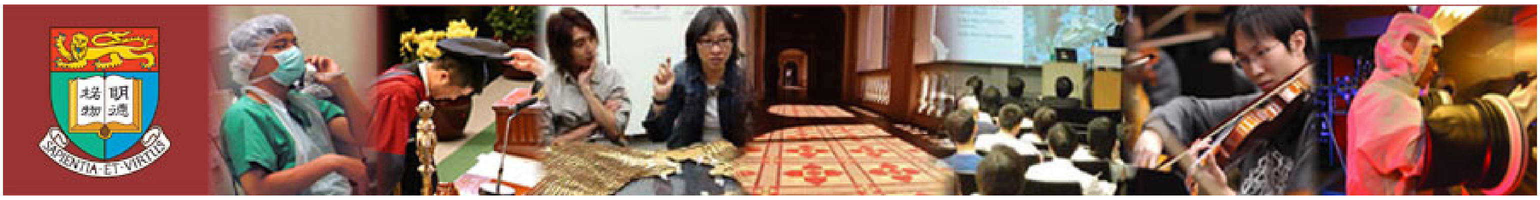

Title	**Printed Multiband Antenna with Independent Setting Suitable for Fixed and Reconfigurable Wireless Communication Systems**
Author(s)	**AbuTarboush, H F; Nilavalan, R; Cheung, SW; Nasr, K**
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Compact Printed Multiband Antenna With Independent Setting Suitable for Fixed and Reconfigurable Wireless Communication Systems

Hattan F. Abutarboush, *Member, IEEE*, R. Nilavalan, *Senior Member, IEEE*, S. W. Cheung, *Senior Member, IEEE*, and Karim M. Nasr, *Senior Member, IEEE*

***Abstract*—This paper presents the design of a low-profile compact printed antenna for fixed frequency and reconfigurable frequency bands. The antenna consists of a main patch, four sub-patches, and a ground plane to generate five frequency bands, at 0.92, 1.73, 1.98, 2.4, and 2.9 GHz, for different wireless systems. For the fixed-frequency design, the five individual frequency bands can be adjusted and set independently over the wide ranges of 18.78%, 22.75%, 4.51%, 11%, and 8.21%, respectively, using just one parameter of the antenna. By putting a varactor (diode) at each of the sub-patch inputs, four of the frequency bands can be controlled independently over wide ranges and the antenna has a reconfigurable design. The tunability ranges for the four bands of 0.92, 1.73, 1.98, and 2.9 GHz are 23.5%, 10.30%, 13.5%, and 3%, respectively. The fixed and reconfigurable designs are studied using computer simulation. For verification of simulation results, the two designs are fabricated and the prototypes are measured. The results show a good agreement between simulated and measured results.**

***Index Terms*—Cognitive radio, fixed antenna, independent control, multiband antenna, reconfigurable antenna, small antenna, wide tuning range.**

I. INTRODUCTION

DIFFERENT techniques to achieve multiband operations for compact antennas using planar technology have been investigated. These techniques include using different slot shapes [1]–[7], shorting walls and V-shaped configuration [8], stack and multi-layers [9], and fractal shape in the ground plane [9], [10]. Recently, independent control in frequencies for multiband antennas has received much attention. For example, in [11] a planar inverted-F antenna (PIFA) with a relatively large size of $105 \times 30 \times 9$ mm^3 was studied to control three resonant frequencies. In [12], [41] a multi-frequency band antenna was designed to control the low-frequency band and first high-frequency band. In [13] a PIFA was studied to independently control three frequency bands between 1.5 and 6.8 GHz.

Fixed multiband antennas lack the flexibility to accommodate new services compared with frequency-reconfigurable antennas [14]; the latter antennas can be classified into two categories: continuous tuning and discrete tuning. Continuous tuning can be achieved using varactor diodes; the antennas can be tuned to have smooth transitions within or between operating bands [15]–[24]. Discrete tuning can be achieved using PIN-diode switches; the operating frequencies can be switched among different services, depending on the switching states [25]–[27]. All the designs in [15] to [29] were limited to single- or dual-band operations.

A number of techniques have been proposed for reconfigurable antennas to achieve independent tuning for one or more frequency bands over wide ranges. For example, in [22] a reconfigurable dual-band antenna was designed with a wide tuning range of 2.02 GHz. However, a high voltage of 30 V was required, and the size of the antenna was large at 150×110 mm^2. In [23] a reconfigurable dual-band dual-port chassis-antenna was designed for a wide tuning range. In this design, the antenna was of high profile with 7 mm and so was not suitable for slim devices. In [24] a square-ring dual-band antenna was designed; it had a fixed upper resonant frequency and a tunable lower resonant frequency. All these techniques have the problem of 1) requiring high voltages to perform tuning, 2) being high profile, 3) being large in size, or 4) having small tuning ranges.

This paper presents the design of a compact antenna for fixed and reconfigurable frequency bands. The antenna employs a main patch and four sub-patches to generate five frequency bands. In the fixed-frequency design, the frequency bands can be set independently over a wide range using just one key parameter of the antenna. For the reconfigurable design, the frequency bands can be independently controlled/tuned using varactors.

This paper is a further study of [30] and [31]. This further study includes the design methodology, frequency setting in the fixed design, and independent tuning in the reconfigurable design. It also includes the radiation patterns for the reconfigurable design, and the efficiency and gain comparison for the fixed and reconfigurable designs.

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H. F. Abutarboush was with Brunel University, London, U.K., he is with the Electrical Engineering, King Abdullah University of Science and Technology (KAUST), Saudi Arabia (e-mail: Hattan.Abutarboush@ieee.org).

R. Nilavalan is with the Wireless Networks and Communications Centre (WNCC), School of Engineering and Design, Brunel University, London UB8 3PH, U.K.

S. W. Cheung is with the Department of Electrical and Electronics Engineering, The Hong Kong University, Hong Kong.

K. M. Nasr is with the National Physical Laboratory (NPL), Teddington TW11 0LW, U.K.

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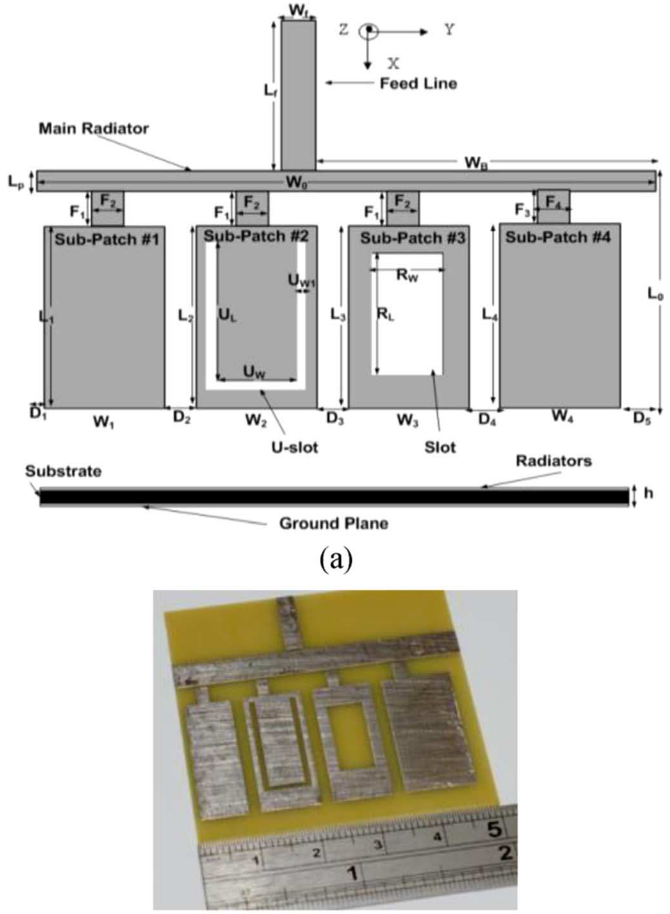


(a)

(b)

Fig. 1. (a) Structure of proposed fixed-design antenna and (b) prototype of fixed-design antenna.

TABLE I
DIMENSIONS OF PROPOSED ANTENNA (UNITS IN mm)

L_o	L_1	L_2	L_3	L_4	L_f	L_P	W_o
31	24	24	24	24	14.6	4	50
W_1	W_2	W_3	W_4	W_f	W_B	F_1	F_2
8	10	10	12	3	27	3	2
F_3	F_4	D_1	D_2	D_3	D_4	D_5	h
3	2.5	2	2	2	3	2	1.57
U_L	U_W	R_L	R_W	U_{W1}	**Total Volume**		
19	7	14	6	1	50 x 50 x 1.57 mm^3		

II. DESIGN OF FIXED MULTIBAND ANTENNA

A. Design of Fixed Multiband Antenna

Fig. 1(a) shows the geometry of the antenna, having five frequency bands, numbered 1, 2, 3, 4, and 5 at 0.92, 1.73, 1.98, 2.4, and 2.9 GHz, respectively. Table I lists the key parameters. The antenna consists of a main patch, four sub-patches (sub-patches 1, 2, 3, and 4), a ground plane, and a 50-Ω feed line. The antenna is designed on an FR-4 substrate with a thickness of 1.57 mm and a relative permittivity of 4.4, occupying an area of 45.6×50 mm^2 on one side of the substrate and an area of 50×50 mm^2 for the ground plane on the other side. The design steps can be described with the aid of Fig. 2(a) to (e) as follows:

Step 1: The main radiator is designed to generate band 4 at 2.4 GHz for the wireless local area network (WLAN) band, and its dimensions are optimized in terms of minimizing the reflection coefficient s_{11} across the band by computer simulation. Fig. 2(a) shows the layout and the optimized s_{11} for the main radiator. At 2.4 GHz, $s_{11} = -18$ dB.

Step 2: Sub-patch 1 is added to the main radiator, as shown in Fig. 2(b), to generate the resonant frequency for band 1 at 0.92 GHz with $s_{11} = -7$ dB. To make room for adding the sub-patch without increasing the antenna size, the width of the main radiator is reduced from 30 mm to 4 mm, so the main radiator in Fig. 2(b) looks like a strip line. Adding sub-patch 1 and reducing the width of the patch increase the s_{11} for band 4 at 2.4 GHz from -18 dB to about -7 dB.

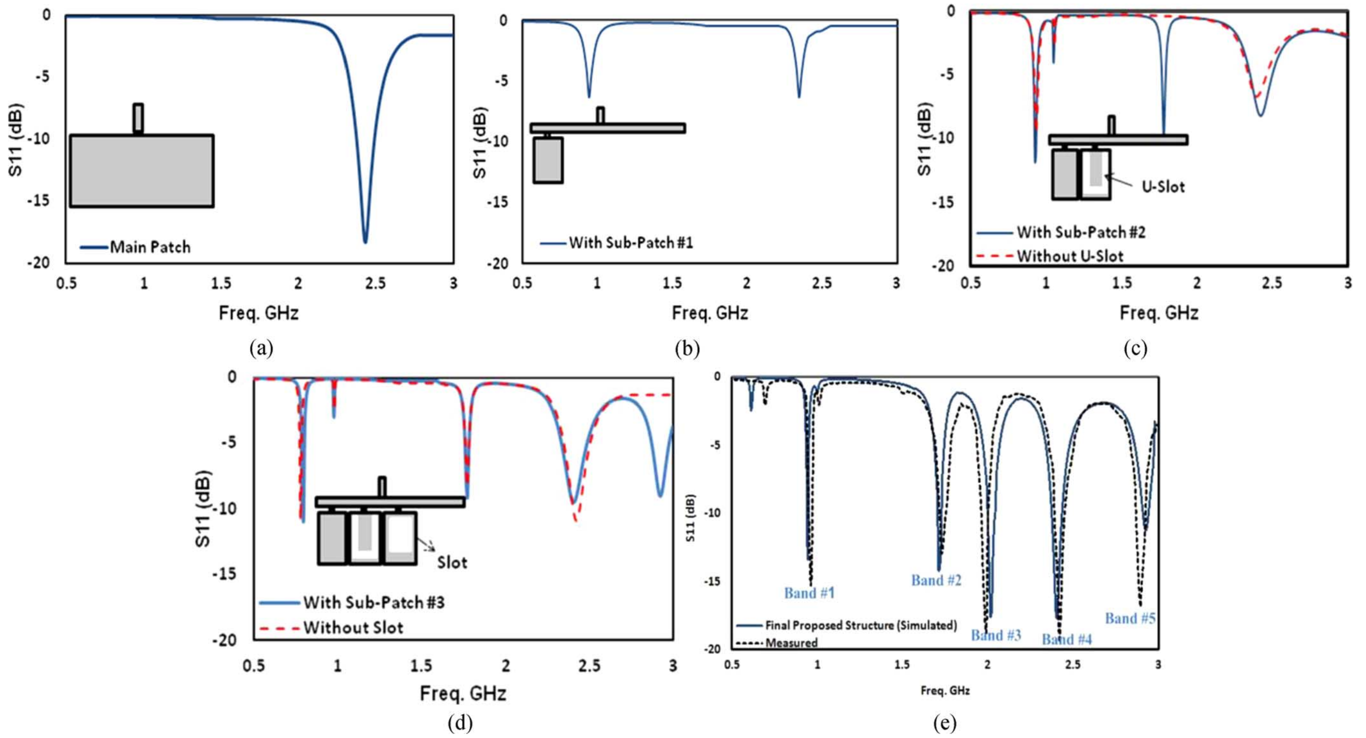
Step 3: Sub-patch 2, with layout shown in Fig. 2(c), is added to the main radiator. A U-slot cut on sub-patch 2 is used to generate band 2 at 1.73 GHz. Sub-patch 2 does not alter the frequencies for bands 2 and 4 generated by the main patch and sub-patch 1, respectively, but it lowers their s_{11} values. Sub- patch 2 also generates an unwanted band at 1 GHz, which will become insignificant in the final design (in step 5). Note that, without the U-slot, band 2 disappears, as can be seen in Fig. 2(c).

Step 4: Sub-patch 3 is added as shown in Fig. 2(d). A rectangular slot is cut on the sub-patch to generate band 5 at 2.9 GHz. It can be seen from Fig. 2(d) that all the bands generated are not affected by sub-patch 3, except band 1 at 0.92 GHz, which is slightly detuned. It will be seen later, however, that adding sub-patch 4 in step 5 will tune the resonant frequency back to 0.92 GHz. Note that, without the rectangular slot, band 5 disappears.

Step 5: Sub-patch 4 is added to generate band 3 at 1.98 GHz, as shown in Fig. 2(e), resulting in five bands, at 0.92, 1.73, 1.98, 2.4, and 2.9 GHz. The s_{11} values in all five bands are much lower than those without having sub-patch 4. For example, when sub-patch 1 is added to the main radiator in step 1, the s_{11} in band 1 is only about -7 dB. When all the sub-patches are added, the s_{11} in band 1 is reduced to more than -10 dB. Thus sub-patch 4 plays a major role in matching. The antenna is fabricated on a substrate, as shown in Fig. 1(b). The s_{11} of the prototyped antenna is measured and shown in Fig. 2(e) for comparison. The simulated and measured s_{11} are in good agreement. The bandwidths ($s_{11} < -10$ dB) for bands 1, 2, 3, 4, and 5 are 45, 61, 70, 140, and 110 MHz, respectively.

B. Current Distribution

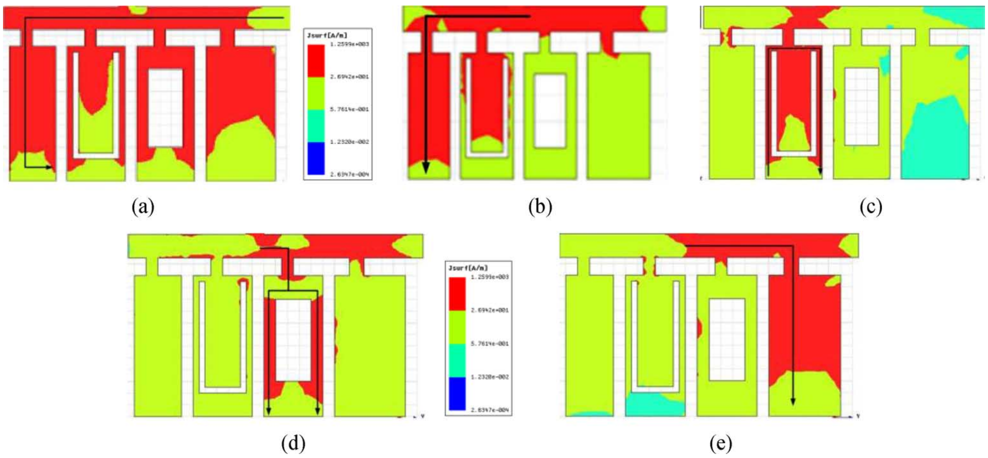
The operations of the antenna at the five resonant frequencies are further studied using surface current distribution. Fig. 3 shows the simulated results. For band 1 at 0.92 GHz, Fig. 3(a) shows that the current mainly flows on the main radiator and sub-patch 1, and this contributes the most radiation. The other sub-patches simply help improve matching. This explains why, when all sub-patches are added to the main patch, the s_{11} at



(a) (b) (c)

(d) (e)

Fig. 2. Simulated s_{11} in different design steps for the proposed antenna: (a) main patch, (b) main patch and sub-patch 1, (c) main patch and sub-patches 1 and 2 with and without U-slot, (d) main patch and sub-patches 1, 2, and 3 with and without rectangular slot, and (e) final design.



(a) (b) (c)

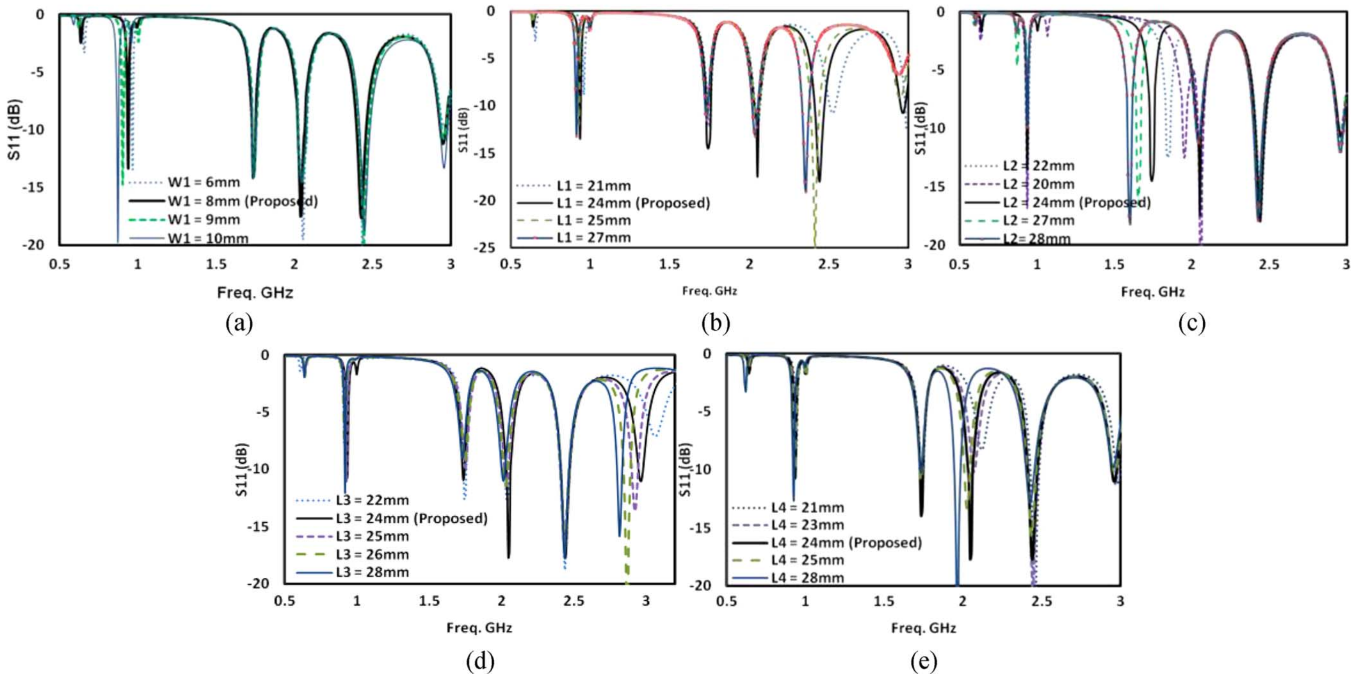
(d) (e)

Fig. 3. Simulated surface current distributions at (a) 0.92 GHz, (b) 2.4 GHz, (c) 1.73 GHz, (d) 2.9 GHz and (e) 1.98 GHz.

0.92 GHz is reduced from −7 dB to more than −10 dB. For band 4 at 2.4 GHz, Fig. 3(b) shows that the current is mainly concentrating on the main radiator and sub-patch 1 (x-direction), and this contributes the most radiation. For band 3 at 1.73 GHz, Fig. 3(c) shows that the current is mainly concentrating on sub-patch 2, which contributes the most radiation. Similarly, for bands 5 and 3 at 2.9 and 1.98 GHz, respectively, sub-patches 3 and 4 have the highest current densities as shown in Fig. 3(d) and (e) and so are responsible for the corresponding radiation. Figs. 3(a) to (e) show the major current paths at the resonant frequencies, corresponding to approximately 0.5λ, where λ is the wavelength at the resonant frequency of the respective band given by $\lambda = \lambda_0/\sqrt{(\varepsilon_r+1)/2}$, λ_0 being the free space wavelength.

C. Independent Control Concept

In the design of multiband antennas, it is desirable to have the ability to set the frequency bands independently from each other, but achieving this is very challenging [13]. Very often, when some parameters are adjusted to set a band to a particular frequency, the frequencies of all other bands are affected [32]–[35], and so the antenna has to be re-designed. In our multiband antenna, however, we can independently set the individual frequency bands, one by one, without affecting other bands. In our studies, we have identified the current paths responsible for radiation at different resonant frequencies, as shown in Fig. 3. Thus, we can change those antenna parameters, which in turn alter the lengths of the current paths and set the



(a) (b) (c)

(d) (e)

Fig. 4. Simulated effects of varying (a) W_1 on 0.92 GHz, (b) L_1 on 2.4 GHz, (c), L_2 on 1.7 GHz (d) L_3 on 2.9 GHz and (e) L_4 on 1.98 GHz.

TABLE II
EFFECTS OF CHANGING $\mathrm{W}_1, \mathrm{L}_1, \mathrm{L}_2, \mathrm{L}_3$ AND L_4, ON s_{11}

Parameters	0.92 GHz	1.73 GHz	1.98 GHz	2.4 GHZ	2.9 GHz
W_1	820–990 MHz (18.78%)	Fixed	Fixed	Fixed	Fixed
L_1	Fixed	Fixed	Fixed	2310–2580 MHz (11%)	Fixed
L_2	Fixed	1550–1948 MHz (22.75%)	Fixed	Fixed	Fixed
L_3	Fixed	Fixed	1952–2044MHz (4.51%)	Fixed	Fixed
L_4	Fixed	Fixed	Fixed	Fixed	2800–3044 MHz (8.21%)
Variation range	6–10 mm	18–28 mm	21–28 mm	20–28 mm	22–28 mm

resonant frequencies independently. For example, at 0.92 GHz band, Fig. 3(a) shows that the current travels along sub-patch 1 in the Y-direction. Thus, changing the width W_1 of sub-patch 1 alters the resonant frequency 0.92 GHz without much effect on the other bands. At 2.4 GHz, Fig. 3(b) shows that the current travels along sub-patch 1 in the X-direction, so the length L_1 can be used to change this frequency without altering other bands. Applying this same principle to Figs. 3(c) to (e), the lengths $\mathrm{L}_2, \mathrm{L}_3$, and L_4 in sub-patches 2, 3, and 4, respectively, can be used to independently set the corresponding frequencies 1.73, 2.9, and 1.98 GHz to other values. Fig. 4 shows the simulation results on the effects of varying the parameters $\mathrm{W}_1, \mathrm{L}_1, \mathrm{L}_2, \mathrm{L}_3$, and L_4 on the frequency bands. It can be seen from Figs. 4(a) to (e) that the parameters $\mathrm{W}_1, \mathrm{L}_1, \mathrm{L}_2, \mathrm{L}_3$, and L_4 can be used to independently adjust the frequency bands at 0.92, 2.4, 1.73, 2.9, and 1.98 GHz over the wide ranges of 18.78%, 11%, 22.75%, 4.51%, and 8.21%, respectively. Table II summarizes these results.

III. RECONFIGURABLE MULTIBAND ANTENNA

A. Design of Reconfigurable Multiband Antenna

The results obtained in the previous section are used here to design a frequency-reconfigurable antenna. The dimensions used to design our frequency-reconfigurable antenna here, as shown in Fig. 5, are same as those of the fixed design, listed in Table I. Four varactors, numbered 1, 2, 3, and 4, are placed at the inputs of the sub-patches. The positions of the varactors and the capacitor on the antenna are optimized so that the maximum tunable ranges with independent control can be accomplished. A surface-mount-ceramic-chip capacitance is used for blocking the DC signal from the biased circuits for the varactors, preventing the DC signal from flowing to the antenna while

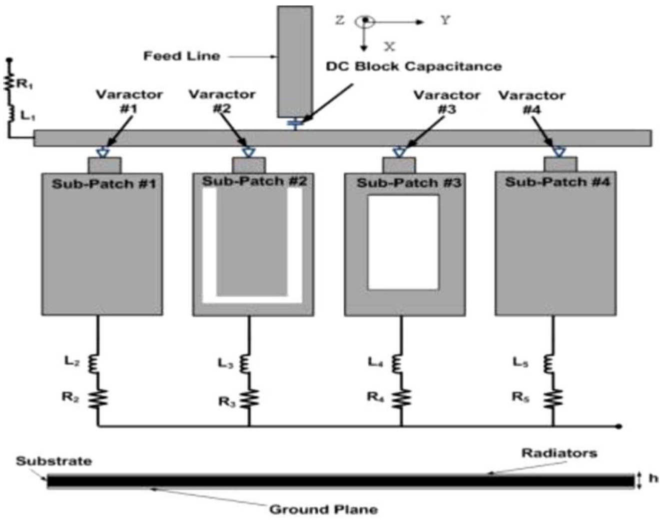


Fig. 5. Proposed reconfigurable design.

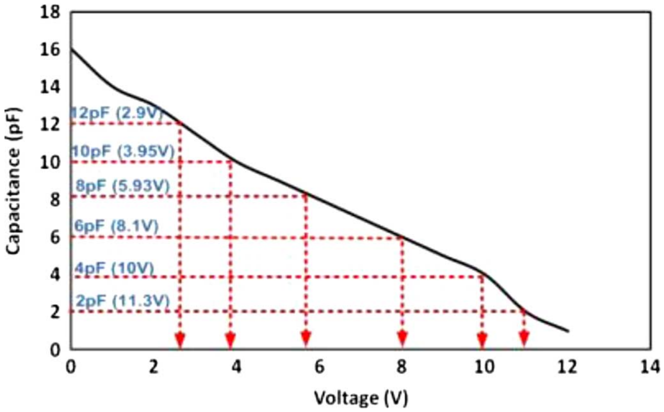


Fig. 6. Capacitance versus DC bias voltage for varactor (from BB184 data sheet).

allowing the radio-frequency (RF) signal to go through. The inductors $\mathrm{L}_1, \mathrm{L}_2, \mathrm{L}_3, \mathrm{L}_4$, and L_5 are used as RF chokes, providing low impedance for the DC signal and high impedance for the RF signal. The resistors $\mathrm{R}_1, \mathrm{R}_2, \mathrm{R}_3, \mathrm{R}_4$, and R_5 are used to give extra protection to the varactors from being damaged. Fig. 5 shows a detailed structure of the bias network. The electromagnetic simulation tool HFSS from ANSYS [36] is used to study antenna performance. Just to prove our design concept, we use the practical varactors BB184 from Philips, with the capacitance versus DC characteristic shown in Fig. 6. It is difficult to model the packaging of the capacitor in a full-wave solver, so the varactors are modeled using the resistance, inductance, and capacitance (RLC) boundary sheet, which gives 0.6 nH for inductance and 0.65 ohm for resistance, and Fig. 6 for the characteristic of the varactors in reverse bias. The varactor has capacitances ranging from 2 to 14 pF for the biased voltages from 14 to 1 V.

The reflection coefficient s_{11} and insertion loss s_{21} have been measured as follows. A 50-Ω microstrip line is fabricated on a PCB. A small slot is cut in the middle of the line to make it two halves of equal length. A DC biased varactor is then placed over the slot to join them together. A network analyzer is used to measure the S-parameters with the biased voltage varied from 14 to 1 V corresponding to 2 to 14 pF. Results show that, with all the biased voltages tested, the varactor has a maximum insertion loss of 0.12 dB at around 2 GHz.

Note that we use practical varactors in our design to prove our design concept. These varactors may not be able to handle high power such as 2 W, but there are high-power varactors that can handle power of up to 4 W [37].

B. Independent Tuning and Control Range

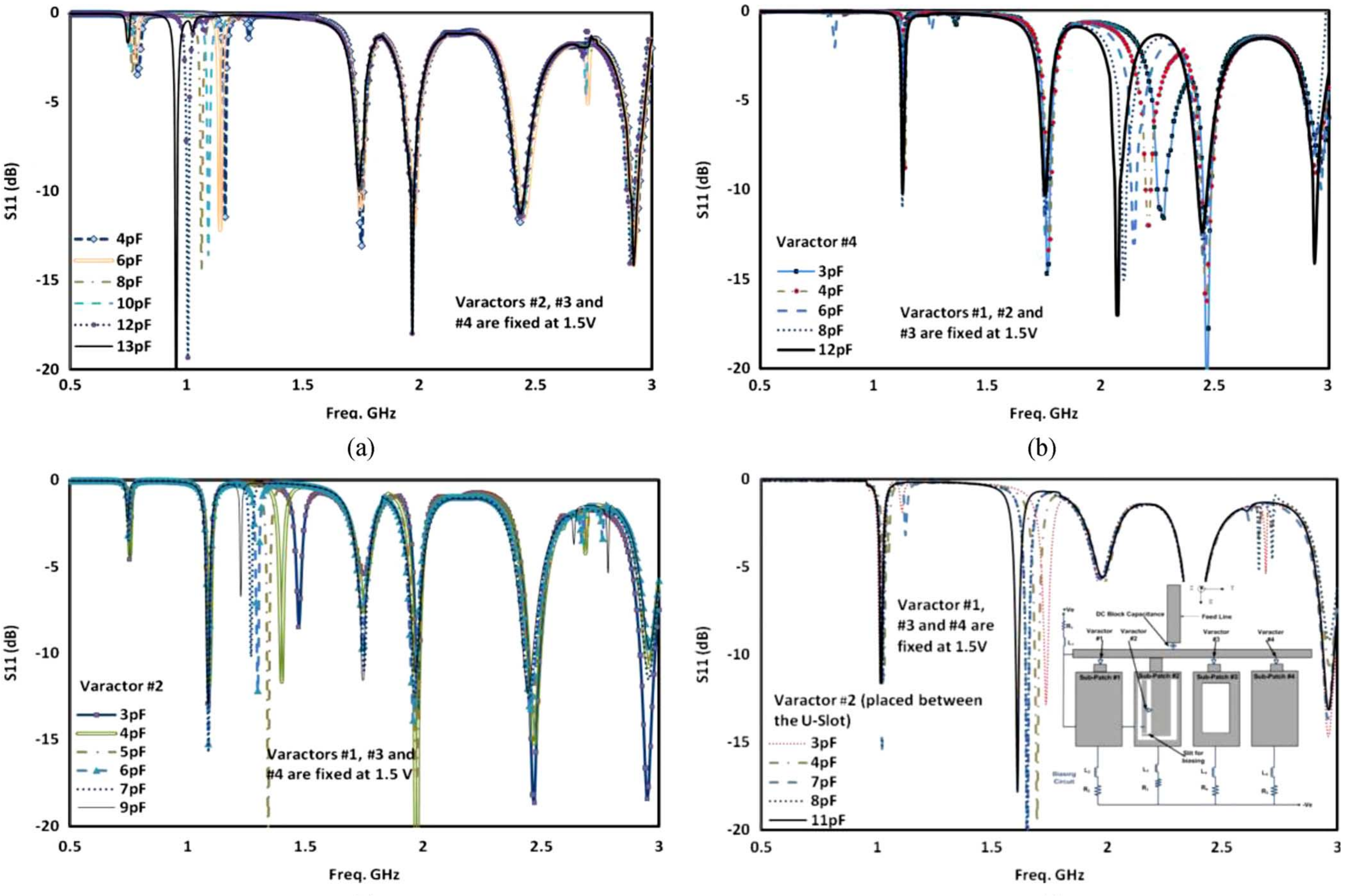
When a DC biased voltage of 1 V is applied to all varactors, simulation results have shown that all the resonant frequencies remain the same as those in the fixed antenna design, i.e., the varactors under such biased condition have no effect on the resonant frequencies. However, if the biased voltage of all varactors is increased to about 1.5 V simultaneously, all resonant bands slightly shift up, with the tuning ranges already shown in [31]. Here, we study the tuning range for each band using the corresponding varactor, at the same time keeping all other bands fixed. To study the tuning range of band 1 at 0.92 GHz, we vary the biased voltage for varactor 1, while keeping the biased voltages for other varactors at 1.5 V (the other varactors can be fixed at any other biased voltages; here we choose 1.5 V just as an example). Fig. 7(a) shows the effect of varying the capacitance of varactor 1 on the resonant frequency 0.92 GHz band. It can be seen that the 0.92 GHz band can be independently tuned between 0.92 and 1.16 GHz without much disturbance to the other four frequency bands. For the tuning range of band 3 at 1.98 GHz, the biased voltage for varactor 4 is varied. We also fix the biased voltage for other varactors at 1.5 V, which slightly shifts all five bands: bands 1, 2, 3, 4, and 5 to 1.08, 1.75, 1.99, 2.48, and 2.98 GHz, respectively. Fig. 7(b) shows the results. It can be seen that band 3 at 1.99 GHz can be tuned independently without much effect on the other four bands. For the tuning range of band 5 at 2.9 GHz, the biased voltage for varactor 3 is varied. Results show that for the capacitance varied from 3 to 12 pF the 2.9 GHz band is moved only by about 3%, which is quite small. (For simplicity, the result is not shown in Fig. 7.) This might be due to the location of the slot, which does not allow the current on this sub-patch to be changed. For the tuning range of band 2, varactor 2 is used. Surprisingly, however, the result in Fig. 7(c) shows that the undesirable frequency band at 1 GHz is enhanced and moved, instead of band 2 at 1.73 GHz. The reason is that the varactor capacitance only improves the matching at this 1 GHz frequency. To solve this problem, we re-designed a U-slot on sub-patch 2 and moved the varactor to the slot gap, as shown in Fig. 7(d), which also shows the effect of varying the capacitance of varactor 2 on the resonant frequency 1.73 GHz band. It can be seen that now the 1.73 GHz band can be tuned independently from 1.73 to 1.56 GHz, while the other four bands remain unchanged. Table III summarizes these results.

Simulation was also carried out on this antenna in a similar manner, using the varactor model described previously, and the simulated results match well with the measured results. For simplicity, we show only the measured results in this paper.

Notice that the bandwidths ($\mathrm{s}_{11} < -10$ dB) for these tunable bands, i.e., bands 1, 2, 4, and 5, are quite narrow at 45, 61, 70, and 110 MHz, respectively, as shown in Fig. 7. However, the tunable ranges of these bands are quite large. The overall bandwidths achieved by superposing the individual bandwidths over the tunable ranges are approximately 23.5%, 10.3%, 13.5%, and 3%, for 0.93, 1.73, 1.98, and 2.9 GHz, respectively. Although the tunable ranges (or operational bandwidths) of the individual bands are quite large, any applications that utilize the antenna are still limited to a few percentage bandwidths of the tuned center frequencies. However, for narrowband mobile systems such as TD-SCDMA or TDD WCDMA which require only 2 and 5 MHz bandwidth, respectively, to operate, the bandwidths of our proposed antenna are good enough [38].

IV. SIMULATED AND MEASURED PERFORMANCES FOR FIXED AND RECONFIGURABLE DESIGNS

The radiation patterns of the fixed and reconfigurable designs are studied by simulation and measurements. For the fixed design, the normalized measured and simulated radiation patterns for co-polarizations and cross-polarizations in the X-Z and Y-Z planes are shown in [30]. For the reconfigurable design, we



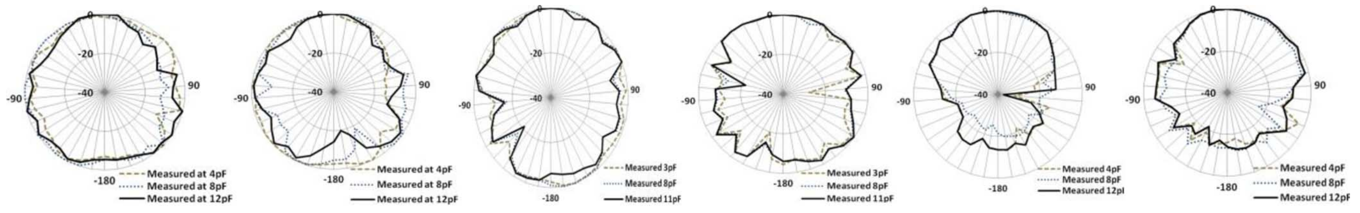
(a) (b)

(c) (d)

Fig. 7. Measured s_{11} for reconfigurable design with independent control using (a) varactor 1, (b) varactor 4, (c) varactor 2 (at the input of sub-patch 2), and (d) varactor 2 (re-located on the U-slot).

TABLE III
EFFECT OF VARYING CAPACITANCES OF VARACTORS INDEPENDENTLY AND/OR SIMULTANEOUSLY

	Band 1	Band 2	Band 3	Band 4	Band 5
Varactor 1	920 – 1165 MHz	Fixed	Fixed	Fixed	Fixed
Varactor 2	Fixed	1560-1730 MHz	Fixed	Fixed	Fixed
Varactor 3	Fixed	Fixed	Fixed	Fixed	2900 – 2990 MHz
Varactor 4	Fixed	Fixed	1980 – 2267MHz	Fixed	Fixed
Bandwidth covered	23.5%	10.3%	13.5%	--	3%



X-Z (a) Y-Z X-Z (b) Y-Z X-Z (c) Y-Z

Fig. 8. Measured Co-Pol radiation patterns for reconfigurable design for X-Z and Y-Z planes with different capacitance values at (a) band 1, (b) band 2, and (c) band 3.

studied the effects of varactor capacitance on the radiation patterns in three bands, i.e., bands 1, 2, and 3 as shown in Fig. 8(a) to (c). The study was not done for band 4 (which is not tunable) or band 5 (which has a very small tunable range of only 3%). The measured gains for the fixed design are -4.2 dBi at 0.92 GHz, 0.95 dBi at 1.73 GHz, 1.19 dBi at 1.98 GHz, 0.91 dBi at 2.4 GHz, and 2 dBi at 2.9 GHz, whereas the corresponding simulated gains are $-1.0, 1.6, 1.2, 1.05$, and 2.2 dBi, respectively. The differences between the simulated and measured gains might be due to the following reasons. i) The loss of the FR-4 material used varies with frequency, but, in simulation, a fixed tangent loss was assumed at all frequencies. ii) The cable and connector were used in measurements, while they were not taken into account in simulation. iii) The fabrication tolerance in the prototype would also affect the measured results. iv) There would be tolerances in the measurement system. For the reconfigurable design, simulation results show that the peak gains are less than those of the fixed design. The simulated efficiency in the fixed design ranges from 39% to 59%. With a varactor capacitance of 14 pF, the simulated peak gains for the five bands are -2.2, -0.42, -0.2, -0.6, and 0.4 dBi, and the simulated efficiency ranges from 29% to 50%, having a drop of about 10% compared with those of the fixed design. The resistance of the varactor could affect radiation efficiency, as demonstrated in [28], [39], and [40], which showed that a high resistance had significant effects on the gain and radiation efficiency of the antenna. In our design, however, the resistance in the varactor diodes is quite small at 0.65 ohm and so has much less effect on efficiency. In fact, our further studies show that radiation efficiency would increase by 5% if this resistance is reduced to zero.

V. CONCLUSION

This paper has presented the designs of compact five-band printed antennas for fixed or reconfigurable communications systems. The fixed design has five frequency bands at 0.92, 1.73, 1.98, 2.4, and 2.9 GHz. The design procedure for the antenna has been described in detail. By adding four varactors to the design, it becomes a reconfigurable design, enabling the four bands to be electrically and independently tuned over wide ranges. Both designs have been fabricated and measured. The measured and simulated results are in good agreement.

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Hattan F. Abutarboush (M'07) received the B.Sc. (Eng.) Honours degree in electrical communications and electronics engineering from Greenwich University, London, U.K., in 2005, the M.Sc. degree in mobile personal and satellite communications from Westminster University, London, U.K., in 2007, and the Ph.D. degree from Brunel University, London, U.K., in July 2011. His Ph.D. research work was mainly on fixed and reconfigurable multiband antennas.

He was a Research Visitor to Hong Kong University and the National Physical Laboratory (NPL), Teddington, U.K. He also worked as a Research Associate for the American University in Cairo from April to July 2011. He is a Research Fellow at King Abdullah University of Science and Technology (KAUST). He has published several technical papers in international journals and conferences. He also has served as reviewer for different international journals and conferences in the areas of antennas and propagation. His current research interests lie in the design of reconfigurable antennas, multiband antennas, antennas for mobile phones, miniaturized antennas, smart antennas, antenna arrays, EBG, RF/microwave circuit design, mm-wave antennas, on-chip antennas and lens antennas.

Dr. butarboush is a member of IET.

R. Nilavalan (M'05–SM'10) received the B.Sc. Eng. in electrical and electronics engineering from the University of Peradeniya, Sri Lanka, in 1995 and the Ph.D. in radio frequency systems from University of Bristol, Bristol, U.K., in 2001.

From 1999 to 2005, he was a Researcher at the Centre for Communications Research (CCR), University of Bristol, U.K. At Bristol, his research involved theoretical and practical analyses of post reception synthetic focussing concepts for near-field imaging and research on numerical FDTD techniques. Since 2005, he has been with the Electronics and Computer Engineering department, Brunel University, where he is currently a Senior Lecturer in wireless communications. His main research interests include antennas and propagation, microwave circuit designs, numerical electromagnetic modelling and wireless communication systems. He has published over 90 papers and articles in international conferences and journals in his research area.

Dr. Nilavalan was a member of the European commission, Network of Excellence on Antennas (2002–2005) and a member of the IET.

S. W. Cheung received the B.Sc. degree (with First Class Honours) in electrical and electronic engineering from Middlesex University, U.K., in 1982 and the Ph.D. degree from Loughborough University of Technology, U.K., in 1986.

From 1982 to 1986, he was a Research Assistant in the Department of Electronic and Electrical Engineering, Loughborough University of Technology, where he collaborated with Rutherford Appleton Laboratory and many U.K. universities to work a project for new generations of satellite systems. During the period from 1986 and 1988, he was a Postdoctoral Research Assistant with the Communications Research Group of King's College, London University, working on research for future generations of satellite systems. In 1988, he joined the Radio and Satellite Communications Division in British Telecom Research Laboratories (now British Telecom Laboratories), as an Assistant Executive Engineer. He is an Associate Professor at the University of Hong Kong and in charge of the Microwave, RF Frequency and Telecom Laboratories. His current research interests include antenna designs, 2G, 3G and 4G mobile communications systems, MIMO systems and satellite communications systems, predistortion of high power amplifiers and e-learning. He has published over 150 technical papers in international journals and conferences in these areas. He also has served as reviewer for different international journals and conferences in the areas of antennas and propagation and mobile communications.

Dr. Cheung has been serving the IEEE in Hong Kong for the past 20 years. In 2009 and 2010, he was the Chairman of the IEEE Hong Kong Joint Chapter on Circuits and Systems and Communications. Since 2011, he has been the Treasurer of the IEEE Hong Kong Section and help organizing different international conferences.

Karim M. Nasr received the Ph.D. degree from the University of Manchester, U.K., in 2005, with a dissertation on "Smart Antenna Systems for Indoor Wireless Networks."

He previously held postdoctoral research posts at the University of Manchester, Brunel University, and BBC Research investigating future wireless and broadcast communication systems and applications through a number of U.K. and European research projects. He was also a Visiting Researcher at the antennas and propagation of Aalborg University, Denmark. He is presently a Higher Research Scientist at the National Physical Laboratory (NPL), Teddington, U.K., investigating advanced wireless communication systems and high precision large volume laser based metrology. His research interests include: propagation measurements and modelling, digital signal processing and metrology for broadband wireless and broadcast systems, smart antennas and multiuser MIMO systems, UWB, joint physical/MAC layers optimization, coexistence of wireless systems, advanced antenna metrology and laser based coordinate metrology.

Dr. Nasr is a Chartered engineer (CEng.) and a member of the IET and European COST Actions on wireless communication systems. He is a reviewer for several IEEE TRANSACTIONS and a member of TPC of several international conferences.