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COMPARISON BETWEEN THREE RADIATION PATTERN USING BUTLER MATRIX FOR BEAMFORMING NETWORK

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Abstract. Butler Matrix is a beamforming network (BFN), functioning as a feeding network of antenna array. It provides multiple values of progressive phase different of excitation current to an antenna array. By integrating Butler Matrix with antenna array, multiple beams on radiation pattern could be created. In this work, three different types of antenna array have been integrated with the same Butler Matrix and the radiation patterns of each configuration have been compared. The chosen antenna types in this project are 4 × 1 proximity feed square patch antenna array, 4 × [4 × 2] antenna array and 4 × 1 monopole antenna array. They are chosen as each of them has different radiation pattern characteristic. The obtained results show that four independent beams with different angles are generated by individual array where square patch antenna array has Half Power Beamwidth (HPBW) about 30° for each beams and manage to cover 120° of coverage area, [4 × 2] antenna array has HPBW about 7° and cover 30° while monopole antenna produce two kind of beams, broader and narrower beams. The comparison between the measured and computed radiation pattern of each antenna array are presented.

Keywords: Multibeam antenna; 4 × 4 Butler Matrix; microstrip antenna; antenna array; beamforming network

Abstrak. Butler Matrix merupakan jaringan pembentuk alur (BFN), berfungsi sebagai jaringan suapan kepada tatasusun antena. Ia menghasilkan pelbagai nilai anjakan fasa progresif pada arus yang diujakan kepada antena. Dengan menyepadukan *Matrix Butler* bersama tatasusun antena, banyak sinaran pada corak radiasi boleh dihasilkan. Dalam kerja ini, tiga jenis tatasusun antena yang berbeza disepadukan dengan Matrik Butler dan corak radiasi untuk setiap konfigurasi dibandingkan. Antena yang dipilih dalam projek ini adalah 4 × 1 antena tampalan segi empat sama dengan suapan proximity, 4 × [4 × 2] tatasusun antena dan 4 × 1 antena eka-kutub. Ia diplih kerana setiap satu daripadanya mempunya cirri-ciri corak radiasi yang berbeza. Keputusan yang diperolehi menunjukkan empat sinaran yang berasingan dengan sudut yang berbeza dihasilkan oleh setiap tatasusun di mana antena tampalan segi empat sama mempunyai Lebarjalur Setengah Kuasa (HPBW) sebanyak 30° untuk setiap sinaran dan berjaya meliputi 120° kawasan liputan, 4 × 2 tatasusun antenna mempunyai HPBW sebanyak 7° dan meliputi 30° manakala antenna eka-kutub menghasilkan dua jenis sinaran, lebar dan sempit. Perbandingan antara pengukuran dan pengiraan corak radiasi untuk setiap tatasusun antena juga dibentangkan.

Kata kunci: Antena pelbagai sinaran; 4 × 4 Matrik ; antena microstrip; tatasusun antena; jaringan pembentuk alur

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1.0 INTRODUCTION

The topic of multibeam antenna constructed using Butler Matrix as a beamforming network (BFN) has received much attention due to its simplicity and low cost of implementation. It becomes more popular nowadays, as it is capable to reduce co-channel interference and then increase the channel capacity of a system [1]. Co-channel interference could be reduced using multibeam antenna by focusing directional beams to the desired user direction, and be null to undesired user directions. In fact, there are few popular methods of constructing a multibeam antenna such as using digital beamformer [2], Blass Matrix [3] and lens based beamformer [4], but the simplest one is by integrating linear antenna array with Butler Matrix. Butler Matrix is a well known BFN where it has a capability of producing multiple independent beams that directed at different directions. The number of generated beams, the beams angle directions, HPBW of each beams and total coverage angle of multibeam antenna could be varied dependent on the antenna array design configuration itself. The radiation patterns characteristics of the multibeam antenna could be analyzed through pattern multiplication theorem of antenna array.

According to the theory of pattern multiplication theorem, a radiation pattern of an antenna array could be affected by two main factors; the type of antenna array and its feeding network [1]. Since the feeding network in this project is fixed on Butler Matrix, the radiation pattern of the antenna array then could be changed by using different types of antenna. This work is an effort to observe and analyze the performance mainly in terms of radiation patterns characteristics by using different types of antenna array on Butler Matrix. The antenna arrays that have been used in this project are 4 x 1 square patch antenna array, $4 \times [4 \times 2]$ planar antenna array and 4×1 monopole antenna array while 4×4 Butler Matrix is chosen for its feeding network. These antennas are chosen as each of them has different radiation pattern characteristics which are broader pattern for single square patch antenna, directional pattern for single 4×2 antenna array and omnidirectional pattern for single monopole antenna. The numerical analysis of antenna array and Butler Matrix are also presented in this paper.

2.0 THE NUMERICAL ANALYSIS OF ANTENNA ARRAY

Antenna array consist of many radiating elements, which are fed by signal of appropriate phase and amplitude provided from feeding network. The analysis of antenna array could be done according to its radiating elements arrangements. For linear array case which arranged along a straight line, its radiation pattern may be found using pattern multiplication theorem, by multiplying single element pattern with its array factor (*AF*).

$$\text{Array pattern} = \text{Single element pattern} \times \text{AF} \tag{1}$$

Single element pattern is the pattern of the individual array element while *AF* is a function dependent only on the geometry of the array and the excitation (amplitude, phase) of the elements [5]. Single element pattern is relied on the type of the radiating element that used in the array configuration which can be a directional antenna, omnidirectional antenna or non-directional antenna. The data may obtained from simulation or measured data while for *AF*, the own calculation is needed in order to know how does the radiation pattern looks like.

The derivation of AF formula could be started from Figure 1. Figure 1 shows an example of linear antenna array that consist of **N** elements equally spaced at distance **d** apart with identical amplitude excitation and has a progressive phase difference, β between the adjacent elements. The amplitude excitation and β are generally controlled by a feeding network. In this project, the feeding network of an antenna array is Butler Matrix. The derivation of the *AF* formula begins by finding the formula of the phase difference between adjacent elements which is given as follows:

$$\psi = kd \sin\theta + \beta \tag{2}$$

where:

ψ = phase difference between adjacent elements

$k = \frac{2\pi}{\lambda}$

d = distance between adjacent elements

β = phase difference of excitation current between adjacent elements

θ = angle relative to the normal to the array

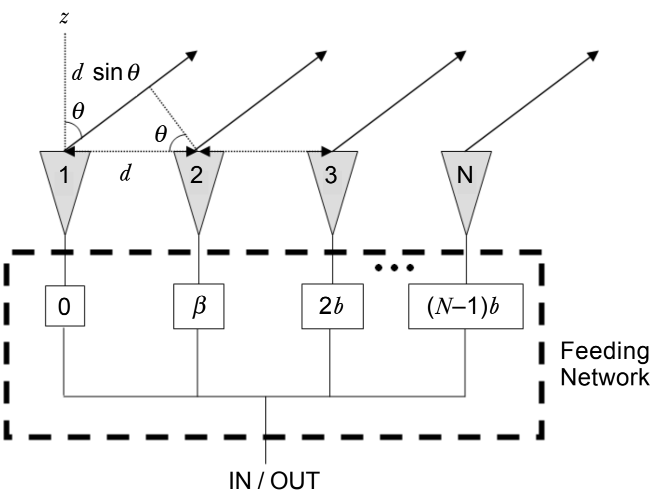


Figure 1 Uniform Linear Array Configuration

Next, the array radiation pattern can be found by summing up the entire received power of each element. The *AF* of *N*-element linear array of isotropic sources is:

$$AF = e^{j0} + e^{j\psi} + e^{j2\psi} \ldots + e^{j(N-1)\psi} \tag{3}$$

The above equation can be simplified and written as:

$$AF = \sum_{n=1}^{N} e^{+j(N-1)\psi} \tag{4}$$

In order to make the pattern analysis more convenient, the above *AF* relation can be expressed in a closed form as shown below.

$$AF = \frac{1}{N}\left[\frac{\sin\left[\frac{N}{2}\psi\right]}{\frac{\psi}{2}}\right] \tag{5}$$

According to the above equation, three main parameters manipulate the AF's patterns which are as follows:

(a) *N*: Number of antenna elements

Number of element controls the beamwidth of main beam's pattern. Figure 2 shows the effect of varying *N* to the radiation pattern of array factor. It can be seen that as the number of antenna increases, the beamwidth of main beam becomes narrower while the number of side lobe increases.

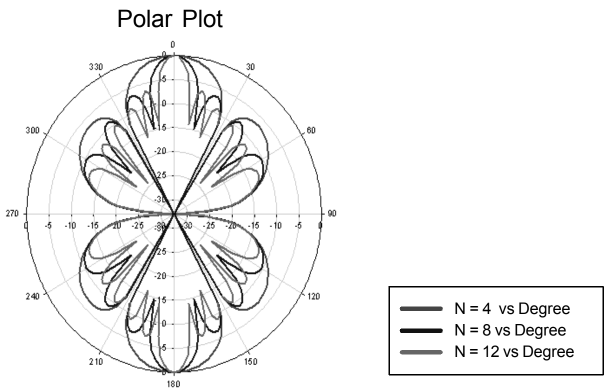


Figure 2 Plots of AF with $d = \lambda/2$, $\beta = 0$, and $N = 4$, 8 and 12

(b) *d*: distance between adjacent element

The distance between elements controls the appearance of side lobe's number. It can be seen that as the distance of the elements increases, the number of side lobes also increases while decreasing the beamwidth of main lobe.

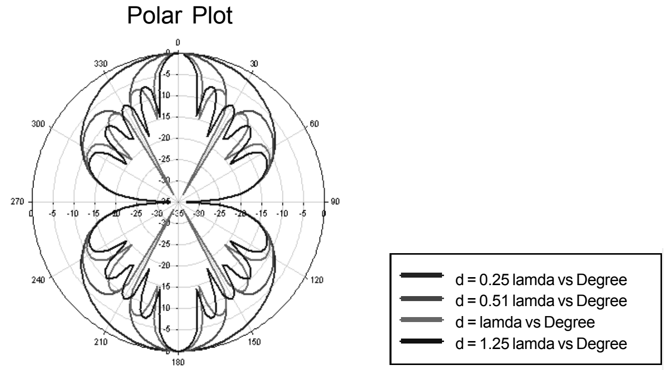
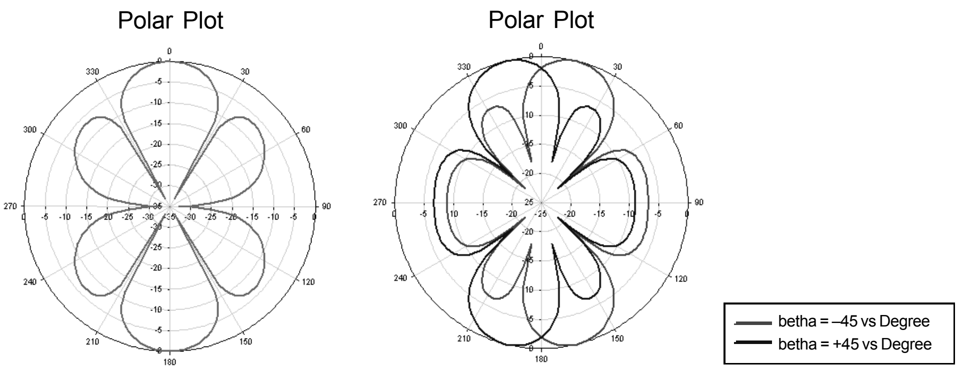


Figure 3 Plots of AF with, $N = 4$, $\beta = 0$, and $d = 0.25\lambda$, 0.5λ, λ, 1.25λ

(c) β: phase difference of excitation current between adjacent elements

Phase difference of the excitation current between the adjacent elements control the tilted angle of the main lobe. This effect can be illustrated in Figure 4. When β have some value, the main lobe can be directed from center to certain direction. It can be concluded that by varying the value of β, the main lobe can be tilted to a certain direction. This parameter is controlled by the feeding network of an antenna array which in this work is controlled by Butler Matrix.



(a) (b)

Figure 4 Plots of Array factor (AF) with, $N = 4$, $d = 0.25\lambda$, (a) $\beta = 0°$, (b) $\beta = \pm 45°$

3.0 THE NUMERICAL ANALYSIS OF BUTLER MATRIX

Butler Matrix is a $2n \times 2n$ network which has $2n$ inputs, $2n$ outputs, $2n\text{-}1 \log 2\ 2n$ hybrids and several phase shifters [6]. Typically, it has the N number of input, and N number of output to produce N number of orthogonal beam. The most famous configuration of the Butler Matrix is 4 × 4, which has 4 input and 4 output ports to generate four independent beams at four different directions. There are 8 × 8 Butler Matrix also, which has 8 input and 8 outputs ports to generate eight independent beams but this configuration is less famous as it has a bigger size compared to 4 × 4 Butler Matrix. Butler Matrix has capability to steer a beam by providing progressive phase difference between adjacent output ports, β. By knowing the value of β and N, the patterns of AF that generated by Butler Matrix can be plotted by using Equation 5. The block diagram and AF plot for conventional 4 × 4 and 8 × 8 Butler Matrix is shown in the following figure. The input ports of Butler Matrix are named according to the beam position in polar plot that correspond to each β.

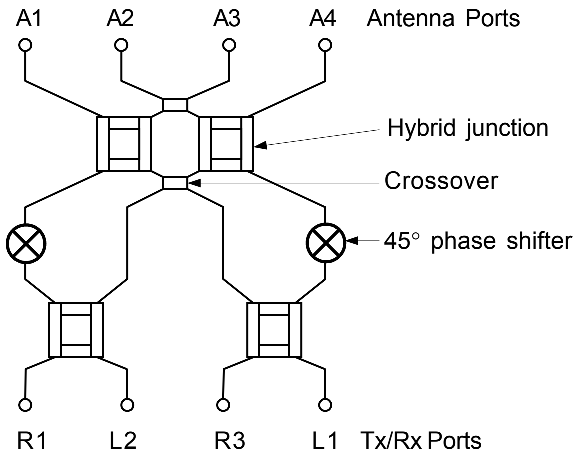


Figure 5 Block Diagram of 4 × 4 Butler Matrix [6]

Table 1 Numerical value for 4 × 4 Butler Matrix

Input Port	β	**Beam position in polar plot**	**3 dB beamwidth**
R1	–45°	+14.5°	33.4°
L2	+135°	–48.6°	44.3°
R2	–135°	+48.6°	44.3°
L1	+45°	–14.5°	33.4°

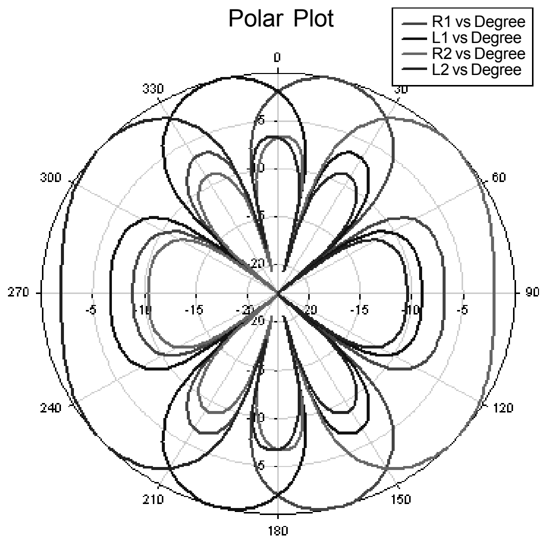


Figure 6 *AF* plot for 4 × 4 Butler Matrix ($N = 4$, $\beta = \pm 45°, \pm 135°$)

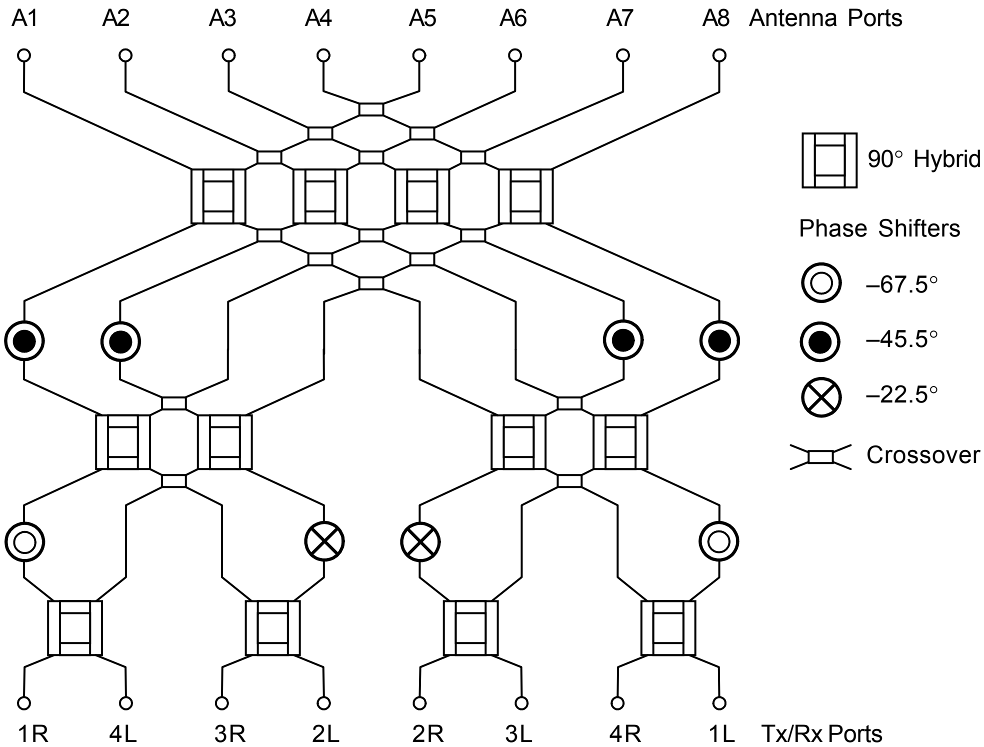


Figure 7 Block Diagram of 8 × 8 Butler Matrix [8]

Table 2 Numerical value for 8 × 8 Butler Matrix

Input Port	β	Beam position in polar plot	3 dB beamwidth
1R	–22.5°	+7.2°	20°
4L	+157.5°	–61°	42°
3R	–112.5°	+38.7°	24.8°
2L	+67.5°	–22°	21.2°
2R	–67.5°	+22°	21.2°
3L	+112.5°	–38.7°	24.8°
4R	–157.5°	+61°	42°
1L	+22.5°	–7.2°	20°

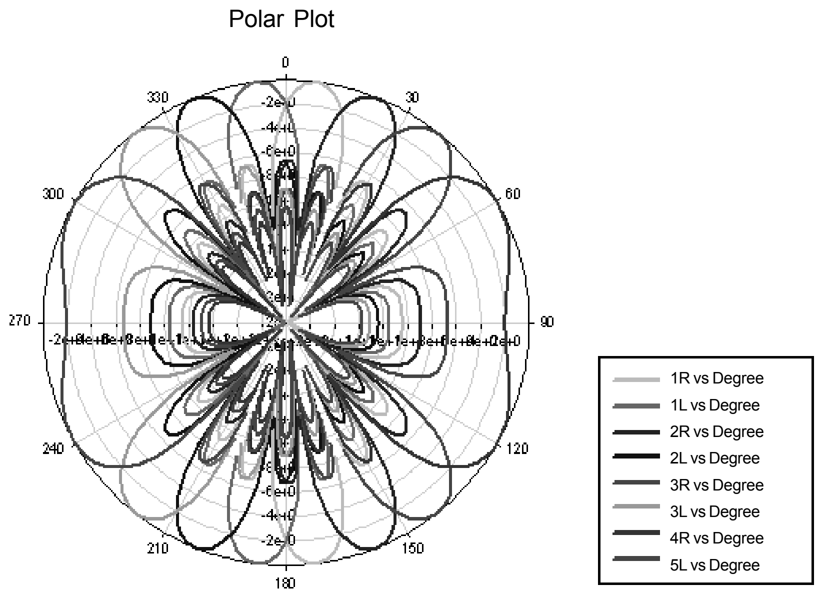


Figure 8 *AF* plot for 8 x 8 Butler Matrix (N = 8, β = ±22.5°, ±67.5°, ±112.5°, ±157.5°)

4.0 DESIGN CONSIDERATION

In this work, two major components are needed to be designed which are antenna array and Butler Matrix. The prototypes are designed at 2.4 GHz, implemented by using microstrip transmission line technique and fabricated on FR4 board with dielectric constant (εr) of 4.5, thickness (h) of 1.6 mm and dissipation factor ($tan\ \delta$) of 0.019. In this project, three different types of antenna array has been developed which are 4 × 1 square patch antenna array, 4 × (4 × 2) antenna array and 4 × 1 monopole antenna array while 4 × 4 Butler Matrix is chosen as its feeding network. All of antenna array elements are arranged in a linear form and spaced at half-wavelength apart. All

Table 3 The design equation of patch antenna

	Parameter	Design Equation	Legend
1	Patch Width (W)	$W = \frac{1}{2f\sqrt{\varepsilon_0\mu_0}}\sqrt{\frac{2}{\varepsilon_r+1}}$	ε_r = relative dielectric constant m_0 = permeability in free space f = resonant frequency W = patch width ε_{eff} = effective dielectric constant h = substrate thickness ΔL = patch length extension L = patch length L_{eff} = effective patch length
2	Effective dielectric constant (e_{eff})	$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-\frac{1}{2}}$	
3	Patch Length extension (ΔL)	$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}+0.258)\left(\frac{W}{h}+0.8\right)}$	
4	Patch Length (L)	$L = \left(\frac{1}{2f\sqrt{\varepsilon_{eff}}\sqrt{\varepsilon_0\mu_0}}\right)-2\Delta L$	
5	Effective Patch Length (L_{eff})	$L_{eff} = L+2\Delta L$	

simulations of antenna design are done using Method of Moments (MoM) in Microwave Office software. In order to design a patch resonating at desired frequency of 2.4 GHz, the equations in Table 3 are used.

4.1 Square Patch Antenna Array Design

The first type of the antenna that has been used with 4×4 Butler Matrix is square patch microstrip antenna array which has a broader beamwidth pattern for its single element. It is constructed on two layer substrates where square patch antenna are printed on the upper substrate while the feeding line are printed on the lower substrate. After the optimization process using Microwave Office software, the final optimum parameter for the single square patch antenna is obtained, where the width and length are found to be 28 mm × 28 mm. The design configuration of the antenna array is shown in Figure 5. Figure 9 shows the 2D layout of the patch antenna. A good impedance matching is obtained at the operating frequency as S_{11} values are lower than –10 dB [1][8]. Figure 10 shows the simulated radiation pattern obtained by 4×1 square patch proximity coupled antenna. The radiation pattern characteristics of Figure 10 correspond to each plane can be written as shown in Table 4. Since each port connected to antenna separately, each antenna is behaved as a single antenna, thus the radiation pattern obtained by co-polarization of E-plane has a broader beamdwidth with HPBW approximately about 106°.

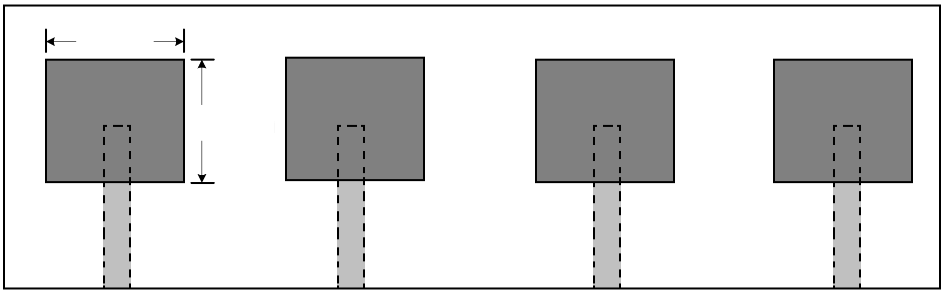


Figure 9 Square patch antenna configuration

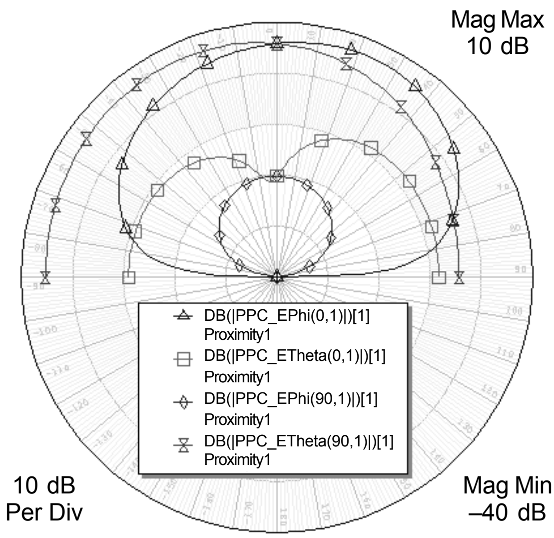


Figure 10 Simulated radiation pattern of 4 × 1 square patch antenna

Table 4 Radiation pattern of 4 × 1 square patch interpretation

Label	Type of polarization	Plane
PPC_EPhi(0,1)	Co-polarization at Æ = 0°	E-plane
PPC_ETheta(0,1)	Cross-polarization at Æ = 0°	E-plane
PPC_EPhi(90,1)	Cross-polarization at Æ = 90°	H-plane
PPC_ETheta(90,1)	Co-polarization at Æ = 90°	H-plane

4.2 Four by (4 × 2) Array Patch Antenna

The second type of the antenna that has been studied with 4 × 4 Butler Matrix is directional antenna. The directional antenna that has been used in this project is [4 × 2] microstrip patch planar antenna array. The design configuration of [4 × 2] antenna is shown in Figure 11. Each of the [4 × 2] element antenna arrays is then fabricated onto four individual identical FR4 board. Figure 12 shows the simulated radiation pattern of individual [4 × 2] antenna array. It was verified through simulation that the antenna has the capability to produce a directional beam pattern with the HPBW of approximately 24° [9][10].

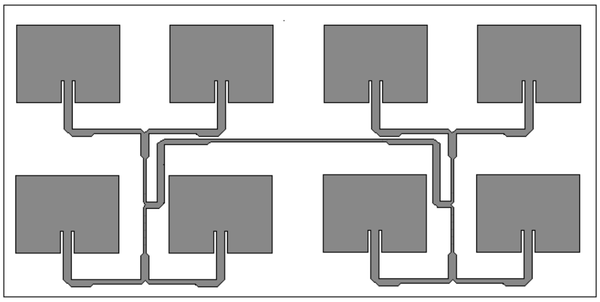


Figure 11 Fabricated single 4 × 2 rectangular array patch antennas.

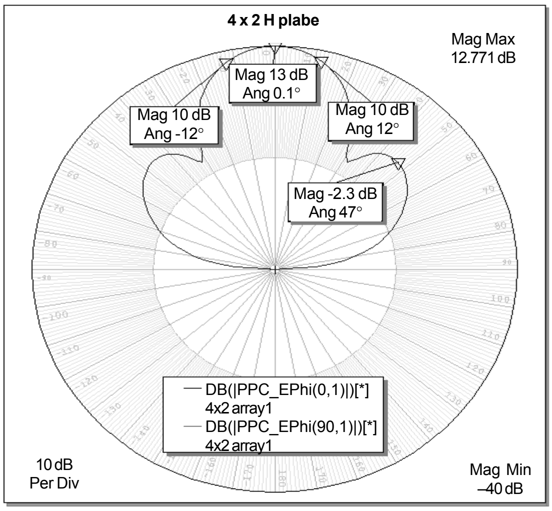


Figure 12 E-plane co-polarization radiation pattern of 4 × 2 array patch

4.3 Implementation of 4 × 1 Monopole Antenna Array

The used radiating elements in this project that has omnidirectional pattern are commercial monopole antennas manufactured by D-Link Company [11]. The antenna is designed to operate at 2.4 GHz frequency band, and is aimed for WLAN applications. As this antenna is bought from market, no simulation is done for this antenna.

4.4 Design Configuration of Butler Matrix

In this project, the designed 4 × 4 Butler Matrix consists of four 90° hybrid coupler, two 0 dB crossover, two –45° phase shifter and Two 0° phase shifter. Each component is designed at the operating frequency of 2.4 GHz and simulated using MoM Agilent ADS software. The width, (W) and length (l) of the each component is calculated using the microstrip transmission line theory which can be computed by using the following equation. Equation 6 and 7 gives the width of transmission line while equation 8 and 9 gives the length of transmission lines. The length of the transmission line depends on the phase shifter of the line (e.g. 45° or 0°)

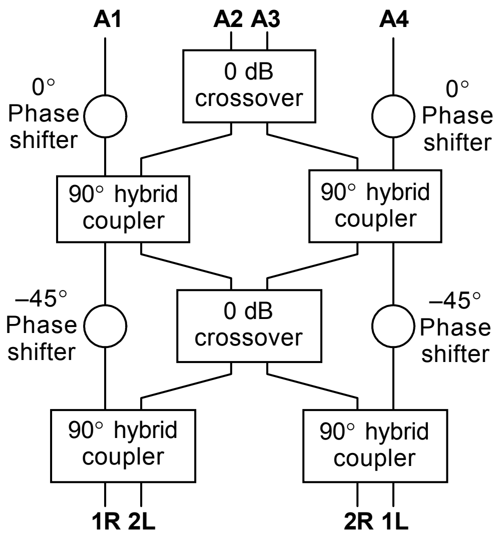
$$W = \left(\frac{e^H}{8} - \frac{1}{4e^H} \right)^{-1} .h \tag{6}$$

$$H = \left(\frac{Z_0 \sqrt{2(\varepsilon_r + 1)}}{119.9} \right) + \frac{1}{2}\left(\frac{\varepsilon_r - 1}{\varepsilon_r + 1} \right)\left(\ln\left(\frac{\pi}{2}\right) + \ln\left(\frac{4}{\pi}\right) \right) \tag{7}$$

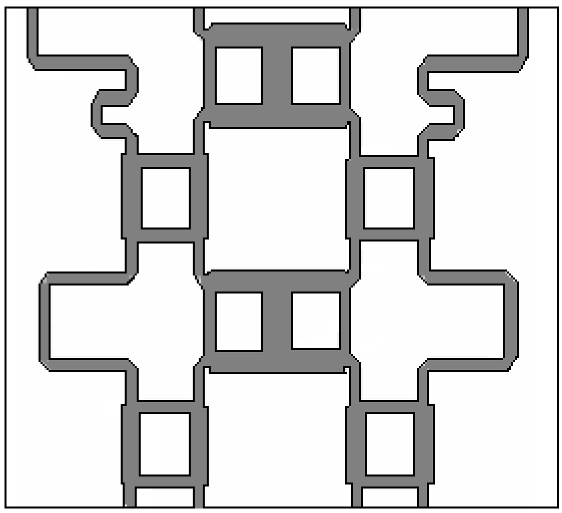
$$\lambda_g = \frac{c}{f\sqrt{\varepsilon_{ff}}} \tag{8}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2}\left(1 - \frac{1}{2H}\left(\frac{\varepsilon_r - 1}{\varepsilon_r + 1} \right)\left(\ln\left(\frac{\pi}{2}\right) + \frac{1}{\varepsilon_r}\ln\left(\frac{4}{\pi}\right) \right) \right)^{-2} \tag{9}$$

The designed 4 × 4 Butler Matrix has four inputs 1R, 2L, 2R and 1L, and four outputs A1, A2, A3 and A4. The input ports of the Butler Matrix are named according to the beam position which will be generated by activating one of the input ports of the Butler Matrix. The four outputs are used as inputs to antenna elements to produce four beams. Figure 13 shows the block structure and layout of Butler Matrix. The details about the design of each component in Butler Matrix could be found in [1].



(a)



(b)

Figure 13 Butler Matrix Configuration (a) Block Structure, (b) Layout

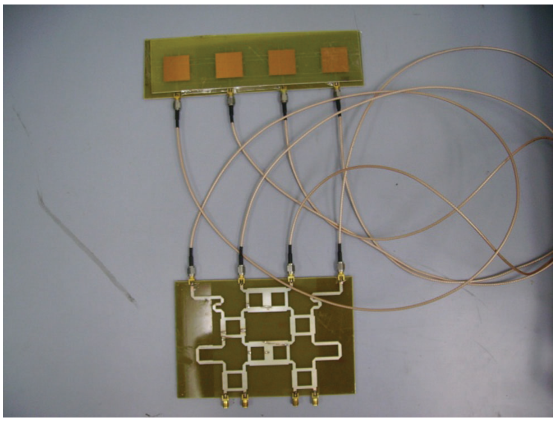
The conventional Butler Matrix can provide four different values of β which are –45°, +135°, –135°, +45°. It was designed in such a way so that when current excited to any input ports, the phase different between adjacent output ports will only has one constant β as shown in Table 5. By having β = –45°, +135°, –135°, +45° from each input port, the multiple orthogonal beams on radiation patterns could be generated.

Table 5 Design Target of the Butler Matrix

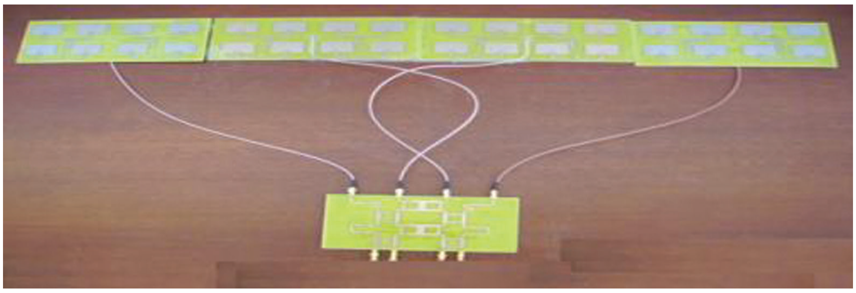
Port	β
1R	–45º
2L	+135º
2R	–135º
1L	+45º**4.5**

4.5 IMPLEMENTATION OF BUTLER MATRIX AND ANTENNA

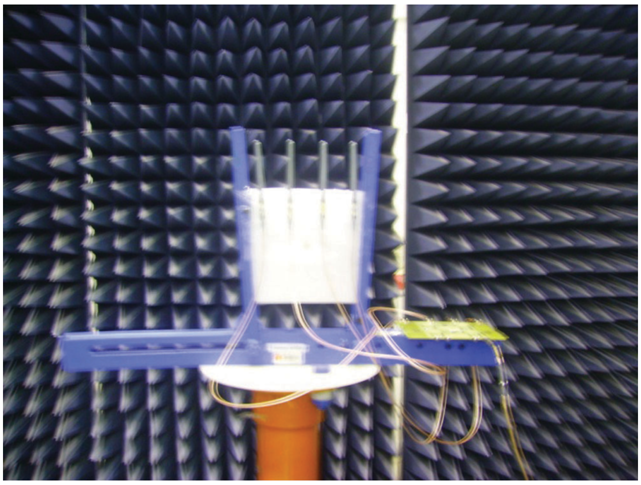
The ports of the antenna array are connected to the output ports of the Butler Matrix by using four equal length coaxial cables. The photographs of the integrated project are shown in Figure 14.



(a) Butler Matrix with single patch antenna



(b) Butler Matrix with array of antenna



(c) Butler matrix with monopole antenna

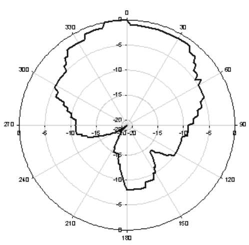
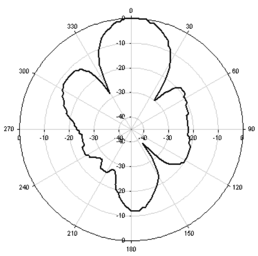
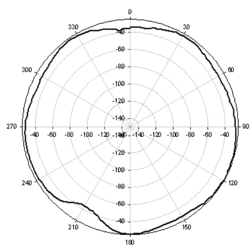
Figure 14 The implementation of the project

5.0 MEASUREMENT RESULT OF RADIATION PATTERN

The radiation characteristics of the beams are measured using far-field method in the anechoic chamber. At first, the radiation pattern of the single antenna is measured. The obtained radiation pattern of the single antenna can be used later to calculate the predicted radiation pattern of the integrated project by using Equation 1. The measured radiation pattern of single and array antenna is shown in Table 6.

By referring to Table 6, it can be seen that the radiation pattern of square patch antenna has a broader HPBW approximately about 89° while 4×2 antenna array

Table 6 Measured radiation pattern of single and array antenna

Antenna Type	Square patch antenna	4×2 Antenna Array	Dipole Antenna
Measured Radiation Pattern			
Radiation Pattern Type	Broader beamwidth pattern	Directional pattern	Omnidirectional pattern
HPBW	89°	27°	All directions

provide a directional pattern with HPBW approximately about 27°. On the other hand, dipole antenna shows an omnidirectional pattern which receives power almost equal to all direction. The measured radiation patterns of single element results show that three different types of antenna were used when integrating antenna array with 4 × 4 Butler Matrix.

For the measurement of the integrated project, all input ports are fed with the same signal but only one port is activated at instant while the other ports are terminated with 50Ω. Table 7 illustrates the measured radiation patterns of port 1R, 2L, 2R and 1L of each type of antenna array.

Four by one square patch antenna array has four different beams at four different directions (+14.5°, –40.6°, +43.0°, –14.0°) have been generated when exciting signal at one port at instant. The beamwidth size of beam 2L and 2R is narrower compared to beam 1R and 1L. However, if the beamwidth size is not taken at exactly –3 dB, by observation, all beams have a beamwidth size approximately about 30°.

For the case of using four by (4 × 2) antenna array, four different beams at four different directions were also generated but the tilted angle of each beams only a few degrees different between adjacent beams (+4.4°, –10.0°, +11.8°, –2.7°). The beamwidth size of each beams also very narrow which approximately about 6° – 7°. Besides, a few side lobes with a higher amplitude level also exist particularly at beam 2L and 2R.

By replacing with monopole antennas, it can be observed that when port 1R is excited, two main beams appeared and directed to the upper, +18° and bottom part, +157° of the polar plot. Similar thing happen to port 1L where two main beams also appeared at upper part, –16°, and bottom part, –155° of the polar plot. The beamwidth size of the main beams is narrower while for port 2L and 2R, the beamwidth size of the main lobe is broader.

Table 8 shows the overlapping radiation pattern of the Port 1R, 2L, 2R and 1L on the same plot for each type of antenna. It can be shown that, in the case of square patch antenna, the system capable to cover up to 120°, in the case of (4 × 2) antenna array, it covers up to 30°, while in the case of monopole antenna, it covers up to 360° of coverage area. It can be concluded that, by applying different types of antenna array to the 4 × 4 Butler Matrix, the obtained radiation patterns has different characteristics mainly in terms of beamwidth and coverage area.

6.0 RESULT ANALYSIS

The radiation pattern of the integrated project can be predicted using pattern multiplication theorem as given in Equation 1. The data of a single array unit pattern is obtained from the measured result of single antenna (Table 6) while the data of the array factors are obtained from the computed results of Equation 5 (Figure 6). Table 9 illustrates the comparison between the calculated and measured radiation patterns of each integrated project.

Table 7 Measured radiation patterns for each configuration

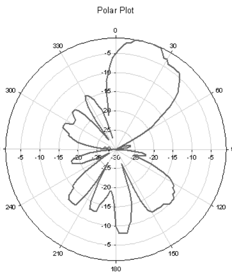
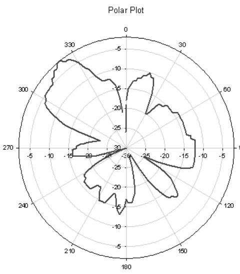
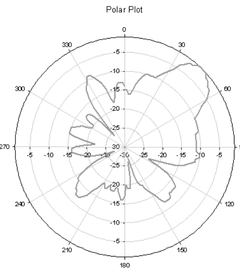
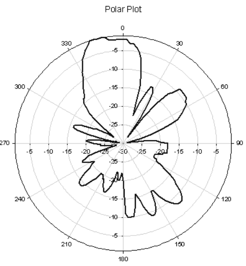
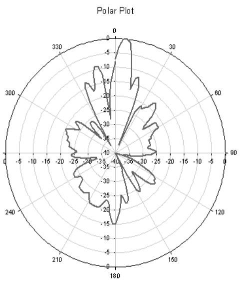
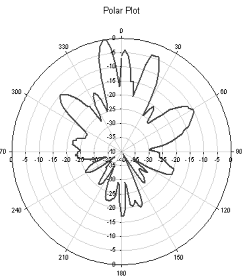
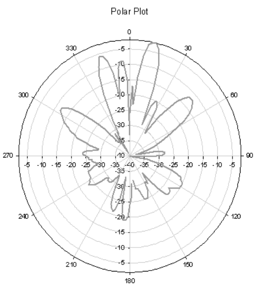
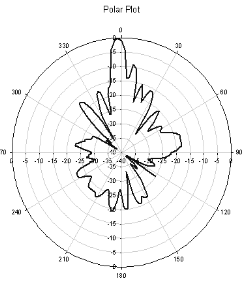
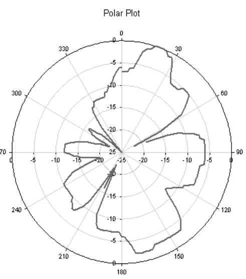
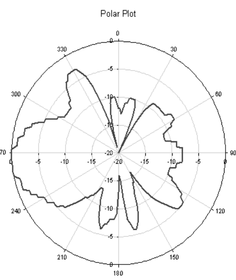
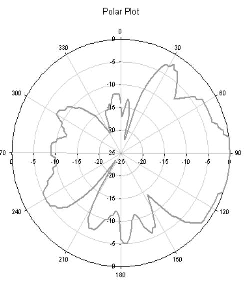
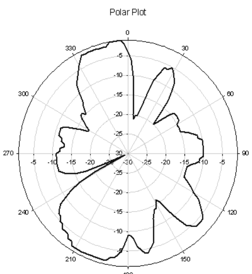
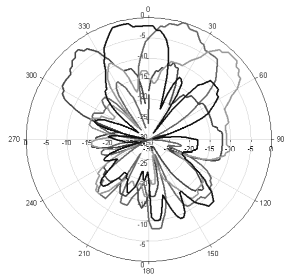
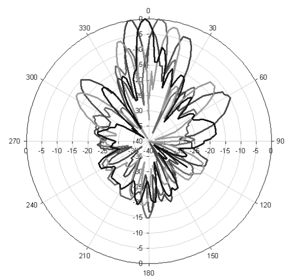
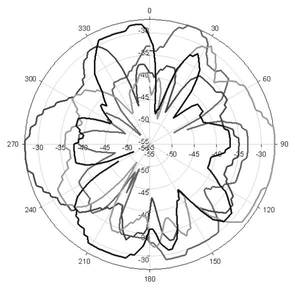
1R	2L	2R	1L
4 × 4 Butler Matrix with 4 × 1 Square Patch Antenna Array			
			
Beam angle: +14.5° HPBW : 32.5° Max SLL (dB) : –8.0	Beam angle: –40.6° HPBW : 10.3° Max SLL (dB) : –10.0	Beam angle: +43.0° HPBW : 18.0° Max SLL (dB) : –9.0	Beam angle:-14.0° HPBW : 31.6° Max SLL (dB) : –7.9
4 × 4 Butler Matrix with 4 x (4 x 2) Antenna Array			
			
Beam angle: +4.4° HPBW : 6.2° Max SLL (dB) : –9.1	Beam angle: –10.0° HPBW : 6.6° Max SLL (dB) : –3.7	Beam angle: +11.8° HPBW : 5.1° Max SLL (dB) : –5.6	Beam angle: –2.7° HPBW : 6.8° Max SLL (dB) : –9
4 × 4 Butler Matrix with 4 x 1 Dipole Antenna Array			
			
Beam angle: +18.0°, +157° HPBW : 20.0°, 40.0° Max SLL (dB) : –6.0	Beam angle: –90° HPBW : 29.4° Max SLL (dB) : –3.0	Beam angle: +90° HPBW : 67.5° Max SLL (dB) : –5.0	Beam angle: –16°, –155° HPBW : 26.0°, 40.0° Max SLL (dB) : –4.3

Table 8 Overlapped radiation patterns of each configuration

4 × 1 Square Patch Antenna Array	4 × (4 × 2) Antenna Array	4 × 1 Dipole Antenna Array	Legend
			
Total coverage angle: ~120° HPBW of each beam: ~30°	Total coverage angle: ~30° HPBW of each beam: ~7°	Total coverage angle: ~360° HPBW of each beam: 2R & 2L : ~90° 1R & 1L : ~30°	

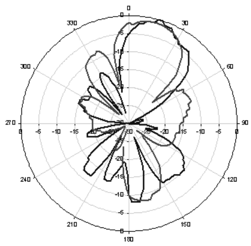
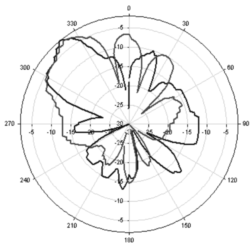
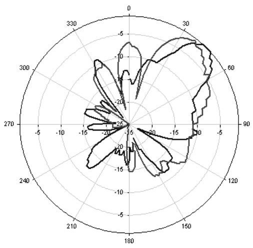
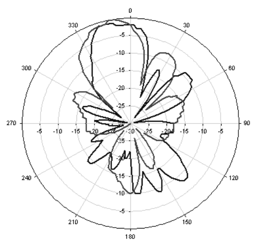
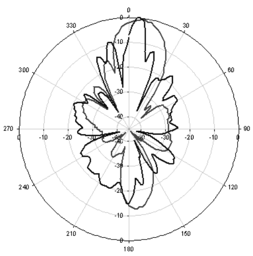
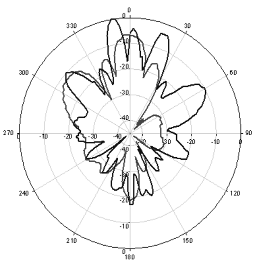
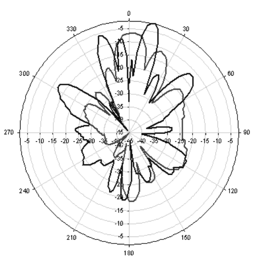
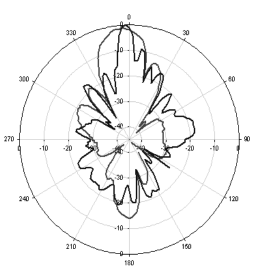
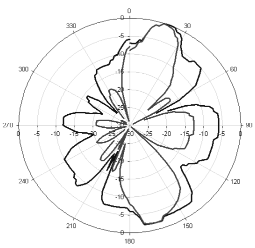
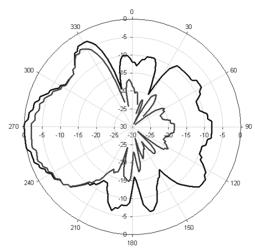
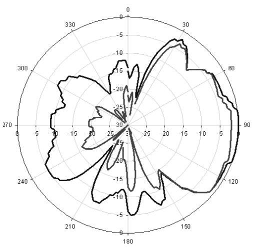
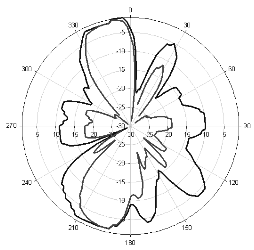
For square patch antenna, it can be observed that the measured radiation pattern has a similar pattern to the computed pattern. This is verified that the experiment is reliable as it has a good agreement with the theoretical calculation.

For the case of 4 × 2 antenna array, it can be observed that the calculated patterns have a bigger beamwidth compared to measured result. The direction of beams of 1R and 1L are similar to the calculated patterns which are directed to 5º and –2° respectively. The main beam of port 2R and 2L are directed to 13° and –9° respectively, which are a little bit different from the computed patterns. Computed patterns show that the main beam appears at the centre of the polar plot with lower magnitude as the beam position of the array factor, 2R and 2L are directed to 48.6° and –48.6°. The measured result shows a narrower beamwidth and more side lobes. This may be due to non-uniform surface of the antenna holder which is then caused the distance between [4 × 2] antenna array is higher than $\lambda/2$. As described in Section 2, side lobes will be appeared when distances between elements increases.

For the case of monopole antenna, it can be observed that the measured radiation has a similar pattern to the computed pattern. The little differences may be due to the misalignment of the rotator inside the chamber. As a conclusion, the entire measured result shows a good agreement with the theoretical calculation.

The calculated radiation pattern is not smooth enough because the value taken into consideration of the array factor is the same value from the experimental result of the single element antenna used for the beam forming network.

Table 9 Comparison between computed and measured radiation patterns for each configuration

1R	2L	2R	1L
4 × 4 Butler Matrix with 4 × 1 Square Patch Antenna Array			
			
4 × 4 Butler Matrix with 4 × [4 × 2] Antenna Array			
			
4 × 4 Butler Matrix with 4 × 1 Dipole Antenna Array			
			
Legend ——— Computed Radiation Pattern ——— Measured Radiation Pattern			

7.0 CONCLUSION

Three different radiation patterns constructed by integrating three different antenna arrays with 4 × 4 Butler Matrix have been presented. Three types of antenna array that have been used in this project are square patch antenna, [4 × 2] planar antenna array and monopole antenna. They have been proved that through measurement each of them produces different radiation patterns which are broader beamwidth for square patch antenna, directional beam for [4 × 2] antenna array and omnidirectional pattern for monopole antenna. With the existence of Butler Matrix, it has been proved that four different independent beams with four different directions have been generated. The obtained result shows that square patch antenna array has HPBW about 30° for each beams and manage to cover 120° of coverage area, [4 × 2] antenna array has HPBW about 7° and cover 30° while dipole antenna produce two kind of beams, broader and narrower beams. Furthermore, the radiation characteristics are compared between the theoretical and measured result, and they correlate well.

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