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Metasurface Based Positional Modulation Design

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ABSTRACT Directional modulation (DM) can transmit information to the desired direction or directions with known constellation mappings, but with scrambled ones in other directions. However, one problem of the design is that when desired receivers and eavesdroppers are in the same transmission direction, their beam responses cannot be distinguished, as steering vectors for these locations are the same. To solve the problem, positional modulation (PM) is introduced where a given modulation pattern can only be received at certain desired positions. In this work, the multi-path effect is exploited for positional modulation with the aid of metasurface acting as a low-cost flexible reflecting surface. Design examples are provided to show the effectiveness of the proposed design.

INDEX TERMS Positional modulation, directional modulation, metasurface.

I. INTRODUCTION

The Fifth Generation (5G) wireless communication technology has been studied extensively [1], [2], and one crucial part is beamforming. Directional modulation (DM) as a beamforming based technology can keep a known modulation scheme to the desired direction or directions, while scrambling the pattern in other directions, and since it was proposed in [3], DM has been studied by many researchers [4]–[9]. In [10], a reconfigurable array was designed by switching elements for each symbol to make their constellation points not scrambled in desired directions, but distorted in other directions. A method named dual beam DM was introduced in [11], where the I and Q signals are transmitted by different antennas. In [12], [13], phased arrays were employed to show that DM can be implemented by phase shifting the transmitted antenna signals properly. Multi-carrier based phased antenna array design for directional modulation was studied in [14], followed by a combination of DM and polarisation design in [15]. The bit error rate (BER) performance of a system based on a two-antenna array was studied using the DM technique for eight phase shift keying modulation in [16].

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A more systematic pattern synthesis approach was presented in [17], followed by a time modulation technique for DM to form a four-dimensional (4-D) antenna array in [18]. The introduction of artificial noise (AN) has further advanced the directional modulation technology [19]–[21].

However, eavesdroppers aligned with or very close to the desired direction/directions will be a problem for secure signal transmission, as their received modulation patterns are similar to the one received by the desired user. To make sure that a given modulation pattern can only be received at certain desired positions, positional modulation (PM) based technique was introduced. For frequency diverse antenna arrays, a random frequency diverse array-based directional modulation with artificial noise (RFDA-DM-AN) [22] was proposed to achieve positional modulation. RFDA-DM-AN was design by randomly allocating frequencies to transmit antennas. In [23], a non-linear frequency diverse array was proposed as the transmitter to provide range-dependent beampattern. An OFDM (orthogonal frequency division multiplexing) signal transmitter with frequency diverse array [24] was designed to achieve security and stability of information transmission. For phased antenna arrays, two methods to achieve it were proposed. One is using a fixed reflecting surface [25], which is difficult to control and not flexible enough to deal with the ever changing user conditions, while the other one is applying multiple antenna arrays at different locations [26] and a clear drawback is the very high cost associated with implementing multiple antenna arrays at different locations.

In this work, we focus on the positional modulation problem and propose a new design by employing the metasurface as a low-cost flexible reflecting material to control the modulation pattern at different spatial locations. Metasurface is the surface version of a metamaterial [27], and its use in wireless communications has been widely studied in recent years [28]–[32]. For implementation of metasurface on hardware, each electromagnetic micro unit on the metasurface consists of two copper plates on both sides and a varactor diode in the middle as a bridge. The electrode apertures on the copper plates on both sides are used to apply voltage to the varactor diode. Its electromagnetic controllable characteristics are reflected in the varactor diode. Through the digital control voltage sequence output by the control circuit, each electromagnetic micro unit is controlled in real time to show different electromagnetic characteristics, which represents different values of weight coefficients applied to the metasurface. The proposed method can also be extended to use in harsh environments. When one path weakens or disconnected, we can choose other paths to transmit signals to achieve multi-path transmission effect for positional modulation design.

The remaining part of this paper is structured as follows. A review of DM design based on linear antenna arrays is given in Sec. II. Positional modulation design using metasurface is presented in Sec. III. Design examples are provided in Sec. IV, followed by conclusions in Sec. V.

II. REVIEW OF DM DESIGN BASED ON LINEAR ANTENNA ARRAYS

A narrowband N-element linear antenna array for transmit beamforming is shown in Fig. 1, where the spacing between the zeroth antenna and the n-th antenna is represented by d_n ($n = 0, 1, \ldots, N-1$). Each antenna has its corresponding weight coefficient w_n, $n = 0, 1, \ldots, N-1$. The transmission angle of the antenna array is represented by θ with a range $[-90°, 90°]$. Desired locations are represented by L, and eavesdroppers denoted by E are around desired locations. The steering vector of the array as a function of angular frequency ω and transmission angle θ is given by

$$\mathbf{s}(\omega,\theta) = [1, e^{j\omega d_1 \sin\theta/c}, \ldots, e^{j\omega d_{N-1} \sin\theta/c}]^T, \tag{1}$$

where $\{\cdot\}^T$ is the transpose operation, and c is the speed of propagation. Then, the beam response of the array can be given by

$$p(\omega,\theta) = \mathbf{w}^H \mathbf{s}(\omega,\theta), \tag{2}$$

where $\{\cdot\}^H$ represents the Hermitian transpose, and $\mathbf{w}$ is the weight vector

$$\mathbf{w} = [w_0, w_1, \ldots, w_{N-1}]^T. \tag{3}$$

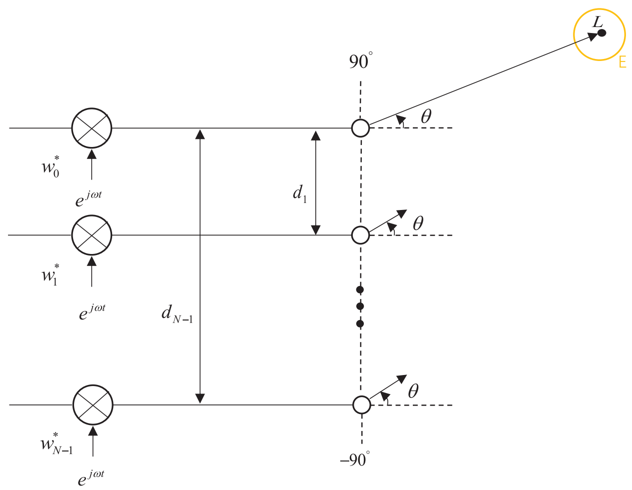


FIGURE 1. A narrowband transmit beamforming structure.

For M-ary signaling, such as quadrature amplitude modulation (QAM), M sets of desired array responses $p_m(\theta)$ ($m = 0, 1, \ldots, M-1$) exist with M sets of weight coefficients

$$\mathbf{w}_m = [w_{m,0}, w_{m,1}, \ldots, w_{m,N-1}]^T, \quad m = 0, 1, \ldots, M-1. \tag{4}$$

We assume R transmission directions are considered in the design, including r directions in the mainlobe and $R-r$ directions in the sidelobe, i.e.,

$$\begin{aligned}\theta_{ML} &= [\theta_0, \theta_1, \ldots, \theta_{r-1}],\\ \theta_{SL} &= [\theta_r, \theta_{r+1}, \ldots, \theta_{R-1}].\end{aligned} \tag{5}$$

Then, the desired responses in the mainlobe and sidelobe regions for the m-th symbol can be represented by

$$\begin{aligned}\mathbf{p}_{m,ML} &= [p_m(\omega,\theta_0), p_m(\omega,\theta_1), \ldots, p_m(\omega,\theta_{r-1})],\\ \mathbf{p}_{m,SL} &= [p_m(\omega,\theta_r), p_m(\omega,\theta_{r+1}), \ldots, p_m(\omega,\theta_{R-1})].\end{aligned} \tag{6}$$

Similarly, the steering matrix in the mainlobe and sidelobe ranges can be expressed as

$$\begin{aligned}\mathbf{S}_{ML} &= [\mathbf{s}(\omega,\theta_0), \mathbf{s}(\omega,\theta_1), \ldots, \mathbf{s}(\omega,\theta_{r-1})],\\ \mathbf{S}_{SL} &= [\mathbf{s}(\omega,\theta_r), \mathbf{s}(\omega,\theta_{r+1}), \ldots, \mathbf{s}(\omega,\theta_{R-1})].\end{aligned} \tag{7}$$

Note that all symbols for a fixed θ share the same steering vector.

Then, for the m-th symbol, its corresponding weight coefficients for DM design can be obtained by solving the following problem

$$\begin{aligned}&\min \ ||\mathbf{p}_{m,SL} - \mathbf{w}_m^H \mathbf{S}_{SL}||_2\\ &\text{subject to } \mathbf{w}_m^H \mathbf{S}_{ML} = \mathbf{p}_{m,ML},\end{aligned} \tag{8}$$

where $||\cdot||_2$ denotes the l_2 norm.

III. PROPOSED DESIGN FOR POSITIONAL MODULATION USING METASURFACE

PM keeps a given modulation pattern at certain desired positions by exploiting the characteristics of multi-path transmission. As shown in Fig. 2, a metasurface is introduced in the design as a controllable reflecting surface for effective beamforming. It has Q elements and is H distance

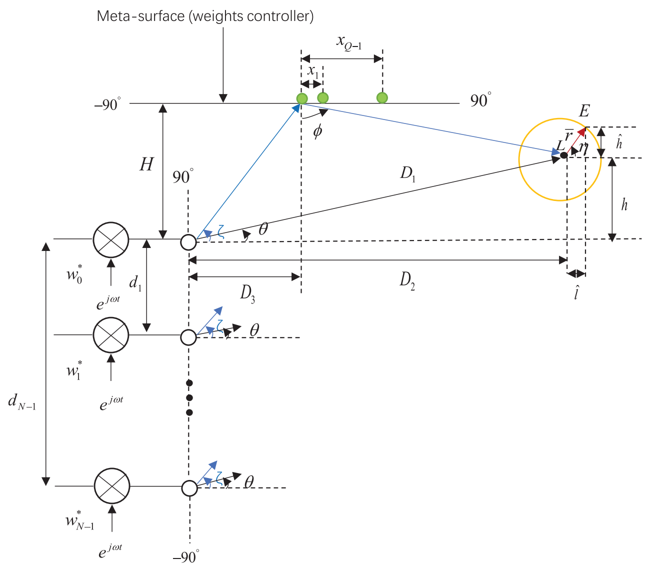


FIGURE 2. Multi-path signal transmission to the desired receiver *L* and eavesdroppers *E*.

above the transmission antenna array. The corresponding weight coefficients for each element is represented by $\tilde{w}_q$ for $q = 0, \ldots, Q-1$. The distance between the zeroth element and the q-th element is represented by x_q ($q = 0, 1, \ldots, Q-1$). The angle for the reflected path from metasurface to receivers is represented by $\phi \in [-90°, 90°]$. Similar to the DM design structure in Sec. II, the transmitter is an N-element omni-directional linear antenna array, with a spacing d_n ($n = 1, \ldots, N-1$). The transmission angle for line of sight (LOS) path from transmitter to receivers is represented by $\theta \in [-90°, 90°]$, and the angle for reflected path from transmitter to metasurface is denoted by $\zeta \in (0°, 90°]$. Desired positions are represented by L and eavesdroppers E are on the circumference of the circle $\eta \in [0°, 360°)$, with radius $\bar{r}$. D_1 denotes the distance from the desired receiver to the transmission array, and h represents the vertical distance to the broadside direction where h is positive for L above the broadside direction and negative for the opposite. The projection of D_1 onto the broadside direction is represented by D_2. D_3 is the horizontal distance from the element ($q = 0$) on metasurface to transmitter. For eavesdroppers in the direction η, we have the corresponding $\hat{h}$ and $\hat{l}$, representing the vertical height and horizontal length relative to the centre point L, with $\bar{r} = \sqrt{\hat{h}^2 + \hat{l}^2}$.

For signals transmitted to the desired location L, as shown in Fig. 2, we have

$$D_2 = \sqrt{D_1^2 - h^2},$$
$$\theta = \tan^{-1}(h/D_2), \tag{9}$$

For signals transmitted to the eavesdroppers,

$$\hat{h}(\eta) = \bar{r}\sin\eta,$$
$$\hat{l}(\eta) = \bar{r}\cos\eta,$$
$$\theta(\eta) = \tan^{-1}((h+\hat{h})/(D_2+\hat{l})). \tag{10}$$

For the reflected path from metasurface to the desired location and eavesdroppers, we have the following equation respectively

$$\phi = \tan^{-1}((D_2 - D_3)/(H - h)),$$
$$\phi(\eta) = \tan^{-1}((D_2 + \hat{l} - D_3)/(H - \hat{h} - h)). \tag{11}$$

For the reflected path from transmitter to metasurface, we have the corresponding angle

$$\zeta = \tan^{-1}(H/(D_3 + x_q)). \tag{12}$$

The steering vectors for the LOS path and the reflected path in the two-ray model can be given by

$$\mathbf{s}(\omega,\theta) = [1, e^{j\omega d_1 \sin\theta/c}, \ldots, e^{j\omega d_{N-1}\sin\theta/c}]^T,$$
$$\hat{\mathbf{s}}(\omega,\zeta) = [1, e^{j\omega d_1 \sin\zeta/c}, \ldots, e^{j\omega d_{N-1}\sin\zeta/c}]^T,$$
$$\tilde{\mathbf{s}}(\omega,\phi) = [1, e^{-j\omega x_1 \sin\phi/c}, \ldots, e^{-j\omega x_{Q-1}\sin\phi/c}]^T. \tag{13}$$

Then, in this two-ray model, the beam response of the array as a combination of signals through the LOS path and the reflected path can be represented by $p(\theta, \zeta, \phi)$

$$p(\theta,\zeta,\phi) = \mathbf{w}^H\mathbf{s}(\omega,\theta) + (\mathbf{w}^H\hat{\mathbf{s}}(\omega,\zeta)\cdot\tilde{\mathbf{w}})\tilde{\mathbf{s}}(\omega,\phi), \tag{14}$$

where $\cdot$ represents the dot product, with the weight vector

$$\mathbf{w} = [w_0, w_1, \ldots, w_{N-1}]^T,$$
$$\tilde{\mathbf{w}} = [\tilde{w}_0, \tilde{w}_1, \ldots, \tilde{w}_{Q-1}]. \tag{15}$$

Here, $\tilde{\mathbf{w}}$ is the weight vector for all elements on metasurface to control the phase and magnitude of reflected signals.

For PM design, we need to find M sets of weight coefficients $\mathbf{w}_m$ and one set of $\tilde{\mathbf{w}}$, as it is difficult to get the meta surface synchronised with the transmit antenna array. Note that $\tilde{\mathbf{w}}$ is the single weight vector employed on the metasurface to achieve all transceiver pair communication simultaneously. Similar to parameter definition in DM design, for M-ary signaling, we have M sets of desired array responses $p_m(\theta,\zeta,\phi)$ ($m = 0, 1, \ldots, M-1$), with a corresponding weight vector

$$\mathbf{w}_m = [w_{m,0}, \ldots, w_{m,N-1}]^T, \quad m = 0, \ldots, M-1. \tag{16}$$

Here, we assume in total R locations in the design (r desired locations and $R-r$ eavesdropper locations), then we have the corresponding transmission angles θ_k for LOS, ζ_k and ϕ_k for the reflected path to the k-th position, $k = 0, \ldots, R-1$. Then, an $N \times r$ matrix $\mathbf{S}_L$ is constructed as the set of steering vectors for the LOS path to desired receivers

$$\mathbf{S}_L = [\mathbf{s}(\omega,\theta_0), \mathbf{s}(\omega,\theta_1), \ldots, \mathbf{s}(\omega,\theta_{r-1})], \tag{17}$$

and an $N \times (R-r)$ matrix

$$\mathbf{S}_E = [\mathbf{s}(\omega,\theta_r), \mathbf{s}(\omega,\theta_{r+1}), \ldots, \mathbf{s}(\omega,\theta_{R-1})] \tag{18}$$

for the LOS path to eavesdroppers. The steering matrix for the reflected path from transmitter to metasurface is given by $\hat{\mathbf{S}}$

$$\hat{\mathbf{S}} = [\hat{\mathbf{s}}(\omega,\zeta_0), \hat{\mathbf{s}}(\omega,\zeta_1), \ldots, \hat{\mathbf{s}}(\omega,\zeta_{Q-1})]. \tag{19}$$

The steering matrices for the reflected path from metasurface to desired receivers and eavesdroppers are denoted by $\tilde{\mathbf{S}}_L$ and $\tilde{\mathbf{S}}_E$

$$\begin{aligned}\tilde{\mathbf{S}}_L &= [\tilde{\mathbf{s}}(\omega, \phi_0), \tilde{\mathbf{s}}(\omega, \phi_1), \ldots, \tilde{\mathbf{s}}(\omega, \phi_{r-1})],\\ \tilde{\mathbf{S}}_E &= [\tilde{\mathbf{s}}(\omega, \phi_r), \tilde{\mathbf{s}}(\omega, \phi_{r+1}), \ldots, \tilde{\mathbf{s}}(\omega, \phi_{R-1})]. \quad (20)\end{aligned}$$

The beam responses for desired locations and eavesdroppers for the m-th constellation point are represented by $\mathbf{p}_{m,L}$ ($1 \times r$ vector) and $\mathbf{p}_{m,E}$ ($1 \times (R-r)$ vector),

$$\begin{aligned}\mathbf{p}_{m,L} &= [p_m(\omega, \theta_0, \zeta_0, \phi_0), \ldots, p_m(\omega, \theta_{r-1}, \zeta_{r-1}, \phi_{r-1})],\\ \mathbf{p}_{m,E} &= [p_m(\omega, \theta_r, \zeta_r, \phi_r), \ldots, p_m(\omega, \theta_{R-r}, \zeta_{R-r}, \phi_{R-r})]. \quad (21)\end{aligned}$$

Then, for the m-th constellation point, as a start, the coefficients can be formulated as

$$\begin{aligned}&\min_{\mathbf{w}_m, \tilde{\mathbf{w}}} ||\mathbf{p}_{m,E} - (\mathbf{w}_m^H \mathbf{S}_E + (\mathbf{w}_m^H \hat{\mathbf{S}} \cdot \tilde{\mathbf{w}})\tilde{\mathbf{S}}_E)||_2\\ &\text{subject to } \mathbf{w}_m^H \mathbf{S}_L + (\mathbf{w}_m^H \hat{\mathbf{S}} \cdot \tilde{\mathbf{w}})\tilde{\mathbf{S}}_L = \mathbf{p}_{m,L}. \quad (22)\end{aligned}$$

However, if we consider the weight coefficients for the transmission antenna array and coefficients for the metasurface for each symbol individually as in (22), then for each symbol m, we will end up with a different $\tilde{\mathbf{w}}$. To guarantee the same $\tilde{\mathbf{w}}$ for different symbols, we first construct the following matrices

$$\mathbf{P}_E = [\mathbf{p}_{0,E}; \mathbf{p}_{1,E}; \ldots; \mathbf{p}_{M-1,E}], \quad (23)$$
$$\mathbf{P}_L = [\mathbf{p}_{0,L}; \mathbf{p}_{1,L}; \ldots; \mathbf{p}_{M-1,L}], \quad (24)$$
$$\mathbf{W} = [\mathbf{w}_0, \mathbf{w}_1, \ldots, \mathbf{w}_{M-1}], \quad (25)$$
$$\tilde{\mathbf{W}} = diag(\tilde{\mathbf{w}}), \quad (26)$$

where $diag$ is to convert the vector $\tilde{\mathbf{w}}$ to be a diagonal matrix $\tilde{\mathbf{W}}$ with the size $Q \times Q$. Then, we can construct the matrix $\mathbf{Y}$ ($M \times (R-r)$)

$$\mathbf{Y} = \mathbf{P}_E - (\mathbf{W}^H \mathbf{S}_E + \mathbf{W}^H \hat{\mathbf{S}}_E \tilde{\mathbf{W}} \mathbf{S}_E). \quad (27)$$

As a result, we can change (22) to the following formulation

$$\begin{aligned}&\min_{\mathbf{W}, \tilde{\mathbf{w}}} ||[\mathbf{Y}(1,:), \mathbf{Y}(2,:), \ldots, \mathbf{Y}(M,:)]||_2\\ &\text{subject to } \mathbf{W}^H \mathbf{S}_L + \mathbf{W}^H \hat{\mathbf{S}}_L \tilde{\mathbf{W}} \mathbf{S}_L = \mathbf{P}_L. \quad (28)\end{aligned}$$

As metasurface is regarded as a reflecting surface and no amplifying function, we have to add the following constraint

$$||\tilde{\mathbf{w}}||_\infty \leq 1. \quad (29)$$

Then, the PM design with the magnitude constraint for metasurface can be finally formulated as

$$\begin{aligned}&\min_{\mathbf{W}, \tilde{\mathbf{w}}} ||[\mathbf{Y}(1,:), \mathbf{Y}(2,:), \ldots, \mathbf{Y}(M,:)]||_2\\ &\text{subject to } \mathbf{W}^H \mathbf{S}_L + \mathbf{W}^H \hat{\mathbf{S}}_L \tilde{\mathbf{W}} \mathbf{S}_L = \mathbf{P}_L\\ &\qquad ||\tilde{\mathbf{w}}||_\infty \leq 1. \quad (30)\end{aligned}$$

For the two sets of variables in the design, we use the following alternating optimization method to solve the problem:

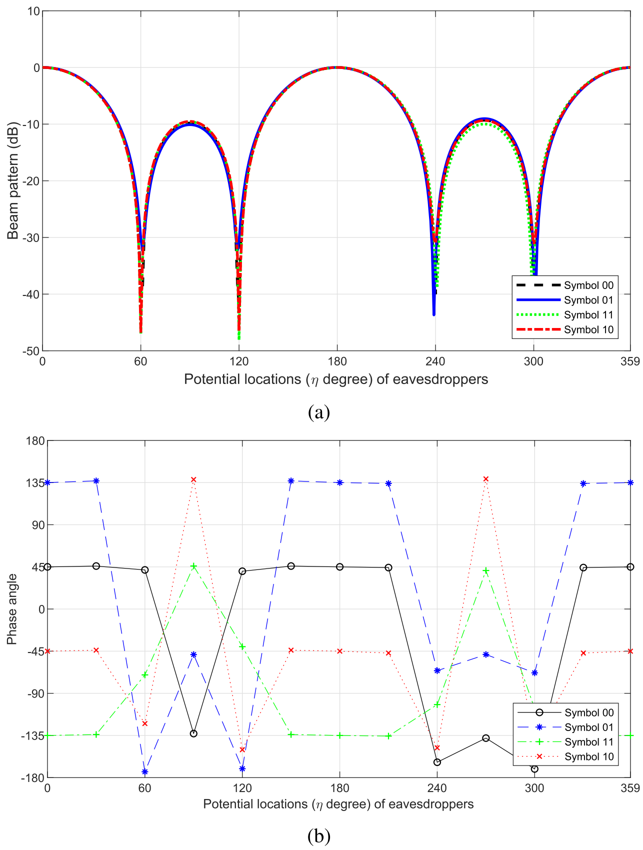


FIGURE 3. Resultant beam and phase patterns for eavesdroppers by the DM design (8).

Step 1 We first randomly generate the vector $\tilde{\mathbf{w}}$ with the maximum magnitude value lower than 1.

Step 2 Based on the given $\tilde{\mathbf{w}}$, the optimised $\mathbf{W}$ can be calculated by (30).

Step 3 With the new $\mathbf{W}$, we re-calculate $\tilde{\mathbf{w}}$ in (30), and then go back to step 2. The iteration stops when the cost function $||[\mathbf{Y}(1,:), \mathbf{Y}(2,:), \ldots, \mathbf{Y}(M,:)]||_2$ converges.

The above problem (30) can be solved by the CVX toolbox in MATLAB [33], [34].

IV. DESIGN EXAMPLES

The metasurface is composed of 64 elements with adjacent element distance $x = \lambda/2$. There is one desired location at the circle centre with $\theta = 0°$, $H = 1000\lambda$, $D_1 = 900\lambda$ and $D_3 = 700\lambda$. Eavesdroppers are located at the circumference of the circle with $\bar{r} = \lambda$ and $\eta \in [0°, 360°)$, sampled every $10°$. The desired response is a value of one in magnitude (the gain is 0dB) with $90°$ phase shift at the desired location (QPSK), i.e. symbols '00', '01', '11', '10' correspond to $45°$, $135°$, $-135°$ and $-45°$, respectively, and a value of 0.2 (magnitude) with randomly generated phase shifts at locations of eavesdroppers. The number of antennas for the ULA transmitter is $N = 50$ with $d = \lambda/2$. Moreover, the bit error rate (BER) result is also presented. Here the signal to noise ratio (SNR) is set at 12 dB at the desired location, and

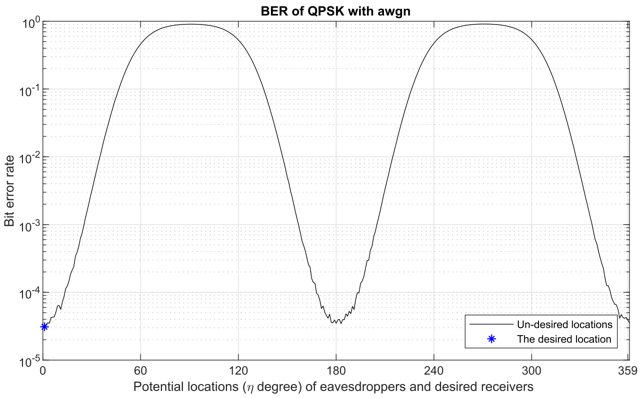
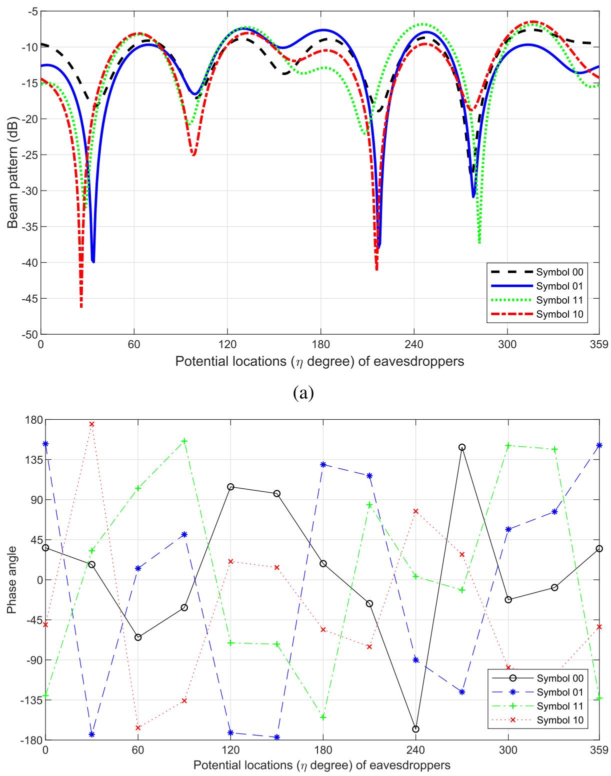


FIGURE 4. BERs patterns for the eavesdroppers and desired receiver by the DM design (8).



(a)

(b)

FIGURE 5. Resultant beam and phase patterns for eavesdroppers by the PM design (30).

we assume the additive white Gaussian noise (AWGN) is at the same level for all eavesdroppers.

The resultant beam and phase patterns for the eavesdroppers based on the DM design in (8) are shown in Figs. 3(a) and 3(b), where the beam response level for eavesdroppers around $\eta = 0°$ and $180°$ are equal to 0dB which is the beam response level for the desired receiver. The phase of signal at these locations are the same as the required QPSK modulation for the desired location. Moreover, their corresponding BER is also down to 10^{-5}, as shown in Fig. 4, demonstrating that the DM design cannot distinguish desired locations and eavesdroppers when they are in the same transmission direction.

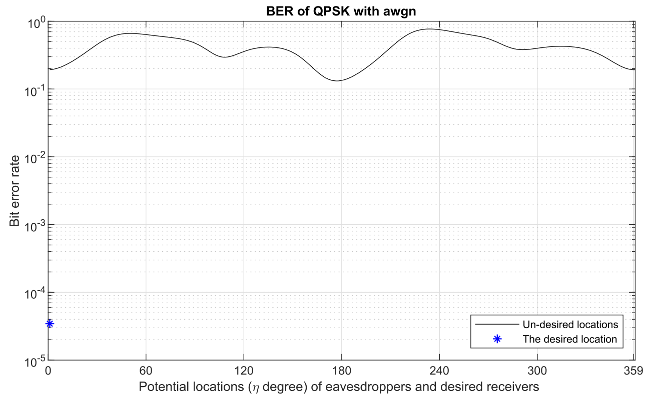


FIGURE 6. BERs patterns for the eavesdroppers and desired receiver by the PM design (30).

By comparison, the beam and phase patterns for the PM design with metasurface in (30) are shown in Figs. 5(a) and 5(b), where the beam response level at all locations of the eavesdroppers $\eta \in [0°, 360°)$ is lower than 0dB which is the beam response for the desired locations, and the phase of signal at these eavesdroppers are random. The BER performance is shown in Fig. 6. It can be seen that at the desired location the value is down to 10^{-5}, while at other locations it fluctuates around 0.5, illustrating the effectiveness of the proposed design.

V. CONCLUSIONS

In this paper, positional modulation design with the aid of metasurface as a low-cost flexible reflecting surface has been introduced for the first time, where signals via LOS and reflected paths are combined at the receiver side. Compared with fixed reflection surface the advantage of using metasurface is the flexible control of reflection direction, phase and intensity of incident signal, while compared with the high cost of using multiple antenna arrays to achieve positional modulation, metasurface provides a convenient low-cost solution for system construction. With the proposed design, signals with a given modulation pattern can only be received at desired locations, but scrambled for positions around them. The effectiveness of the proposed design has been demonstrated by design examples in comparison with the traditional DM technique. Note that, in our current work, the focus is on how to find the optimal coefficients for the antennas and metasurface elements, given an existing antenna array and metasurface with known antenna/element number and geometry/layout. On the other hand, given a performance criterion, how to find the optimal number of antennas and metasurface elements and their associated geometrical layouts will need a different approach and further research is needed, which will form part of our future research plan in this area.

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