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Dual-Beam Multiplexing Under an Equal Magnitude Constraint Based on a Hybrid Beamforming Structure

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***Abstract*—By adjusting the adjacent antenna spacing in terms of the relationship between the two required directions, previous techniques can multiplex two beams by changing the phase of different antennas. In this work, to maintain the adjacent antenna spacing as a fixed value and reduce the implementation complexity, one novel design with an equal magnitude constraint for all antennas, together with the inter-subarray coding scheme is proposed, which can achieve dual-beam multiplexing for arbitrary directions to serve two users via merely changing the analogue phase shift of each antenna. Following a most recent development in this area, the idea can be easily extended to multiple beams. Designed examples are provided to demonstrate the effectiveness of the proposed method.**

***Index Terms*—equal magnitude constraint, interleaved subarray architecture, hybrid beamforming, beam multiplexing**

I. Introduction

For the next-generation (5-G) communication systems, two key enabling technologies are massive MIMO and millimetre wave communication [1], and both require the employment of a large number of antennas working at high frequencies with a wide bandwidth. If the traditional beamforming process is implemented completely in the digital domain, the extremely high cost associated with the large number of high-speed analogue to digital converters (ADCs) and the high-level power consumption will render it practically infeasible.

One solution to the problem is to combine the analogue beamforming technique [2]–[4], and the digital beamforming technique together [2]–[5], leading to the well-known hybrid beamforming structure [6]–[13]. One representative hybrid beamforming structure is the sub-aperture based hybrid beamformer [8], [10], [14]–[16]. There are mainly two types of implementation for the subarray scheme: one is the side-by-side type or localised architecture and the other one is the interleaved architecture [17]. For the interleaved structure, which is the focus of this paper, the antenna elements of each subarray are distributed over a much larger aperture and the spacing between adjacent subarray elements is much larger than the standard array spacing. As a result, a narrower beam can be formed by the interleaved structure; however, this narrow beamwidth is achieved at the cost of generating high sidelobes or even grating lobes or spatial aliasing, although this effect can be suppressed to some extent at a later stage by digital beamforming with improved desired beam gain [18], [19].

Recently, a hybrid beamforming method which involves multiplexing two beams using one common set of analogue phase shifts was proposed in [20]. However, a limitation is that the directions of the two beams must satisfy a specific relationship and therefore it is not suitable for users located at arbitrary directions. To overcome the limit, one method was proposed by treating the adjacent antenna spacing as a variable which is designed according to the specific relationship between the two required beams [21], but a clear issue is that it may not be practical to constantly change the spacing to meet the needs of changing user directions. To solve the problem, a new class of multi-beam multiplexing designs were developed with a fixed antenna spacing for arbitrary beam directions in [22]. In this work, the beam multiplexing problem is further studied and one novel design with a fixed antenna spacing is proposed and one particular feature of the design is that an equal-magnitude constraint is imposed on the common analogue coefficients so that only analogue phase shifts are needed to steer the two different beams to different directions. Without magnitude change of the analogue coefficients, the implementation of the proposed design is significantly simplified [23]. As demonstrated by

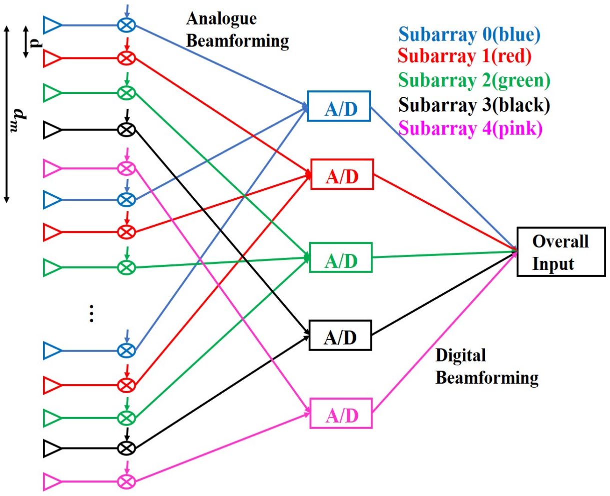

Fig. 1. An interleaved subarray based hybrid beamforming structure.

design examples, the proposed design can generate two high-quality beams in arbitrary directions by merely adjusting the phase for each antenna to serve two users, which was not considered in [20]–[22], [24]. Moreover, following the multi-beam design approach in [22], the proposed equal-magnitude design can be easily extended to the case with multiple beams.

The remaining part of this paper is organised as follows. A review of the interleaved subarray architecture is presented in Section II. An inter-subarray coding scheme with an equal magnitude constraint on analogue coefficient of each antenna for two users in arbitrary directions is described in Section III. Design examples are provided in Section IV and conclusions are drawn in Section V.

II. The Interleaved Subarray Architecture

The interleaved subarray structure based on an N-element uniform linear array (ULA) is shown in Fig. 1, where the adjacent antenna spacing is d. Suppose the N elements of the ULA are split into M interleaved subarrays. Then, each subarray consists of $N_s = N/M$ antennas with an adjacent antenna spacing $d_m = Md$. The phase shift between adjacent subarrays is $e^{j2\pi\frac{d}{\lambda}sin\theta}$, where the direction of angle θ is measured from the broadside.

Through inter-subarray coding, the M-subarray based hybrid beamforming scheme produces M beams using the interleaved subarray architecture. The overall beam pattern using the M subarrays with a main beam in direction ϕ_x is

$$P(\theta,\phi_x) = \sum_{m=0}^{M-1} w_{D,x,m} \sum_{n=0}^{N_s-1} w_{A,m,n}(\phi_m) \exp\left[j2\pi(p_m + \frac{d_m}{\lambda}n)\sin\theta\right], \tag{1}$$

where $w_{D,x,m}$ denotes the digital weighting factor for the m-th subarray with $x = 0, 1$, $p_m = m\frac{d}{\lambda}$ denotes the starting location of the m-th subarray in terms of the signal wavelength λ, and $w_{A,m,n}(\phi_m)$ denotes the analogue weighting factor of the n-th antenna of the m-th subarray for the main beam direction pointing to ϕ_m.

III. The Proposed Design and Associated Inter-Subarray Coding Scheme

Consider the case of $M = 2$. The steering vectors of the two interleaved subarrays are given by

$$\begin{aligned} \mathbf{s}_0(\theta) =&[1, e^{j2\pi\frac{2d}{\lambda}\sin\theta}, ..., e^{j2\pi\frac{2d}{\lambda}(N_s-1)\sin\theta}]^{\mathrm{T}},\\ \mathbf{s}_1(\theta) =&[e^{j2\pi\frac{d}{\lambda}\sin\theta}, e^{j2\pi\frac{3d}{\lambda}\sin\theta}, ..., e^{j2\pi(2N_s-1)\frac{d}{\lambda}\sin\theta}]^{\mathrm{T}}, \end{aligned} \tag{2}$$

where $[.]^{\mathrm{T}}$ denotes the transpose operation. Then, the beam response generated by the m-th subarray is

$$P_{\mathrm{m}}(\theta) = \mathbf{w}_{\mathrm{A,m}}^{\mathrm{H}}\mathbf{s}_m(\theta), \tag{3}$$

where $[.]^{\mathrm{H}}$ denotes the Hermitian transpose and $\mathbf{w}_{\mathrm{A,m}}$ is the vector of analogue weighting factors for the m-th subarray

$$\mathbf{w}_{\mathrm{A,m}} =[w_{\mathrm{A,m,0}}, w_{\mathrm{A,m,1}}, ..., w_{\mathrm{A,m,N_s-1}}]^{\mathrm{T}}. \tag{4}$$

Without loss of generality, a general digital coding scheme is employed, whose coefficients for the beam in direction ϕ_x are given by

$$\mathbf{w}_{\mathrm{D,x}} = [w_{\mathrm{D,x,0}}, w_{\mathrm{D,x,1}}] = [a_{x,0} \quad a_{x,1}], \tag{5}$$

where $a_{x,0}, a_{x,1}$ $(x = \{0, 1\})$ are four digital coefficients to be determined later. So the designed beam response for the beam pointing to direction ϕ_x is

$$\begin{aligned} P_{\phi_{\mathrm{x}}}(\theta) &= a_{x,0}P_0(\theta) + a_{x,1}P_1(\theta)\\ &= a_{x,0}\mathbf{w}_{\mathrm{A,0}}^{\mathrm{H}}\mathbf{s}_0(\theta) + a_{x,1}\mathbf{w}_{\mathrm{A,1}}^{\mathrm{H}}\mathbf{s}_1(\theta). \end{aligned} \tag{6}$$

Moreover, the summation of sidelobe responses for the two beams is

$$\begin{aligned} E_{\mathrm{s}} =& \sum_{\theta\in\Theta_{s_0}} |P_{\phi_0}(\theta)|^2 + \sum_{\theta\in\Theta_{s_1}} |P_{\phi_1}(\theta)|^2\\ =& \sum_{\theta\in\Theta_{s_0}} \left|a_{0,0}\mathbf{w}_{\mathrm{A,0}}^{\mathrm{H}}\mathbf{s}_0(\theta) + a_{0,1}\mathbf{w}_{\mathrm{A,1}}^{\mathrm{H}}\mathbf{s}_1(\theta)\right|^2\\ &+ \sum_{\theta\in\Theta_{s_1}} \left|a_{1,0}\mathbf{w}_{\mathrm{A,0}}^{\mathrm{H}}\mathbf{s}_0(\theta) + a_{1,1}\mathbf{w}_{\mathrm{A,1}}^{\mathrm{H}}\mathbf{s}_1(\theta)\right|^2, \end{aligned} \tag{7}$$

where Θ_{s_0} and Θ_{s_1} denote the sidelobe regions for the zeroth and first beams and (7) can be expanded as

$$\begin{aligned} E_{\mathrm{s}} =&\mathbf{w}_{\mathrm{A,0}}^{\mathrm{H}}\left(a_{0,0}^2\mathbf{Q}_{\mathrm{S00}} + a_{1,0}^2\mathbf{Q}_{\mathrm{S10}}\right)\mathbf{w}_{\mathrm{A,0}}\\ &+\mathbf{w}_{\mathrm{A,1}}^{\mathrm{H}}\left(a_{0,1}^2\mathbf{Q}_{\mathrm{S01}} + a_{1,1}^2\mathbf{Q}_{\mathrm{S11}}\right)\mathbf{w}_{\mathrm{A,1}}\\ &+\mathbf{w}_{\mathrm{A,0}}^{\mathrm{H}}\left(a_{0,0}a_{0,1}\mathbf{P}_{\mathrm{S00}} + a_{1,0}a_{1,1}\mathbf{P}_{\mathrm{S10}}\right)\mathbf{w}_{\mathrm{A,1}}\\ &+\mathbf{w}_{\mathrm{A,1}}^{\mathrm{H}}\left(a_{0,0}a_{0,1}\mathbf{P}_{\mathrm{S01}} + a_{1,0}a_{1,1}\mathbf{P}_{\mathrm{S11}}\right)\mathbf{w}_{\mathrm{A,0}}, \end{aligned} \tag{8}$$

with

$$\mathbf{Q}_{\mathrm{S_{pq}}} = \sum_{\theta \in \Theta_{s_{\mathrm{p}}}} \mathbf{S}_{\mathrm{q}}(\theta), \tag{9}$$

$$\mathbf{P}_{\mathrm{S_{p0}}} = \sum_{\theta \in \Theta_{s_{\mathrm{p}}}} \mathbf{s}_0(\theta)\mathbf{s}_1(\theta)^{\mathrm{H}}, \tag{10}$$

$$\mathbf{P}_{\mathrm{S_{p1}}} = \sum_{\theta \in \Theta_{s_{\mathrm{p}}}} \mathbf{s}_1(\theta)\mathbf{s}_0(\theta)^{\mathrm{H}}, \tag{11}$$

$$\mathbf{S}_{\mathrm{p}}(\theta) = \mathbf{s}_{\mathrm{p}}(\theta)\mathbf{s}_{\mathrm{p}}(\theta)^{\mathrm{H}}, \tag{12}$$

where $p = \{0, 1\}$ and $q = \{0, 1\}$. Combining the analogue coefficients $\mathbf{w}_{\mathrm{A},0}$ and $\mathbf{w}_{\mathrm{A},1}$ into one vector, given by

$$\mathbf{w}_{\mathrm{A}} = \begin{bmatrix} \mathbf{w}_{\mathrm{A},0} \\ \mathbf{w}_{\mathrm{A},1} \end{bmatrix}, \tag{13}$$

equation (8) can be rewritten as

$$E_{\mathrm{s}} = \mathbf{w}_{\mathrm{A}}^{\mathrm{H}} \left(\mathbf{Q}_{\mathrm{S}} + \mathbf{P}_{\mathrm{S}} \tilde{\mathbf{I}}_{\mathrm{LS_0}} \right) \mathbf{w}_{\mathrm{A}}, \tag{14}$$

with

$$\mathbf{Q}_{\mathrm{S}} = \begin{bmatrix} \mathbf{G}_{\mathrm{S_0}} & \mathbf{0} \\ \mathbf{0} & \mathbf{G}_{\mathrm{S_1}} \end{bmatrix}, \tag{15}$$

$$\mathbf{P}_{\mathrm{S}} = \begin{bmatrix} \mathbf{H}_{\mathrm{S_0}} & \mathbf{0} \\ \mathbf{0} & \mathbf{H}_{\mathrm{S_1}} \end{bmatrix}, \tag{16}$$

$$\tilde{\mathbf{I}}_{\mathrm{LS_0}} = \begin{bmatrix} \mathbf{0} & \mathbf{1} \\ \mathbf{1} & \mathbf{0} \end{bmatrix}, \tag{17}$$

$$\mathbf{G}_{\mathrm{S_q}} = a_{0,\mathrm{q}}^2 \mathbf{Q}_{\mathrm{S_{0q}}} + a_{1,\mathrm{q}}^2 \mathbf{Q}_{\mathrm{S_{1q}}}, \tag{18}$$

$$\mathbf{H}_{\mathrm{S_q}} = a_{0,0}a_{0,1}\mathbf{P}_{\mathrm{S_{0q}}} + a_{1,0}a_{1,1}\mathbf{P}_{\mathrm{S_{1q}}}, \tag{19}$$

where $\mathbf{0}$ and $\mathbf{1}$ are $N_s \times N_s$ null and identity matrices, respectively. To make all the analogue coefficients of the two subarrays have the same magnitude, we consider the MinMax approach which minimises the maximum value among the $2N_s$ coefficients for each antenna as follows

$$\min \parallel \mathbf{w}_{\mathrm{A}} \parallel_{\infty}, \tag{20}$$

where $\parallel . \parallel$ is the l_∞ norm, representing the maximum magnitude of the entries in the vector. For a given set of $a_{\mathrm{p,q}}(\{p, q\} \in \{0, 1\})$, through combining the above cost function with the previous cost function in (14), the new formulation of this problem is given by

$$\begin{aligned} \min \quad & (1-\alpha) \parallel \mathbf{L}^{\mathrm{H}}\mathbf{w}_{\mathrm{A}} \parallel_2 + \alpha \parallel \mathbf{w}_{\mathrm{A}} \parallel_{\infty}, \\ \text{subject to} \quad & \mathbf{w}_{\mathrm{A}}^{\mathrm{H}} \begin{bmatrix} a_{0,0}\mathbf{z}_{\mathrm{S_{00}}} & a_{1,0}\mathbf{z}_{\mathrm{S_{10}}} \\ a_{0,1}\mathbf{z}_{\mathrm{S_{01}}} & a_{1,1}\mathbf{z}_{\mathrm{S_{11}}} \end{bmatrix} = \begin{bmatrix} 1 & 1 \end{bmatrix}, \end{aligned} \tag{21}$$

with

$$\mathbf{z}_{\mathrm{S_{pq}}} = \sum_{\theta \in \Theta_{m_{\mathrm{p}}}} \mathbf{s}_{\mathrm{q}}(\theta), \tag{22}$$

where Θ_{m_0} and Θ_{m_1} denote the mainlobe regions for the zeroth and first beams and $\mathbf{L} = \mathbf{V}\mathbf{U}^{1/2}$, with $\mathbf{U}$ being the the diagonal matrix including all the eigenvalues of $(\mathbf{Q}_{\mathrm{S}} + \mathbf{P}_{\mathrm{S}}\tilde{\mathbf{I}}_{\mathrm{LS_0}})$ in (14) and $\mathbf{V}$ being the corresponding eigenvector matrix [25]. In addition, $\alpha \in (0, 1)$ is a trade-off factor between the two parts. The problem in (21) can be solved by the CVX toolbox in [26].

On the other hand, if we know the analogue coefficients $\mathbf{w}_{\mathrm{A}}$, we can obtain the optimum digital coding coefficients as follows.

Similar to (13), combining the digital coefficients for two beams into one vector, given by

$$\mathbf{w}_{\mathrm{D}} = \begin{bmatrix} \mathbf{w}_{\mathrm{D},0}^{\mathrm{T}} \\ \mathbf{w}_{\mathrm{D},1}^{\mathrm{T}} \end{bmatrix} = \begin{bmatrix} a_{0,0} \\ a_{0,1} \\ a_{1,0} \\ a_{1,1} \end{bmatrix}, \tag{23}$$

(8) can be rewritten as

$$E_{\mathrm{s}} = \mathbf{w}_{\mathrm{D}}^{\mathrm{T}} \mathbf{M}_{\mathrm{LS}} \mathbf{w}_{\mathrm{D}}, \tag{24}$$

with

$$\mathbf{M}_{\mathrm{LS}} = \mathbf{Q}_{\mathrm{LS}} + \mathbf{P}_{\mathrm{LS}}, \tag{25}$$

$$\mathbf{Q}_{\mathrm{LS}} = \begin{bmatrix} \mathbf{G}_{\mathrm{LS_{00}}} & 0 & 0 & 0 \\ 0 & \mathbf{G}_{\mathrm{LS_{01}}} & 0 & 0 \\ 0 & 0 & \mathbf{G}_{\mathrm{LS_{10}}} & 0 \\ 0 & 0 & 0 & \mathbf{G}_{\mathrm{LS_{11}}} \end{bmatrix}, \tag{26}$$

$$\mathbf{P}_{\mathrm{LS}} = \begin{bmatrix} \mathbf{P}_{\mathrm{LS_0}}\tilde{\mathbf{I}}_{\mathrm{LS_1}} & \mathbf{0} \\ \mathbf{0} & \mathbf{P}_{\mathrm{LS_1}}\tilde{\mathbf{I}}_{\mathrm{LS_1}} \end{bmatrix}, \tag{27}$$

$$\mathbf{G}_{\mathrm{LS_{pq}}} = \mathbf{w}_{\mathrm{A}}^{\mathrm{H}} \mathbf{Q}_{\mathrm{LS_{pq}}} \mathbf{w}_{\mathrm{A}}, \tag{28}$$

$$\mathbf{P}_{\mathrm{LS_p}} = \begin{bmatrix} \mathbf{H}_{\mathrm{LS_{p0}}} & 0 \\ 0 & \mathbf{H}_{\mathrm{LS_{p1}}} \end{bmatrix}, \tag{29}$$

$$\tilde{\mathbf{I}}_{\mathrm{LS_1}} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \tag{30}$$

$$\mathbf{Q}_{\mathrm{LS_{p0}}} = \begin{bmatrix} \mathbf{Q}_{\mathrm{S_{p0}}} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix}, \tag{31}$$

$$\mathbf{Q}_{\mathrm{LS_{p1}}} = \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{Q}_{\mathrm{S_{p1}}} \end{bmatrix}, \tag{32}$$

$$\mathbf{H}_{\mathrm{LS_{pq}}} = \mathbf{w}_{\mathrm{A}}^{\mathrm{H}} \mathbf{P}_{\mathrm{LS_{pq}}} \tilde{\mathbf{I}}_{\mathrm{LS_0}} \mathbf{w}_{\mathrm{A}}, \tag{33}$$

$$\mathbf{P}_{\mathrm{LS_{p0}}} = \begin{bmatrix} \mathbf{P}_{\mathrm{S_{p0}}} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix}, \tag{34}$$

$$\mathbf{P}_{\mathrm{LS_{p1}}} = \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{P}_{\mathrm{S_{p1}}} \end{bmatrix}, \tag{35}$$

where $\mathbf{0}$ in (27) is a 2×2 null matrix. Given the obtained values of $\mathbf{w}_{\mathrm{A}}$ in step 1), to find the closed-form solution of digital coefficients $\mathbf{w}_{\mathrm{D}}$, the optimisation problem is formulated as

$$\begin{aligned} \min \quad & \mathbf{w}_{\mathrm{D}}^{\mathrm{T}} \mathbf{M}_{\mathrm{LS}} \mathbf{w}_{\mathrm{D}}, \\ \text{subject to} \quad & \mathbf{C}^{\mathrm{T}} \mathbf{w}_{\mathrm{D}} = \mathbf{f}, \end{aligned} \tag{36}$$

with

$$\mathbf{C}=\begin{bmatrix}\mathbf{w}_{\mathrm{A}}^{\mathrm{H}}\hat{\mathbf{z}}_{\mathrm{S}_{00}} & 0\\ \mathbf{w}_{\mathrm{A}}^{\mathrm{H}}\hat{\mathbf{z}}_{\mathrm{S}_{01}} & 0\\ 0 & \mathbf{w}_{\mathrm{A}}^{\mathrm{H}}\hat{\mathbf{z}}_{\mathrm{S}_{10}}\\ 0 & \mathbf{w}_{\mathrm{A}}^{\mathrm{H}}\hat{\mathbf{z}}_{\mathrm{S}_{11}}\end{bmatrix},\mathbf{f}=\begin{bmatrix}1\\1\end{bmatrix}, \tag{37}$$

$$\hat{\mathbf{z}}_{\mathrm{S}_{p0}}=\begin{bmatrix}\mathbf{z}_{\mathrm{S}_{p0}}\\ \mathbf{0}\end{bmatrix},\quad \hat{\mathbf{z}}_{\mathrm{S}_{p1}}=\begin{bmatrix}\mathbf{0}\\ \mathbf{z}_{\mathrm{S}_{p1}}\end{bmatrix}, \tag{38}$$

where $p=\{0,1\}$ and $\mathbf{0}$ in (38) is an $N_s\times 1$ null matrix.

The solution of problem (36) is given by

$$\mathbf{w}_{\mathrm{D_{opt}}}=\mathbf{M}_{\mathrm{LS}}^{-1}\mathbf{C}\left(\mathbf{C}^{\mathrm{T}}\mathbf{M}_{\mathrm{LS}}^{-1}\mathbf{C}\right)^{-1}\mathbf{f}. \tag{39}$$

Joint optimisation of the digital coefficients $a_{0,0}$, $a_{0,1}$, $a_{1,0}$, $a_{1,1}$ and the corresponding analogue coefficients $\mathbf{w}_{\mathrm{A}}$ can be achieved by the following iterative process:

1) First, via initialising $a_{0,0}=a_{1,0}=a_{1,1}=1$ and $a_{0,1}=-1$, the values of $\mathbf{w}_{\mathrm{A}}$ are obtained by substituting $a_{0,0}$, $a_{0,1}$, $a_{1,0}$, and $a_{1,1}$ into (21).
2) Given the optimum values of the analogue coefficients in step 1), obtain the optimum values for the digital coefficients using (39).
3) Given the obtained values of $\mathbf{w}_{\mathrm{D}}$ in step 2), the new set of values of $\mathbf{w}_{\mathrm{A}}$ can be obtained by (21).
4) Repeat the steps of 2) and 3) until the cost function converges. The final digital coefficients $\mathbf{w}_{\mathrm{D}}$ and the corresponding analogue weighting factors $\mathbf{w}_{\mathrm{A}}$ are then obtained.

IV. Designed Examples

In this section, we give some design examples for the proposed method. Assume that each subarray consists of twenty antennas, i.e., $N_s = 15$, and we consider two fixed antenna spacings $d=\frac{\lambda}{4}$ and $d=\frac{\lambda}{3}$ to show the effectiveness of this method. The mainlobe direction of the zeroth beam is $\Theta_{m_0}=-25^\circ$ with the sidelobe region $\Theta_{s_0}\in[-90^\circ,-35^\circ]\cup[-15^\circ,90^\circ]$, and the mainlobe direction of the first beam is $\Theta_{m_1}=15^\circ$ with the sidelobe region $\Theta_{s_1}\in[-90^\circ,5^\circ]\cup[25^\circ,90^\circ]$.

With $d=\frac{\lambda}{4}$ and $d=\frac{\lambda}{3}$, the trade-off factor in (21) is chosen as $\alpha=0.9999$ and $\alpha=0.999$ and the two resultant beams obtained using the scheme in Section III are shown in Figs. 2 and 3. The corresponding analogue coefficients are displayed in Tables I and II, respectively.

With $d=\frac{\lambda}{4}$, the corresponding digital coefficients are $a_{0,0}=1.3433$, $a_{0,1}=0.0578$, $a_{1,0}=-0.0004$, $a_{1,1}=1.3416$. With simple calculation, it can be verified that all the weight magnitudes for the two subarrays are equal to 0.0494. With $d=\frac{\lambda}{3}$, the corresponding digital coefficients are $a_{0,0}=0.1287$, $a_{0,1}=-1.3317$, $a_{1,0}=1.3216$, $a_{1,1}=0.0515$ and all the weight magnitudes for the two subarrays are equal to 0.0496.

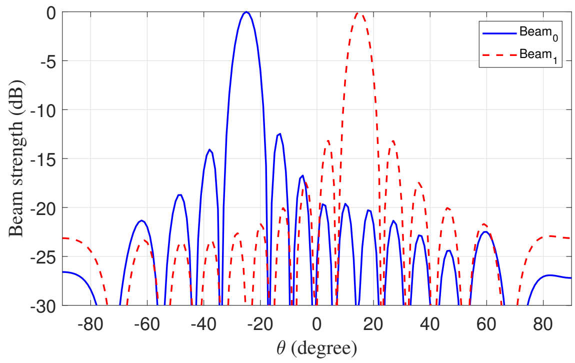

Fig. 2. The resultant beam patterns of two beams with $\phi_0=-25^\circ$ and $\phi_1=15^\circ$, respectively ($d=\lambda/4$).

TABLE I

Analogue coefficients $\mathbf{w}_{\mathrm{A},0}$ and $\mathbf{w}_{\mathrm{A},1}$ when $\phi_0=-25^\circ$ and $\phi_1=15^\circ$ ($d=\lambda/4$).

n \ m	$\mathbf{w}_{\mathrm{A},0}$	$\mathbf{w}_{\mathrm{A},1}$
0	0.0481-0.0115i	0.0471+0.0149i
1	0.0084-0.0487i	0.0217+0.0444i
2	-0.0463-0.0174i	-0.0176+0.0462i
3	-0.0288+0.0402i	-0.0456+0.0191i
4	0.0306+0.0389i	-0.0452-0.0199i
5	0.0462-0.0177i	-0.0164-0.0466i
6	-0.0144-0.0473i	0.0224-0.0441i
7	-0.0494-0.0018i	0.0474-0.0139i
8	-0.0151+0.0471i	0.0427+0.0250i
9	0.0443+0.0220i	0.0114+0.0481i
10	0.0325-0.0373i	-0.0273+0.0412i
11	-0.0258-0.0422i	-0.0487+0.0086i
12	-0.0456+0.0192i	-0.0398-0.0294i
13	0.0092+0.0486i	-0.0057-0.0491i
14	0.0462+0.0175i	0.0315-0.0381i

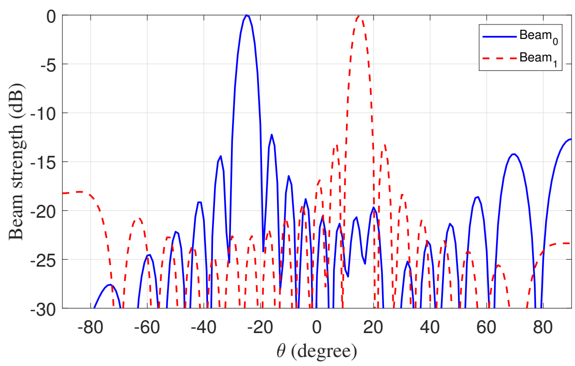

Fig. 3. The resultant beam patterns of two beams with $\phi_0=-25^\circ$ and $\phi_1=15^\circ$, respectively ($d=\lambda/3$).

TABLE II
Analogue coefficients $\mathbf{w}_{\mathrm{A},0}$ and $\mathbf{w}_{\mathrm{A},1}$ when $\phi_0 = -25°$ and $\phi_1 = 15°$ ($d = \lambda/3$).

n \ m	$\mathbf{w}_{\mathrm{A},0}$	$\mathbf{w}_{\mathrm{A},1}$
0	0.0494-0.0043i	-0.0110+0.0483i
1	0.0316+0.0382i	0.0464+0.0175i
2	-0.0229+0.0440i	-0.0014-0.0496i
3	-0.0494+0.0036i	-0.0496+0.0003i
4	-0.0229-0.0440i	0.0175+0.0464i
5	0.0251-0.0428i	0.0459-0.0188i
6	0.0493+0.0057i	-0.0343-0.0358i
7	0.0212+0.0448i	-0.0343+0.0358i
8	-0.0311+0.0386i	0.0442+0.0224i
9	-0.0489-0.0080i	0.0135-0.0477i
10	-0.0144-0.0474i	-0.0483-0.0114i
11	0.0353-0.0348i	0.0103+0.0485i
12	0.0473+0.0148i	0.0494-0.0046i
13	0.0064+0.0492i	-0.0267-0.0418i
14	-0.0368+0.0333i	-0.0453+0.0200i

V. Conclusions

In this paper, the millimetre-wave beam multiplexing design with an equal magnitude constraint for the analogue coefficients has been proposed based on the interleaved subarray architecture. For the two minimisations in the design, we combine them into one single cost formulation using a trade-off factor. Since all antennas in this system share the same magnitude in their analogue coefficients, the overall system complexity has been reduced to a lower level by phase-only beamforming and two beams can be generated in arbitrary directions to serve two users from arbitrary directions.

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