On Directional Modulation: An Analysis of Transmission Scheme with Multiple Directions

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***Abstract*—Increasing the spectral efficiency was always the motivation behind the evolution of wireless communication systems. Also, due to the widespread usage of wireless systems, securing the transmitted data rises as a main concern nowadays. Hereby, we introduce a scheme that increases the capacity of wireless systems by transmitting multiple independent data streams, while using the space domain as a source of separation. The scheme also utilizes the space domain, in order to provide a secure communication link for each of the transmitted streams. The analysis is performed by using different orders of QAM constellations, and also baseband orthogonal-frequency-division-multiplexing signal structure. The scheme shows a high randomization for the received signal along the directions out of the desired transmission beams, and fits to the standard bit-error-rate curves for all desired transmission directions. Besides, the scheme can be easily synthesized, using low complexity algorithms.**

***Index Terms*—Directional Modulation, Antenna Arrays, Physical-Layer Security, OFDM.**

I. INTRODUCTION

The increasing demand on higher rates of data transfer, and the limitation of the wireless resources, particularly the spectrum, were the main motivation in the wireless systems evolution. Time-division-multiplexing (TDM), code-division-multiplexing (CDM), and orthogonal-frequency-division-multiplexing (OFDM) are some examples of wireless transmission techniques that utilize the different domains of the wireless systems and increase the spectral efficiency. Recent developments focus on including and wisely using the space domain to enhance the system performance, by using multiple antenna techniques, e.g., multiple-input-multiple-output (MIMO) systems.

The current MIMO techniques are investigated under three main categories [1]:

- *Open-Loop Approach*: It improves the performance in terms of bit-error-rate (BER) by increasing the signal-to-noise-ratio (SNR) using spatial diversity, e.g., space-time-coding [2]. This category can reach a full diversity gain, with low receiver complexity. Thus, even in bad channel conditions, it provides good performance.
- *Closed-Loop Approach*: This one requires knowledge of the channel at the transmitter, and uses the decomposed channel matrix as a pre-coder to achieve capacity gains [3].
- *Layered Space-Time Approach*: It transmits multiple independent data streams over the antennas to increase the capacity, e.g. BLAST [4]. This algorithm has a high level of complexity that may make it impractical, also it suffers from high inter channel interference.

On the other hand, due to the broadcast nature of the wireless channel, and the widespread of the wireless applications, the secrecy of the transferred data rises as a main concern nowadays. These concerns increased the interest of providing a measure of security into the physical-layer algorithms [5], [6].

Recently, two multiple transmit antennas algorithms were proposed in the literature, namely,

- *Spatial Modulation* (SM) [7]: This scheme tries to increase the spectral efficiency of the system by using the active antenna number as a source of information. In SM, there is one active antenna per each symbol transmission period, and based on that, we can use the number of the transmitting antenna. For instance, we can send 2 bits/symbol by only using BPSK mapping and two transmitting antennas, or 3 bits/symbol by using BPSK and 4 antennas, or QPSK and 2 antennas. This scheme requires extra processing at the receiver to estimate the transmitting antenna number to be able to decode the received signal.
- *Directional Modulation* (DM): In this scheme, the antenna pattern is recognized as a spatial complex constellation, but it's not used as a source of information. Here, the antenna pattern complex value, at a certain desired direction, is set to have the same complex value of the symbol to be transmitted. That scheme also randomizes the signal in the undesired directions. This randomization process provides a source of directional security.

As mentioned above, the DM uses the complex antenna pattern to provide directional security. Contrary to the regular beam-forming, which provides directional power scaling, DM technique is applied in the transmitter by 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.

The idea was first considered as changing the stage where modulation takes place. The authors of [13] and [10] started to explain the idea of directional modulation using phased arrays, and demonstrated (synthesized) it in [12] and [11]. Based on their methodology, the modulation process needs to take place at the RF stage, instead of the regular base

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band modulation. Another algorithm for synthesizing DM is the antenna subset modulation (ASM) presented in [8]. In this technique, they only use few selected elements from the available antenna array to transmit. The elements used in transmission are randomly selected for each transmitted symbol to provide a randomized constellation pattern for the undesired direction. In [14], quadrature modulated I and Q data streams were separately encoded at the baseband, up-converted to radio frequency (RF) and then separately transmitted.When the two streams are combined in the far-field, the resultant IQ data is only detectable along a pre-specified spatial direction.

We can look at the difference between the conventional beam-forming and DM from another perspective. In the conventional beam-forming, the complex weights, which scale the antenna array, are changing based on the rate of change of the communication channel. Contrary, in the case of DM, the rate of change of the weights is related to the transmitted data rate [9]. In [17], a general analysis for DM using vector-domain is performed. The authors categorize DM algorithms into two groups. The first one they call it *"Static"* algorithms, where the generated antenna pattern does not change for any selected constellation point, i.e., if we choose to transmit one single point of the constellation, the generated pattern will always be the same. The second group is the *"Dynamic"* algorithms, where we can transmit the same constellation point with a different pattern each time, which makes it hard to track and decipher. Due to the lack of tools that can evaluate the performance of such system, some parameters based on BER, error-vector-magnitude (EVM), and secrecy rate were suggested in [16].

To the extent of the authors knowledge, all the suggested DM algorithms were only concerned about single direction transmission, and more focused on low order modulation schemes. Here, we are considering the multiple directions transmission scheme. Moreover, we suggest some low complexity solutions for its implementation. Also, we include the effect of using higher order modulation constellation, including OFDM baseband modulation, from the perspectives of both secrecy and error rate at the desired direction.

The rest of this study is organized as follows; In section II, we present the system model and implementation concept. Section III discusses the system characteristics, performance with different signal structures, and synthesizing algorithms . Finally. we conclude the paper in section IV.

II. MULTIPLE DIRECTION TRANSMISSION SCHEME

Here, we consider that we have a broadcast channel with a single source (base-station) and L destinations, namely directions. Each direction has its own desired data stream $x_i(k)$, and has a different transmission angle with respect to the base-station θ_i, where $i = 1, 2, \ldots, L$, and k is the time index. Different directions share the same resources of time slots, frequency bands, or codes simultaneously. The base-station uses a linear antenna array, with N elements, for transmission. Based on the idea of directional modulation, we need to set $W = [w_1(k), w_2(k), \ldots, w_N(k)]^T$, so that $f(\theta_i, k) = x_i(k)$, where W is the vector containing the complex weights for the antenna arrays, and f is the value of the resulting complex antenna pattern at a time instant k by the receiver located at a certain direction θ,

$$f(\theta, k) = h^*(\theta) W(k), \tag{1}$$

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

and $h^*(\theta)$ is the array steering vector for a receiver positioned at the direction θ.

Let us define F as the column vector that contains the desired pattern values, for each of the desired transmission directions.

$$\begin{aligned} F &= [f(\theta_1, k), f(\theta_2, k), \ldots, f(\theta_L, k)]^T \\ &= H^H W = \begin{bmatrix} h^*(\theta_1) \\ h^*(\theta_2) \\ \vdots \\ h^*(\theta_L) \end{bmatrix} [w_1(k), w_2(k), \ldots, w_N(k)]^T \end{aligned} \tag{3}$$

where, $H \in \mathbb{C}^{N \times L}$, and we consider that $L \leq N$, i.e., the number of desired transmission directions is less than the number of the antenna array elements. This makes (3) an under-determined linear equation. Using the least-norm solution [18], we will find that

$$W_{ln} = H \left(H^H H\right)^{-1} F \tag{4}$$

By replacing F with $X = [x_1(k), x_2(k), \ldots, x_L(k)]^T$, we can produce the required weights to modulate the resulting antenna pattern, so that the pattern takes the desired values at the desired directions. Based on that, the value of the received pattern can be rewritten as,

$$f(\theta, k) = h^*(\theta) H (H^H H)^{-1} X(k) \tag{5}$$

Note that, the usage of any other antenna array structure is applicable, as long as the appropriate steering vector $h^*(\theta)$ is used for the generation of the weights W. Moreover, if we assume that the channel state information (CSI) for each of the users is available at the transmitter, we can enhance the secrecy performance of the system by multiplexing it within the generated weights.

$$W = A^H (A A^H)^{-1} X \tag{6}$$

where, $A = C H^H$, and C is the $(L \times L)$ diagonal matrix containing the CSI of each of the users.

III. DISCUSSION AND NUMERICAL EVALUATION

For the sake of simplification, we take a look into the case, where we need to transmit in only two directions, we will find that the received signal at any arbitrary direction θ_s is

$$f(\theta_s, k) = \frac{1}{N^2 - y_{12}^2} \left[(N y_{s1} - y_{s2} y_{12}) x_1 + (N y_{s2} - y_{s1} y_{12}) x_2\right] \tag{7}$$

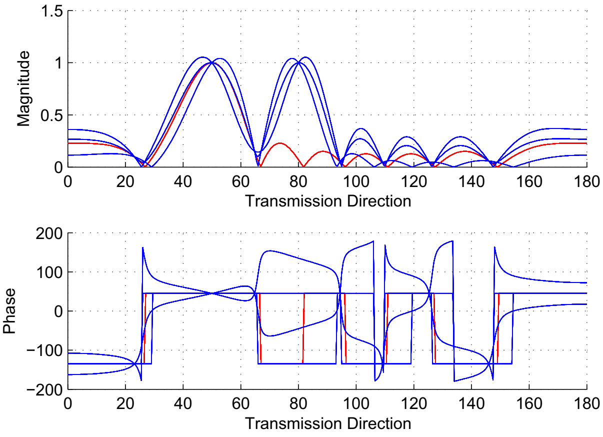

Fig. 1. The upper section shows the magnitude of the received antenna pattern for each spatial direction, single intended direction transmission (red), two directions transmission (blue), users are located at 50^o and 80^o. The Lower section shows the phase of the received pattern with the same setup.

where,

$$y_{pq} = y_{qp} = \sum_{n=0}^{N-1} e^{j(n-\frac{N-1}{2})\frac{2\pi d}{\lambda}(\cos\theta_p - \cos\theta_q)} = \frac{\sin\left(N\frac{\pi d}{\lambda}(\cos\theta_p - \cos\theta_q)\right)}{\sin\left(\frac{\pi d}{\lambda}(\cos\theta_p - \cos\theta_q)\right)} \tag{8}$$

Based on (7), we can notice that, for the values of $\theta_s \approx (\theta_1, \theta_2)$, the received value of f is close to (x_1, x_2), respectively. Otherwise, the value of f oscillates around zero. Also, we can consider this as if we create some intended interference using the transmission of the other directions. The amount of this interference depends on the number of different directions L and the separation between these directions.

A. *System Characteristics*

If we try to categorize the scheme based on the definition in [16], the used algorithm can be considered static for the case of single direction transmission. On the other hand, if we add one more transmission direction to the system, we will find that the scheme provides similar results as in the dynamic property. Fig. 1 shows the generated magnitude and phase of the transmitted pattern using QPSK signal structure.

The system here transmits only the symbol $e^{j\frac{\pi}{4}}$ for the user located at 50^o, while transmitting a random symbol for the other user located at 80^o. We can see that in the case of single direction transmission (red curves), the magnitude and the phase of the resulting antenna pattern have a static value for all directions while, in the case of two directions (blue curves), the magnitude and the phase take multiple values depending on the transmitted symbol to the other direction. By increasing the number of directions to four (50^o, 80^o, 110^o, 140^o), we can recognize from Fig. 2 that the phase is becoming more random and may be considered as uniformly distributed on the values between $-\pi$ and π. Increasing the number of possible combinations of interfering symbols by using higher order modulation schemes, i.e., 16-QAM, 64-QAM, will definitely increase the randomization of the received signal outside the desired transmission beams.

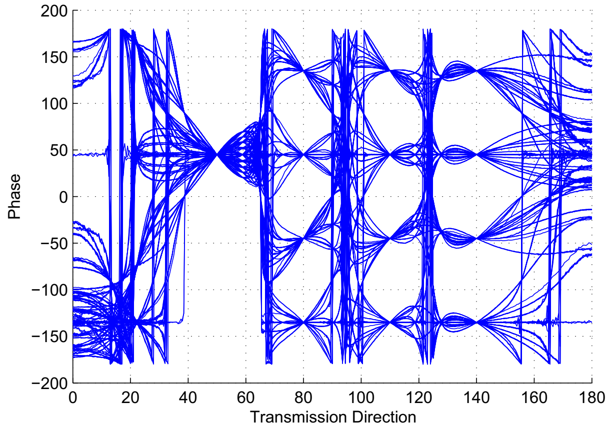

Fig. 2. The phase of the received antenna pattern at each spatial direction, the transmission is intended for 4 different directions, users are located at 50^o, 80^o, 110^o, and 140^o.

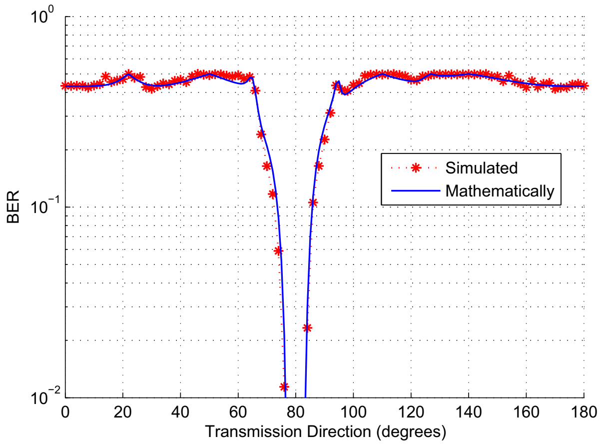

Fig. 3. Comparing the mathematical and simulated results of the BER of decoding the data directed towards 80^o. Here, we do not include the effect of the noise, so the figure shows only the effect of the interference created by the signals transmitted to other directions.

B. *Reception Error Rate*

Now, we will discuss the effect of this system structure on the error at the user-end. For BER evaluation, we use euclidean distance detectors for QAM, and a half-wavelength linear antenna array, with eight antenna elements (i.e. $N = 8$). The transmission is directed to 50^o, 80^o, 110^o, and 140^o, with an independent data stream for each of them. Fig. 3 and 4 show the error graphs for the reception obtained from 80^o direction, and the same apply for the other directions.

We can rewrite (6) as

$$f(\theta_s) = [a_1(\theta_s), a_2(\theta_s), \ldots, a_L(\theta_s)] \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_L \end{bmatrix} \tag{9}$$

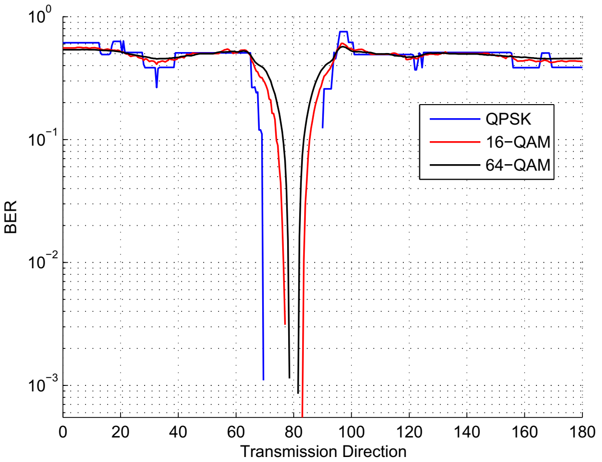

Fig. 4. The BER of decoding the data directed towards 80^o, while using different modulation orders for the transmitted data.

Based on that, we can define the signal-to-interference-plus noise- ratio (SINR) for the data stream i received at the direction θ_s as

$$\rho_i(\theta_s) = \frac{|a_i(\theta_s)|^2}{\sum_{\forall j \neq i} |a_j(\theta_s)|^2 + N_{\theta_s}} \tag{10}$$

where $j \in \{1, 2, \ldots, L\}$.

Hence, the BER for a Gray-coded M-QAM modulation scheme (without channel coding) is approximated by:

$$BER_{QAM}(\theta_s) \approx \frac{\sqrt{M}-1}{log_2(M)-1} \left(\frac{log_2(M)}{\sqrt{M}} \right) Q \left(\sqrt{\frac{3\rho_i(\theta_s)}{M-1}} \right) \tag{11}$$

where $Q(.)$ represents the Q-function, and M is the modulation order. In general, the lower bound of $BER(\theta_s)$ for any system can be calculated by substituting the value of the SINR by $\rho_i(\theta_s)$. This acts as a lower bound because it only considers the effect of the interference created by the signals of other users, and it does not include the distortion embedded to the signal by the DM algorithm.

In Fig. 3, we show the illustration of (11) in case of a 16-QAM transmitted signal. The result is compared to the one from the system simulation.

Fig.4 shows the BER for different order QAM modulation schemes. It's obvious that when the modulation order increases, even though the effect of noise is neglected, the probability of error increases as we go far from the intended direction. This is noticeable through the change of the width of the main beam around 80^o.

In Fig. 5, we calculate the secrecy capacity based on effective SINR from (10), where the SNR for the desired direction at 80^o is 10 dB. Again, the figure shows high secrecy gain outside the main lobe, which indicates that the data obtained from non-intended directions will not be detected reliably. The figure also shows that the communication is not secure in the direction of the legitimate user, however, the multi-path nature of the channel can be used to generate a pre-coding scheme that insure secrecy for that direction. The precoder generation is out of the scope of this work. The secrecy capacity $C_{Secrecy}$, and capacities of the channels are obtained from

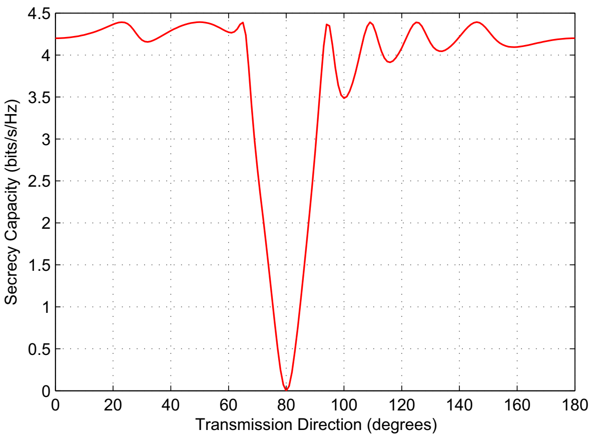

Fig. 5. Secrecy capacity based on the SINR of the received symbols.

$$C_{Secrecy} = C(\theta_d) - C(\theta) \tag{12}$$

$$C(\theta) = log_2(1 + \rho_i(\theta)), \tag{13}$$

where $C(\theta_d)$ is the capacity at the desired direction θ_d.

C. OFDM Signal Structure

What we noticed from the previous discussions is that, with the increasing number of the possible values of the transmitted signal, the randomness of the received signal outside of the interest beam increases. Also, the width of the correct reception beam decreases. Considering the extreme situation where the signal has the same structure as the noise, i.e., a Gaussian signal, OFDM as an example, we can highly reduce the probability of detection outside of the main interest beam. Besides, the usage of an OFDM signal will facilitate the estimation and equalization of the effects of fading channels. For the OFDM system we used the Extended Pedestrian A (EPA) propagation model from the LTE standard [20], and the first OFDM symbol of each transmitted block is allocated for pilot signals to be used for channel estimation. It's assumed that the pilot signals are known for all the receivers in the system. Fig. 6 shows the BER for all the transmitted data streams with the direction of the transmission. We can see that each stream can be delivered correctly to a pre-specified direction, while it is observed as noise-like signal in other directions. The figure also shows the advantage of including the CSI as mentioned in (6). We can notice that having CSI as a part of the signal generation reduces the width of the detection beam (dashed curves). Here, CSI adds another source of randomization for the signal transmitted to the undesired directions.

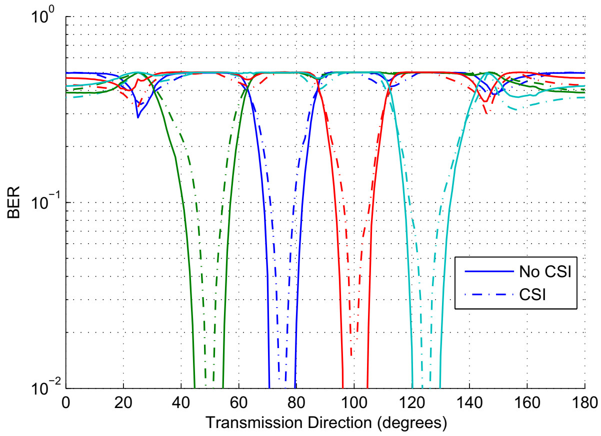

Fig. 6. Each of these curves represents the resultant BER at each direction, based on decoding each one of the transmitted streams. There are 4 different data streams directed to 50^{o}, 75^{o}, 100^{o}, and 125^{o}

D. Algorithms for the Implementation of the Multiple-Direction Scheme

As we expect to have large dimensions for H, and due to the high complexity of the matrix inversion operation, we suggest to employ least-mean-squares (LMS) adaptive filtering algorithm [19] to synthesize this system with low complexity. The algorithm is shown in Table I, and the value of the convergence factor μ is determined based on the construction of H. One of the main concerns about LMS is the convergence rate, which would affect the pattern generation rate, and the transmission rate. There are many other different techniques that can be used to generate the pattern, each of them has its own complexity and rate parameters (e.g., Recursive least squares (RLS), QR Decomposition, etc.) [19].

TABLE I
COMPLEX LMS ALGORITHM

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1. $W(0)$ =zeros$(N,1)$;
2. while $c \geq 0$;
3. $E = X^{H} - W(c)^{H}H$;
4. $W(c+1) = W(c) + \mu H E^{H}$;
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IV. CONCLUSION

Here, we provided an analysis of the DM system under the multiple directions transmission scheme. It has been shown that DM can provide a way to increase the total throughput of the system, in addition to providing a secure communication link. We have shown that multiple direction transmission can be implemented using low complexity algorithms and simple hardware construction (single RF chain). It also does not necessitate the implementation of special receiving algorithms. The analysis shows that even the used algorithm does not provide sufficient secrecy in the case of single direction transmission, the interference created by adding multiple directions into the construction provides the required randomness outside of the main transmission beam. The system keeps the same simple construction even by using higher order modulation constellations, and gives better performance regarding the secrecy.

ACKNOWLEDGMENT

This material is based upon work supported by the National Science Foundation under Grant No.2106118400.

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