How Secure Is the Time-Modulated Array-Enabled OFDM Directional Modulation?

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Work supported by ARO grant W911NF2320103 and NSF grants ECCS-2033433, ECCS-2320568

ICASSP 2024 KOREA

Outline

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Introduction

- Physical Layer Security (PLS) can ensure wireless communication security when cryptographic methods fail to provide low latency and scalability.

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- Directional modulation (DM) is a PLS approach, that modulates the antenna transmissions so that the communication information is distorted in all directions except in the directions of the legitimate receivers[1].
- Thus, DM makes it difficult for an eavesdropper who is located in a different direction than the legitimate users to intercept the communication signals it receives.

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- Thus, DM makes it difficult for an eavesdropper who is located in a different direction than the legitimate users to intercept the communication signals it receives.
- DM can be achieved by appropriately designing the antenna weights, or via symbol level precoding, that creates interference between the transmitted data symbols.

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Time-Modulated Arrays (TMA)

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- TMA is a hardware-based approach and does not require location info on the eavesdroppers or the complex design on the transmitted signals. Its drawback is reduced energy efficiency.

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[3] Shan et al. 2018; Huang et al. 2022.

Our Contribution

- Previous studies on the TMA DM technique have mainly focused on hardware implementation, energy efficiency improvement, ON-OFF pattern design, and applications, but have not looked into how secure the TMA DM system is.[4]
- In this paper, we investigate the level of security provided by the TMA achieved scrambling.

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- We show for the first time that
  - Unless certain action is taken, the TMA OFDM system is actually not secure enough.
  - An eavesdropper could use an Independent Component Analysis (ICA)-based approach and exploit prior knowledge of TMA to defy the TMA scrambling.

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- We also propose a novel TMA implementation mechanism to make the eavesdropper's job harder.

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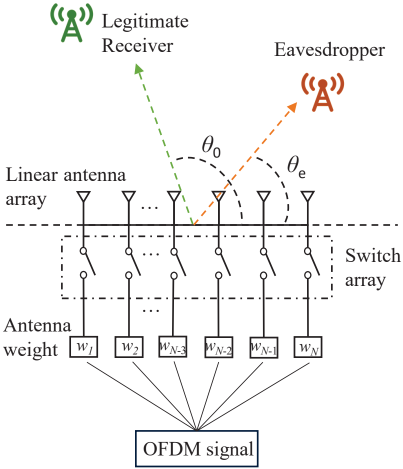
- Consider a TMA using a uniform linear array with N elements.
- The array transmits an OFDM waveform with K subcarriers spaced by f_s.



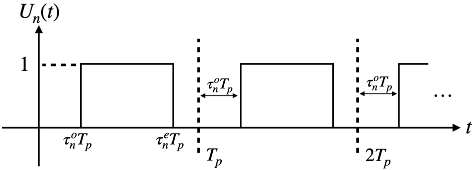
System Model

- Let s_k be the digitally modulated data symbol assigned to the k-th subcarrier. The OFDM symbol equals

$$x(t) = \frac{1}{\sqrt{K}} \sum_{l=1}^{K} s_k e^{j2\pi[f_0+(l-1)f_s]t}. \quad (1)$$

- The OFDM symbol radiated towards direction $\theta \in [0, \pi]$ can be expressed as

$$y(t,\theta) = \frac{1}{\sqrt{N}} \sum_{n=1}^{N} x(t) w_n U_n(t) e^{j(n-1)\pi\cos\theta}, \quad (2)$$



- We set $w_n = e^{-j(n-1)\pi\cos\theta_0}$ to focus the beam towards θ_0.

System Model

- Let the normalized switch ON time instant and the normalized ON time duration be denoted by τ_n^o and $\Delta\tau_n$, respectively, we can expand $U_n(t)$ in the form of Fourier series as

$$U_n(t) = \sum_{-\infty}^{\infty} a_{mn} e^{j2m\pi f_s t}, \tag{3}$$

where

$$a_{mn} = \Delta\tau_n \operatorname{sinc}(m\pi\Delta\tau_n) e^{-jm\pi(2\tau_n^o + \Delta\tau_n)}. \tag{4}$$

- By combining the above equations, we rewrite $y(t,\theta)$ as

$$y(t,\theta) = \frac{1}{\sqrt{NK}} \sum_{l=1}^{K} s_k e^{j2\pi[f_0+(l-1)f_s]t} \sum_{m=-\infty}^{\infty} e^{j2m\pi f_s t} V_m, \tag{5}$$

where

$$V_m = \sum_{n=1}^{N} a_{mn} e^{j(n-1)\pi(\cos\theta - \cos\theta_0)}. \tag{6}$$

- In order to implement DM functionality, τ_n^o and $\Delta\tau_n$ are chosen to satisfy

$$V_{m\neq 0}(\tau_n^o, \Delta\tau_n, \theta = \theta_0) = 0,$$
$$V_{m=0}(\tau_n^o, \Delta\tau_n, \theta = \theta_0) \neq 0. \quad (7)$$

- This can be achieved by the following three conditions:
  - (C1) $\Delta\tau_n, \tau_n^o \in \{\frac{h-1}{N}\}_{h=1,2,\ldots,N}$ (note that the subscript n is not necessarily equal to h)
  - (C2) $\tau_p^o \neq \tau_q^o, \Delta\tau_p = \Delta\tau_q = \Delta\tau$ for $p \neq q$
  - (C3) $\sum_{n=1}^{N} \Delta\tau_n \neq 0$

- For simplicity, we skip noise and assume that same power is assigned to each antenna in each subcarrier.

Outline

The Proposed Formulation at the Eavesdropper

- After OFDM demodulation, the received data symbol on the i-th subcarrier can be expressed as $y_i(\theta) = 1/\sqrt{NK}\sum_{l=1}^{K} s_k V_{i-l}$.

- Based on the signals received on all subcarriers, $\boldsymbol{y}$, the eavesdropper can formulate the problem

$$\boldsymbol{y} = \boldsymbol{V}\boldsymbol{s}, \tag{8}$$

where $\boldsymbol{V} \in \mathbb{C}^{K\times K}$ is a Toeplitz matrix as follows

$$\boldsymbol{V} = \frac{1}{\sqrt{NK}} \begin{bmatrix} V_0 & V_{-1} & \cdots & V_{-(K-2)} & V_{-(K-1)} \\ V_1 & V_0 & \cdots & V_{-(K-3)} & V_{-(K-2)} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ V_{K-2} & V_{K-3} & \cdots & V_0 & V_{-1} \\ V_{K-1} & V_{K-2} & \cdots & V_1 & V_0 \end{bmatrix}, \tag{9}$$

and $\boldsymbol{s} = [s_1, s_2, \cdots, s_K]^T$.

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- In $\boldsymbol{y} = \boldsymbol{V}\boldsymbol{s}$, the elements of $\boldsymbol{s}$ are statistically independent and non-Gaussian. Although $\boldsymbol{V}$ is unknown to the eavesdropper, $\boldsymbol{s}$ can be estimated from $\boldsymbol{y}$ with **ambiguities** via an ICA approach.

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- ICA tries to find $\boldsymbol{W}$ such that $\boldsymbol{W}\boldsymbol{y}$ is maximally non-Gaussian.
- In this work, we adopt negentropy to measure non-Gaussianity and implement FastICA[5] to find $\boldsymbol{W}$.

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Addressing Scaling and Permutation Ambiguities in $\boldsymbol{W}$

- The inverse of $\boldsymbol{W}$, produced by ICA, may not be equal to the actual mixing matrix, $\boldsymbol{V}$, since there exist scaling and permutation ambiguities in $\boldsymbol{W}$. Those ambiguities would prevent the correct recovery of source symbols.

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- **Assumptions:** The eavesdropper knows
  - The OFDM specifics of the transmitted signals, e.g., the number of subcarriers, K, and spacing f_s
  - The data modulation scheme
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- The scaling ambiguity can be divided into amplitude and phase ambiguity. Knowledge of the transmit constellation can be used to resolve the amplitude scaling ambiguity.

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- We reorder $\boldsymbol{F}$, checking whether the reordering creates a Toeplitz matrix.
  - There are $K!$ possible orderings
  - Considering the fact that the main diagonal elements can determine the Toeplitz structure of $\boldsymbol{F}$, we focus on the main diagonal elements
  - We use standard deviation, σ, to measure the similarity of the main diagonal elements

Resolving the Permutation Ambiguity

Algorithm 1 Reordering Algorithm

1: Calculate the amplitude of each elements in $\boldsymbol{F}$ and get a new matrix $\boldsymbol{Q}$, the ith column of which is denoted by $\boldsymbol{q}_i$;
2: **for each** $i = 1, 2, ..., K$ **do**
3: Take $\boldsymbol{q}_i(1)$ as the first diagonal element in the first row of $\boldsymbol{Q}$;
4: Find the closest elements to $\boldsymbol{q}_i(1)$ in the remaining rows of $\boldsymbol{Q}$ and put them in the corresponding diagonal placements;
5: Obtain a diagonal vector $\boldsymbol{d}$ after step 4 and normalize it by $\boldsymbol{d}/\|\boldsymbol{d}\|$;
6: Compute the standard deviation σ_i of normalized $\boldsymbol{d}$;
7: **end for**
8: Let $\boldsymbol{\sigma} = [\sigma_1, ..., \sigma_K]$ and find the index of the minimum element in $\boldsymbol{\sigma}$ as I;
9: Let $i = I$ and execute steps 3 and 4, we can obtain a reordered $\boldsymbol{Q}$ and accordingly reordered $\boldsymbol{F}$.

- The complexity of the process is $O(K^3)$.

Resolving the Scaling Phase Ambiguity

- Regarding the **phase scaling ambiguity**, we exploit the knowledge of the Toeplitz structure first.
  - For M-PSK modulation, there will be M^K phase possibilities for $\boldsymbol{F}$
  - The Toeplitz constraint can reduce it to M since the phases of diagonal elements of $\boldsymbol{F}$ must be the same, and each source signal can have up to M phase transformations. Denote these possibilities as $\boldsymbol{F}_1, \boldsymbol{F}_2, ..., \boldsymbol{F}_M$.

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- Let $\phi = \cos\theta_e - \cos\theta_0$. It holds that

$$V_0 = \Delta\tau \sum_{n=1}^{N} e^{j(n-1)\pi\phi} = \Delta\tau \frac{\sin(\frac{N}{2}\pi\phi)}{\sin(\frac{1}{2}\pi\phi)} e^{j\frac{(N-1)}{2}\pi\phi}. \tag{10}$$

- Then we obtain

$$\gamma \triangleq \frac{Re(V_0)}{Im(V_0)} = \frac{1}{\tan \frac{N-1}{2}\pi\phi} = \frac{Re(\mathbf{V}(1,1))}{Im(\mathbf{V}(1,1))}, \tag{11}$$

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- To resolve the remaining phase ambiguity, we check whether there exist solutions of N, $\Delta\tau$, $\{\tau_n^o\}_{n=1,2,\ldots,N}$ according with (C1)-(C3) and φ that correspond to exactly one of the elements in $\{\boldsymbol{F}_u\}_{u=1,2,\ldots,M}$.

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- The steps of resolving the phase ambiguity are exhibited in the following algorithm.

Resolving the Scaling Phase Ambiguity

Algorithm 2 Phase Ambiguity Resolving Algorithm

```
Obtain {F_u}_{u=1,2,...,M} according to the transmission constellation and the Toeplitz structure;
Calculate the ratio of the real part and the imaginary part of each F_u, denoted as {λ_u}_{u=1,2,...,M}, respectively;
for each λ_u do
    Compute N_u and Δτ_u according to (6) and λ = 1/tan((N−1)/2 πφ);
    Check if N_u ∈ G_N and if Δτ_u ∈ [0,1]: if both are yes, keep this group of solutions; otherwise, discard them;
end for
if Only one group of N_u and Δτ_u found then
    Return F_u corresponding to this group of solutions;
else
    for each group of N_u and Δτ_u do
        Check if {τ_n^o}_{n=1,2,...,N} can be found by (C1)-(C3) and (5): if yes, keep this group of solutions and return the corresponding F_u; otherwise, discard them.
    end for
end if
```

Defending the TMA Scrambling

- Since the above ICA can work only in stationary environments and necessitates long data for estimating the required higher-order statistics, we can disturb the applicability of ICA by changing the mixing matrix of TMA over time.

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- This can be done by selecting randomly $\{\tau_n^o\}_{n=1,2,\ldots,N}$ in each OFDM symbol period according to $\tau_n^o \in \{\frac{h-1}{N}\}_{h=1,2,\ldots,N}$ and $\tau_p^o \neq \tau_q^o$.

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- Also, this mechanism is able to maintain the DM functionality as it still satisfies the above scrambling scheme.

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Numerical Results

- We simulated a TMA OFDM scenario with $N = 7$ antennas, $K = 16$ subcarriers, and BPSK data modulation. The eavesdropper collects $H = 1\text{e}5$ OFDM symbols.

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- We conducted 6 experiments: in each one, the legitimate user is at θ_0, and the eavesdropper at θ_e.

Table: Average BER of the TMA system

No.	$\theta_0(^\circ)$	$\theta_e(^\circ)$	φ	BER1	BER2	BER3
1	50	90	-0.6428	0.3080	0	0.4504
2	60	30	0.3660	0.2640	0	0.5218
3	80	40	0.5924	0.4474	0	0.5004
4	30	70	/	0.5487	0	0.4168
5	40	90	/	0.3754	0	0.4824
6	50	130	/	0.2744	0	0.4789

Numerical Results

- Next, we set $\theta_0 = 60^\circ$, $\theta_e = 30^\circ$, $N = 7$, $\Delta\tau = 1/N$, $\{\tau_n^o\}_{n=1,2,\ldots,N} = (n-1)/N$, φ is assumed to be known.

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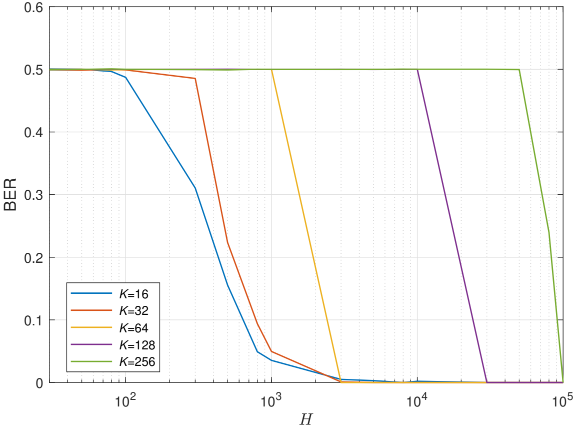

Figure: Scrambling defying performance comparison.

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- We have shown that based on the scrambled symbols, the eavesdropper can formulate a blind source separation problem, and introduced a novel ICA-based scheme that can infer the mixing matrix with no ambiguities and recover the transmitted symbols.
- We have also proposed a simple TMA implementation mechanism to make the job of the eavesdropper harder.
- Numerical results have demonstrated the effectiveness and efficiency of proposed defying and defending approaches.

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