



Thinned Planar Aperture Array with High Polarization Purity for SKA

Yongwei Zhang⁽¹⁾, Ahmed El-makadema⁽¹⁾, Nima Razavi-Ghods⁽²⁾ and Anthony K. Brown*⁽¹⁾

(1) The University of Manchester, Manchester, M13 9PL, UK e-mail: david.zhang@manchester.ac.uk

(2) Cavendish Laboratory, University of Cambridge, Cambridge, CB3 0HE, UK

Abstract

Array geometry has a significant impact on aperture array design. For large scale array applications such as the Mid-Frequency Aperture Array (MFAA) of the Square Kilometre Array (SKA) telescope, a regular type grid can result in over 20 million array elements to fulfill the sensitivity requirement. Such a fully filled array has an essentially flat effective area with frequency and can provide excellent control of the radiation pattern, particularly the sidelobe level (SLL). Thinning techniques undersample the aperture to reduce the number of elements required, and hence overall system cost, whilst maintaining angular resolution. In principal, the effective area now becomes a function of frequency, depending on the number and type of elements used and their layout. This is also true of sidelobe levels, particularly at wider angular regions. Initially a mathematical model on aperture arrays has been used to develop the thinning algorithms with the goal of exploring how much thinning could be used without significantly affecting the fully filled array performance for a MFAA application. The robustness of the thinning strategy developed is verified by a full wave simulation on finite array using a broadband planar interconnected array approach. This type of array lends itself to economic production of large scale arrays. A thinned array version can in principal be easily implemented although has not been previously reported in the literature. It is confirmed that the total number of elements can be reduced by 7% without a significant impact on overall array performance compared to a fully filled array. Polarization purity is one of the most stringent requirements for future radio telescopes. The polarization performance of the thinned planar array is analyzed including the intrinsic cross polarization ratio and the polarization orthogonality.

1. Introduction

Wideband antenna arrays have become increasingly important in a number of applications, especially with high polarization purity and wide scan angle. These include radio astronomy, such as the SKA [1][2], satellite based sub-mm wave instruments, and radars in defense and security. For the application of the SKA Mid-Frequency Aperture Array (MFAA) instrument, tens of million antenna elements are required to form a sufficiently large effective aperture. The geometry of the elements in the

array play a dominant role for the array performance. Dense aperture arrays which are defined as having a $\lambda/2$ inter-element spacing determined by of the highest operating frequency demonstrate unparalleled capability for wide field of view and high dynamic range imaging. The elements in the array can be arranged as a regular square or triangular grid, with the triangular geometry having approximately 13% less elements whilst delivering a similar performance [2]. However, the total number of elements needed is still significant number [2]. Thinning algorithms can be applied to regular grid arrays to reduce the total number of elements further. The feasibility of the array geometry with thinning is closely associated with array element designs. Octagonal Ring Antenna (ORA) has been developed based on a 2-D planar structure to form a dual polarized aperture array [3]. The unique property of this structure is that the elements can be arranged easily with either square or triangular grids. This paper is to use ORA and its variation type to examine the effectiveness of random thinning on dense arrays.

2. Crossed Octagonal Ring Antenna

Initially, Octagonal Ring Antenna (ORA) was proposed by using two pairs of mutually capacitive enhanced octagonal rings but one of the rings is shared for dual polarization [3]. It can achieve a 5:1 bandwidth with an extra layer of metamaterial above the active antenna array surface. The total thickness of the array is approximately $\lambda/10$ (At the lowest frequency of the operating band). The low profile and the planar structure of ORA array make it a low-cost promising solution for large scale applications such as SKA. Crossed Octagonal Ring Antenna (C-ORA) is further proposed with a better isolation between dual polarized elements [4]. The C-ORA design model is shown in Fig. 1. The passive layer is formed by placing only the circle rings above the active layer, and with a specified distance. In both square and triangular grid based arrays for this study, the distance between the ground plane and the active layer is 70mm; the distance between the active layer and passive layer is 35mm. With an equilateral triangular grid, the distance between the centre of the adjacent elements, d_{tri} , has the following relationship with the element separation under a square grid configuration, d_{sqr} , with the same grating lobe criteria,

$$d_{tri} = 2d_{sqr}/\sqrt{3} \quad (1)$$

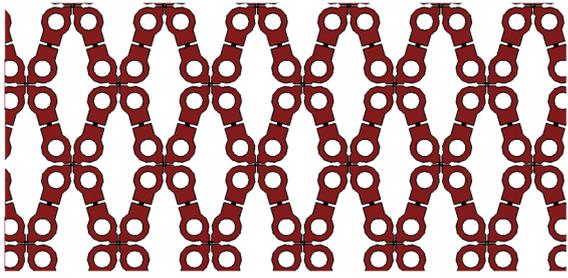


Figure 1. A section of the active layer of the triangular grid based C-ORA array.

3. Finite Array Analysis

C-ORA design model is optimized to cover the frequency range between 400MHz and 1450MHz. The element separation is 144 mm for the triangular grid, which corresponds to 125 mm for a square grid based array to produce the same grating lobe performance. A finite array of 16×16 was manufactured for characterization with the physical aperture of the array being $2.4\text{m} \times 2.05\text{m}$ for the triangular grid, and $2\text{m} \times 2\text{m}$ for the square grid. The C-ORA finite arrays based on both square and triangular grid have been investigated and compared. The C-ORA finite array based on triangular grid is shown in Fig. 2. It is indicated that 16×16 dual polarized elements have been used in the array, with this size the performance of the centre element is close enough as in an infinite array environment. It also reach the limit that the computer power can handle for full wave analysis. As aperture size of a real array will be much greater, a mathematical model is also developed to predict the array performance.

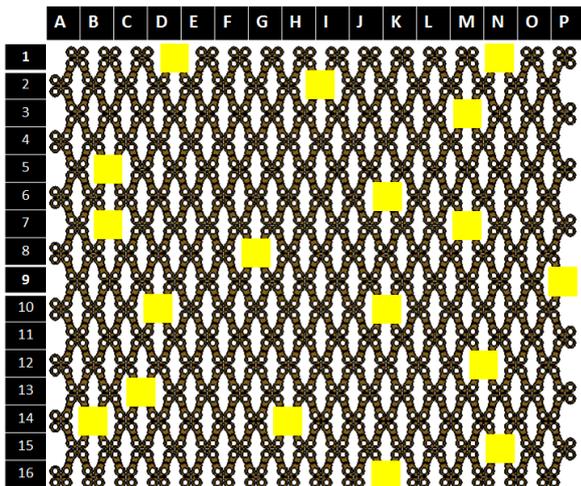
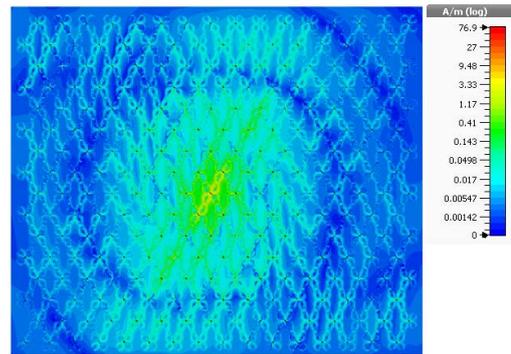


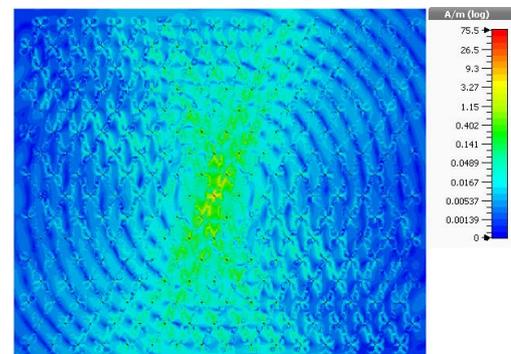
Figure 2. The finite array model based on triangular grid C-ORA, the elements at positions coloured in yellow are removed for the thinned array.

The tight mutual coupling between the elements in the C-ORA array is critical for the array to achieve the

bandwidth, especially at the low frequencies. The mutual coupling between the centre element and the surrounding elements has been analyzed with full-wave simulations. As expected the mutual coupling at the low frequency becomes less significant gradually as the separation between the two observed elements increases. This complexity is examined by monitoring the surface currents on the active layer when the centre element is excited. This is shown in Fig. 3, where several wavefronts can be observed across the finite array aperture at the high frequency. At the low frequency of 400 MHz, only one wavefront occurs within this finite array aperture. It is noticed that the current flows a longer distance along the E-plane which is the diagonal direction on the aperture.



(a)



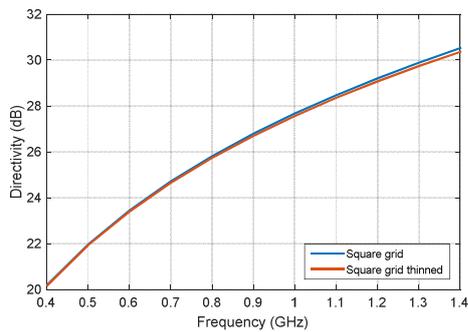
(b)

Figure 3. The surface current when the centre element is excited, triangular grid array, (a) 400 MHz; (b) 1400 MHz.

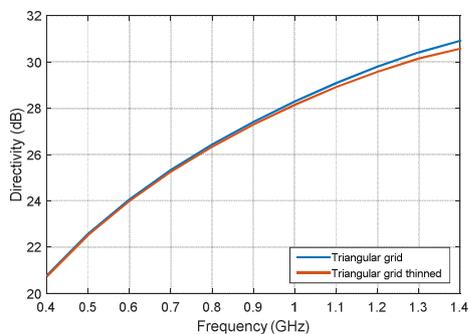
4. Results and Discussions

Initially, a mathematical model has been used to study the algorithm for thinning. Scan element patterns are derived from the 16×16 finite array for the centre elements. The patterns at different frequencies are loaded into the simulation model for array performance calculation. In the mathematical model, at each element position, a same scan element pattern is applied to calculate the total array radiation performance, and the mutual coupling effect is not included. It should also be noted that in the actual finite array, the patterns for elements at different locations in the

array are different. Here the model simplifies the situation by assuming that the element patterns are unanimous for elements in the finite array studied. When the random thinning technique is applied, a certain percentage of elements from the array are removed in random. As shown in Fig. 2, 16 elements out of 256 elements have been removed from the finite array when the array is being thinned. Total directivity of the array for both cases have been calculated based on the same scan element pattern. The directivity of the 16×16 finite array based on the mathematical model is shown in Fig. 4. Both square and triangular grid based finite arrays have been analyzed. It indicates there is no significant performance degradation when 7% elements are randomly removed.



(a)



(b)

Figure 4. The finite array performance based on the mathematical model, same radiation pattern for each element and no mutual coupling considered, (a) Square Grid; (b) Triangular Grid.

The array geometry plays a very important role on the array performance. It is indicated that with the same number of elements (16×16 finite array), the array based on a triangular grid yields a higher directivity as expected in spite of different mutual coupling conditions among elements in both arrays. This is indicated in Fig. 5.

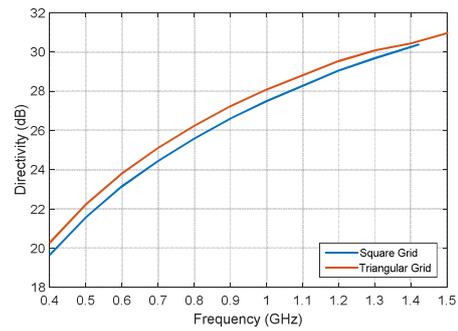


Figure 5. The directivity of the 16×16 finite array.

Applying 7% thinning has no impact on directivity for frequencies below center band. The performance for the array based on a triangular grid with 7% thinning is shown in Fig. 6 by using the full-wave simulation. Compared with the results shown in Fig. 4(b) where the mathematical model has been used, it indicates that the mathematical model is a powerful tool and can be used to examine a much larger array structure without losing a significant accuracy when a full wave simulation becomes impossible to be used in that case.

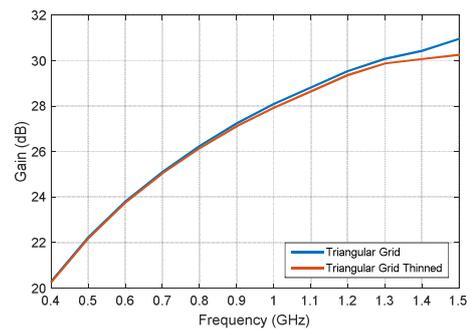
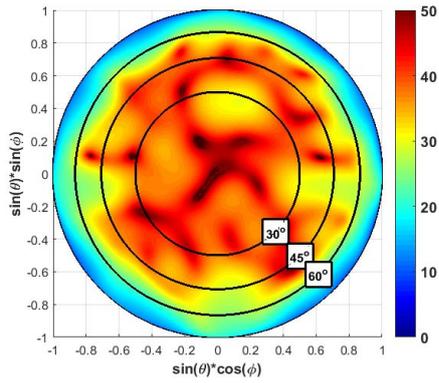
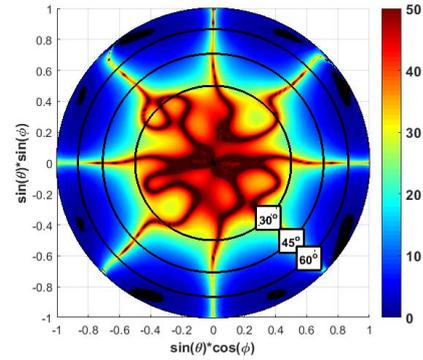


Figure 6. The directivity of the 16×16 finite array based on a triangular grid.

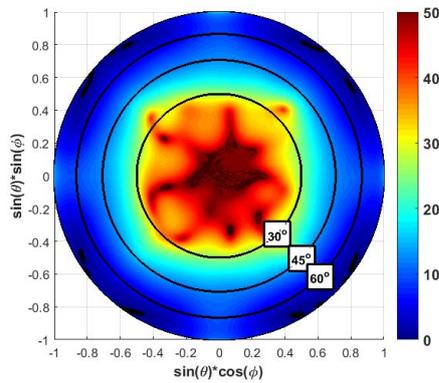
In many applications such as SKA, high-precision polarimetry is required. Polarimetric performance of the array must be understood to measure the state of polarization of radio sources. Intrinsic Cross-Polarization Ratio (IXR) is widely used in radio astronomy community for its close connection with calibration accuracy and independence from coordinate systems [5]. Orthogonality is another parameter to assess the polarization purity performance [6]. It is widely used in wireless communication fields. Both polarization characteristics of the C-ORA array have been calculated. The IXR performance is given in Fig. 7. The IXR for the C-ORA array is above 25 dB over the entire frequency band and the 45 degree scan range from the zenith. This is significant to reduce the calibration error for high-precision polarimetric observations.



(a)



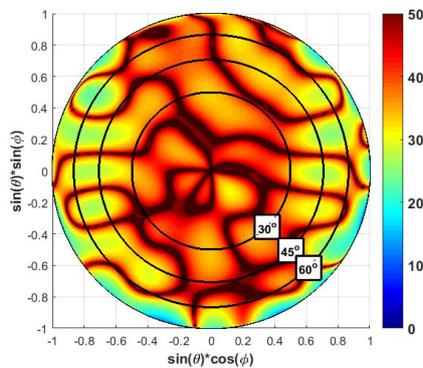
(b)



(b)

Figure 7. The IXR of the finite C-ORA array, (a) 900 MHz; (b) 1400 MHz.

The orthogonality of the finite C-ORA array is shown in Fig. 8. Within the 45° scan range, approximately 30 dB orthogonality between the two polarizations can be achieved.



(a)

Figure 8. The Orthogonality of the finite C-ORA array, (a) 900 MHz; (b) 1400 MHz.

6. Acknowledgements

The author want to thank STFC UK for the financial support of this work.

7. References

1. W.A. van Cappellen, M. Santos, J.P. Macquart, F. Abdalla, E. Petroff, A. Siemion, R. Taylor, O. Smirnov, D. Davidson, J. Broderick, J. van Leeuwen, P. Woudt, M.A. Garrett, A.J. Faulkner, S.A. Torchinsky, I.M. van Bemmell, J. Hessels, "MANTIS: The Mid-Frequency Aperture Array Transient and Intensity-Mapping System," Instrumentation and Methods for Astrophysics, Fri, 23 Dec 2016.
2. A. El-Makadema, Y. Zhang, M. Yang, A. K. Brown, "On the geometry of the Square Kilometer Array Mid-Frequency Aperture Array," ICEAA 2015, 7-11 Sept. 2015, Turin, Italy. pp. 533-536.
3. Y. Zhang, A. K. Brown, "Octagonal Ring Antenna for a Compact Dual-Polarized Aperture Array," IEEE Transactions on Antennas and Propagation, Vol. 59, No. 10, pp. 3927-3932, October 2011.
4. Y. Zhang, A. El-Makadema, M. Yang and A. K. Brown, "Dual polarised crossed ring antenna array with high polarimetric purity," 2017 International Conference on Electromagnetics in Advanced Applications (ICEAA), Verona, 11-15 Sept. 2017, pp.1358-1360. doi: 10.1109/ICEAA.2017.8065528
5. T. D. Carozzi and G. Woan, "A Fundamental Figure of Merit for Radio Polarimeters," in IEEE Transactions on Antennas and Propagation, vol. 59, no. 6, pp. 2058-2065, June 2011. doi: 10.1109/TAP.2011.2123862.
6. Collins, B.S.. (2000). Effect of imperfect antenna cross-polar performance on the diversity gain of a polarization-diversity receiving system. Microwave Journal. 43. pp.1-7.