This paper is available online at www.praiseworthyprize.org
International Journal on Communications Antenna and Propagation (I.Re.C.A.P.), Vol. 9, N. 2
ISSN 2039 – 5086
April 2019

Complementary Interleaved CDS Arrays to Improve Antenna Aperture Utilization

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Abstract – *Volume usage is an important issue in space-based satellite communication systems. In this paper, antenna array elements are interleaved into one aperture in order to avoid using two separated antennas. The method utilizes two complementary cyclic difference set (CDS) arrays, where equal array element excitations reduce the complexity of the driving network and improve the efficiency of its direct current-to-radio frequency power conversion. Adding elements to each array member and placing them in symmetry with respect to the origin at distances arranged to form an equivalent amplitude using Hamming and cosine squared taperings decrease the side lobe levels and beam widths. The amplitude-to-space conversion is achieved through an equal area approximation. The results demonstrate the effectiveness of the proposed method in interleaving two arrays sharing one aperture for two beam antennas, each one with a narrowed beam width and decreased side lobes. The proposed method offers antenna design flexibility for a given aperture size despite the limited number of CDSs. The measurements demonstrate that compared to the original CDS performance, the arrays have a narrower beam width of at least 3 degrees and a lower side lobe level of at least 1.66 dB, with a difference of less than 0.9 dB between simulations and reality.* ***Copyright © 2019 The Authors.***

Keywords: *Cyclic Difference Set, Equal Area Approximation, Interleaved, Sparse Array, Aperture Sharing*

Nomenclature

CDS	Cyclic Difference Set
V	Total CDS length in number of elements
$A_T(x)$	Truncated version of an unlimited length of array
$A_O(x)$	Original CDS array
$A_C(x)$	Complement CDS array
y_H	Hamming taper function
$y_{S\,\mathrm{Cos}}$	Squared cosine taper function
x_o	Grid uniform distance
$\delta(x)$	Dirac delta function
$d_{\min}$	Minimum distance between the elements to avoid overlap
n	Array element number
l	Aperture total length of the CDS array
a_n	Member of the complementary CDS
$\bar{a}_n$	Member of the complementary CDS
m	total number of sub area
m_o	Total number of improvement elements to the original CDS set
m_c	Total number of improvement elements to the complement CDS set
s_i	Distances from origin of the i-th element of the improvement set to the original CDS
s_j	Distances from origin of the j-th element of the improvement set to the CDS complement
int	Integral function in the MATLAB
fzero	Fzero function in the MATLAB
VSWR	Voltage Standing Wave Ratio
U	Utilization of the aperture
l_p	Length of a single patch
L	Total length of the interleaved array
N	Total number of antenna elements
EIRP	Equivalent Isotropic Radiated Power

I. Introduction

Smaller satellites are always in demand due to the limited cargo space in a space transporter. An array antenna can potentially take up only one-third of the space taken up by a satellite parabolic reflector antennas, thereby providing the same amount of functionality occupying much less space. The exponential growth of telecommunications traffic has necessitated better utilization of the frequency band. Utilization of the frequency spectrum can be expressed as its traffic carrying capacity (bit/Hz/km^2), leading to a quest for multi-beam radiation from an aperture antenna. There are several ways to form multi-beam radiation, such as

Available online by April 30th, 2019
https://doi.org/10.15866/irecap.v9i2.16317

multiple horns on a common parabolic reflector, multiple horns with lenses, and directly radiating antenna element arrays. The latter can provide multiple beams of multiple sub-arrays within an aperture [1]-[7]. Sparse array antenna element placement enables many arrays to share an aperture, as the portion of the aperture that is not used may be utilized for other antenna arrays so that several arrays can share a single aperture. The sparse placement advantages include a decrease in the total number of required elements and the avoidance of grating lobes through a break in periodicity. The sparse placement disadvantages include a wider beam width, less efficient use of the aperture, which causes a decrease in the maximum EIRP, limited control of the shape of the radiation pattern, and a loss of the regular building block array that enables easier manufacturing [8]-[15]. Two strategies for placing the elements of an array are separate physical sub-division placement of the array elements and interleaved placement. The advantages of sub-division by area separation are the ability to achieve minimum interference between array members and the possibility of the utilization of established array design strategies. The disadvantage of sub-division by area separation is the difficulty of achieving a highly directive pattern due to the relatively limited availability of aperture space. In an interleaved design, the entire aperture can be exploited, and collocation of the phase centres of the array can be realized at the expense of a more complex design and a possible increase in the interference between sub-arrays [16]-[19]. In satellite communications, uniform amplitude excitation of the antenna elements is desirable both to achieve efficient operation of the power amplifiers and to simplify the driver network. This simpler arrangement also leads to higher system reliability. In this case, a particular pattern of illumination density can be obtained by the utilization of varying distances between the elements of the array antenna [20], [21]. Swenson has reported on a method for improving the side lobe level in a regular uniform inter-element distance for a linear array in order to construct a radio astronomy telescope. A square cosine taper was utilized to improve the side lobe level of an array antenna, but this taper is applied to only one beam radiation pattern [22].

Leeper has demonstrated the usage of a cyclic difference set (CDS) in order to construct arrays with equal amplitude excitation for non-equal inter-element distances. CDSs can generate thinned arrays that have a predictable gain with a lower side lobe level. A ‘1’ on the set represents the presence of an antenna element, whereas a ‘0’ represents its absence.

When compared to random placement, the autocorrelation of the CDS is maximized, and therefore, a better side lobe level can be achieved. Furthermore, Leeper has showed that the complementary CDS also inherits the same performance as the CDS [23]. Rahardjo et al. [15] have demonstrated a method for improving the side lobes of CDS arrays by arranging two similar arrays to achieve higher illumination density in the middle of the apertures to produce nearly Taylor-optimal distribution. Trampuz et al. [24] demonstrated improvements in side lobe performance through a complex arrangement of complimentary CDS arrays, where one sub-array is used for the transmission of an FMCW radar and its complement array is used in order to receive the returning radar signal. In this arrangement, the complementary arrangement has resulted in a better side lobe performance than for an individual member.

However, the improvement methods have been applied to only one beam per aperture [24]. Chun-Xu Mao et al have shared antenna aperture with uniform distances arrays where addition of number of elements will requires amplitude tapering in order to get optimum results [25], [26]. The above mentioned methods are tabulated in the Table I.

TABLE I
APERTURE UTILIZATION METHODS

Authors	Results Of The Method
C.-X. Mao et al. [25], [26]	Two array and three arrays sharing one aperture, the array have uniform distance between array’s elements.
Rahardjo et al. [15]	One array per aperture, limited set CDS only, uniform excitation, elements are placed at the center of aperture, realatively difficult to interleaved.
Swenson [22]	One radiation per aperture only, no interleave, non-uniform distance between array elements, therefore aperture is less utilized
Leeper [23]	Two radiation pattern of two arrays in interleaved manner from one aperture, uniform excitation, limited set of CDS only.
Trampuz et al. [24]	One combined radiation pattern from two arrays in interleaved manner, limited set CDS only

Utilizing both the CDS and its complement in an interleaved manner for the antenna aperture has largely filled the available space and it has avoided the grating lobe by breaking the periodicity of the antenna element placement. In this paper, a method for improving the radiation pattern of the two interleaving CDS arrays by sharing one aperture by utilizing both the CDS and its complement in an interleaved manner for the antenna aperture largely filled the available space and avoided the grating lobe by breaking the periodicity of the antenna element placement is presented. A CDS has been used in order to construct interleaved aperture sharing arrays, thus guaranteeing the filling of the majority of the inner side of an aperture of a linear antenna by utilizing its complementary set and adding more elements to the outer part of the aperture to reduce its side lobe level and beam width.

While an opportunity for a more complex one can be considered, in order to form the array simple low cost patch antenna elements are used here [27], [28].

The paper is organized as follows. Proposed design methodology and design implementation, and simulation, are presented in Section II. Realization and measurement of the manufactured array and discussion are presented in Section III. Finally, Section IV illustrates the conclusions.

II. Complementary Interleaved Array Design

The designed array consists of the placement of CDS antenna elements and its complementary set in the middle part of the aperture. The added elements are placed in the outer region of the aperture and in symmetry with respect to the origin. In this manner, the position of the phase centres of the arrays are kept in the middle of the aperture and allow for the exploitation of the entire aperture length, resulting in a small angular width and maximum possible gain for the produced radiation pattern. The operating frequency has been chosen by considering that the transmitted power from the satellite is very limited and the very long distance between the transmitter and receiver results in high path loss attenuation. In addition, the frequency should be subject to low environmental noise. The distance between the array elements should not be less than the minimum distance dictated by the size of the antenna element in order to avoid overlapping between adjacent elements. Here, the allowable antenna elements sizes are smaller for a higher frequency.

II.1. Design Methodology

The design procedure is as follows. A CDS is chosen, and its median is identified and set as the origin point of the x-axis. The minimum distance between the elements is chosen based on the dimensions of the planned array.

The aperture size is chosen and normalized to $-1 \le x \le 1$ of the length. Since additional elements are added and placed in symmetry with respect to the origin, only an even number of added elements can be used. The inter-element distances of the added elements are calculated via an equal area approximation. The illumination density has been calculated, based on unequal elements distances that are equivalent to the illumination density of an amplitude taper associated with regularly spaced elements. In this design, only additional elements that do not overlap with the CDS antenna elements are used. The same steps are repeated in order to add elements to the complementary CDS.

Thus, in this design, two aperture illumination densities are formed by two space tapered arrays in an interleaved manner. The grating lobe should be considered when the chosen regular distance is more than the half of the wavelength of the operating frequency. In this case, however, the grating lobe is no longer a dominant issue due to the break in the periodicity caused by the use of thinned arrays and irregularly spaced elements. The CDS minimum distance between antenna element $d_{\min}$ is set such that the interference between arrays is reduced [29]. The shape of the radiation pattern is justified by the fact that eight degrees of illumination should be provided in order to cover a geosynchronous orbit around Earth. Any excess degrees will provide radiation that will fall outside Earth. A CDS array is a truncated version of the unlimited length of the array and it can be represented as [23], [30], [31]:

$$A_T(x) = \sum_{n=0}^{V-1} a_n \delta(x - nx_o) \tag{1}$$

where $\delta(x)$ is the *Dirac* delta function, V is the total CDS length, and a_n is either "1" or "0" according to the CDS, where *n* is the CDS element number. When CDS is placed symmetrically with respect to the origin, the CDS array shown in equation (1) can be rewritten as:

$$A_T(x) = \sum_{n=0}^{V-1} a_n \delta\left(x - nx_o + \frac{l}{2}\right) \tag{2}$$

where l is the aperture length of the CDS array and a_n is each member of the CDS array. The added elements have equal amplitudes and they are symmetrically arranged relative to the origin; however, they also have non-equal inter-element distances. The distances of the added elements are calculated in order to mimic an equivalent amplitude illumination taper. Two taper functions are utilized both to avoid an overlap between the added elements and to take advantage of their availability in the literature [32]. The first set of added elements utilizes the Hamming taper y_H. If it is used as an illumination distribution taper for an aperture, this taper provides the lowest first side lobe level and has a ripple nearly equal to that of the side lobe level. The taper linear distribution is formulated as:

$$y_H = 0.54 + 0.46\cos\left(\frac{\pi x}{a}\right) \tag{3}$$

where *x* is the element coordinate, 2*a* is the array length, and *y* is the illumination density. The second taper uses a squared cosine taper function y_{SCos}. If it is used as a radiation taper for an aperture, this taper has the smallest side lobe level compared to the triangle, cosine and uniform distributions because it has the smoothest distribution. This distribution is defined as:

$$y_{S\,\mathrm{Cos}} = \cos^2\left(\frac{\pi x}{2a}\right) \tag{4}$$

By employing two complementary CDSs and two illumination tapers, two interleaved arrays are constructed with a performance approaching the optimum achievable illumination density. The conversion from the above amplitude tapers to a space taper was has been performed using an equal area approximation. The array element distances have been derived by approximating a rationalized cumulative distribution for the illumination of the aperture. The illumination cumulative distribution have been divided by the number of the representative array elements, resulting in equal areas, as shown in Figs. 1. Thus, every array element represents a sub-area of the illumination cumulative distribution function. The distances of elements s_i and s_j approximate the equal area division of the cumulative distribution for the Hamming and the square cosine tapers consecutively and have been calculated by integrating the represented area under the related tapering function such that:

$$\int_{Subarea} y(x)dx = \frac{2\int_0^a y(x)dx}{m} \tag{5}$$

where m is the total number of sub area, $y(x)$ is the tapering function.

The MATLAB [33] software's *int* and *fzero* functions have been utilized to place the elements representing the midpoints of the representative area, as shown in Figs. 1.

For a CDS array length of l, s_i and s_j are the distances of the improvement array elements from the origin. Using these elements, we can write the original CDS array in equation (2) can be written as follows:

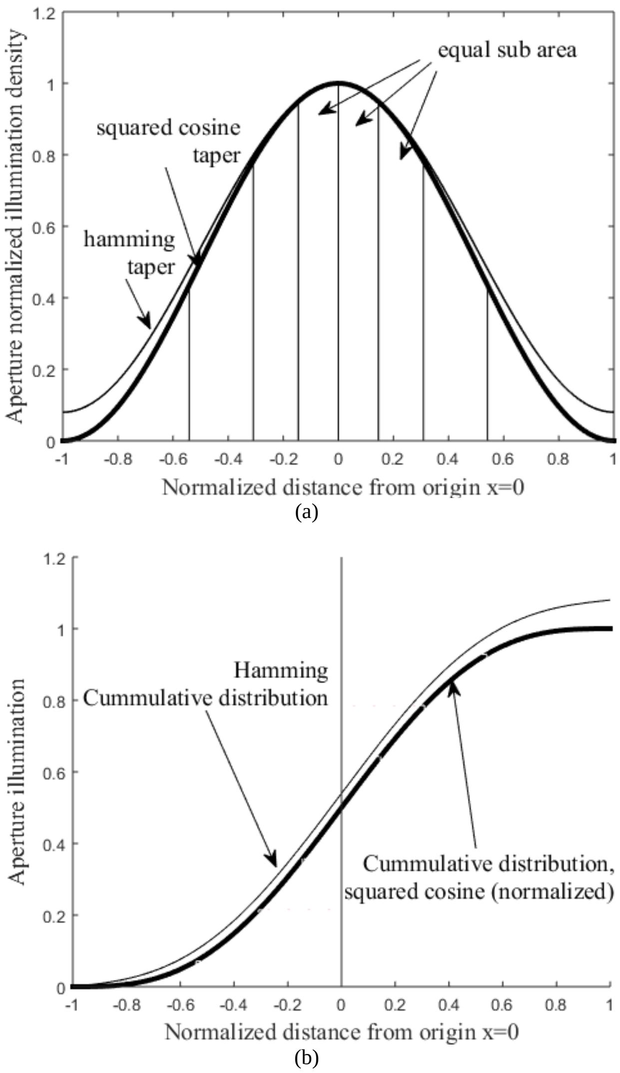
$$A_O(x) = \sum_{n=0}^{V-1} a_n \delta\left(x - nx_o + \frac{l}{2}\right) + \sum_{n=V-1+m}^{V-1+m_o/2} \delta(x \pm s_i) \tag{6}$$

where m_o is the total number of improvement elements added to the original CDS, and s_i is the distance of the i-th element of the improvement set. Combining the complement CDS array and its improvement elements with equation (2) yields:

$$A_C(x) = \sum_{n=0}^{V-1} \bar{a}_n \delta\left(x - nx_o + \frac{l}{2}\right) + \sum_{n=V-1+m}^{V-1+m_c/2} \delta(x \pm s_j) \tag{7}$$

where $\bar{a}_n$ is a member of the complementary CDS, m_c is the total number of improvement elements to the complement CDS, and s_j is the distance of the j-th element of the improvement set. The numbers m_o and m_c imply that the added improvement of antenna elements does not have to be similar. The radiation pattern from the array is a multiplication of the element factor with the array factor. The array factor is the Fourier transform of the autocorrelation of the array element position.

However, due to the additional improvement elements, which resulted in the loss of the aperture grid uniformity, a closed-form solution to equations (5) and (6) cannot be easily established, meaning that the available Fourier transform of the autocorrelation cannot be used. Therefore, simulations have been used to observe the resulting radiation pattern from the CDS array containing the additional improvement elements.

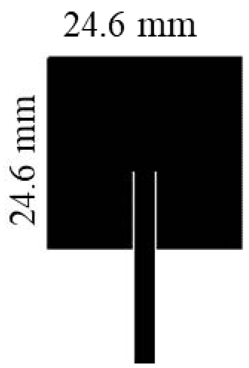


Figs. 1. Equal area approximation for distance determination

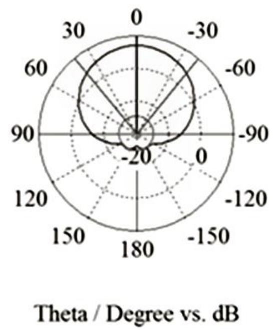
II.2. Design Implementation

An operating frequency of 4 GHz has been used due to the low environmental noise at this level in the atmosphere. This low-noise condition is required due to the limited power of a satellite transmitter. Patch antennas has been used as antenna elements. Simulations of the arrays have been performed using computer simulation technology (CST) software. A 24.6 mm × 24.6 mm square patch antenna element, 0.8 mm thick Taconic TLY 05 substrate has been designed. The patch provided a bandwidth of 49 MHz in the 4 GHz frequency band with a VSWR< 2, a main lobe magnitude, a side lobe level of -21.5 dB, and 79.2° of 3 dB angular width, as shown in Figs. 2. Five arrays have been constructed using the proposed method. Considering that the minimum distance d_{min} should be larger than the patch width, a regular grid for the CDS with 4 cm uniform distance has been employed. Five CDS have been used:

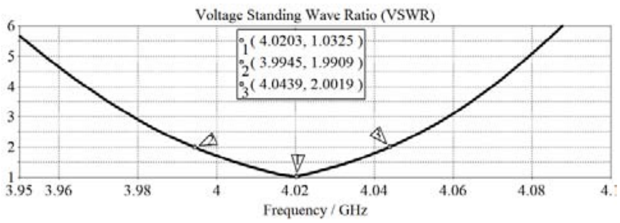
CDS (11,5,2), CDS (15,7,3), CDS (19,9,4), CDS (23,11,5) and CDS (31,15,7). The space tapering coordinates of the patches have been calculated for each array and they are shown in Table II. Six patches have been added and arranged in symmetry with respect to the origin. The total array length is greater than the original CDS length. Longer CDS lengths will have more influence on the total array radiation pattern.



(a)



(b)



(c) Bandwidth 49 MHz, VSWR =2

Figs. 2. Patch antenna and its radiation pattern: (a) Rectangular patch antenna. (b) Radiation pattern. (c) Bandwidth 49 MHz at VSWR =2

II.3. Array Simulation

Figs. 3 show the CST software simulation results of the radiation patterns before and after the addition of the improvement elements. Table III presents a summary of the results. Only three out of five simulation results are presented here, with abbreviations that include Ori=original set and com=complement set, as depicted in The simulation results have showed that the addition of antenna elements to the CDS has been arranged to mimic the amplitude resulted in smaller angular widths, and the side lobes are decreased. A more substantial improvement can be achieved by adding more elements, resulting in a longer aperture size.

TABLE II
DISTANCES FROM THE ORIGIN *X*=0 OF
THE IMPROVED INTERLEAVED CDS ARRAY

	Element Number	**CDS (31,15,7)**	**CDS (23,11,5)**	**CDS (19,9,4)**	**CDS (15,7,3)**	**CDS (11,5,2)**
x = distance to the left side of the origin (m).	21	-1.27				
	20	-1.15				
	19	-0.91				
	18	-0.84				
	17	-0.69	-0.99			
	16	-0.64	-0.87			
	15	**-0.60**	-0.71	-0.69		
	14	*-0.56*	-0.64	-0.61		
	13	*-0.52*	-0.53	-0.53	-0.68	
	12	**-0.48**	-0.48	-0.48	-0.58	
	11	*-0.44*	**-0.44**	-0.43	-0.48	-0.58
	10	*-0.40*	*-0.40*	-0.39	-0.42	-0.51
	9	**-0.36**	*-0.36*	**-0.36**	-0.37	-0.41
	8	*-0.32*	*-0.32*	*-0.32*	-0.32	-0.38
	7	*-0.28*	*-0.28*	**-0.28**	*-0.28*	-0.31
	6	*-0.24*	**-0.24**	**-0.24**	*-0.24*	-0.29
	5	*-0.20*	*-0.20*	*-0.20*	*-0.20*	**-0.20**
	4	**-0.16**	**-0.16**	*-0.16*	**-0.16**	*-0.16*
	3	**-0.12**	*-0.12*	*-0.12*	*-0.12*	**-0.12**
	2	**-0.08**	*-0.08*	*-0.08*	*-0.08*	*-0.08*
	1	*-0.04*	**-0.04**	**-0.04**	**-0.04**	*-0.04*
	Origin =0	**0.00**	**0.00**	*0.00*	**0.00**	*0.00*
x = distance to the right side from origin (m)	1	*0.04*	*0.04*	**0.04**	*0.04*	**0.04**
	2	**0.08**	*0.08*	*0.08*	**0.08**	**0.08**
	3	*0.12*	**0.12**	**0.12**	*0.12*	**0.12**
	4	*0.16*	**0.16**	**0.16**	**0.16**	*0.16*
	5	*0.20*	*0.20*	**0.20**	**0.20**	**0.20**
	6	**0.24**	**0.24**	**0.24**	**0.24**	0.29
	7	**0.28**	*0.28*	*0.28*	**0.28**	0.31
	8	**0.32**	**0.32**	*0.32*	0.32	0.38
	9	**0.36**	**0.36**	**0.36**	0.37	0.41
	10	*0.40*	**0.40**	0.39	0.42	0.51
	11	**0.44**	**0.44**	0.43	0.48	0.58
	12	**0.48**	0.48	0.48	0.58	
	13	*0.52*	0.53	0.53	0.68	
	14	**0.56**	0.64	0.61		
	15	**0.60**	0.71	0.69		
	16	0.64	0.87			
	17	0.69	0.99			
	18	0.84				
	19	0.91				
	20	1.15				
	21	1.27				
	Total Array Length (m)	2.55	1.97	1.39	1.35	1.15
	Total CDS length (m)	1.21	0.89	0.72	0.56	0.40

Note: The cells with light grey background are the distances of CDS elements and its complement, where bold printed cells are distances CDS complement elements, italic printed cells are the distance CDS original elements. The cells with white back ground are improve complement elements, dark grey back ground cells are the improved original elements.

III. Arrays Realization and Measurement

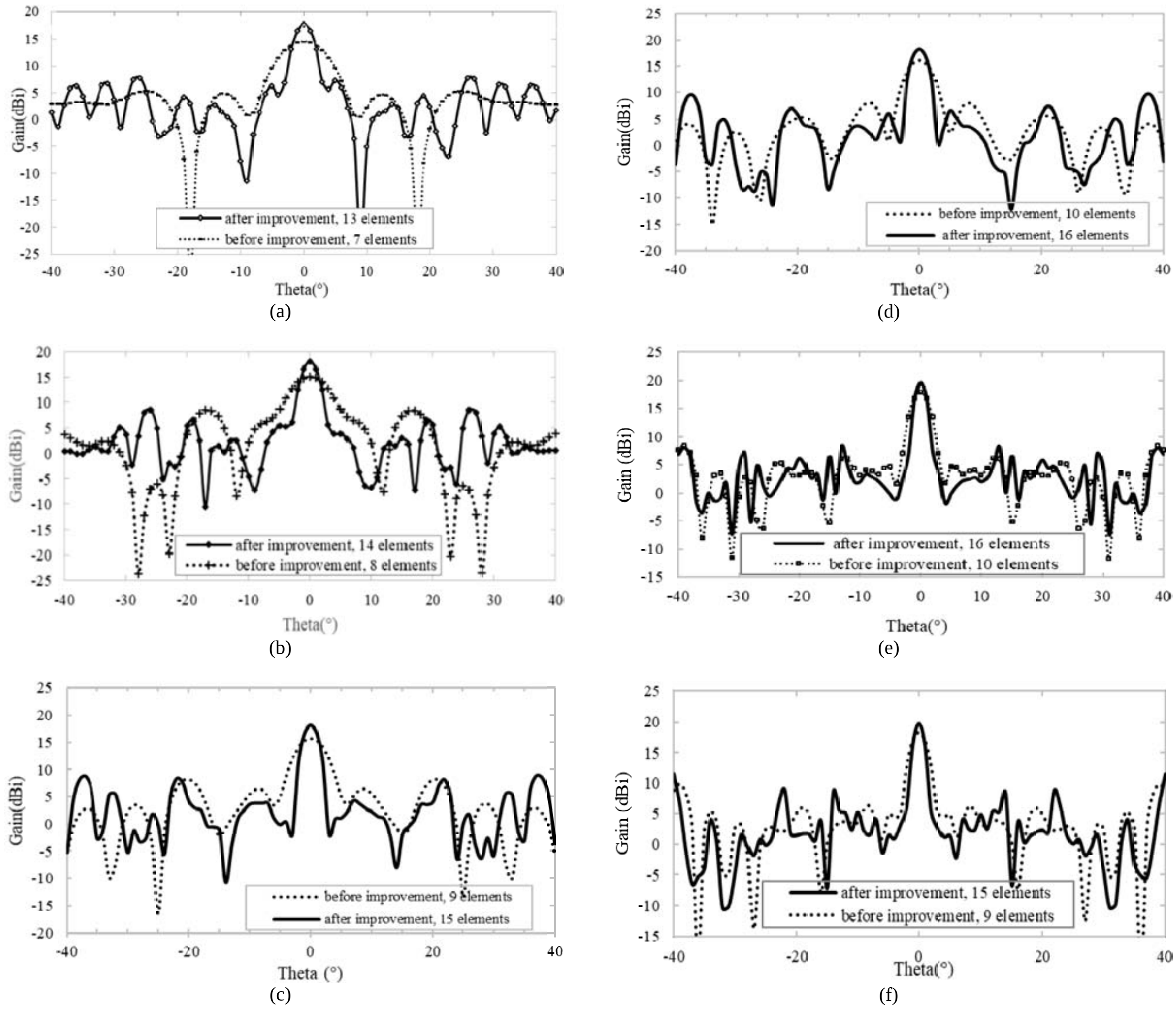
Considering that a longer array will requires a longer free space distance, in order to comply with far-field conditions and a relatively higher power amplification to handle the related path loss and to address the practicality of manufacturing, it has been chosen to manufacture a CDS (19,9,4) as shown in Table II. Aperture utilization of the linear array U is the ratio between occupied length of array to total length of the array and it is define as:

$$U = \frac{\sum_{i=1}^{N} l_p(i)}{L} \tag{8}$$

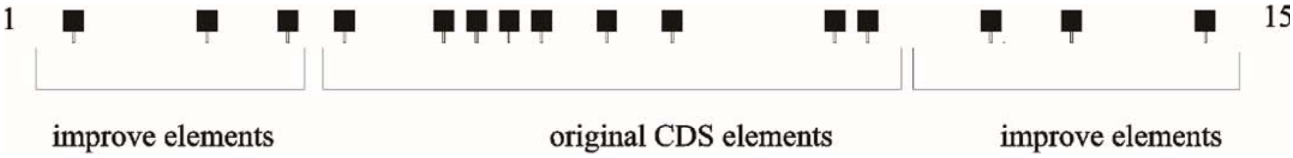
where U is utilization of total length of the aperture in %, l_p is the single length of the patch, L is total interleaved linear array length, N is the total number of antenna elements. This linear array construction delivered total aperture length utilization 55% as shown in Table IV. An improved CDS (19,9,4) interleaved array has been manufactured, where two sets of a six antenna element were added and placed at a symmetrical distance with respect to the origin of the CDS (19,9,4) sub-array and its complement.

III.1. Array Measurement Setup

The far-field radiation pattern of the antennas has been determined using building rooftops with approximately 150 metres between the array antenna being tested and the receiving standard measuring antenna. A 20 dBm wide-band power amplifier has been placed at the transmitting array antenna, whereas a standard horn antenna followed by a 50 dBi gain 45 K noise temperature C-band amplifier has been inserted at the receiver in order to combat an approximately 88 dB calculated path loss. A spectrum analyser has been used to measure the received signal. A direct current motor rotated the antenna over the ±40° azimuth range. In order to provide equal power excitation, three power dividers with a frequency range of 3.5-4.2 GHz have been used, one two way and two 16-way power divider units. One of the 16- way power divider ports was terminated with a 50-Ohm termination in order to achieve a 15 equal power excitation. The measured array gain must account for the loss of the feeding network of the feeding network. In order to avoid measuring associated path losses, an antenna substitution measurement method is used by means of a calibrated horn with known performance.

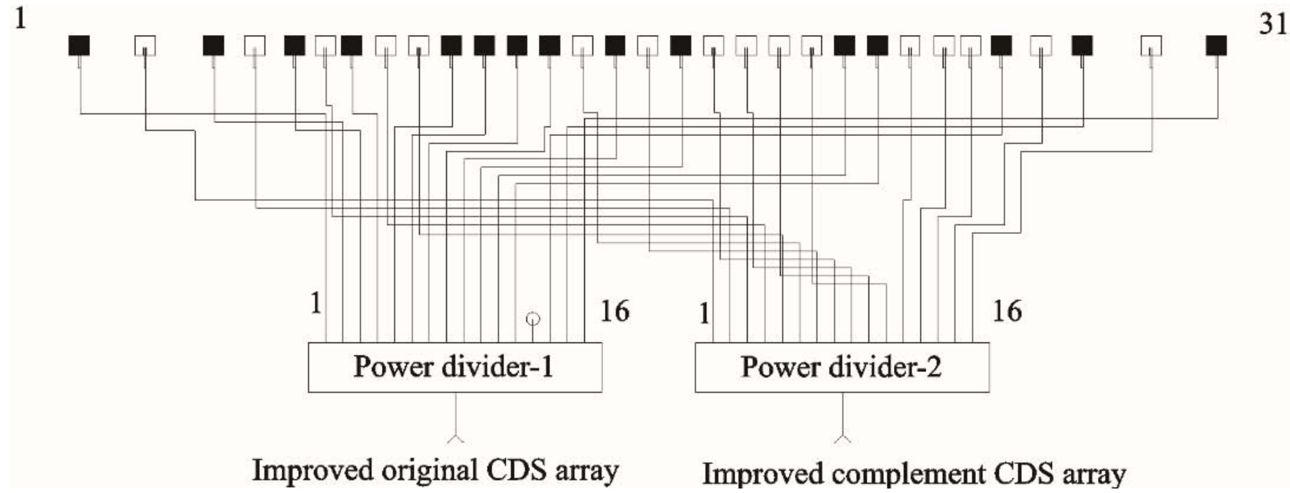


Figs. 3. Computer simulation results of the Radiation Pattern of arrays before and after improvement. (a) CDS(19,9,4); (b) CDS(15,7,3) complement; (c) CDS(19,9,4); (d) CDS(19,9,4) complement, (e) CDS(31,15,7); (f) CDS(31,15,7) complement



(a)

(b)



(c)

Figs. 4. Elements placement of the improved interleaved CDS (19,9,4) array antenna (a) improved original CDS(19,9,4) array, (b) improved complement CDS(19,9,4) array. (c) interleaved improved CDS (19,9,4) array

TABLE III
SUMMARY OF THE RADIATION PATTERNS FROM THE SIMULATION OF THE INTERLEAVED CDS ARRAY MEMBERS BEFORE AND AFTER THE ADDITION OF THE IMPROVED ELEMENTS

Array		**Number of element**		**Angular width (°)**			**Main lobe magnitude (dB)**			**Peak Side lobe level (dB)<8° from main lobe**		
		before	**after**	**before**	**after**	**impr**	**before**	**after**	**impr**	**before**	**after**	**impr**
CDS (11,5,2)	ori	5	11	8.6	3.4	5.2	13.9	17.9	4.0	-4.1	-15.9	11.8
	comp	6	12	8.5	3.3	5.2	14.5	17.6	3.1	-6.4	-16.5	10.1
CDS (15,7,3)	ori	7	13	8.0	3.2	4.8	14.6	17.7	3.1	-10.0	-11.4	1.4
	comp	8	14	7.6	3.0	4.6	15.1	18.0	2.9	-11.3	-12.4	1.1
CDS (19,9,4)	ori	9	15	5.4	2.7	2.7	15.7	18.2	2.5	-9.1	-14.0	4.9
	comp	10	16	4.8	2.7	2.1	16.1	18.5	2.4	-8.0	-14.5	6.5
CDS (23,11,5)	ori	11	17	4.9	2.3	2.6	16.1	18.6	2.5	-11.0	-16.9	5.9
	comp	12	18	4.2	2.2	2.0	16.5	18.8	2.3	-13.0	-15.0	2.0
CDS (31,15,7)	ori	15	21	3.4	1.9	1.5	18.5	20.3	1.8	-9.3	-13.1	3.8
	comp	16	22	2.8	1.8	1.0	18.8	20.5	1.7	-12.0	-15.4	3.4

Note: ori=original CDS array, comp= complement CDS array, impr = improvement

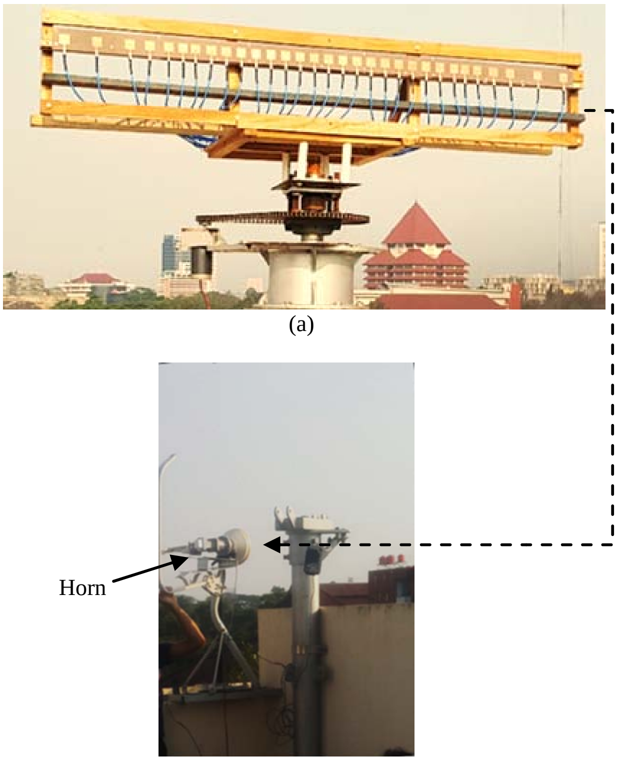
The measured gain must account for both the loss of the cable and the insertion loss of the array's feeder network, which contains cables and connector losses and the insertion loss associated with the 1:16 power divider.

Figs. 4(a) and (b) show the realization of the improved CDS (19,9,4) arrays, where after improvement each one has 15 and 16 elements. Fig. 4(c) shows the improved array's antenna after interleaving and its feeding network diagram respectively. The manufactured interleaved array and turning table are presented in Fig. 5(a), whereas the horn for completeness of the array measurement system is presented in Figs. 5(b).

III.2. Measurement Results and Discussion

The first measurement has aimed to compare the radiation patterns of the simulation and the measurement of the arrays. The radiation patterns from the improved original CDS (19,9,4) array and the improved complementary CDS (19,9,4) array are presented in Figs. 6 and summarized in Table V. The main lobe gain measurement and the simulation results differ by less than 0.9 dB due to the precision of the measurement system and the efficiency of the realized array.

The gain in the improved original CDS with 16 patches is slightly greater than the gain in the improved array with 15 patches. The achieved side lobe performances are better than before the improvement, but the individual side lobes are worse than the approximation of the optimum tapered illumination due to the use of the CDS in the middle part.



(a)

(b)

Figs. 5. (a) Realization of the improved interleaved CDS (19,9,4) array antenna and its rotating table. (b) Horn

The side lobe fall-off rate of the measured arrays has been faster than in the simulation because the radiation pattern is the result of the multiplication of the element factor of the patch with the array factor.

A better antenna element is needed in order to achieve a faster side lobe fall-off rate. Lower side lobe levels may be achieved by using a longer CDS or more improved patches, both of which will result in longer total length interleaved arrays.

The second measurement has aimed to compare the radiation patterns of the measurement of the original and complement CDS arrays before and after the improvements, as shown in Figs. 7.

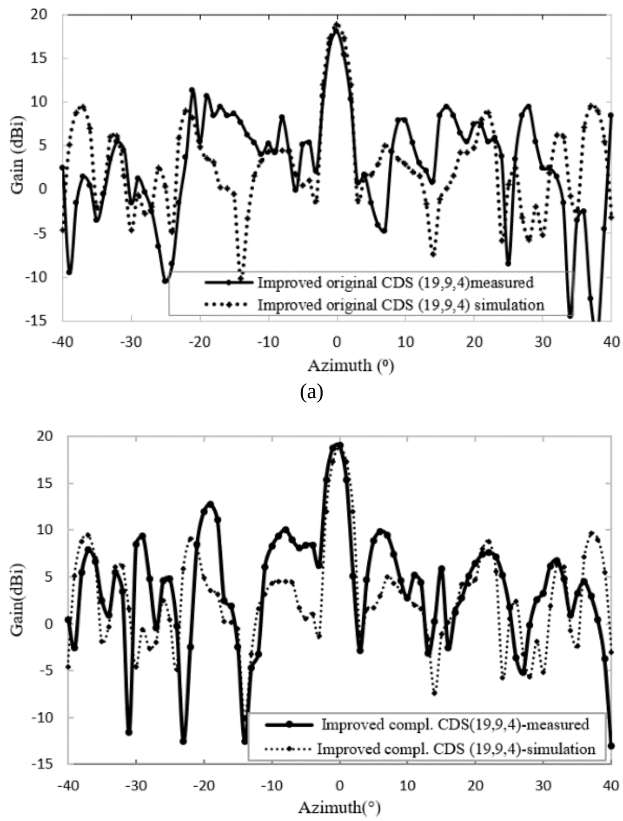
The results are summarized in Table VI, which shows that after improvement, the side lobes have been suppressed by 3.7 dB and 1.66 dB, whereas the beam widths have been both narrowed by 3 degrees. The radiation pattern is the result of the array factor and the element factor.

The array factor is determined by the space tapering. Different tapering functions can be employed and will be investigated in future research activities.

The results of this study have demonstrated the effectiveness of this method for interleaving two arrays sharing one aperture for a multi-beam antenna, with each one containing a narrowed beam width and decreased side lobes.

TABLE IV
APERTURE UTILIZATION CALCULATION OF THE IMPROVE INTERLEAVED CDS (19,9,4) LINEAR ARRAY

CDS (19,9,4) Linear Array Aperture Utilization				
Array	**Total number of elements (N)**	**Array Length L (m)**	**Occupied Aperture (m)**	**Aperture Utilization U (%)**
Improved CDS Original	15	1.23	0.37	30%
Improved CDS Complement	16	1.39	0.39	28%
Improve interleaved CDS	31	1.39	0.76	55%



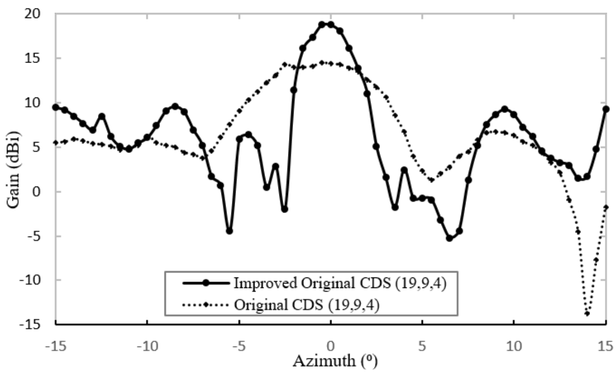
(a)

(b)

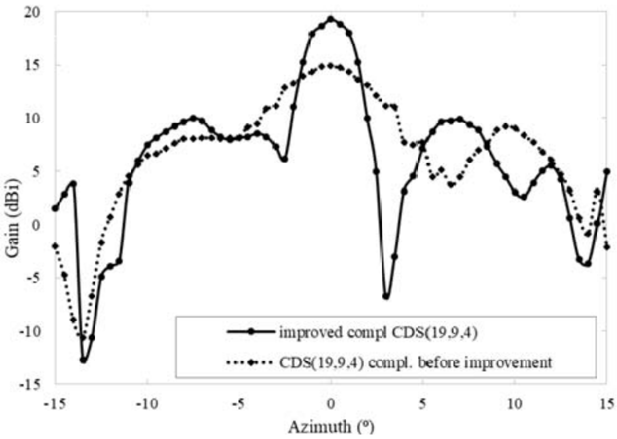
Figs. 6. Comparison of the CST array simulation and measurement results: (a) improved original CDS (19,9,4) array with a feeder and (b) improved complementary CDS (19,9,4) array

TABLE V
COMPARISON OF THE RADIATION PATTERNS FOR THE IMPROVED INTERLEAVED CDS (19,9,4) ARRAYS

CDS(19.9,4)				
CDS(19.9,4)	**Original**		**Complement**	
Radiation Pattern	**Simulation**	**Measurement**	**Simulation**	**Measurement**
Gain(dBi)	18.9	18.08	18.86	18.78
Angular width (°)	2.7	2.7	3	3
1st sidelobe level (dB)	9.84	7.7	13.823	8.7



(a)



(b)

Figs. 7. Radiation pattern measurement results before and after the improvements: (a) CDS (19,9,4) and (b) complementary CDS (19,9,4)

TABLE VI
COMPARISON OF THE RADIATION PATTERNS FOR THE CDS (19,9,4) ARRAYS BEFORE AND AFTER IMPROVEMENT

CDS (19.9,4) Radiation Pattern			
	Gain (dBi)	**Angular width (°)**	**Peak sidelobe level (dB)**
Original CDS array			
Before improvement	13.68	5	-7.8
After improvement	17.98	2	-11.5
Improvement	4.3	3	3.7
Complement CDS array			
Before improvement	14.86	5.5	-7.27
After improvement	18.43	2.5	-8.93
Improvement	4.3	3	1.66

IV. Conclusion

An improved interleaved linear CDS has been designed and simulated. The measurements of the arrays have showed that this method is capable of improvements to their gain, beam width, and side lobe levels. It is demonstrated that compared to the original CDS performance, the improved arrays have a narrower beam width of least 3 degrees and a side lobe level suppression of at least 1.66 dB, with a difference of gain of the main lobe less than 0.9 dB between the simulations and measurement. The method has showed an increase to 55% of aperture utilization compared to the previous individual arrays before interleaving, where the latter has achieved only 30% and 28 %, subsequently for Improved Original CDS and Improve Complement CDS.

Therefore, it is concluded that the proposed method is an effective interleaved method for aperture sharing. The proposed method also provides flexibility in the design of interleaved array of a given aperture despite the limited availability of CDS. Future work will include the introduction of different polarizations for the arrays, the utilization of different tapering functions, the introduction of different antenna elements and an extension method to planar arrays.

Acknowledgements

This project is supported by: Hibah Tugas Akhir Mahasiswa Doktor Universitas Indonesia. Nomor: 1345/UN2.R3.1/HKP.05.00/2018

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