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Receiver Array Thinning using Digitally Assisted Mills Cross

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Abstract— **This paper presents a new approach for receiver steered antenna thinning using a digitally assisted Mills cross array architecture. First, we derive the power patterns of an *M×N* element planar rectangular array of isotropic radiators. In the next step, we replicate these power patterns using two implementation approaches which result in digitally assisted Mills cross arrays. The first approach used a multiplication block, while the second approach used a convolution block, both in the digital domain. The power patterns of a 121 element 30 dB Dolph-Chebyshev uniform rectangular array are recreated using 41 and 21 elements respectively by the techniques we propose. Simulated results, verifying the theoretical findings, are presented and discussed.**

Index Terms—**Mills cross array, massive MIMO, antenna array.**

I. INTRODUCTION

Next generation communication systems, e.g. multi-input multi-output (MIMO), mm-wave vehicular communications technology have been studied extensively because of their promising features which improve the reliability and the capacity of a wireless system, and safety (vehicular systems). For example in a standard massive MIMO system, a very large number of antenna elements show numerous benefits in terms of interference and fast fading [1]. The down side is, by increasing the number of antenna elements, the number of associated RF chains (mixers, LNAs, A/D converter etc.) also increases. This subsequently increases overall system cost, as well as the physical space required to accommodate the equipment. Some recent efforts like [2-3] suggested ways to reduce the required expensive mm-wave equipment, primarily by moving the basic signal processing close to the antennas, while other approaches (e.g. [4]–[7]) investigated the best choice of array aperture for massive MIMO imaging applications, that may result in a reduced number of RF chains.

In this paper, we discuss the approaches to aggressively thin a receive antenna array while maintaining its ability to be steered. To allow this to occur we introduce a new concept, "the digitally assisted Mills cross array". The classical Mills cross array permits high resolution antenna array to be synthesized and its operation is described in [8]. In the digitally assisted Mills Cross array we used computational assistance in the form of multiplication or convolution in the receiver's digital domain. Elementary theory of the approach is presented in section II, the attained performance level is investigated and discussed in section III, while the findings are concluded in section IV of the paper.

II. DIGITALLY ASSISTED MILLS CROSS ARRAYS

Consider an antenna array receiver with $M×N$ uniformly distributed isotropic antenna elements. The array factor of the antenna elements is defined by:

$$AF(\theta,\phi) = \sum_{m=0}^{M-1} I_{mx} e^{jk(md_x \sin\theta\cos\phi + a_x)} \sum_{n=0}^{N-1} I_{ny} e^{jk(nd_y \sin\theta\sin\phi + a_y)} \quad (1)$$

where the terms I, a and d denotes, the excitation amplitude, the progressive phase gradient and the distance between mth and nth antenna element distributes along xy-plane. For the $+z$ hemisphere, the terms $sin\theta cos\phi$ and $sin\theta sin\phi$ can be replaced by u and v to represent the array factor in uv-space. The array factor [9] can be defined as:

$$F(u,v) = F^{-1}(w_x^t \cdot w_y) \quad (2)$$

where Φ^{-1} is the inverse Fourier transform in two dimensions, $(\cdot)$ operation donate vector multiplication, t donates the transpose, $w_x(m)$ and $w_y(n)$ are the weighting elements with magnitude and phase information of a uniform rectangular array, when $m = 1, 2, 3 … M$, and $n = 1, 2, 3 … N$, distributed along the x and y directions, respectively. Equation (2) can be rewritten as:

$$F(u,v) = F^{-1}(w_x^t) \cdot F^{-1}(w_y) \quad (3)$$

The power patterns of a uniform rectangular array are given by:

$$P = F(u,v) \times F(u,v)^* \quad (4)$$

where $[]^*$ represents a complex conjugate operation and $\times$ donates element by element or Hadamard [10] multiplication. By substituting and using the distributive property of Fourier Transform, we get:

$$P = \left(F^{-1}(w_x^t) \times \left[F^{-1}(w_x^t) \right]^* \right) \cdot \left(F^{-1}(w_y) \times \left[F^{-1}(w_y) \right]^* \right) \quad (5)$$

It has been shown in [11] that by shifting the multiplication into an auto-convolution of the complex weighting elements, provided that the following conditions meets
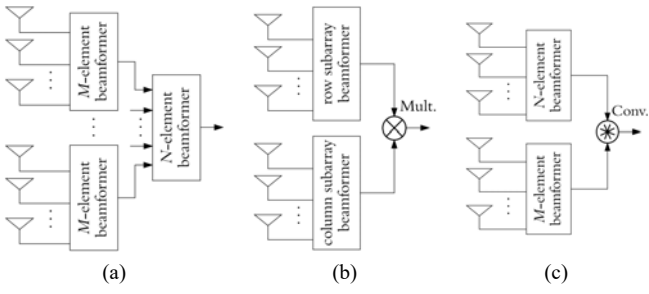
Fig. 1. Architecture of (a) conventional uniform planar rectangular array (b) digitally assisted Mills multiplicative array and (c) digitally assisted Mills convolved array.
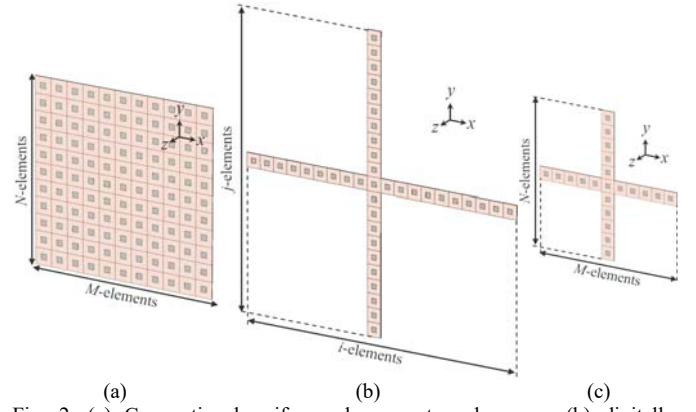

(a)   (b)   (c)

Fig. 2. (a) Conventional uniform planar rectangular array (b) digitally assisted Mills cross multiplicative array and (c) digitally assisted Mills cross convolved array. In each case, the consecutive element spacing is λ/2.
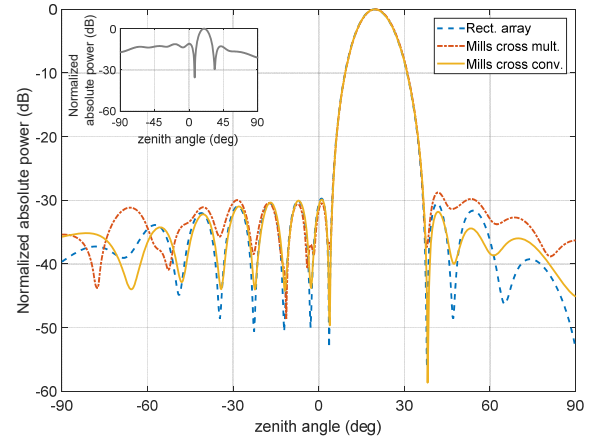

Fig. 3. Pattern comparison between conventional uniform planar array, digitally assisted Mills cross multiplicative and digitally assisted Mills cross convolved array (Inset – patterns of thinned mills cross approach without post digital processing at $\phi = 0°$ cut).

$$F^{-1}(w) = \left[F^{-1}(w) \right]^* \tag{6}$$

the power patterns of a $M \times N$ element planar rectangular array can be replicated using only two 1-dimensional array placed orthogonally to each other given by:

$$P = \left(F^{-1}(w_x^t \otimes w_x^t)^* \right) \cdot \left(F^{-1}(w_y \otimes w_y) \right) \tag{7}$$

where $\otimes$ represents the convolution operation in one dimension. This approach can be used to decrease the number of array elements from $M \times N$ to i and j elements when, $i = 2M{-}1$ and $j = 2N{-}1$ as suggested by 1D convolution. In order for the desired spatial power pattern function to be realized a further post processing unit responsible for the multiplication, of i and j element patterns is required, Fig.1(b).

In this paper we describe, for the first time, another approach that reduces even further the number of array elements required for desired steered pattern synthesis. This is presented in Fig. 1(c). Consider two matrices containing the complex weights of the array elements along x-axis and y-axis.:

$$w_x^t = \begin{bmatrix} w_{x1} & w_{x2} & w_{x1} & \cdots & w_{xm} \end{bmatrix}^t \tag{8}$$

$$w_y = \begin{bmatrix} w_{y1} & w_{y2} & w_{y1} & \cdots & w_{yn} \end{bmatrix} \tag{9}$$

For a planar rectangular array:

$$w_x^t \cdot w_y = \begin{bmatrix} w_{x1}w_{y1} & \cdots & w_{x1}w_{yn} \\ \vdots & \ddots & \vdots \\ w_{xm}w_{y1} & \cdots & w_{xm}w_{yn} \end{bmatrix} \tag{10}$$

By the definition of 2D convolution, the two 1-dimensional orthogonal vectors will convolve as:

$$w_x(m,0)^t \otimes w_y(0,n) = \sum_{p=-\infty}^{\infty} \sum_{q=-\infty}^{\infty} w_x(p,0)^t w_y(0,n-q) \tag{11}$$

where $w_x(p, 0)$ and $w_y(0, n{-}q)$ represents the array element excitation elements distributed along x-axis and y-axis. Comparison of (5), (7) and (11) suggests that the power patterns obtained from any of the approaches used in Fig. 1 should yield the same power patterns using significantly less number of RF chains than required for the full 2D array. For small arrays there is no significant advantage, e.g. the number of antenna elements in the digitally assisted Mills cross schemes, Fig.1 (b) for $i = j = 5$ will be 10, and for the

planar rectangular array, Fig. 1(a), with $N = M = 3$ will be 9 elements, so there is a minor gain of using digitally assisted Mills cross over standard rectangular array. However, this situation changes dramatically for higher number of array elements, for example, for $N = M = 20$, the rectangular array will have 400 elements, while respectively, the corresponding digitally assisted Mills cross multiplicative and convolved array require only 78 and 40 antenna elements. Hence the thinning factors for digitally assisted Mills cross multiplicative and convolved array can be defined as:

$$tf_{ma} = \frac{2(M+N-1)}{M \times N} \tag{12}$$

$$tf_{ca} = \frac{M+N}{M \times N} \tag{13}$$

The presented approaches thus offer major advantage for mm-wave receiver arrays where the prescribed number of antenna elements is very large e.g. steerable massive MIMO or high gain steerable vehicular radar arrays.

III. Performance Evaluation

In this section, we evaluated the aggressively thinned array approach by considering a 28 GHz array of the type required in modern 5G massive MIMO demonstrations, [12]. We used a standard multi-layer rectangular microstrip patch antenna [13] as a unit cell, designed on Roger's RT6006 substrate in CST microwave studio. The half power beam width (HPBW) of the antenna in both θ and ϕ plane is ~93°. We tested all three scenarios in Fig. 1 and the resulted patterns are presented in Fig. 3. Note that we are only showing the 3D patterns on a 2D plane at $\phi = 0°$ for brevity. We applied 11 element $\lambda/2$ Dolph-Chebyshev weights to both w_x and w_y, when the main beam direction was intended to be steered towards +20° zenith angle, while the side lobe level was kept at -30 dB. It can be observed that the main beam pattern for both digitally assisted Mills cross schemes of Fig. 2(b) and (c) match almost perfectly to the main lobe of a 441 element conventional uniform rectangular array. The resultant power pattern cut for the thinned mills cross approach without post digital processing is also given for comparison in the inset of Fig. 3. To fully characterize the theoretical findings of the previous section, we did not extend the ground planes of the digitally assisted Mills cross schemes much beyond the edge of the microstrip patch radiating elements. Consequently, both the digitally assisted Mills cross schemes presented in Fig. 2(b) and (c) are backed only by a (+) shaped ground plane. The impact of lack of a large ground plane is visible on the side lobes (especially at the zenith angle = ±40° to ±90°) where the difference between the three side lobe contours becomes evident. Nevertheless, the side lobe power level for all three contours stays below 30 dB throughout the $+z$ hemisphere. The choice of a larger ground plane should further increase the correlation between the three patterns. Equations (7) and (11) also suggests that the central antenna element of both digitally assisted Mills linear subarrays do not necessarily need to coincide at the array's phase center. In other words, quasi-T and quasi-L formations of the two linear subarrays are also acceptable, provided that the spatial orthogonality between the two arrays is maintained. This fact further enhances the benefits of the presented array schemes in terms of the utilization of the available space to host single or even multiple arrays and subarrays nested in any orthogonal formulation.

IV. Conclusion

Two schemes for new types of digitally assisted Mills cross receive arrays, namely multiplicative and convolved arrays are presented and discussed. The theoretic principle governing the operation of the arrays have been discussed and full wave EM simulation of the digitally assisted arrays has been studied at 28GHz (a key frequency for massive MIMO applications). It has been shown that through digital computational assistance, the Mills cross array schemes possesses a number of benefits over conventional 2D planar arrays, especially in terms of reducing the number of RF chains required and prospect of better utilization of the available space.

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