

# Directional Antenna Modulation Technique using A Two-Element Frequency Diverse Array

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## ABSTRACT

Direction dependent antenna modulation (DAM), as a potential physical-layer security technique, is able to enhance the security of wireless communication systems by virtue of the capability of its direction-dependent signal modulation format transmission. In this paper, DAM using frequency diverse array (FDA) to produce the modulation is presented. By phase shifting each element, the desired amplitude and phase of each symbol can be produced during a particular transmission in a given range and angle position determined by the switching speed of the phase shifters. Accordingly, the proposed method offers a robust security for wireless transmission, as the transmitted signal can be purposely distorted in undesired positions, while preserving a clear constellation along pre-specified position(s). Numerical examples are given to illustrate the effectiveness of the proposed method.

## 1 Introduction

Directional antenna modulation (DAM) transmitter has been recently proposed [1, 2, 3] which has the capability of projecting deliberately distorted signals in all directions in free space other than the pre-specified secure communication directions. In doing so, only intended receivers located along this the secure communication direction are able to capture the signal leading to successful demodulation, while distorted signal emitted along undesired directions make signal demodulation by an eavesdropper a difficult task. Unlike classical cryptographic technique adopted at higher protocol layers to provide encryption, DAM technology does not share any keys, and secures data transmission directly at physical-layer which enables information theoretical security [4].

The basic concept of DAM is that it transmits a signal with a known modulation format to the desired receiver. The transmitted signal can be successfully recovered and demodulated by a receiver with a-prior modulation scheme [3]. For any directions distinct from the desired direction(s), the modulation format imposed on the transmitted signal will change. Thus making it difficult for the eavesdroppers to demodulate. In [2] a similar concept directional modulation (DM) was proposed which employs phased-array antenna. Other researches has proposed different DM transmitters such [5, 6, 7, 8]. Nevertheless, up to now, all published DAM transmitters employs phased-array. Although

the DAM techniques using phased-array can steer the beam to an arbitrary direction, but the steering is independent of the range. This is because phased-array produces fixed steering direction at an angle for all the ranges [9].

In fact, the ability to control range dependent transmit energy distribution becomes an important requirement in many applications, for instance, range-dependent interference suppression [10, 11, 12] and directional communications [2]. To address the current needs, frequency diverse array (FDA) provides new opportunities to realize DAM. The FDA concepts was initially introduced in 2006 [13, 14]. They reported that the range-angle-time dependent far-field array pattern formation are the core attributes of the concept. FDA has been defined by [15] as an antenna aperture where the frequency of each antenna element is controlled independently to steer the main beam, depending on the time domain of each frequency component in the far-field. The most significant feature of FDA is that, it employs a small frequency increment across its antenna array elements. This frequency increment makes the array beam-pattern to change as a function of the range, angle and time [9, 13, 14].

In this contribution FDA elements is configured using DAM technique to achieve physical-layer security in range-angle dependent. The range and angle dependent DAM is achieved with 2-bit phase controls across the array elements for secure point-to-point communications. The main contributions can be summarized as: 2-bit phase shifters combi-

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nations is formulated for the FDA-based DAM to achieve directional range-angle dependent M-ary signal constellations. Compared with conventional phased-array based method, our proposed system achieves narrower demodulation beamwidth for the desired receiver.

In Section II of this paper, FDA DAM for secure point-to-point communications is presented. Numerical results are provided in Section III. Finally, this paper is concluded in Section IV.

## 2 FDA DAM for Secure Point-To-Point Communications

The FDA elements can be excited by either the same waveform or different waveforms. Here, the waveform radiated from each array element is assumed to be identical with a frequency offset of  $\Delta f$  Hz. Consider a uniform linear array (ULA) FDA composed of identical transmit elements with element spacing  $d$ . The radiated frequency of a standard FDA from the  $m$ th element is given as

$$f_m = f_0 + m\Delta f, m = 0, 1, \dots, M - 1 \quad (1)$$

where  $f_0$  and  $\Delta f$  are the carrier frequency and frequency offset, respectively, and  $M$  is the number of array elements. The transmit beampattern can be represented by (2), [16] with the common phase  $\Phi_0$  given in (3), where  $c_0$  denotes the speed of light and  $r_m \approx r - md \sin \theta$ , is the target slant range for the  $m$ th element and  $d = \frac{c_0}{2f_0}$  denotes the element spacing. Equation (2) implies that FDA has range, angle and time dependent transmit beampattern.

To describe directional antenna modulation for M-ary transmission, a two-element FDA antenna with 2-bit phase control which provides four state units  $\alpha_A = \alpha_B = [\alpha_1, \alpha_2, \alpha_3, \alpha_4]$  is configured for each FDA array element as shown in Figure 2. Each FDA element is controlled by the RF switch embedded to specifically select one of four possible phase state units. The four phase state units  $[\alpha_1, \alpha_2, \alpha_3, \alpha_4]$  herein represents  $[0^0, 90^0, 180^0, 270^0]$  phase shifters, respectively. The signals are modulated individually by controlling the element phase shifters with the RF switchers. In doing so, the array radiation pattern will change at each symbol in the digital modulation scheme. A desired constellation pattern can be produced along pre-specified range-angle positions. At the same time, constellation patterns generated for other positions will be distorted.

The array factor for this FDA based DAM transmitter configuration can be expressed as

$$AF(\theta, r) = \sum_{m=1}^M e^{j\alpha_{AB}(t)} \times e^{-j[(m-1)\frac{2\pi}{\lambda}d \sin \theta - \frac{2\pi\Delta f \cdot r}{c_0}]} \quad (4)$$

where  $e^{j\alpha_{AB}(t)}$  is a time dependent phase shifters. From Figure 2, the directional modulated range and angle dependent signals of two-element configuration can be written as

$$AF(\theta, r) = e^{j\alpha_A(t)} + e^{j(\alpha_B(t) + \phi - \pi \sin \theta - \frac{2\pi\Delta f \cdot r}{c_0})} \quad (5)$$

where  $e^{jA}$  and  $e^{jB}$ , denotes the phase shifters for each element A and B, respectively. The frequency offset  $\Delta f$  and phase offset  $\phi$  are used here as a fixed value in a particular signal transmission. The  $\Delta f$  and  $\phi$  can be adjusted when considering different signal transmissions. The phase shifter produce by the  $\phi$  is assumed to be chosen between  $-80^\circ$  and  $80^\circ$ . It is important to note that, the phase shifters provided for FDA elements are based on assumption and their corresponding values are shown in Table I.

It is worth noting that, because the FDA DAM technique depends on switching the antenna elements at each symbol rate, a series of high frequency single-pole multi-throw (SPMT) or single-pole-4-throw (SP4T) switches with nanosecond or sub-nanosecond speeds is required [17, 18].

## 3 Simulation Results and Analysis

### 3.1 Directional Modulated 16-ary Transmission Analysis

Analogous to [3], sixteen data points was calculated for the desired receiver at the range-angle position  $(R, \theta) = (90 \text{ km}, 60^\circ)$ . The proposed transmitter system can modulates up to 16-ary unique signal constellation at the far field. When 16-ary transmission is considered, Figure 3 shows the 16-ary unique signal constellation at the intended receiver position  $(R, \theta) = (90 \text{ km}, 60^\circ)$ . The modulated signal can be successfully decoded easily by the receiver. Note that in Figure 3,  $\Delta f = 70\text{Hz}$  and  $\phi = 45^\circ$  was adopted. These arbitrary values of both frequency offset  $\Delta f$  and phase offset  $\phi$  was chosen to generate 16 unique points at the desired position.

Next, the effect of changing the arbitrary values of both frequency offset  $\Delta f$  and phase offset  $\phi$  are examined. As shown in Figure 4, it can be noticed that for distinct values of frequency offset  $\Delta f$  and phase offset  $\phi$ , such as  $\Delta f = 70\text{Hz}$ ,  $\phi = 45^\circ$ ;  $\Delta f = 120\text{Hz}$ ,  $\phi = 65^\circ$ ;  $\Delta f = 300\text{Hz}$ ,  $\phi = -75^\circ$ ; respectively, generate different distributions of constellation points. It is important to note that  $\Delta f$  and  $\phi$  may be considered as transmission signatures and can provide a series of different modulation format.

Figure 5 demonstrate how the proposed system provides additional level of security. As shown in Figure 5, the 16 unique data point generated corresponds to  $\Delta f = 70\text{Hz}$ ,  $\phi = 45^\circ$  and range  $R = 90 \text{ km}$  for distinct observation angles of  $\theta = 60^\circ$  (desired angle direction),  $\theta = 40^\circ$  and  $\theta = 80^\circ$ , respectively. It can be observed that at angles distinct from the desired angle direction, new distributions of modulation format are achieved. This implies that apart from the desired angle direction, all other angle directions received signal constellation changes locations making demodulation by an eavesdropper very difficult.

Similarly, Figure 6 illustrate 16 unique constellations for distinct ranges such as  $R = 90 \text{ km}$  (desired range position),  $R = 110 \text{ km}$  and  $R = 150 \text{ km}$  which corresponds to  $\Delta f = 70\text{Hz}$ ,  $\phi = 45^\circ$  and  $\theta = 60^\circ$ . It is noticed that at other range positions apart from the desired range position, the signal constellation have different distributions making it difficult for the eavesdroppers to intercept information.

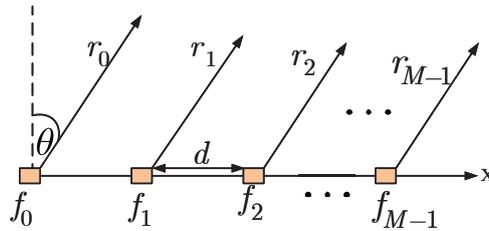


Figure 1: ULA FDA elements with frequency offset  $\Delta f$ .

$$AF(t; r, \theta) = \sum_{m=0}^{M-1} \exp \left\{ -j2\pi f_m \left( t - \frac{r_m}{c_0} \right) \right\} \approx e^{-j\Phi_0} \frac{\sin \left[ M\pi \left( \Delta f t - \frac{\Delta f r}{c_0} + \frac{d f_0 \sin \theta}{c_0} + \frac{\Delta f d \sin \theta}{c_0} \right) \right]}{\sin \left[ \pi \left( \Delta f t - \frac{\Delta f r}{c_0} + \frac{d f_0 \sin \theta}{c_0} + \frac{\Delta f d \sin \theta}{c_0} \right) \right]} \quad (2)$$

$$\Phi_0 = 2\pi f_0 (t - r/c_0) - \pi(M-1)\Delta f r/c_0 + \pi(M-1)f_0 d \sin \theta/c_0 + \pi(M-1)\Delta f d \sin \theta/c_0 \quad (3)$$

Table 1: Possible phase shifters combinations for FDA DAM using two-element configuration.

Number	FDA element $[\alpha_A \ \alpha_B + \phi]$	Number	FDA element $[\alpha_A \ \alpha_B + \phi]$
1	$0^0 \ 0^0$	9	$180^0 \ 0^0$
2	$0^0 \ 90^0$	10	$180^0 \ 90^0$
3	$0^0 \ 180^0$	11	$180^0 \ 180^0$
4	$0^0 \ 270^0$	12	$180^0 \ 270^0$
5	$90^0 \ 0^0$	13	$270^0 \ 0^0$
6	$90^0 \ 90^0$	14	$270^0 \ 90^0$
7	$90^0 \ 180^0$	15	$270^0 \ 180^0$
8	$90^0 \ 270^0$	16	$270^0 \ 270^0$

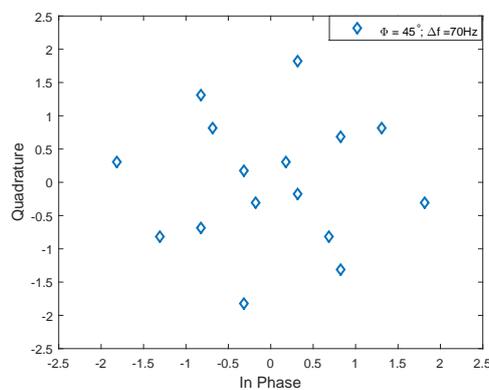


Figure 3: Illustration of 16-ary unique points when  $\Delta f = 70\text{Hz}$  and  $\phi = 45^\circ$  is adopted.

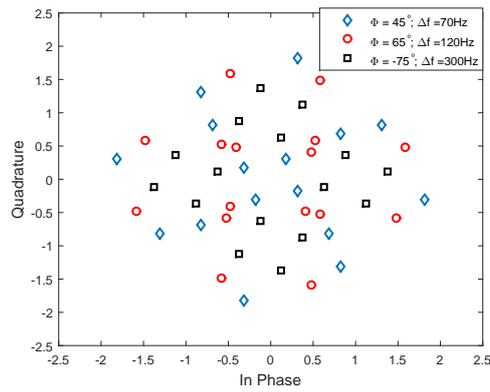


Figure 4: Comparisons of 16 unique constellations for distinct  $\Delta f$  and  $\phi$ .

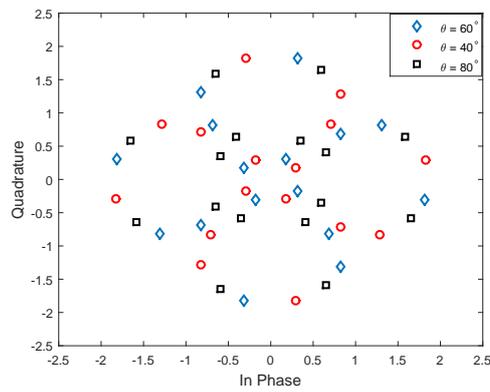


Figure 5: Comparisons of 16 unique constellations for distinct angles.

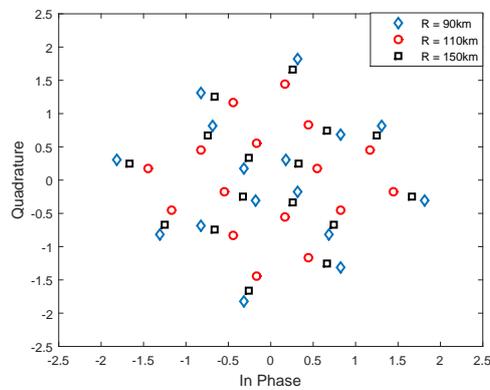


Figure 6: Comparisons of 16 unique constellations for distinct ranges.

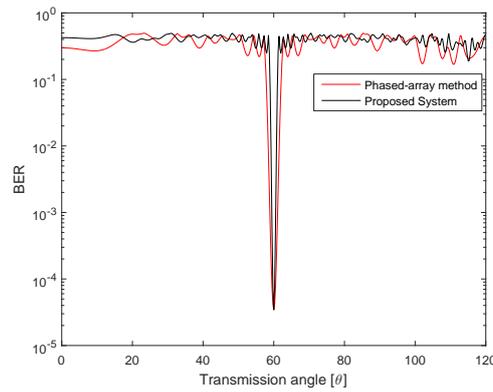


Figure 7: BER performance in angle dimension.

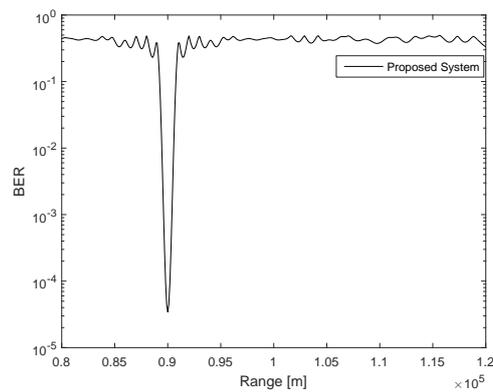


Figure 8: BER performance in range dimension.

### 3.2 Bit error rate (BER) Analysis

To demonstrate how the proposed system can be applied to a secure communication system, the simulated bit error rate (BER) of the system is calculated in angle and range dimensions using an algorithm based on minimum distance decoding [2].

The essence of Directional modulation technique is to achieve low BER in a narrow beamwidth toward the intended receiver and still enforce a high BER in other undesired directions. The resulting BERs are shown in Figure 7 and Figure 8. It is fair to ensure that, all BERs are normalized until they are the same at the desired position. In this fashion, the security in undesired directions can be compared while they have the same performance in the intended direction.

In angle dimension, the proposed system achieves a lower BER in a narrow beamwidth with a relatively constant high BER in other directions than phased-array based method. In range dimension as shown in Figure 8, the phased-array-based method has no range resolution capability. In contrast, the proposed system still has good BER performance in the range dimension due to the frequency offsets  $\Delta f$ . These results confirm that, the proposed method achieves good security performance in both range and angle dimensions, not just in the angle dimension as the phased-array-based method and thus yields the worst security performance.

## 4 Conclusion

This paper has presented a directional antenna modulation scheme using a two-element FDA antenna. The directional manipulation of the constellation points is possible because the signals are modulated at antenna-level with phase shifters changing in each symbol transmission. The proposed system achieves both range and angle dependent DAM for secure 16-ary transmitted symbols for wireless communications. The effectiveness of the proposed system is validated with the aid of constellation diagrams and BER performances. Compared with the phased-array-based DAM method, which scrambles the signal constellations only in undesired angles, the proposed scheme scrambles the signal constellation in both range and angle dimensions. Future work will include the design of genetic algorithm for phase shifters to improve the security performance.

**Conflict of Interest** The author declare no conflict of interest.

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