

Metamaterial-Enabled 2D Directional Modulation Array Transmitter for Physical Layer Security in Wireless Communication Links

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Abstract—A new type of time modulated metamaterial (MTM) antenna array transmitter capable of realizing 2D directional modulation (DM) for physical layer (PHY) security is presented in this work. The proposed 2D DM MTM antenna array is formed by a time modulated corporate feed network loaded with composite right/left-handed (CRLH) leaky wave antennas (LWAs). By properly designing the on-off states of the switch for each antenna feeding branch as well as harnessing the frequency scanning characteristics of CRLH LWAs, 2D DM can be realized to form a PHY secured transmission link in the 2D space. Experimental results demonstrate the bit-error-rate (BER) is low only at a specific 2D angle for the orthogonal frequency-division multiplexing (OFDM) wireless data links.

Keywords—Directional modulation (DM), metamaterials (MTMs), orthogonal frequency division multiplexing (OFDM), physical-layer (PHY) security, time modulated array.

I. INTRODUCTION

Directional modulation (DM)-based physical-layer (PHY) security for wireless communication systems has advanced rapidly in recent years, owing to its ability to create wireless link at a specific direction with low bit-error-rate (BER) [1]-[3]. One way to realize DM is based on a time-modulated array (TMA), where the excitation of each array element is periodically enabled and disabled with the use of switches [4]. By properly choosing the control waveform of switches, DM can be synthesized in a way that the signal is transmitted in a desired angle and distorted in all other unwanted angles, thereby resulting in PHY security.

Nevertheless, most of the reported TMA-based DM schemes can only provide PHY security in the 1D space, which may limit the applications where 2D secured links are needed. To this end, this work proposes a new DM scheme where we use CRLH LWA as antenna elements with frequency dependent beam scanning characteristics for TMA [5]-[7]. It will be shown that such integration enables a 2D DM where a secured angle can be formed for both azimuth and elevation directions. As proof-of-concept, a prototype of TMA containing four CRLH MTM LWAs is designed and developed, in which both simulated and measured results for the BER show that the proposed MTM TMA can preserve the signal in desired direction while distorting it in all other angles in 2D space.

II. OPERATING PRINCIPLES

As shown in Fig. 1, the proposed configuration utilizes CRLH MTM LWAs as antenna elements at the end of each branch of TMA. By using pin diodes as RF switches in each

branch and controlling the on-off state, denoted as $U_m(t)$, the radiation pattern can be obtained by following the array factor approach [8]-[10]:

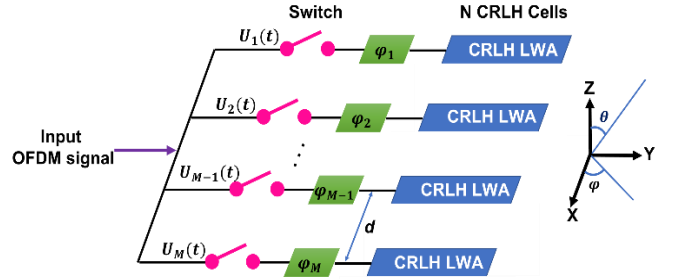


Fig. 1. Proposed 2D DM MTM array transmitter.

$$R(t, \theta, \varphi) = S(t) \sum_{m=1}^M U_m(t) e^{jk_0 d(m-1) \sin \theta \cos \varphi + j \varphi_m} \times \sum_{n=1}^N I_n e^{jk_0 p(n-1) \sin \theta \sin \varphi + j \zeta_n} \quad (1)$$

where $S(t)$ is the input signal,

$$\varphi_m = -(m-1)k_0 d \sin \theta_0 \cos \varphi_0, I_n = I_0 e^{-\alpha(n-1)p}, \quad (2)$$

$$\zeta_n = -(n-1)k_0 p \sin \gamma, \gamma = \sin^{-1} \left(\frac{\beta(\omega)}{k_0} \right), \quad (3)$$

while M is the number of branches and N is the number of cells in each CRLH MTM LWA. Also, k_0 is the free space wave number, d is the distance between the adjacent LWAs, γ is the main beam angle for an individual LWA, which is a function of frequency, p is the length of CRLH unit cell, α is the leakage factor, and $\beta(\omega)$ is the phase constant of CRLH transmission line. So, for focusing the main beam of the 2D prototype to the point (θ_0, φ_0) , the input frequency should be tuned to have:

$$\sin \theta_0 \sin \varphi_0 = \sin \gamma \quad (4)$$

and the required phase shift of the signal in each branch should be given by φ_m . In addition, $U_m(t)$ is a periodic square switching waveform starting at time t_m^s and ending at t_m^e , which can be defined as:

$$U_m(t) = \begin{cases} 1 & \text{if } t_m^s \leq t \leq t_m^e, \\ 0 & \text{otherwise,} \end{cases} \quad (5)$$

$$\text{and} \quad U_m(t) = \begin{cases} 1 & \text{if } 0 \leq t \leq t_m^e, \\ 1 & \text{if } t_m^s \leq t \leq T_p, \\ 0 & \text{otherwise,} \end{cases} \quad (6)$$

for the cases $t_m^e > t_m^s$ and $t_m^e < t_m^s$, respectively. Here, $T_p = \frac{1}{f_p}$ denotes the period of the switching waveform. By expanding $U_m(t)$ in terms of the Fourier series, we obtain:

$$R(\theta, \varphi, t) = \frac{1}{\sqrt{M}} S(t) \left(\sum_{n=1}^N I_0 e^{-\alpha(n-1)p} e^{j(n-1)k_0 p \sin \theta \sin \varphi + j \zeta_n} \right) \times \sum_{i=-\infty}^{\infty} V(t, i, M, T_m^s, \Delta t_m, \theta, \varphi), \quad (7)$$

where

$$V(t, i, M, T_m^s, \Delta t_m, \theta, \varphi) = \sum_{m=1}^M \left(\frac{\sin(i\pi f_p \Delta t_m)}{i\pi} e^{j2\pi i f_p (t - T_m^s - \Delta t_m/2)} \right) \times e^{jk_0 d(m-1)(\sin \theta \cos \varphi - \sin \theta_0 \cos \varphi_0)}, \quad (8)$$

The on-time period for the m^{th} switch is always less than T_p and equals to $\Delta t_m = t_m^e - t_m^s$ when $t_m^e > t_m^s$, or $\Delta t_m = T_p + t_m^e - t_m^s$ when $t_m^e < t_m^s$. It can be shown that by providing specific delay between $U_m(t)$'s with the same duty cycle Δt , the input signal along (θ_0, φ_0) during transmission is preserved while being distorted along other directions. The DM can be achieved if the switch parameters are chosen as [3],[11]:

$$\frac{t_m^s}{T_p} \in \left\{ \frac{w-1}{M} \mid w = 1, 2, \dots, M \right\} \quad (9)$$

$$\frac{\Delta t}{T_p} \in \left\{ \frac{w-1}{M} \mid w = 1, 2, \dots, M \right\} \quad (10)$$

Finally, by sweeping the carrier frequency (f_0) in the fast wave region of LWAs and providing appropriate φ_m through the use of external phase shifters, beam scanning in the 2D space is achieved. Moreover, thanks to the time-modulation technique, the signal is preserved in the desired direction while being distorted in all other unintended directions in the 2D, thereby enabling the PHY security.

III. PROTOTYPE DESIGN AND EXPERIMENTAL VERIFICATION

As proof-of-concept of the proposed 2D DM MTM array, 12 CRLH cells with interdigital capacitors and shunt stub inductors are cascaded to realize the CRLH LWAs to form a four-element array (i.e., $N = 12, M = 4$). The center frequency of the unit cell is designed to be 2.3 GHz with the fast wave region ranging from 1.9 to 3.5 GHz, in which the measured radiation patterns of fabricated LWAs are shown in Fig. 2.

Fig. 3 shows the simulation results with and without the time modulation, respectively. The distance between branches (d) is equal to 6.5 cm and the length of the unit cell (p) is 11.4 mm. In this scenario, the carrier frequency is 2.3 GHz and the number of OFDM sub-carriers is 16. In addition, QPSK is used as the modulation scheme for OFDM transmission with SNR per bit equal to 8 dB and $\theta_0 = 45^\circ, \varphi_0 = 180^\circ$. It can be

observed that with the time modulation, in undesired angles higher BER is obtained in comparison with the case without the time modulation, demonstrating the feasibility of PHY security enhancement.

Fig. 4. shows the fabricated prototype and measurement setup, where we inject an OFDM input signal with 16 sub-carriers using the QPSK modulation scheme and measure BER for different cases. The time modulated antenna feed network is realized by a one-to-four Wilkinson power divider with PIN diodes (SMP1345 from Skyworks) used as RF switches. Moreover, phase shifters and CRLH LWAs are connected to the end of each branch of the time modulated feed network, respectively.

The control signals for the switches are realized using function generators based on (9) and (10). A broadband Vivaldi antenna located in the far field region is used as a receive antenna. The measured BER results are obtained through commercially available software-defined radio (SDR) modules connected to both transmit and receive antennas, as shown in Fig 5 to Fig. 8, where GNU Radio interface is used to implement the IEEE 802.11 standard for transmission and reception of OFDM packets with QPSK modulation over an AWGN channel. In Fig. 5 and Fig. 6, the main beam is set to be $\theta_0 = 0^\circ$. In Fig. 5, we sweep θ from zero to 90° in $\varphi = 0^\circ$ and $\varphi = 180^\circ$ planes. In Fig. 6, θ is scanned from zero to 90° in the $\varphi = 85^\circ$ and $\varphi = 265^\circ$ planes. In Fig. 7, phase shifters and input frequency are adjusted to set $\theta_0 = 45^\circ, \varphi_0 = 180^\circ$, whereas θ is swept from zero to 90° in $\varphi = 0^\circ$ and $\varphi = 180^\circ$ planes. In Fig. 8, by changing the input frequency to 2.7 GHz the main beam becomes $\theta_0 = 40^\circ, \varphi_0 = 90^\circ$ and the φ is swept from 0° to 180° at $\theta = 40^\circ$. These results demonstrate the enhancement of PHY security after enabling the time modulation waveforms for DM. In particular, it is shown that the BERs are very low for the cases with and without DM in the desired angle, whereas the BER is much higher at the undesired angles with DM.

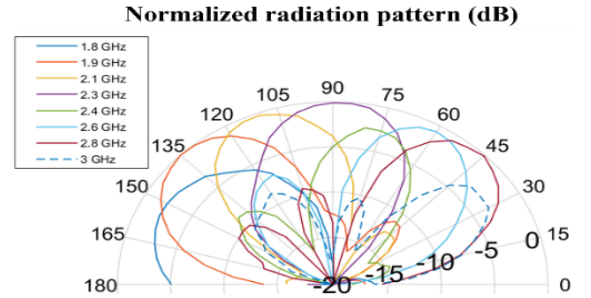


Fig. 2. Measured radiation pattern of each CRLH MTM LWA.

IV. CONCLUSION

In this paper, a time modulated DM transmitter using CRLH MTM LWA as antenna elements is proposed. This transmitter enables 2D DM for PHY security. Experimental results by transmitting OFDM signal using the proposed 2D DM MTM array demonstrate a very low BER in the desired 2D angle, while much higher BER can be observed in all other undesired angles in comparison with the case without DM. The proposed 2D DM MTM array can be utilized to transmit PHY secured signals for wireless communications in the 2D space.

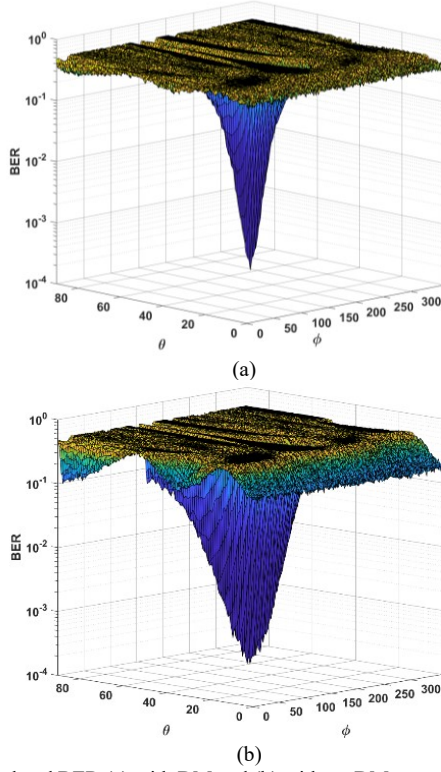


Fig. 3. Simulated BER (a) with DM and (b) without DM.

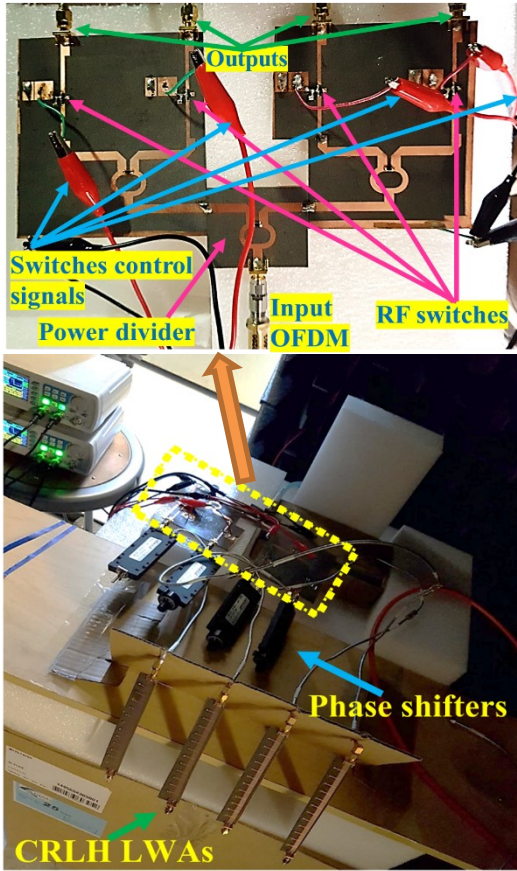


Fig. 4. Fabricated 2D DM MTM array with a closed-up view of the time-modulated antenna feed network.

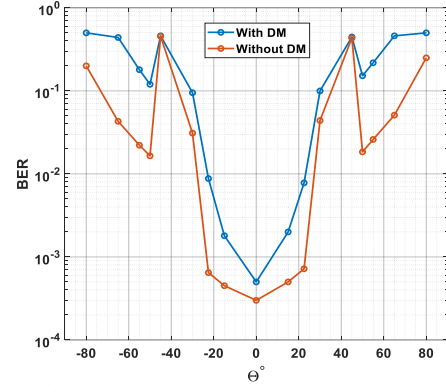


Fig. 5. Measured BER with and without DM at $\varphi = 0^\circ, 180^\circ$ planes by sweeping θ when $\theta_0 = 0^\circ$.

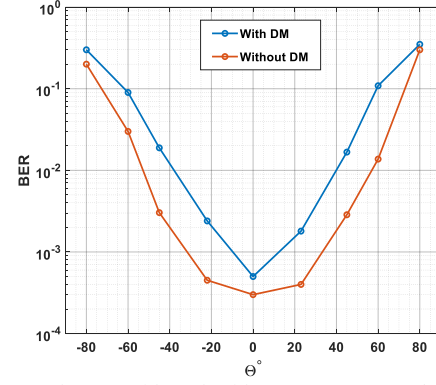


Fig. 6. Measured BER with and without DM at $\varphi = 85^\circ, 265^\circ$ planes by sweeping θ when $\theta_0 = 0^\circ$.

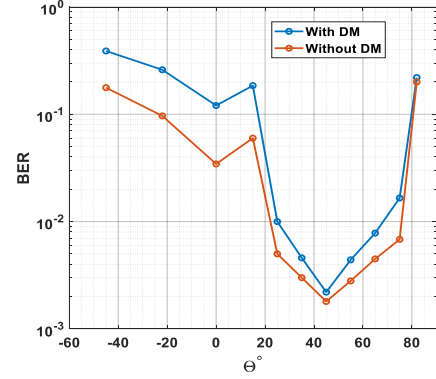


Fig. 7. Measured BER with and without DM at $\varphi = 0^\circ, 180^\circ$ planes by sweeping θ when $\theta_0 = 45^\circ, \varphi_0 = 180^\circ$.

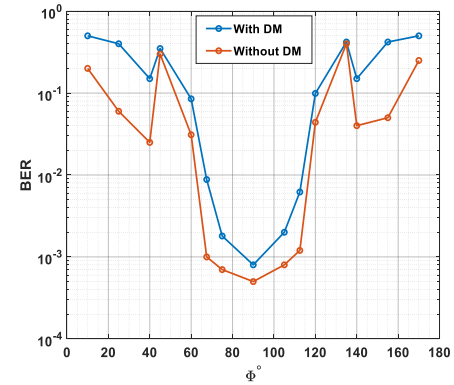


Fig. 8. Measured BER with and without DM at $\theta = 40^\circ$ by sweeping φ when $\theta_0 = 40^\circ, \varphi_0 = 90^\circ$.

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