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Linear Array Thinning with Cavity backed U-slot Patch Antenna using Genetic Algorithm

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Abstract: In this paper, a thinned linear array with a Cavity-backed U-slot Patch has been investigated using the Genetic Algorithm to minimize peak sidelobe level and the number of antenna elements. One of the essential steps in the Genetic Algorithm method is a crossover, which uses the Paired Top Ten and Combined Top Five rules applied to the Cavity-backed U-slot Patch antenna. Simulation results from 30 element linear array are shown. The peak sidelobe level value is -18.63 dB with an array filling of 63.33% at the broadside angle using Combined Top Five rules. In Paired Top Ten, the peak sidelobe level value is -19.48 dB with an array filling of 70%. The two methods are still better as compared to a dense array and the resulting beamwidth is <5◦. This study is essential in the development of radar technologies since it needs a low sidelobe level and narrow beamwidth.

Keywords: *crossover rule, Cavity backed U-slot Patch antenna, Genetic Algorithm, linear array, thinned array*

Abstrak: Pada paper ini, penipisan antena array linear dengan *Cavity backed U-slot Patch* telah diinvestigasi menggunakan metode Algoritma Genetika untuk meminimalkan *peak sidelobe level* dan jumlah elemen antena. Salah satu tahapan penting pada Algoritma Genetika adalah perkawinan silang, yang mana menggunakan aturan *Paired Top Ten* dan *Combined Top Five* yang diaplikasikan pada antena *Cavity backed U-slot Patch*. Hasil simulasi dari 30 elemen Cavity backed U-slot Patch element linear array ditunjukkan. Nilai *peak sidelobe level* yang diperoleh adalah -18,63 dB dengan pengisian array 63,33% pada arah broadside menggunakan aturan *Combined Top Five*. Pada *Paired Top Ten*, nilai *peak sidelobe level* yang diperoleh adalah -19,48 dB dengan pengisian array 70%. Hasil dari penerapan dua metode tersebut masih lebih baik dibandingkan dengan dense array dan beamwidth yang dihasilkan rata-rata <5◦. Studi ini sangat penting dalam perkembangan teknologi radar yang memerlukan sidelobe level yang rendah dan beamwidth yang sempit.

Kata Kunci: *Algoritma Genetika, aturan perkawinan silang, Cavity backed U-slot Patch antenna, linear array, penipisan array*

Introduction

Large antenna arrays are required to obtain radiation pattern with narrow beamwidth and low side lobe level (SLL). However, it needs high cost, weight, power consumption, and computational complexity in implementation. Thinning an array removes some active elements of the antenna without reducing system performance and can solve these problems to obtain the desired pattern. Also, it can reduce the sidelobe level when an active element (ON) operate equal amplitude.

In recent years, optimization techniques have been applied in the thinned array such as Genetic Algorithm [1]–[10], Particle Swam Optimization (PSO) [11]–[13], simulated annealing [14], ant colony optimization [15], probability density tapering [16], Iterative Fast Fourier Technique (IFFT) [17], Modified Iterative Fourier Technique (MIFT) [18]. These approaches are useful to optimize thinned linear and planar arrays to obtain lower sidelobe levels. For PSO, it is useful for Direct Broadcast Satellite (DBS) systems. Peak Side Lobe Level (PSLL) value with the PSO technique is reduced to 3.8-5.1 dB compared to a fully populated array [11]. Another method is simulated annealing for thinning and weighting of large arrays. This approach can optimize positions and weight coefficients. Another method is Ant

Colony Optimization (ACO) for thinned array synthesis with minimum sidelobe level. This method is useful for the resolution of medium or large problems as global search. Most of these optimization methods are based on an algorithm with random processes and focused on obtaining a lower sidelobe level. In this paper, we focused on the Genetic Algorithm method due to its ability to optimize the unlimited number of antenna elements.

Genetic Algorithm, which was earlier presented by R. Haupt for thinning linear and planar array [1], [2], had been further developed by K. Yan and Y. Lu for array pattern synthesis using a flexible and straightforward GA applied in linear and planar arrays [3], this approach is avoid coding and working with a complex number. It makes simple computing and speeds up computation. Other modifications were applied by G.K Mahanti et al. for the synthesis of the thinned linear array using a real coded genetic algorithm with elitist strategy [5]. In their study, two cases were compared. For the first case, there are no restrictions for the turned ON or OFF element, while for the second case, the final element of the array is intentionally turned off to reduce the length of thinned arrays.

Modification of GA is also reported by M. Jijenth et al. for the synthesis of thinned planar antenna array with low peak sidelobe level over desired scan volume using a novel technique [6]. This approach is derived from the binary-coded GA by introducing randomization techniques such as crossover and mutation. This approach is useful to reduce sidelobe level and beam steering capability.

R. Jain and G.S Mani proposed a dynamic thinning of the antenna array using the Genetic Algorithm [4]. The concept of dynamic thinning is useful for a real-time thinning antenna. There are four approaches to dynamic thinning such as Bulk Array Computation, Zoning, the concept of acceptable solution, and Dynamic thinning Programmer. It was used for computational complexity, system integration, and implementation.

Our previous work using a novel crossover rule, namely Combined Top Five (CTF) and Paired Top Ten (PTT) has been applied in 30 isotropic elements with an inter-element spacing of 0.5 λ and 10 trials [19]. The result of the sidelobe level is reduced by about 4 dB compared to the existing rule.

This paper proposes the GA method with a crossover CTF and PTT applied in the linear array with Cavity Backed U-Slot Patch (CUP) element to produce a lower sidelobe level and a minimum number of elements. CUP, which is consisting of metal plates through-holes, namely cavity [20]. The primary motivation of the CUP element pattern is to reduce inter elements coupling and increase impedance bandwidth. Furthermore, the result would be compared to the dense array (without thinning) in section experiment and analysis.

Method

Cavity-backed U-slot Patch (CUP) is fully implemented in thinned linear array antennas because of easy manufacturing, low cost, and single layer fabrication technology on PCB board. U-slot Patch has a variant as E-shaped patch antenna has been proven to improve impedance bandwidth when compared with the standard patch [20]. The cavity is a hole with a surface coated by copper so it can suppress mutual coupling between elements. In this paper, the PCB design using Roger with a dielectric constant ε_r is 3.35 of the material substrate and operates at a frequency of 3 GHz. Design and simulation have been discussed in [21], [22].

Furthermore, to minimize PSLL and the number of elements in the CUP antenna, the first step is parameter initialization. It determines the parameters to be optimized and then encodes them in the form of a chromosome variable consisting of several genes. Chromosomes can be coded to binary (0 and 1). Here, the set parameter consists of 20 chromosomes, and each chromosome consists of 30 genes. The genes represent CUP elements with an element space of ½λ and 30 trials. The initial population begins by forming a chromosome matrix [20x30]. Each matrix row represents each chromosome determined randomly to produce a fitness function value as a solution for this optimization.

The second step is to determine the fitness function, which is the CUP array's far-field pattern function. The minimized output is the maximum PSLL value. The parameter that affects the output is the condition of antenna elements (ON or OFF). The far-field pattern of the CUP array is expressed by [1], [19]

$$F_{far-field}(u) = \sum_{n=1}^{N} A_n \cos(2\pi n d u + \delta_s) F_{element}(u) \quad (1)$$

where A_n is the amplitude of the elements excited where the value is 0 (off) or 1 (on), n is the number of array elements, d is spacing between elements, $u=\cos(\varphi)$, δ_s is steering phase $(\delta_s=-2\pi n d u\theta_0)$, and the $F_{element}(u)$ *Elpat* is the *element pattern* of the array antenna.

The third step is natural selection. After obtaining each chromosome's fitness value, the chromosomes are selected based on the fitness value ordered from the best chromosome to the worst chromosome. The best chromosome is determined by the lowest PSLL value, which has a greater chance of being maintained than the worst chromosome. The best-selected chromosomes are used as parents to produce better offspring.

The fourth step is the crossover. Paired Top Ten (PTT) and Combined Top Five (CTF) crossover rules were used in this study [19]. **Figure 1** shows natural selection using the PTT rule. The best 10 chromosomes are taken from the 20 chromosomes based on the fitness value, while the others are discarded. **Figure 2** shows the PTT crossover rule by pairing the parents according to the ranking order. For example, parents 1 was paired with parents 2 and so on. The results in 5 parent pairs and each pair produces 2 offspring. So the next generation contains 20 chromosomes consisting of 10 parent chromosomes and 10 offspring chromosomes.

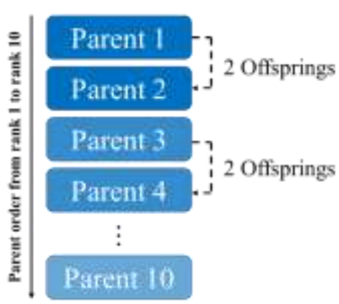

Figure 1. Natural selection for crossover PTT rule.

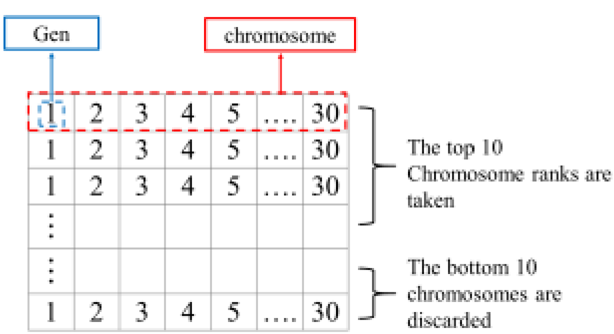

Figure 2. Crossover PTT rule.

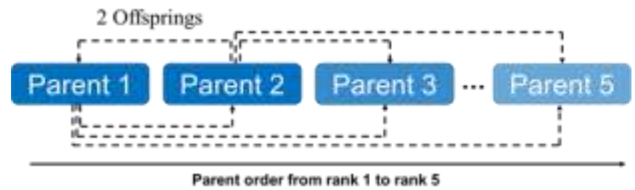

Figure 3. Natural selection for crossover CTF rule.

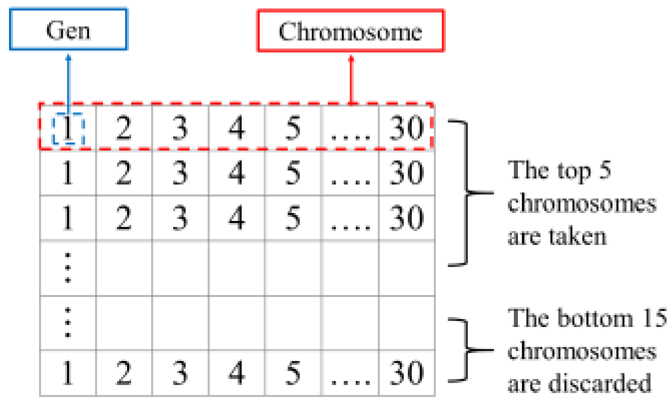

Figure 4. Crossover CTF rule.

Figure 3 shows a natural selection in the CTF rule. The best five chromosomes are taken from 20 chromosomes based on the fitness value, while the others are discarded. **Figure 4** shows the CTF crossover rule by pairing the parents according to a combination of the best 5 chromosomes. This combination results in 10 pairs of parents; each pair produces 2 offsprings. So the next generation contains 25 chromosomes consisting of 5 parents and 20 offsprings.

The last step is random mutation, which is a process to induce random variations in a population. It is carried out on each iteration by changing the binary digits in the mutated position, i.e., 0 to 1, or vice versa. Usually, mutations do not improve the solution. However, without the mutation process, it can be stuck at a local minimum [1], [2]. Then, the next generation process is restarted to the second step. When the desired criteria are obtained, this process is finished.

Results and Discussion

One of the most critical stages of the GA technique is crossover rules, which determine the quality of produced parents and offspring. To ensure its effectiveness, the thinned array results using the GA

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Table 1. Minimization result obtained by the GA technique for thinned linear array antenna with CUP element.

Trial Number	CTF Crossover rules				PTT Crossover rules			
	PSLL (dB)	CG	N1	Filling (%)	PSLL (dB)	CG	N2	Filling (%)
#1	-17.47	5	19	63.33	-17.00	14	20	66.67
#2	-15.42	8	16	53.33	-19.48	101	21	70.00
#3	-17.67	27	22	73.33	-19.97	96	22	73.33
#4	-18.60	29	24	80.00	-16.76	8	21	70.00
#5	-14.63	4	16	53.33	-19.03	37	23	76.67
#6	-17.24	35	21	70.00	-19.09	20	21	70.00
#7	-16.84	3	21	70.00	-18.79	51	21	70.00
#8	-16.60	17	21	70.00	-16.73	7	20	66.67
#9	-18.00	30	20	66.67	-15.59	25	18	60.00
#10	-15.98	4	19	63.33	-19.52	41	22	73.33
#11	-16.80	8	23	76.67	-19.73	70	23	76.67
#12	-16.67	12	20	66.67	-18.70	14	21	70.00
#13	-19.19	40	23	76.67	-18.78	87	22	73.33
#14	-19.10	60	23	76.67	-19.23	116	23	76.67
#15	-18.71	36	21	70.00	-19.07	82	21	70.00
#16	-19.73	120	23	76.67	-18.34	102	22	73.33
#17	-16.61	10	17	56.67	-19.00	39	23	76.67
#18	-18.63	29	19	63.33	-18.78	71	23	76.67
#19	-18.56	30	24	80.00	-16.35	46	19	63.33
#20	-17.68	22	21	70.00	-16.81	5	19	63.33
#21	-18.57	37	20	66.67	-20.16	22	23	76.67
#22	-17.52	22	19	63.33	-19.13	69	23	76.67
#23	-19.32	14	22	73.33	-20.77	105	22	73.33
#24	-19.69	25	23	76.67	-19.19	47	22	73.33
#25	-17.72	50	22	73.33	-19.14	38	23	76.67
#26	-20.87	41	22	73.33	-17.67	20	19	63.33
#27	-16.62	13	19	63.33	-17.45	26	21	70.00
#28	-18.99	36	23	76.67	-16.63	33	20	66.67
#29	-16.36	4	19	63.33	-17.40	51	20	66.67
#30	-17.27	30	20	66.67	-18.10	25	24	80.00

technique with CTF and PTT crossover rules on CUP antennas will be compared with a dense array CUP. **Table 1** presents the minimization results obtained by the GA technique for the thinned array. Each CTF and PTT crossover rule describes PSLL and the number of element minimization results. N1 and N2 represent the number of turned ON elements in these two rules. Where the result of the two rules depends on each trial. This simulation is limited to 30 trials.

CTF Crossover Rules

In **Table 1**, the lowest PSLL in the CTF rule is about -20.87 dB in trial #26 for N1=22, and the lowest array filling is 53.33% in trial #2 for N1=16. **Figure 5** shows a convergence curve of PSLL versus a array filling of 30 trials with the CTF rule. The three best individual criteria are chosen, i.e., trial #26, #18, and #17. This selection is based on the lowest PSLL, with a minimum number of radiation elements. Therefore, only a few trials can produce thinned arrays with a minimum PSLL.

Trial #26 with N1=22 has a the lowest PSLL (-20.87 dB) but higher array filling (73.33%). Trial #17 with N1 =17 has the highest PSLL (-16.61 dB) and a minimum array filling of 56.67%. Trial #18 with N1=19 has intermediate PSLL (-18.63 dB) and array filling (63.33%) between trial #26 and #17. The best selection is taken in Trial #18 to show the minimization of both PSLL and array filling.

Figure 6 (a) shows a far-field pattern in Trial #18. The status of the element (1=ON or 0=OFF) is shown at the top of the image, sorted from left to right. The edge of the array is set to be 1. So the size of the array dimensions does not change. **Figure 6 (b)** shows the PSLL value decreases and reaches the convergent point (CG) in the 29th generation for the same trial. CG is convergence generation, which is the point when the generation reaches the desired PSLL value. The minimum PSLL is reduced by 5.34 dB, and the number of ON elements is reduced by 36.67%, as compared to the CUP dense array. This condition occurs when the array is scanned in the broadside direction.

Figure 7 shows far-field patterns scanned at different angles of 0°, 30°, dan 60°. An increase in PSLL is observed for 30° and 60° scanning angles. For scanning 30°, the PSLL value is -11.59 dB, which is ~7 dB higher than the broadside direction. For scanning at 60°, the PSLL value is -10.31 dB, which is ~8.32 dB higher than the broadside direction.

PTT Crossover Rules

From **Table 1**, the lowest sidelobe level of the PTT crossover rule is -20.77 dB in trial #23 for N2=22, and the lowest array filling is 60% in trial #9 for N2=18. **Figure 8** shows the convergence curve of PSLL versus array filling of 30 trials with PTT crossover rule. The three best individual criteria are chosen (trial #23, #2, and #26). For Trial #23 (N2=22), the lowest PSLL is -20.77 dB, and the array filling is 73.33%. Trial #26 (N2=19) has a minimum PSLL of -17.67 dB and a array filling of 63.33 %. Trial #2 (N2=21) has PSLL value of -19.48 dB and a array filling of 70 %. It shows that the PSLL value and array filling are between trial #23 and #26. Thus, Trial #2 is chosen due to the ideal PSLL value and radiated elements based on PTT crossover rule.

The far-field pattern is shown in **Figure 9 (a)**. The status of element 1=ON or 0=OFF is shown at the top of the image. Arrays are sorted from left to right and from end to end of the array in set 1, so the array dimensions' size does not change. For the same trial, **Figure 9 (b)** shows the PSLL value is slowly decreasing and reaching the convergent point (CG) in the 101st generation to the maximum generation. This minimum PSLL is -19.48 dB, which is approximately 6.2 dB lower than the CUP dense array (without thinning), and the number of ON elements is reduced by 30% compared to the CUP dense array. This condition occurs when the array is scanning in the broadside direction.

Figure 10 shows that the increase of PSLL values is observed at scanning angles of 30° and 60°. When scanning at 30°, the PSLL value is -13.71 dB, which is ~5.77 dB higher than the broadside direction. For scanning at 60°, the PSLL value is -12.52 dB, which is ~6.96 dB higher than the broadside direction.

The effectiveness of thinned array (CTF and PTT crossover rules) and dense array are compared in

Table 2. Both rules are superior compared to dense array owing to minimum PSLL and radiation elements. The difference of PSLL values for the dense array, CTF, and PTT at the broadside is -13.28, -18.63, and -19.48 dB, respectively**.**

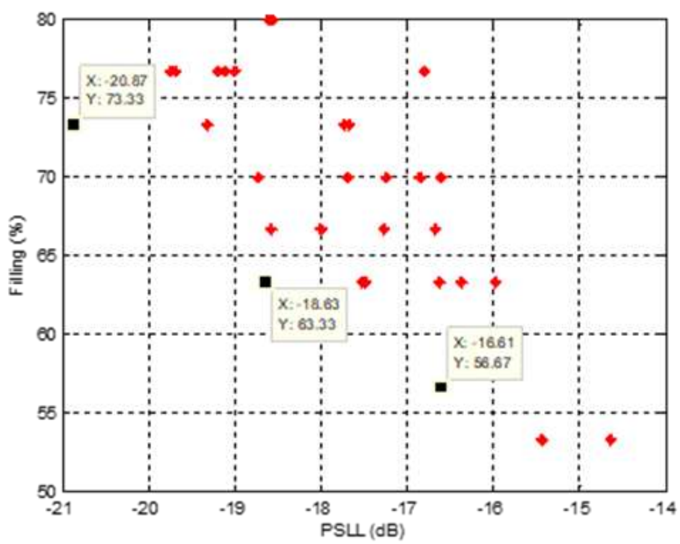

Figure 5. Convergence curve of PSLL versus array filling of 30 trials with CTF crossover rule. The red marker is PSLL value versus array filling for 27 individuals. A black marker is the best of three individuals based on the lowest PSLL and array filling.

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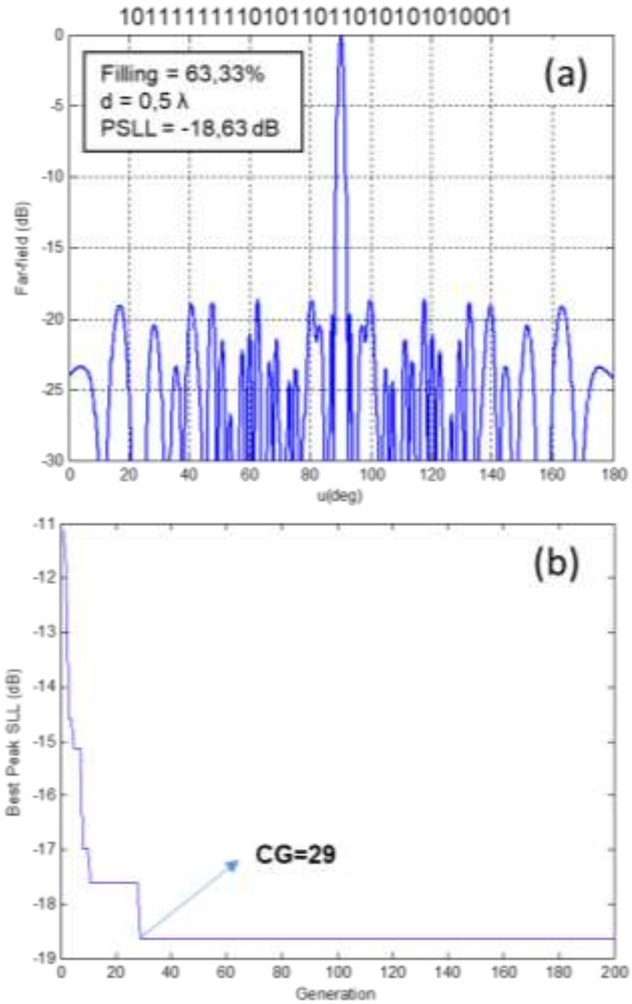

Figure 6. (a) Far-field pattern for CUP antenna based on CTF rule with 63.33% turned ON elements and PSLL of -18.63 dB in trial #18. (b) Convergence curve of generation versus best PSLL for the same trial.

Table 2. GA minimization in dense array, CTF, and PTT with CUP antenna.

CUP antenna	Scanning (°)	Elemen ON	Filling (%)	PSLL (dB)	Beamwidth -3dB (°)
Dense Array	0	30	100	-13.28	3.38
	30			-14.25	3.9
	60			-17.72	6.67
CTF rule (thinning)	0	19	63.33	-18.63	1.45
	30			-11.59	2.19
	60			-10.31	3.77
PTT rule (thinning)	0	21	70	-19.48	1.87
	30			-13.71	2.15
	60			-12.52	3.72

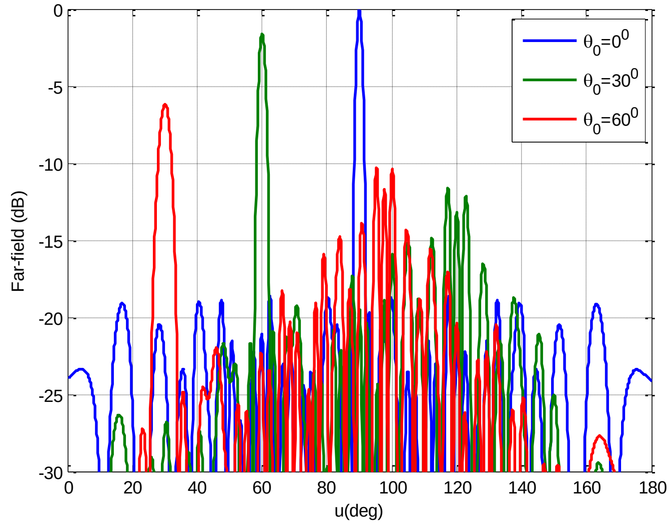

Figure 7. Scanning the far-field pattern from Figure 6(a) at 0°, 30°, dan 60°.

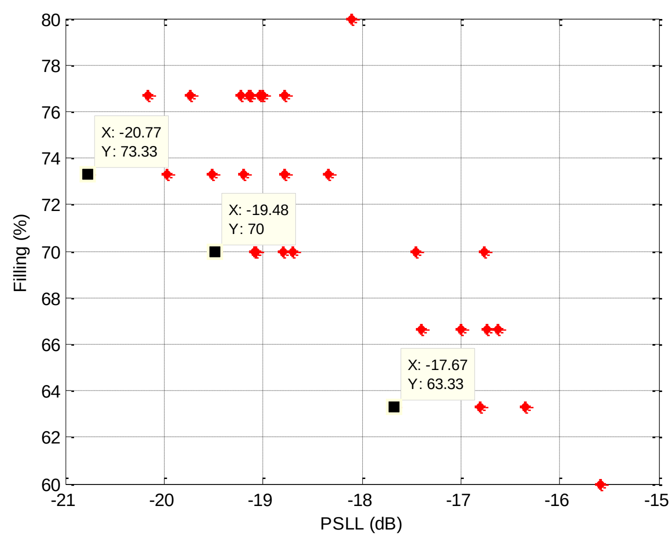

Figure 8. Convergence curve of PSLL versus array filling of 30 trials with PTT crossover rule. The red marker is PSLL value versus array filling for 27 individuals. A black marker is the best of three individuals based on the lowest PSLL and array filling.

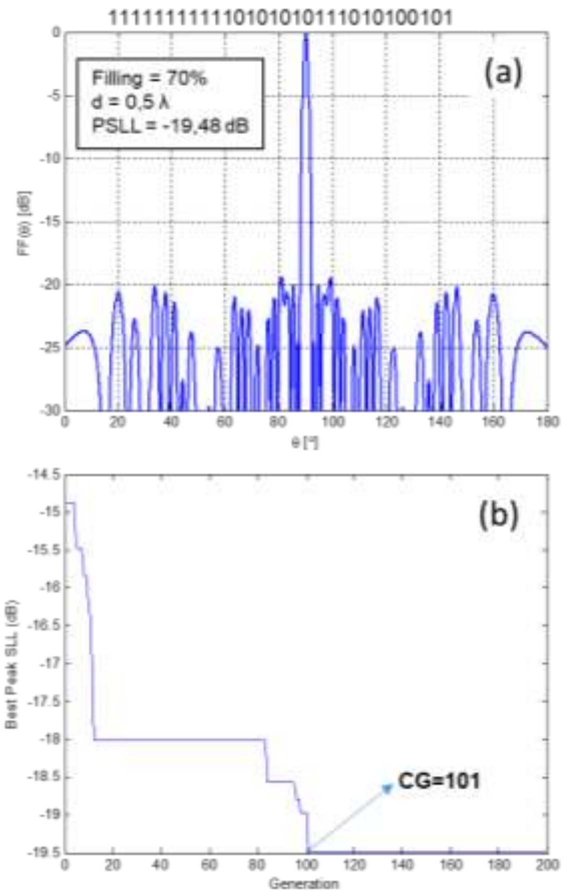

Figure 9. (a) Far-field pattern for CUP antenna based on PTT rule with 70% turned ON elements, and PSLL is -19.48 dB in trial #2. (b) Convergence curve of generation versus best PSLL for the same trial.

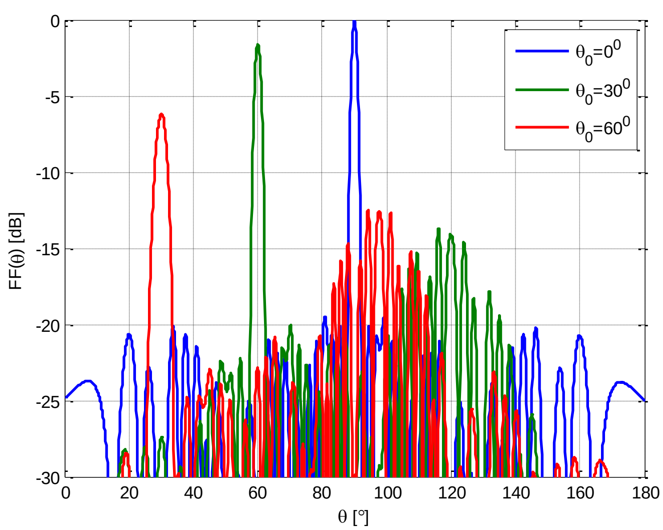

Figure 10. Scanning the far-field pattern from Figure 9 (a) at the angle of 0°, 30°, dan 60°.

Conclusions

CTF and PTT rules produce a different number of elements and PSLL. At the broadside angle, the PSLL of PTT rules is 0.85 dB superior to CTF rules. In terms of minimizing the number of elements, the CTF rule is 6.67% superior to the PTT rules. By comparing the two rules to the dense array with the same antenna, the PSLL is reduced by 6.2 and 5.35 dB for PTT and CTF rules, respectively. The thinned CUP antenna only shows superior performance by scanning through the broadside angle. The average beamwidth is lower than 5°, which is suitable for the desired antenna.

Conflicts of interest

There are no conflicts to declare.

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