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Vector Representation of Directional Modulation Transmitters

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Abstract— Directional Modulation (DM) is a recently proposed technique for securing wireless communication. In this paper we point out that modulation-directionality is a consequence of varying the beamforming network, either in baseband or in the RF stage, at the information rate. In order to formalize and extend on previous analysis and synthesis methods a new theoretical treatment using vector representations of directional modulation (DM) systems is introduced and used to obtain the necessary and sufficient condition for achieving requisite DM transmitter characteristics.

Index Terms—constellation track, directional modulation, vector path, vector representation.

I. INTRODUCTION

Security is an important requirement for commercial wireless systems. Recently the directional modulation (DM) technique has been proposed as a promising method to provide an extra layer of security for wireless communication systems by exploiting flexibility directly at the physical layer [1]-[8]. Generally, DM is a transmitter side technology that is capable of projecting digitally encoded information signals into a pre-specified spatial direction while simultaneously distorting the constellation formats of the same signals in all other directions. In [1], [2] parasitic DM structures for millimeter-wave operations, termed by authors as near-field direct antenna modulation (NFDAM), were described. However, the requirement of a large number of parasitic array elements, which is hardly applicable in microwave systems, and the complex near-field electromagnetic boundaries hinder the further development of this DM structure. Since then, a simplified DM synthesis method was proposed based on actively driven antenna arrays [3]-[7]. It utilizes optimization algorithms, e.g., the genetic algorithm in [3]-[5] and particle swarm optimization in [6], [7], to minimize the value of an appropriate cost function, which links the DM system performance and the DM transmitter array settings. More recently, the concept of antenna subset modulation (ASM) was developed [8]. Here by randomly exciting a subset of antenna elements in an array on a per transmitted symbol basis, the DM properties can be obtained.

All of the authors in the above mentioned DM schemes claimed that DM properties were obtained due to the modulation occurring at the RF stage, and not at baseband as in a conventional transmitter. However, in [9]-[12] other DM structures were proposed with modulation taking place within

both baseband and RF modules.

In this paper we argue that it is not where in the transmitter architecture modulation occurs, but the capability of altering the gain of beam-forming networks at modulation rates, which can be performed at either analogue RF stage or digital baseband, that makes a system exhibit DM characteristics.

In Section II of this paper, the essence of the DM technique is reappraised. This leads to a development of a new type of DM transmitter which uses a digital DM architecture. In Section III, a generic tool of vector representation in IQ space for DM transmitter arrays is developed. Using this tool, the necessary and sufficient condition for achieving DM characteristics is deduced. In Section IV, some typical DM transmitters are analyzed from this vector perspective to illustrate its effectiveness. Conclusions are drawn in Section V.

II. 1-D CONVENTIONAL AND DM TRANSMITTER ARRAY CONFIGURATIONS

A general equation for calculating the superimposed radiation from a series of radiating antenna elements can be formed by using complex exponent formulation. Thus in the free space if we wish to predict the vector summation of a series of radiators organized in a one-dimensional (1-D) array, as for example in Fig. 1, then we consider the electric field vector \mathbf{E} (the polarization is assumed to be linear throughout this paper), we can write that for N elements, the summed electric field at some distant observation point R is

$$\mathbf{E}(\theta) = \frac{e^{j\vec{k}\cdot\vec{r}}}{|\vec{r}|} \begin{bmatrix} \mathbf{A}P_1(\theta) \\ \mathbf{A}P_2(\theta) \\ \vdots \\ \mathbf{A}P_N(\theta) \end{bmatrix}^T \begin{bmatrix} A_1 \cdot e^{j\vec{k}\cdot\vec{x}_1} \\ A_2 \cdot e^{j\vec{k}\cdot\vec{x}_2} \\ \vdots \\ A_N \cdot e^{j\vec{k}\cdot\vec{x}_N} \end{bmatrix} \quad (1)$$

where \vec{k} is the wavenumber vector along the spatial transmission direction, and \vec{r} represents the location vector of the receiver relative to the transmitter array phase center.

Without loss of generality, we assume that the antenna far-field radiation patterns of each array elements ($\mathbf{A}P_n(\theta)$, $n = 1, 2, \dots, N$) are isotropic and spatial spacing ($|\vec{x}_{n+1} - \vec{x}_n|$) between each two consecutive elements is uniform and equals one half wavelength. As a consequence, the electric field \mathbf{E} is solely determined by array element excitations (A_n), (2),

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$$\mathbf{E}(\theta) = \sum_{n=1}^N \underbrace{\left(A_n \cdot e^{j\pi \left(n - \frac{N+1}{2} \right) \cos \theta} \right)}_{B_n} \quad (2)$$

It is noticed that the term, $e^{j\vec{k} \cdot \vec{r}} / |\vec{r}|$, is dropped for convenience.

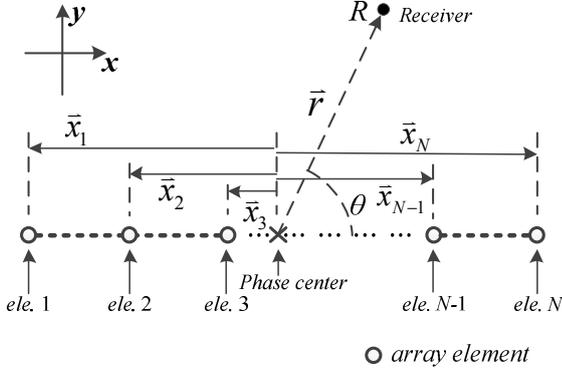


Fig. 1. Illustration of a 1-D antenna array.

A. 1-D Conventional Transmitter Array

Generally, in a conventional transmitter with a 1-D antenna array, Fig. 2, prior to coupling onto the antenna elements, information data is inserted at baseband and up-converted, then distributed to each antenna element via a beam-forming network. Since the beam-forming network is linear and usually can only vary at the channel fading rate, which is far slower than the modulation rate, the complex gain \mathbf{G}_n can be regarded as a constant. Thus the \mathbf{E}_m is only a scaled version of information signal \mathbf{D}_m at each spatial direction, (3), where subscript 'm' refers to the m^{th} symbol transmitted. As a consequence, in this conventional omni-directional modulation (ODM) system, the modulation format, namely the constellation patterns in IQ space, is preserved along all spatial direction, i.e., \mathbf{M} in (3) is the magnitude of the received signal.

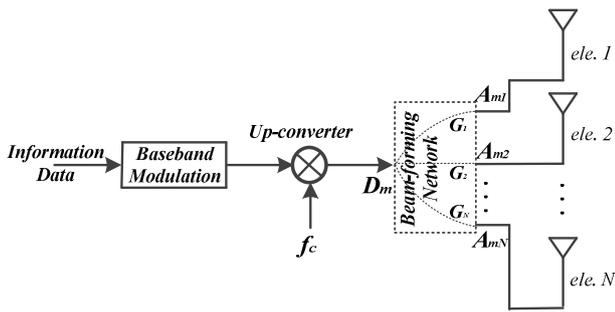
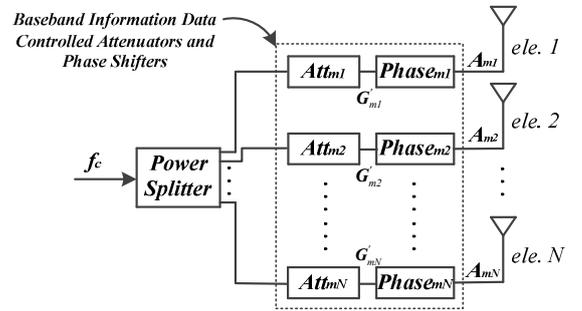


Fig. 2. Conventional 'non-DM' transmitter array structure.

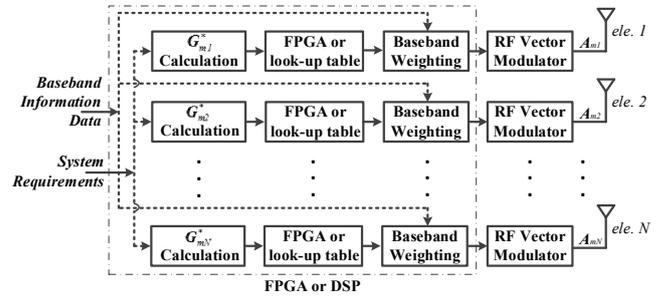
$$\mathbf{E}_m(\theta) = \sum_{n=1}^N \underbrace{\left(\frac{\mathbf{D}_m \cdot \mathbf{G}_n^*}{A_{mn}} \cdot e^{j\pi \left(n - \frac{N+1}{2} \right) \cos \theta} \right)}_{\mathbf{M}} = \mathbf{D}_m \cdot \sum_{n=1}^N \underbrace{\left(\mathbf{G}_n^* \cdot e^{j\pi \left(n - \frac{N+1}{2} \right) \cos \theta} \right)}_{\mathbf{M}} \quad (3)$$

B. 1-D DM Transmitter Array

In order to further enhance the security level, another degree of freedom can be introduced by varying \mathbf{G}_n and hence \mathbf{M} during the data transmission at the modulation rate, denoted as \mathbf{G}_{mn} and \mathbf{M}_m respectively, to release the direct dependence of \mathbf{E}_m on \mathbf{D}_m , in other words distort constellation patterns along unsecured spatial directions. By re-writing (3) as (4) and (5) for DM case, two interpretations can be drawn. The first, from a microwave engineering perspective, (4), $(\mathbf{D}_m \cdot \mathbf{G}_{mn}^*)^*$ can be considered as the complex gain, \mathbf{G}'_{mn} , of a baseband information data controlled analogue beam-forming network, into which an RF carrier f_c , instead of the modulated data stream \mathbf{D}_m , is injected, Fig. 3(a). Alternatively, from a signal processing aspect, (5), $\mathbf{D}_m \cdot \mathbf{G}_{mn}^*$ can be regarded as uniquely weighted m^{th} data fed into the n^{th} array element. The weighting is readily to be implemented at baseband prior to the up-conversion, Fig. 3(b).



(a) Generic analogue DM transmitter structure



(b) Generic digital DM transmitter structure

Fig. 3. Generic analogue and digital DM transmitter architectures.

$$\mathbf{E}_m(\theta) = 1 \cdot \sum_{n=1}^N \left(\left(\mathbf{D}_m \mathbf{G}_{mn}^* \right) \cdot e^{j\pi \left(n - \frac{N+1}{2} \right) \cos \theta} \right) \quad (4)$$

$$\mathbf{E}_m(\theta) = \begin{bmatrix} \mathbf{D}_m \mathbf{G}_{m1}^* & \mathbf{D}_m \mathbf{G}_{m2}^* & \cdots & \mathbf{D}_m \mathbf{G}_{mN}^* \end{bmatrix} \cdot \begin{bmatrix} 1 \cdot e^{j\pi \left(1 - \frac{N+1}{2} \right) \cos \theta} \\ 1 \cdot e^{j\pi \left(2 - \frac{N+1}{2} \right) \cos \theta} \\ \vdots \\ 1 \cdot e^{j\pi \left(N - \frac{N+1}{2} \right) \cos \theta} \end{bmatrix} \quad (5)$$

It is noted that the analogue DM transmitter architecture illustrated in Fig. 3(a) is similar to the DM structures proposed in [3] and [7]. In this DM architecture very demanding requirements are imposed onto the analogue beam-forming networks, in which the switching speed of high-precision attenuators and phase shifters has to be equivalent to the modulation rate, which makes the system implementation costly and unreliable. On the contrary, the digital DM transmitter architecture, Fig. 3(b), in which beam-forming is performed digitally at baseband, i.e., baseband weighting, can utilize mature digital baseband technology to bypass the barriers that analogue DM systems confront.

With the analyses and discussions in this section, we can see that the modulation directionality is owed to updating the beam-forming network (either by analogue or digital means) at the modulation rate, and not owed to the actual stage at which the modulation takes place.

III. VECTOR REPRESENTATION FOR DM ARRAYS

In this section we propose a description technique, i.e., vector representation in IQ space, for DM transmitter arrays, which could lend itself to both analysis and synthesis of any class of DM structures.

From the signal processing perspective, the \mathbf{E} in (2) can be regarded as a constellation point in IQ space, denoted as \mathbf{C}_m for the m^{th} symbol transmitted, (6). The complex number $\mathbf{B}_{mn}(\theta)$ can be regarded as a vector. In this paper we choose \mathbf{B}_{mn} along a prescribed secure communication direction θ_0 , instead of along an arbitrary spatial direction θ , as the vector representation for the DM transmitter array, because not only does $\mathbf{B}_{mn}(\theta_0)$ determine array excitation A_{mn} as does $\mathbf{B}_{mn}(\theta)$, but also the vector summation of $\mathbf{B}_{mn}(\theta_0)$ for each n reaches the standard constellation point $\mathbf{C}_{m, st}$ in IQ space. In Fig. 4(a), an example vector path along θ_0 for a five-element array is illustrated. It needs to be pointed out here that the vector path is different to the phasor diagram [13], in which the excitation strategies are not involved. When scanning the observation angle θ in (6), the constellation track in IQ space, $\mathbf{C}_m(\theta)$, of the m^{th} symbol can be obtained. For example, Fig. 4(b) shows the constellation track corresponding to the vector settings in Fig. 4(a).

$$\mathbf{C}_m(\theta) = \sum_{i=1}^N \underbrace{\left(A_{mi} \cdot e^{j\pi \left(n - \frac{N+1}{2} \right) \cos \theta} \right)}_{\mathbf{B}_{mi}(\theta)} \quad (6)$$

Since $e^{j\pi \cos \theta}$ for different n are orthogonal to each other within the spatial range 0° to 180° , linearly independent excitation settings A_{mn} (or vector paths $\mathbf{B}_{mn}(\theta_0)$) for different m inevitably lead to linearly independent constellation tracks in IQ space. In other words, constellation patterns along other unselected communication directions are inherently distorted as long as vector paths for each unique modulation symbol at desired direction θ_0 are linearly independent.

From the above discussions we can infer that the DM property is achieved only when:

$$\begin{cases} \sum_{n=1}^N \mathbf{B}_{mn}(\theta_0) = \mathbf{C}_{m, st}(\theta_0) & (7) \\ \begin{bmatrix} \mathbf{B}_{q1}(\theta_0) & \mathbf{B}_{q2}(\theta_0) & \cdots & \mathbf{B}_{qN}(\theta_0) \end{bmatrix} \\ \neq \mathbf{K} \cdot \begin{bmatrix} \mathbf{B}_{m1}(\theta_0) & \mathbf{B}_{m2}(\theta_0) & \cdots & \mathbf{B}_{mN}(\theta_0) \end{bmatrix} \end{cases} \quad (8)$$

where \mathbf{K} can take any arbitrary complex value and q, m correspond to different modulated symbols.

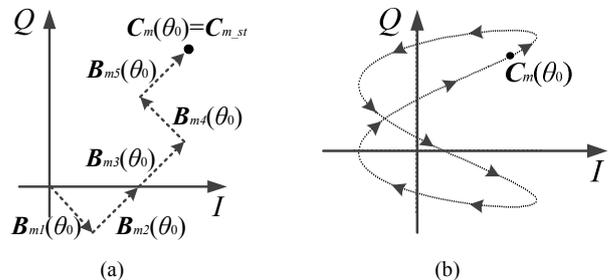


Fig. 4. (a) An example vector path and (b) its corresponding constellation track for a 1-D five-element array with one half wavelength spacing.

IV. ANALYSES OF SOME TYPICAL DM TRANSMITTER ARRANGEMENTS FROM THE VECTOR PERSPECTIVE

In this section we analyze for the first time using the vector tools presented in Section III some typical DM transmitter arrangements that have appeared in the recent literature.

A. Phased DM transmitter arrays [3], [5]-[7]

Compared with the parasitic DM structures reported in [1], [2], an effective effort on simplifying the synthesis process was made by introducing active phased DM array architectures [3], [5]. However, one major drawback of the synthesis method is that the standard constellation format cannot be consistently formed along a pre-specified secure communication direction. This indicates that a certain amount of energy is wasted under the same bit error rate (BER) criteria. Thus a DM transmitter obeying the complete necessary and sufficient requirement given in Section III cannot be synthesized with this method. From the vector point of view, this problem can be readily solved by imposing the constraint in (7) during the optimization. The problem can also be solved by post-calibrations as explained in [6] and [7], however a this approach results in a loss of control on the total power consumed by these DM arrays.

With vector representation, we can graphically illustrate the DM transmitter array in IQ space, and set constraints, including system power efficiency, in a straightforward and visualized manner.

B. Array-subset-modulation DM transmitter arrays [8]

By updating the selection of actively driven subset in a redundant antenna array on a per symbol basis, a DM transmitter, termed by authors as antenna subset modulation (ASM), has been reported [8]. Since the distorted constellation patterns along each unsecured communication direction is dynamically updated over time, instead of distorted, but

constant with respect to time, constellations in the DM systems in [1]-[7], ASM DM systems attach more challenges to potential eavesdroppers' attempting to recover information data. In the ASM DM system in [8], the array element number in the selected subset was fixed to the number of RF transmitter chains, and the value of the phase shifter before each antenna was chosen to be the one for classical beam-steering array with main beam pointing to the desired spatial direction. Using the vector representations, an example five-element ASM DM transmitter array modulated for QPSK is illustrated in Fig. 5(a). The array element number in subset is set to 3. The resulting constellation tracks were shown in Fig. 5(b). Gray coding is adopted throughout in this paper, thus QPSK symbols '11', '01', '00' and '10' should lie in the first to the fourth quadrants in IQ space respectively along the direction pre-assigned for transmission. When the choice of subset changes, which happens constantly during the symbol stream transmission, the corresponding constellation track changes accordingly.

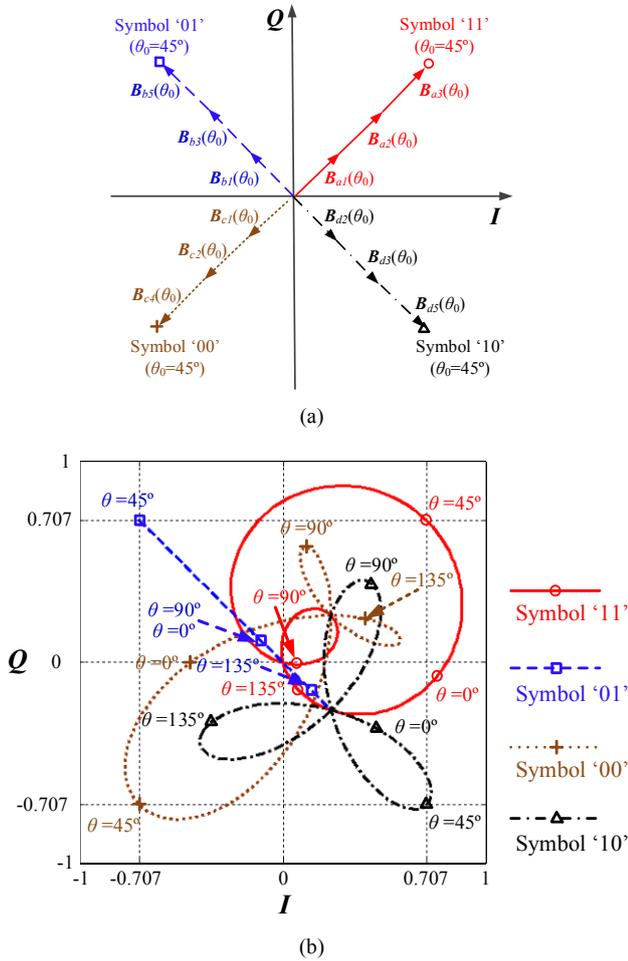


Fig. 5. (a) Vector paths for an example five-element ASM DM transmitter array modulated for QPSK and (b) their corresponding constellation tracks.

C. Fourier lens DM transmitter arrays [11], [12]

By orthogonally injecting information signal and artificial

interference into Fourier lens, e.g., Butler matrix in [12] and Fourier Rotman lens in [11], DM transmitters can be constructed. These avoid the use of RF switches or switchable RF components adopted by DM systems in [1]-[10]. Take a DM transmitter with a 5 by 5 Fourier lens as an example, when the third beam port is excited with a QPSK symbol '11', i.e., $e^{j\pi/4}$, this signal is distributed to 5 antennas at array ports with half wavelength spacing, and then focused in the far-field in-phase along the array boresight direction. If there are no excitations at other remaining beam ports, the vector path for this symbol in IQ space is shown in Fig. 6(a), from which we can see that the antenna array is excited by signals with uniform amplitude and progressive phases. When a signal of $0.5e^{j0}$, for example, is injected into the second beam port, it alters the antenna array excitations, and hence the vector path, Fig. 6(b). It can be seen that there is no contribution of this signal on the vector summation along the boresight direction, as guaranteed by the characteristic of beam orthogonality processed by the Fourier lens. Whereas this altered vector path indicates a scrambled constellation point along all other spatial directions, (8). If the injected signal at the second beam port is constantly updated during data transmission, the constellations

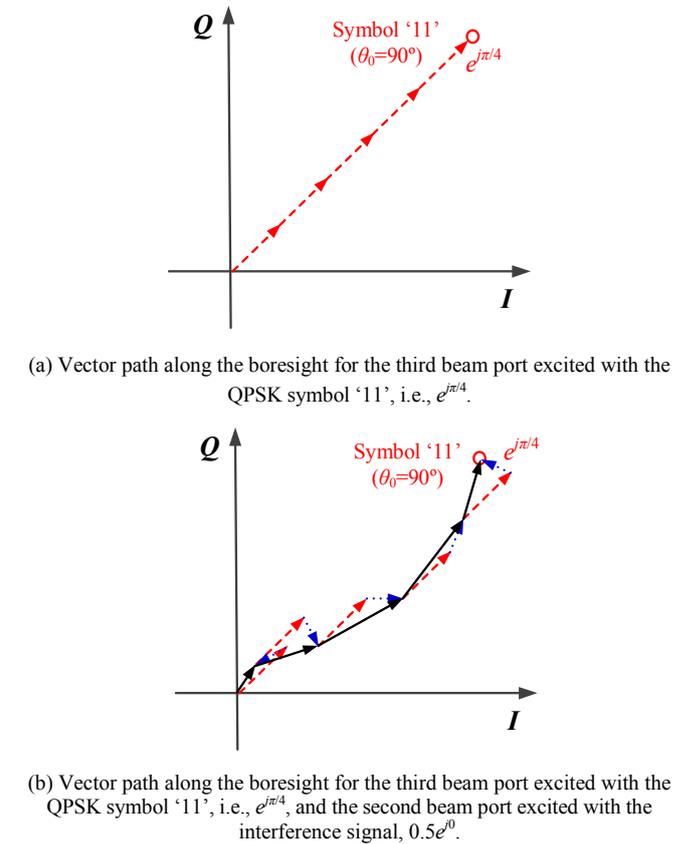


Fig. 6. Vector paths along the boresight, the selected secure communication direction, for an example 5 by 5 Fourier lens DM transmitter. (' \cdots '): the vectors associated with the QPSK symbol '11', i.e., $e^{j\pi/4}$, excited at the third beam port; (' \cdots '): the vectors associated with the interference signal, $0.5e^{j0}$, injected at the second beam port; (' \rightarrow '): the vectors when the second and the third beam ports are, respectively, excited with the same QPSK symbol and the interference signal)

of the QPSK symbol '11' at directions other than boresight would be dynamically scrambled as happens in [8]. Similar results can be obtained for the cases of artificial interference injected at the other remaining beam ports.

Let us now analyze this DM configuration from a different perspective. Imagine that we arbitrarily alter the vector path while fixing the path destination at the standard constellation point, (7), which is the received symbol along a prescribed direction. After subtracting the vectors associated with array excitations routed from the beam port into which the information signal injected, from each vector segment, the resulting vectors can be used to calculate the antenna array excitations contributed by interference signal at other beam ports. With these parameters, the transfer function of the lens before the antenna array can be constructed. Since the initial manipulation on vector path is arbitrary, the resulting network can be a non-Fourier lens. This finding suggests that Fourier lens DM is only a special case DM transmitter implementation.

With the reappraisal of the three typical DM transmitters presented in this section, we can see that vector representation is an effective and powerful tool by which DM systems can be analyzed.

Using this vector perspective it can be concluded that, all previous DM attempts, as well as the digital DM transmitter structure proposed in this paper, are just particular physical implementations of different vector paths under various constraints, e.g., the length of each vector segment is identical for the DM systems in [3], [5]; a fixed number of vectors have uniform length and the same direction pointing to the standard constellation symbol in IQ space while the other vectors have zero length in [8]; vectors with uniform length and the same direction are disturbed by 'interference vectors', which cancel each other along the secure communication direction in [11], [12]; no constraints, except for the necessary and sufficient condition (7), (8), are imposed in digital DM transmitters.

V. CONCLUSION

This paper revealed the essence of the DM technique. A formal tool using vector representation was developed that can be used to analyze any DM system. The necessary and sufficient conditions for DM transmitters synthesis was derived directly from this vector approach. The effectiveness

of the vector representations was illustrated via the reappraisal of several typical DM transmitters reported in the recent literature.

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