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# Sparse Antenna Array Based Positional Modulation Design With a Low-Complexity Metasurface

**BO ZHANG[1], (Member, IEEE), WEI LIU[2], (Senior Member, IEEE), JINGXIAO MA[3], ZICHEN QI[4], JUNWEI ZHANG[2], (Graduate Student Member, IEEE), LIANG HAN[1], (Member, IEEE), YANG LI[1], XIAONAN ZHAO[1], CUIPING ZHANG[1], AND CHENG WANG[1], (Member, IEEE)**

[1]Tianjin Key Laboratory of Wireless Mobile Communications and Power Transmission, College of Electronic and Communication Engineering, Tianjin Normal University, Tianjin 300387, China
[2]Communications Research Group, Department of Electronic and Electrical Engineering, The University of Sheffield, Sheffield S1 4ET, U.K.
[3]College of Electronics and Information Engineering, Tongji University, Shanghai 201804, China
[4]Taikang Life Insurance Company Ltd., Beijing 100031, China

Corresponding author: Bo Zhang (b.zhangintj@tjnu.edu.cn)

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**ABSTRACT** Positional modulation (PM) has been introduced recently where a given modulation pattern can only be received at certain desired positions. To achieve it, the multi-path effect is exploited for positional modulation with the aid of metasurface acting as a low-cost flexible reflecting surface. In this paper, sparse antenna array based positional modulation design is proposed for the first time; to reduce the implementation complexity of the metasurface, the number of active units is also minimised for a given PM design requirement. Design examples are provided to show the effectiveness of the proposed design.

**INDEX TERMS** Positional modulation, directional modulation, metasurface, sparse antenna array.

## I. INTRODUCTION

Directional modulation (DM) based on various antenna arrays has received significant attention due to its ability to keep a known modulation scheme to the desired direction or directions but scramble the pattern in other directions [1]–[15]. In [16], static and dynamic interference signals were added to the transmitter, which achieves better security performance under the same transmission power. Particle swarm optimization (PSO) in [17] was used to optimize the weight coefficients of a phased antenna array to reduce the beam width of directional modulation transmitted signal. In [18], the application scenarios of directional modulation were extended from additive white Gaussian noise (AWGN) channel to multipath fading channel. In [19], [20], peak to average power ratio (PAPR) characteristics of directional modulation transmitted signal based on a phased array was studied.

However, in traditional directional modulation design, eavesdroppers aligned with 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) was introduced. Frequency diverse antenna arrays have been used to achieved PM due to its consideration of distance between the transmitter to receivers [21], [22]. For phased antenna arrays, two methods for PM were proposed. One is using a fixed reflecting surface [23], and the other one is applying multiple antenna arrays at different locations [24]. Recently, a PM design was proposed in [25] using metasurface as a low-cost flexible reflecting material to control the modulation pattern at different spatial locations. The benefit of using metasurface over reflecting surface is the flexibility in direction control and

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reflected signal strength, while the benefit of using metasurface over antenna arrays is the low cost. For implementation using antenna arrays in the design, a power amplifier and a phase shifter are required for each antenna element, while for metasurface implementation, only some simple control circuits are needed [26], [27].

However, the above mentioned design for PM is mainly based on uniform linear arrays (ULAs) with a maximum half wavelength spacing to avoid grating lobes. To reduce the number of antennas and the number of active micro electromagnetic units on the metasurface, sparsity is introduced into both the antenna array and the metasurface in this work, leading to a PM system composed of a sparse antenna array and a low-complexity metasurface. Moreover, the increased degrees of freedom (DOFs) in the spatial domain allow the array system to incorporate more constraints into the design, and given the same number of antennas, an improved performance can be achieved [28].

The remaining part of this paper is structured as follows. A review of PM design based on a fixed linear antenna array and a metasurface is given in Sec. II. The proposed sparse PM design is presented in Sec. III. Design examples are provided in Sec. IV, followed by conclusions in Sec. V.

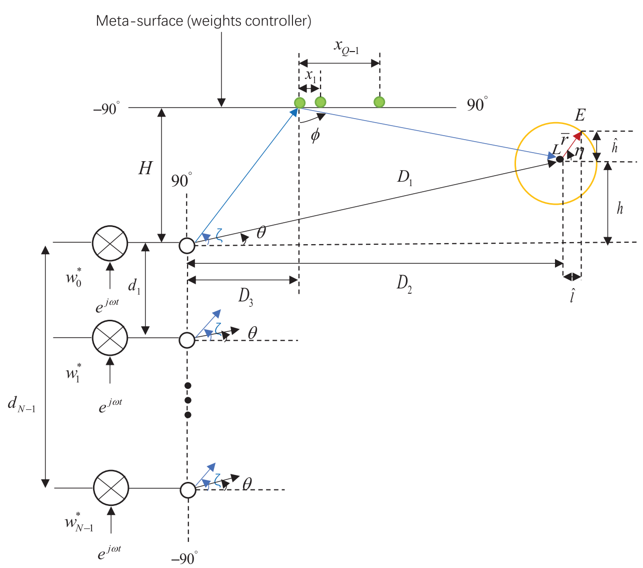


**FIGURE 1. Structure for positional modulation design.**

## II. REVIEW OF PM DESIGN

The recently proposed metasurface based PM design is reviewed in this section. As shown in Fig. 1, the transmitter is a linear array including $N$ antennas with a spacing $d_n$ ($n = 1, \ldots, N-1$) between the zeroth antenna and the $n$-th antenna. A metasurface as the reflecting surface has $Q$ micro electromagnetic units and is above the transmitter with a distance $H$ away from the transmitter. The distance between the the zeroth unit and the $q$-th unit on the metasurface is represented by $x_q$ ($q = 1, \ldots, Q-1$). The transmission angle for the direct path from the transmitter to receivers is represented by $\theta \in [-90^{\circ}, 90^{\circ}]$, while the transmission angle for the first half of the reflected path from the transmitter to receivers via the metasurface is represented by $\zeta$, and angle for the second half of the path is represented by $\phi$. The weight coefficients for the $n$-th antenna and the $q$-th micro electromagnetic unit on metasurface are represented by $w_n$ and $\tilde{w}_q$, respectively ($n = 0, \ldots, N-1, q = 0, \ldots, Q-1$). $L$ represents the desired receiver and $E$ is used to represent an eavesdropper which is on the circle of radius $\bar{r}$, with a vertical height $\hat{h}$, horizontal length $\hat{l}$ and $\eta \in [0^{\circ}, 360^{\circ})$. $D_1$ is 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 the position above the broadside direction and negative for the position below. The projection of $D_1$ onto the broadside direction is represented by $D_2$. $D_3$ is the horizontal distance from the zeroth micro electromagnetic unit to the transmitter.

The steering vector for the direct path from the transmitter to the desired receiver is given by

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

Similarly, the steering vectors for the reflected path via the metasurface can be formulated as

$$\begin{aligned} \hat{\mathbf{s}}(\omega, \zeta) &= [1, e^{j\omega d_1 \sin\zeta/c}, \ldots, e^{j\omega d_{N-1} \sin\zeta/c}]^T, \\ \tilde{\mathbf{s}}(\omega, \phi) &= [1, e^{-j\omega x_1 \sin\phi/c}, \ldots, e^{-j\omega x_{Q-1} \sin\phi/c}]^T. \end{aligned} \tag{2}$$

Then, the beam response can be represented by

$$p(\theta, \zeta, \phi) = \mathbf{w}^H \mathbf{s}(\omega, \theta) + (\mathbf{w}^H \hat{\mathbf{s}}(\omega, \zeta) \cdot \tilde{\mathbf{w}}) \tilde{\mathbf{s}}(\omega, \phi), \tag{3}$$

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

$$\begin{aligned} \mathbf{w} &= [w_0, w_1, \ldots, w_{N-1}]^T, \\ \tilde{\mathbf{w}} &= [\tilde{w}_0, \tilde{w}_1, \ldots, \tilde{w}_{Q-1}]. \end{aligned} \tag{4}$$

Here, we assume $r$ desired locations and $R - r$ eavesdropper locations in the design, with the corresponding angles $\theta_k$, $\zeta_k$ and $\phi_k$ for the path to the $k$-th location, $k = 0, \ldots, R-1$. Thereafter, $\mathbf{S}_L$, $\mathbf{S}_E$, $\hat{\mathbf{S}}$, $\tilde{\mathbf{S}}_L$ and $\tilde{\mathbf{S}}_E$ are constructed [25]

$$\begin{aligned} \mathbf{S}_L &= [\mathbf{s}(\omega, \theta_0), \mathbf{s}(\omega, \theta_1), \ldots, \mathbf{s}(\omega, \theta_{r-1})], \\ \mathbf{S}_E &= [\mathbf{s}(\omega, \theta_r), \mathbf{s}(\omega, \theta_{r+1}), \ldots, \mathbf{s}(\omega, \theta_{R-1})], \\ \hat{\mathbf{S}} &= [\hat{\mathbf{s}}(\omega, \zeta_0), \hat{\mathbf{s}}(\omega, \zeta_1), \ldots, \hat{\mathbf{s}}(\omega, \zeta_{Q-1})], \\ \tilde{\mathbf{S}}_L &= [\tilde{\mathbf{s}}(\omega, \phi_0), \tilde{\mathbf{s}}(\omega, \phi_1), \ldots, \tilde{\mathbf{s}}(\omega, \phi_{r-1})], \\ \tilde{\mathbf{S}}_E &= [\tilde{\mathbf{s}}(\omega, \phi_r), \tilde{\mathbf{s}}(\omega, \phi_{r+1}), \ldots, \tilde{\mathbf{s}}(\omega, \phi_{R-1})]. \end{aligned} \tag{5}$$

To achieve $M$-ary signaling PM design, the following vector is first constructed

$$\mathbf{w}_m = [w_{m,0}, \ldots, w_{m,N-1}]^T, \quad m = 0, \ldots, M-1. \tag{6}$$

$\mathbf{p}_{m,L}$ and $\mathbf{p}_{m,E}$ are used to represent the beam responses for desired locations and those for eavesdroppers for the $m$-th symbol, respectively.

$$\begin{aligned} \mathbf{p}_{m,L} &= [p_m(\omega, \theta_0, \zeta_0, \phi_0), \ldots, p_m(\omega, \theta_{r-1}, \zeta_{r-1}, \phi_{r-1})], \\ \mathbf{p}_{m,E} &= [p_m(\omega, \theta_r, \zeta_r, \phi_r), \ldots, p_m(\omega, \theta_{R-r}, \zeta_{R-r}, \phi_{R-r})]. \end{aligned} \tag{7}$$

Then, we build

$$\begin{aligned}\mathbf{P}_E &= [\mathbf{p}_{0,E}; \mathbf{p}_{1,E}; \ldots; \mathbf{p}_{M-1,E}],\\ \mathbf{P}_L &= [\mathbf{p}_{0,L}; \mathbf{p}_{1,L}; \ldots; \mathbf{p}_{M-1,L}],\\ \mathbf{W} &= [\mathbf{w}_0, \mathbf{w}_1, \ldots, \mathbf{w}_{M-1}],\\ \tilde{\mathbf{W}} &= diag(\tilde{\mathbf{w}}), \end{aligned}\tag{8}$$

where $diag$ converts the vector $\tilde{\mathbf{w}}$ into a diagonal matrix $\tilde{\mathbf{W}}$ with the size $Q \times Q$. Based on the above matrices, we have

$$\mathbf{Y} = \mathbf{P}_E - (\mathbf{W}^H\mathbf{S}_E + \mathbf{W}^H\hat{\mathbf{S}}\tilde{\mathbf{W}}\tilde{\mathbf{S}}_E). \tag{9}$$

Since metasurface has no amplifying function, the following constraint is needed

$$||\tilde{\mathbf{w}}||_\infty \leq 1. \tag{10}$$

Then, the complete formulation for PM design with the aid of metasurface is given by

$$\begin{aligned}&\min_{\mathbf{W},\tilde{\mathbf{w}}} \quad ||[\mathbf{Y}(1,:), \mathbf{Y}(2,:), \ldots, \mathbf{Y}(M,:)]||_2\\ &\text{subject to } \mathbf{W}^H\mathbf{S}_L + \mathbf{W}^H\hat{\mathbf{S}}\tilde{\mathbf{W}}\tilde{\mathbf{S}}_L = \mathbf{P}_L\\ &\qquad\qquad ||\tilde{\mathbf{w}}||_\infty \leq 1,\end{aligned}\tag{11}$$

where $||\cdot||_2$ and $||\cdot||_\infty$ represent $l_2$ norm (square root of the sum of squares of the elements in a vector) and $l_\infty$ norm (the maximum absolute value of each element in a vector), respectively.

## III. PROPOSED SPARSE ANTENNA ARRAY BASED POSITIONAL MODULATION DESIGN

The PM design proposed in [25] is based on ULAs with a maximum half wavelength spacing to avoid grating lobes. The performance of the PM design can be improved by optimizing the antenna locations, leading to a sparse array based design; on the other hand, the number of active micro electromagnetic units on the metasurface can be minimised for reduced implementation complexity.

### A. $l_1$ NORM MINIMISATION

First, for the optimization of antenna locations, a given maximum aperture is set first and it is densely sampled with a large number of potential candidate antenna locations [28]. Accordingly as shown in Fig. 1, we assume the number of potential antennas of the linear array is very large, and each antenna has its corresponding weight coefficient. Through selecting the minimum number of non-zero valued weight coefficients to keep the desired PM response close to the designed one, sparseness is introduced in the array as those with zero-valued coefficients can be considered as inactive and removed from the antenna array. Here, we consider the traditional $l_1$ norm minimisation to maximise sparsity in place of $l_0$ norm. Then, to find the set of weight coefficients for the $m$-th symbol in the PM design, we have the following formulation

$$\begin{aligned}&\min_{\mathbf{w}_m} \quad ||\mathbf{w}_m||_1\\ &\text{subject to } ||\mathbf{p}_{m,E} - (\mathbf{w}_m^H\mathbf{S}_E + (\mathbf{w}_m^H\hat{\mathbf{S}}\cdot\tilde{\mathbf{w}})\tilde{\mathbf{S}}_E)||_2\\ &\qquad\qquad \mathbf{w}_m^H\mathbf{S}_L + (\mathbf{w}_m^H\hat{\mathbf{S}}\cdot\tilde{\mathbf{w}})\tilde{\mathbf{S}}_L = \mathbf{p}_{m,L}\\ &\qquad\qquad ||\tilde{\mathbf{w}}||_\infty \leq 1,\end{aligned}\tag{12}$$

where $||\cdot||_1$ represents the $l_1$ norm.

However, the results to (12) cannot guarantee the same set of active antenna positions for all symbols. For example, if a weight coefficient is zero in an antenna position for one symbol, but non-zero for others, the corresponding antenna still cannot be removed. To solve the problem, we consider group sparsity based design, where the weight coefficients for all symbols are processed simultaneously. Based on the matrix $\mathbf{W} = [\mathbf{w}_0, \mathbf{w}_1, \ldots, \mathbf{w}_{M-1}]$ in (8), we construct a new vector $\bar{\mathbf{w}}$

$$\bar{\mathbf{w}} = [||\mathbf{W}(0,:)||_2, ||\mathbf{W}(1,:)||_2, \ldots, ||\mathbf{W}(N-1,:)||_2]^T. \tag{13}$$

Then, with the matrices $\mathbf{P}_E$, $\mathbf{P}_L$, $\mathbf{W}$, $\tilde{\mathbf{W}}$ in (8) and $\mathbf{Y}$ in (9), the group sparsity based sparse array design for antenna location optimisation can be formulated as

$$\begin{aligned}&\min_{\bar{\mathbf{w}}} \quad ||\bar{\mathbf{w}}||_1\\ &\text{subject to } ||[\mathbf{Y}(1,:), \mathbf{Y}(2,:), \ldots, \mathbf{Y}(M,:)]||_2 \leq \alpha\\ &\qquad\qquad \mathbf{W}^H\mathbf{S}_L + \mathbf{W}^H\hat{\mathbf{S}}\tilde{\mathbf{W}}\tilde{\mathbf{S}}_L = \mathbf{P}_L\\ &\qquad\qquad ||\tilde{\mathbf{w}}||_\infty \leq 1,\end{aligned}\tag{14}$$

where $\alpha$ is the allowed difference between the desired and designed responses.

Similarly, for the metasurface, each micro electromagnetic unit has its corresponding weight coefficient. The $l_1$ norm minimisation of weight coefficients can reduce the number of active units, i.e.,

$$\min_{\tilde{\mathbf{w}}} \quad ||\tilde{\mathbf{w}}||_1. \tag{15}$$

Here, we combine (15) with (14) to form a new cost function for the optimisation of antenna locations and active micro electromagnetic units simultaneously, given by

$$\begin{aligned}&\min_{\bar{\mathbf{w}},\tilde{\mathbf{w}}} \quad \rho||\bar{\mathbf{w}}||_1 + (1-\rho)||\tilde{\mathbf{w}}||_1\\ &\text{subject to } ||[\mathbf{Y}(1,:), \mathbf{Y}(2,:), \ldots, \mathbf{Y}(M,:)]||_2 \leq \alpha\\ &\qquad\qquad \mathbf{W}^H\mathbf{S}_L + \mathbf{W}^H\hat{\mathbf{S}}\tilde{\mathbf{W}}\tilde{\mathbf{S}}_L = \mathbf{P}_L\\ &\qquad\qquad ||\tilde{\mathbf{w}}||_\infty \leq 1.\end{aligned}\tag{16}$$

where $\rho \in (0, 1)$ is a weight factor between the two parts of the new cost function. A larger value close to 1 for $\rho$ will be more focused on minimizing the number of antennas, while a smaller value close to 0 will have more emphasis on the minimum number of active micro electromagnetic units on the metasurface. Due to the tangling of $\mathbf{W}$ and $\tilde{\mathbf{W}}$ in the constraints part, we propose to solve it through the following iterative process:

1) Randomly generate the initial values for $\tilde{\mathbf{w}}$ with the maximum magnitude value no greater than 1.
2) Based on the given $\tilde{\mathbf{w}}$, optimise $\bar{\mathbf{w}}$ by (16).
3) With the new $\bar{\mathbf{w}}$, $\tilde{\mathbf{w}}$ is re-optimised by (16), and then return to step 2. The iteration stops when the positions of non-zero values of the weight coefficients do not change for a consecutive number of iterations (three in our designs).

### B. REWEIGHTED $l_1$ NORM MINIMISATION

Different from $l_0$ norm which uniformly penalises all non-zero valued coefficients, the $l_1$ norm penalises larger weight coefficients more heavily than smaller ones. To make the $l_1$ norm a closer approximation to the $l_0$ norm, a reweighted $l_1$ norm minimisation method can be adopted here [29], [30]. Here, we introduce two weighting parameters $\delta_n$ and $\gamma_q$ for the $n$-th antenna and the $q$-th micro electromagnetic unit. Large values of $\delta_n$ and $\gamma_q$ will go with the corresponding small non-zero values of weight coefficients, while small values of $\delta_n$ and $\gamma_q$ are used with the corresponding large non-zero values. These two weight parameters will change according to the resultant coefficients at each iteration, as shown later. At the $i$-th iteration we solve the following problem

$$\begin{aligned}
\min_{\mathbf{W},\tilde{w}_q} \quad & \rho \sum_{n=0}^{N-1} \delta_n^i ||\mathbf{W}^i(n,:)||_2 + (1-\rho)\sum_{q=0}^{Q-1} \gamma_q^i |\tilde{w}_q^i| \\
\text{subject to } & ||[\mathbf{Y}^i(1,:), \mathbf{Y}^i(2,:), \ldots, \mathbf{Y}^i(M,:)]||_2 \leq \alpha \\
& (\mathbf{W}^i)^H \mathbf{S}_L + (\mathbf{W}^i)^H \hat{\mathbf{S}} \tilde{\mathbf{W}}^i \tilde{\mathbf{S}}_L = \mathbf{P}_L \\
& ||\tilde{\mathbf{w}}^i||_\infty \leq 1, \qquad (17)
\end{aligned}$$

where the superscript $i$ indicates the $i$-th iteration, and $\delta_n$ and $\gamma_q$ are given by

$$\begin{aligned}
\delta_n^i &= (||\mathbf{W}^{i-1}(n,:)||_2 + \beta)^{-1}, \\
\gamma_q^i &= (|\tilde{w}_q^{i-1}| + \beta)^{-1}. \qquad (18)
\end{aligned}$$

Here $\beta = 0.001$ is selected to prevent $\delta_n^i$ and $\gamma_q^i$ becoming infinity at the $i$-th iteration [28]. The iteration process is described as follows:

1) Randomly initialise $\tilde{w}_q$ for $q = 0, \ldots, Q-1$ with the maximum magnitude value no greater than 1.
2) Based on the given $\tilde{w}_q$, optimise $\mathbf{W}(n,:)$ by (16) for the iteration $i = 0$.
3) Set $i = i + 1$. Use the value of the last $||\mathbf{W}^{i-1}(n,:)||_2$ and $|\tilde{w}_q^{i-1}|$ to calculate $\delta_n^i$, $\gamma_q^i$ and the corresponding $||\mathbf{W}^i(n,:)||_2$ and $|\tilde{w}_q^i|$ by solving (17).
4) Repeat step 3 until the positions of non-zero values of the weight coefficients do not change for a consecutive number of iterations (three used in our designs).

The above problems (16) and (17) can be solved by the CVX toolbox in MATLAB [31], [32]. Note that the wavelength involved in the method is universal and can be set at any value.

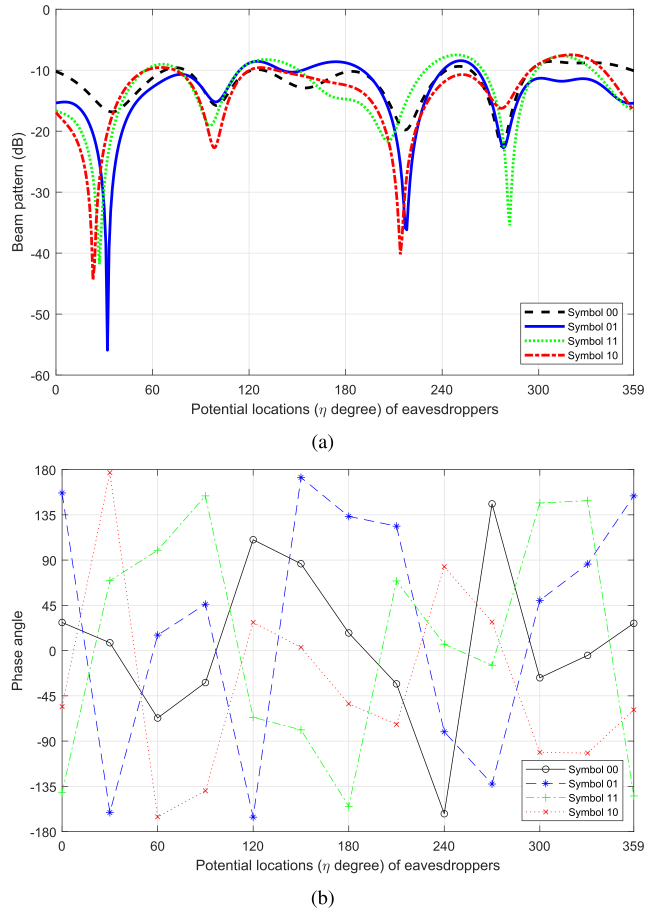


**FIGURE 2. a) Resultant beam pattern; b) resultant phase pattern for eavesdroppers with the traditional $l_1$ norm minimisation method (16).**

## IV. DESIGN EXAMPLES

The number of potential antennas and the number of micro electromagnetic units are $N = Q = 200$ with $d = 0.1\lambda$ and $x = 0.5\lambda$ between adjacent units. Here, we assume eavesdroppers are located on the circle of the radius $\bar{r} = \lambda$, with $\eta \in [0°, 360°)$, sampled every 10°. The desired receiver is located at the position of $\theta = 0°$, $H = 1000\lambda$, $D_1 = 900\lambda$, $D_3 = 700\lambda$. The desired responses are $\sqrt{2}/2 + \sqrt{2}/2i$, $-\sqrt{2}/2 + \sqrt{2}/2i$, $-\sqrt{2}/2 - \sqrt{2}/2i$ and $\sqrt{2}/2 - \sqrt{2}/2i$ at the desired location for symbols '00', '01', '11', '10', and a value of 0.2 (magnitude) with randomly generated phase shifts at locations of eavesdroppers. $\rho = 0.5$ is used for cost functions in (16) and (17). Moreover, the signal to noise ratio is set at 12dB at the desired location, with the same level of noise for all eavesdroppers. Note that all the parameters can be determined by the designer in advance according to the specific requirements.

The resultant beam and phase patterns for the eavesdroppers with the traditional $l_1$ norm minimisation method in (16) are shown in Figs. 2(a) and 2(b), where the beam response level for eavesdroppers at all locations are lower than $-5$dB, and the phases of signal at all locations are not the same as required which are 45°, 135°, $-135°$ and $-45°$ representing

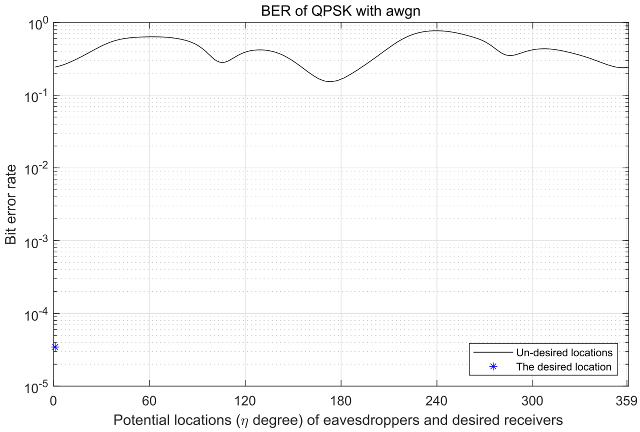


**FIGURE 3.** BERs patterns for the eavesdroppers and desired receiver with the traditional $l_1$ norm minimisation method (16).

**TABLE 1.** Optimised antenna locations based on the $l_1$ norm design (16).

| n | $d_n/\lambda$ | n | $d_n/\lambda$ | n | $d_n/\lambda$ |
|---|---|---|---|---|---|
| 1 | 0 | 7 | 4.9 | 13 | 14.9 |
| 2 | 0.1 | 8 | 6.3 | 14 | 19.1 |
| 3 | 0.2 | 9 | 11.5 | 15 | 19.2 |
| 4 | 0.3 | 10 | 11.6 | 16 | 19.9 |
| 5 | 0.4 | 11 | 13.6 | | |
| 6 | 0.5 | 12 | 14.8 | | |

**TABLE 2.** Optimised micro electromagnetic unit locations based on the $l_1$ norm design (16).

| q | $x_q/\lambda$ | q | $x_q/\lambda$ | q | $x_q/\lambda$ |
|---|---|---|---|---|---|
| 1 | 0 | 7 | 34 | 13 | 97.5 |
| 2 | 6.5 | 8 | 34.5 | 14 | 98 |
| 3 | 7 | 9 | 68 | 15 | 98.5 |
| 4 | 7.5 | 10 | 69 | 16 | 99 |
| 5 | 8 | 11 | 69.5 | 17 | 99.5 |
| 6 | 33 | 12 | 70 | | |

**TABLE 3.** Optimised antenna locations based on the reweighted $l_1$ norm design (17).

| n | $d_n/\lambda$ | n | $d_n/\lambda$ | n | $d_n/\lambda$ |
|---|---|---|---|---|---|
| 1 | 0 | 3 | 5.9 | 5 | 18.9 |
| 2 | 0.7 | 4 | 14.6 | 6 | 19.5 |

the phases of the desired responses $\sqrt{2}/2+\sqrt{2}/2i$, $-\sqrt{2}/2+\sqrt{2}/2i$, $-\sqrt{2}/2-\sqrt{2}/2i$ and $\sqrt{2}/2-\sqrt{2}/2i$ for symbols '00', '01', '11', '10'. Their BERs at all eavesdroppers locations fluctuated around 0.5, while at the desired location the value is down to $10^{-5}$, as shown in Fig. 3, illustrating the effectiveness of the proposed design. Tables 1 and 2 show the positions of optimised antennas and active micro electronic units, respectively, demonstrating a sparse PM design.

The beam pattern, phase pattern and BER for the eavesdroppers with the reweighted $l_1$ norm minimisation in (17) are similar to the design with traditional $l_1$ norm minimisation method. Tables 3 and 4 show their corresponding positions, demonstrating the achievement of a sparse PM design.

**TABLE 4.** Optimised micro electromagnetic unit locations based on the reweighted $l_1$ norm design (17).

| q | $x_q/\lambda$ | q | $x_q/\lambda$ | q | $x_q/\lambda$ |
|---|---|---|---|---|---|
| 1 | 0 | 4 | 31.5 | 7 | 99 |
| 2 | 0.5 | 5 | 56 | 8 | 99.5 |
| 3 | 10 | 6 | 85.5 | | |

**TABLE 5.** Summary of performances between traditional $l_1$ norm and reweighted $l_1$ norm minimisation methods.

| | Traditional $l_1$ | Reweighted $l_1$ |
|---|---|---|
| # Active antennas | 16 | 6 |
| # Active micro electromagnetic units | 17 | 8 |

As shown in Table 5, we can see that fewer antennas and fewer micro electromagnetic units are used for the sparse PM design than the traditional $l_1$ norm minimisation method.

## V. CONCLUSION

In this paper, sparse antenna array based positional modulation design with the aid of low implementation complexity metasurface has been introduced for the first time. Traditional $l_1$ norm minimisation method and reweighted $l_1$ norm minimisation method are considered in the design. As shown in the provided design examples, both methods can result in a sparse design, while the reweighted $l_1$ norm minimisation method can provide a sparser solution as expected, achieving a similar performance as the traditional $l_1$ norm minimisation method but with fewer number of antennas and fewer number of micro electromagnetic units.

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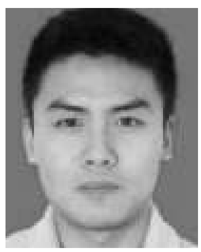
**BO ZHANG** (Member, IEEE) received the B.Sc. degree from Tianjin Normal University, China, in 2011, and the M.Sc. and Ph.D. degrees from the Department of Electrical and Electronic Engineering, The University of Sheffield, in 2013 and 2018, respectively.

He is currently with the College of Electronic and Communication Engineering, Tianjin Normal University. His research interests include array signal processing (beamforming, direction of arrival estimation, and so on), directional modulation, sparse array design, and natural language processing.

**WEI LIU** (Senior Member, IEEE) received the B.Sc. and L.L.B. degrees from Peking University, China, in 1996 and 1997, respectively, the M.Phil. degree from The University of Hong Kong, in 2001, and the Ph.D. degree from the School of Electronics and Computer Science, University of Southampton, U.K., in 2003.

He held a postdoctoral position in Southampton. He was also with the Department of Electrical and Electronic Engineering, Imperial College London. Since September 2005, he has been with the Department of Electronic and Electrical Engineering, The University of Sheffield, U.K., as a Lecturer and a Senior Lecturer. He has published more than 250 journal and conference papers, three book chapters, and a research monograph about wideband beamforming *Wideband Beamforming Concepts and Techniques* (John Wiley, March 2010) and another book *Low-Cost Smart Antennas* (Wiley-IEEE, March 2019). His research interests include signal processing with a focus on sensor array signal processing (beamforming and source separation/extraction, direction of arrival estimation, target tracking and localisation, and so on), and its various applications, such as robotics and autonomous vehicles, human-computer interface, big data analytics, radar, sonar, satellite navigation, and wireless communications.

Dr. Liu is a member of the Digital Signal Processing Technical Committee of the IEEE Circuits and Systems Society and the Sensor Array and Multichannel Signal Processing Technical Committee of the IEEE Signal Processing Society (Vice-Chair in January 2019). He serves as an Associate Editor for the IEEE Transactions on Signal Processing and IEEE Access. He also serves as an Editorial Board Member for *Frontiers of Information Technology and Electronic Engineering* journal.



**JINGXIAO MA** received the B.Eng. degree from the University of Birmingham, U.K., in 2011, the M.Sc. degree in wireless communications from the University of Southampton, U.K., in 2012, and the Ph.D. degree from The University of Sheffield, in 2018. He is currently with the College of Electronics and Information Engineering, Tongji University. His research interests include relay beamforming, massive MIMO systems, and cognitive radio networks.

**ZICHEN QI** received the B.Sc. degree from the University of Science and Technology Beijing, China, in 2014, and the M.Sc. and M.Phil. degrees from the Department of Electrical and Electronic Engineering, The University of Sheffield, in 2016 and 2019, respectively.

He is currently with the Department of Intelligent Data, Taikang Life Insurance Group. His research interests include natural language processing, computer vision, and array signal processing.

**JUNWEI ZHANG** (Graduate Student Member, IEEE) received the B.Eng. degree from Dalian Maritime University, China, in 2016, and the M.Sc. degree from the Department of Electronic and Electrical Engineering, The University of Sheffield, in 2017, where he is currently pursuing the Ph.D. degree. His research interests include array signal processing (beamforming based on interleaved subarray architecture) and multibeam multiplexing.

**LIANG HAN** (Member, IEEE) received the B.S. degree in applied mathematics and the M.S. and Ph.D. degrees in communication and information systems from the University of Electronic Science and Technology of China, Chengdu, China, in 2007, 2010, and 2013, respectively. Since 2014, he has been with the Tianjin Key Laboratory of Wireless Mobile Communications and Power Transmission, Tianjin Normal University, Tianjin, China. From 2016 to 2017, he was a Postdoctoral Fellow with The University of Texas at Arlington, USA. He is currently an Associate Professor with Tianjin Normal University. His current research interests include full-duplex communications, D2D communications, and V2X communications.

**YANG LI** received the B.E. and M.E. degrees from the College of Information Technology and Science, Nankai University, Tianjin, in 2008 and 2012, respectively, and the Ph.D. degree from the Department of Engineering, Tohoku University, Sendai, in 2017. He is currently with the College of Electronic and Communication Engineering, Tianjin Normal University. His research interests include antenna design, EM-wave propagation, and sensor networks.

**XIAONAN ZHAO** received the Ph.D. degree from Tianjin University, Tianjin, in 2015. He is currently with the College of Electronic and Communication Engineering, Tianjin Normal University. His research interests include wireless communication channel measurement and modeling.

**CUIPING ZHANG** received the M.S. degree from Tianjin Normal University, Tianjin, China, in 2018. She is currently with the College of Electronic and Communication Engineering, Tianjin Normal University. Her main research interests include wireless sensor networks and image processing.

**CHENG WANG** (Member, IEEE) received the B.E. degree in measurement and control technology from Xidian University, Xi'an, China, in 2006, and the M.E. and Ph.D. degrees in communication engineering and electrical engineering from Nankai University, Tianjin, China, in 2010 and 2014, respectively.

From 2012 to 2014, he was a Joint Training Doctoral Scholar (China Scholarship Council) with Columbia University, New York, NY, USA. He held an Interdisciplinary Postdoctoral Research with Tsinghua University, Beijing, China, from 2015 to 2017. He joined Tianjin Normal University, as a Principal Investigator, in 2017, directing the Interdisciplinary Laboratory of Advanced Materials and Devices (X-Lab). His current research interests include two-dimensional nanomaterials and devices, condensed matter physics, and nanoelectronics.