

Simplified Sidelobe Reduction Techniques for Concentric Ring Arrays

Mostafa Nofal · Sultan Aljahdali · Yasser Albagory

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Abstract In this paper, a simplified sidelobe reduction technique for uniform concentric circular antenna arrays (UCCA) is proposed. This technique is based on modifying some conventional windows to control the amplitude feeding instead of using adaptive techniques which require excessive processing and calculations and suffer from the lack of practical application especially for UCCA. The modified windows are applied to individual rings of the array that will taper the corresponding current amplitudes. The resulted sidelobe level, beamwidth and stability for amplitude errors are discussed for the different proposed windows where it shows a sidelobe reduction to about 49 dB as in the case of Binomial UCCA while the Hamming window shows the most immunity to tapered amplitude errors.

Keywords Smart antenna · Mobile communication · Sidelobe level reduction

1 Introduction

Concentric circular antenna arrays has a widespread use in various applications such as mobile, radar, sonar and direction finding due to its features [1–5]. The array consists of concentric circular arrays each has a number of elements arranged in a circle of certain radius. The sidelobe level in this array is 17.5 dB for most sizes which is less than that of the two-dimensional arrays by 4 dB [5]. A popular array geometry is the uniform concentric

M. Nofal

Department of Computer Engineering, College of Computers and Information Technology,
Taif University, Taif, Kingdom of Saudi Arabia

S. Aljahdali

Department of Computer Science, College of Computers and Information Technology,
Taif University, Taif, Kingdom of Saudi Arabia

Y. Albagory (✉)

Department of Information Technology, College of Computers and Information Technology,
Taif University, Taif, Kingdom of Saudi Arabia
e-mail: dalbagory@gmail.com

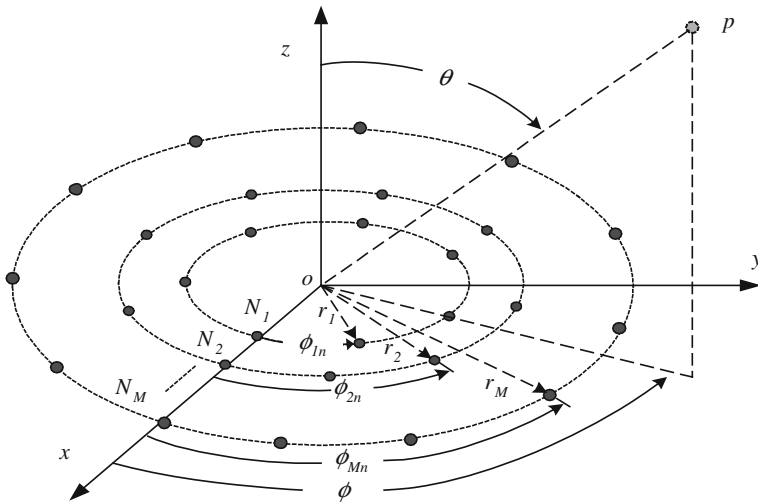


Fig. 1 Concentric circular arrays (CCA)

circular array (UCCA) in which the rings as well as the individual ring elements are separated by almost half of the wavelength where the number of elements of the neighbored rings is incremented by 6 elements [6]. Although the UCCA at this separating distance has the minimum beamwidth with single mainlobe it still has higher sidelobe levels which are not suitable in many applications. Sidelobe level reduction can be achieved either adaptively or by tapered beamforming techniques [7–10] in which the array feeding currents are tapered in amplitudes. Adaptive techniques provide the optimum solution but suffer from the difficulty in practical application due to the complex calculations and extensive processing especially for large arrays such as UCCA. On the other hand, the tapering technique provides non-optimal solutions, however it requires simpler and direct calculations and is applicable rather than adaptive techniques. In addition, tapering technique is well known and studied for the one-dimensional linear arrays such as Binomial and Dolph–Chebyshev arrays [5]. Also, a similar technique has been utilized and equivalent to the tapered beamforming but in filter design to improve the stopband characteristics (sidelobes) by windowing. This technique includes some windows such as Triangular, Hamming, Hanning, Blackman, Binomial, etc. [11]. Therefore, in this paper, some of the conventional windows are modified to be applied to the UCCA for radiation pattern smoothing. In addition, the sidelobe level and beamwidth characteristics are discussed for the different windows. Also the array stability against tapered amplitude errors is discussed for the different tapering windows and the immunity against these errors is demonstrated. The paper is arranged as follows; in Sect. 2, the array geometry of the UCCA and its related parameters are displayed. Section 3 introduces the different beamforming windows applied for tapering the UCCA and Sect. 4 discusses the sidelobe level and beamwidth variations. Section 5 discusses the stability of the array against amplitude errors and finally, Sect. 6 concludes the paper.

2 Uniform Concentric Circular Arrays (UCCA)

Figure 1 displays the geometry of a concentric circular antenna array consisting of M concentric rings each has a number of elements N_m where $m = 1, 2, \dots, M$. The elements in

each ring are assumed to be omnidirectional and the interelement separation is almost half of the wavelength which can be obtained if the number of elements in the rings is incremented by 6 [7] or:

$$N_{m+1} = N_m + 6 \tag{1}$$

The separating distance of $\lambda/2$ is chosen to have a radiation pattern that has one mainlobe and no grating lobes which appear at larger separating distances. Also, the radiation pattern has wider beamwidth if we used a smaller interelement separation which reduces the efficiency of the array. If the mutual coupling between the neighbored elements is neglected, we can determine an expression for the array factor at any direction if we know the weights of the rings and the array steering matrix.

For the UCCA, the array steering matrix can be given by [7]:

$$AS(\theta, \phi) = [S_1(\theta, \phi) S_2(\theta, \phi) \dots S_m(\theta, \phi) \dots S_M(\theta, \phi)] \tag{2}$$

where each column in $AS(\theta, \phi)$ represents the ring steering vector which generally for the m th ring is given by:

$$S_m(\theta, \phi) = [e^{jkr_m \sin \theta \cos(\phi - \phi_{m1})} e^{jkr_m \sin \theta \cos(\phi - \phi_{m2})} \dots e^{jkr_m \sin \theta \cos(\phi - \phi_{mn})} \dots e^{jkr_m \sin \theta \cos(\phi - \phi_{mN_m})}]^T \tag{3}$$

where $k = \frac{2\pi}{\lambda}$ and this m th ring has a radius r_m and number of elements N_m .

In tapered beamforming, we multiply the array steering matrix with a tapering weight matrix $W(\theta, \phi)$ given by:

$$W(\theta, \phi) = [\alpha_1 S_1(\theta_o, \phi_o) \alpha_2 S_2(\theta_o, \phi_o) \dots \alpha_m S_m(\theta_o, \phi_o) \dots \alpha_M S_M(\theta_o, \phi_o)] \tag{4}$$

where for $m = 1, 2, \dots, M$, α_m is the amplitude coefficients of the m th ring current and $S_m(\theta_o, \phi_o)$ is the ring steering vector at the mainlobe direction (θ_o, ϕ_o) . From Eq. (4), we notice that all elements in an individual ring is weighted by the same value therefore the array factor will be given by

$$G(\theta, \phi) = SUM \left\{ W(\theta, \phi)^H AS(\theta, \phi) \right\} \tag{5}$$

where the SUM operator is the summation of the elements of the resulted matrix and H is the complex conjugate transpose.

In this section, some conventional windows are modified and applied for amplitude tapering of the UCCA. These windows are well defined for filtering applications such as finite impulse response (FIR) filter designs such as Triangular, Hamming, Hanning, Blackman and Binomial windows. It had showed the possibility to reduce the sidelobe-to-mainlobe ratio in the filter magnitude response. Conventional one-dimensional tapered arrays have tapered the currents of the individual array elements, while in the case of UCCA, we consider the individual ring to be equivalent to an element of the one-dimensional linear array. The following subsections defines these possible amplitude tapering windows.

3 Tapering Windows for UCCA

In this section, we will modify the expression of some filtering windows to suit the amplitude weighting of the UCCA. These windows include Triangular, Hamming, Hanning, Blackman and Binomial functions. Conventional one-dimensional tapered arrays have tapered the

currents of the individual array elements, while in the case of UCCA, we consider the individual ring to be equivalent to an element of the one-dimensional linear array. The following subsections define these possible amplitude tapering windows.

3.1 Uniform Feeding Window

This is actually not a tapering window and can be considered as the basic simplest weighting function. The uniformly-fed UCCA has the same amplitude coefficients which is the unity or

$$\alpha_m = 1, \quad m = 1, 2, \dots, M \quad (6)$$

these coefficients give the smallest beamwidth compared to any other window and the highest sidelobe level of about 17.5 dB as shown in Fig. 2a for a typical array of $N_1 = 5$ and $M = 10$.

3.2 Triangular Amplitude Tapering

The second direct applied function is the Triangular window in which the amplitude weighting follows a triangular function that equals zero at a virtual ring of number $M + 1$. The m th ring amplitude coefficient for this scheme is given by:

$$\alpha_m = \frac{(M - m + 1)}{M}, \quad m = 1, 2, \dots, M \quad (7)$$

where m is the ring number in the array. The innermost ring has a weight value $\alpha_1 = 1$ while the outermost ring has a weight value of $\alpha_M = \frac{1}{M}$.

Figure 2b displays a typical radiation pattern of the same array configuration as in Fig. 2a.

3.3 Modified Hamming Amplitude Tapering

The Hamming window is modified and gives the following ring coefficient for a UCCA of M rings:

$$\alpha_m = 0.54 - 0.46 \cos\left(\frac{\pi(m - M - 2)}{M + 1}\right), \quad m = 1, 2, \dots, M \quad (8)$$

Figure 2c displays the radiation pattern of Hamming UCCA where the sidelobe level will be 29.5 dB

3.4 Modified Hanning Amplitude Tapering

The modified Hanning window is very similar to the Hamming window and provides an m th coefficient given by:

$$\alpha_m = 0.5 - 0.5 \cos\left(\frac{\pi(m - M - 2)}{M + 1}\right), \quad m = 1, 2, \dots, M \quad (9)$$

Figure 2d depicts the radiation pattern of the Hanning tapered array which has a very similar value of the sidelobe level as in the Hamming array.

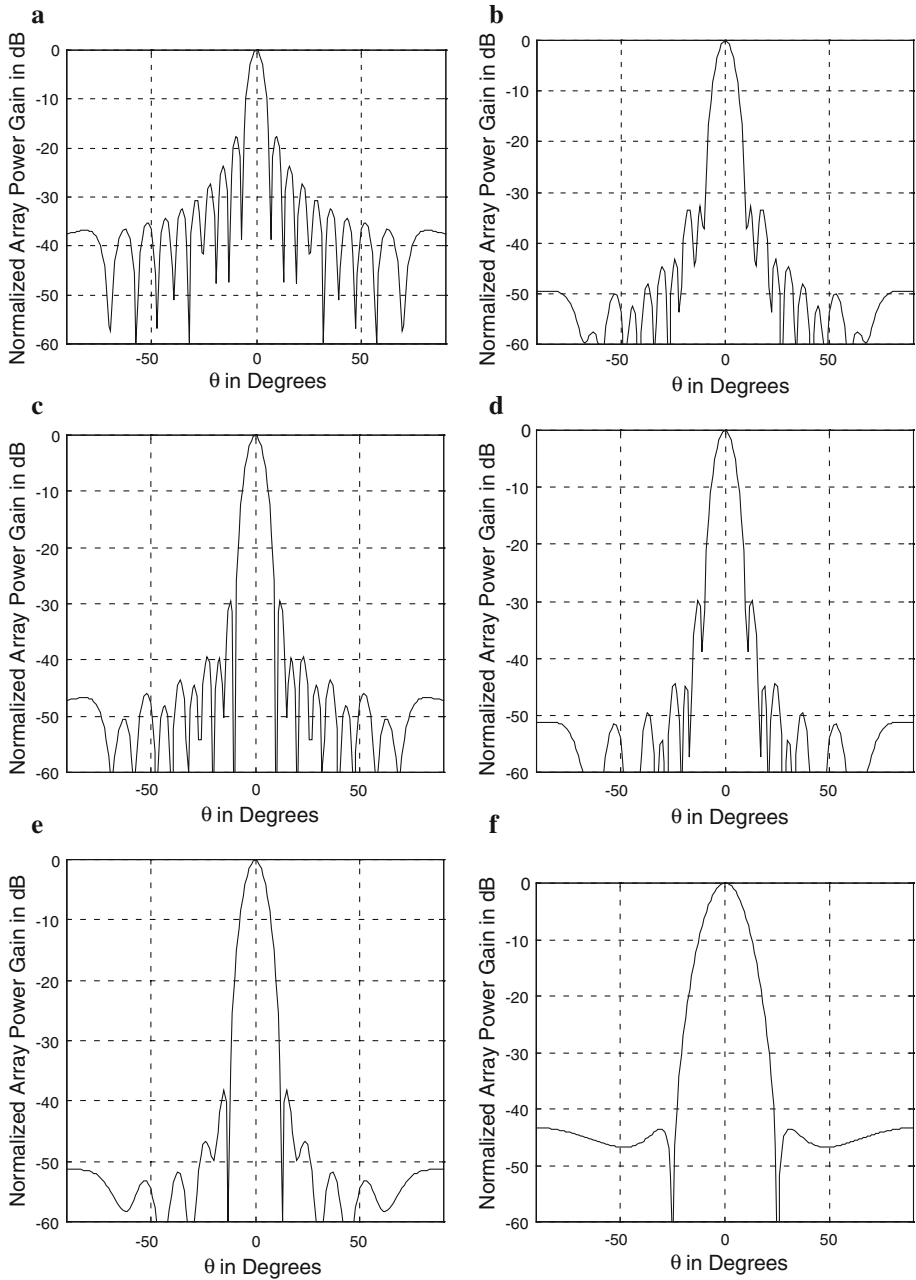


Fig. 2 **a** Typical radiation pattern of uniformly fed UCA of $N_1 = 5$ and $M = 10$. **b** Typical radiation pattern of triangular UCA of $N_1 = 5$ and $M = 10$. **c** Typical radiation pattern of Hamming UCA of $N_1 = 5$ and $M = 10$. **d** Typical radiation pattern of Hanning UCA of $N_1 = 5$ and $M = 10$. **e** Typical radiation pattern of Blackman UCA of $N_1 = 5$ and $M = 10$. **f** Typical radiation pattern of Binomial UCA of $N_1 = 5$ and $M = 10$

Table 1 Binomial coefficients of the UCCA

| M | k | Binomial coefficients for linear arrays of k elements | Binomial coefficients for UCCA |
|-----|-----|---|--------------------------------|
| 1 | 2 | 1, 1 | 1 |
| 2 | 4 | 1, 3, 3, 1 | 3, 1 |
| 3 | 6 | 1, 5, 10, 10, 5, 1 | 10, 5, 1 |
| 4 | 8 | 1, 7, 21, 35, 35, 21, 7, 1 | 35, 21, 7, 1 |
| 5 | 10 | 1, 9, 36, 84, 126, 126, 84, 36, 9, 1 | 126, 84, 36, 9, 1 |

3.5 Modified Blackman Amplitude Tapering

Blackman window provides another cosine term for further sidelobe reduction. The modified coefficients function for the UCCA tapering is given by:

$$\alpha_m = 0.42 - 0.5 \cos\left(\frac{\pi(m-M-2)}{M+1}\right) + 0.08 \cos\left(\frac{2\pi(m-M-2)}{M+1}\right), \quad m = 1, 2, \dots, M \quad (10)$$

The radiation pattern for this type of tapering is shown in Fig. 2e which reduces the sidelobe level to 38 dB.

3.6 Binomial Amplitude Tapering

The Binomial amplitude feeding [5] of the UCCA can be obtained if we apply the Binomial coefficients to the ring arrays. Starting with the Binomial expansion for the following expression:

$$(1+x)^{k-1} = 1 + (k-1)x + \frac{(k-1)(k-2)}{2!}x^2 + \frac{(k-1)(k-2)(k-3)}{3!}x^3 + \dots \quad (11)$$

In this expansion, we use the right-hand side polynomial where it has the following k coefficients:

$$1, (k-1), \frac{(k-1)(k-2)}{2!}, \frac{(k-1)(k-2)(k-3)}{3!}, \dots \text{ upto } k \text{ coefficients} \quad (12)$$

For example when $k = 5$, we have the following coefficients; 1, 4, 6, 4, 1 which gives a Binomial tapering profile. For example in linear one-dimensional Binomial arrays, the elements coefficients are taken as the k coefficients obtained from Eq. 12. To apply the Binomial coefficients in Eq. 12 to the UCCA, we may assume that $k = 2M$, then the binomial amplitude coefficients are taken as the coefficients from $M+1$ to $2M$ as depicted in Table 1.

With this assumption, we may have Binomial UCCA, for example, if we have $M = 4$, then the innermost ring will be weighted in amplitude by $\alpha_1 = 35$ and for the second outer ring $\alpha_2 = 21$ etc..., while for any number of rings in the array, the outermost ring will always has $\alpha_M = 1$. As in Binomial linear arrays, Binomial UCCA will provide the lowest possible sidelobe level and the largest beamwidth compared with any other tapering scheme. A typical radiation pattern of Binomial UCCA of the same configuration as in the last cases is depicted in Fig. 2f where the sidelobe level will be 43.5 dB.

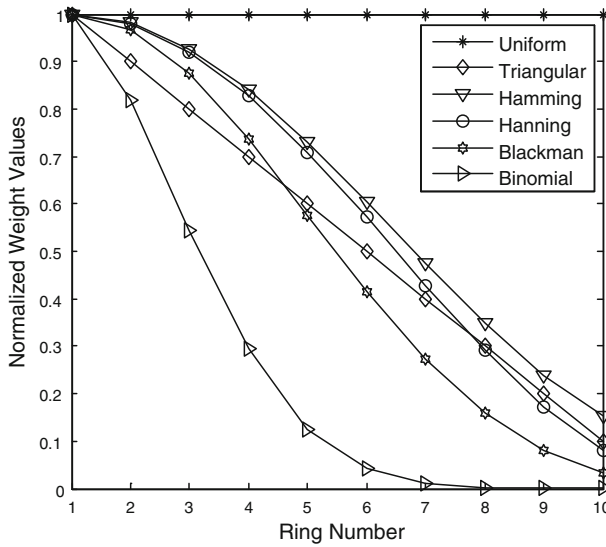


Fig. 3 Typical values of the windows for tapered UCCA of $M = 10$

Figure 3 displays the variations of the different proposed windows for a UCCA of $N_1 = 5$ and $M = 10$ where the values are normalized with respect to that of the innermost ring. In this figure, the weights of the Binomial window has the largest values spread which introduces some practical limitations and will be sensitive to amplitude errors while the lowest spread in values occurs in the case of Hamming window.

4 Sidelobe and Beamwidth Performance

The maximum sidelobe level as well as the mainlobe beamwidth are discussed in this section for the different weighting schemes. Figure 4a–c display the sidelobe levels in dB for the tapered UCCA as a function of the number of rings at different internal ring size. From these figures we notice in general that the sidelobe level will decrease for all windows with increasing the number of rings in the array at a specific innermost size. The uniform feeding case provides the highest sidelobe level, while the Binomial tapering provides the lowest possible levels especially for lower number of elements in the innermost ring and approaches 49 dB below the mainlobe at $M = 20$ ring for the UCCA of $N_1 = 5$ as shown in Fig. 4a. If we increase the number of elements in the innermost ring, the tapered UCCA performance degrades for all windows and the sidelobes will raise again as depicted in Fig. 4b, c. Also the curves in these figures will converge more and become closer together at larger number of elements in the innermost ring.

On the other hand, Fig. 5a–c depict the beamwidth of the mainlobe for the different feeding schemes where it decreases with both increasing the number of rings in the array and the number of elements of the innermost ring. The Binomial window will result in the largest beamwidth while in all cases the lowest beamwidth is obtained from the uniform feeding. As noticed with the sidelobe performance, the curves of the beamwidth will converge more together as the number of elements in the innermost ring increases.

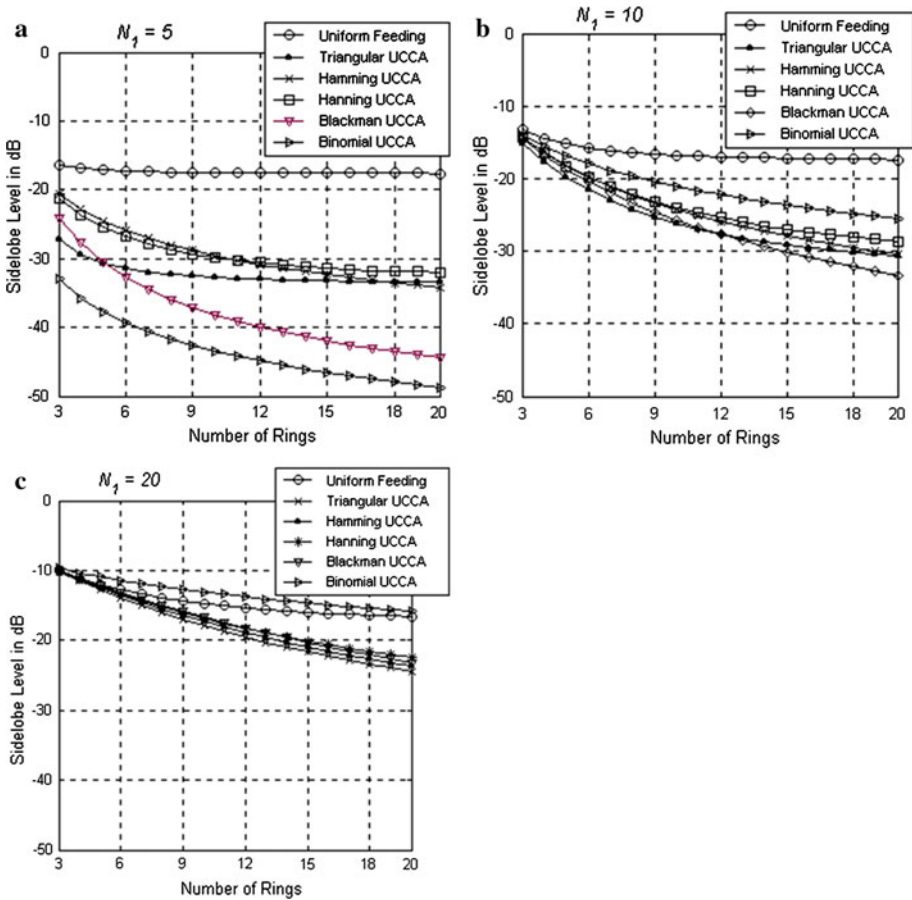


Fig. 4 **a** Sidelobe level variation of tapered UCCA at $N_1 = 5$. **b** Sidelobe level variation of tapered UCCA at $N_1 = 10$. **c** Sidelobe level variation of tapered UCCA at $N_1 = 20$

5 Stability of Tapered UCCA

A very important issue of the tapered beamforming is the stability of the array performance against the amplitude feeding errors. These errors will affect greatly the radiation pattern of the UCCA and result in higher sidelobes. The performance of the UCCA with tapering errors can be discussed assuming an erroneous ring feeding and show the effect on the sidelobe level. These errors may occur at any ring and it is expected that the errors in the outer rings will result in more degradation than if it was in the inner ones. As a case study, we consider a tapered UCCA of $N_1 = 5$ and $M = 10$ and assuming an error that can be occurred in any ring results from changing the coefficient value to be equal to 1. Figure 6 depicts the sidelobe level of this tapered UCCA as a function of the error location for various proposed tapering windows where the sidelobe level for all windows will converge to 17.5 dB when the error occurs in the outermost ring. The increase in the sidelobe level is faster in the case of Binomial tapering while there is an immunity showed in the case of Hamming window. To clarify the amount of degradation in the array performance, we take the difference between

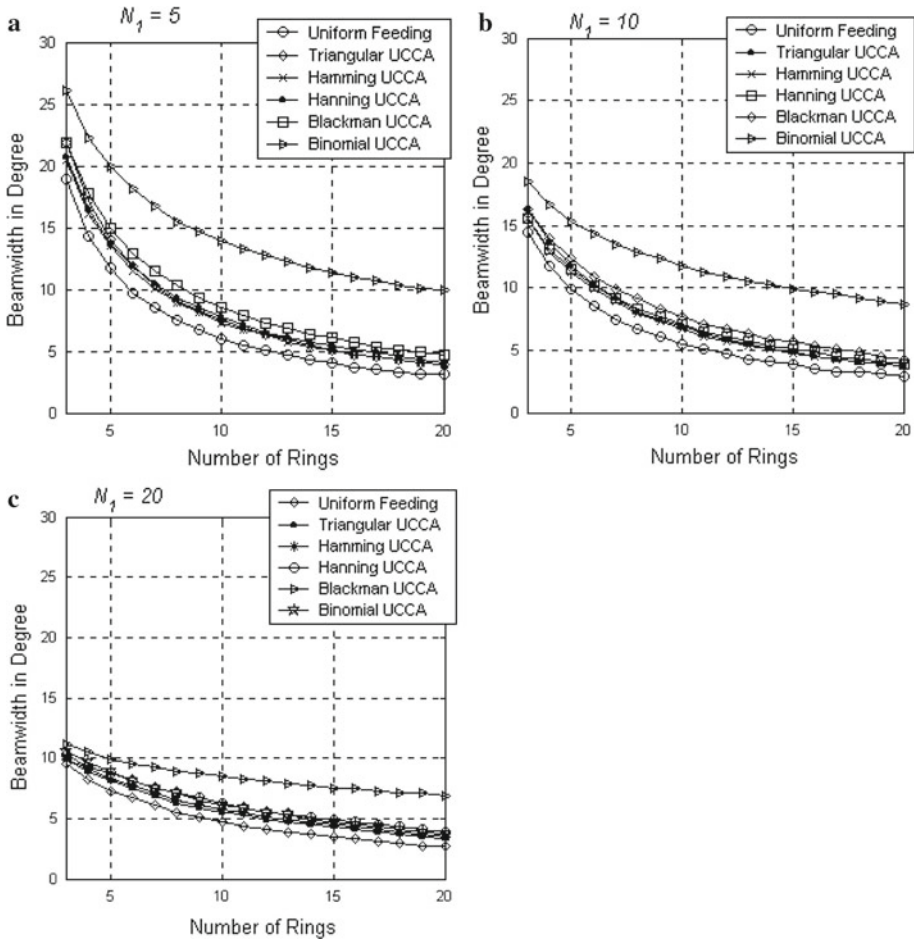


Fig. 5 **a** Beamwidth variation of tapered UCCA at $N_1 = 5$. **b** Beamwidth variation of tapered UCCA at $N_1 = 10$. **c** Beamwidth variation of tapered UCCA at $N_1 = 20$

the resulted sidelobe levels before and after the feeding errors as shown in Fig. 6. In this figure, the difference is largest for the Binomial window while the Hamming window shows the smallest difference indicating an immunity to amplitude errors compared with the other schemes.

6 Conclusion

In this paper, some conventional windows are modified to suit the tapered beamforming for the UCCA. These windows are discussed in details and the array performance in terms of the sidelobe levels and the beamwidth variations are discussed. It has been noticed that the sidelobe level and beamwidth for any window are sensitive to the number of elements in the innermost ring and the number of rings in the array. Also the lowest possible sidelobe level occurs in the case of Binomial tapering while it provides the maximum beamwidth

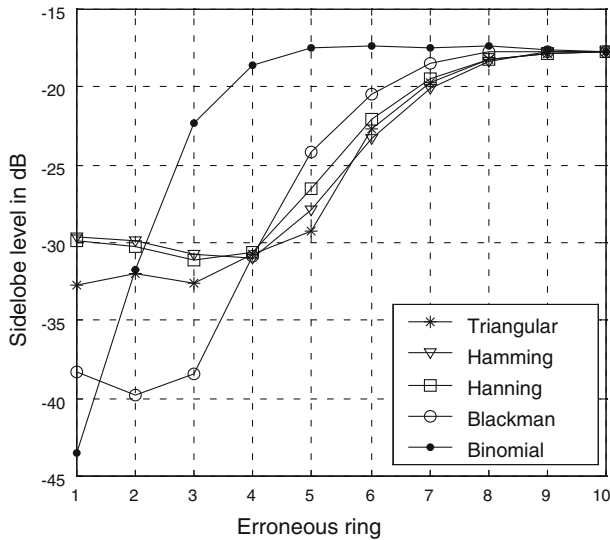


Fig. 6 Sidelobe degradation as a function of the error location within the UCCA

compared with the other windows. The array performance with the tapered amplitude errors is also discussed and showed that the Binomial windowing is highly sensitive with amplitude variations while the Hamming window has the highest immunity against these errors.

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Author Biographies



Mostaf Nofal Ph.D. in Computer Networks, Menoufia University, Egypt in collaboration with Southampton University, UK M.Sc. in electronics and communications engineering. He is now a professor in the Department of Computer Engineering, College of Computers and Information Technology, Taif University, KSA. He has joined many conferences and is the author of several papers in the field of mobile communications, satellite communications and networks, network security. He has many books in the field of computer engineering and mobile networks.



Sultan Aljhdali is the Dean of the College of Computers and Information Technology at Taif University, Kingdom of Saudi Arabia. Before joining Taif University, he has served as Information Technology Manager at General Authority of Civil Aviation and Saudi Airlines respectively. Dr. Aljhdali received the B.S. from Winona State University, M.S. with honor from Minnesota State University Mankato, and Ph.D., in Information Technology from George Mason University in Fairfax, Virginia. He is the recipient of the prestigious higher education scholarship from the government of Saudi Arabia for pursuing his B.S., M.S., and Ph.D., in a row. Dr. Aljhdali has made research contributions on software testing, developing Software Reliability Models, Soft Computing for Software Engineering, Computer Security, Reverse Engineering and Medical Imaging. He is an author or co-author of over 40 peer reviewed academic publication. He is a member of professional societies like ACM, IEEE, Arab Computer Society (ACS) and International Society for Computers and Their Applications (ISCA). He is in

the editorial board of many international journals like International Journal of Science and Advanced Technology, International Journal of Computer Technology and Applications, World of Computer Science and Information Technology, Journal of Intelligent Computing, International Journal of Computer Science & Emerging Technologies, Universal Journal of Computer Science and Engineering Technology. He functioned as the General Chair, Program Chair, Session Chair, and member of the International Program Committee of the international conferences sponsored by various professional societies or organizations including the IEEE Computer Society, ACS and ISCA. He is also the conference chair of the forthcoming 24th International Conference on Computer Applications in Industry and Engineering (CAINE 2011) November 12–14, 2011, Honolulu, Hawaii, USA.



Yasser Albagory B.Sc. in electronic engineering in 1998 and the M.Sc. in adaptive arrays for mobile radio communications in 2002 from the Faculty of Electronic Eng. Egypt. He also has been awarded the Ph.D. degree in electronic engineering in high-altitude platform wireless communications system in 2008. His research interests are in adaptive antenna arrays, mobile communications, and high altitude platforms. He joined and referees many papers in international conferences in wireless communications and has many journal papers in the area of smart antennas and high-altitude platforms. He is now an assistant professor at the College of Computers and Information Technology, Taif University, Saudi Arabia.