Directional Modulation Retrodirective Array-Enabled Physical Layer Secured Transponder for Protected Wireless Data Acquisition

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***Abstract*—A time-modulated retrodirective array (RDA) is proposed to achieve directional modulation (DM) for physical layer (PHY) security in wireless communication. The designed and fabricated RDA is based on the phase conjugation technique, in which the retransmitted signal is time-modulated by using pin diodes as RF switches. By feeding proper periodic sequences to the pin diodes-based switches, the resulting harmonic signals can be suppressed in the desired secure angle, while their levels rise and distort the retransmitted signal in other unwanted angles, thereby enabling PHY security. Measured bit-error-rate (BER) results by injecting an orthogonal frequency-division multiplexing (OFDM) signal to the LO port of the PHY secured RDA verify better security performance in comparison with a conventional RDA without time modulation.**

***Keywords*—directional modulation (DM), physical-layer security (PHY), retrodirective array, time modulation, transponder.**

I. Introduction

Retrodirective arrays (RDAs) are known for the feature of reradiating an incoming signal towards the source direction without having any prior knowledge about its location [1]–[3]. Being in possession of this characteristic, RDAs serve as great candidates for various wireless communication applications such as self-target tracking, radiofrequency identification (RFID)/backscatter radio, wireless power transmission, transponder, etc. [3], [4].

In the context of communication, security is an important issue in the design and use of wireless networks [5]. Although RDA replies to the interrogator toward its direction, any eavesdropper located in other directions may be able to receive a weak version of the array response and therefore can retrieve the information with a high sensitivity receiver. In order to overcome this issue a very directive beam is required, and it is achieved by increasing the number of array elements. Nevertheless, for phase conjugation of the incoming signal, all the branches of RDA should create nearly the same phase shift and any difference will affect the retransmitted beam direction and radiation pattern accordingly [3], which is a challenge in the design of a large-scale RDA.

On the other hand, directional modulation (DM) incorporating time modulation leads to preserving the signal in a specific secure angle while distorting it in all other directions, thereby achieving physical layer (PHY) security [6]–[12]. While in [10] a time modulated or 4D RDA is utilized to achieve DM, the polarization of the retransmitted signal is orthogonal to the polarization of the incoming signal for TX/RX isolation, which may not be practical for devices usually equipped with a single linearly-polarized antenna. Moreover, a cost function is constructed and the time modulated sequences controlling the RF switches are determined by employing optimization algorithms to achieve DM where the retransmitted signal is a single carrier, resulting in computational burden. It is also noted that the measured bit-error-rate (BER) results are not reported in [10].

In this work, we propose a DM RDA by incorporating diodes as RF switches in the retransmitted signal path. By properly designing the switch control voltage waveforms, the phase-conjugated signal will be transmitted correctly to the desired direction, while being distorted in all other directions, resulting in secure communication as shown in Fig. 1. In this case, the received and retransmitted signal have the same polarization, which reduces the antenna system complexity. Furthermore, there is no need for any optimization method for obtaining periodic sequences fed to the pin diodes [11]. As proof of concept an RDA including two branches is fabricated, in which the retransmitted signal is an OFDM signal, a multi-carrier signal broadly utilized in modern wireless communication networks. The measured BER results are also reported to prove the DM functionality of our RDA prototype.

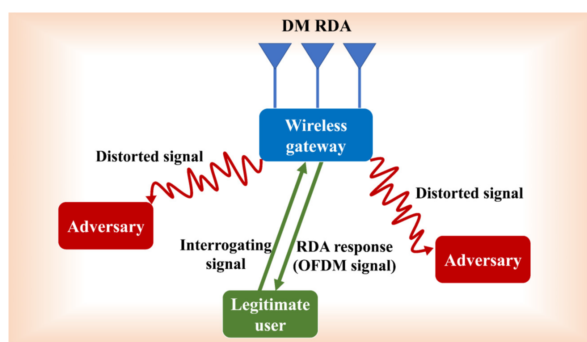

Fig. 1. Achieving physical-layer security by utilizing proposed DM RDA in a wireless communication network.

II. Proposed Time-Modulated DM RDA

The schematic of our proposed DM RDA including two array elements is illustrated in Fig. 2. In order to generate phase conjugated IF from the incoming RF, the phase conjugator circuit has two branches, inspired by the topology shown in [13], which does not have the DM functionality. The LO frequency is set to $f_{LO} = 2f_{RF}$; after passing a power divider, in each branch the LO signal is injected to the gates of two field-effect transistors (FETs) employed as mixers with 180° out of phase.

On the other hand, the incoming RF signal is received by the antenna elements, and then enters port 1 of the circulator. After passing from a designed 180° hybrid coupler, the RF signal is applied to the drain of FETs in phase.

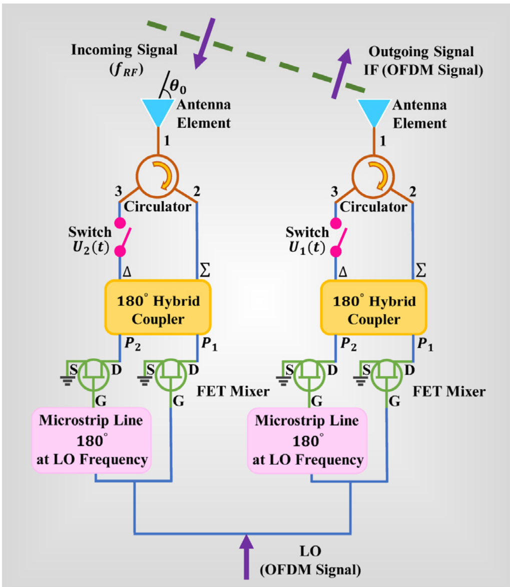

Fig. 2. The schematic of our proposed DM RDA.

It is noted that the generated IF signals with an amplitude A in the two FET based phase conjugator circuits are 180° out of phase. By assuming the phase of the incoming RF signal reaches to the n^{th} branch as θ_n, the down-converted signal at the Δ port can be written as:

$$\Delta: \ P_1 - P_2 = A\cos\big((\omega_{LO} - \omega_{RF})t - \theta_n\big) - A\cos\big((\omega_{LO} - \omega_{RF})t - \pi - \theta_n\big) = 2A\cos(\omega_{IF}t - \theta_n). \quad (1)$$

Therefore, at the Δ port the phase conjugated IF will go to port 3 of the circulator after being time modulated by a PIN diode with a predetermined periodic sequence to achieve DM.

By considering $\theta_n = j(n-1)\beta d \cos\theta_0$, the radiation pattern of the time modulated IF signal, which is the retransmitted signal of the RDA, can be expressed as:

$$R(\theta, t) = \sum_{n=1}^{N} s(t)\, U_n(t) e^{j(n-1)\beta d(\cos\theta - \cos\theta_0)} \quad (2)$$

$$s(t) = \sum_{k=1}^{K} P_k e^{j2\pi t[f_{LO} + (k-1)f_p - f_{RF}]} = \sum_{k=1}^{K} P_k e^{j2\pi t[f_{IF} + (k-1)f_p]} \quad (3)$$

where β is the free space phase constant, d is the distance between the adjacent array elements, θ_0 represents the interrogator direction, N is the number of array branches, $s(t)$ denotes the retransmitted multi-carrier OFDM signal where its carriers have been shifted from the LO frequency band to the IF band after mixing with the RF signal through the FET mixers. In addition, K is the total number of sub-carriers, f_p is the frequency spacing between the successive subcarriers, and P_k is the applied symbol to the k^{th} sub-carrier. Moreover, $U_n(t)$ is a periodic square wave with period T_p controlling the on and off states of the switches, which can be expressed as:

$$U_n(t) = \begin{cases} 1 & \text{if } \ t_n^s \le t \le t_n^e, \\ 0 & \text{otherwise,} \end{cases} \quad (4)$$

where t_n^s and t_n^e denote the beginning and ending time of the on-time period of the switch in the nth branch, respectively. In order to realize DM, the $U_n(t)$ waveform should meet the following equation [11]:

$$\frac{t_n^s}{T_p}, \frac{\Delta t}{T_p} \in \left\{\frac{w-1}{N} \middle| w = 1,2,\dots,N\right\},\ T_p = \frac{1}{f_p}. \quad (5)$$

It is noted that all the switches should have the same on-time period, i.e., $\Delta t = t_n^e - t_n^s$, while they will be on at different time intervals.

For the attack model, we consider an eavesdropper located in an angle other than the interrogator's direction, equipped with an RF receiver to decode the OFDM packets. It will be shown experimentally that by satisfying (5), the retransmitted OFDM signal of the time modulated RDA can be received in the θ_0 direction correctly, while being distorted in all other angles. Therefore, the possibility of interception by the eavesdropper decreases drastically. In so doing, the proposed scheme improves PHY security in an RDA by using a simple structure without solving any optimization algorithm or employing high number of branches, which is challenging due to the discrepancy in the phase shift provided by the RDA phase conjugators.

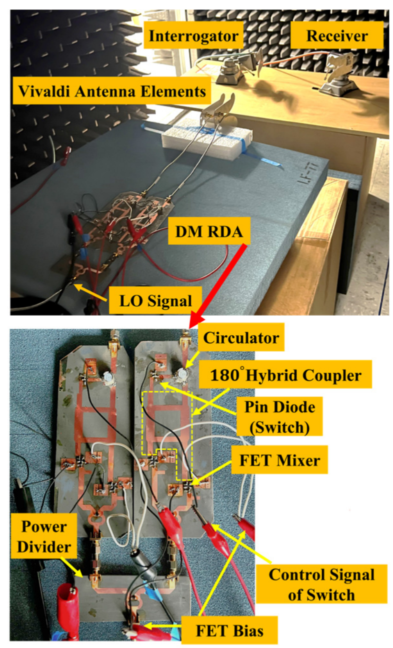

Fig. 3. The schematic of our proposed DM RDA and measurement setup.

III. Design Procedure and Experimental Verification

As proof-of-concept of the proposed DM RDA, a prototype including two branches of RDA element is fabricated and shown in Fig. 3. In addition, Vivaldi antennas are employed as antenna elements with spacing around 0.45 free space-wavelength at 2.3 GHz. The LO frequency is 4.6 GHz, and the RF frequency is 2.31 GHz, resulting in an IF signal of 2.29 GHz.

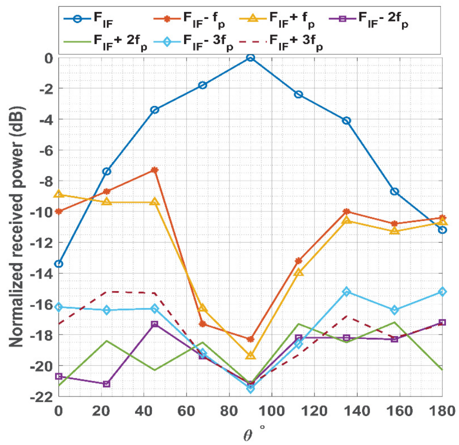

Fig. 4. Measured normalized pattern of the RDA response when the interrogator is located at $\theta_0 = 90°$.

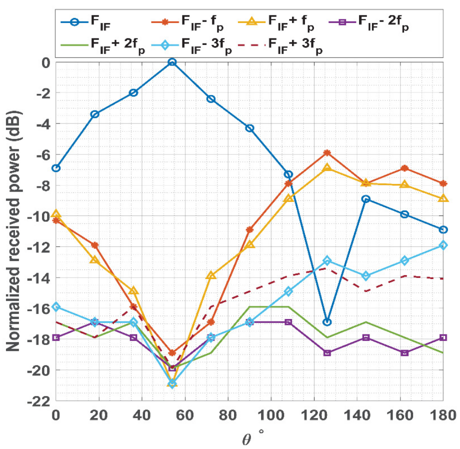

Fig. 5. Measured normalized pattern of the RDA response when the interrogator is located at $\theta_0 = 54°$.

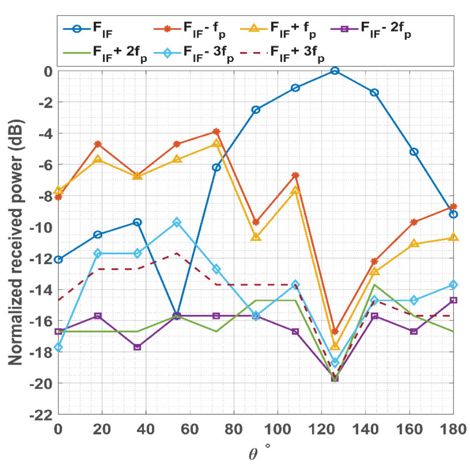

Fig. 6. Measured normalized pattern of the RDA response when the interrogator is located at $\theta_0 = 126°$.

It is noted that the slight frequency offset is a well-known technique for separating the incoming and outgoing signals. It is also worth mentioning that in the proposed RDA topology, a conventional rat race coupler will make the layout design challenging since the sum port is located between the two input/output ports. To overcome this, a quarter wavelength section is added to one of the ports of a branchline coupler to realize a 180° hybrid coupler, as can be seen in Fig. 3. In addition, NE3509M04 FETs are used as mixer, $V_{DS} = 0.05$ V and $V_{GS} = -0.14$ V, making the FETs operate as a resistive mixer. SMP1345 PIN diodes from Skyworks are employed as RF switches, whereas the circulators are SKYFR-001390 that can work around 2.3 GHz. The control signals of the switches are generated based on (5) by using a function generator with two output channels.

For the radiation pattern measurement, a broadband Vivaldi antenna is utilized as the interrogator to send a RF signal of 2.31 GHz, whereas a 4.6 GHz signal is injected to the LO port of RDA. Furthermore, the modulation frequency of switches is 0.5 MHz. Another Vivaldi antenna is utilized to collect the IF and harmonic levels in different angles. Fig. 4, Fig. 5, and Fig. 6 show the results when the interrogator is located at $\theta_0 = 90°$, $\theta_0 = 54°$, and $\theta_0 = 126°$, respectively. As can be observed, harmonics are suppressed around the interrogator direction while their levels increase in other angles and this rise leads to the distortion of the response signal constellation.

In order to show the security performance of our proposed DM RDA in comparison to a conventional one, the BERs for the two cases, i.e., with and without time modulation, are measured, where the flowchart of the BER measurement is illustrated in Fig. 7. IEEE 802.11 standard without utilizing any error-correcting codes is implemented for transmission and reception of OFDM packets with QPSK modulation in GNU Radio software [14]. By using a universal software radio peripheral (USRP) module, an OFDM signal with the center frequency of 4.6 GHz and 64 sub-carriers is injected to the RDA prototype as LO. Another USRP is connected to the receiver antenna to collect the response of the RDA from different angles for BER measurement. The results are shown in Fig. 8, Fig. 9, and Fig. 10 for the case that the interrogator is located at $\theta_0 = 90°$, $\theta_0 = 54°$, and $\theta_0 = 126°$, respectively.

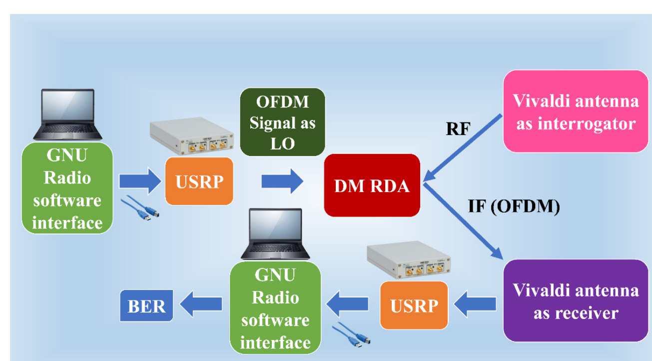

Fig. 7. BER measurement flowchart.

As can be clearly seen, the measured BER results verify a better security performance of our proposed DM RDA, since higher BER is achieved in unwanted angles in comparison with RDA without any time modulation. It is worth mentioning that there is a trade-off between transmit power and security, in which a portion of the power is lost due to the off-time state of switches, thereby resulting in a slightly higher BER at the desired direction due to a decreased signal-to-noise ratio (SNR).

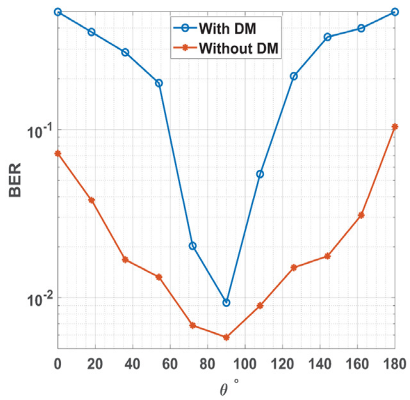

Fig. 8. Measured BER for with and without DM when interrogator is located at $\theta_0 = 90°$.

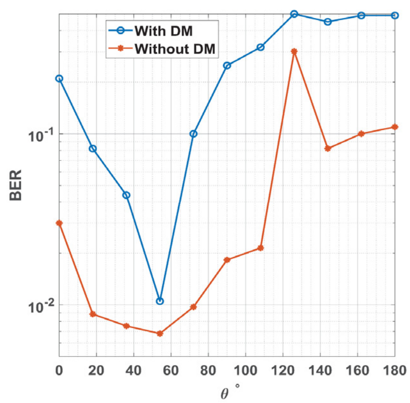

Fig. 9. Measured BER for with and without DM when interrogator is located at $\theta_0 = 54°$.

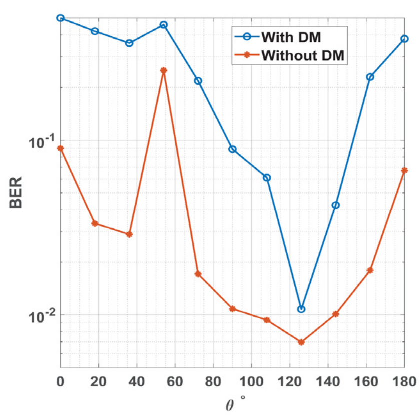

Fig. 10. Measured BER for with and without DM when interrogator is located at $\theta_0 = 126°$.

IV. Conclusion

In this work, a time modulated DM RDA is proposed, which can enable PHY security for wireless data transmission. Measured BER results by injecting an OFDM signal as LO to the fabricated DM RDA prototype verify a very low BER in the interrogator direction, while a much higher BER is observed in all other angles in comparison with a conventional RDA without DM. The proposed DM RDA can be employed in wireless communications networks as a transponder to respond to an interrogator by transmitting PHY secured OFDM signals.

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