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Developments in Directional Modulation Technology

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Abstract—**Directional modulation (DM), as a promising physical-layer security technique, is able to secure wireless communications by virtue of the property of its direction-dependent signal modulation format transmission. Here modulated signal waveform signatures can only be detected by legitimate receiver(s) positioned along a-prior assigned directions. This paper reviews the development in DM technology over recent years, and provides some recommendations for future studies.**

Index Terms— **Directional modulation (DM), Physical-layer security, Secure wireless communication.**

I. INTRODUCTION

A directional modulation (DM) transmitter has the unique capability of projecting intentionally distorted signals along all spatial directions other than an a-priori selected secure communication direction(s) in free space. In such a fashion only receivers located along this pre-specified direction(s) are able to capture the correct signal signature, leading to successful dada recovery, while distorted signal waveforms radiated along other directions make potential eavesdropping difficult [1]. Instead of mathematical encryption at higher protocol layers as adopted in classical cryptographic means [2], this promising technology does not involve any keys, and secures wireless information transmission directly at physical-layer, enabling information theoretical security [3].

There have been various reported transmitter architectures that can achieve direction-dependent signal modulation. To facilitate discussion we separate these physical arrangements into two broad categories, (i) those that manipulate directly the antenna radiating structures and (ii) those that manipulate antenna array excitation weights.

The direct manipulation of antenna radiating structures means utilizing reconfigurable antennas or antenna arrays to construct DM transmitters. This is achieved by constantly reconfiguring antenna radiators, normally at per symbol basis, during the entire data transmission period. The change of the radiator near field alters their far-field radiation behaviors as a function of spatial direction. Thus through careful design DM properties, i.e., preservation of standard signal waveforms along pre-selected direction and waveform distortion along all other directions, can be achieved. The first such type of DM transmitter consisted of a large number of reconfigurable passive reflectors coupled in the near field of a center-driven antenna, [4]-[6], and was named as near-field direct antenna modulation (NFDAM). The concept of the NFDAM DM transmitter is shown in Fig. 1. Each set of switch state combinations on the near-field passive reflectors contributes to a unique far-field radiation pattern, which can be translated into constellation points in IQ space detected along each spatial direction in free space. After tedious measurements of a multiplicity of patterns, with regard to a large number of possible switch combinations, have been done, a usable constellation pattern detected along the desired direction may be selected, and the corresponding switch settings for secure transmission of each symbol memorized in order to reproduce this usable state. Because the passive near-field diffraction effect is complex with respect to spatial direction, the constellation diagrams along un-selected directions are distorted in a complicated, and nearly unpredictable, manner. This complex interaction in the near-field and their spatial dependent transformation into the far-field makes the synthesis of these NFDAM DM transmitter states a difficult and time-consuming task. What's more, the large number of passive reflectors required make this DM structure difficult to realize for microwave applications.
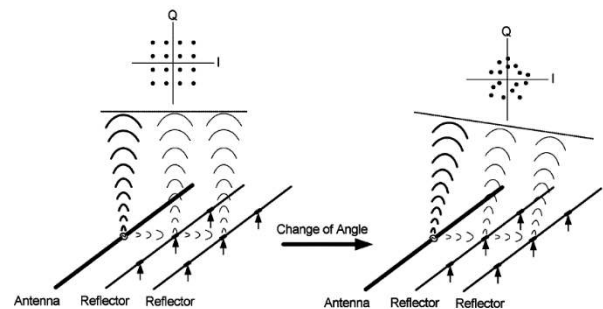

Fig. 1. Concept of NFDAM DM structure [4].

Similar to the NFDAM DM structure, a DM transmitter consisting of an array of continuous-wave (CW) excited reconfigurable antenna elements was presented in [7], Fig. 2.

Here the relaxation of the complex near-field coupling associated with NFDAM makes the mathematical representation of far-field patterns in these types of active DM transmitters possible, enabling the use of optimization algorithms for synthesis through tedious repetitive analysis.
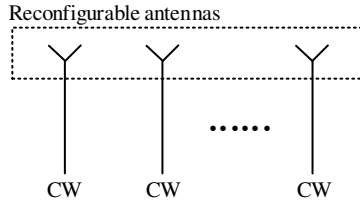

Fig. 2. Active DM transmitter with reconfigurable array elements

Apart from the unfriendly synthesis methods associated with the above two DM structures, another major problem is that this approach cannot always guarantee a usable outcome for each synthesis with regard to various signal modulation formats and different pre-specified communication directions due to the limited number of antenna or antenna array configurations available.

The above mentioned issues can be solved by replacing reconfigurable antenna radiators with independent reconfigurable array element excitations. A generic excitation-reconfigurable DM transmitter array, using radio frequency (RF) components positioned before each antenna element, is depicted in Fig. 3. Since the number of states of attenuators and phase shifters are normally much higher than the states available from reconfigurable antennas, then suitable far-field patterns can be readily obtained for each array setting provided the arrays active element patterns (AEPs) [8] are known. This type of excitation-reconfigurable DM transmitter arrays is more synthesis-friendly, and thus has been widely investigated in different variants. In [9]-[11] bit-error-rate-driven (BER-driven) and optimization-algorithm-assisted DM synthesis approaches were described, and the system prototype was demonstrated in [12]. DM transmitter performance with 2-bit phase shifters, were discussed or experimentally illustrated in [13]-[16].
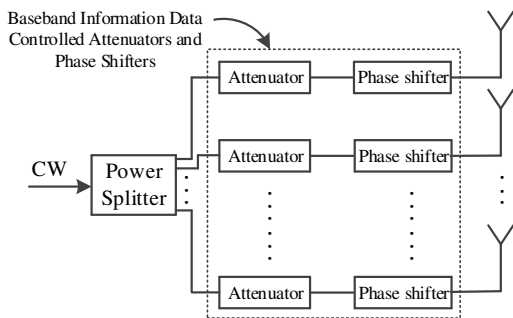

Fig. 3. Generic excitation-reconfigurable DM transmitter array [11].

In order to facilitate the discussion on recent DM advancement in Section II, the pros and cons of two previously developed DM transmitter types, i.e., radiator-reconfigurable and excitation-reconfigurable DM transmitters, are summarized in Table I. Some recent DM development for multi-beam transmission and multipath applications are presented in Section III. Section IV concludes this review paper and provides some recommendation for future work.

II. RECENT ADVANCEMENTS IN DIRECTIONAL MODULATION TECHNOLOGY

From Table I it can be concluded that all the cons of the radiator-reconfigurable DM transmitter type are rooted in its structure and its working mechanism, thus these intrinsic features cannot be overcome. As a consequence all recent advancements have focused on the excitation-reconfigurable DM transmitter type.

A. DM Transmitter Mathematical Model

A vector model for DM transmitters was introduced in [1], [17]. This model, in principle, covers both DM transmitter types summarized in Section I. However, since there is no effective and analytical way to control vectors in IQ space for radiator-reconfigurable DM type transmission, the proposed vector model is only useful for the analysis and synthesis of the excitation-reconfigurable DM transmitter. With the help of the vector representation model, it can be concluded that modulation directionality can be made to be entirely dependent on updating the beamforming networks, either by analogue or digital means at the modulation rate. The necessary conditions for DM transmitter arrays to operate successfully in this fashion were proven, see (5) and (6) in [1]. Some other definitions, also derived from the vector method, that are essential for further DM development are presented below;

Definition: Signal constellation distortion in IQ space along unselected communication directions can be either constant during the entire transmission sequence, or can be dynamically updated usually at the information symbol rate. These are, respectively, defined as **static** and **dynamic** DM systems [1].

Definition: **DM power efficiency** (PE_{DM}) describes the percentage of the total radiated energy that is utilized for useful information transmission. Mathematically, it is defined as in (1), [1],

$$PE_{DM} = \frac{\sum_{i=1}^{N}\left(\sum_{n=1}^{N}\left|A_{in\_nonDM}\right|^2\right)}{\sum_{i=1}^{N}\left(\sum_{n=1}^{N}\left|A_{in\_DM}\right|^2\right)} \times 100\% \qquad (1)$$

where I is, for static DM, the number of modulation states, or, for dynamic DM, the total number of symbols in a data stream. A_{in_nonDM} and A_{in_DM} are the nth (with a total number N) array element excitations for the ith symbol transmitted in

Table. I. Pros and cons of two previously developed DM transmitters types described in Section I

	Pros	Cons
Radiator-reconfigurable DM transmitter	• Only one RF chain is required for NFDAM; • Integration into a single chip for millimeter wave applications is possible.	• No effective and efficient synthesis methods, other than the exhaustive trial and error; • The coupling between central driven antenna and parasitic elements need to be carefully designed for NFDAM. Too strong or too weak coupling would ruin DM characteristics; • Antenna input impedance matching needs to be reconfigurable at the symbol rate; • No adaption for modulations other than QAM is possible; • Difficult to extend it for multipath and/or multi-beam applications; • Quasi-standard signal formats along the pre-specified communication direction; • Complex RF switch bias and control network; • Switches need to work at a rate much higher than the symbol rate.
Excitation-reconfigurable DM transmitter	• Synthesis-friendly; • Have some control on the secrecy performance of DM systems; • Potentially extensible for multipath and multi-beam application.	• Multiple RF chains are required; • Re-synthesis is required if the desired communication direction or modulation schemes change; • The updating speeds of reconfigurable RF components, which also induce quantization errors and losses, have to work at a rate much higher than the symbol rate.

Table II. Summaries of Metrics for DM System Performance Assessment

		Static DM	Dynamic DM			Calculation complexity
			Zero-mean Gaussian orthogonal vectors	Zero-mean Non-Gaussian orthogonal vectors	Non-zero-mean orthogonal vectors	
EVM_{DM}		−	+	−	−	Low
BER	Closed-form equation	•	•	−	−	Low
	Data stream simulation	+	+	+	+	Medium
Secrecy rate	Numerical calculus [19], [20]	+	+	−	−	Medium
	Bit-wise [21]	−	+	−	−	High

'+': Metric works
'•': Metric works for QPSK, but not for higher order modulations
'−': Metric cannot be calculated or does not work

the corresponding non-DM array and DM array, respectively.

B. Assessment Metrics for DM Systems

In order to evaluate the performance of DM systems in a way that is consistent and which allows direct comparison between different systems, assessment metrics were systematically discussed in [18]. It was shown that for static DM systems BER, calculated from either closed-form equations or random data streams, as well as secrecy rate were applicable for system performance evaluation, whereas error-vector-magnitude-like (EVM-like) metrics did not perform well. For dynamic DM systems under the scenarios of zero-mean Gaussian distributed orthogonal interference, see definition in [1], EVM-like metrics, BER, and secrecy rate were equivalent and can be converted into each other. For other interference distributions no closed-form BER and secrecy rate equations were found.

In order to provide readers with a clear picture on metrics for assessing performance of DM systems, all the findings presented in [18] are summarized in Table II.

C. DM synthesis approaches

Seeking new and effective DM synthesis approaches, based on the excitation-reconfigurable DM transmitter architecture, is the most active area in DM research recently. The orthogonal vector method developed in [1], which shares a similar idea with the artificial noise concept, [22], [23], studied in the information theory community, was found to furnish a fundamental and universal DM synthesis strategy. The reason for this is because all existing and other newly proposed DM synthesis methods can be regarded as seeking a subset of orthogonal vectors subject to various constraints and/or system requirements. For example, in [9] and [10] the DM arrays require uniform array excitation magnitudes, equivalent to identical length of excitation vector for each array element in IQ space, and constraints on BER spatial distributions are imposed; for the DM array far-field pattern synthesis approaches in [24]-[26] constraint templates or masks on constellation tracks in IQ space, which, when viewed from microwave engineering perspective, can be translated as far-field radiation patterns, are set; finally for the far-field pattern separation DM synthesis approach in [27] and [28] extra manipulations on

far-field interference patterns that can be considered as patterns generated by orthogonal vectors are applied.

Through various DM synthesis approaches and their associated examples, it is found that DM functionality is always enabled by projecting extra energy into undesired communication directions in free space. This extra energy, which can be either static or dynamic with respect to time, corresponding to static and dynamic DM systems, acts as interference which scrambles constellation symbol relationships along these unselected directions. Intuitively, the larger the interference energy projected, the more enhanced the DM system secrecy performance that can be achieved. It is concluded that the essence of a functional DM system synthesis approaches lies in generating artificial interference energy that is orthogonal to the directions where the intended receivers locate.

D. Other Excitation-reconfigurable DM Transmitter Architectures

In [1] and [17] the digital DM architecture was presented, Fig. 4. It has been further implemented with the help of the Wireless Open-Access Research Platform (WARP) [29], and demonstrated at 2.4 GHz with the real-time data transmission in an anechoic chamber [30]. Compared with the high-cost and low-precision analogue RF solution in Fig. 3, the digital means, which makes use of extensively available high-precision digital components, is more flexible, with respect to the hardware realization of various DM synthesis methods, and is more suitable for advanced dynamic DM systems. More importantly, the digital solution is compatible with the modern transmitter architecture and facilitates the classical mathematic-based cryptographic technology to be appended if additional security is required.
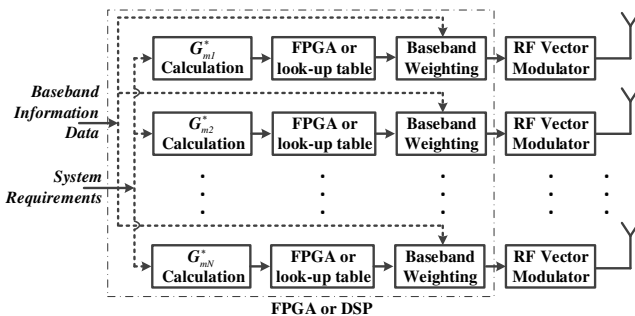

Fig. 4. Generic digital DM transmitter architecture [17].

Other newly proposed excitation-reconfigurable DM transmitter architectures tend to reduce the number of required RF chains. In [31], [32] DM transmitters were constructed using Fourier beamforming networks, of which the orthogonality property in beam space helps separate orthogonal interference from useful information signal excitations, thus only two RF chains are needed, see Fig. 5. This architecture, based on a Fourier Rotman lens, was experimentally verified for 10 GHz operation for real-time data transmissions with both analogue and digital modulations in [33] and [34], respectively. Other research revealed that by inserting a switch array before antennas to

randomly select a subset of elements in an antenna array on a per transmitted symbol basis, dynamic DM transmitters could have been constructed, see Fig. 6. This architecture, name by authors as antenna subset modulation (ASM) in [35] or 4-D antenna arrays in [36], [37], requires only one RF chain, though, on the other hand, beamforming gains are reduced or lost.
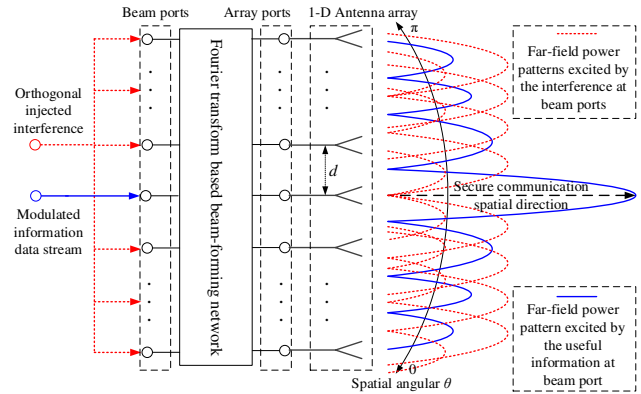

Fig. 5. Fourier beamforming network enabled DM transmitters [32].
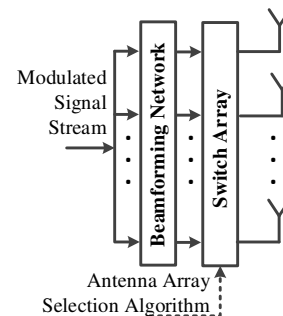

Fig. 6. Structure of ASM or 4-D antenna array.

III. FURTHER EXTENSION OF DIRECTIONAL MODULATION TECHNOLOGY

DM technology was first proposed for secure wireless information transmission along *one* pre-specified direction only in *free space*. It is natural to consider developing *multi-beam* DM systems and also extending its application to *multipath* scenarios. These two aspects are addressed separately below.

A. Multi-beam DM Transmitters

Multi-beam DM transmitters have the capability of projecting multiple independent information data streams into different spatial directions, while simultaneously distorting information signal formats along all other unselected directions. The first multi-beam DM synthesis attempt based on the analogue excitation-reconfigurable DM transmitter architecture in Fig. 3 with 2-bit phase shifters can be found in [38]. Further in [39] the orthogonal vector approach was successfully adapted for multi-beam DM synthesis. When realizing that the orthogonal vectors generate far-field radiation patterns, termed as interference patterns, which have nulls along all desired secure directions,

the far-field pattern separation approach was developed, [28]. Recently a study in [40] revealed that the DM system can be regarded as a kind of multiple-input and multiple-output (MIMO) system, whose intrinsic property includes parallel independent data transmission, when operating in free space and separately located non-cooperating receivers are considered. Thus this multi-beam DM functionality is achieved at the price of loss of spatial multiplexing capacity.

B. DM Transmitters in Multipath Scenarios

'Spatial direction' only makes sense for free space communication, in terms of where receivers locate. In multipath environment a more relevant concept is that of a channel that determines the response each receiver detects. Thus the extension of the DM technology for multipath application can be readily achieved by replacing the transmission coefficients in free space, which are functions of spatial directions, with the channel responses in multipath environment, which are functions of spatial positions. In [41] and [42] examples were provided for the extension of the orthogonal vector approach for multipath environment with the realization facilitated by retrodirective arrays (RDAs) that have the ability to obtain the required channel response automatically. Other DM synthesis methods could have equally been adapted in a similar way for multipath applications.

IV. CONCLUSIONS AND RECOMMENDATION FOR FUTURE WORK

This paper reviewed the development in the DM technology. Specifically Section I summarized some very first proposals of the DM concept. Section II was devoted to the recent advancements in various aspects, including a mathematical model, assessment metrics, synthesis methods, and some new architecture. The extension of the DM technology for multi-beam application and multipath environment was addressed in Section III.

Although rapid development in the DM technology has been achieved in recent years, it is still not mature, needing to be perfected in the following aspects;

- The vector model of the DM technology was established based on a static signal constellation pattern in IQ space. This makes the model not usable for analogue modulation schemes, e.g., amplitude modulation (AM) and frequency modulation (FM), which are trajectories with respect to time if represented in IQ space.

- Current DM technology depends on the assumption of narrow band signals. Wideband transmissions would require new mathematical model and associated synthesis methods.

- The theory of DM enabled RDAs for multipath scenarios has been presented in [41] and [42]. However, the question of how dynamic orthogonal vectors can be generated effectively using minimum hardware resources needs to be addressed.

- Assessment metrics and power efficiency concept may need to be revisited when recently emerged multi-beam DM systems are under consideration.

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