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Design and Performance Analysis of a Triple-band Rectangular Slot Microstrip Patch Antenna for Wi-Fi, Wi-MAX and Satellite Applications

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***Abstract*—A triple-band microstrip patch antenna is presented in this article with detail investigation of its working mechanism and performance characteristics. The antenna consists of a rectangular slot on the patch to achieve multiband operation. Three distinct frequencies of 2.4 GHz, 5.5 GHz and 7.5 GHz are achieved with return losses of 27 dB, 29 dB and 29 dB respectively. The Impedance Bandwidths are 70 MHz (2.52 GHz-2.44 GHz) at 2.4 GHz, 220 MHz (5.65 GHz-5.43 GHz) at 5.5 GHz and 250 MHz (7.57 GHz-7.32 GHz) at 7.5 GHz, which satisfy the requirements of Wi-Fi, Wi-MAX and satellite communications bands. The fabricated prototype of the antenna has total dimension of 53×53×1.6 mm^3 over FR4 substrate. The antenna is simple and has sensible radiation characteristics with considerable gain. This work also focuses on developing a Link Budget model for its application in satellite communication. Most notably, it examines overall system efficiency and optimum path loss, distance analysis, system noise temperature, signal to noise power ratio, the size of antenna and the overall customer satisfactions. The highest gain of the antenna is achieved as 3.5 dB in the band (5.65 GHz-5.43 GHz), while the highest directivity and bandwidth are found as 8.7 dBi and 250 MHz respectively in the higher operating band. The affordable agreement between the simulated and measuring outcomes justifies that the antenna is often applicable for Wi-Fi (2.4 GHz), Wi-MAX (5.25 – 5.85 GHz) and satellite (7.24 – 7.57 GHz) communications.**

***Keywords*—wireless communication; triple band antenna; gain; directivity; transmission power; link budget**

I. Introduction

THERE has been a significant technical advancement in the area of wireless communication systems such as Wi-Fi, WiMAX, and satellite communication in recent years [1]. Because of the cost effectiveness, simple structure, high directivity and low power consumption, microstrip patch antennas have grown in popularity in such wireless applications [2]. However, a multiband or wideband antenna that can work at multiple frequencies is becoming more popular as multiple wireless communication systems are integrated into a single device [2-3]. In the literature, there are a range of works devoted in designing antennas for multiband operations [4-9]. Etching slots, metamaterial structure, loading stubs and fractal technology are some of the techniques used to design such multiband antennas. A compact dual-band metamaterial antenna with virtual ground plane was designed for WiMAX and satellite communications [4]. In [5], a hybrid fractal antenna for multiband applications is presented. A miniature multi band antenna is presented in [6] for WLAN and X-Band satellite communication applications. Multiband monopole antenna for WLAN/WiMAX/X-band application reported in [7] consists of CPW-fed line. Besides, the slotted techniques are becoming popular for multi-band antenna architecture because of its low profile, large bandwidth, and compatibility with other equipment.

Various multiband slot antennas have been developed in recent years [8-17]. The slot antenna's dual-band [8], triple-band [9-13], and more than three-band [14-18] properties are accomplished by etching many tiny slots or stubs on the patch and the ground plane The E-shaped multiband slot [8], inverted cone slot [9], butterfly shaped slot [10], inverted L and F shaped slot [11], double I shape slots [12], stub loaded multiband slot [13], inverted U and E shaped slot [14], tapered slot [15], circular slot for multiband [16] and meandering split ring slot [17] have all been presented for multiband operations across many wireless technologies. However, many of these antennas demonstrated relatively higher return loss, at least at some frequency bands among all the operating bands. For example, a very recent work demonstrated a compact flexible antenna with the smallest return losses of -21.4 dB at 2.45 GHz, -18.2 dB at 3.65 GHz and -30.8 dB at 5.63 GHz [11]. A five-band slot antenna incorporating a toothbrush-shaped patch (TSP), a meander line (ML), and an inverted U-shaped patch (IUSP) was presented in [18]. The antenna had a peak gain of only 1.3 to 3 dB in the frequency band of 2 GHz to 8 GHz.

Previously, a compact triple-band rectangular slot microstrip patch antenna for wireless communications has been presented in [2]. The antenna was designed at 2.4 GHz, 5.5 GHz, and 7.5 GHz with minimal return loss and a wide impedance bandwidth across all bands. This antenna can be useful in Bluetooth, Wi-Fi IEEE 802.11b and 802.11g (2.4 GHz), Wireless LAN (5.5 GHz), Wireless computer networking (2.4 GHz and 5.5 GHz), Wi-MAX (5.25 GHz–5.85 GHz), Satellite communication (7.24–7.57 GHz) applications.

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The work presented in this article further elaborates the work presented in [2]. In particular, this work brought a detail investigation of the antenna performance like power distribution, gain, directivity and current distribution to justify its practical applications. Additionally, a link budget optimization for practical satellite communication has also been presented. The link budget optimization includes pathloss, figure of merit, carrier power to noise power ratio and distance analysis. In satellite microwave transmission system, parameters that influences the efficiency of satellite communication, likewise gain, distance, G/T (figure of merit), C/N (the ratio of carrier power to noise power) etc. Many shortcomings are revealed in the communication channel between a satellite and an earth station, such as atmospheric attenuation, losses due to rain, path loss and so on [20].

Rest of the article organized as: the technique followed to design the antenna in [2] together with the simulated and measured results is defined in the following section (Section 2). Section 3 outlines the link budget optimization and finally, much of the preceding debate is brought to a close in section 4.

II. TRIPLE BAND ANTENNA DESIGN METHODS AND RESULTS

The step-by-step design procedure of the proposed antenna is shown in Fig .1. At first, we have to set the target specification and design strategy. To determine the 50 Ω impedance matching, the width of feeding line is calculated then. After that by using parameter sweep feature, the antenna parameters are optimized. Then the antenna is simulated by using CST software tool. After that simulation result for specific applications like Wi-Fi, WiMAX and satellite communications is analyzed. Finally, the antenna is fabricated and compare its performance with simulated antenna.

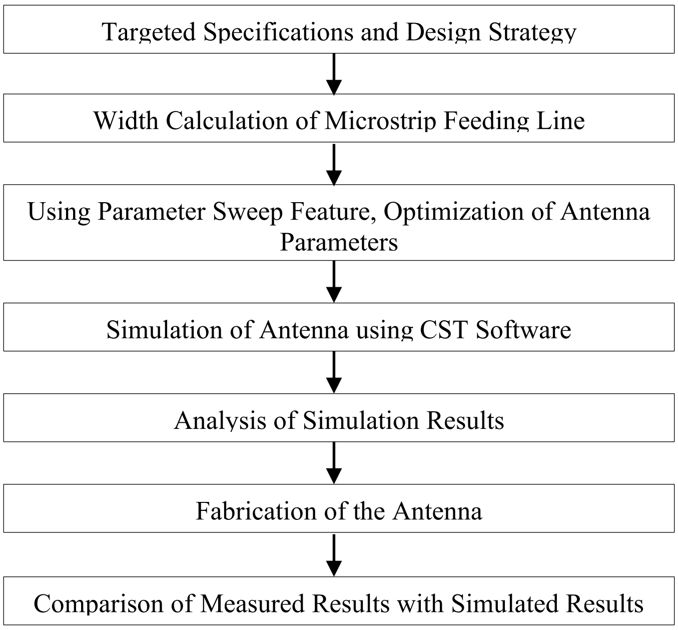

Fig. 1. Design procedure of proposed antenna.

The simulated and the fabricated front view of the designed antenna is illustrated in Fig. 2(a) and Fig. 2(b) respectively. The antenna is made out of FR4 as substrate material while the patch and ground are made of lossy Copper (annealed) material. CST Microwave Studio is used to design the antenna and following a parametric analysis, the overall specifications of the proposed antenna are: Wsub = Lsub = Wg = Lg = 53 mm, Tsub = 1.6 mm, Wp = Lp = 26.50 mm, Tp = 0.035 mm, Ws = 11 mm, Ls = 13.25 mm, Wf = 1.137 mm and Lf = 22.25 mm.

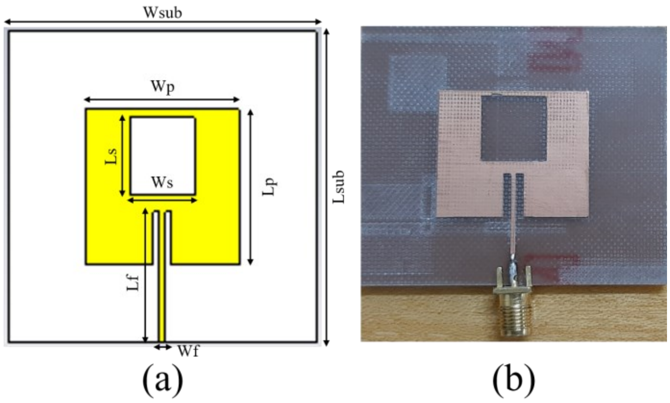

Fig. 2. Front view of the proposed antenna (a) Simulated (b) Fabricated.

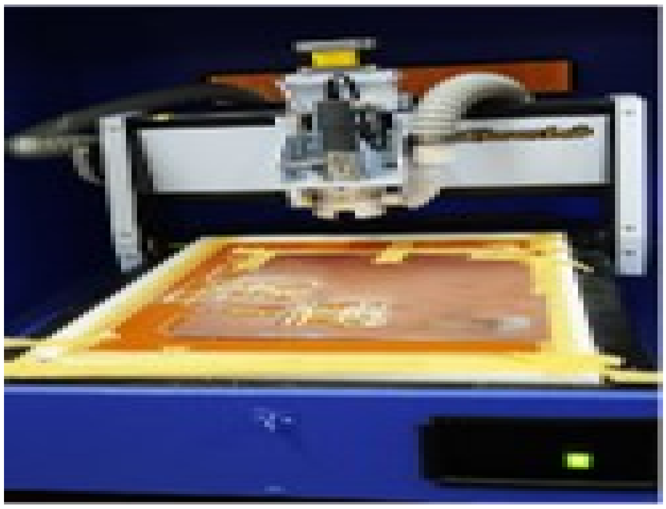

Fig. 3. Photograph of the MITS Eleven Lab Machine.

The antenna is made with the MITS Eleven Lab instrument and its performance is evaluated using the Vector Network Analyzer (VNA). Modeling > Export > 2D Files > Gerber is used to produce the Gerber file (.gbr) for not only the border as well as patch from the simulated layout. Then using MITS Design Pro software, the .gbr file is transformed to .mit file that can be read by MITS machine shown in Fig. 3. After that, the machine fabricates the antenna, which is then tested using a Vector Network Analyzer (Agilent E5071C).

Initially, a basic microstrip patch antenna with a 2.4 GHz frequency band was created. After that a slot on patch is created to make this single band antenna to multiband. Fig. 4(a) demonstrates the simulated return losses for different configurations of slot lengths with constant width and Fig. 4(b) represents different configurations of slot widths with constant length on the patch. The modification in slot lengths and widths has a significant impact on antenna performance. The lengths of the slot vary from 9.25 mm to 16.25 mm, keeping the width of slot constant at 11 mm. The return losses for the necessary three bands reduce as the slot length increases from 9.25 mm to 13.25 mm. When the length is increased, the return losses for two bands increases whereas only one band (5.5 GHz) shows a reduction. Similarly, the widths of slot vary from 8 mm to 14 mm, keeping the length of slot constant at 13.25 mm. The result displays that with the increase in slot width from 8 mm, the return losses for the requisite three bands reduce until the value of slot width is 11 mm. Return losses for two bands rise when the width is more increased, but only one band (5.5 GHz) displays a reduction. The designed antenna's ideal slot dimensions are 13.25 mm in length and 11 mm in width for acceptable return losses and the desired bandwidth of 2.4 GHz, 5.5 GHz, and 7.5 GHz.

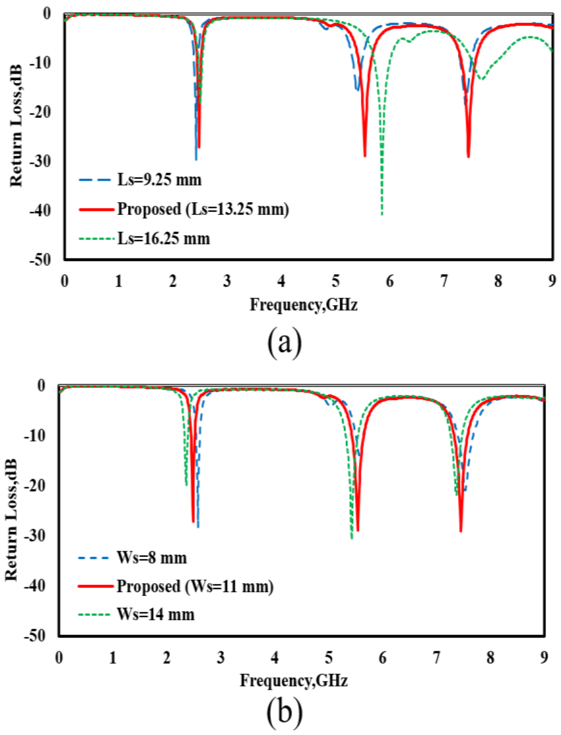

Fig. 4. Simulated return losses with the variation of slot (a) Lengths (Ls) with constant width=11 mm and (b) Widths (Ws) with constant length=13.25mm.

Fig. 5 presents a comparison of the simulated and fabricated return losses for the proposed antenna. Because of factors such as fabrication resistance and connector soldering, the estimated return losses are marginally skewed to the right when comparing with the simulated performance. At 2.4 GHz, 5.5 GHz, and 7.5 GHz, the simulated return losses are 27 dB, 29 dB, and 29 dB, while the estimated return losses are 14 dB, 20 dB, and 17 dB respectively. The simulated return losses are quite good for the performance of wireless antenna and the losses are 26% and 58% lower than the two bands in [11]. Considering all the possible losses, the measured result still makes the antenna practically usable.

Selecting an antenna for a particular application, the gain and directivity characteristics plays an important role. Fig. 6 depicts the simulated 3D gain and directivity at 2.4 GHz, 5.5 GHz, and 7.5 GHz. The designed triple-band antenna has radiation gain of 1.5 dB, 3.5 dB, and 3.3 dB along the broadside direction at 2.4 GHz, 5.5 GHz, and 7.5 GHz respectively. These gains are comparatively better for the radiation intensity, which are 14% higher at 2.4 GHz and 18% higher at 5.5 GHz, than the antenna proposed in [18]. The antenna is good directive at each operating frequency with the relevant directivities of 6.3 dBi, 7.0 dBi and 8.8 dBi at 2.4 GHz, 5.5 GHz, and 7.5 GHz respectively.

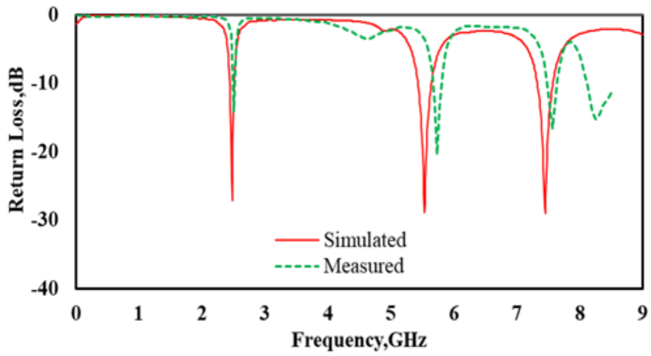

Fig. 5. Simulated and measured return loss of the proposed antenna.

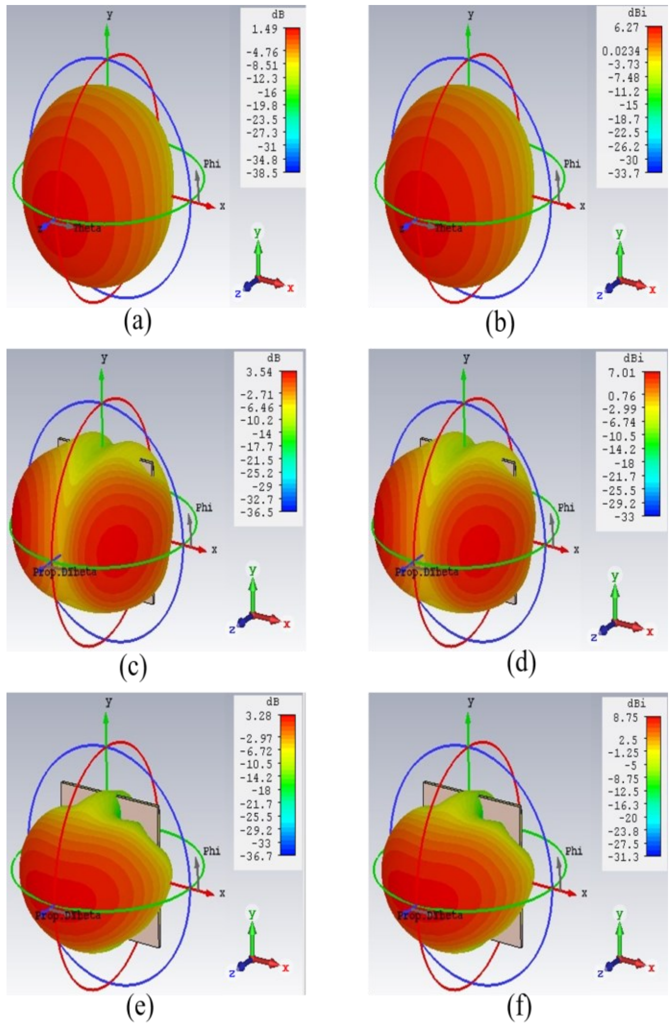

Fig. 6. 3D antenna Gain and Directivity at different operating frequencies. (a) 2.4 GHz Gain, (b) 2.4 GHz Directivity, (c) 5.5 GHz Gain, (d) 5.5 GHz Directivity, (e) 7.5 GHz Gain and (f) 7.5 GHz Directivity.

Fig. 7(a-c) demonstrates the current distribution on the proposed planar antenna at 2.4 GHz, 5.5 GHz, and 7.5 GHz. A greater amount of current distribution is needed to obtain the higher gain and radiation characteristics. It can be observed from the figure that the current is more concentrated near the radiating edges of upper side patch at 2.4 GHz. At 5.5 GHz, a larger amount of current is displaced throughout both the slot and the radiating edges of the lower side patch, causing this slot to achieve the 5.5 GHz resonant frequency. Similarly, at 7.5 GHz, most of the surface current is distributed at the microstrip feeding line and at the lower side of the patch. A small region of the upper side of the patch also gets the higher current distribution at this operating frequency. The observed peak E-currents are 208 A/m, 415 A/m, and 667 A/m at the resonant frequencies of 2.4 GHz, 5.5 GHz and 7.5 GHz, respectively.

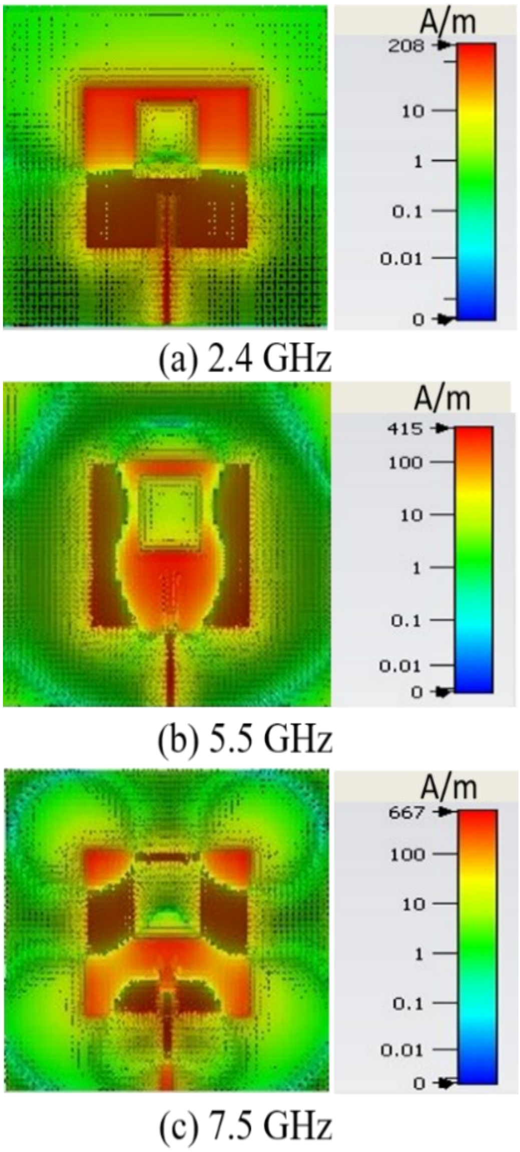

Fig. 7. Simulated current distribution of the designed antenna at (a) 2.4 GHz, (b) 5.5 GHz and (c) 7.5 GHz.

Fig. 8 demonstrates the excitation power distribution of the designed antenna. The maximum power of 0.49 W has been discovered in the lower frequency band. At 2.4 GHz, 5.5 GHz, and 7.5 GHz, the radiated power is 0.09 W, 0.18 W, and 0.15 W respectively. On the desired three frequency bands, the accepted power and radiated power are both high. As a result, antenna efficiency in that frequency range is extremely good, with the designed antenna achieving a maximum total efficiency of 98% at 7.5 GHz. Power absorbed at all ports is 0.01 W, 0.02 W and 0.01 W at 2.4 GHz, 5.5 GHz and 7.5 GHz respectively.

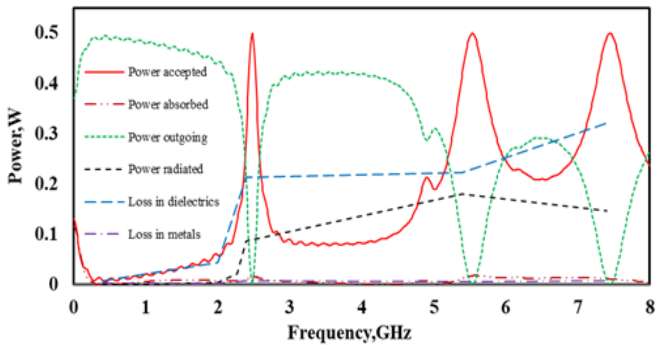

Fig. 8. Power vs. Frequency of the designed antenna.

III. LINK BUDGET OPTIMIZATION

An important aspect of determining signal gains and losses from the transmitter to the receiver is the link budget analysis. The link budget examines efficiency and the optimal power that must be obtained at receiver. Table I summarizes the link budget parameters as obtained using link budget calculator in [30] for

TABLE I
UPLINK AND DOWNLINK BUDGET OF THE LINK BUDGET CALCULATOR

Parameters	Values
Uplink frequency GHz	5.5
Uplink antenna diameter m	0.029
Uplink antenna aperture efficiency e.g., 0.65	0.834
Uplink antenna transmit gain dBi	3.667439
Uplink antenna, power at the feed W	850
Uplink EIRP dBW	32.96162
Range (35778-41679) km	38500.0
Uplink path loss dB	198.9665
Uplink pfd at satellite dBW/m^2	-129.7479
Bandwidth Hz	220000000
Satellite uplink G/T dB/K	40.939
Uplink C/N dB	20.10893
Downlink frequency GHz	4
Downlink received antenna diameter m	0.029
Downlink received antenna aperture efficiency e.g.,0.65	0.834
Downlink system noise temperature (antenna+LNA) K	120
Downlink received antenna gain dBi	0.901385
Downlink received antenna G/T dB/K	-19.89043
Downlink satellite EIRP dBW	35.5
Downlink path loss dB	196.20004
Downlink C/N dB	-35.41506

uplink (Tx), satellite, downlink (Rx), distance analysis and rain attenuation. Because of the similarities between the gain obtained through simulation and the gain obtained by the calculator, which is roughly equivalent to 3.50 dB, we can see that our proposed antenna device is practically realizable.

For a variety of transmission frequencies as used in satellite communications, Fig. 9 depicts the variation of uplink received antenna diameters with antenna gain. A linear relationship has been observed between the gain and diameter.

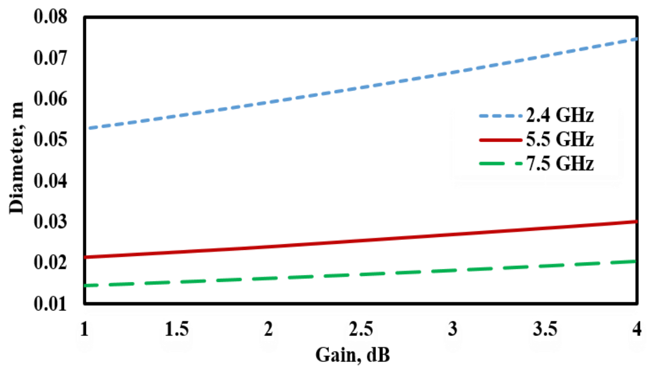

Fig. 9. Diameter vs. Gain at different frequencies.

Fig. 10 demonstrates the differentiation of path loss with frequency for various orbits. Three categories of orbits usually used for communications satellites, these are Low Earth Orbit (LEO), Medium Earth Orbit (MEO) and Geostationary Orbit (GEO) with a limit of 500-1500km, 5000-10000km and 36000-41000km respectively. The ranges have been taken as 1500km, 10000km and 41000km for LEO, MEO and GEO orbits respectively.

The figure of merit determines the capability of an earth station or a satellite to receive a signal. The carrier power to noise power ratio (C/N) is the ratio of signal-to-noise strength. Fig. 11 shows the changes of C/N with bandwidths for various orbits. It is found that the C/N reduces as the bandwidth as well as distance of orbits increases.

The performance of the proposed antenna is also compared with some existing literatures. Table II summarizes such comparison in terms of overall dimensions of antenna, resonance frequency, return loss and gain. The return loss of the proposed antenna (-27.2 to -28.9 dB) is found better than the other literatures (-15.58 to -26.41). The gain of the proposed antenna (1.24 – 3.57 dB) is also better than most of those literature works (0.56 – 3.2 dB), except [23] which demonstrated comparatively high gain GHz (4.1 – 5.5 dB) at 5.5 GHz.

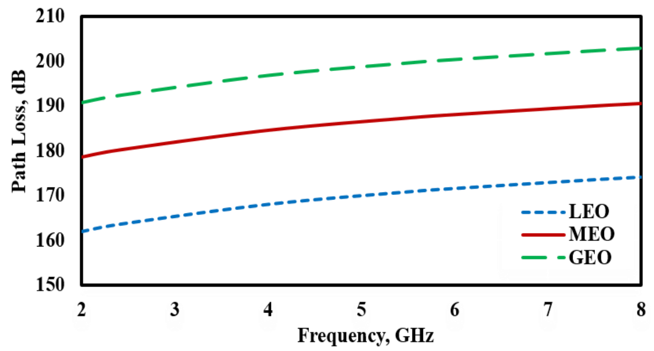

Fig. 10. Path loss vs. Frequency at different orbits.

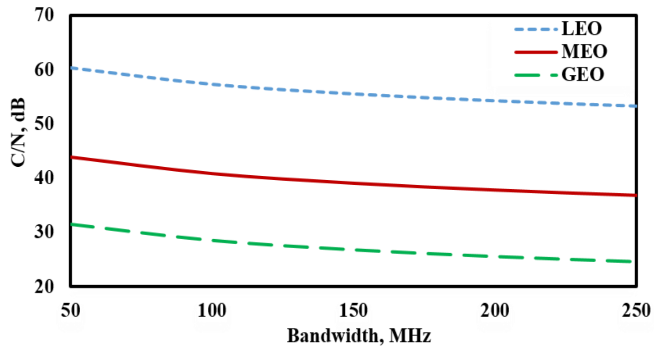

Fig. 11. C/N vs. Bandwidth at different orbits.

IV. CONCLUSION

This study shows a triple band slotted patch antenna for wireless communication, as well as link budget optimization. The proposed antenna has a total size of 53×53×1.6 mm^3,

TABLE II
PERFORMANCE COMPARISION OF PROPOSED ANTENNA OF THIS WORK WITH SOME REFERENCE ANTENNAS

References	Overall Dimension (mm^3)	Operaring Frequency (GHz)	Return Loss (dB)	Gain (dB)
[23]	32×50×1.6	2.45, 5.5	-15.58, -25.19	1.9-2.9, 4.1-5.5
[25]	50×30×1.6	2.45, 5.5	-19.92, -24.77	1.4-1.9, 3.2-4.3
[28]	60×40×1.5	2.4, 5.2	-20, -18	3, 2.7
[29]	30×45×3.2	2.45, 5.8	-22.53, -26.41	0.56, -1.59
This Work	53×53×1.6	2.4, 5.5, 7.5	-27.2, -28.9, -28.9	1.24, 3.57, 3.28

making it extremely compact as well as its efficiency has been evaluated numerically and experimentally. The antenna radiates in a consistent manner across the entire frequency spectrum. The proposed antenna system is basically realizable since its simulated gain is almost identical to the gain obtained from the link budget calculator. A number of factors should be considered when planning a satellite link, and most of the key factors have been outlined and their relationship seen using plotting figures. The suggested antenna is ideal for Wi-Fi (2.4-GHz), WiMAX (5.25-5.85 GHz), and satellite communications (7.24-7.57 GHz) triple band applications, as shown by simulated and calculated performance.

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