Directional Modulation Design Based on Hybrid Beamforming Structure for Massive MIMO

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Abstract. As a physical layer security technique, directional modulation (DM) is normally realized using a fully digital structure due to its easy and flexible hardware design. However, for a large antenna array, such as the case of massive MIMO, to reduce the cost and power consumption, a hybrid digital and analog beamforming structure is widely adopted. In this paper, the DM design problem is studied based on such a hybrid implementation for the first time. As a representative example, the interleaved subarrays are used for the proposed design. Design examples are provided to show the effectiveness of the proposed design.

Keywords: Directional modulation · Hybrid beamforming · Interleaved subarrays

1 Introduction

Traditional wireless communication transmitters implement digital modulation at baseband, where the constellation pattern of signals received in different azimuth angles are only different in their overall amplitudes. As a physical layer security technique, direction modulation (DM) can keep the constellation pattern in the desired direction but scramble it in other directions, further improving the security of a communication system [1–4]. In [5], a phased array was proposed that scrambles the amplitude and phase of the signal in undesired directions and maintains the modulation pattern in the desired direction by phase-shifting each element. A four-symbol modulation was proposed in [6], and the phase shift was chosen to maximize the bit error rate in the eavesdropping direction.

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In [7], a four-dimensional (4-D) modulation scheme was proposed on two polarization diversity channels using the polarization information of the signal, and the number of antennas was reduced based on the compressive sensing technique. A dual-beam directional modulation technique was proposed in [8], which utilizes in-phase and quadrature (IQ) baseband signals to interfere with phase in undesired directions.

The above DM designs are normally applied on either a fully analogue or digital structure. The advantage of analogue implementation is low cost, but its performance is sub-optimal compared with the digital one due to practical constraints on the analogue coefficients. The advantage of digital structure is its easy and flexible hardware design, where the amplitude and phase of the signal can be adjusted with very high precision. However, in a fully digital implementation each antenna needs to be equipped with an independent digital to analogue converter (DAC), which incurs high energy and hardware costs when a large number of antennas are needed, in particular in the case of massive MIMO for future communication systems [9]. To solve the problem, various hybrid digital and analog beamforming structures and designs have been studied extensively for massive MIMO, which greatly reduce the number of required DACs [10–12]. One representative structure for hybrid beamforming is the sub-aperture or subarray based, such as the side by side or localised implementation and the interleaved one [13–15], while the interleaved structure can provide a much narrower beam but with a higher sidelobe level.

In this work, the directional modulation design problem is studied for the first time employing the sub-aperture based hybrid beamforming structure. Although the proposed design can be applied to both the localised and the interleaved structures, without loss of generality, we adopt the interleaved subarray structure as a representative example.

The remaining part of this paper is structured as follows. The hybrid DM design problem based on interleaved subarrays is formulated in Sect. 2. Design examples are provided in Sect. 3, followed by conclusions in Sect. 4.

2 DM Design Based on Interleaved Subarrays

As shown in Fig. 1, the uniform linear array (ULA) T_x is divided into N interleaved subarrays, each subarray consists of M array elements, and the distance between the zeroth and the m-th antenna is d_m $(m = 1, \ldots, MN-1)$. Then, the spacing between adjacent antennas in each subarray is $d_M = Nd_1$. Each subarray is connected to a DAC for digital precoding to form an interleaved subarray structure. The steering vector of the n-th subarray can be represented by

$$\begin{aligned} &\mathbf{s}_n(\omega,\theta) = [e^{j\omega d_n \cos\theta/c}, \ldots, e^{j\omega d_{n+(M-2)N}\cos\theta/c}, e^{j\omega d_{n+(M-1)N}\cos\theta/c}]^T, \\ &\text{for} \quad n = 0, \ldots, N-1; \quad \text{with} \quad d_0 = 0 \end{aligned} \tag{1}$$

where $\{\cdot\}^T$ is the transpose operation, ω is the angular frequency, $\theta \in [0^\circ, 180^\circ]$ is the transmission angle, and c is the speed of propagation. The digital beamformer

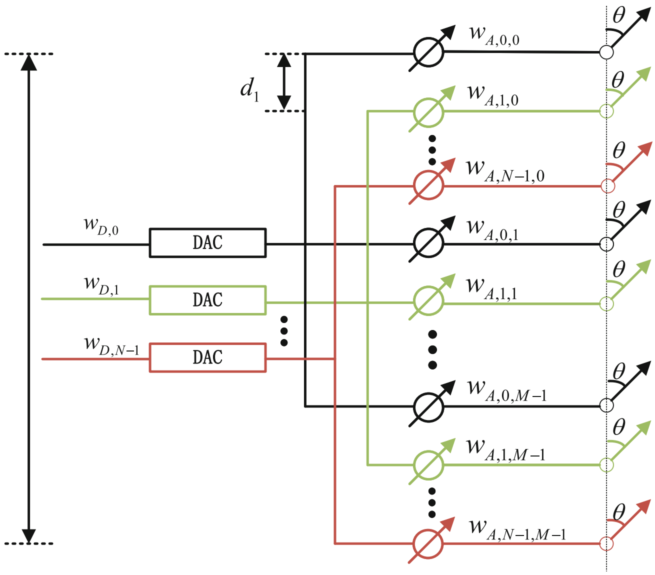

Fig. 1. Interleaved subarrays based hybrid DM structure.

coefficient vector and the analog weighting factors can be represented by

$$\begin{aligned} \mathbf{w}_D &= [w_{D,0}, w_{D,1}, \dots, w_{D,N-1}], \\ \mathbf{w}_{A,n} &= [w_{A,n,0}, w_{A,n,1}, \dots, w_{A,n,M-1}], \end{aligned} \tag{2}$$

where $w_{D,n}$ $(n = 0, \dots, N-1)$ corresponds to the weight corresponding to the n-th subarray, which is a complex number. Suppose r points are sampled in the mainlobe region and $R-r$ points are sampled in the sidelobe region. Then, we have the corresponding steering matrices where $\mathbf{S}_{h,n}$ and $\mathbf{S}_{l,n}$ corresponding to the n-th subarray are represented by

$$\begin{aligned} \mathbf{S}_{h,n} &= [\mathbf{s}_n(\omega, \theta_0), \mathbf{s}_n(\omega, \theta_1), \dots, \mathbf{s}_n(\omega, \theta_{r-1})], \\ \mathbf{S}_{l,n} &= [\mathbf{s}_n(\omega, \theta_r), \mathbf{s}_n(\omega, \theta_{r+1}), \dots, \mathbf{s}_n(\omega, \theta_{R-1})]. \end{aligned} \tag{3}$$

In DM design, for B-ary signaling, the beam responses of the two regions are $\mathbf{p}_{b,H}$ and $\mathbf{p}_{b,L}$, respectively, where $b = 0, \dots, B-1$. Then, the digital beamformer coefficient vector $\mathbf{w}_{b,D}$ and the analog weighting factors $\mathbf{w}_{b,A,n}$ for the b-th symbol can be written as

$$\begin{aligned} \mathbf{w}_{b,D} &= [w_{b,D,0}, w_{b,D,1}, \dots, w_{b,D,N-1}], \\ \mathbf{W}_{b,A} &= \begin{bmatrix} \mathbf{w}_{b,A,0} \\ \mathbf{w}_{b,A,1} \\ \cdots \\ \mathbf{w}_{b,A,N-1} \end{bmatrix} \\ \text{with} \quad \mathbf{w}_{b,A,n} &= [w_{b,A,n,0}, w_{b,A,n,1}, \dots, w_{b,A,n,M-1}]. \end{aligned} \tag{4}$$

Accordingly, the designed responses for each symbol at the R sampling points can be expressed as

$$\begin{aligned} \mathbf{p}_{b,h} &= [p_b(\omega,\theta_0),\ldots,p_b(\omega,\theta_{r-1})], \\ \mathbf{p}_{b,l} &= [p_b(\omega,\theta_r),\ldots,p_b(\omega,\theta_{R-1})]. \end{aligned} \tag{5}$$

Then, to maintain the desired response in the mainlobe region, and disturb the phase of the received signal with a low magnitude level in the sidelobe region, optimisation of the set of digital coefficients and analog coefficients for DM design for the b-th symbol can be formulated as

$$\begin{aligned} &\min_{\mathbf{w}_{b,D},\mathbf{W}_{b,A}} ||\mathbf{p}_{b,l} - \sum_{n=0}^{N-1} \mathbf{w}_{b,D}(n)\mathbf{W}_{b,A}(n,:)\mathbf{S}_{l,n}||_2 \\ &\text{subject to} \quad \sum_{n=0}^{N-1} \mathbf{w}_{b,D}(n)\mathbf{W}_{b,A}(n,:)\mathbf{S}_{h,n} = \mathbf{p}_{b,h}, \end{aligned} \tag{6}$$

where $b = 0, 1, \ldots, B-1$ and $||\cdot||_2$ represents the l_2 norm. The analog matrix $\mathbf{W}_{b,A}$ is implemented by phase shifters and satisfies the constant modulus constraint, i.e., $|\mathbf{W}_{b,A}| = \mathbf{I}_{N\times M}$, where $\mathbf{I}_{N\times M}$ represents an all-ones matrix of size $N\times M$. To solve the non-convex constant modulus constraint problem, we assume a new constraint

$$||vec(|\mathbf{W}_{b,A}|)||_\infty \leq 1, \tag{7}$$

where $vec(\cdot)$ and $||\cdot||_\infty$ represent matrix vectorization and l_∞ norm, respectively. Adding constraint (7) to (6), we have

$$\begin{aligned} &\min_{\mathbf{w}_{b,D},\mathbf{W}_{b,A}} ||\mathbf{p}_{b,l} - \sum_{n=0}^{N-1} \mathbf{w}_{b,D}(n)\mathbf{W}_{b,A}(n,:)\mathbf{S}_{l,n}||_2 \\ &\text{subject to} \\ &\sum_{n=0}^{N-1} w_{b,D}(n)\mathbf{W}_{b,A}(n,:)\mathbf{S}_{h,n} = \mathbf{p}_{b,h} \\ &||vec(|\mathbf{W}_{b,A}|)||_\infty \leq 1. \end{aligned} \tag{8}$$

Then, in order to guarantee the constraint that the constant modulus is one, $\mathbf{w}_{b,D}$ and $\mathbf{W}_{b,A}$ are optimized alternately by the following method:

1. Initialize $\mathbf{W}_{b,A} = e^{j\pi}\mathbf{I}_{N\times M}$.
2. Optimize $\mathbf{w}_{b,D}$ by (8) based on $\mathbf{W}_{b,A}$.
3. Taking $\mathbf{w}_{b,D}$ as a given value, $\mathbf{W}_{b,A}$ is optimized using (8).
4. Let $\mathbf{W}_{b,A} = e^{j\angle\mathbf{W}_{b,A}}\mathbf{I}_{N\times M}$, i.e., the amplitudes of analog coefficient factors are all corrected to one; then use (8) to re-optimize $\mathbf{w}_{b,D}$.
5. Go back to step 3 until the cost function no longer changes and the iteration ends.

The above optimization problem can be solved with the cvx toolbox in MATLAB and a minimum cost function can be found [16].

3 Design Examples

In this section, design examples are provided for the proposed method. The number of antennas for the ULA transmitter T_x is 32 with $d_1 = \lambda/3$, and each

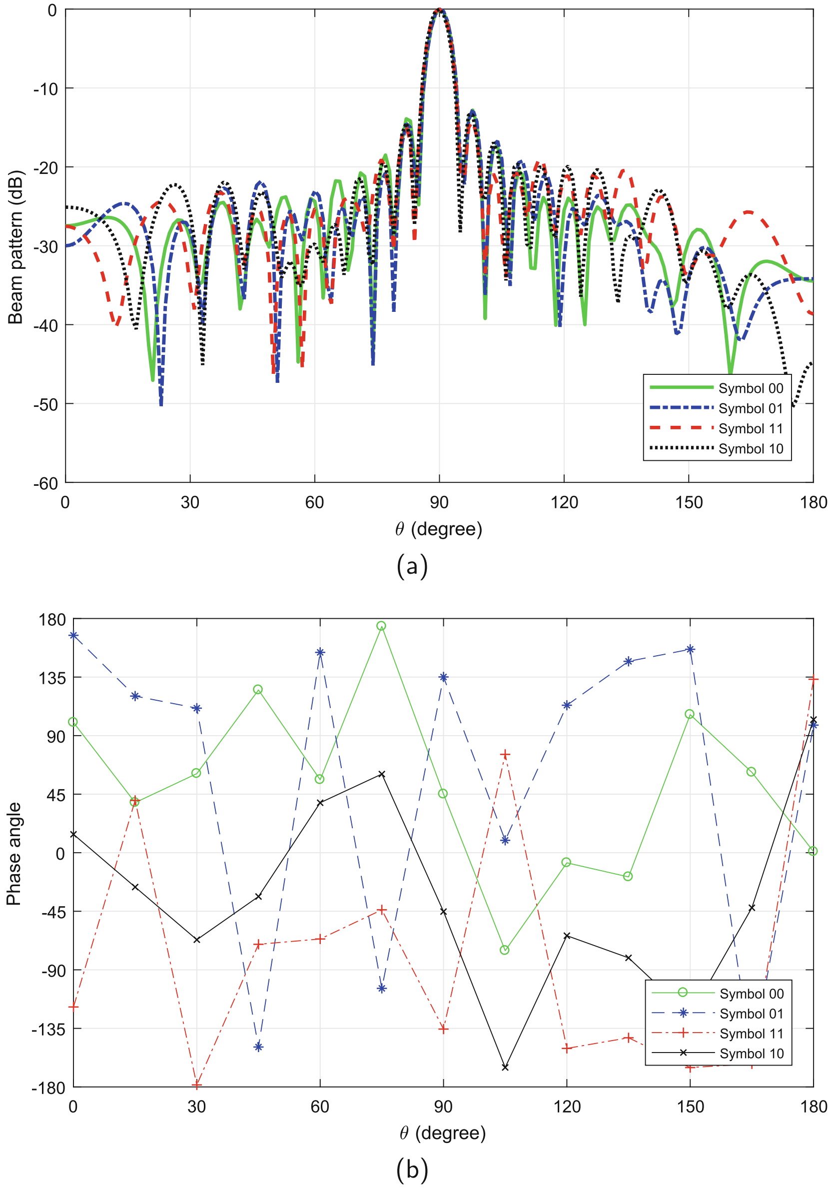

Fig. 2. (a) Resultant beam responses and (b) phase responses for DM design.

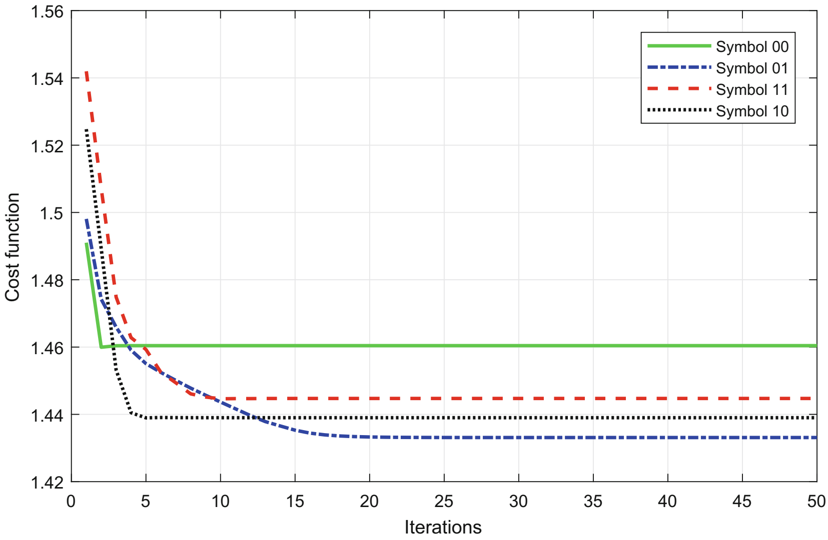

Fig. 3. Cost function vs Iterations in (8).

subarray consists of eight antennas, i.e., $M = 8$. The mainlobe direction is $\theta_h = 90°$ and the sidelobe region is $\theta_l \in [0°, 85°] \cup [95°, 180°]$, sampled every 1°. The desired response received in the direction of the mainlobe is a value of one in magnitude (the gain is 0 dB) with 90° phase shift, i.e. symbols '00', '01', '11', '10' correspond to 45°, 135°, −135° and −45°, respectively, and a value of 0.1 (magnitude) with randomly generated phase shifts in the sidelobe region.

The resultant magnitude and phase responses for all sampling angles are shown in Figs. 2a and 2b. The beam response level for all sampling angles $\theta_l \in [0°, 85°] \cup [95°, 180°]$ in the sidelobe region is lower than 0dB which is the magnitude response for the mainlobe direction, and the phases of signal at these sampling angles θ_l are random. The change of the cost function value with the number of iterations is shown in Fig. 3, which shows that the cost function values corresponding to all symbols converge.

4 Conclusions

In this paper, the interleaved subarrays based hybrid DM design is investigated and a new method is proposed. As shown in the resultant magnitude and phase responses, signals with a given modulation pattern can only be received in the desired direction, but scrambled in other directions. The proposed optimization process is effective, as demonstrated by the convergence of the cost function values for different symbols.

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References

1. Babakhani, A., Rutledge, D.B., Hajimiri, A.: Near-field direct antenna modulation. IEEE Microwave Mag. **10**(1), 36–46 (2009)
2. Xie, T., Zhu, J., Li, Y.: Artificial-noise-aided zero-forcing synthesis approach for secure multi-beam directional modulation. IEEE Commun. Lett. **22**(2), 276–279 (2018)
3. Shu, F., et al.: Directional modulation: a physical-layer security solution to B5G and future wireless networks. IEEE Netw. **34**(2), 210–216 (2020)
4. Zhang, B., et al.: Directional modulation design under a given symbol-independent magnitude constraint for secure IoT networks. IEEE Internet Things J., 8(20), 15:140–15:147 (2021)
5. Daly, M., Bernhard, J.: Directional modulation technique for phased arrays. IEEE Trans. Antennas Propag. **57**(9), 2633–2640 (2009)
6. Daly, M.P., Daly, E.L., Bernhard, J.T.: Demonstration of directional modulation using a phased array. IEEE Trans. Antennas Propag. **58**(5), 1545–1550 (2010)
7. Zhang, B., Liu, W., Lan, X.: Orthogonally polarized dual-channel directional modulation based on crossed-dipole arrays. IEEE Access **7**, 34:198–34:206 (2019)
8. Hong, T., Song, M.-Z., Liu, Y.: Dual-beam directional modulation technique for physical-layer secure communication. IEEE Antennas Wireless Propag. Lett. **10**, 1417–1420 (2011)
9. Larsson, E.G., Edfors, O., Tufvesson, F., Marzetta, T.L.: Massive MIMO for next generation wireless systems. IEEE Commun. Mag. **52**(2), 186–195 (2014)
10. Sohrabi, F., Yu, W.: Hybrid analog and digital beamforming for mmWave OFDM large-scale antenna arrays. IEEE J. Selected Areas Commun. **35**(7), 1432–1443 (2017)
11. Satyanarayana, K., El-Hajjar, M., Kuo, P.-H., Mourad, A., Hanzo, L.: Hybrid beamforming design for full-duplex millimeter wave communication. IEEE Trans. Veh. Technol. **68**(2), 1394–1404 (2019)
12. Molisch, A.F., et al.: Hybrid beamforming for massive MIMO: a survey. IEEE Commun. Mag. **55**(9), 134–141 (2017)
13. Zhang, J.A., Huang, X., Dyadyuk, V., Guo, Y.J.: Massive hybrid antenna array for millimeter-wave cellular communications. IEEE Wireless Commun. **22**(1), 79–87 (2015)
14. Shimizu, M.: Millimeter-wave beam multiplexing method using subarray type hybrid beamforming of interleaved configuration with inter-subarray coding. Int. J. Wireless Inf. Netw. **24**(3), 217–224 (2017)
15. Zhang, J., Liu, W., Gu, C., Gao, S.S., Luo, Q.: Multi-beam multiplexing design for arbitrary directions based on the interleaved subarray architecture. IEEE Trans. Veh. Technol. 69(10), 11:220–11:232 (2020)
16. Grant, M., Boyd, S., Ye, Y.: CVX: matlab software for disciplined convex programming, version 2.0 beta (2013)