Performance Evaluation of Automatic Switched-Beam Antennas for Indoor WLAN Systems

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Abstract: - In this paper, the design of a compact low cost switched-beam antenna for users in Wireless Local Area Networks (WLAN) is introduced. Four antenna elements are arranged in 2×2 lattice. The modification of beamforming network based on Butler matrix is originally proposed for 2×2 planar array. The design is verified through computer simulations and also the prototype of automatic switched-beam antenna is constructed to confirm its performance. Moreover, the validation of performance enhancement is investigated through the signal strength measurements at the users operating in existing WLAN infrastructure. The results confirm the advantage of switched-beam antenna employing modified Butler matrix by improving signal strength with average power of 4.37 dB over the use of omni-directional antenna.

Key-words: - Antenna arrays, Beamforming, Butler matrix, Measurement, Signal strength, WLAN

1 Introduction

NOWADAYS, Wireless Local Area Networks (WLANs) has been popularly installed as one of the basic infrastructure for indoor networking [1]. This WLAN system is usually designed to offer high data-rate transmission in indoor environment and slowly moving mobile terminals. The key factor to indicate the quality of air interface is the received signal strength which is sensitively influenced when situated in indoor environment. From literatures, there are many techniques to enhance the signal strength in wireless communication systems. Among those techniques, smart antennas promise an increase in performance of wireless communication systems without the need of additional radio spectrum or transmitted power [2-3]. The smart antennas have been an upsurge of interest since 1980. They constitute with a set of antenna array in various forms and signal processing unit containing spatial/temporal signal processing algorithms to improve wireless communication systems [4]. The improvement can be seen through the following benefits:

-An increase in the rate of expansion, resulting in energy-saving, prolonged lifetime of batteries, more comprehensive coverage, and higher speed in data communications

-An improvement of the system performance stability – signals reflected from other directions expose the system of greater opportunity to receive the signal

-A Reduction of signals interfered from other systems, especially, communication systems in unauthorized band without signal interference control

-A Reduction of interfered signals across other systems

Therefore, the smart antennas have been increasingly popular to improve signal quality for wireless communication systems. Especially for WLANs, improvement of signal strength can be easily obtained using smart antennas with low-cost switched-beam antennas. The simplified type of smart antennas offering the mentioned advantages without any additional costs and complications is switched-beam antennas [5-6]. For these antenna systems, a number of predefined beam patterns forming its main beam to different directions are produced. A suitable beam having the maximum signal strength is selected. So far, many researchers have introduced the switched-beam antennas to WLAN system in order to increase the signal strength, hence the system quality can be enhanced. However, there was no evidence so far in literatures to illustrate the true advantages of using switched-beam antennas under real circumstances. Even though the work presented in [7] has indicated the advantage of applying smart antenna system to WLAN through the measured throughputs but those results were obtained under close environment in laboratory. The impairments caused by multipath and shadowing are questionable in real circumstances. Therefore, a contribution of this paper is to provide the real insight of WLAN enhancement by a full prototype of switched-beam antennas. The beam switching is accomplished automatically using an economic micro-controller. The obtained experimental results reflect the real advantages and brighten the road for commercial products.

The remainders of this paper are as follows. After brief introduction, a brief concept of smart antenna technology is described in Section 2. In Section 3, the utilized array sensors are discussed. The design of beamforming network utilized in the prototype is detailed in Section 4. Section 5 shows the full prototype of the proposed switched-beam systems. Afterwards, the prototype is constructed and tested to confirm its performance. Section 6 shows the experimental results. Finally, Section 7 concludes the paper.

2 Smart Antenna Technology

Smart antenna technology is an antenna technology with capacity of beamforming in which its main lobe is directed to one specific direction while turning nulls or sidelobes to directions of interference signals. This phenomenon gives rise to the wireless communication systems performance in term of signal quality. In general, smart antennas can adjust the beam to direction of interest while reducing the effect of interference signals from other directions such as co-channel interference. In addition, they can reduce the time delay of signal caused by environment that signals arrive at receiving side over than one path, so called multipath signal. This is because the signals reflected from objects such as wall, door, glass, etc, although the same source of signals, reach the destination at different time. This impairment can be eased using smart antennas. Adoption of smart antennas in future-generation wireless communication systems would require the smart antenna feature to be an inherent part of the system design in order to provide the expected beneficial impact on efficient use of the spectrum, minimization of the cost of establishing new wireless networks, enhancement of the quality of service, and realization of reconfigurable, robust, and transparent operation across multitechnology wireless network. To this end current research effect in the area is focusing on the following critical issues:

- The design and development of advanced smart antenna processing algorithms that allow adaptation to varying propagation and network conditions and robustness against network impairments

- The design and development of innovative smart antenna strategies for optimization of performance at the system level and transparent operation across different wireless systems and platforms

- Realistic performance evaluation of the proposed algorithms and strategies, based on the formulation of accurate channel and interference models, and the introduction of suitable performance matrices and simulation methodologies

- Analysis of the implementation, complexity, and cost efficiency issues involved in realization of the proposed smart antenna techniques for future-generation wireless systems

Smart antenna systems can improve link quality by combating the effects of multipath propagation or constructively exploiting the different paths, and increase capacity by mitigating interference and allowing transmission of different data streams from different antennas. More specifically, the benefits of smart antennas can be summarized as follows:

- Increased range/coverage: The array or beamforming gain is the average increase in signal power at the receiver due to a coherent combination of the signals received at all antenna elements. It is proportional to the number of receive antennas and also allows for lower battery life.

- Lower power requirements and/or cost reduction: Optimizing transmission toward the wanted user (transmit beamforming gain) achieves lower power consumption and amplifier costs.

- Improved link quality/reliability: Diversity gain is obtained by receiving independent replicas of the signal through independently fading signal components. Based on the fact that it is highly probable that at least one or more of these signal components will not be in a deep fade, the availability of multiple independent dimensions reduces the effective fluctuations of the signal. Forms of diversity include temporal, frequency, code, and spatial diversity obtained when sampling the spatial domain with smart antennas. The maximum spatial diversity order of a non-frequency-selective fading MIMO channel is equal to the product of the number of receive and transmit antennas. Transmit diversity with multiple transmit antennas can be exploited via special modulation and coding schemes, whereas receive diversity relies on the combination of independently fading signal dimensions.

- Increased spectral efficiency: Precise control of the transmitted and received power and exploitation of the knowledge of training sequence and/or other properties of the received signal (e.g., constant envelope, finite alphabet, cyclostationarity) allows for interference reduction/ mitigation and increased numbers of users sharing the same available resources (e.g., time, frequency, codes) and/or reuse of these resources by users served by the same base station/access point. The latter introduces a new multiple access scheme that exploits the space domain, space-division multiple access (SDMA). Moreover, increased data rates — and therefore increased spectral efficiency — can be achieved by exploiting the spatial multiplexing gain, that is, the possibility to simultaneously transmit multiple data streams, exploiting the multiple independent dimensions, the so called spatial signatures or MIMO channel eigenmodes. It was shown that in uncorrelated Rayleigh fading the MIMO channel capacity limit grows linearly with min(M,N), where M and N denote the number of transmit and receive antennas, respectively.

According to recent studies smart antenna technology is now deployed in one of every 10 base stations in the world, and the deployment of smart antenna systems will grow by 60 percent in the next four years. The smart antenna technology has been successfully implemented for as little as 30 percent more cost than similar base stations without the technology. Smart antennas are already part of current releases of 3G standards (e.g., Alamouti STBC), and more sophisticated approaches are considered for future releases. Furthermore, there is currently increasing interest in the incorporation of smart antenna techniques for IEEE wireless LAN/MAN (802.11n and 802.162). However, implementation costs can vary considerably, and cost-effective implementation is still the major challenge in the field. At the base station of particular importance is the development of improved antenna structures (possibly employing micro-electromechanical system, MEMS, technology, e.g., micro-switches, or left-handed materials), improved cabling structures, and efficient low-cost radio frequency/digital signal processing (RF/DSP) architectures. At the terminal the application of smart antenna techniques can have a significant impact, in terms of not only system performance but also cost and terminal physical size. Promising areas for further research are efficient smart antenna algorithm design, small low-power RF structures, and viable low-power DSP implementations. Moreover, antenna structures, RF architectures, and DSP implementations are expected to operate efficiently within a wide variety of air interface scenarios, both separately and in parallel. To this end, innovative development flow methodologies jointly covering the RF and baseband parts of complex wireless systems-on-a-chip should be studied. A key output of this area of study is an understanding of the base technologies that are required to make the future use of smart antennas viable. The financial impact of the deployment of smart antenna technologies in future wireless systems was studied in for cdma2000 and UMTS. The results showed that smart antenna techniques are key to securing the financial viability of operators' business, while at the same time allowing for unit price elasticity and positive net present value. They are hence crucial for operators that want to create demand for high data usage and/or gain high market share. Based on this type of analysis, technology roadmaps along with their associated risks can be concluded that will enable appropriate technology intercept points to be determined, resulting in the development of technologies appropriate for each application area.

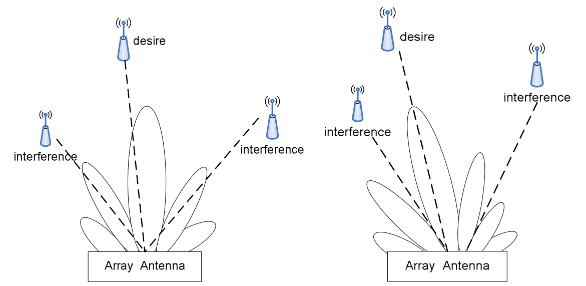
The smart antennas are normally categorized into two types: switched-beam antennas and adaptive antennas [8]. The brief detail of individual type is shown as follows.

2.1 Switched-beam antennas

The switched-beam antenna systems are the simplest smart antenna technique as they consist of antenna array and simple beamforming network. The spatial filtering is accomplished by antenna array. The configuration of array arrangement can be one or two-dimension (1D or 2D). For 1D arrange, linear array, the array is usually spaced by half-wavelength of the operating frequency. This is because we can obtain only one main lobe and also we can obtain the lowest sidelobe levels. The beamforming network of switched-beam antennas can be easily constructed using simple printed-circuit board. As a result, switched-beam systems are considered to be a low-cost system to enhance the signal quality of wireless communication systems. A number of predefined beams are produced in beamforming network. All signal received from those predefined beams are compared in term of signal strength. The configuration of switched-beam antennas is shown in Fig. 1(a). The beam giving strongest signal strength is selected to be the output of the beamforming network. This is because we believe that interference signal does not affect much in the beam give strongest signal strength. The beam switching can be simply performed using basic switching network which does not need fast or high computational function. The mention process is automatically repeated in order to confirm that we can follow the desired user all the time. However, gain of signal expansion is still low in beam direction with the limitation on signal inference reduction in case of unclear signal or shadow signals. Signal inference or signals arrive in several board angles can also result in the mistakes of signal selection. The overall goal of the switched-beam systems is to increase gain, according to the location of the user. However, since the beams are fixed, the intended user may not be in the center of the main beam. If there is an interferer near the center of the active beam, it may be enhanced more than the desired user

2.2 Adaptive Antennas

The adaptive antennas have a different concept from the switched-beam antennas mentioned in last section. Fig.1(b) shows the configuration of adaptive antennas which is constituted by an antenna array and signal processing unit. The antenna array deals with the signal processing in spatial domain while the signal in time domain is



(a) (b)

Fig. 1 beamforming lobes and nulls of (a) switched-beam antennas and (b) adaptive antennas.

the signal in time domain is accomplished by signal processing unit. From the figure, we can see that the main beam can be directed to the desired user all the time while nulls can be pointed to undesired or interfering directions simultaneously. As a result, the undesired signal such as co-channel interference and multipath signals can be completely eliminated from the systems. In part of signal processing unit, the received signals are weighted with suitable weighting coefficients in order to eliminate the effect of undesired signals. This part can also be called beamforming network. In order to have the best performance, the signal processing unit must be very fast in order to track the user when moving from place to place. In addition, high computational signal-processing unit is required in order to have accuracy in time domain. The adaptive antenna systems provide more degrees of freedom since they have the ability to adapt the radiation pattern to the RF signal environment in real time. In other words, they can direct the main beam toward the pilot signal or Signal Of Interest (SOI), while suppressing the antenna pattern in the direction of the interferers or Signals Not Of Interest (SNOIs). To put it simply, adaptive-array systems can customize an appropriate radiation pattern for each individual user. This is far superior to the performance of a switched-beam system. Because of the ability to control the overall radiation pattern in a greater coverage area for each cell site, adaptive antenna systems greatly increase capacity. In the presence of a low-level interference, both types of smart antennas provide significant gains over conventional sectored systems. However, when a high-level interference is present, the interference rejection capability of the adaptive systems provides significantly more coverage than either the conventional or switched-beam systems

Adaptive antennas can locate and track signals (users and interferers), and can dynamically adjust the antenna pattern to enhance reception while minimizing interference, using signal processing algorithms. After the system down-converts the received signals to baseband and digitizes them, it locates the signal of interest using the Direction-Of-Arrival (DOA) algorithm. It continuously tracks the signal of interest and signals not of interest by dynamically changing the weights (amplitudes and phases of the signals). Basically, the DOA algorithm computes the direction of arrival of all signals by computing the time delays using a cost function, computes the appropriate weights that result in an optimum radiation pattern. Because adaptive arrays are generally more digital-processing intensive than switched-beam systems, they tend to be more costly.

3 Array Antennas

A rectangular planar array is herein chosen with the reason of array size reduction. Also, the 2D antenna array can be managed to provide only one main beam over 360°. The choice of number of antenna elements is 2×2 as it is the minimum number for planar case. The inter-element spacing of the array is $\lambda/2$ or 6.12 cm at 2.45 GHz. The configuration of switched-beam antennas employing 2×2 planar array is shown in Fig. 2. As seen in this figure, the received signal at i^{th} antenna element when the signal is coming from azimuth direction (θ) can be expressed by

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

where β stands for phase constant of the signal, A represents the signal amplitude and i is index of antenna element shown in Fig. 2. Fig. 3 shows the relative phase of signal at each receiving antennas versus Direction Of Arrival (DOA) of incoming signal. Note that the variation of relative phase in Fig. 3 is the key design for the beamforming network which is detailed in Section 4.

Next, an example of radiation pattern of 2×2 planar array utilizing omni-directional antennas is investigated. For this case, the main beam has been managed to be pointed at 45°, 135°, 225° and 315°

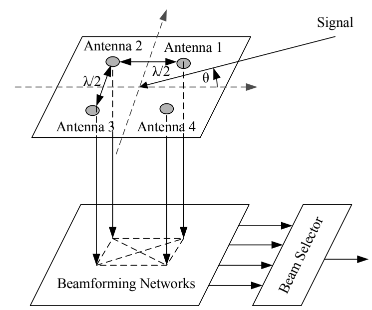


Fig. 2 Configuration of switched-beam antennas employing 2×2 planar array.

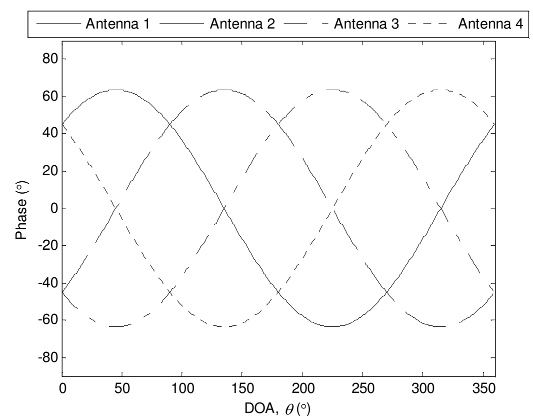


Fig. 3 Relative phase of each element on 2×2 planar array vs. DOA.

as show in Fig. 4. This can be accomplished by adjusting relative phase shift between the antenna elements which will be more detailed in next section. As we can see, each beam is identical and there is only one main beam for each pattern with directive gain of 10.47 dBi. As shown in Fig. 2, the beam selection is a process to select the best beam for transmitting or receiving signals. According to the obtained result shown in Fig. 4, the intersection between adjacent beams occurs at -1.65 dB. It reflects that one beam has to be switched to the others when a level of signal is below -1.65 dB. This presents the dynamic range of 1.65 dB.

4 Design of Beamforming Networks

The Butler matrix [9] is considered to be a typical type of beamforming network for switched-beam antennas as its simplicity. The switched beam antenna constitutes of the beam-forming network as

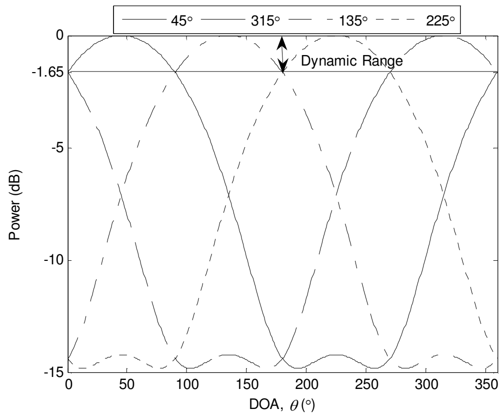


Fig. 4 Simulated radiation patterns of 2×2 planar array managed to point main beam at 45°, 135°, 225°, 315°.

beam adjustor to the desired specific direction. There are many ways for beam-forming network. The classic beam-forming network is "Butler matrix" which can apply to the linear array 4×1 antenna solely. The important component of the Butler matrix is circuit 90° hybrid coupler in 4×4 structures Fig.5 shows "Block Diagram" 4×4 Butler matrix, consisting of two cross signals, 4 antennas (linear array) , and 4 90° hybrid couplers. When signal source reaches the linear array antenna and passes onto the Butler matrix beam-forming network, the phase angle is sledged through circuit 90° hybrid coupler. The 45° sliding phase direction lays between port 1 and 3, and between port 2 and 4 to produce beam-forming 45° sliding phase. resulting in the differences of phase angles for each four ports as shown in Table 1.

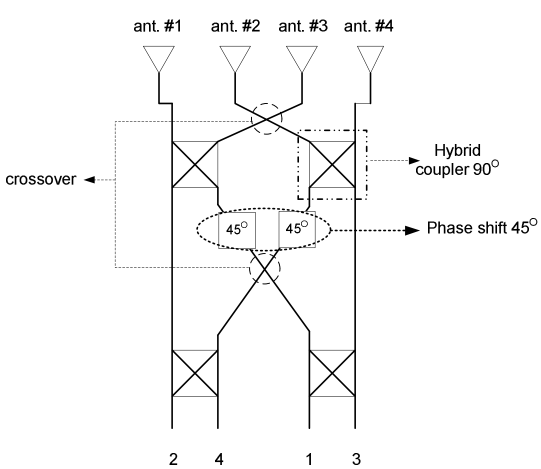


Fig.5 Butler matrix for 4×1 linear array antennas.

Table 1. Beam direction and inter-element phasing for Butler matrix.

	Antenna Element #1	Antenna Element #2	Antenna Element #3	Antenna Element #4	Beam Direction	Inter-Element Phasing
Port1	−45°	−180°	−45°	−90°	138.6°	−135°
Port2	0°	−45°	−90°	−135°	104.5°	−45°
Port3	−135°	−90°	−45°	0°	75.5°	45°
Port4	−90°	45°	−180°	−45°	41.4°	135°

It consists of 90° hybrid couplers, crossovers and 45° phase shifters. The network 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 multiplied by weighting coefficients, which is correspondent to one specific direction. Hence, the outcome of Butler matrix provides 4 simultaneous beams corresponding to 4 directions. This conventional Butler matrix is strictly designed for 4×1 linear array. However, utilizing 2×2 planar array is desirable for this paper. Therefore, the new design of beamforming network is required.

In this paper, the modification of Butler matrix is originally proposed in order to produce 4 beams when utilizing 2×2 planar array. Fig. 6 shows the configuration of modified Butler matrix. As seen in this figure, only two components are required, which are x° hybrid couplers and a crossover. The deletion of 45° phase shifters is due to the ease of design. In order to find the value of x°, the phase difference of all responses of modified Butler matrix has to be examined.

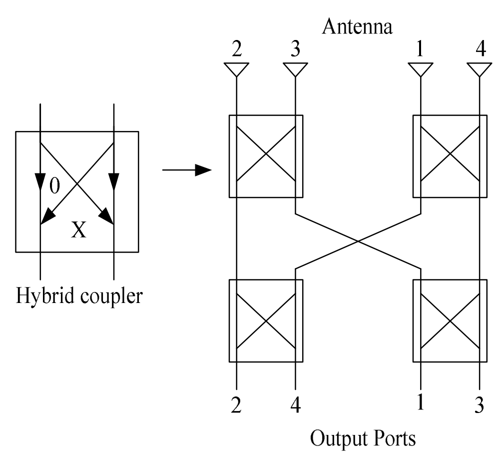


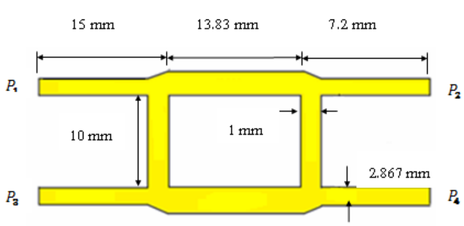
Fig. 6 Configuration of modified Butler matrix.

Table 2 presents the phase difference between input and output ports according to the configuration shown in Fig. 6. It is clearly seen that each output port has the same components of phase shifting which are 0°, x°, x° and $2x^{\circ}$. Then, the next attempt is to match the sequence of phase difference with the phase responses of each antenna elements shown in Fig. 3. With a quick inspection, the phase sequences in Table 1 can be matched with the phase responses in Fig. 3. The output port number 1, 2, 3 and 4 are correspondent to DOA of signals coming from 45°, 315°, 135° and 225°, respectively. Also found in Fig. 3, the x° has to be 68° otherwise the set of DOA signals becomes non-constructive. Therefore, the new design for 68° hybrid coupler is required.

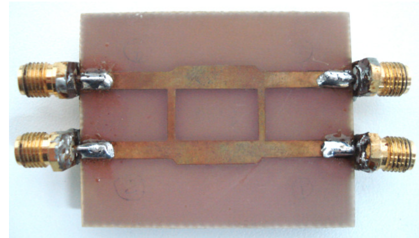
Table 2. Phase responses between input and output ports shown in Fig. 12

Output Port	Antenna Element			
	2	3	1	4
2	0°	x°	x°	$2x^{\circ}$
4	x°	$2x^{\circ}$	0°	x°
1	x°	0°	$2x^{\circ}$	x°
3	$2x^{\circ}$	x°	x°	0°

Using the Microwave Office program package, the size and dimension of 68° hybrid coupler is obtained which is shown in Fig. 7(a). Also, the fabricated coupler is shown in Fig. 7 (b). For crossover, the same design presented in [10] is utilized. The Fig. 8 shows size/dimension and the photograph of fabricated crossover. Note that the prototype constructed on FR4 microstrip having dielectric constant of 4.5 and thickness of 1.67 mm.

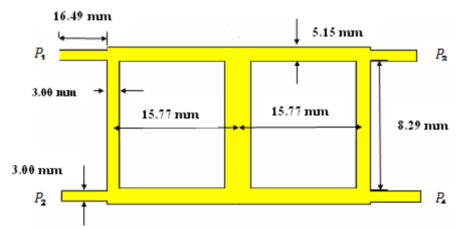


(a)



(b)

Fig. 7 68◦ hybrid coupler (a) size and dimension (b) photograph of constructed prototype.



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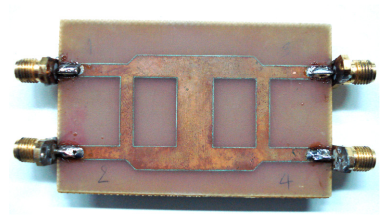


(b)

Fig. 8 Crossover (a) size and dimension (b) photograph of constructed prototype.

5 Automatic Switched-Beam Prototype

After having completed the design for antennas and beamforming network, a full prototype of switched-beam antennas is assembled as shown in Fig. 9. The 2×2 rectangular array of microstrip antennas and modified Butler matrix designed at 2.45 GHz are utilized. The Fig. 10 shows a full system of automatic switched-beam antennas and also the constructed prototype. The 4 output ports of modified Butler matrix are connected to switching network which is controlled by microcontroller Atmega 128. The output signal from switching

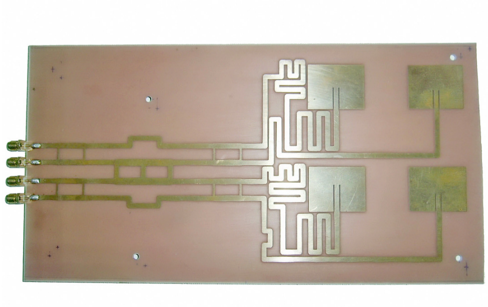
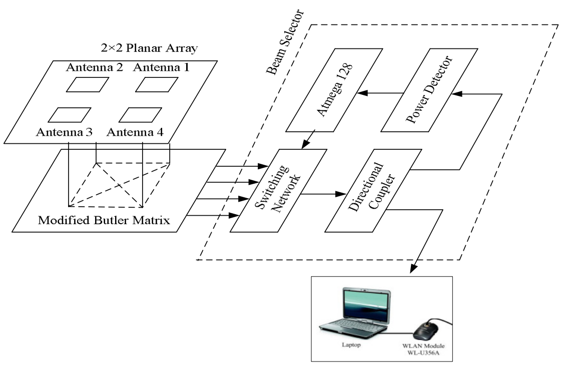
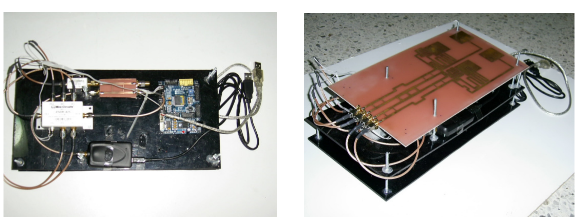


Fig. 9 Full prototype of switched-beam antennas employing 2×2 planar array and modified Butler matrix.



(a)



(b)

Fig. 10 Full prototype of automatic switched-beam antennas (a) diagram (b) photograph of constructed prototype.

network is coupled to measure the signal power in power detector. The 4 signal powers from 4 beams from modified Butler matrix is compared to find the maximum one in micro-controller. The process is automatically repeated every minute. As a result, the WLAN user can utilize maximum signal strength all the time.

6 Measurement

The power level of signal in WLAN transmission is able to designate quality of services including with guaranteed data rate transmission, achievable coverage area and acceptable bit error rate. In this paper, the measurement of received signal strength is undertaken to represent the performance enhancement of WLAN user when applying the switched-beam antennas. The photograph of measurement setup is illustrated in Fig. 11. The laptop shown in Fig. 11 is a general mobile terminal that can measure signal strength from WLAN module. This paper adopts NetStumbler 0.4.0 which is a freeware program to detect the received power from all access points. For WLAN module, the external unit from PLANET Technology Corporation (WL-U356A module) is preferred because the antenna element is removable. According to the aim of this paper, the measured signal strength utilizing omni-directional antenna and the proposed switched-beam antennas is recorded in laptop. For omni-directional antenna, the 5dBi monopole antenna originally included with WLAN module is utilized. All losses due to cable and beamforming network are taken into account, thus the measured signal strength indicates a true performance of switched-beam antennas under real circumstance.

Fig. 11 Photograph of measurement setup.

The measurement is undertaken on the 4th floor of C-Building at Suranaree University of Technology. The layout of measurement area is shown in Fig. 12. This floor has four access points located on area of 75×75 m^2. Four access points (AP1, AP2, AP3 and AP4) operating on IEEE 802.11 b/g standard transmit the same power at 18 dBm. The AP3 is allocated with channel 1 while AP1, AP2 and AP4 are allocated with channel 11. The measurement is performed on 20 locations distributed to cover most area on the floor. In each location, two cases of antenna parts: omni-directional and switched-beam antennas are performed and the 5 measured signal strengths are collected and stored on laptop. Note that the automatic beam selection is performed when utilizing switched-beam antennas.

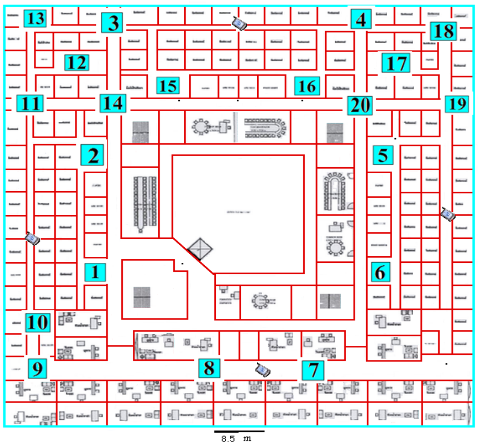


Fig. 12 Map of measurement area.

Fig. 13 shows probability of measured signal strength comparing between using the proposed antennas and omni-directional antenna. As observed in this figure, the probability of signal strength using omni-directional antenna is distributed in range from -70 to -49 dBm while the range of using automatic switched-beam antennas is spread from -67 to -47 dBm. This indicates that the higher signal quality can be expected by the proposed antenna system. For the average signal strengths calculated by the results shown in Fig. 13, using automatic switched-beam antennas can offer up to -58.56 dBm, thus 4.37 dB higher than using omni-directional antenna.

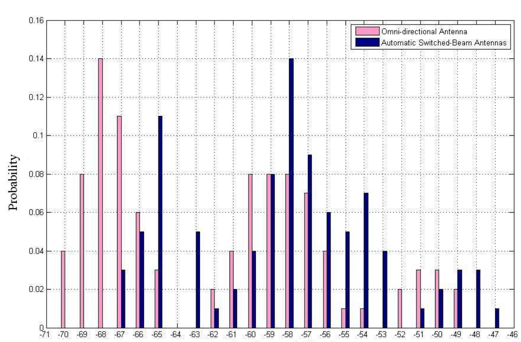


Fig. 13 Probability of measured signalstrength (dBm) of the systems employing omni-directional antenna and automatic switched-beam antennas.

Fig. 14 shows the outage probability of systems employing omni-directional and automatic switched-beam antennas. The star and dot points represent the measured data while the solid and dash lines represent the approximated curve fit to the measured data. As noticed in this figure, at the

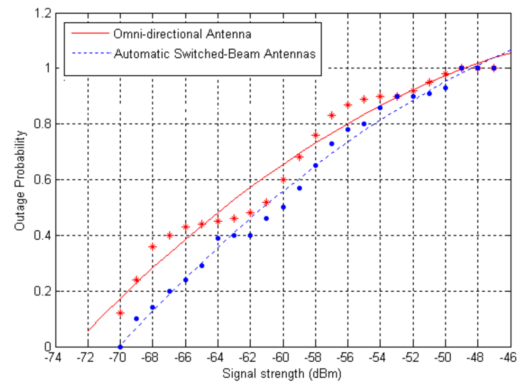


Fig. 14 Outage probability of the systems employing omni-directional antenna and automatic-switched-beam antennas.

same signal strength value, automatic switched-beam antennas provide lower outage probability. Moreover at one particular low outage probability, which is required for wireless communication designer, the automatic switched-beam antennas can offer higher signal strength. This means that the automatic switched-beam antennas guarantee higher signal quality at the required outage probability over using omni-directional antenna. In addition, the percentage of coverage area illustrated in Fig. 15 shows the better outcome when using automatic switched-beam antennas. At 80% coverage area, the proposed antenna system can guarantee the signal quality higher than -65.64 dBm while using omni-directional antenna can only offer at -68 dBm. These results emphasize the success of using automatic switched-beam antennas for enhancing WLAN signal quality.

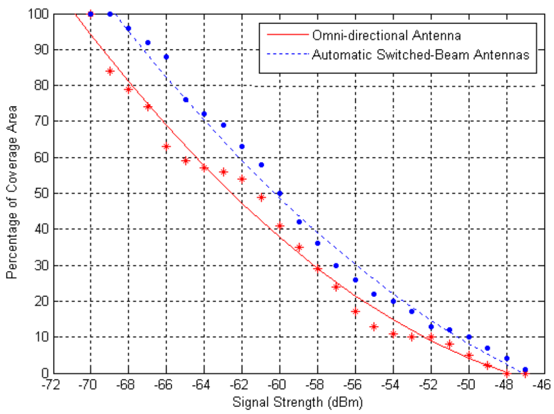


Fig. 15 Percentage of coverage area of the systems employing omni-directional antenna and automatic-switched-beam antennas.

7 Conclusion

This paper has been demonstrated the performance enhancement of WLAN users using automatic switched-beam antennas employing modified Butler matrix and 2×2 planar array. The measured signal strength is considered as enhancing indicator under real scenario of existing WLAN infrastructure. The original design of modified Butler matrix for 2×2 planar array is proposed to make the system more compact in size than conventional 4×1 linear array. Both simulation and experimental results indicate that the proposed switched-beam antennas provide higher capability of receiving signal strength and higher reliability on coverage area.

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