DFT-Based Multi-Directions Directional Modulation

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***Abstract*—In this letter, a physically secure multi-directions directional modulation scheme is proposed. The scheme provides an adaptive beam-width assignment, where each user is granted a different beam width based on its channel condition. The scheme can be efficiently implemented using a discrete Fourier transform (DFT)-based algorithm that divides the spatial dimension into orthogonal narrow sub-beams. Each user is assigned multiple sub-beams that satisfies its pre-set direction of transmission and beam-width requirements. The scheme preserves the secrecy properties of directional modulation algorithms, where each legitimate user is guaranteed a secure communication link to its trusted receiver. The proposed scheme is practically efficient since it can be directly implemented using a DFT-based signal processing core.**

***Index Terms*—Adaptive beam-width, antenna arrays, directional modulation, physical-layer security.**

I. INTRODUCTION

THE CONFIDENTIALITY of wireless data exchange has raised considerable concern, due to the enormous spread of wireless networks and the vulnerability of the wireless channel to various attacks. Alongside the conventional cryptography algorithms, physical layer security was introduced to provide an extra level of protection against malicious attacks [1].

Physical layer security utilizes random properties of the wireless channel to establish a secure path for data transfer to legitimate receivers. Using multiple antennas introduces extra degrees-of-freedom (DoF) in the communication system [2]. This extra DoF can be used to provide the desired secrecy requirements [3]. One of the latest strategies to provide secrecy through multi-antenna systems is *Directional Modulation*.

Directional modulation (DM) is a transmitter side algorithm. It enables the transmission of confidential messages towards a pre-specified direction while transmitting random patterns towards all other directions. The algorithm uses a set of data-driven attenuators and phase-shifters along with antenna arrays, to accomplish directional control over the transmitted signal pattern. Many algorithms are proposed for DM, most of which are focused on single direction transmission [4], while a multi-user multi-path-based DM system appeared in [5]. All these techniques focus on optimizing the secrecy features of DM, leaving the beam-shape to be decided based on the physical structure of the array.

High interest in research focusing on the spatial domain of communication systems has been observed, especially with the rising interest in massive multi-input-multi-output (MIMO) and hybrid beamforming as enabling technologies for 5G networks [6]. The sparse nature of the wireless channel, in the future-targeted mm-wave frequency range, encourages the deployment of large antenna arrays and beamforming algorithms. These new characteristics of the channel initiated a new point of view towards the incorporated channel models. The non-flexible beam structure considered by the DM techniques above, may not be beneficial in such sparse environments.

Recently, the mm-wave community is adopting the *virtual channel* model [7]. Contrary to the widely used statistical model that represents the relation between each transmit/receive *antenna* pair, the virtual channel model dissects the statistical model into three parts, an N_T size fixed steering matrix on the transmitter side, an N_R size fixed steering matrix on the receiver side, and a statistical part that represents the mutual effect between each transmit/receiver *direction* pair, where N_T and N_R are the sizes of the antenna arrays at the transmitter and receiver, respectively. Such representation reflects some of the actual physical structure of the communication channel while maintaining a congenial pattern for capacity calculations.

In the sequel, we introduce a novel secure multi-direction DM transmission algorithm. Based on the virtual channel representation, the proposed algorithm divides the spatial domain into a set of narrow sub-beams. Each transmitted data stream is mapped to a subset of these sub-beams based on the desired transmission direction and beam-width. Such a design has the following benefits:

- Secure communication link for each of the transmitted data streams, with a straightforward extension to multi-path environments.
- Simple implementation via a fixed discrete Fourier transform (DFT) generation matrix, which reduces the system complexity by eliminating the need to change the generation matrix with the change of any transmission direction.
- Adaptive direction and beam-width assignment for each of the transmitted data streams.

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The rest of this letter is organized as follows: Section II provides a review of DM and virtual channel concepts. Section III introduces the system model and the proposed scheme. The results are shown in Section IV. Finally, this letter is concluded in Section V.

II. PRELIMINARIES

In this section, we describe the two main concepts used in this letter; namely, *Directional Modulation* and *Virtual Channel Representation*, which set up the necessary basis for our proposed system.

A. Directional Modulation (DM)

The difference between the DM and conventional beam-forming is in the way of generating the array weights. In conventional beam-forming, array weights only depend on the transmission direction towards the desired receiver θ_i. In contrast, DM generates the weights based on both, the direction, and the data symbol $x(k)$ [8]. While both approaches have the same design target for the received signal, $r(\theta_i, k) = x(k)$, at any time index k, the generated pattern of DM is different as it is randomized along all other directions (i.e., $\theta \neq \theta_i$) [9]. Based on the DM approach, the received signal, r, at any direction, θ, is given by,

$$r(\theta, k) = \mathbf{h}^H(\theta)\mathbf{w}(k), \tag{1}$$

where $\mathbf{w}$ is the vector containing the array weights at the time index k, $\mathbf{h}(\theta)$ is the steering vector of the array towards the direction θ, and $(.)^H$ refers to the conjugate transpose. The steering vector for a uniform linear array (ULA)[1] of size N is given by

$$\mathbf{h}(\theta) = [e^{-j\left(\frac{N-1}{2}\right)\frac{2\pi d}{\lambda}\cos\theta}, e^{-j\left(\frac{N-1}{2}-1\right)\frac{2\pi d}{\lambda}\cos\theta}, \\ \ldots, e^{j\left(\frac{N-1}{2}\right)\frac{2\pi d}{\lambda}\cos\theta}]^T, \tag{2}$$

where λ is the carrier wavelength, and d is the spacing between the array elements.

For a multi-direction transmission, the work in [4] suggests a zero-forcing approach, which leads to weights of the following form,

$$\mathbf{w}(k) = \mathbf{D}\mathbf{x}(k) = \mathbf{H}\left(\mathbf{H}^H\mathbf{H}\right)^{-1}\mathbf{x}(k), \tag{3}$$

with

$$\mathbf{H} = [\mathbf{h}(\theta_1), \mathbf{h}(\theta_2), \ldots, \mathbf{h}(\theta_P)], \tag{4}$$

where θ_i is the desired direction of transmission for the ith data stream, P is the total number of streams to be transmitted simultaneously, and $\mathbf{x} = [x_1(k), x_2(k), \ldots, x_P(k)]^T$ is the data to be transmitted.

B. Virtual Channel Representation

Instead of the black-box statistical representation of the spatial channel, which represents the link between each transmit/receive antenna pair, the authors in [7] suggest that more detailed insights on the physical structure of the channel can be achieved by introducing a virtual model. The approach introduces the channel model as a set of N_T virtual transmitting directions, and N_R virtual receiving directions, where N_T and N_R are the number of antenna array elements at the transmitter and receiver, respectively.

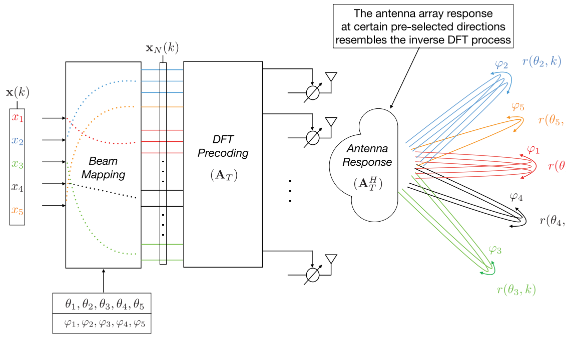

Fig. 1. DFT-based directional modulation block diagram.

Hence, the channel matrix can be deconstructed as follows:

$$\mathbf{G} = \mathbf{A}_R\mathbf{G}_v\mathbf{A}_T^H, \tag{5}$$

where $\mathbf{A}_T = \{\alpha_{pq}^{(T)}\}_{N_T \times N_T}$ and $\mathbf{A}_R = \{\alpha_{pq}^{(R)}\}_{N_R \times N_R}$ are the steering responses of the array at transmitter and receiver, respectively. The matrix entries for a ULA are given by

$$\alpha_{pq}^{(b)} = \frac{1}{\sqrt{N_b}}\exp\left[-j2\pi\left(p - \frac{N_b - 1}{2}\right)\frac{d}{\lambda}\cos\theta_q^{(b)}\right], \tag{6}$$

where $p, q \in [0, 1, \ldots, N_b - 1]$ depending on $b \in \{T, R\}$ for transmitter or receiver blocks, respectively. Here, the virtual directions should represent orthogonal spatial basis to reflect independent information about the channel. To ensure orthogonality of these bases, the directions, $\theta_q^{(b)}$, should be selected according to

$$\theta_q^{(b)} = \arccos\left[\frac{\lambda}{dN_b}\left(q - \frac{N_b - 1}{2}\right)\right]. \tag{7}$$

Remark 1: The selection of such basis results in $\mathbf{A}_T$ and $\mathbf{A}_R$ that exhibit inverse-DFT matrix structure, which performs a transformation from the spatial domain to the angular domain.

Remark 2: $\mathbf{G}_v = \{g_{mn}\}_{N_R \times N_T}$ is the virtual channel matrix, which exposes some insights on the physical structure of the channel. For example, a dense matrix would reflect an environment rich in scatterers, while a sparse matrix means that the channel has distributed sets of clustered scatterers.

III. DFT-BASED DIRECTIONAL MODULATION

Here, we consider a system with a single base-station (BS), which is equipped with an N-sized ULA (i.e., $N_T = N$). The BS has P independent data streams $\mathbf{x} = [x_1(k), x_2(k), \ldots, x_P(k)]$, which are transmitted towards P different directions, $\Theta = [\theta_1, \theta_2, \ldots, \theta_P]$. Moreover, each of the streams has its own beam-width requirement, $\Phi = [\varphi_1, \varphi_2, \ldots, \varphi_P]$. All legitimate and illegitimate receivers are considered to be equipped with a single antenna. The communication channel is a single-path fading channel. The following theorem summarizes our proposed practical system architecture for DM implementation.

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[1] ULA is considered to simplify analysis. For different array geometry, the corresponding steering vector and direction requirements will change.

Theorem 1: The angular domain can be directly controlled by integrating the DFT-processor, $\mathbf{A}_T$, in the generation of the array weights, leading to an array weights generation represented by

$$\mathbf{w}(k) = \mathbf{A}_T \mathbf{x}_N(k), \tag{8}$$

where $\mathbf{x}_N(k)$ is a $N \times 1$ vector containing the data to be transmitted, $x_n(k)$, mapped to their corresponding sub-beams (angles) indexes.

Proof: As mentioned previously, the ULA response acts as an inverse-DFT from the spatial domain to the angular domain when sampled based on equation (7). Figure 1 shows the block diagram for the generation process of the array weights as proposed in the theorem. This structure imitates an OFDM system structure but with both the DFT and its inverse located at the transmitter, with the sub-beams here resembling the subcarriers in the OFDM case. ■

A. Practical Implementation

The proposed system architecture as represented by (8) has several practical implementation benefits as follows:

- The generation matrix, $\mathbf{A}_T$, is a fixed matrix, which is independent of the desired transmission direction, θ_i. This independence simplifies the adaptation process in case of changes in one of the transmissions. Only the sub-beam assignment[2] needs to be changed.
- The generation matrix has a DFT structure, making the weights generation process less complex and more computationally efficient using the FFT-algorithm, compared to the previously suggested zero-forcing scheme.
- With the availability of large size antenna arrays, this structure provides flexibility in controlling the total beam-width assigned to each transmitted stream. If one stream requires a large beam-width,[3] assigning a set of sub-beams to the same stream would serve as a single large beam that satisfies the required width.

B. Physical Layer Security

Proposition 1: The use of DM structure in the proposed system architecture provides a secure communication path for each of the data streams.

Proof: The signal delivered to any receiver will take the form

$$r(\theta, k) = \mathbf{G}\mathbf{w}(k) + z(k) = \mathbf{A}_R \mathbf{G}_v \mathbf{x}_N(k) + z(k), \tag{9}$$

where z is a complex additive white Gaussian noise. Based on the adopted model of single antenna receiver and single path channel,[4] $\mathbf{A}_R = 1$, and $\mathbf{G}_v = \{g_n\}_{1\times N}$. If we consider a subset $\mathcal{N} \subset \{\theta_n\}$, composed of only the sub-beams connecting the intended receiver to the transmitter, then,

$$|g_n| = 0 \qquad \forall n \mid \theta_n \notin \mathcal{N}. \tag{10}$$

We define another subset, $\mathcal{P} \subset \{\theta_n = \theta_p\}$, composed of all sub-beams carrying the information, $x_p(k)$, $p \in [1, 2, \ldots, P]$ (i.e., the transmitter utilized sub-beams out of all the available N sub-beams). Therefore,

$$r(\theta_n, k) = z(k) \qquad \forall n \mid \theta_n \notin (\mathcal{N} \cap \mathcal{P}). \tag{11}$$

Equation (11) refers to the case where the receiver is aligned to any of the virtual directions that are not utilized (i.e., $x_n = 0$). In such case, there is no information transmitted towards the location of that receiver. This limits the access to transmitted signals from outside the information beams. ■

In the following two corollaries we address special secrecy concerns that may rise in special situations.

Corollary 1: The system can be secured even in the case where the eavesdropper is aligned to the information beam, $\theta_n \in (\mathcal{N} \cap \mathcal{P})$.

Proof: In such case, several methods can be applied. One way would be exploiting the multi-path environment. The extension of the proposed scheme to multi-path channels is straightforward, and a cooperative scenario can also be beneficial, similar to the suggestions in [5]. ■

Corollary 2: The system can be secured even in the case where the eavesdropper is out of the information beam, however, it is not aligned to any of the nulled virtual directions

Proof: Contrary to (11), the eavesdropper receives a mixture of all transmitted streams. Here, we can make use of the similarity between the proposed scheme and OFDM structure by applying some OFDM based secrecy method (e.g., reducing the out-of-band transmission). Alternatively, the insertion of artificial noise into the non-utilized sub-beams (nulled virtual directions) would be effective, but it needs careful management to avoid self-interference. ■

Remark 3: The case in Corollary 2 can be represented by a mismatch between the generation matrix, $\mathbf{A}_T$, and the transmission steering matrix, $\tilde{\mathbf{A}}_T$, and the received signal will be

$$r(\theta, k) = \mathbf{G}_v \tilde{\mathbf{A}}_T^H \mathbf{A}_T \mathbf{x}_N(k) + z(k). \tag{12}$$

This resembles the case of OFDM transmission with inter-carrier-interference due to sampling offset. Using [10, eq. (22)], we can define the average received power of the desired symbol at a certain direction, normalized to the symbol power, as

$$\eta(\theta) = \frac{\sin^2\{\pi\beta(\theta)N_s\}}{N_s^2 \sin^2\{\pi\beta(\theta)\}}, \tag{13}$$

where $\beta(\theta) = \Delta\theta/\pi$, and $\Delta\theta = |\theta_i - \theta|$ is the difference between the direction of the desired symbol and the direction of the eavesdropper. Hence, the received SINR at the eavesdropper for the symbol x_p would be

$$\gamma(\theta) = \frac{\eta_p(\theta)}{\sum_{i\neq p} \eta_i(\theta) + \sigma_z^2}. \tag{14}$$

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[2] The sub-beams assignment is included in the vector $\mathbf{x}_N(k)$, where the vector $\mathbf{x}(k)$ is mapped to the desired directions, and the other elements of $\mathbf{x}_N(k)$ are equal to zero.

[3] This can occur if there is a larger area of coverage requirement or the receiver is suffering from a blockage.

[4] A single path fading channel model is considered for the sake of expression and analysis simplification. The extension to the general fading channel case is straight forward and can be attained through a precoding matrix added before the beam mapping step in order to align the interference between users [5].

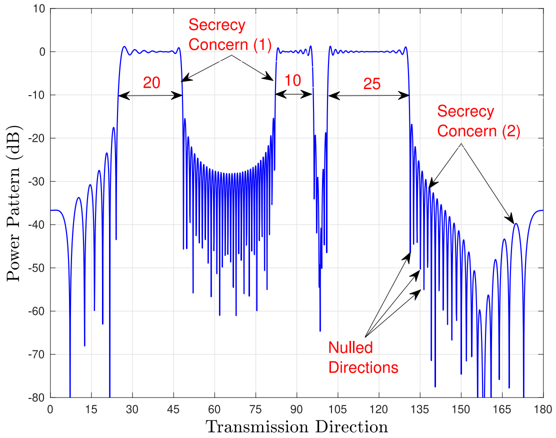

Fig. 2. The transmitted power pattern with three different desired directions, and different beam-width requirements.

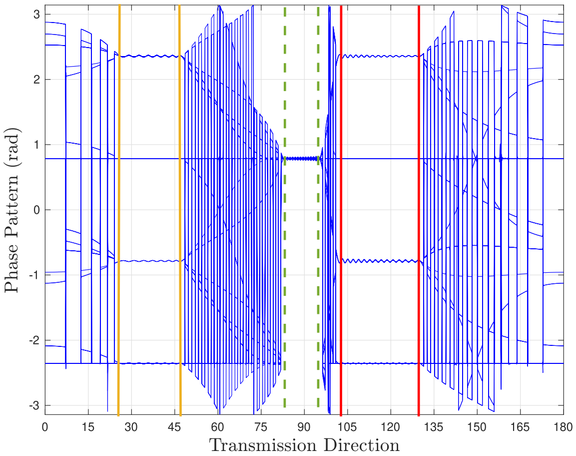

Fig. 3. The transmitted phase pattern for the three desired directions. The stream transmitted towards 90° has a single realization (green dashed lines). Full QPSK constellations (4 phase values) are transmitted towards 35° and 115° (yellow and red solid lines).

IV. RESULTS

Here, we consider an array of size $N = 127$, with array spacing $d = \lambda/2$. The transmission is directed towards three directions $\theta = [35^\circ, 90^\circ, 115^\circ]$, with beam-width requirements $\phi = [20^\circ, 10^\circ, 25^\circ]$.[5] The transmitted data streams are uncoded QPSK symbols.

Figure 2 shows the transmitted power pattern. We can see the flexibility provided by the proposed scheme in terms of using variable sub-beam assignment to achieve beam-width change.

Figure 3 represents the transmitted phase pattern. In order to be able to notice the randomization of the phase, a single constellation point was transmitted towards 90°, while the whole constellation was transmitted for the other two directions. We can see that the phase is taking the constellation values within the information beams, while having a high uncertainty outside the beams.

Moreover, to illustrate the secrecy performance of the scheme, Figure 4 shows the average achievable secrecy rate calculated as [1]

$$R_s(\theta) = \log_2(1+\gamma_p) - \log_2(1+\gamma(\theta)), \tag{15}$$

where γ_p is the signal-to-noise-ratio (SNR) received by the legitimate receiver ($\gamma_p = 10$) dB, while the eavesdropper has a noiseless channel $\sigma_z^2 = 0$. The eavesdropper channel suffers a degradation due to the multiuser interference imposed from the other transmitted streams.

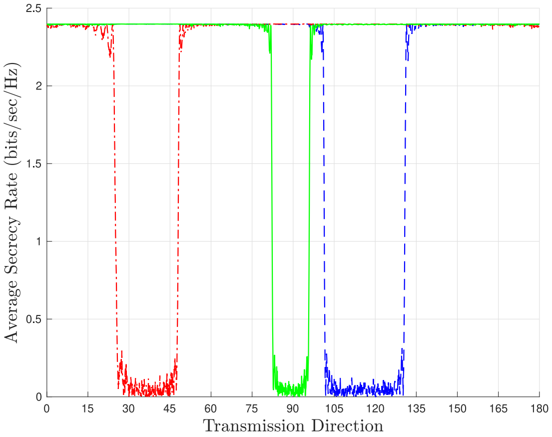

Fig. 4. Average secrecy rate for each transmitted stream.

V. CONCLUSION

We proposed a multi-direction directional modulation transmission scheme, with a simple DFT-based structure. This structure provides a simple implementation with fixed FFT matrix, and adaptive direction and beam-width assignment. Moreover, the scheme provides a secure communication link for each of the transmitted data streams through multi-user interference. The scheme can easily be modified to fit multi-path environments and multiple receiving antennas systems. Moreover, the secrecy features of the scheme can be enhanced by the insertion of an artificial noise signal to the non-utilized transmission directions (angles).

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[5] Different beam-widths can also represent the different stages of beam-search approaches. Here, odd array size just simplifies the numbers but does not affect the generality.