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2.4 GHz DOA Finder using Modified Butler Matrix for 2×2 Array Antennas

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***Abstract*- Technique to find Direction Of Arrival (DOA) has been promisingly constructed by smart antenna technology. It consists of array antennas and signal processing unit. Because of the limitation of space in commercial products, the size of antenna array should be designed with the smallest dimension. Also the processing unit is expected for low complexity and expense. Most of DOA finders were recently proposed employing linear array in which the size is linearly increased by a number of antenna elements. Also the processing units were fully comprised with high level of computation. In this paper, the low profile of 2.4 GHz DOA finder is proposed. The DOA finder is designed in the compact size of 2×2 array antennas. Using modified Butler matrix, the processing unit is very simple in which it can be handled by any economic microprocessors. The experimental results confirm the success of proposed DOA finder.**

Keywords:-DOA; Butler matrix; Smart Antenna; Switched Beam; Planar Array

I. INTRODUCTION

So far, the possibilities and opportunities for location-based services have attracted lots of attention from companies and researchers. One of the key issues is the positioning technology. For outdoor usage, the Global Positioning System (GPS) has been popularly accepted as the main positioning technology. The evidence can be seen through a number of GPS users increasing every year. However, the GPS cannot be used for indoor purpose. Therefore, the new technology for indoor positioning is still required. Nowadays, Wireless Local Area Network (WLAN) is becoming a network infrastructure for every building. It is based on the IEEE 802.11b standard, also known as Wi-Fi, using radio frequencies in the 2.4GHz band [1]. Recently, many techniques based on WLAN signals have been proposed for indoor positioning. Most of them utilize a signal propagation model and the information regarding the geometry of the building to convert signal strength to a distance measurement [2, 3]. At least, the information from three access points is required to form the triangle locating. However, this method cannot provide the exact distance from measured signal strength because of signal attenuation due to the penetration losses through walls and floors. As a result, the new efficient technique is still required for indoor positioning. In recent years, the concept of utilizing directions instead of distances has gain a lot of attention in positioning technology. For this concept, the user can be located by identifying the Direction Of Arrival (DOA) from three access points instead of using signal strength.

For DOA finding techniques, it has been well-known that the smart antenna technology is able to provide the most promising outcome. Recently, DOA finders are available in the commercial market [4] but they operate at low frequency under 1 MHz and employ mechanical-steering antennas. The higher frequency operation and automate indication are expected for WLAN positioning system. In [5], the electronically tunable devices to analog directive antennas were proposed. Using varactor-loaded passive radiators, the total 12 directions are detected by 7 antenna elements. This finder has resolution of 30° with precision of 15 and needs a large space for 7 antenna elements which is not commercially attractive. In [6], the electronically steerable parasitic array radiator was proposed using reactance domain MUSIC algorithm. This finder employs the same antenna configuration as presented in [5] but it provides higher resolution and precision. As the requirement of large sampling data resulting in complex computation, using MUSIC algorithm is considered to be impractical. The improved algorithms for this concept were proposed in [7-8]. However, the practical realization has not been implemented to confirm the performances proposed in [6-8]. In [9-11], the measured results of DOA finder were presented. The neural network algorithm was proposed in [9-10] to improve MUSIC algorithm. However, it needs the training set of data before beginning the process, which is not applicable for positioning purpose. Recently, DOA finders proposed in literatures require a large number of antenna elements and their processing units were fully comprised with high level of computation. For example, the works presented in [11-12] have indicated that the more antenna element is employed the higher capability in DOA estimating is achieved. This is not commercially practical because of the limitation of space.

In this paper, the low profile of 2.4 GHz DOA finder is proposed. The DOA finder is designed for compact size employing 2×2 array antennas. Using modified Butler matrix, the DOA finder can simultaneously form 4 uniform beams. Using the measured signal strength of all 4 beams, then the finder is able to delicately specify DOA in every angle from 0° to 360°. The precision of proposed DOA finder is approximately +5°. With the criteria of 4 radiation patterns, the programming is easy to gain the estimated DOA from measured signal strength. The processing unit is very simple as it can be handled by any economic microprocessor.

The remainder of this paper is organized as follows. In Section II, the configuration of 2×2 planar array is

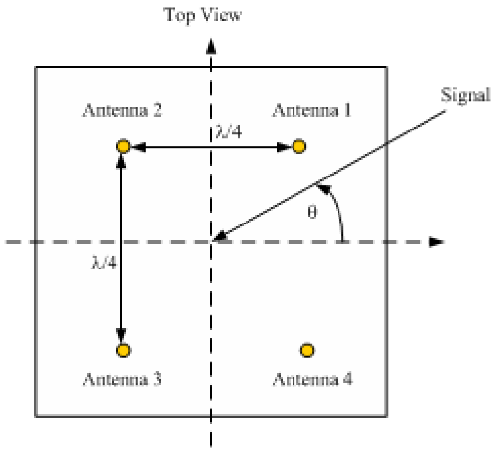

Figure 1. Configuration of 2×2 planar array.

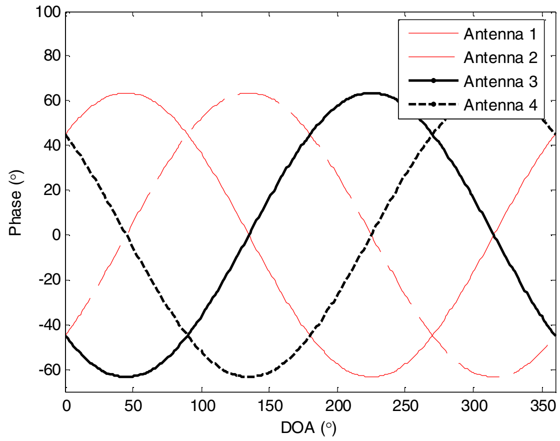

Figure 2. Relative phase of each antenna elements vs. DOA.

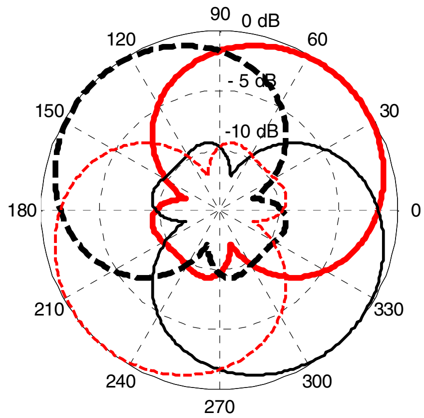

Figure 3. Simulated radiation patterns of 2×2 array for 4 beams: 45°, 135°, 225° and 315°.

presented. In order to simultaneously form 4 uniform beams using planar array, the beamforming network employing modified Butler matrix is originally designed, which is explained in Section III. Section IV provides the detail of processing unit for DOA detection. The experimental results are given in Section V and finally Section VI concludes the paper.

II. 2×2 PLANAR ARRAY

The choice of 2×2 planar array for DOA finder is made by the reason of limited space. With the same number of antenna elements, size of 2×2 planar array is smaller compare with linear array antenna. The configuration of 2×2 planar array is shown in Fig. 1. As seen in this figure, the received signal at ith antenna element is expressed by

$$x_i = Ae^{\left(-j\beta\frac{\sqrt{2}\lambda}{8}(\cos(90i-45-\theta))\right)} \quad (1)$$

where A is the amplitude of received signals at individual antenna elements, β is the phase constant and θ is the DOA of signal in degree. Fig. 2 shows the relative phase of signal at each receiving antennas versus DOA of source. Note that the variation of relative phase in Fig. 2 is the key design for the modified Butler matrix which is detailed in next section.

Next, the radiation pattern of 2×2 planar array is investigated. In order to cover all directions, the radiation patterns are selected to be uniformly distributed. In this case, the separation between each beam is fixed at 90°, for example a set of 0°, 90°, 180° and 270° or a set of 45°, 135°, 225° and 315°. In Fig. 3, the radiation patterns of a set of 45°, 135°, 225° and 315° are presented. It can be seen that each beam is identical and there is only one main beam for each pattern. This is superior to linear array because the radiation of linear array has two main beams pointing two opposite directions in the range from 0° to 360°. In literatures, most of the works dealing with the success in DOA finding were limited to the range of 0° to 180° only. In other words, their finders notify the source of signal from two possible directions, which is not practical. In summary, the use of 2x2 planar array is more advantageous than 4-element linear array in term of size as well as DOA finding capability.

III. MODIFIED BUTLER MATRIX

The Butler matrix is considered to a typical beamforming network for switched beam antenna as its simplicity. The conventional Butler matrix is consisted of 90° hybrid, cross over and 45° phase shifter. The circuit is designed for 4 inputs and 4 outputs. The input is connected to 4 antenna elements. Each output port represents the summation of all 4 inputs multiplying with weighting coefficients which is correspondent one specific direction. Hence, the outcome of Butler matrix provides 4 simultaneous responses to 4 DOAs. However, the conventional Butler matrix is strictly designed for linear array. Therefore, the new design for 2×2 planar array is required.

In this paper, the modification of Butler matrix is originally proposed in order to produce 4 beam responses for 2×2 planar array. Fig. 4 shows the configuration of modified Butler matrix. As seen in this figure, two components are required, which are $x°$ hybrid and crossover. The deletion of 45° phase shifter is due to the

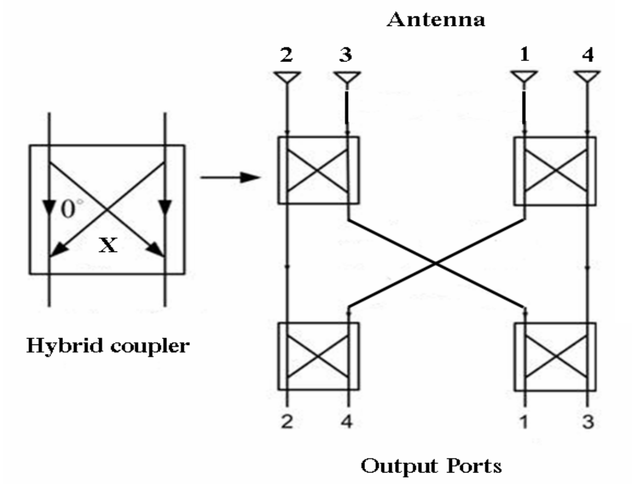

Figure 4. Configuration of modified Butler matrix

TABLE I
PHASE RESPONSES BETWEEN INPUT AND OUTPUT PORTS SHOWN IN FIG. 4

Port No.	Antenna Element			
	2	3	1	4
2	0°	x°	x°	2x°
4	x°	2x°	0°	x°
1	x°	0°	2x°	x°
3	2x°	x°	x°	0°

ease of design. In order to find x° hybrid, the phase shifts of all responses of modified Butler matrix have to be examined.

Table I presents the phase shift between input and output ports according to the configuration shown in Fig. 4. It is clearly seen that each output port has the same components of phase shift which are 0°, x°, x° and 2x°. Then the next attempt is to match the sequence of phase shift with the phase response of each antenna element shown in Fig. 2. With a quick search, the phase sequences in Table I can be matched with the phase responses in Fig. 2. The output port number 1, 2, 3 and 4 are correspondent with DOA signals from 45°, 315°, 225° and 135°, respectively. Also found in Fig. 2, the x° hybrid has to be 64° hybrid otherwise the set of DOA signals become non-constructive.

Using the Microwave Office program package, the size and dimension of 64° hybrid is obtained which is shown in Fig. 5. For crossover, the same design presented in [13] is utilized. Fig. 6 shows the modified Butler matrix consisting of one crossover and four 64° hybrids.

IV. DOA FINDER

The configuration of proposed DOA finder in this paper is shown in Fig. 7. Four element antennas are connected to inputs of modified Butler matrix and then the outputs

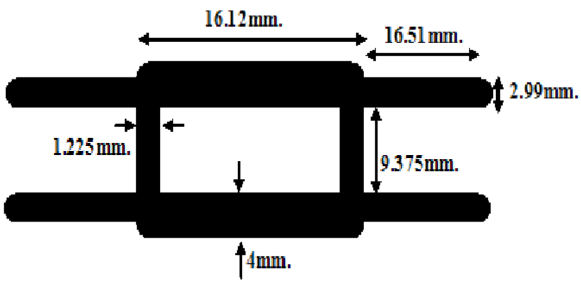

Figure 5. Design of 64° hybrid.

Figure 6. Modified Butler matrix

are passed to the signal strength detector. Note that the 2.4 GHz monopole having gain of 5 *dBi* is employed to be an antenna element. The powerful IC of Linear Technology, LT5570, convert the power of 2.4 GHz into the certain voltage level. Then the task to analyze DOA finding is on the intelligence of processing unit. As mentioned earlier, any economic microprocessors can handle this task. In this paper, the AVR STAMP ATmega128 has been chosen as it is low of cost. Also this microprocessor still has the ability to read the voltage level by performing analog to digital conversion. Hence, it is easy for processing unit to realize the different level of signal power from 4 output ports via this simple configuration. Fig. 8 shows the photograph of complete set of proposed DOA finder.

The radiation patterns of each output port from modified Butler matrix have been measured as shown in Fig. 9. Comparing between Fig. 3 and Fig. 9, the response from our DOA finder provides the similar radiation patterns as expected from theory. Each radiation pattern has only one main beam and each beam covers a 90° sector. Using the measured data, the DOA finding can be programmed into the microprocessor which is detailed as follows.

From the radiation patterns in Fig. 3 and Fig. 9, it is able to conclude that both neighbor beams are nearly identical. Therefore, one can find the criteria of estimating DOA by separating the considered regions. To be specific, the power differences between two output ports having neighbor main beams are determined as shown in Fig. 10. These powers are calculated from measured data. As seen in this figure, the proposed DOA finder uses eight paths,

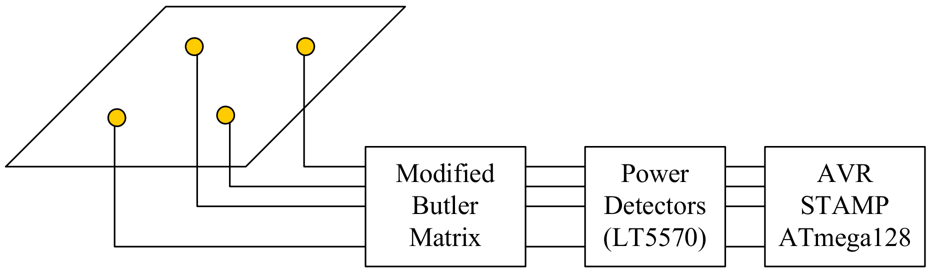

Figure 7. Configuration of proposed DOA finder

Figure 8. Complete set of DOA finder

f_1 to f_8, to be the criteria for estimating DOA. For example, in the region of 45° main beam, the path of f_1 and f_2 are selected to find the formula in estimating DOA which is valid for 0° to 90°. After concerning all 4 regions, the estimated DOA are calculated by the given formulas shown in (2), where P_i is the signal power at i^{th} port and $P_{ij} = P_i$-P_j.

After programming (2) into the microprocessor, the DOA finder is now ready for testing. The experiments are carried out by rotating the source of 2.4 GHz around DOA finder from 0° to 360°. The output of DOA finder is the direction estimated using (2) and it is passed to computer for recording via RS-232 connection. The experiments are undertaken for five times and the results are presented in Fig. 11. In this figure, it can be seen that the proposed DOA finder can find the direction over 360°. The mean error of DOA finding is 4.65° with standard deviation of 3.21°. It means that the precision of our DOA finder is approximately ±5°.

V. Conclusion

This paper has presented the low profile of 2.4 GHz DOA finder. The finder is constituted by 2×2 planar array, beamforming network, power detector and economic

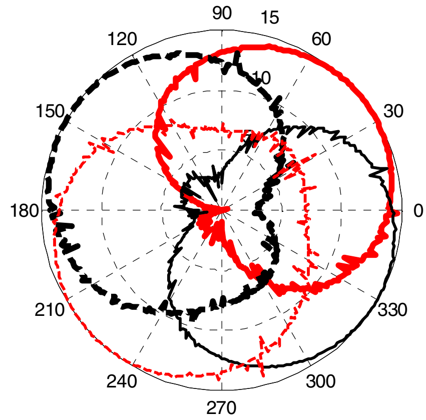

Figure 9. Measured radiation patterns of 45°, 135°, 225° and 315°

microprocessor. In order to be compatible with planar array, the beamforming network is modified from Butler matrix. The experimental results have confirmed the direction finding capability of the prototype. This DOA finder has been found very attractive for commercial in WLAN positioning system or other system providing location-based services. This is because it is low of cost and complexity.

Acknowledgment

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