (11), and hence (8), are always satisfied.

When setting \( \Delta t_n \) and \( \tau'_n \) according to (10), and denoting the identical \( \Delta t_n \) with respect to different \( n \), as \( \Delta t \), the received OFDM signal along \( \theta_0 \) becomes

\[
R(\theta_0, t) = \Delta t \cdot \sqrt{\frac{N}{K}} \cdot \sum_{k=1}^{K} D_k \cdot e^{j2\pi f_j (k-1)/f_p} \cdot V(m-k, N, \tau'_n, \Delta t_n, t, \theta_0). \quad (12)
\]

From (12) it can be observed that the normalized switch ‘on’ time period \( \Delta t \) determines the proportion of the transmit beamforming gain, i.e., \( \sqrt{N} \), that can be preserved. For extreme cases, when \( \Delta t \to 0 \), no gain is available as the transmitter is essentially shut down; and when \( \Delta t \to 1 \), a power gain of \( 10\log_{10}(N) \), in \( dB \), is enabled as the TMA operates identically as a classical phased beam-steering array.

- Distortion of the transmitted signal waveform along the spatial directions other than \( \theta_0 \).

When \( \theta \neq \theta_0 \), the received \( x^{th} (x = 1, 2, \ldots, K) \) sub-carrier is

\[
R_x(\theta, t) = \sum_{k=1}^{K} \left\{ \frac{1}{\sqrt{NK}} \cdot D_k \cdot e^{j2\pi f_j (k-1)/f_p} \cdot V(m-k, N, \tau'_n, \Delta t_n, t, \theta) \right\},
\]

Fig. 2. Illustrations of the switch controlling waveform \( U_n(t) \).
which, obviously, is corrupted by the random data that are
modulated onto all the sub-carriers, and the randomly selected
Δτ_{s} and τ_{r}, when (10) is satisfied.

To sum up, the constraints in (10) are the sufficient conditions
to construct a time-modulated OFDM DM transmitter.

III. SIMULATION RESULTS

In order to facilitate the understanding of the operation principle of
the proposed time-modulated OFDM DM transmitters, examples
showing \( \sqrt{1/N} \cdot \left[ y \left( m,N,\tau_{s},\Delta \tau,t,\theta \right) \right] \) in dB, denoted as \( \Gamma_{m} \), are plotted
in Fig. 3 for various parameters that satisfy (10). Operator \(|\cdot|\) returns
the absolute value of the enclosed complex number. It can be seen
from (1) and (6) that this term is the magnitude weighting coefficient
along spatial direction \( \theta \) applied upon the \( k \)th sub-carrier of
the transmitted OFDM signal, while transforming this \( k \)th sub-carrier to
the \( (m+k) \)th sub-carrier at the receiver end. In the examples in Fig. 3,
we assume that the desired communication direction \( \theta_{0} \) equals 60°, and
the linear transmit array has 7 elements, i.e., \( N = 7 \). It can be seen that
along \( \theta_{0} \) the OFDM signals, including all \( K \) sub-carriers, are only
radiated through \( \Gamma_{0} \), satisfying (7) and (8). This means the OFDM
wavesforms are well preserved, subject only to magnitude scaling. As
predicted by (12), \( \Delta \tau \cdot \sqrt{N} \) determines the achievable gain, resulting in
\( (2/7) \times \sqrt{7} < 1 \) (lower than 0 dB) and \( (4/7) \times \sqrt{7} > 1 \) (higher than 0 dB), see Fig. 3. Whereas along any other directions, the received \( \tau_{d} \)th sub-carrier (\( x = 3 \)), for example, is the vectoral summation of 5 terms with magnitudes of
\( |1/\sqrt{5}|\cdot D_{1}\Gamma_{s}, \; |1/\sqrt{5}|\cdot D_{1}\Gamma_{r}, \; |1/\sqrt{5}|\cdot D_{r}\Gamma_{r}, \; |1/\sqrt{5}|\cdot D_{r}\Gamma_{r}, \) and \( |1/\sqrt{5}|\cdot D_{2}\Gamma_{r} \). In fact, \( \Gamma_{m} \) exists for any integer \( m \).

Thus, in general case, the received \( x \)th sub-carrier along directions
other than \( \theta_{0} \) is the summation of \( K \) terms with each magnitude of
\( |1/\sqrt{K}|\cdot D_{j}\Gamma_{r}, \) subject to \( k + m = x \). In addition, even for the same \( m \) and \( \Delta \tau \), different choices of \( \tau_{s} \) result in different \( \Gamma_{m} \), enabling
the construction of dynamic DM [21], i.e., dynamically updating orthogonal interference at symbol rates, see the examples of case1 and
case2 (shown in legend) in Fig. 3.

![Fig. 3. Illustrations of the example \( \Gamma_{m} \) for various parameters that satisfy (10).](image)

In Fig. 4 and Fig. 5, BER simulations across the half space, i.e., \( \theta \in [0, \pi] \), are simulated for two different energy per bit to noise power
spectral density ratios (E_b/N_0) for the proposed time-modulated
OFDM DM systems. Here E_b/N_0 is measured along the desired secure
communication direction \( \theta_{0} \) of 60°, and the noise power is assumed
identical along every direction. Two choices of E_b/N_0 are equivalent
to different distances between transmitter and receivers that include
the legitimate one along \( \theta_{0} \) and potential eavesdroppers along all other
directions. In the examples, it is assumed that \( N = 7, \; K = 64 \), and
the OFDM sub-carriers are QPSK modulated. It should be pointed out that
the proposed time-modulated OFDM DM system works for any
modulation types, as, seen in (6), the generated orthogonal (in both
spatial and frequency domains) artificial noise function \( \nu \) is
independent to the input data \( D_i \). Due to page limits, only the QPSK
modulation case is simulated and presented. The same conclusions
can be reached for any other types of modulations. The case of \( '\Delta \tau = 1' \), as we discussed in the last section, refers to the corresponding
conventional beam-steering array. The power efficiency of DM
systems P_{E\text{DM}}, [3], [21], defined as the percentage of total radiated
energy that is used to transfer useful information, can be calculated as
\( P_{E\text{DM}} = \Delta \tau \times 100\% \). In Fig. 4, it can be observed that the signals are
not corrupted along 60°, i.e., the BERs achieved at this direction are
nearly identical, around 2×10^{-4}, in both DM systems and the
conventional beam-steering system. Since the BER main beam is
already narrow and its sidelobes are already high for the low E_b/N_0 = 8 dB case in Fig. 4, we increase the E_b/N_0 to 23 dB in Fig. 5, meaning
the potential eavesdroppers are located much closer to the transmitter.
This is done in order to demonstrate the secrecy enhancement that the DM
functionality can bring. It can be clearly observed that the proposed
time-modulated OFDM DM systems can help narrow the BER
main beam and suppress BER sidelobes, reducing the possibility
of information interception. This enhanced secrecy performance is
achieved at the cost of low power efficiency, because some energy is
consumed in the process of radiating orthogonal interference, both in
the spatial domain and in the frequency domain.

IV. CONCLUSION

An OFDM DM transmitter was developed by exploiting the spectral
expansion property of the TMA. By properly designing the time
switching waveforms orthogonality between the OFDM signals to be
transmitted and the dynamic artificial interference, in both spatial
domain and frequency domain, can be achieved. The conditions
necessary for constructing the proposed time-modulated OFDM DM
transmitters have been derived, and validated through radiation
patterns and BER simulations. Furthermore, the trade-off between the
enhanced system secrecy performance and power efficiency has been
revealed.

![Fig. 4. Simulated BERs of the time-modulated OFDM arrays for various \( \Delta \) when E_b/N_0 along \( \theta_0 \) of 60° equals 8 dB. '\Delta \tau = 1' refers to the conventional beam-steering array. It is assumed that each sub-carrier is QPSK modulated and N = 7, K = 64.](image)
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Fig. 5. Simulated BERs of the time-modulated OFDM arrays for various $\Delta \tau$ when $E_b/N_0$ along $\theta_0$ of 60° equals 23 dB. $\Delta r = 1'$ refers to the conventional beam-steering array. It is assumed that each sub-carrier is QPSK modulated and $N = 7$, $K = 64$.

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