Research Article

A Time Modulated Printed Dipole Antenna Array for Beam Steering Application

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This paper presents time modulated beam steered antenna array without phase shifters. The beam steering is analyzed considering a two-element time modulated antenna array (TMAA) of printed dipoles with microstrip via-hole balun. The proposed array resonates at the Industrial, Scientific, and Medical (ISM) radio bands, 2.45 GHz and 5.8 GHz, and offers wide bandwidth inherited due to modified structure of ground plane. Array elements are excited by complex exponential excitation signal through broadband power divider and radio frequency (RF) switches to achieve amplitude and phase variation without phase shifters. Differential Evolution algorithm is used to modify the time sequences of the RF switches connected to the antennas to generate radiation pattern with optimum dynamic efficiency by suppressing sideband radiations. Also switch-on time instant of RF switch connected to the subsequent element is modulated to steer the beam towards different directions. The proposed prototype is fabricated followed by parametric optimization. The fabrication results agree significantly well with simulated results.

1. Introduction

Antenna arrays are widely used in communication systems to obtain desired radiation characteristics. Various techniques for synthesizing arrays are available in literature [1]. Phased array antennas are widely used for conventional beam scanning, beam steering, and adaptive beam forming applications by adapting the excitation amplitude and phase distribution [2]. The limitations associated with the phased array antenna to generate radiation patterns with various stringent designing constraints are cost, size, power consumption, and high complexity. A substantial amount of efforts has been devoted to develop low cost highly reliable phased array antenna since early 1960s. Time modulation applied to linear antenna array is a technique to adapt its radiated power pattern by periodically enabling and disabling the excitations of the individual array elements [3]. Since early 2000s there has been renewed interest in taking up the investigations on this field due to the arrival of the high performance RF switches.

Different time sequences [4–7] were used to control the RF switching. Different optimization strategies have been used in TMAA to synthesize its radiated power pattern [8, 9] to realize beam steering [10], beam forming [11–14], null synthesis [15, 16], and direction finding [17] without using conventional phase shifters. Application of TMAA in cognitive radio has been analyzed in [14]. In [18], TMAAs has been applied to achieve directional modulation for secure communication. Printed antenna owing to variety of beneficial properties including light weight, low profile, and low cost has become explosively popular and widely investigated in articles [19–22]. Wideband printed antennas utilized in modern wireless communication systems are presented in [23–27]. TMAA as a versatile adequate radiation system for modern wireless applications has increased significantly over recent past.

The presented article proposes TMAA of printed dipoles for beam steering without using phase shifters. The traditional printed dipoles using novel U-shaped ground

FIGURE 1: Simplified block diagram of the proposed TMAA.

plane and quarter wavelength microstrip via-hole balun are designed at 2.45 GHz and 5.8 GHz inspired by [20]. Introduction of the U-shaped ground plane reflects the electromagnetic waves towards the feeding direction. It improves the reflection coefficient and broadens the bandwidth more effectively than the V-shaped structure used in [20]. The dipoles are connected through a broadband power divider ranging from 2.1 GHz to 7 GHz and PIN diode single pole single throw RF switches. DE is applied to obtain the time sequence to suppress the side band power level (SBL). Application of complex exponential signal steers the beam towards different directions as the switching time sequences of RF switches are modulated. Article [12] has simulated a beamforming network for TMLA using Artificial Bees Colony algorithm. However the present article has successfully implemented the design structure of dual band TM beam steered array using DE.

The antenna structure is rigorously optimized through simulation using CST microwave studio to realize wide bandwidth responses at the two proposed resonances. Experimental testing of the fabricated antenna array shows good agreement with the simulated results.

The rest of the paper is organized as follows. The problem is mathematically formulated in Section 2. Section 3 provides the outline of DE. The design specifications of proposed TMAA are described in Section 4. A set of numerical results is reported and discussed in Section 5. Finally the paper is concluded in Section 6.

2. Theoretical Background

Consider an array of two collinear dipoles with spacing d positioned along the z -axis as shown in Figure 1. Both the array elements are excited using a complex excitation signal $e^{-j2\pi f_p t}$ and controlled by a high-speed RF switch having f_p . When a plane wave of frequency f_0 is incident at an angle θ with respect to the normal of the array, the far field pattern of the array considering the element pattern is

$$F(\theta) = e^{j2\pi f_0 t} \sum_{n=1}^2 I_n(t) e^{j\beta d_n \cos \theta} \left[\frac{\cos((\pi/2) \cos \theta)}{\sin \theta} \right]. \quad (1)$$

Here $f_0 \gg f_p$ ($f_p = 1/T_p$, T_p is the TM period). $\beta = 2\pi/\lambda$ is the free space wave number, $\lambda = c/f_0$ is the wavelength, and c is the speed of light in free space.

$$I_n(t) = \begin{cases} U_n(t), \\ U_n(t) e^{-j2\pi f_p t}, \end{cases} \quad \text{for } n = 1, 2. \quad (2)$$

$U_n(t)$ is the time switching function of the RF switches modelling the periodic on-off time of the switches. Thus

$$U_n(t) = \begin{cases} 1, & kT_p + t_{\text{on}} \leq t \leq kT_p + t_{\text{on}} + \tau_n, \\ 0, & \text{otherwise.} \end{cases} \quad (3)$$

τ_n are the switch-on duration of the RF switches connected to n th element and k is an integer. Due to the periodicity of the modulating pulse functions $I_n(t)$ can be decomposed into Fourier series with different frequency components, given by

$$I_n(t) = \sum_{m=-\infty}^{\infty} \Gamma_n^{(m)} e^{j2\pi m f_p t}, \quad (4)$$

$$\Gamma_1^{(m)}(t) = \frac{1}{T_p} \int_0^{T_p} U_n(t) e^{-j2\pi m f_p t} dt, \quad (5)$$

$$\Gamma_2^{(m)}(t) = \frac{1}{T_p} \int_0^{T_p} U_n(t) e^{-j2\pi(m+1)f_p t} dt, \quad (6)$$

$$\Gamma_n^{(m)} = \frac{\tau_n}{T_p} \frac{\sin(\pi m f_p \tau_n)}{\pi m f_p \tau_n} e^{-j\pi(m+n-1)f_p(2t_{\text{on}}+\tau_n)}. \quad (7)$$

Under the hypotheses that $f_p \ll f_0$ and $\Delta f_s < f_p$, where Δf_s is the maximum bandwidth of the received signals, the signal at the working frequency f_0 can be then extracted by filtering out the SR and eventually the received signal turns out at infinite number of harmonic terms spaced at $m f_p$ ($m \in \mathbb{Z}$) from f_0 . Accordingly, the array factor at f_0 turns out to be

$$F^{(0)}(\theta) = e^{j2\pi f_0 t} \sum_{n=1}^2 \frac{\tau_n}{T_p} e^{-j\pi(n-1)f_p(2t_{\text{on}}+\tau_n)} e^{j\beta n d \cos \theta}, \quad (8)$$

$$F^{(m)}(\theta) = e^{j2\pi f_0 t} \sum_{n=1}^2 \Gamma_n^{(m)}(t) e^{j\beta n d \cos \theta}.$$

FIGURE 2: Elements of the TMAA: (a) configuration of the antenna array; (b) prototype of the antenna array; (c) configuration of the power divider; (d) prototype of the power divider; (e) prototype of the RF switch and CPLD test board.

The average power density radiated by the array over T_p

$$S(\theta) = \frac{1}{T_p} \int_{-T_p/2}^{T_p/2} [\text{Re} \langle F(\theta) \rangle]^2 dt. \quad (9)$$

So the total power radiated can be calculated using

$$P(\theta) = \int_0^{2\pi} \int_0^\pi S(\theta) \sin \theta d\theta d\phi. \quad (10)$$

Thus using (8), we evaluate the expression of the power radiated at central frequency (P_0) and at the side bands (P_{SR})

$$P_0 = 2\pi \sum_{n=1}^2 \left(\frac{\tau_n}{T_p} \right)^2, \quad (11)$$

$$P_{SR} = 2\pi \sum_{n=1}^2 \frac{\tau_n}{T_p} \left(1 - \frac{\tau_n}{T_p} \right).$$

FIGURE 3: (a) Simulated and measured scattering parameters of power divider. (b) Magnitude of simulated S_{21} and S_{31} parameter. (c) Phase of simulated S_{21} and S_{31} parameter.

So the dynamic efficiency of the array is

$$\eta = \frac{\tau_1^2 + \tau_2^2}{T_p(\tau_1 + \tau_2) - \tau_1^2 - \tau_2^2}. \quad (12)$$

In order to suppress the SLL and enhance the dynamic efficiency, the DE algorithm is applied as the global optimization method. To achieve the design goal the following fitness function is formulated for minimization over iterations using DE

$$\text{Fitness}(t_{\text{on}}, \tau_n) = k_1 \text{SLL} + k_2 \left(\frac{1}{\eta} \right), \quad (13)$$

while SBL at the first sideband is not allowed to rise beyond -25 dB. The constants k_1 and k_2 are the corresponding weighing factors of SLL and dynamic efficiency, respectively. In the designing problem, equal weightage ($k_1 = k_2 = 1$) of both the parameters is considered. The switch-on time (t_{on}) and switch-on duration (τ_n) of each element are considered as population vectors and varied in order to minimize the fitness function.

3. Differential Evolution

Differential Evolution (DE) proposed by Storn and Price [28, 29] is well known population based simple and efficient method for global optimization. DE algorithm consists of the following basic steps: initialization, mutation, crossover, selection, and termination.

(1) *Initialization of Population.* DE searches for a global optimum within a continuous search space of dimension D . Generate K D -dimensional population of target vectors for each generation G .

$$\vec{A}_{i,G} = [a_{i,G}^1, a_{i,G}^2, a_{i,G}^3, \dots, a_{i,G}^D], \quad (14)$$

where $i = 1, 2, 3, \dots, K$.

Target vectors with better results may be found in a definite region of search space with maximum and minimum bounds in each dimension as

$$\begin{aligned} \vec{A}_{\text{max}} &= [a_{\text{max}}^1, a_{\text{max}}^2, \dots, a_{\text{max}}^D], \\ \vec{A}_{\text{min}} &= [a_{\text{min}}^1, a_{\text{min}}^2, \dots, a_{\text{min}}^D]. \end{aligned} \quad (15)$$

FIGURE 4: Optimized return loss of antenna array: (a) S_{11} for different d ; (b) S_{11} for different G_h ; (c) S_{11} for different g .

FIGURE 5: Simulated and measured return loss of antenna array.

The j th component of the i th vector is initialized as

$$a_{i,0}^j = a_{\min}^j + \text{rand}_i^j(0, 1) \cdot (a_{\max}^j - a_{\min}^j), \quad (16)$$

$$j \in \{1, 2, 3, \dots, D\},$$

where $\text{rand}_i^j(0, 1)$ is a uniformly distributed random number lying between 0 and 1.

(2) *Mutation.* After initialization, a donor vector $\vec{M}_{i,G}$ corresponding to best population member $\vec{A}_{\text{best},G}$ in the current generation is created through mutation.

$$\vec{M}_{i,G} = \vec{A}_{\text{best},G} + F \cdot (\vec{A}_{r_1^i,G} - \vec{A}_{r_2^i,G}). \quad (17)$$

The indices r_1^i and r_2^i are mutually exclusive integers and randomly chosen from the range $(1, 2, \dots, K)$. F is called scaling

FIGURE 6: Optimized radiation pattern at centre frequency 2.45 Ghz.

FIGURE 7: Optimized radiation pattern at centre frequency 5.8 Ghz.

factor which will be tuned according to the fitness function generated by each vector. $\vec{A}_{\text{best},G}$ is the best individual vector with minimum fitness value in the population at generation G .

(3) *Crossover*. In crossover operation the donor vector mixes its components with the target vector $\vec{A}_{i,G}$ to obtain

the trial vector of the same index denoted as $\vec{T}_{i,G} = [t_{i,G}^1, t_{i,G}^2, t_{i,G}^3, \dots, t_{i,G}^D]$. The trial vector created is

$$t_{i,G}^j = \begin{cases} m_{i,G}^j & \text{if } (\text{rand}_i^j(0,1) \leq \text{CR or } j = j_{\text{rand}}), \\ a_{i,G}^j & \text{otherwise,} \end{cases} \quad (18)$$

FIGURE 8: Radiation pattern at centre frequency 2.45 Ghz and sidebands.

FIGURE 9: Radiation pattern at centre frequency 5.8 Ghz and sidebands.

where CR is the crossover rate belongs the interval $(0, 1)$. $j_{\text{rand}} \in [1, 2, \dots, D]$ is a randomly chosen index which differentiate trial vector $\vec{T}_{i,G}$ from its corresponding target vector $\vec{A}_{i,G}$.

(4) *Selection*. Selection is introduced to determine which of the target or trial vectors survives to the next generation. If the fitness value of the trial vector is equal to or less than that of the corresponding target vector then the trial vector is selected for next generation; otherwise the target vector is selected for next generation.

(5) *Termination*. If termination condition is not satisfied the execution is returned to Step (2); otherwise it is terminated.

4. Prototype Design

A prototype of the overall system is implemented and presented in this section. The overall system consists of 2-element printed dipole antenna array, RF switches, pulse generator, power divider, and an analog multiplier. The antenna array, power divider, and RF switches are printed

on the FR4 dielectric material of dielectric constant 4.4 and thickness 1.6 mm. The configurations and prototype of the antenna array and power divider are shown in Figure 2 and the dimensions are presented in Table 1. The overall dimension of the antenna array is 136 mm $\times$ 37 mm. The RF switch is realized by connecting a series capacitor, 10 nF before and after the pin diode, BAR63-02. Capacitors are connected to provide the RF connectivity and to prevent the dc. The prototype of the RF switch is shown in Figure 2(e). A rectangular pulse train of 3 V at a repetition frequency of 1 MHz is applied to bias the PIN diode. The CPLD test board (Figure 2(e)) is programmed to generate the desired rectangular pulse and can be tuned for different time sequences. The antenna array, RF switches, and power divider are connected through 50 Ω SMA male/female connectors. The complex exponential signal and RF signals are provided through the signal generator and RF source.

5. Results and Discussion

The proposed steering technique is experimented with an array prototype comprising of two microstrip fed printed

TABLE 1: Structural parameters of dipole antenna array and power divider.

Part of dipole	Dipole antenna array (136 mm $\times$ 37 mm)		Power divider (41 mm $\times$ 30 mm)	
	Parameter	Dimension	Parameter	Dimension
PCB substrate	Thickness	1.6 mm	Substrate thickness	1.6 mm
	ϵ_r	4.4	ϵ_r	4.4
	$\tan \delta$	0.0018	$\tan \delta$	0.0018
Ground plane	d	2 mm	L	41 mm
	G_h	6 mm	W	30 mm
	L_g	10 mm	$L1$	12.56 mm
	W_g	15 mm	$L2$	19 mm
	L_p	13 mm	$L3$	4 mm
	W_p	5 mm	$W1$	4 mm
Dipole arm	L	16 mm	$W2$	3.057 mm
	W	6 mm	$W3$	3.83 mm
Microstrip balun	W_b	3 mm	$W4$	2.947 mm
	Via-hole radius	1 mm	R	100 Ω

FIGURE 10: Simulated and measured radiation pattern for different values of t_{02} at 2.45 GHz. (a) $t_{02} = 0 \mu\text{sec}$. (b) $t_{02} = 0.125 \mu\text{sec}$. (c) $t_{02} = 0.25 \mu\text{sec}$. (d) $t_{02} = 0.375 \mu\text{sec}$.

FIGURE 11: Simulated and measured radiation pattern for different values of t_{02} at 5.8 GHz. (a) $t_{02} = 0 \mu\text{sec}$. (b) $t_{02} = 0.125 \mu\text{sec}$. (c) $t_{02} = 0.375 \mu\text{sec}$.

dipoles for dual band operation at 2.45 GHz and 5.8 GHz, as shown in Figure 2. The structure of the printed dipoles is designed to provide good impedance matching over the operating frequency bands. The feed network of the proposed TMAA is composed of an ultra-wideband power divider covering 2.1 GHz to 7 GHz (Figure 3(a)) and RF switches. The antenna, power divider, and RF switch are optimized using EM simulator and CST microwave studio and tested using the Network Analyzer E5071C of Agilent Technologies. The prototype of the power divider is fabricated and the scattering parameters are presented in Figure 3. Figure 3(b) shows that the magnitude of S_{21} and S_{31} is marginally deviated from -3 dB ensuring almost equal power division at 2.45 GHz. However it becomes almost -4.5 dB at 5.8 GHz. Figure 3(c) presents a small phase difference between port 2 and port 3 over the bandwidth and ensures almost equal power splitting. The structure of front and the back side of the broadband power divider is identical allowing equal current distribution at both sides. The dimensions of the ground plane, d and G_h , and the gap g between the two arms of the bottom ground

layer are rigorously studied in order to obtain optimized design parameters, as shown in Figure 4. The prototype of the antenna array is fabricated and presented in Figure 5. The on state insertion loss and off state isolation of the RF switch are studied and found 0.6 dB and 25 dB, respectively. The return loss and bandwidth of proposed prototype TMAA at both the frequencies are tabulated in Table 2.

Firstly, the on time duration (τ_n) and switch-on instance (t_{on}) of the rectangular pulses applied to RF switches are optimized using DE in order to obtain radiation pattern with suppressed SLL and enhanced dynamic efficiency at both the operating frequencies. To achieve $\eta \geq 98\%$, the optimized time sequences of the input pulse train are set at $\tau_1 = 0.6035$, $\tau_2 = 0.2548$, $t_{01} = 0$, and $t_{02} = 0.1226$ using programmed CPLD to modulate the input excitation according to (7). The radiation pattern obtained using time modulated excitation distribution is shown in the corresponding contour and Cartesian plot given in Figures 6, 7, 8, and 9 at 2.45 GHz and 5.8 GHz, respectively. The DE optimized simulated radiation patterns, presented in Figures 8 and 9, confirm that the SBL

TABLE 2: Results of proposed prototype antenna array.

Prototype	Frequency	Parameter	Simulated value	Measured value
Proposed array of two printed dipoles with U-shaped ground	2.5 GHz	S_{11}	-25.28 dB	-20.2 dB
		Bandwidth	1.21 GHz	1.2 GHz
	5.8 GHz	S_{11}	-19.33 dB	-16.99 dB
		Bandwidth	1.11 GHz	1.02 GHz

TABLE 3: Desired and obtained SLL.

Design parameter	Side lobe level (dB)	
	Desired	Obtained
2.45 GHz		
f_0 (2.45 GHz)	-8	-7.1
$f_0 + f_p$ (2.451 GHz)	≤ -25	-26.28
$f_0 - f_p$ (2.449 GHz)	NA	-68.34
5.8 GHz		
f_0 (5.8 GHz)	-8	-7.68
$f_0 + f_p$ (5.801 GHz)	≤ -25	-24.53
$f_0 - f_p$ (5.799 GHz)	NA	-48.142

are lowered significantly at the first two sidebands for both the cases. Table 3 gives the desired and obtained values of SLL and SBL of the radiation patterns, shown in Figures 8 and 9 at centre frequency as well as first two sidebands. The beam steered polar radiation patterns (E plane) at the centre frequencies without considering SLL constraints are shown in Figures 10 and 11. In this case, the input pulse train are set at $\tau_1 = 1$, $\tau_2 = (1 - t_{02})$, $t_{01} = 0$, and t_{02} is calculated using (7) to steer the main beam at different directions and implemented with the programmed CPLD. To ensure the flawless radiation pattern, the measurements are taken in a shielded surrounding.

6. Conclusion

A prototype TMAA using printed dipoles operating at 2.45 GHz and 5.8 GHz is proposed for beam steering. Parametric optimization of the proposed array utilizing modified ground structure is done to obtain wider impedance bandwidth. A complex exponential signal applied through the power divider and PIN diode RF switches are used to excite the phase differences between dipoles. DE has been used to suppress the sideband radiations increasing the dynamic efficiency of the radiation pattern steered at different directions. The modulation of the switching sequences of the rectangular pulses controls the relative phase difference between elements and steers the beam in different directions without phase shifter. Experimental validation confirms the effectiveness of the proposed technique over conventional phased array antenna.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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