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SWITCHED BEAM ANTENNA ARRAY WITH PARASITIC ELEMENTS

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Abstract—This paper describes the design of the disk-loaded monopole with a parasitic array for beam switching. Usually the radiation pattern of a single element such as a $\lambda/4$ monopole and the disk-loaded monopole provide low values of gain. The beamwidth is normally large and the coverage is wide. This may be appropriate in an on-body channel where the antenna orientation may not be easily controlled, such as when the users put the terminal in their pocket. In some non-body applications such as WLAN, it is necessary to design antennas with high gain to meet other demands such as high capacity or long range. Also, in the on-body environment it is essential to have such gain in order to minimize the path loss between the antennas, and hence increase the battery life. The antenna was excited using coaxial cable produced more gain and pattern compared to the single element top disk-loaded antenna. The reduced-size antenna namely a sector antenna array also has been discussed in detail in this paper. Such design has allowed at least 50% of the size reduction. The simulation results have shown very good agreement with the measurement for both antennas.

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1. INTRODUCTION

Switched beam arrays can give higher gain than single elements and can be used to improve the performance of small communications base stations and terminals. In addition, Body Area Network (BAN) using communication channels between two body mounted antennas, can also benefit. In [1] the path gain of the antennas for two body channels has been established and the optimum antenna type was found to be a monopole antenna for these channels.

In these on-body or other terminal and base station applications, beam switching can be used to increase gain and hence reduce link loss and battery consumption, or to reduce interference or multipath. The disk-loaded monopole antenna has the advantages that the height of the monopole antenna can be reduced significantly whilst still giving approximately the same performance as described in [2].

An antenna with multi-elements that act together to form an array is required to increase the gain. One example is the well-known Yagi-Uda antenna [3, 4]. Such an antenna is widely used for television communication in which it operates at high frequency (HF), very high frequency (VHF) and ultra high frequency (UHF). It consists of a driven element and a number of parasitic radiators, in which currents are induced by mutual coupling. Some applications consider the mutual coupling effect undesirable because it degrades the performance [5–7]. However, in the parasitic array it is central to the operation. The parasitic elements are useful to increase the gain, create a directional beam [8] and enhance the bandwidth impedance of the antenna [9].

Researchers have transformed the conventional Yagi antenna into the microstrip form to give a broadband antenna that can be suited for wireless technologies [10–14], Microstrip has a number of advantages such as low profile, ease of fabrication, and low cost. However, a different approach is needed in designing such antennas. For example, in a conventional Yagi dipole antenna, the electromagnetic wave is coupled from the driven element to the parasitic elements and produces a directional beam. In a microstrip Yagi antenna, the coupling not only happens through space but also occurs through the surface wave in the substrate.

It is well known that the dipole emits power equally around its axis and this allows its neighbours to get a strong signal even when the distance between them is large. On the contrary, the microstrip patch radiates in a broadside direction. As a result, very little energy is coupled with its neighbour especially when the distance increases. Therefore Huang [15] reports that in order to get enough coupling, the gap distance between two patches should be equal to or less than the dielectric substrate thickness. The dimensions of the microstrip Yagi antenna including the gap between the directors, driven element and reflector are given in [15, 16].

An alternative approach based on the basic principle of a Yagi-Uda array that uses one driven element encircled by a number of parasitic elements can be also applied to monopole antenna arrays [17–19], dipole antenna array [20] and microstrip patch antenna arrays [21, 22]. The antenna's input return loss and radiation patterns will be modified due to the mutual coupling between the driven and the parasitic elements. For instance, in the monopole and patch array, the parasitic element becomes a reflector when shorted to the ground plane, and when not shorted, acts as a director. In other word, the termination impedances of parasitic elements are switchable to change the currents flowing. This is different to the conventional Yagi, in which the reflector and directors are determined by their length. This configuration is therefore useful for switched beam control because the actions of the changes in currents of each parasitic and their combined effect on the driven element can give rise to change in radiation pattern.

Examples of coaxial-fed monopole antenna arrays, based on the Yagi concept, that have been published recently are the switched parasitic monopole antenna arrays, electrically steerable passive array radiators (ESPAR) and dielectric embedded ESPAR antenna arrays for wireless communications [17–19]. It is clear in [17] that the beam of the antenna can be switched by isolating one of the parasitic elements from the ground plane whilst, the other elements are shorted to the ground. Meanwhile, in [18, 19] by changing the control voltage to the parasitic elements, it is possible to form the main beam radiation in the direction of the director.

2. SWITCHED TOP LOADED MONOPOLE ARRAY FED BY A COAXIAL CABLE

Figure 1 shows the switched top loaded monopole array, designed for this project, consisting of five elements on a small thin circular ground plane, fed by a coaxial cable. The antenna is designed for the 2.45 GHz ISM band. Switching is simulated by open circuiting one of the elements. From the figure, it can be seen that the driven element (1) is located at the centre of the ground plane and encircled by four equidistant disk-loaded parasitic elements (2–5). The antenna was simulated using a CST Microwave Studio.

The driven and parasitic elements consist of a disk above a cylindrical rod monopole. The rods in the driven element and parasitic

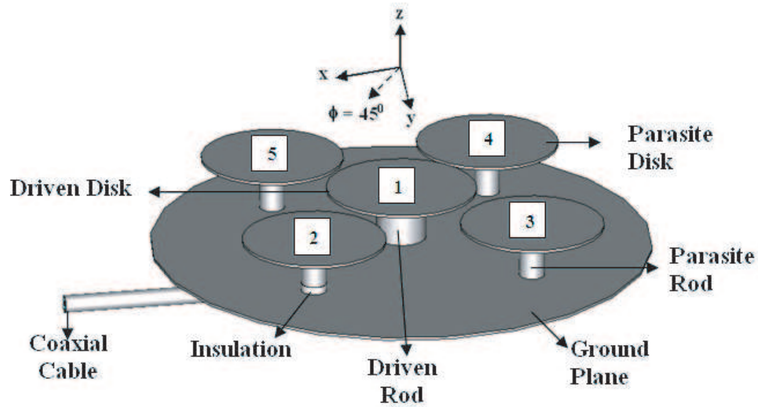


Figure 1. Disk-loaded monopole array antenna (No. 1 = driven element, No. 2–No. 5 = parasitic elements).

are of different diameter. The disks used for parasitic elements are also made about 5% smaller in radius compared to the driven disk. The antenna parameters that have been studied were the driven disk radius, R_d and parasitic disk radius, R_p (from 13 mm to 15 mm), the ground plane radius, R_g (from 30 mm to 50 mm), the height of elements, h (from 9 mm to 14 mm), the driven cylindrical rod radius, R_{cd} (from 2.5 mm to 5 mm) and the parasitic cylindrical rod radius, R_{cp} (from 1 mm to 3 mm). The aims of the optimized antenna dimensions were to obtain good matching at the feeding point and the gain improvement. The final dimensions are given in Table 1.

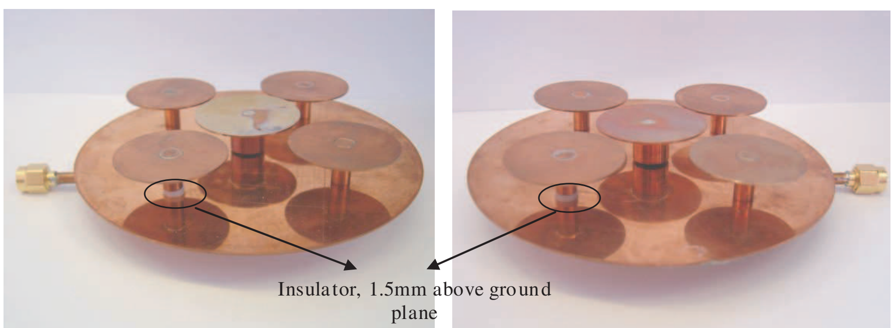
The antenna matching is mainly controlled by the diameter of

Table 1. Dimensions of a disk-loaded monopole array antenna.

Components	Unit (mm)
Ground plane radius, R_g	50.00
Driven disk radius, R_d	15.00
Parasitic disk radius, R_p	14.25
Height of elements, h	11.00
Driven cylindrical rod radius, R_{cd}	5.00
Parasitic cylindrical rod radius, R_{cp}	2.53
Disk and ground plane thickness, t	0.55

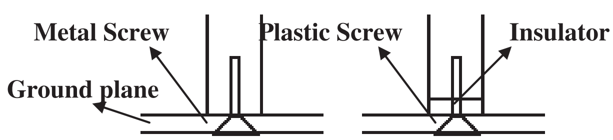
the driven element rod. The gain of the antenna is related to the dimensions of the parasitic elements including disk size, rod radius and their distance to the driven element. The distance between the centre of the driven element to the centre of the parasitic has been chosen to be about $\lambda/4$ (31 mm) which is in line with traditional Yagi antenna spacing.

There are two variations of the array that have been made as shown in Figure 2. The reason behind this is to investigate the beam switching when changing the parasitic state. Figure 2(a) shows three of the parasitic are screwed to the ground plane as in Figure 3(a). These act as reflectors, while the remaining parasitic (director) is elevated by about 1.5 mm and is bolted to the ground plane using a plastic screw and insulator, Figure 3(b). In Figure 2(b), the director is in the opposite location to the antenna in Figure 2(a).



(a) (b)

Figure 2. Photographs of the antenna with one of the parasitic element is lifted 1.5 mm using insulator while the remaining are shorted to ground: Frequency 2.45 GHz; (a) Antenna with same configuration as in Figure 1, and (b) antenna with the opposite configuration.



(a) (b)

Figure 3. The technique of shorted and insulated element. (a) Shorted element, (b) insulated element.

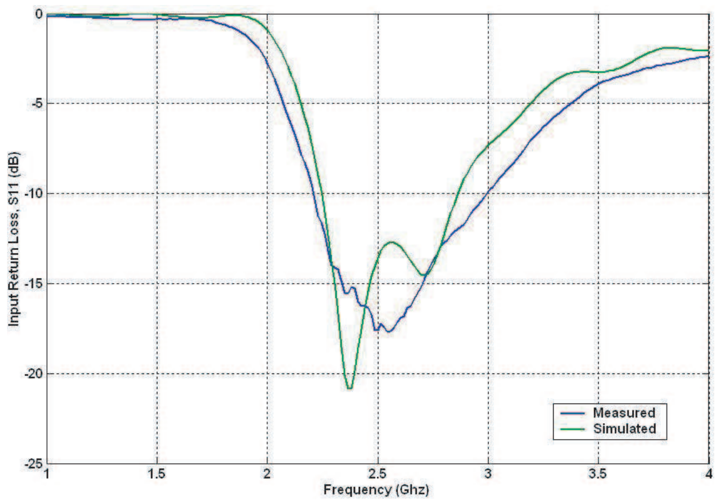


Figure 4. Input return loss against frequency for the antenna in Figure 2(a).

3. RESULTS

Figure 4 shows the simulated and measured results for the input return loss, S_{11}, for the antenna shown in Figure 2(a). From the figure, it can be observed that good agreement between the simulated and measured results has been achieved. However, it can be observed that the measured result produced more impedance bandwidth than the simulated result. This may be due to imperfection occurred during the antenna construction process which may modify the impedance of the antenna. Nevertheless, the fractional bandwidth for reflection coefficient below -10 dB is about 24% (from about 2.2 GHz to 2.8 GHz) and covers the 2.45 GHz ISM band.

Figure 5 illustrates the normalized antenna radiation patterns for both E and H planes for the antenna in Figure 2(a). It can be seen that for the H-plane pattern, the beam has been steered to direction A, that is $\phi = 45°$, which is in the direction of the open circuited element, as expected. However as shown in Figure 5(a) the beam has also been tilted upwards to $\theta = 50°$ above the plane in the open circuited element direction. It also can be noticed that a peak also exists at $\theta = 315°$ in the direction of the short circuited element opposite the open circuited element in the parasitic ring. This is clearly seen in the both simulated and measured results.

The predicted gains at angle $\theta = 50°$ and $\theta = 315°$ are 4.40 dBi and 4.38 dBi respectively. The antenna gives 5.10 dBi of measured gain

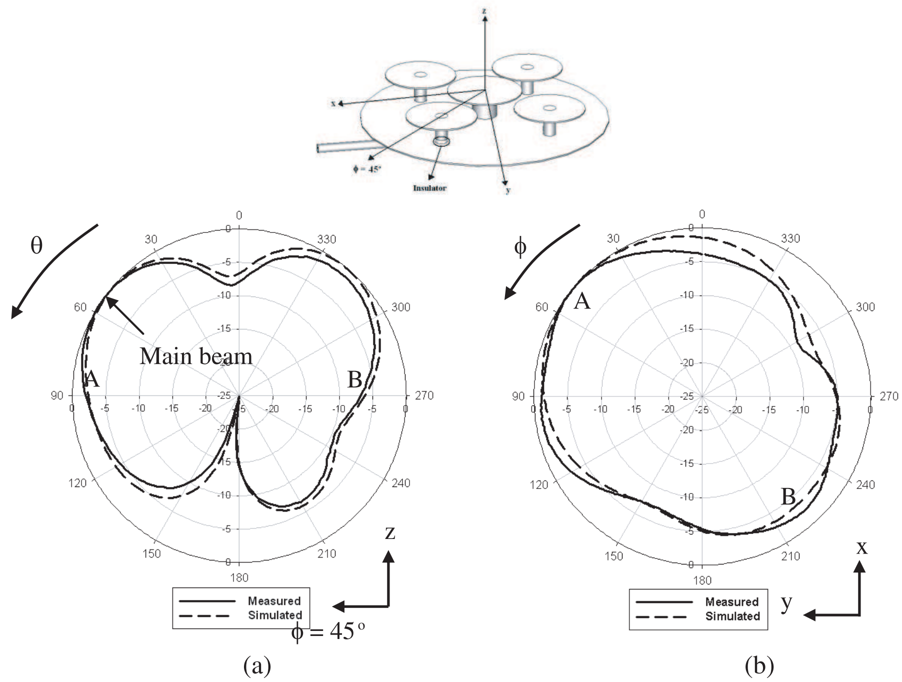


Figure 5. The radiation patterns of the antenna in Figure 2(a). (a) Normalized E-plane pattern at $\phi = 45°$, (b) normalized H-plane pattern.
(A and B respectively in both plots are same direction). Frequency = 2.45 GHz.

which is more than three times greater than the 1.50 dBi of the single disk-loaded antenna [2].

The antenna beam radiation can be switched to other directions by changing the position of the open circuiting element. To prove this, the antenna configuration as shown in Figure 2(b) was measured and simulated. Figure 6 shows the patterns of the antenna. It can be seen that, the antenna pattern has been altered, with a peak in the $\phi = 225°$ and $\theta = 315°$ direction. Again, the two peaks exist at $\theta = 315°$ and $\theta = 50°$ in the $\phi = 45°$ plane, and elevated above the ground plane. Simulations show that the main beam is tilted in elevation due to the finite ground plane. The researchers in [17–19] have demonstrated that the antenna pattern can be brought down to the horizontal plane by utilising the ground skirting attached to the ground plane. The results for the two antennas clearly demonstrate the potential of this array for a switched beam application.

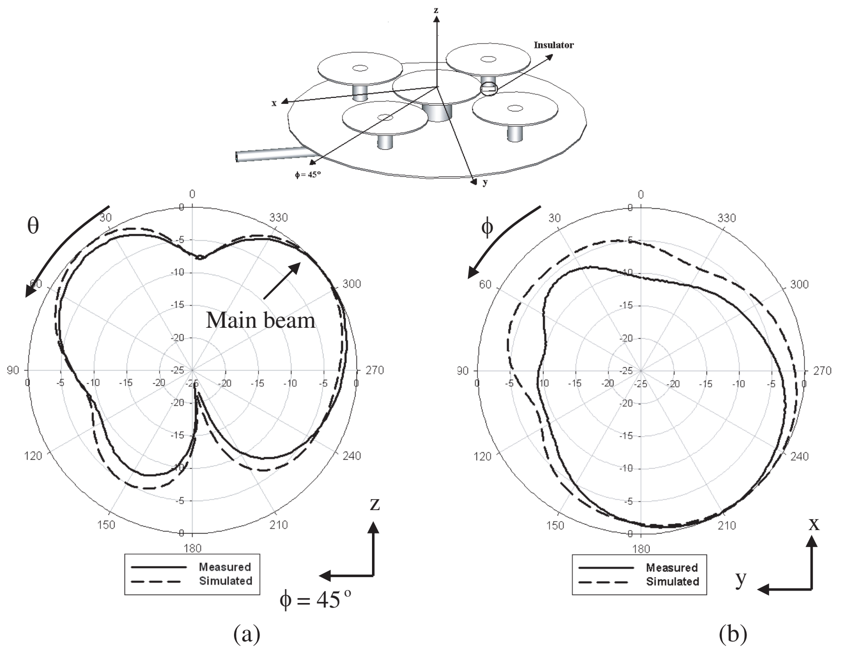


Figure 6. Radiation patterns for the antenna in Figure 2(b). Frequency = 2.45 GHz. (a) Normalized E-plane pattern at $\phi = 45°$, (b) normalized H-plane pattern.

4. SECTOR MONOPOLE ARRAY ANTENNA

The antennas as shown in Figure 2, with an overall size of 100 mm diameter may be considered to be too large especially for on-body communication systems such as Bluetooth. Thus, a sector disk-loaded monopole antenna array is introduced (shown in Figure 7) which allows a small ground plane to be used. The size of the ground plane has been reduced by about 50% compared to the antenna in the previous section. The distance between the parasitic rod monopole and the driven element has also been reduced due to the use of sector disk on the top of cylindrical rod monopoles of parasitic elements.

The aperture angle of the sector shape disk from the centre of the antenna is 86° as can be seen in Figure 8. The gap between the sector and the driven element is about 3 mm. As described in the previous section, beam switching is achieved by open circuiting the parasitic at their base, as appropriate, and is demonstrated here by introducing a small piece of dielectric insulator as seen in front left hand parasitic in

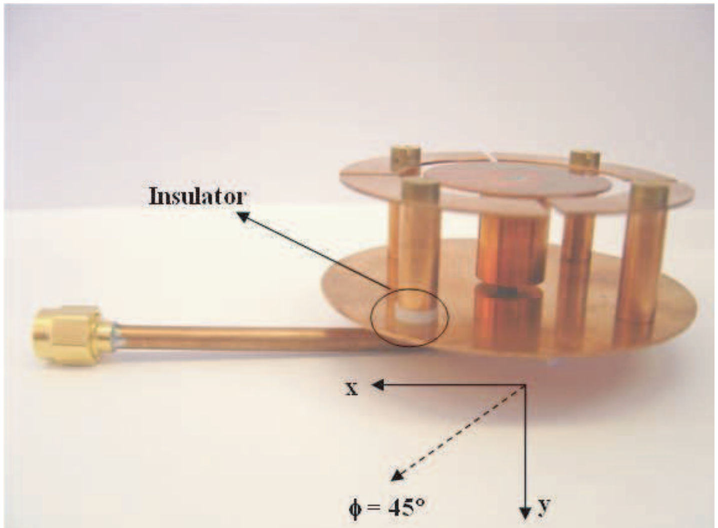


Figure 7. Photograph of reduced size antenna. Frequency = 2.45 GHz.

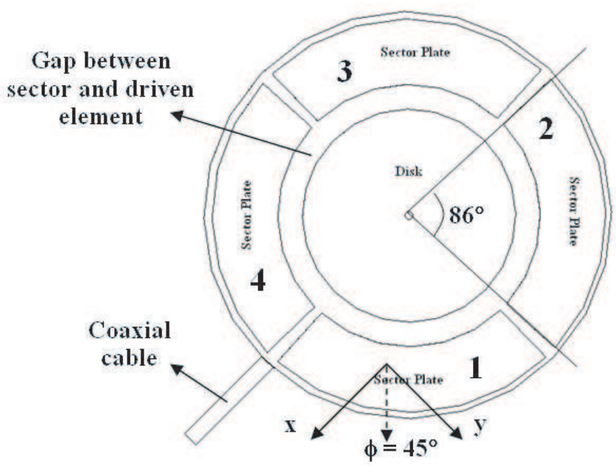


Figure 8. The top view of the antenna.

Figure 7.

The gain of the antenna is related to the dimensions of the parasitic elements including disk size, rod radius and their distance to the driven element. The array dimensions have therefore all been optimized to get a good match at the feeding point and some pattern improvement. The optimizations were focussed on the antenna height (from 11 mm to17 mm), driven disk radius, (from 13 mm to 15 mm), driven rod radius form 2.5 to 5 mm), ground plane radius (from 25 mm to 30 mm) and the sector size. The antenna optimized dimensions are given in Table 2.

Table 2. The optimized dimensions of sector array antenna.

Components	**Unit (mm)**
Ground plane radius	25.00
Driven disk radius	13.00
Driven Rod Radius	4.53
Parasitic Rod Radius	2.53
Height of elements	14.00
Disk and ground plane thickness	0.55

Two sector antennas have been made to investigate this design. One of the antennas has a configuration as in Figure 7 in which sectors (2, 3 and 4) were short circuited whilst sector 1 was insulated from the ground plane. For the other configuration, sector 3 in Figure 8 was open circuited and the other three (1, 2 and 4) were shorted to the ground. Figure 9 shows the reflection coefficient of the sector disk-loaded antenna array for the antenna in Figure 7. From the figure, the measured S_{11} is at lower frequency than simulated. It is found that some difficulties occurred to align the driven element and the sectors. As a result, the gap between them is not equal. This may affect the matching and resonant frequency. The antenna however has an input return loss that covers the frequency from 2.2 GHz to 2.5 GHz at a level below −10 dB.

Figure 10(a) illustrates the normalized E-plane pattern at $\phi = 45^\circ$ and Figure 10(b) shows the normalized H-plane pattern. Figure 11 shows the same but for the opposite configuration. These two E-patterns show that the antenna produces the beam in the direction of the open circuit element. In comparison with the result in Figure 6, this antenna produces no peak in the opposite direction. The sector antenna has a predicted gain of 4.00 dBi. The gain is slightly reduced compared to the predicted gain of a disk-loaded array fed by a coaxial cable and reduced by the gain of 2.70 dBi compared to a CPW-fed array, which are 4.40 dBi and 6.70 dBi, respectively. The measured gain of this antenna is 4.70 dBi. The gains of the array antennas are summarized in Table 3.

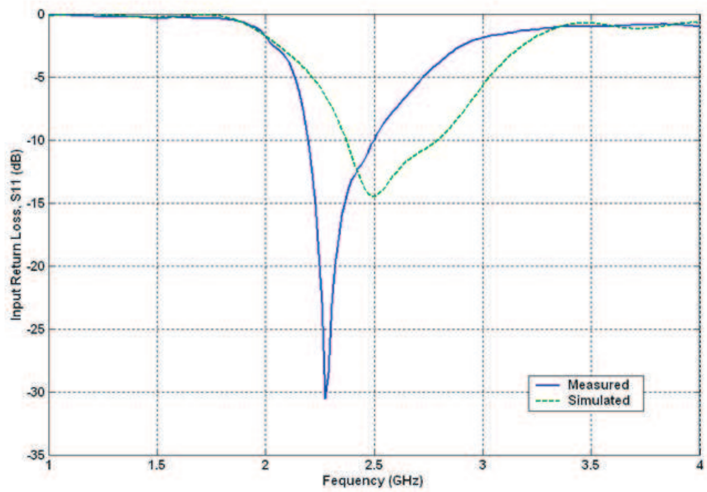


Figure 9. Input return loss of sector antenna.

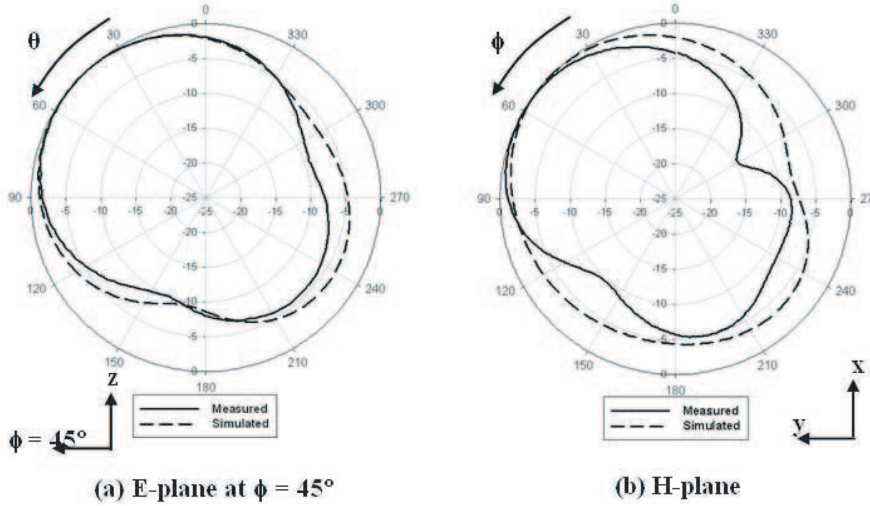


Figure 10. Radiation patterns of the antenna in Figure 7. Frequency = 2.45 GHz.

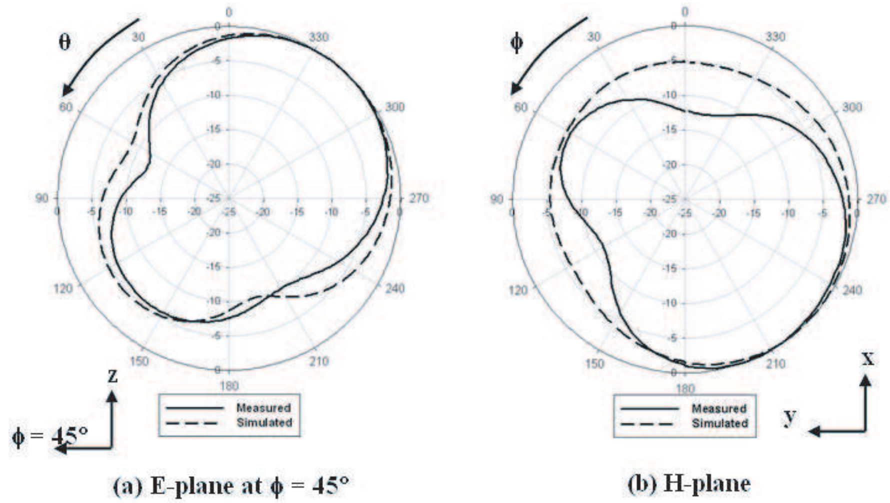


Figure 11. Radiation patterns of the antenna as sector 3 was open circuited whilst the other three were short circuited. Frequency = 2.45 GHz.

Table 3. The antenna gain in the main beam direction.

Type of antennas	Predicted gain (dBi)	Measured gain (dBi)
Disk-loaded monopole array (coaxial-fed)	4.40	5.10
Sector monopole array	4.00	4.70

5. CONCLUSION

A switched disk-loaded monopole antenna array with parasitic elements for BAN application has been proposed. The array was fed by a coaxial cable and had a 100 mm diameter ground plane and 11 mm height. It produces good input return loss and covers the frequency range from 2.2 GHz to 2.8 GHz for S_{11} below -10 dB. The antenna peak radiation was in the direction of the open circuited element and was elevated above the ground plane at about 50°. The antenna had a measured gain of 5.10 dBi, which is more than three times the gain of a single top disk-loaded antenna.

The introduction of a sector shape to the top loading has improved the pattern of the disk-loaded monopole array in which the main beam is steered only in one direction, but the measured gain was reduced, due to the size reduction, to 4.70 dBi which is about 0.40 dBi less than the circular top loading shape (5.10 dBi). The main beam is tilted by about 50° above the ground plane in both array types due to the finite ground. Simulated results of shorted patch antennas also have been discussed. In the simulated E and H-plane, the main beam can be steered by a small angle. However, significant beam switching can be obtained in the plane of the ground plane in which the patterns can been switched in four directions.

REFERENCES

1. Kamarudin, M. R., Y. I. Nechayev, and P. S. Hall, "Antennas for on-body communication systems," *IEEE International Workshop on Antenna Technology: Small Antennas and Novel Metamaterials, 2005. IWAT 2005*, 17–20, Mar. 7–9, 2005.
2. Sim Simpson, T. L., "The disk loaded monopole antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 52, No. 2, 542–550, Feb. 2004.
3. Balanis, C. A., *Antenna Theory Analysis and Design*, 2nd edition, John Wiley & Sons Ltd., 1997.
4. Cheng, D. K., "Gain optimization for Yagi-Uda arrays," *IEEE Antennas and Propagation Magazine*, Vol. 33, No. 3, 42–46, June 1991.
5. Ozdemir, M. K., H. Arslan, and E. Arvas, "Mutual coupling effect in multiantenna wireless communication systems," *Global Telecommunications Conference, 2003. GLOBECOM '03. IEEE*, Vol. 2, 829–833, Dec. 1–5, 2003.
6. Ali, M. A. and P. Wahid, "Analysis of mutual coupling effect in adaptive array antennas," *Antennas and Propagation Society International Symposium, 2002. IEEE*, Vol. 1, 102–105, 2002.
7. Min, K.-S., D.-J. Kim, and Y.-M. Moon, "Improved MIMO antenna by mutual coupling suppression between elements," *The European Conference on Wireless Technology*, 125–128, Oct. 3–4, 2005.
8. Parsons, J. D., *The Mobile Radio Propagation Channel*, 2nd edition, John Wiley and Sons Ltd., 2000.
9. Preston, S. L., D. V. Thiel, T. A. Smith, S. G. O'Keefe, and J. W. Lu, "Base-station tracking in mobile communications using a switched parasitic antenna array," *IEEE Transactions on Antennas and Propagation*, Vol. 46, No. 6, June 1998.

10. Qian, Y., W. R. Deal, N. Kaneda, and T. Itoh, "Microstrip-fed quasi-Yagi antenna with broadband characteristics," *Electronics Letters*, Vol. 34, No. 23, 2194–2196, Nov. 12, 1998.
11. Padhi, S. K. and M. E. Bialkowski, "Parametric study of a microstrip Yagi antenna," *Microwave Conference, 2000, Asia-Pacific*, 715–718, Dec. 3–6, 2000.
12. Song, H. J., M. E. Bialkowski, and P. Kabacik, "Parameter study of a broadband uniplanar quasi-Yagi antenna," *13th International Conference on Microwaves, Radar and Wireless Communications, 2000. MIKON-2000*, Vol. 1, 166–169, May 22–24, 2000.
13. Deal, W. R., N. Kaneda, J. Sor, Y. Qian, and T. Itoh, "A new quasi-Yagi antenna for planar active antenna arrays," *IEEE transactions on Microwave Theory and Techniques*, Vol. 48, No. 6, 910–918, June 2000.
14. Kretly, L. C. and A. S. Ribeiro, "A novel tilted dipole quasi-Yagi antenna designed for 3G and Bluetooth applications," *Microwave and Optoelectronics Conference, 2003. IMOC 2003. Proceedings of the 2003 SBMO/IEEE MTT-S International*, Vol. 1, 303–306, Sept. 20–23, 2003.
15. Huang, J. and A. C. Densmore, "Microstrip Yagi array antenna for mobile satellite vehicle application," *IEEE Transactions on Antennas and Propagation*, Vol. 39, No. 7, 1024–1030, July 1991.
16. Huang, J., "Planar microstrip Yagi array antenna," *Antennas and Propagation Society International Symposium, 1989, AP-S. Digest*, 894–897, June 26–30, 1989.
17. Schlub, R. and D. V. Thiel, "Switched parasitic antenna on a finite ground plane with conductive sleeve," *IEEE Transaction on Antennas and Propagation*, Vol. 52, No. 5, 1343–1347, May 2004.
18. Kawakami, H. and T. Ohira, "Electrically steerable passive array radiator (ESPAR) antennas," *IEEE Antennas and Propagation Magazine*, Vol. 47, No. 2, 43–49, Apr. 2005.
19. Lu, J., D. Ireland, and R. Schlub, "Dielectric Embedded ESPAR (DE-ESPAR) antenna array for wireless communications," *IEEE Transactions on Antennas and Propagation*, Vol. 53, No. 8, Part 1, 2437–2443, Aug. 2005.
20. Islam, R. and R. Adve, "Beam-forming by mutual coupling effects of parasitic elements in antenna arrays," *Antennas and Propagation Society International Symposium, IEEE*, Vol. 1, 126–129, June 16–21, 2002.
21. Kumar, G. and K. Gupta, "Nonradiating edges and four edges gap-coupled multiple resonator broad-band microstrip antennas,"

IEEE Transaction on Antennas and Propagation, Vol. 33, No. 2, 173–178, Feb. 1985.

22. Gray, D., J. W. Lu, and D. V. Thiel, "Electronically steerable Yagi-Uda microstrip patch antenna array," *IEEE Transactions on Antennas and Propagation*, Vol. 46, No. 5, 605–608, May 1998.