Design and evaluation of performance metrics of a pentaband broadband microstrip patch antenna for mm wave applications

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ABSTRACT

This paper reports design and results of a microstrip patch antenna for broadband application in the millimeter wave communication with multiband features. Electromagnetic solver high-frequency structure simulator (HFSS) is employed to measure the effectiveness of the electromagnetic properties and electrical behaviour of the antenna. The proposed microstrip patch antenna (MPA) can be easily fabricated on a single substrate using standard photolithography process to attach the radiating element and feed lines to the dielectric material. On a 4.93 mm×5.86 mm metallic patch, over FR4 epoxy substrate with dielectric constant 4.4 and loss tangent 0.03, two L-shaped slots are placed along with a few micro slots of varied dimensions, and the antenna is fed with microstrip feedline with resistive load termination of 50 Ω. Pentaband resonant frequencies are realized in the K-band at 13.6 GHz, 23.2 GHz, 29.68 GHz, 32.96 GHz, and 38.56 GHz, with minimum return loss of -23.17 dB, bandwidth 2.32 GHz, omnidirectional radiation pattern, and maximum reported gain of 4.5 dB. The designed antenna achieved good electromagnetic radiation properties and electrical behaviour, and is a good choice for broadcasting over short distances, surveillance and monitoring, wireless sensor backhauls and telecommunication in the K-band networks.

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1. INTRODUCTION

Multiband operation in next generation portable devices is an essential requirement. Today's challenge to the researchers is to design microstrip patch antenna (MPA) suitable for high frequency application with multiple bands. A multiband MPA can handle higher frequency with the design of even lower central frequency. MPAs are lightweight, miniature, low profile, and inexpensive than typical microwave antennas. MPA has potential to face challenges before the researchers, in realising lower losses without significantly affecting typical properties of antenna. MPA demonstrates multiband operational capability relevant in backhaul for its versatility in frequency bands, efficient spectrum utilization, cost-effectiveness, simplified deployment, and performance enhancing potential [1]. In this paper we present a low-profile MPA, made of 1.6 mm thick FR4 epoxy substrate having loss tangent 0.03 and relative permittivity 4.4. The sensitivity of an MPA depends on the impedance matching with the patch and feedline [2]. A rectangular ring with fork shaped strip on patch can achieve triple frequency band with minimum signal loss and a good impedance matching [3], [4]. Utilizing slot etching on ground plane, an antenna can realize multiband functionality with simple antenna fabrication technique, over the entire range of fifth/sixth generation frequencies [5], [6]. Broadside radiation of high-order microstrip magnetic dipole antenna (MMD) is improved by using resonant slots. By strategically loading these slots, in phase current are generated, antennas performance has been changed significantly [7], [8]. A novel H-shaped patch antenna has been reported with a feature of reconfigurability, using dual feeding to excite two orthogonal polarization modes. The antenna maintains a directivity surpassing 6 dBi, with cross-polarization levels remaining below -25 dB [9]. A single layer low-profile wideband antenna having planer structure offers unique advantages by utilizing multi-layer (ML) feed and metamaterials substrate (MTS) technology [10].

To achieve good radiation characteristics especially the peak gain for multiple bands, double symmetric L slot may be accepted for 5G frequency band [11]. An antenna of volumetric dimension 5.2 mm^3, aimed at fifth generation communication, based on finite element method and finite integration techniques reports good radiation pattern and a bandwidth of around 1 GHz [12]. A multiple-in-multiple-out (MIMO) antenna provide high gain at the operational frequencies: 4.25 dBi at 2.4 GHz, 5 dBi at 5.2 GHz, and 5.5 dBi at 8.1 GHz, within a small square size of 60 mm×60 mm, useful for wireless local area network (WLAN) and C-band applications [13]. A two band patch antenna designed with a resonance frequency of 38/60 GHz has reported reflection coefficient of -42 dB and -47 dB, and corresponding gain of 6.5 dBi and 5.5 dBi along with omnidirectional radiation patterns [14]. A three band antenna performing at 26/32/39 GHz resonance frequency, useful for indoor condition, has achieved better shadow fading behaviour [15]. A four-band millimeter wave MPA based on substrate RT Duroid 5880 and operating at resonant frequencies 23.2 GHz, 27.09 GHz, 31 GHz, and 42.5 GHz has achieved a reflection coefficient of -19.5 dB and bandwidth of 1.318 GHz [16]. Planar multiple-input multiple-output (MIMO) antenna using different substrate has reported wide bandwidth, high gain and narrow directional radiation [17]. A four-band multi-polarized planar circular disc monopole antenna based on parasitic elements has reached resonance at four frequencies within 10 GHz application [18]. Fertas *et al.* [19] described a miniaturized quintuple band antenna for multiband operation. The antenna design included six L-slots in addition to fifty coplanar waveguide. Another work with RT Duroid substrate having resonant frequencies in the range 27 GHz to 57 GHz, has gain ranging from 7.7 dBi to 10.2 dBi [20]. A three-band resonance frequency 28/40/47 GHz antenna employing FR4 epoxy dielectric material has gain in the range of 5.64 dBi to 8.7 dBi [21]. Mothish *et al.* [22] have reported multiband tree shaped microstrip penta band antenna with volumetric dimension 22×22×0.15 having gain 7.24 dB and bandwidth 1.2 GHz using modified circular patch with circular slot. A defective ground structure approach can convert a MPA to multiband opreration with good directivity and gain has operating frequencies 10 GHz, 21 GHz, 30 GHz, and 34 GHz [23]. A combination of defective ground and sloted patch is a fit candidate for pentaband operating microstrip antenna with resonant frequencies below 20 GHz having maximum gain of 6.6 dB [24]. Another penta-band microstrip antennas have been proposed in the frequency range 2-10 GHz [25] and 4-20 GHz [26] with reasonable gain and limited bandwidth up to 1.6 GHz, using defective ground with a modified arm and partial ground with slots on patch respectively.

Mostly, researches have focussed on two-, three-, and four-bands. Few studies are found on penta band element. Therefore, the current study is a valid attempt looking out for improvised solutions for the fifth/sixth generation communication. In this work we intend to achieve a compact sized microstrip patch antenna, with multiple slots in the patch, for multiple K band operation, with good electromagnetic radiation properties and electrical behaviour to support broadcasting over short distances, surveillance and monitoring, wireless sensor backhaul and telecommunication. There are a few works on the pentaband MPA in K band with compact size and omnidirectional pattern, but not with multiple slots in patch. In this connection, this work may put a remarkable impression on the size of MPA and operating frequency band. Mostly, researchers have worked with modified patch and singular slots with operational frequency in S-band, C-band, X-band, K-band and Ku-band. Novelty of this work is that pentaband performance is realised using multiple slots only in the patch and the size miniaturization, in addition to other performance metrics of the antenna, for frequency in the Ku-band, K-band and Ka-band.

For better presentation, remaining paper is arranged as follows. Section 2 includes approach used for antenna design and configuration. In section 3, we describe the results and discussion thereon. In this section, a comparison of the designed antenna to other multiband antennas is included to justify the performance of it. This is followed by the conclusion and scope for further work.

2. METHOD

The performance of a MPA is primarily influenced by their physical geometry, dimension, and material properties [27]-[31]. To attain our objectives, we have used inset-feed impedance matching technique, quarter-wavelength impedance transforms, and optimization of the antenna dimensions as methodology. Methodology flowchart is given in Figure 1. Standard equations to determine dimensions of the different parts of antenna are expressed in Table 1.

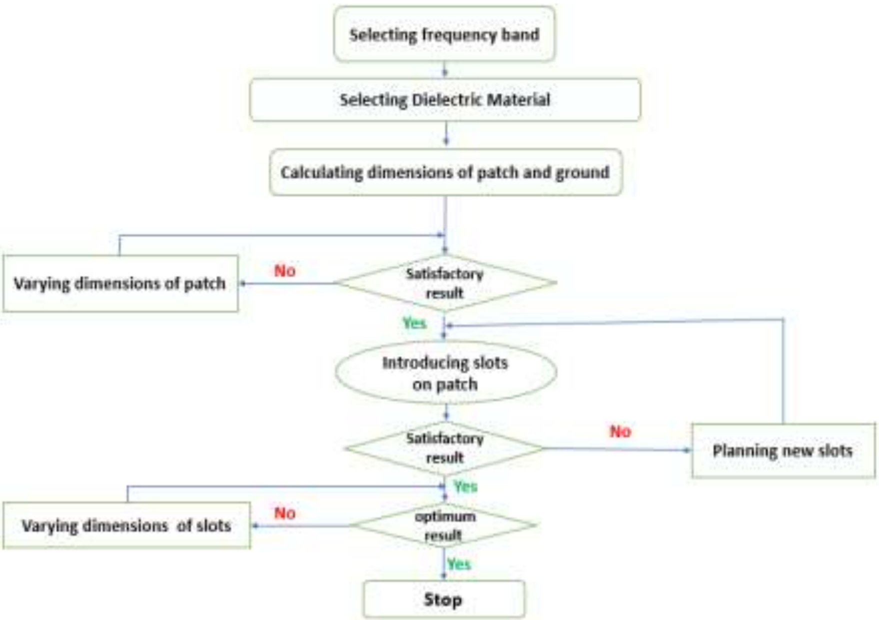


Figure 1. Methodology flowchart of proposed design

Table 1. Design equation for the dimensions of antenna

Parameter	Design equation
Substrate height, h	$h \leq \frac{0.3\,c}{2 * 3.14 f_r \sqrt{\varepsilon_r}}$
Patch length, Lp	$Lp = \frac{c}{2\sqrt{\varepsilon_r^{eff}}}\left(\frac{1}{f_r}\right)$-2($\Delta L$)
Patch width, Wp	$Wp = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}}$
Effective relative permittivity, ε_r^{eff}	$\varepsilon_r^{eff} = \frac{1}{2}(\varepsilon_r + 1) + \frac{1}{2}(\varepsilon_r - 1)(1 + 12\,\frac{h}{W_p})^{-1/2}$
Length extension, ΔL	$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon_r^{eff} + 0.3)\left(\frac{W_p}{h} + 0.264\right)}{\left(\frac{W_p}{h} + 0.8\right)(\varepsilon_r^{eff} - 0.258)}$
Ground plane length, L_g	$6h + L$
Ground plane width, W_g	$6h + W$
Effective length, L_{eff}	$L_{eff} = \frac{c_0}{2f_r\sqrt{\varepsilon_{reff}}}$

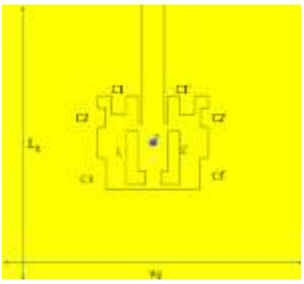
Where, ϵ_r=relative permittivity of substrate, c=velocity of light in vacuum, f_r=resonance frequency.

Dimensions calculated from the standard equations and the corresponding optimized data are expressed in Table 2. The electromagnetic radiator consists of simple rectangular patch augmented with L shaped and rectangular miniature slots. The L-shaped resonators help to realize both horizontal and vertical polarized signals by simple alteration in the dimension of the resonator. Two similar rectangular slots are located symmetrically on either side of connected inset-feed at the edge. Another six slots are situated symmetrically along the corner length. The microstrip feedline having dimension 7.26 mm×1.2 mm maintains a 50 Ω impedance match to the rectangular patch. Figure 2 portrays the distribution of slots on the patch of the designed antenna. Figure 2(a) depicts the layout of patch and slots therein.

Dimensional representation of antenna slots is shown in Figure 2(b). L-shaped slots are of the size 2.8 mm×0.6 mm and 0.7 mm×0.4 mm along the vertical and horizontal direction respectively. Slots C1 and C1' are identical in size (1 mm×0.8 mm). Similarly identical slots C2 and C2' measures 1 mm×0.4 mm. Dimension of C3 and C3' being 1.64 mm×0.43 mm. Other slots are symmetrically located on the other half of the patch. Sequential development of the patch using HFSS is displayed in Figure 3. The optimized antenna comprised four key phases, initially the design focuses on crafting the rectangular patch, followed by four subsequent stages involving slot insertions. For the shake of brevity, the work solely discusses the parametric analysis of the dimensions of the rectangular patch. The frequency shift and return loss are analyzed for four different slots.

Table 2. Design parameters of the primary antenna structure

Design element	Symbol	Calculated values (mm)	Optimized values (mm)
Patch	L×W	4.93×6.52	4.925×6.52
Microstrip feeder	L_f×W_f	6.3×1.19	6.295×1.2
Inset feed	L_{fs}×W_{fs}	1.51×0.2	1.5×0.2
Ground plane	L_g×W_g	14.53×16.12	14.52×16.12
Substrate	L_s×W_s	14.53×16.12	14.52×16.12


(a)

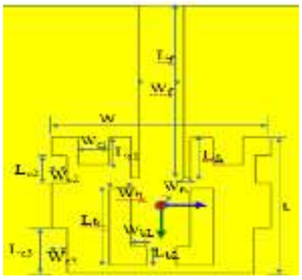

(b)

Figure 2. Distribution of slots on the patch (a) patch and slots layout of the designed microstrip antenna and (b) antenna slots with dimensional representation

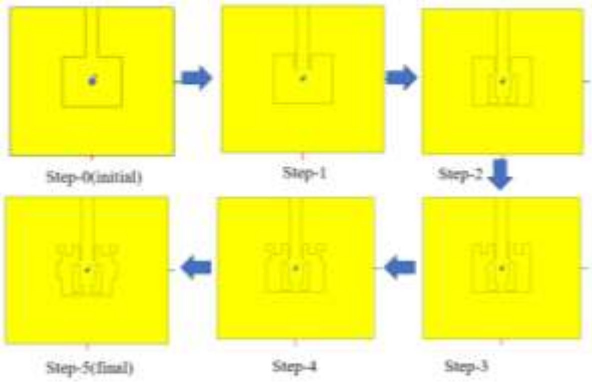


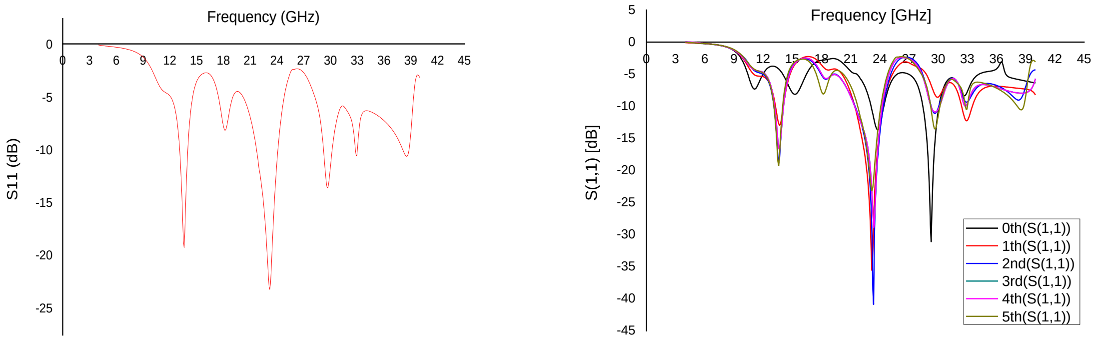
Figure 3. Evolution of antenna design in steps using iteration approach

3. RESULT AND DISCUSSION

This study investigated the effects of multiple slots in patch. While the earlier studies have explored the impact of modified patch, defective ground, and partial ground slots, they have not explicitly addressed the influence of multiple slots in patch only. The proposed work intended to have multi band with higher portion of resonance frequency. Simulation tool being ansoft high-frequency structure simulator. Originally, antenna was designed on the basis of resonant frequency 14 GHz, but after modification and optimization, five resonant frequencies in K-band having frequencies 13.6 GHz, 23.2 GHz, 29.68 GHz, 32.96 GHz, and 38.56 GHz with reflection coefficient S_{11} ≥-10 dB are realized. The best reflection coefficient achieved among all other resonant frequencies are -40.8 dB at 23.2 GHz and -19.23 dB at 13.6 GHz. These resonant frequencies serve as key indicators for evaluating the antennas performance and its compatibility with intended application.

Figure 4 shows the reflection coefficient S_{11} of the designed antenna. S_{11} determines the power loss through the transmission line as power reflected back. The primary design gives two bands at 23.2 GHz and 29.68 GHz as shown in Figure 4(a). When slots for inset feed are introduced for impedance matching, new resonant frequencies were observed at 13.6 GHz, 32.99 GHz, and 38.56 GHz, which indicates that the antenna has capability for multiple bands in K-band.

The final design is confirmed after analyzing the behaviour of S_{11} parameter based on the step wise modification of patch. Figure 4(b) depicts sequential change of S_{11} parameter against frequency. The insertion of L slots makes significant change in resonant frequency which shows five bands at 29.68 GHz, 32.96 GHz, and 38.56 GHz including 13.68 GHz and 23.20 GHz. The observed return loss at the five resonant frequencies in the ascending order, is respectively -19.2 dB, -40.8 dB, -31.11 dB, -12.3 dB, and -10.5 dB. The maximum bandwidth obtained is 2.32 GHz around resonant frequency 23. 2 GHz.

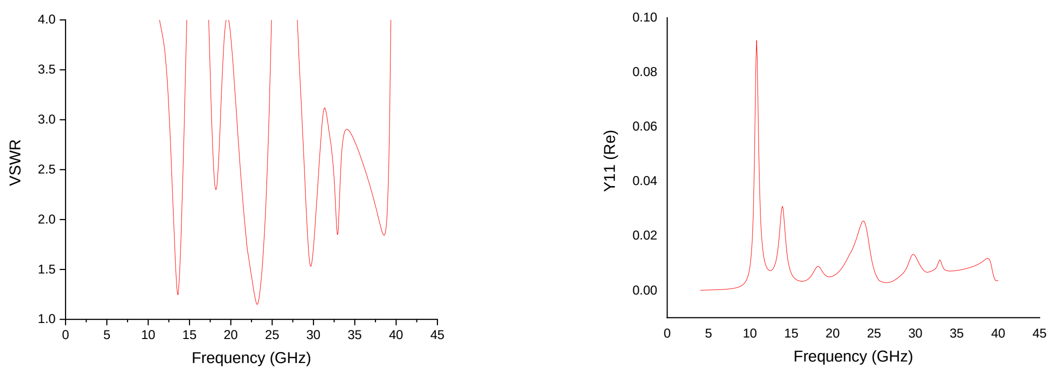


(a) (b)

Figure 4. Reflection coefficient of the antenna due to (a) optimized design against operational frequency range 4 GHz - 40 GHz (left) and (b) step wise design against operational frequency range 4 GHz - 40 GHz (right)

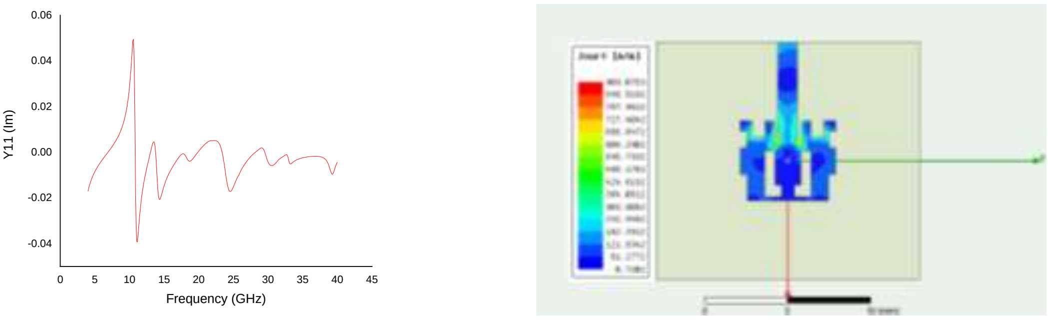
Voltage standing wave ratio (VSWR) and real admittance is shown in Figure 5. VSWR response with respect to the operating frequency is shown in Figure 5(a). At the five resonant frequencies very good values of VSWR are obtained as 1.24, 1.16, 1.53, 1.86, and 1.84 respectively. To understand the electrical behaviour of the antenna, the admittance (Y) and magnitude of surface current are observed. At the suitable operating frequencies, the real Y plot produces five better conductance of 0.0221, 0.0222, 0.0132, 0.0112, and 0.0116 (Figure 5(b)).

The imaginary admittance and surface current profile is shown in Figure 6. The antenna might be better useful at the five bands having susceptance 0.0041, 0.0019, -0.0015, -0.0033, and -0.0043 (Figure 6(a)). Fifth resonant band is just above -10 dB with good VSWR value of 1.84, and appreciable conductance and susceptance. Figure 6(b) depicts profile of surface current at resonance frequency, highlighting the electromagnetic radiation properties of the optimized antenna in the operating band. At the five resonance frequencies, a significant surface current density is observed at the junction of the feedline and the patch, as well as a moderate current distribution over the surface of each active portion of the patch.



(a) (b)

Figure 5. Voltage standing wave ratio and real admittance of the antenna (a) voltage standing wave ratio (VSWR) of the optimized designed antenna as function of operational frequency range 4 GHz - 40 GHz and (b) real admittance Y11 of the optimized designed antenna as function of operational frequency range 4 GHz - 40 GHz

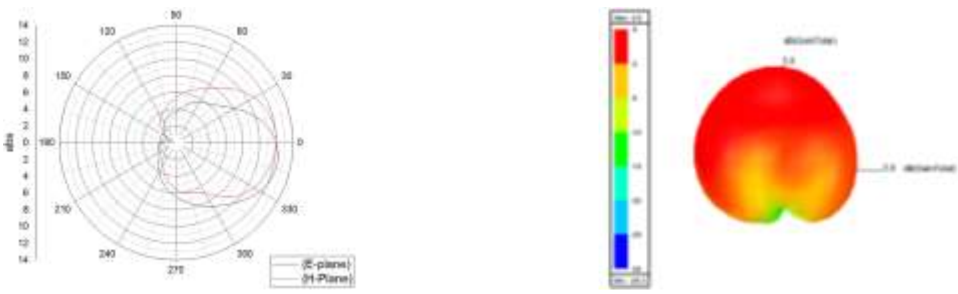


(a) (b)

Figure 6. Imaginary admittance and surface current profile (a) imaginary admittance Y11 of the optimized designed as function of operational frequency range 4 GHz - 40 GHz and (b) current profile at the resonant frequency

The radiation pattern of the E-plane and H-plane are studied for better understanding of radiation response. The radiation pattern of the antenna is omnidirectional in nature. Figure 7 displays the radiation pattern and 3D gain of the antenna. Figure 7(a) exhibits the E-plane and H-plane radiation patterns. The maximum gain is around 4.5 dB and is shown in Figure 7(b). High gain antennas have better directivity, whereas low gain antennas receive electromagnetic signals uniformly in all directions, at a compromised range.

The outcomes of the present work are compared to published works on MPA with multiple bands across several key parameters, including the antenna size, frequency bands, gain, and bandwidth and is reported in Table 3. The compared results show that the antenna has higher bandwidth with reasonably good gain and its performance bands extend towards higher frequencies around 40 GHz. Better impedance matching, lesser return loss, good voltage standing wave ratio, improved surface current distribution, and radiation pattern are other significant features of it.



(a) (b)

Figure 7. Radiation pattern and 3D gain of the antenna (a) radiation pattern (E-plane and H-plane) due to the optimized design and (b) 3D gain (dB) at the resonant frequency

Table 3. Comparison of present work

Papers	Antenna dimensions (mm)	Design approach	Frequency (GHz)	Bands	Gain (dB)	Bandwidth (GHz)
[22]	22×22×0.15	Modified circular patch with circular slot	8.27, 14, 20.20, 24.30, 29.70	5	7.24	1.2
[23]	21×16×0.51	Defective ground	10, 21, 30, 34	4	7.78	-
[24]	30×30×1.6	Modified patch	6.51, 8.25, 9.96, 10.52, 14.99	5	-	1.06
[25]	50×30×1.6	Defective ground with modified arm	2.55, 3.24, 4.03, 6.80, 9.80	5	4.29	-
[26]	30×26×1.6	Partial ground with slots on patch	4.65, 8.01, 11.10, 14.10, 19.20	5	4.70	1.6
This work	16.12×14.53×1.6	Multiple slots in patch only	13.60, 23.20, 29.68, 32.96, 38.56	5	4.5	2.32

The proposed antenna outperforms the others in terms of its compact size, robustness, pentaband operation and appreciable bandwidth. Our study suggests that multi band operation is not associated with poor performance in another prominent antenna parameter. Contribution of the antenna is identified with respect to its multiband function, much reduced dimensions and other performance metrics. An in-depth study may be needed to confirm the response of antenna towards temperature variation, physical stress and especially regarding the sensitivity towards humidity. Future studies may explore the performance of the antenna with defective ground, circular patch and circular slots with feasible ways of producing penta and multiband operation for the Ku, K and Ka-band frequency.

4. CONCLUSION

This paper discusses a rectangular microstrip patch antenna, having two L-shaped slots and few micro-slots, has been introduced, with 1.6 mm height of FR4 epoxy substrate having dielectric constant 4.4 and power loss tangent 0.03. Feeding of antenna is through microstrip feedline, and is terminated at 50 Ω resistive load. The design and simulation is done on elctromagnetic solver HFSS, and the antenna is tailored specifically for sensor backhaul applications. Suggested antenna successfully achieved five resonant frequencies, 13.68 GHz, 23.20 GHz, 29.68 GHz, 32.96 GHz, and 38.56 GHz, with average reflection coefficient of -22.78 dB, average VSWR of 1.5, bandwidth of 2.32 GHz, and maximum gain of 4.5 dB. Comparison with other published works provides conclusive evidence of the contribution of this proposed design in terms of its multiband functionality, comparitively smaller size, low-profile, strong omnidirectional radiation, and reasonably good gain across all frequency bands. The proposed work emerges as a strong candidate for future fifth generation/sixth generation communication in K-band with appropriate electromagnetic radiation pattern and electrical properties. Future studies might look at the working of antenna under different environmental conditions like temperature, humidity, and stress.

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