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Citation for published version:
Ding, Y & Fusco, V 2015, 'MIMO Inspired synthesis of directional modulation systems', *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 580-584. https://doi.org/10.1109/LAWP.2015.2459752

Digital Object Identifier (DOI):
10.1109/LAWP.2015.2459752

Link:
Link to publication record in Heriot-Watt Research Portal

Document Version:
Peer reviewed version

Published In:
IEEE Antennas and Wireless Propagation Letters

MIMO Inspired Synthesis of Directional Modulation Systems

Yuan Ding and Vincent F. Fusco, *Fellow, IEEE*

***Abstract*—By identifying the similarities and differences between multiple-input and multiple-output (MIMO) and directional modulation (DM) technologies, a new approach for the synthesis of DM transmitters is proposed in this paper. The synthesis method is validated using DM simulation examples, in free space and in a simplified multipath environment, using bit error rate (BER) as the performance metric.**

***Index Terms*— Bit error rate (BER), directional modulation (DM), multiple input multiple output (MIMO)**

I. Introduction

Directional modulation (DM) is a transmitter side technology which permits digitally encoded information signals to be sent into a pre-specified spatial direction while simultaneously distorting the constellation formats of the same signals in all other directions during a free space transmission [1]. DM as a promising keyless physical-layer security means has developed in many aspects in recent years [1]–[16]. Specifically the passive DM architectures for millimeter wave operation were described in [2], [3], which, however, were not synthesis-friendly. Actively excited DM arrays utilizing analogue radio frequency (RF) phase shifters or switches, which limit the achievable symbol rates, were proposed in [4]–[9]. Several DM synthesis approaches, focusing on different DM properties, were presented in [1], [11]–[14]. The digital DM arrangement in [1] is an appropriate candidate to implement the proposed DM synthesis algorithm in this paper.

In this paper it is shown for the first time that;

- DM technology can be regarded as a kind of multiple-input and multiple-output (MIMO) system operating in free space when separately located non-cooperating receivers are considered.
- That the characteristic of security performance enhancement possessed by DM systems is achieved at the price of loss of spatial multiplexing capacity.

This paper is organized as follows. In Section II a simplified MIMO model for free space operation with separately located cooperating receivers is established. In Section III by modifying receivers to be non-cooperating, the MIMO system becomes a DM system, and a free space DM synthesis approach is developed from this finding. At the end of this section a discussion on adapting this approach for the synthesis of DM systems in multipath environment is provided. Bit error rate (BER) simulations for the DM example systems created using the synthesis method are provided in Section IV. Conclusions are drawn in Section V.

Manuscript received April 28, 2015; revised July 06, 2015. This work was sponsored by the Queen's University of Belfast High Frequency Research Scholarship.

Yuan Ding and Vincent Fusco are with the Institute of Electronics, Communications and Information Technology (ECIT), Queen's University of Belfast, Belfast, United Kingdom, BT3 9DT (phone: +44(0)2890971806; fax: +44(0)2890971702; e-mail: yding03@qub.ac.uk; v.fusco@qub.ac.uk).

II. Cooperating Receivers

It is well known that under multipath rich wireless channel conditions systems which deploy both multiple transmit and multiple receive antennas provide an additional spatial dimension for communication and yield degree-of-freedom gain. The additional degree-of-freedom can be exploited by spatially multiplexing several parallel independent data streams onto the MIMO channel leading to an increase in channel capacity [17].

In order to investigate the link between MIMO and DM technology a simplified MIMO model, illustrated in Fig. 1, is established wherein the receivers are separately placed along different spatial directions in order to retain spatial multiplexing [17].

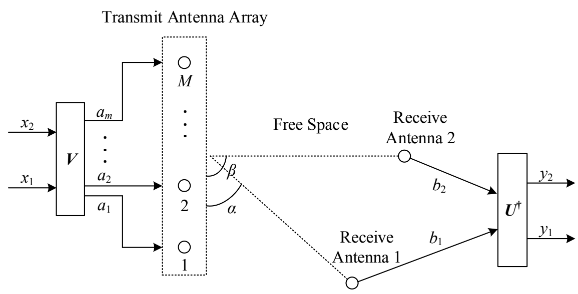


Fig. 1. Simplified MIMO model in free space with two separately located receive antennas.

The operation mechanism of the simplified MIMO system in Fig. 1 is now described;

- Perform singular value decomposition (SVD) on $\boldsymbol{H}$, (1). $\boldsymbol{H}$ is the channel matrix, whose the $(m,n)^{th}$ entry is the transmission coefficient between the m^{th} transmit antenna and the n^{th} receive antenna. For the example in Fig. 1, m = 1, 2, …, M, and n = 1, …, N, (N = 2). Operator '$[\cdot]^{\dagger}$' indicates the complex conjugate transpose (Hermitian) matrix.

$$\boldsymbol{H} = \boldsymbol{U}\boldsymbol{\Lambda}\boldsymbol{V}^{\dagger} \tag{1}$$

Here $\boldsymbol{U}$ and $\boldsymbol{V}$ are unitary matrices, i.e., $\boldsymbol{U}\boldsymbol{U}^{\dagger} = \boldsymbol{U}^{\dagger}\boldsymbol{U} = \boldsymbol{V}\boldsymbol{V}^{\dagger} = \boldsymbol{V}^{\dagger}\boldsymbol{V} = \boldsymbol{I}$. $\boldsymbol{I}$ is the identity matrix. $\boldsymbol{\Lambda}$ in (1) is a rectangular matrix whose diagonal elements λ_k, (k = 1, 2, …, K; K = min(M, N)), are non-negative real numbers and whose off-diagonal elements are zero.

- Design networks $\boldsymbol{V}$ and $\boldsymbol{U}^{\dagger}$ and insert them into transmit and receive sides, seen in Fig. 1, respectively. These networks can be constructed by either RF analogue means or by baseband digital means.

Using the structure in Fig. 1, which is a well-known V-BLAST architecture, the M-by-N MIMO wireless channel is transformed into K (K = 2 in this example) parallel channels. The two independent data streams x_1 and x_2 are recovered at the receive side as y_1 and y_2, (2).

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \boldsymbol{U}^{\dagger} \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \boldsymbol{U}^{\dagger} \left(\boldsymbol{H} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_M \end{bmatrix} + \boldsymbol{w} \right) = \boldsymbol{U}^{\dagger} \boldsymbol{U} \boldsymbol{\Lambda} \boldsymbol{V}^{\dagger} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_M \end{bmatrix} + \boldsymbol{w}'$$

$$= \boldsymbol{\Lambda} \boldsymbol{V}^{\dagger} \boldsymbol{V} \begin{bmatrix} x_1 \\ x_2 \\ 0 \\ \vdots \\ 0 \end{bmatrix} + \boldsymbol{w}' = \begin{bmatrix} \lambda_1 & 0 & 0 & \cdots & 0 \\ 0 & \lambda_2 & 0 & \cdots & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ 0 \\ \vdots \\ 0 \end{bmatrix} + \boldsymbol{w}'$$

$$\Rightarrow \begin{cases} y_1 = \lambda_1 x_1 + w_1' \\ y_2 = \lambda_2 x_2 + w_2' \end{cases} \tag{2}$$

$\boldsymbol{w}' = \begin{bmatrix} w_1' \\ w_2' \end{bmatrix}$ is the AWGN channel noise. It is noted that the two separately spaced receivers need to cooperate, with the help of the network $\boldsymbol{U}^{\dagger}$, in order to recover the two transmitted information data streams.

III. NON-COOPERATING RECEIVERS

When viewing Fig. 1 from the secure communication perspective, receivers 1 and 2 can be considered as legitimate receiver and eavesdropper respectively. In this case it is imperative that the information data, e.g., x_1, is transmitted only to the receiver 1, while interference, e.g., x_2, is projected only towards receiver 2. In this scenario the two receivers do not cooperate either since the eavesdropper wishes to remain anonymous. Thus for secure communication network $\boldsymbol{U}^{\dagger}$ in Fig. 1 has to be an identity matrix $\boldsymbol{I}$. This alteration leads to the change of the network $\boldsymbol{V}$ at transmit side, denoted as $\boldsymbol{P}$ hereafter, hence (2) becomes (3). '$[\cdot]^T$' denotes the vector transpose operator.

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \boldsymbol{I} \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \boldsymbol{H} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_M \end{bmatrix} + \boldsymbol{w} = \boldsymbol{U} \boldsymbol{\Lambda} \boldsymbol{V}^{\dagger} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_M \end{bmatrix} + \boldsymbol{w}$$

$$= \boldsymbol{U} \boldsymbol{\Lambda} \boldsymbol{V}^{\dagger} \boldsymbol{P} \begin{bmatrix} x_1 & x_2 & 0 & \cdots & 0 \end{bmatrix}^T + \boldsymbol{w} \tag{3}$$

As we stated above inputs x_1 and x_2 should be recovered as y_1 and y_2 without crossover, thus (4) needs to be satisfied.

$$\boldsymbol{U} \boldsymbol{\Lambda} \boldsymbol{V}^{\dagger} \boldsymbol{P} = \underbrace{\begin{bmatrix} q_1 & 0 & 0 & \cdots & 0 \\ 0 & q_2 & 0 & \cdots & 0 \end{bmatrix}}_{\boldsymbol{Q}} \tag{4}$$

From (4) the required network $\boldsymbol{P}$ between transmitted signals and the antenna array can be obtained using (5)

$$\boldsymbol{P} = \boldsymbol{V} \boldsymbol{\Lambda}^{-1} \boldsymbol{U}^{\dagger} \boldsymbol{Q} \tag{5}$$

Here '$[\bullet]^{-1}$' is the Moore-Penrose pseudo-inverse operator.

Using $\boldsymbol{P}$, information data x_1 and interference x_2, the array excitations $\boldsymbol{A}_i$ required for the i^{th} information symbol transmission which obeys information and interference orthogonality along spatial directions α and β can be calculated, (6).

$$\boldsymbol{A}_i = \boldsymbol{P} \, [x_1 \quad x_2 \quad 0 \quad \ldots \quad 0]^T \tag{6}$$

Since the location(s) of the eavesdropper(s) is in general unknown to the transmitter, the spatial direction β of receiver 2 in Fig. 1 is randomly updated within the range from 0° to 180° at the symbol rate, for $\beta \neq \alpha$.

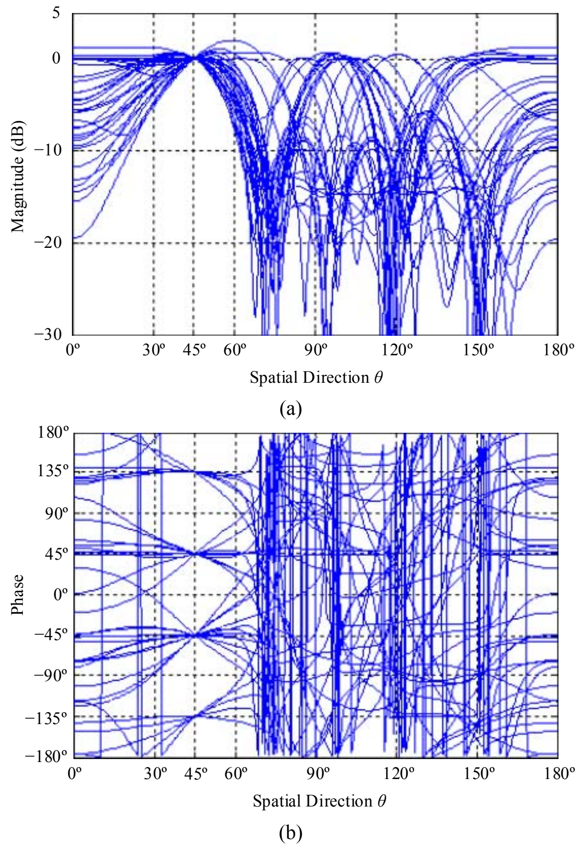


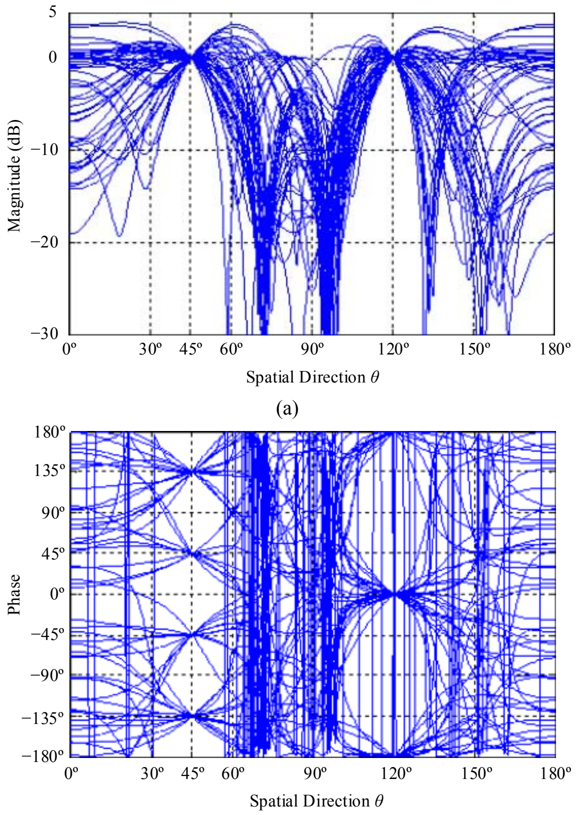
Fig. 2. Array (a) magnitude and (b) phase patterns for 50 random QPSK symbols transmitted in a synthesized dynamic QPSK DM transmitter with selected communication direction of 45°.

Fig. 2 shows example array factor (***AF***) patterns for 50 random Gray-coded QPSK symbols (x_1) transmitted by a one dimensional (1-D) 5-element (M = 5) antenna array with half wavelength ($\lambda/2$) spacing, see (7). The A_{im} denotes the m^{th}

entry in the excitation vector $\boldsymbol{A}_i$. In this example the desired secure communication direction α is chosen as 45°, and interference x_2 has the same power as the information signal x_1, but its phase is randomly updated. This identical power choice selection x_1 and x_2 indicates that the radiation gains along the fixed α and randomly updated β directions are determined by the parameters q_1 and q_2 in matrix $\boldsymbol{Q}$, (4). For the example in Fig. 2, these are set to be identical (unity). As network $\boldsymbol{P}$ does not preserve power between input and output the power of $\boldsymbol{A}_i$ changes for different choices of x_1 and x_2. During the synthesis of the DM transmitter in Fig. 2 its power efficiency, $\mathrm{PE}_{\mathrm{DM}}$, see definition in (25) in [1], is confined to be greater than 50%.

$$\boldsymbol{AF}_i = \sum_{m=1}^{M} \left(A_{im} e^{j\pi\left(m - \frac{M+1}{2}\right)\cos\theta} \right) \quad (7)$$

The analysis above scales since by increasing the number of receivers up to M, with one receiver representing the eavesdropper, multi-beam DM systems (up to $M-1$ beams) can be synthesized. A multi-beam DM system has the capability of simultaneously transmitting independent information data streams along different desired spatial directions in free space, while at the same time distorting signals formats along all other directions by projecting orthogonal interference into these regions.



(b)

Fig. 3. Array (a) magnitude and (b) phase patterns for 50 random QPSK and BPSK symbols transmitted in a synthesized dynamic dual-beam QPSK-BPSK DM transmitter with selected communication directions of 45° and 120° respectively.

For example a 1-D 5-element dual-beam dynamic DM transmitter is synthesized, Fig. 3. Two independent signals x_1 and x_2, modulated with identical symbol rate Gray-coded QPSK and BPSK signals respectively, are selected to be transmitted along 45° and 120°. During the DM synthesis three diagonal elements q_1, q_2, and q_3 in matrix $\boldsymbol{Q}$, for dual-beam DM systems, are set to be unity, which means that the radiation gains along 45° and 120° for the two information data streams are identical, Fig. 3 (a). $\mathrm{PE}_{\mathrm{DM}}$ is confined to be greater than 33%. It is noted that phases are wrapped along direction 120° when the BPSK symbol '0' is sent, Fig. 3 (b).

From Figs. 2 and 3 it is observed that information data, i.e., the QPSK signal in the single-beam DM system, and the QPSK and BPSK signals in the dual-beam DM system, can only be conveyed without distortion along their prescribed directions in free space, while along all other spatial regions, they are scrambled randomly.

The above DM synthesis method described can be extended for applications involving a multipath environment in a straightforward manner. This can be achieved by simply replacing the free space $\boldsymbol{H}$ in (1) with the channel matrix $\boldsymbol{G}$ in a multipath scenario. The columns in $\boldsymbol{G}$ are the channel vectors between the DM transmitter and each receiver. One of these receivers is used to represent a hypothetic eavesdropper randomly positioned within the field of view of the system.

It should be noted that the orthogonal vector DM synthesis method presented in [1], [14], [15] achieves DM properties by projecting interference in the null towards the desired receiver. Each basis in the null space of channel vector or matrix corresponds to one degree of spatial multiplexing capacity in MIMO systems. In other words the orthogonal vector approach can be regarded as a particular application of MIMO systems, i.e., transmitting interference in the de-multiplexing channels that are not occupied by useful information. This statement, to the authors' knowledge, is the first attempt to create a bridge between them.

The orthogonal vector method and the approach presented in this paper are closely linked, as discussed above. They, however, are not equivalent. The orthogonal vector approach focuses on the precise control on the $\mathrm{PE}_{\mathrm{DM}}$ by manipulating the statistical distribution of the injected interference. The details can be found in [1]. While the MIMO inspired DM synthesis approach is devoted to seek generalized transmission coefficients of the beam-forming networks $\boldsymbol{P}$, which are required for DM transmitters. It is noted that the Fourier beam-forming lens adopted in [10] is only one particular option in infinite possible solutions. Since the matrix $\boldsymbol{P}$ does not necessarily preserve power between input and output, this method loses precise control on $\mathrm{PE}_{\mathrm{DM}}$.

IV. BER Simulation Results

In order to evaluate the performance of the example DM systems synthesized in Section III, BER simulations are performed by transmitting 10^{+7} random symbols. Transmission signal to noise ratios (SNRs) along the pre-specified directions are set to 12 dB, and then 20 dB for the free space DM systems. For each case the AWGN contribution is identical in all spatial directions. In the BER

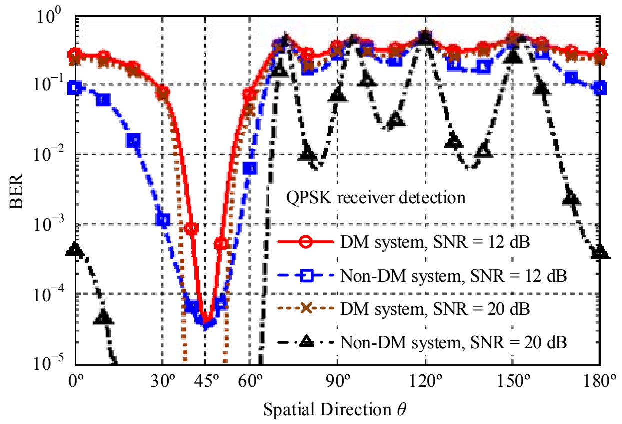


Fig. 4. Simulated BER spatial distributions in non-DM and single-beam dynamic DM systems with Gray-coded QPSK modulation for SNRs of 12 dB and 20 dB.

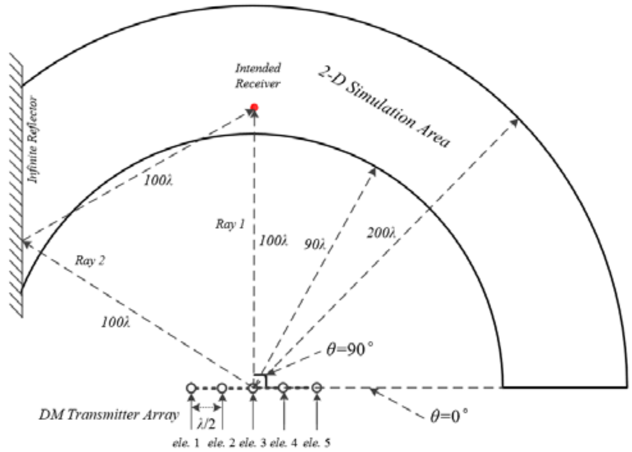


Fig. 6. Simplified two-ray multipath model.

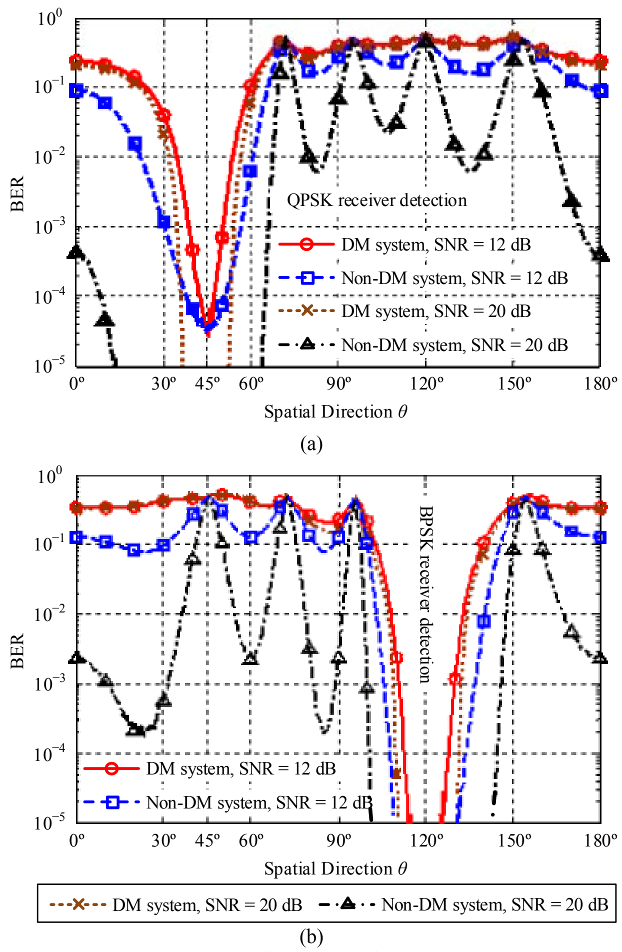


Fig. 5. Simulated BER spatial distributions detected by (a) QPSK receivers and (b) BPSK receivers in non-DM and dual-beam dynamic DM systems for SNRs of 12 dB and 20 dB.

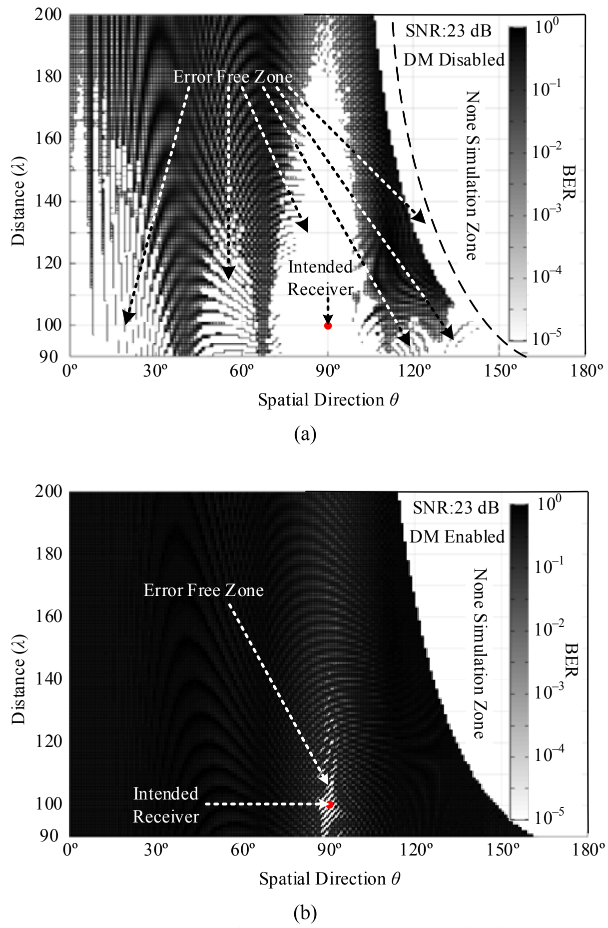


Fig. 7. Simulated BER two-dimensional (2-D) spatial distributions in non-DM and dynamic DM systems with Gray-coded QPSK modulation for SNR of 23 dB. Non-DM system is a classical MISO system, which can be obtained by overlapping the potential eavesdropper and the intended receiver, and setting x_2 in (6) to be zero. None simulation zone is the area blocked by the infinite perfect reflector.

simulations it is assumed that legitimate receiver(s) and eavesdroppers are located at a same distance away from transmitters, which for free space leads to an identical path loss associated with them and makes calculated array factors usable as signal power spatial distributions. The details of the BER calculation procedures used can be found in [16]. From Fig. 4 and Fig. 5 it can be concluded that when compared with the corresponding conventional, i.e., non-DM, systems, whose transmitter array excitations have uniform magnitudes and progressive phases so that the main radiation beams are steered towards selected communication directions, DM systems have the ability to narrow the main BER beamwidth and suppress BER sidelobes, in such a fashion to lower the possibility of unwanted interception. For fair comparison the BERs along the selected communication directions for both non-DM and DM systems are normalized to be identical, i.e., the SNRs in non-DM systems are also set to be 12 dB and 20 dB respectively.

In order to further demonstrate the proposed DM synthesis approach in multipath scenario, a simplified two-ray model in Fig. 6 is used for simulation. The intended receiver is assumed to be located along boresight of a 5-element DM transmitter array at a distance of 100λ from it. At each point between 90λ to 200λ there exists two rays, one of which is reflected from an infinite perfect reflector. In addition the pass loss of each ray is considered here in simulation. To facilitate BER visualization in Fig. 7, Gray-coded QPSK transmission with an SNR value of 23 dB was chosen. Similar to the results obtained for the free space cases presented in Fig. 4 and Fig. 5, the synthesized DM system in the multipath environment helps secure the information transmission by greatly shrinking the decodable area around the intended receiver and alleviating information leakage at other spatial regions.

V. Conclusion

It has been shown that the DM system can be regarded as a MIMO system operating in free space with separately located non-cooperating receivers. In order to gain enhanced security performance one degree-of-freedom of spatial multiplexing is sacrificed by radiating interference that is orthogonal to transmitted useful information. With these findings a new generalized DM synthesis approach was established. The establishment of a link between DM and MIMO technologies may open a way for further DM development.

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