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TECHNICAL PAPER

A small asymmetric coplanar strip fed tri-band antenna for PCS/WiMAX/WLAN applications

Praveen V. Naidu[1] · **Akshay Malhotra**[1]

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Abstract In this paper, a small asymmetric coplanar strip (ACS)-fed monopole antenna for tri-band operation is proposed. The proposed antenna is composed of an arc-shaped monopole strip, a rectangular-shaped branch, and an L-shaped strip attached to an extension of the feed line. The three operating bands are obtained from the excitation of resonances due to these strips. The resonances can be controlled by tuning each individual strip separately. The measured results show that the proposed antenna has −10 dB impedance bandwidth of 250 MHz from 1.75 to 2.0 GHz, 300 MHz from 3.2 to 3.5 GHz and 1.8 GHz from 5.0 to 6.8 GHz. Further, the antenna has good bidirectional radiation patterns in the E-plane, omnidirectional radiation patterns in the H-plane and reasonable peak gains in the all operating bands. With these features and a compact size, the proposed antenna will be suitable for PCS 1900, 3.5/5.5 GHz WiMAX and 5.2/5.8 GHz WLAN portable wireless communication applications.

1 Introduction

In recent years, due to rapid developments in cellular and mobile communication technology, designing a portable wireless system which will work on multiple communication standards is of great interest in antenna research. Especially, the integration of the 1.9 GHz PCS/DCS, 5.2/5.8 GHz wireless local area network (WLAN), 3.6 GHz long term evolution (LTE) and 3.5/5.5 GHz worldwide interoperability of microwave access (WiMAX) frequency bands into one system has grabbed major attention of engineers and researchers because of its maximum usability in all smart phones, tablets and laptops. Thus to meet the above commercial requirements, various types of antenna designs with dual/tri-band operation have been proposed in the literature.

Liu et al. (2004) presented a 20 × 30 mm^2 size meandered patch antenna for dual frequency operation. The proposed antenna consists of CPW feeding with uniplanar rectangular radiating element that can support both the UMTS and WLAN bands. Though the reported structure was simple, it was not able to cover 3.5 GHz WiMAX band. In order to integrate 3.5 GHz WiMAX band, Song et al. (2007) designed a triangular shape CPW-fed multiband antenna for WLAN/WiMAX applications. Adjustable strips were used to enhance the impedance bandwidth in the higher frequency band. Even though the reported antenna covers wider impedance bandwidth, it occupies a very large area of 840 mm^2.

Huang et al. (2011) design and developed a novel monopole slot antenna with embedded rectangular parasitic elements for dual-band applications. Though the reported antenna was having wider impedance bandwidth, it was having drawback of large dimensions i.e. 30 × 50 mm^2 including ground plane. In order to support, all the frequency standards of WLAN and WiMAX, a slot monopole antenna (Hu et al. 2011) with tri-band frequency of operation was obtained. The reported antenna has three operating band from 2.34 to 2.82 GHz, 3.16–4.06 GHz, and 4.69–5.37 GHz respectively, which can cover WLAN and WiMAX bands.

Lin et al. (2012) reported a very large size (50 × 50 mm^2) rhombus shaped slot antenna for dual frequency operation. By properly selecting the feeding structure and rectangular

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✉ Praveen V. Naidu
praveennaidu468@gmail.com

[1] Centre for Radio Science Studies, Symbiosis International University (DU), Pune 412 115, India

strips, two independent resonant frequencies having −10 dB bandwidths of 607 MHz resonated at 2.45 GHz and 1451 MHz resonated at 5.5 GHz were achieved. Teng et al. (2012) proposed a CPW-fed triangular shaped antenna with dimensions of 28 × 26 mm^2. In the design, a Π-shaped slot and a T-shaped strip were introduced to generate two separate impedance bandwidths ranging from 2.36 to 2.50 GHz and from 5.01 to 6.33 GHz respectively. Though the reported structure was small and simple, it was not able to cover 3.5 GHz WiMAX band.

Similarly, to meet WLAN and WiMAX applications, rupee shaped multi-band antennas (Naidu and Kumar 2015a, b) and a bow tie shaped CPW-fed slot antenna (Tsai 2014) were proposed. In the reported design (Tsai 2014), an M-shaped patch at the centre of the slot is used as a radiating element. The developed antenna achieves a dual frequency operation from 2.26–2.57 GHz and 4.81–6.56 GHz and has dimensions of 60 × 45 mm. Again the reported design was having limitations of large size and narrow impedance bandwidth. A detailed comparative study of the recently reported CPW-fed multi-band antennas in terms of its performance characteristics are given in Table 1. From the table, it is seen that even though the CPW feeding is having many advantages such as uniplanar structure, simple to design and has less cost of fabrication (one side printing), all the reported antennas are having drawbacks of large size, narrow bandwidth and limited frequency of operation.

Some other designs based on microstrip feeding like rhombic shaped slot antenna (Xie et al. 2012), L and E-shaped antenna (Sun et al. 2012), rectangular ring with L-shaped strip (Yuan et al. 2013) and a tri-band monopole antenna with L-shaped strip and a meandered strip (Ren et al. 2015) were reported for multi-band applications. Many of these reported designs are having either complex structures or large size and in addition to these drawbacks, very few reported antennas with large size are covering desired WLAN and WiMAX frequency bands. A detailed comparison in terms of parameters like size, type, total area occupied and frequency of operation of the reported microstrip fed antennas are given in Table 2. From the table it has been observed that, all of these reported designs are having either complex structures or large in size, in addition to this some of the reported large size antennas are covering only few WLAN/WiMAX operating bands. None of the reported antennas satisfy all the requirements of a modern portable wireless communication system. This leads to a limited access of service in PCS/DCS, LTE, WLAN, WiMAX, frequency bands. Hence these reported antennas are very difficult to integrate with RF/MMIC circuits.

To decrease the overall size of an antenna, some designs have been reported in Deepu et al. (2007), Song et al. (2008), Naidu and Kumar (2014), Deepu et al. (2009), Naidu and Kumar (2015c), Naidu and Malhotra (2015a), Ashkarali et al. (2012), Li et al. (2013), Naidu and Malhotra (2015b, c), Naidu et al. (2015) by using the new concept called Asymmetric Coplanar Strip (ACS)-feeding. In comparison to general CPW-fed antenna, an ACS-fed antenna structure will consume only 50 % area by considering only half of the ground plane of CPW-fed structure. Table 3 shows the comparison of size, operating bands and average peak gains of the reported antennas. It was found that most of the reported ACS-fed dual-band antennas were compact in size but again they are having drawbacks of complex structure, narrow bandwidth and limited/no access of 5.2 GHz WLAN and 3.5/5.5 GHz WiMAX frequency band services. To overcome these problems, a compact 17.2 × 30 mm^2 ACS-fed tri-band monopole antenna is presented in this paper.

Table 1 Comparison of referenced CPW-fed multi-band antennas

	Type	Size (mm^2)	Area (mm^2)	Bandwidth	Gain (dBi)
Liu et al. (2004)	Dual-band	20 × 30	600	1.92–2.18 GHz and 4.99–5.7 GHz	2.2
Song et al. (2007)	Dual-band	35 × 24	840	2.36–2.50 GHz and 3.40–6.41 GHz	2.7
Lee et al. (2009)	Dual-band	40 × 35	1400	2.2–2.55 GHz, 3.0–5.6 GHz	2.0
Zhuo et al. (2011)	Dual-band	20 × 25	500	2.25–2.48 GHz and 5.0–6.2 GHz	2.4
Huang et al. (2011)	Dual-band	50 × 30	1500	2.38–2.51 GHz and 4.87–6.00 GHz	2.6
Hu et al. (2011)	Tri-band	28 × 32	896	2.3–2.8 GHz, 3.1–4.0 GHz and 4.6–5.3 GHz	3.0
Lin et al. (2012)	Dual-band	50 × 50	2500	2.38–2.99 GHz and 4.95–6.41 GHz	3.5
Teng et al. (2012)	Tri-band	28 × 26	728	2.36–2.50 GHz and 5.01–6.33 GHz	3.0
Xie et al. (2012)	Tri-band	35 × 25	875	2.34–2.50 GHz, 3.1–3.82 and 5.13–5.89 GHz	2.4
Tsai (2014)	Dual-band	60 × 45	2700	2.26–2.57 GHz and 4.81–6.56 GHz	3.2
Proposed antenna	Tri-band	17.2 × 30	516	1.75–2.0 GHz, 3.2–3.5 GHz and 5.0–6.8 GHz.	3.0

It is seen that even though the CPW feeding is having many advantages such as uniplanar structure, simple to design and have less cost of fabrication (one side printing), all the reported antennas are having drawbacks of large size/narrow bandwidth and limited frequency of operation

Table 2 Comparison of referenced microstrip-fed multi-band antennas

Reference	Type	Size (mm^2)	Area (mm^2)	Operating bands	Gain (dBi)
Basaran et al. (2009)	Dual-band	32 × 20	640	2.4–2.484 GHz and 5.151–5.825 GHz	–
Ghalibafan et al. (2010)	Dual-band	100 × 100	10000	2.40–2.48 GHz and 3.6–3.9 GHz	–
Sun et al. (2012)	Dual-band	40 × 30	1200	2.39–2.51 GHz and 5.0–6.1 GHz	1.0
Xie et al. (2012)	Dual-band	40 × 40	1600	3.15–3.70 GHz and 5.05–5.97 GHz	4.0
Mehdipour et al. (2012)	Tri-band	22 × 29	638	2.4–2.6 GHz, 3.4–3.75 and 5.0–6.3 GHz	1.5
Flores-Leal et al. (2012)	Dual-band	40 × 40	1600	2.4–2.484 GHz and 5.151–5.825 GHz	1.6
Yuan et al. (2013)	Tri-band	21 × 33	693	2.39–2.51 GHz, 3.26–4.15 and 5.0–6.43 GHz	2.5
Lin et al. (2014)	Dual-band	35 × 20	700	2.4–2.5 GHz and 5.0–6.0 GHz	2.9
Ren et al. (2015)	Tri-band	38 × 20	760	2.32–2.51 GHz, 3.0–3.95 and 5.4–5.95 GHz	3.1
Proposed antenna	Tri-band	17.2 × 30	516	1.75–2.0 GHz, 3.2–3.5 GHz and 5.0–6.8 GHz.	3.0

It can be seen that, all of these reported designs are having either complex structures or large in size, in addition to this some of the reported large size antennas are covering only few WLAN/WiMAX operating bands

Table 3 Comparison of referenced ACS-fed multi-band antennas

Published literature	Antenna size (mm^2)	Antenna purpose		Antenna type	Average peak gains (dBi)
		WLAN (GHz)	WiMAX (GHz)		
Deepu et al. (2007)	28 × 30	2.4/5.2/5.8	3.5	Dual-band	~2.1
Song et al. (2008)	31 × 15	2.4/5.2/5.8	–	Tri-band	~2.4
Deepu et al. (2009)	21 × 19	2.4/5.2	–	Dual-band	~1.9
Ashkarali et al. (2012)	37.5 × 24	2.4	–	Dual-band	~1.21
Li et al. (2013)	35 × 19	2.4/5.2/5.8	3.5/5.5	Tri-band	~2.2
Proposed antenna	17.2 × 30	5.2/5.8	3.5/5.5	Tri-band	~3.0

It can be seen that many of the reported ACS-fed dual-band antennas were compact in size but again they are having drawbacks of complex structure, narrow bandwidth and limited/no access of 5.2 GHz WLAN and 3.5/5.5 GHz WiMAX band services

The proposed antenna has an arc-shaped monopole strip, a rectangular-shaped branch, an L-shaped strip and a rectangular ground plane are used to meet the PCS and WLAN/WiMAX requirements. The 3-D electromagnetic software CST Microwave Studio is used for the antenna structure design and validation purpose. The evolution process in the generation of the various working bands are given in detail and the effects of key structural parameters like strip length on the antenna performance are explained. The measured 10 dB impedance bandwidths are 250 MHz from 1.75 to 2.0 GHz, 300 MHz from 3.2 to 3.5 GHz and 1.8 GHz from 5.0 to 6.8 GHz. Compared to the aforementioned referenced antennas, the proposed antenna can cover PCS 1900, LTE 3600, WLAN and WiMAX bands by providing a very compact structure with omnidirectional radiation patterns and acceptable gains.

2 Antenna design

The geometry of the proposed tri-band monopole antennas fed by an asymmetric coplanar strip are shown in Fig. 1 and its simulated return loss characteristics are given in Fig. 2. The antenna is designed and printed on a FR4 substrate having dielectric constant 4.4, thickness 1.6 mm and a loss tangent of 0.02. The antenna has an overall dimension of 17.2 × 30 mm^2. The signal strip width of the ACS is kept at 3.2 mm while the gap between the signal strip and the ground plane is fixed at 0.5 mm to obtain the characteristic impedance of 50 ohms for the feed line. To form the monopole, the signal strip is vertically extended. Further, to the rectangular extension of the feed line, an L-shape strip and an arc shape strip (Naidu and Malhotra 2015a) in Fig. 1a and meandered C-shaped strip in Fig. 1b are attached. The triple-band performance of the proposed antenna are obtained from these three radiating monopoles which have different lengths. The optimized parameter values of the antenna are given in Table 4.

2.1 Mathematical analysis

The optimized ground plane parameter values and the gap between the signal strip and the ground plane can be

Fig. 1 Geometry of the proposed compact ACS-fed tri-band antennas. **a** Arc-shape tri-band antenna. **b** C-shape tri-band antenna

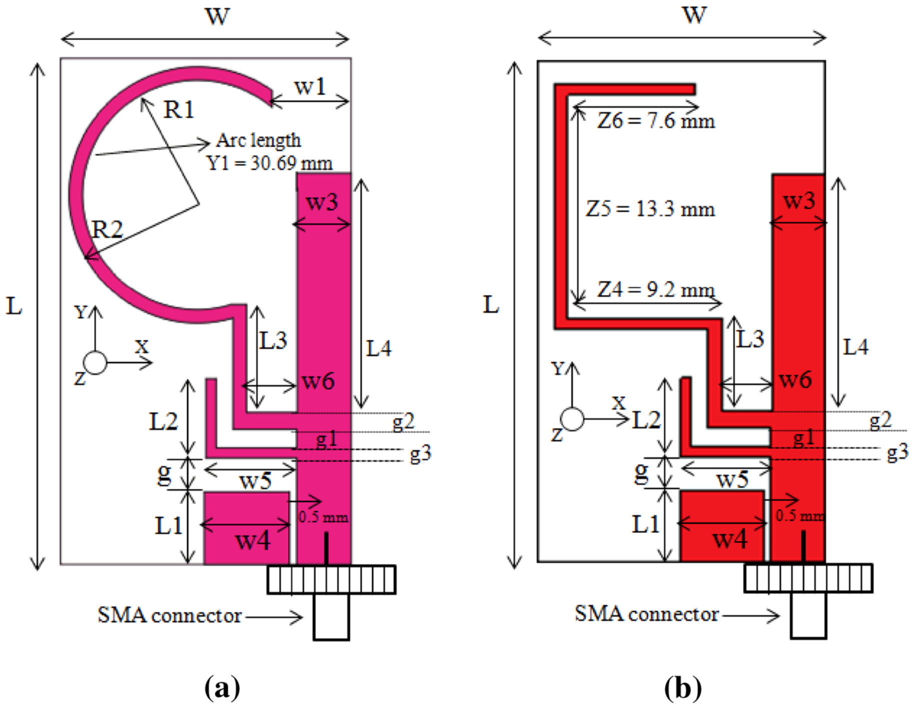


Fig. 2 Simulated return loss against frequency of the proposed tri-band antennas

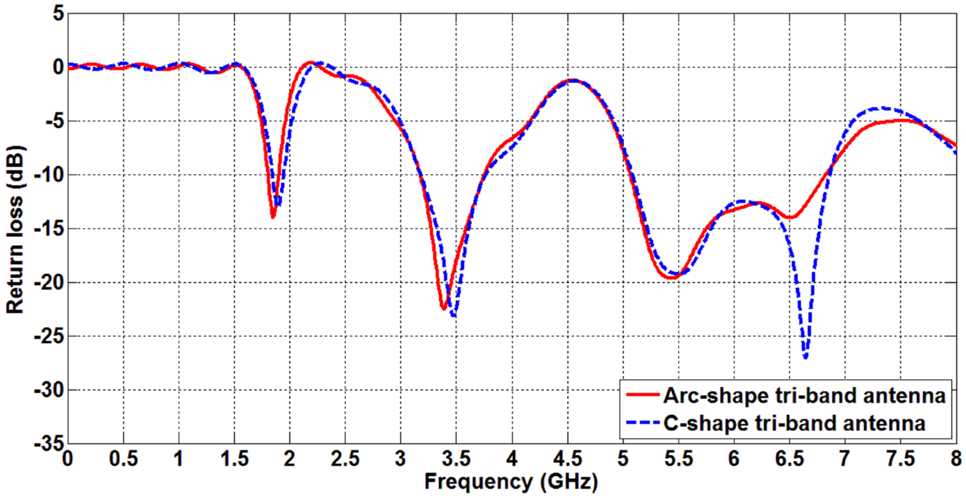


Table 4 Optimized parameter values (in mm)

Parameter	L	W	L1	L2	L3	L4	W1	W3	W4
Value (mm)	30	17.2	4.3	4.1	6.4	14.2	4.7	3.2	5
Parameter	W5	W6	R1	R2	g	g1	g2	g3	
Value (mm)	4.7	3	6.8	7.6	2	1.1	1	0.6	

calculated from the expressions (1)–(3), as given in (Raj et al. 2006).

$$L_1 = \frac{0.041c}{f_1\sqrt{\varepsilon_{r,eff}}} \tag{1}$$

$$W_4 = \frac{0.050c}{f_1\sqrt{\varepsilon_{r,eff}}} \tag{2}$$

$$Gap = \frac{0.0050c}{f_1\sqrt{\varepsilon_{r,eff}}} \tag{3}$$

The coefficients 0.041, 0.050 and 0.0050 were derived empirically after studying the effect of ground plane on the impedance matching for the proposed antenna.

In the design, the resonant lengths of the arc-shaped monopole (Fig. 1a) ‘Z1’, C-shaped monopole (Fig. 1b) ‘Z7’ ($Z7 = Z4 + Z5 + Z7 + L3 + W6 + g + g1 + g2 + g3$) and ($Z1 = Y1 + L3 + W6 + g + g1 + g2 + g3$), rectangular-shaped monopole ‘Y1’ ($Y1 = L4$) and the L-shaped monopole ‘X1’ ($X1 = L2 + W5$) are set close to half-wavelength, quarter-wavelength and quarter-wavelength respectively of the fundamental resonant frequencies which they are supposed to excite. The lengths can be calculated from the desired resonance frequencies from Eqs. (4)–(7). All the three resonant frequencies can be tuned independently by varying the lengths of the individual radiating strips.

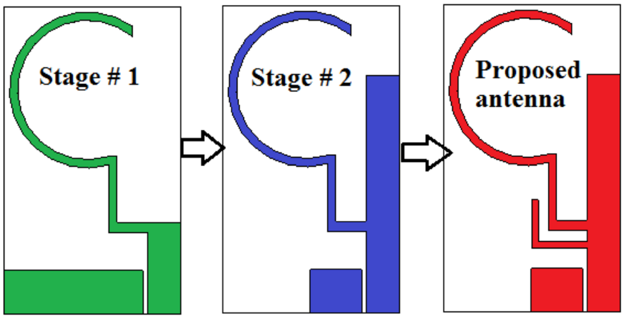


Fig. 3 Evolution process of the proposed arc-shaped tri-band monopole antenna

$$Z7 = Z1 = \frac{c}{2f_1\sqrt{\varepsilon_{r,eff}}} \tag{4}$$

$$Y1 = \frac{c}{4f_2\sqrt{\varepsilon_{r,eff}}} \tag{5}$$

$$X1 = \frac{c}{4f_3\sqrt{\varepsilon_{r,eff}}} \tag{6}$$

$$\varepsilon_{r,eff} = \frac{\varepsilon_r + 1}{2} \tag{7}$$

Fig. 4 Simulated return loss curves of various ACS-fed structures involved in the design evolution process

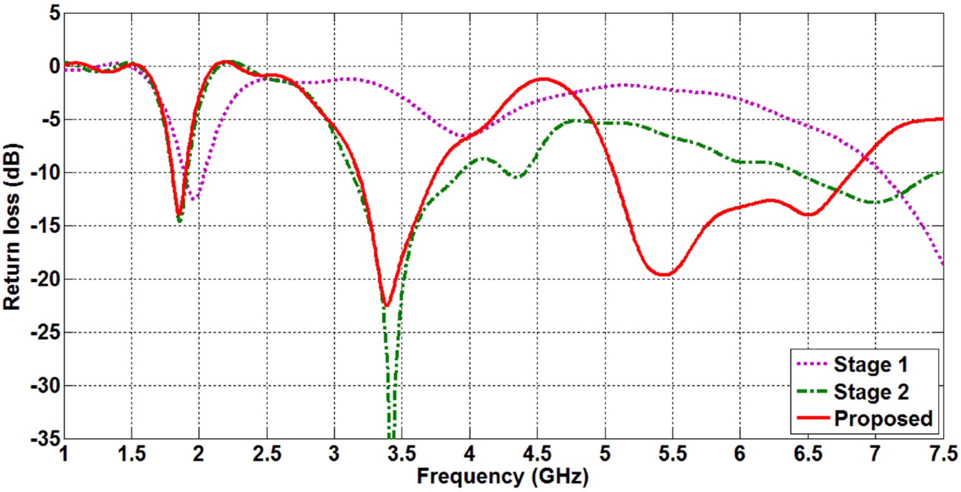


Fig. 5 Simulated surface current distributions of the antenna at 2.3, 3.5 and 5.4 GHz

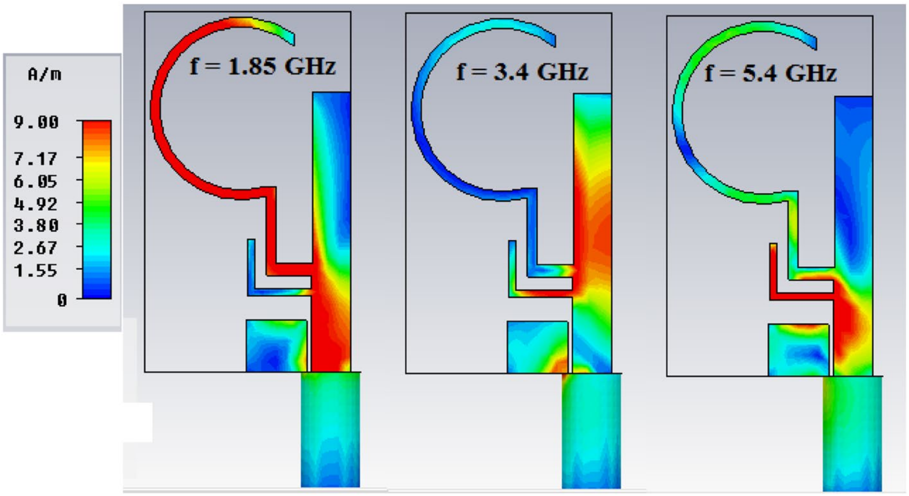
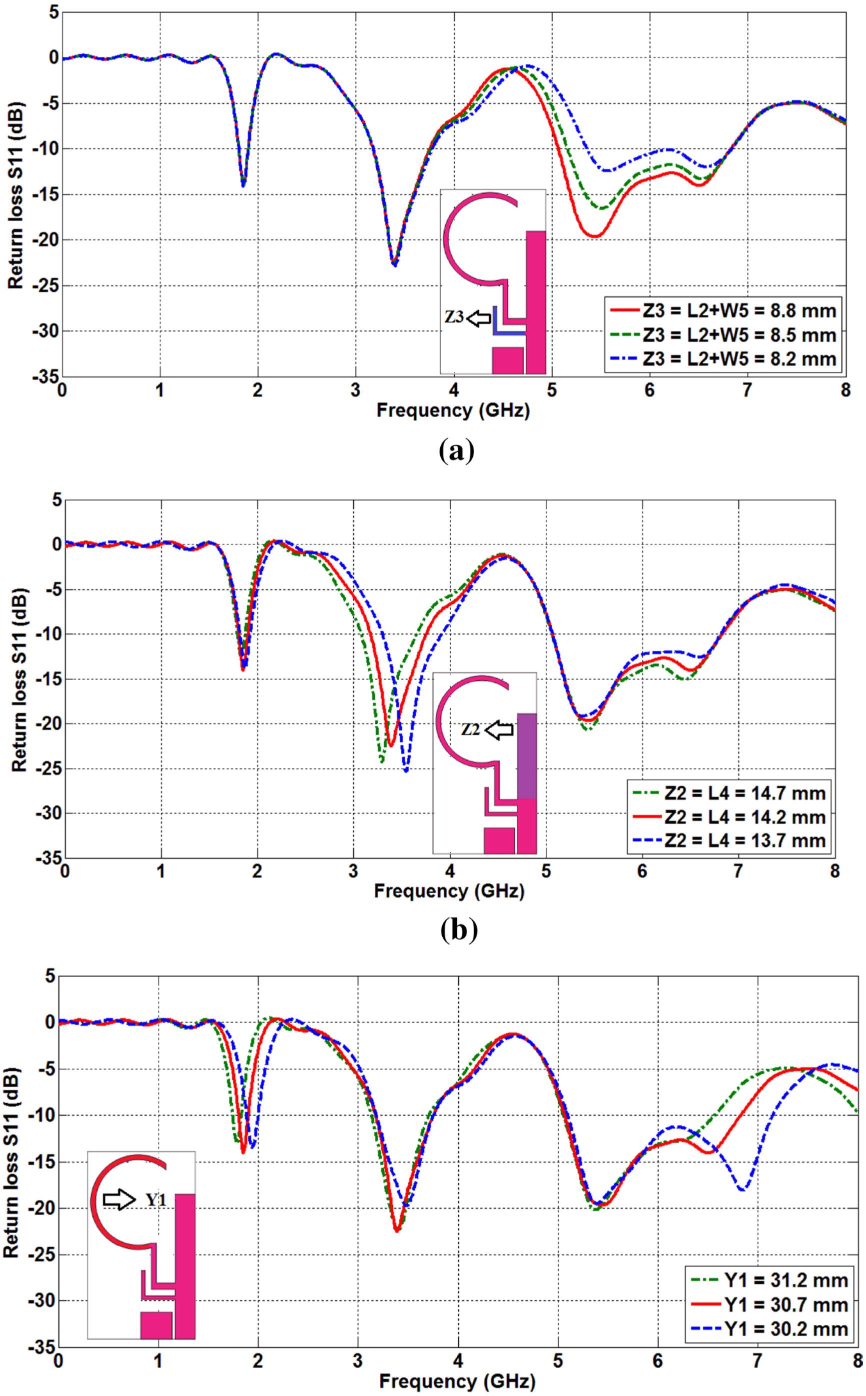


Fig. 6 **a** Simulated reflection coefficients of the proposed antenna with varied Z3. **b** Simulated reflection coefficients of the proposed antenna with varied Z2. **c** Simulated reflection coefficients of the proposed antenna with varied Y1



(a)

(b)

(c)

Here c stands for the velocity of light in free space, $\varepsilon_{r,eff}$ is the effective relative permittivity of the substrate which can be calculated from Eq. (4). For calculating the effective relative permittivity, it is assumed that for a ACS-fed monopole, half of the established field lies in air while the remaining half is distributed in the substrate.

For the design optimization and validation purpose, the commercially available 3-D electromagnetic software CST Microwave Studio was used. Figure 3 shows the evolution of the proposed tri-band antenna while the corresponding simulated return losses are given in Fig. 4. The antenna (stage 1) shown in Fig. 3 is the basic ACS-fed monopole structure, which consists of an ACS-feed and a monopole.

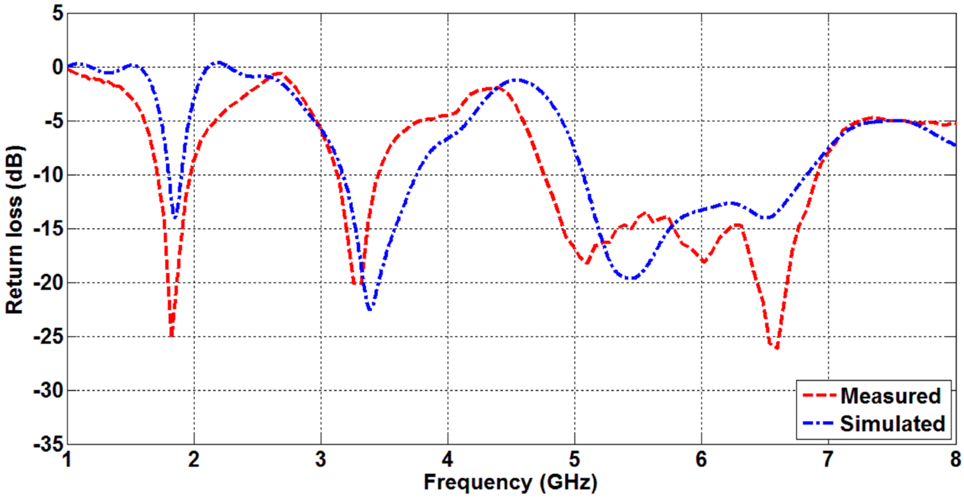


Fig. 7 Simulated and measured return loss against frequency

The monopole considered in this design is an arc-shaped strip. As shown in Fig. 4, with this structure, a resonant frequency at 1.96 GHz is obtained. Next, to generate a second resonant frequency at 3.5 GHz along with the tuning of the first resonant frequency to the desired operating band near 1.85 GHz, a rectangular shaped strip is introduced to stage 1. This along with the modified ground plane forms the stage 2. With this design, dual-band performance is achieved. In Fig. 4, the antenna of stage 2 shows two resonant frequencies at 1.85 GHz and 3.5 GHz. Next, by introducing an L-shaped branch to stage 2 the final stage (proposed antenna) is obtained. Here, a third resonant mode at 5.4 GHz (with a band from 5.0 to 6.8 GHz) is generated. In this way, the proposed antenna has three operating bands from 1.75 to 2.0 GHz, 3.2–3.5 GHz and 5.0–6.8 GHz to meet the requirements of the 1900 MHz PCS, 5.2/5.8 GHz WLAN and 3.5/5.5 GHz WiMAX applications.

In order to understand the formation of the resonances of the proposed ACS-fed tri-band antenna, the simulated surface current distributions on the radiating monopoles at the three resonant frequencies i.e. 1.85, 3.4 and 5.4 GHz are shown in Fig. 5. For the 1.85 GHz, a large surface current distribution is observed on the arc shaped monopole branch (Z1). This indicates that the arc-shaped monopole branch is the key radiating element to excite the 1.85 GHz resonant mode at $\lambda_g/2$. For the 3.4 GHz resonance, from the figure it is observed that more surface current is concentrated on the vertical rectangular shaped monopole (Y1) and very less current density is present on the other radiating branches, implying that the resonance is because of the $\lambda_g/4$ length strip. Finally, at 5.4 GHz, a high current density on the L-shaped branch is observed, which indicates that the third operating band of the proposed antenna is due to the $\lambda_g/4$ length L-shaped monopole.

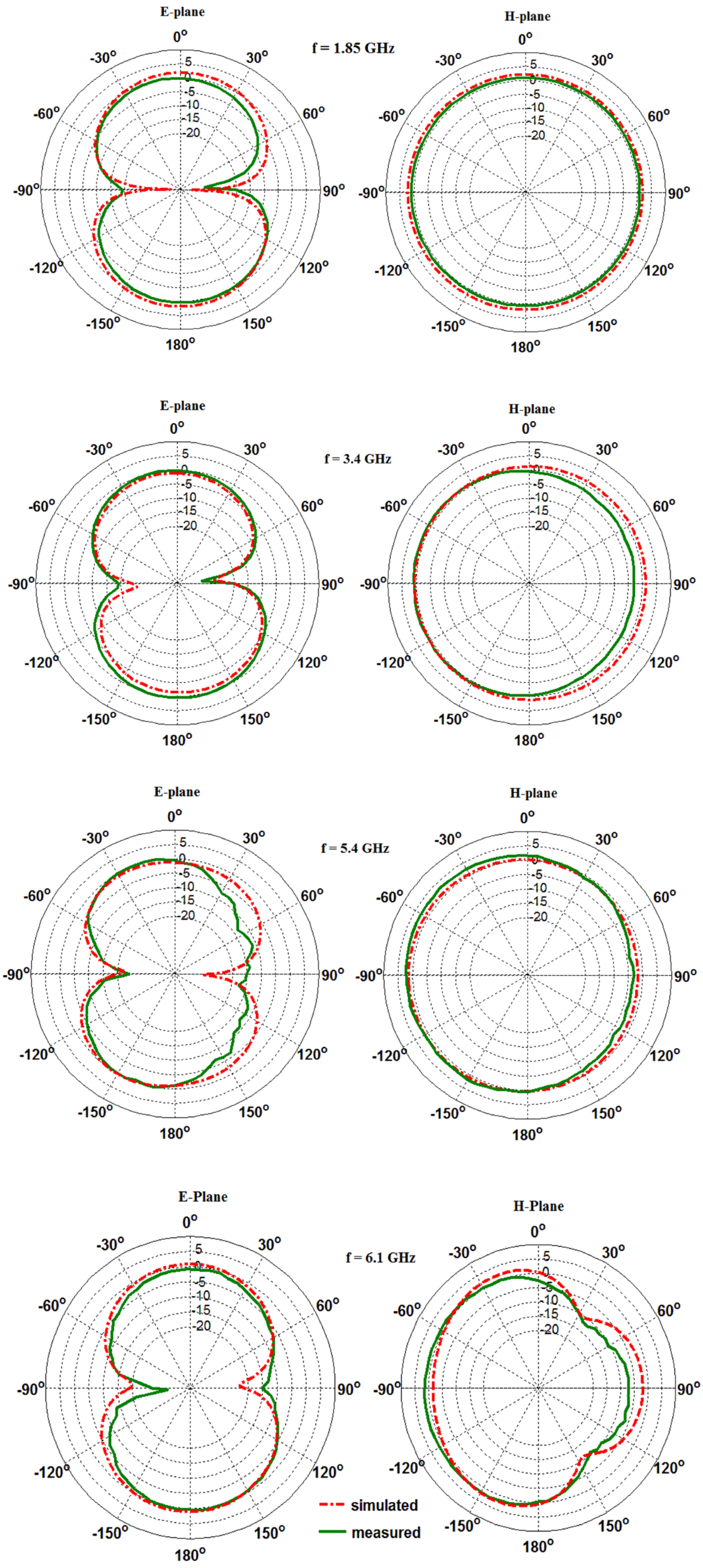
The effect of the key structural parameters on the antenna performance can also be visualized by observing the simulated results of parametric variations. Figure 5a shows the simulated return losses of the antenna when the length of the L-shaped branch ‘Z3’ is varied. It shows that the third resonant frequency shifts towards higher frequencies as Z3 is decreased, while the first and second bands are not affected. A significant effect on the return loss magnitude of the third operating band is also observed when Z3 changes from 8.8 to 8.2 mm. This clearly indicates the fact that the length of the L-shaped branch determines the third resonant frequency of the proposed antenna. Hence an optimum value of 8.8 mm for ‘Z3’ is considered in the proposed structure.

The effects of variations in the lengths Z2 and Y1 on the return loss are studied next and given in Fig. 6b, c) respectively. From Fig. 6b, it can be concluded that with an increase in the branch length Z2, the second resonant frequency shifts to lower side whereas the first and third resonant modes are slightly affected. Similarly from Fig. 6c, it is noticed that the first resonant frequency shifts to the lower side as the arc length Y1 is increased while the second and third bands are affected slightly due to the electromagnetic coupling effect between the radiating branches.

3 Results and discussion

With the optimized values given in Table 4, an ACS-fed arc-shaped tri-band antenna prototype is fabricated and validated experimentally. The fabricated prototype is connected to a 50 Ω SMA connector and its reflection coefficient characterstics are measured by using Rohde and Schwarz Vector Network Analyzer (ZVA-40) (Naidu and Malhotra 2015c). Figure 7 shows the simulated and measured return loss (S11) of the tri-band antenna. The measured −10 dB impedance bandwidths are about 250 MHz from 1.75 to 2.0 GHz with resonance at 1.85 GHz, 300 MHz from 3.2 to

Fig. 8 Simulated and measured radiation patterns of the proposed ACS-fed tri-band antenna at 2.3 GHz, 3.4 GHz, 5.4 GHz and 6.1 GHz



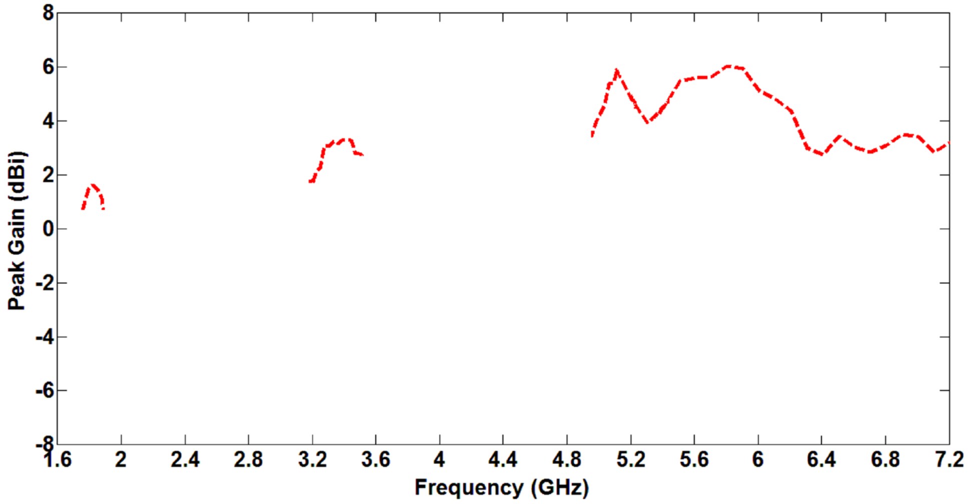


Fig. 9 Measured peak gain of the proposed ACS-fed tri-band antenna

3.5 GHz with resonance at 3.4 GHz and 1.8 GHz from 5.0 to 6.8 GHz with resonance at 5.35 GHz. The slight difference between simulated and measured results is probably due to fabrication tolerances and quality of SMA connector used. The operating bands of the proposed antenna make it suitable for the PCS 1900, LTE 3600, 3.5/5.5 GHz WiMAX and 5.2/5.8 GHz WLAN applications.

The radiation patterns of the proposed tri-band antenna are simulated in the E and H planes using CST Microwave Studio and measured in an in-house anechoic chamber using antenna measurement system. A standard double ridged horn antenna is used as reference antenna. The simulated and measured radiation patterns at different frequencies are shown in Fig. 8.

The H-plane radiation patterns are seen to be omnidirectional in nature while the E-plane radiation patterns are bidirectional (dumb bell shaped). Further, the simulated and measured results are found to be in close agreement with a little difference due to measurement and alignment errors. The measured peak gain of the proposed ACS-fed tri-band antenna across the operating bands is shown in Fig. 9. The measured peak gain remains between 1.5 and 6 dBi in the operating band.

4 Conclusion

A compact ACS-fed monopole antenna for tri-band operation is proposed and experimentally validated in this research paper. The proposed ACS-fed tri-band antenna has a compact size of 17.2 × 30 mm^2 and a simple feeding mechanism which can be easily integrated in any modern wireless communication device. The three desired operating bands have been obtained by adding an arc-shaped monopole strip, rectangular-shaped branch and an L-shaped strip to the ACS-feeding structure. A close agreement is found between the simulated results and measured results. The good return loss characteristics, omnidirectional radiation patterns and peak gains demonstrate the suitability of the proposed antenna for the PCS 1900, LTE 3600, 3.5/5.5 GHz WiMAX and 5.2/5.8 GHz WLAN applications.

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