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Article

Analysis of Performance Enhancement Techniques for Patch Antennas for Small Satellites

Zizung Yoon[1], Mayank Mayank [2,*] and Enrico Stoll [3,*]

[1] Technische Universität Berlin; zizung.yoon@tu-berlin.de
[2] Technische Universität Berlin; mayank@campus.tu-berlin.de
[3] Technische Universität Berlin; e.stoll@tu-berlin.de

* Correspondence: mayank@campus.tu-berlin.de;

Abstract: Patch antennas are compact, less complex, planar structures and therefore widely used in small satellite missions for telecommand, data link and intersatellite link particularly in S- and X-band. Improved performance of these patch antennas in terms of gain and compactness will directly affect the communication efficiency of small satellite missions. Especially the coming IoT (Internet of Things) constellations require high gain and efficient antenna arrays. An optimization of single patch antenna element is an important cornerstone for these missions. Therefore, this article analyses the effect of various antenna enhancement techniques such as slotted ground plane, resistor and capacitor integration, parasitic patch elements. These techniques have been applied on a rectangular patch antenna with parameter variation to identify the optimal performances with respect to bandwidth, operating frequency, gain, polarization, and power flow. Finally, the techniques have been combined to obtain an optimized antenna in terms of gain and compactness. The results were compared to a slotted reference antenna. For the scenario of a 2.4 GHz patch antenna, a gain optimization of 27 % (from 7.09 to 8.14 dBi) or size reduction of 52 % (from 96.04 to 46.2 cm^2) could be achieved. Overall, our study revealed an effective way to increase the patch antenna performance, which can directly contribute in more efficient communication links and design of antenna arrays.

Keywords: satellite communication, antenna optimization, high gain antenna

1. Introduction

Patch antennas are widely used in small satellite applications for telemetry and telecommand link or intersatellite links. They offer undisputed advantages for small satellites with limited resources such as:

- Light weight, low volume and thin profile
- Implementation of linear and circular polarization with simple feeds
- Easy implementation of dual-frequency and dual-polarization antennas
- Easy integration with microwave integrated circuits
- Low fabrication cost and suitable for mass production

These advantages make them an ideal choice for LEO (Low Earth Orbit) space missions. Currently 2350 small satellite missions [22] have been launched, out of which 307 missions (13%) work on S-band frequencies. A more detailed extraction of frequency requirement of S- and X-band missions is given in Table 1.

Improved performance of these patch antennas in terms of gain, size and bandwidth will directly affect the link efficiency. Especially the coming IoT (Internet of Things) constellations require high gain and efficient antenna arrays on the spacecraft to close the link to LPWAN (low power wide area network) ground sensors. Thus, the optimization of a single patch antenna element is an important cornerstone to further optimize the data throughput for such missions.

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Table 1: Small satellite mission S- and X-band link parameter.

Mission	Class, Mass	Link	Freq. [MHz]	BW [MHz]	Tx Pwr [W]	Antenna	ITU Radio service
BEESAT-3	Cubesat, 1kg	Down	2263.0	2.0	0.5	Patch	Space research
TechnoSat	Nanosat, 20kg	Down	2263.0	1.3	0.5	Patch	Space research
S-NET	Nanosat, 9kg	Up	2081.2	0.1	3.5	Patch	Space research
		Down	2266.0	1.75	1.0	Patch	Space research
		ISL	2266.0	0.1	1.0	Patch	Space research
TUBIN	Nanosat, 20kg	Up	2081.2	0.2	5	Patch	Space research
		Down	2266.0	1.3	0.5	Patch	Space research
		Up	7220 (tbd)	0.08		Patch	Space research
		Down	8390 (tbd)	15	1	Patch	Space research

Therefore, this article analyses the effect of various antenna enhancement techniques such as slotted ground plane, resistor and capacitor integration, parasitic patch elements. These techniques have been used in past but their effect on antenna performance based on the magnitude of the techniques (resistance value, slot length and width etc.) have not been well documented [1][3]. Additional enhancement techniques such as stacked parasitic patch, thick substrate, corner truncate, substrate material optimization, manufacturing process optimization, gridded substrate structure etc. have also been documented in literature [3] [7] but are not considered in this article. The selected techniques are easily applicable to a PCB based manufacturing process. Table 2 summarizes the disadvantages of patch antenna along with the planned performance enhancement technique with scientific reasoning.

Table 2: Patch antenna disadvantages and performance enhancement techniques

Disadvantages	**Technique**	**Reasoning**
Narrow bandwidth	Resistance integration	Resistance integrated at patch edge leads to reduction in losses due to fringing effects and surface waves. This increases the bandwidth by compromising on antenna efficiency.
Low gain (~6 dBi)	Parasitic patch	The induced current from the main patch into parasitic patch increases radiation and bandwidth. Overall resulting in higher antenna gain in far-field.
Surface wave losses	Thin substrate	Thin substrate reduces the surface wave losses.
Low polarization purity	Slotted ground plane	The induced surface current on ground plane due to surface current on patch increases the polarization difference between co- and cross- polar radiations.
Lack of multi-frequency operations	Slotted patch	The radiation from patch radiating edge and slot radiating edge makes multi frequency operations possible.

Table 3: Commercially available small satellite S- band antenna parameter.

Company	Type	Size [mm]	Gain [dBi]	Polarization	BW [MHz]
Endurosat	S-band patch	98 x 98 x 14	7	RHCP/LHCP	150
Anywaves	S-band patch	79.8 x 79.8 x 12.1	6.5	RHCP/LHCP	>256
IQ wireless	S-band patch	70 x 70 x 3.2	6	RHCP	50
ISISpace	S-band patch	r = 80, h = 3.2	6.5	RHCP	-
Syrlinks	S-band patch	79.8 x 79.8 x 11.7	4.8	LHCP/RHCP	289
GOMspace	S-band patch ANT-2150 ISL	98 x 98 x 20	8	RHCP/LHCP	250

Thus, the main aim of this article is to analyze the quantitative relation between enhancement techniques and antenna performance. Additionally, the techniques have been combined on a rectangular patch antenna to optimize for gain and size and show that it can outperform currently available design. Some currently commercially available S-band patch antennas are listed in Table 3. They offer roughly a gain of 5-7 dBi for a form factor of max. 98x98 mm to fit on a 1 U Cubesat surface (10x10 mm).

3. Methodology

A slotted patch antenna for 2.4 GHz has been selected as a reference antenna. After selecting the low loss material (copper and RO4003) and target performance, the reference antenna has been simulated. The antenna simulation was performed in CST Studio Suite 2019. To validate the simulation results, the reference antenna has been manufactured and tested in an anechoic chamber facility.

As a next step, the following enhancement techniques were applied: resistance integration, capacitance integration, parasitic patch, slotted ground plane. Parameter variation was performed on each technique to identify the optimal tuning parameter. Performance parameters such as antenna gain, bandwidth, circular/linear polarization, directivity, total efficiency, operating central frequency(s) and beam angle have been considered. In the final step, the techniques have been combined to optimize the antenna towards gain and size. The finalized antenna qualities are summarized in Table 10.

4. Patch antenna background study

This section summarizes the analogy of a simple rectangular patch antenna without implementing any performance enhancement techniques. The reference antenna will have additional slots on this. This highlights the sensitive points for input feed and how it affects the behavior of the antenna [1] as shown below in Figure 1. For efficient antenna, the length and width of patch can be calculated as [3]:

$$W = \frac{c}{2f[\frac{(\varepsilon + 1)}{2}]^{\frac{-1}{2}}} \qquad \text{Eq. 1}$$

$$L = \frac{c}{2f[\frac{(\varepsilon_e + 1)}{2}]^{\frac{-1}{2}}} \qquad \text{Eq. 2}$$

$$\varepsilon_e = \frac{\varepsilon + 1}{2} + \frac{\varepsilon - 1}{2}[1 + 12\frac{h}{W}]^{\frac{-1}{2}} \qquad \text{Eq. 3}$$

Point A and B are the ideal points for input feed at 50-Ω impedance. To further adjust the antenna performance for central frequency operations, return loss etc. the line joining point A and B is the locus for input feed positions. The antenna is designed and simulated with conductive material as copper and substrate material as RO4003. The positions for point A and B can be fixed by determining the TM01 and TM10 mode excitation. The rectangular patch printed on substrate has thickness on 0.035 mm and dimensions of 30 x 30 mm. The thickness of substrate is 3.2 mm. The central frequency at 2.4907 GHz. This central frequency is considered based on common patch antenna applications for small satellites. Patch antennas mostly work on S- and X- band frequency, however larger surface area for S-band increases the need for performance optimization. The bandwidth offered by unslotted rectangular patch antenna is 61.6 MHz, which is quite normal for such antennas. The impedance mismatch losses are also very low in the operating frequency range.

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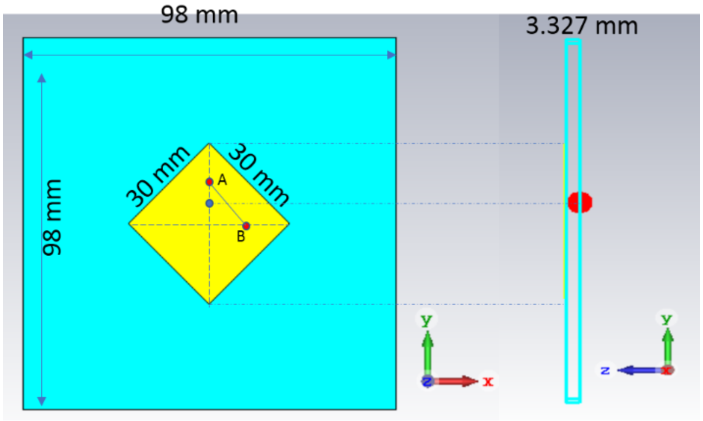

Figure 1: Rectangular patch antenna analogy with 2.4907 GHz central frequency and 7.1dB gain

The antenna is directional as can be seen in the farfield results. The absolute gain of the antenna is 7.1 dB and has directivity at 2 deg. This side lobes are -21.5 dB which signifies that very low power loss due to signal dissipation. Considering the left and right circularly polarized farfield results, the gain of the antenna is 4.09 dBi. Since both circular polarizations are at same level, the antenna is not circularly polarized.

5. Slotted Patch Antenna as Reference

5.1. Theory

The slotted patch antenna shows multi-frequency operation capabilities, high gain, bandwidth and polarization purity compared to the reference antenna. Therefore, to visualize the effect of the enhancement techniques on multiple frequencies, the slotted patch antenna was used as the reference antenna.

Slots are introduced into an antenna patch to increase gain and lower the VSWR (Voltage Standing Wave Ratio) in the antenna performance [1]. The slots add to the capacitive loading of the antennas [8]. Furthermore, the slots make the surface current on the patch to flow in a circular orientation thus increasing the polarization difference. The higher the polarization difference (mode of difference between right and left circular polarization), the higher is the efficiency of the antenna at certain frequency [3]. Additionally, slots also enable antenna to perform on multi frequency operations [1]. By embedding a pair of slots of proper lengths close to the radiating edges, the rectangular patch realizes dual-band broadside radiation [11]. The first resonant frequency is not much affected by slot loading so that its frequency can be predicted by slightly modifying the well-established formula for rectangular unslotted patch; i.e. derivations in reference [12]

$$f_{100} = \frac{c}{2(W + \Delta W' + \Delta W'')\sqrt{[\varepsilon_e(L/t,\ \varepsilon_r)]}} \qquad \text{Eq. 4}$$

$$f_{300} = \frac{c}{2(L + 2l)\sqrt{[\varepsilon_e(w/t,\ \varepsilon_r)]}} \qquad \text{Eq. 5}$$

where c is the free-space speed of light, W the patch width, L the patch length, t the thickness and l are the increased patch length due to fringing effects. The effective dielectric constant ε_e is obtained by

$$\varepsilon_e(x,y) = \frac{y+1}{2} + \frac{y-1}{2}[1 + \frac{10}{x}]^{-1/2} \qquad \text{Eq. 6}$$

W, $\Delta W'$ and $\Delta W''$ are the width of patch and is obtained by

$$\Delta W' = W(1.5\frac{w}{W} - 0.4\frac{l}{L}) \qquad \text{Eq. 7}$$

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$$\Delta W'' = g(\frac{L}{l}, \varepsilon_T)t \quad \text{Eq. 8}$$

where

$$g(x,y) = \frac{1}{\pi}\frac{x + 0.336}{x + 0.556}[0.28 + \frac{y}{y+1}(0.274 + \ln(x + 2.518))] \quad \text{Eq. 9}$$

Slots in patch antenna result in lowering the fundamental resonant frequency. Slots also circularly polarize the antenna and regulate the operating frequency. The slotted patch antenna also enhances the operating bandwidth with a possibility of reduced antenna size by increasing the length of slots. In Figure 2, the antenna shown has three parallel slots in the patch antenna. The dimensions of the antenna and region of interest are highlighted as well. Radiating edge and non-radiating edge has dimensions L and W respectively, while slots have dimensions l and w respectively. The point A and B are port locations on diagonals for obtaining circular polarized antenna performance. The fixed design parameters are summarized in Table 4.

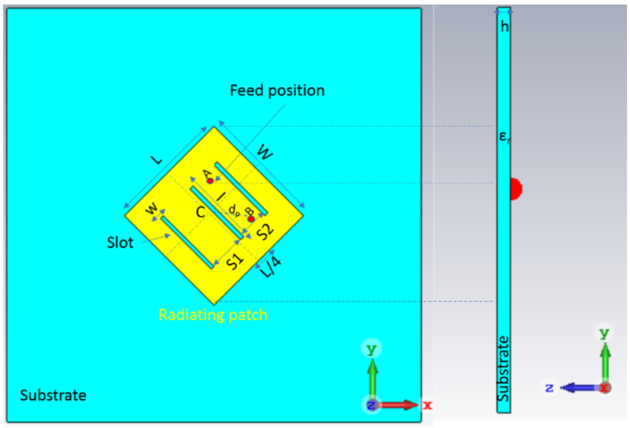

Figure 2: Slotted antenna design

Table 4: Fixed design parameters of slotted patch antenna

Design parameters	Values
Inter-slot distance	S1 (8.85 mm; 0. 0738 λ), S2 (7.15 mm; 0.0596 λ)
Feed impedance	50-Ω
Feed position (distance from center)	d_P (5.2 mm)
Patch non radiating and radiating edge	W = L = 30 mm (λ/4)
Ground plane edge	P = 98 (0.8 λ) mm
Substrate material	RO-4003
Radiating material	Copper
Substrate height	h = 3.2 (0.0267 λ) mm
Dielectric coefficient (RO-4003)	ε = 3.35

5.2. Simulation

To benchmark the effect of slot dimensions, l (slot length) and w (slot width) have been varied in the simulations. The feed position is fixed at point A (dp = 5.2 mm) and the antenna was excited with fundamental mode (TM10). The resonant frequency and impedance bandwidth comparison is shown in Table 5 below. It is clearly seen that by introducing slots the resonant frequency f2 is almost unaffected. On the other hand, frequency f1 has a very considerable effect of changes in slot dimensions (see Figure 3). This shows that by optimizing the length (L) of the antenna patch, the frequency (f2) can be regulated and fixed at a certain desired value whereas, frequency (f1) can be regulated using the slot

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length (l). Another notable finding is that the frequency ratio f2/f1 increases as the slot length is increased.

Table 5: Slot dimension variation and performance of slotted patch antenna

Antenna number	l [mm]	w [mm]	d_p [mm]	f1, f2 [GHz]	BW1, BW2 [MHz]	f2/f1	Abs. Gain [dBi]
Slot-1	0	0	5.2	-	39.8, 61.6	-	4.09
Slot-2	15	1	5.2	2.4043, 2.4907	-	-	7.15
Slot-3	15	0.25	5.2	2.4703	107.1	-	7.10
Slot-4	15	0.50	5.2	2.3785, 2.4703	63.7, 73.3	1.04	7.09
Slot-5	15	1.50	5.2	2.2956, 2.4683	43.2, 49.7	1.08	7.08
Slot-6	15	2	5.2	2.2771, 2.464	40.2, 48.6	1.08	7.08
Slot-7	17	1	5.2	2.2758, 2.4724	39.7, 48.6	1.08	7.09
Slot-8	19	1	5.2	2.2067, 2.4703	28, 43.6	1.12	7.08

Figure 3 shows the respective return loss graphs. The gain of the antenna remains constant through the slot variation. However, with the increase in slot size the impedance bandwidth is affected inversely. As the slot length increases from 15 to 17 mm, the bandwidth (BW1) decreases from 62 to 28 MHz and bandwidth (BW2) decreases from 73.3 to 43.6 MHz.

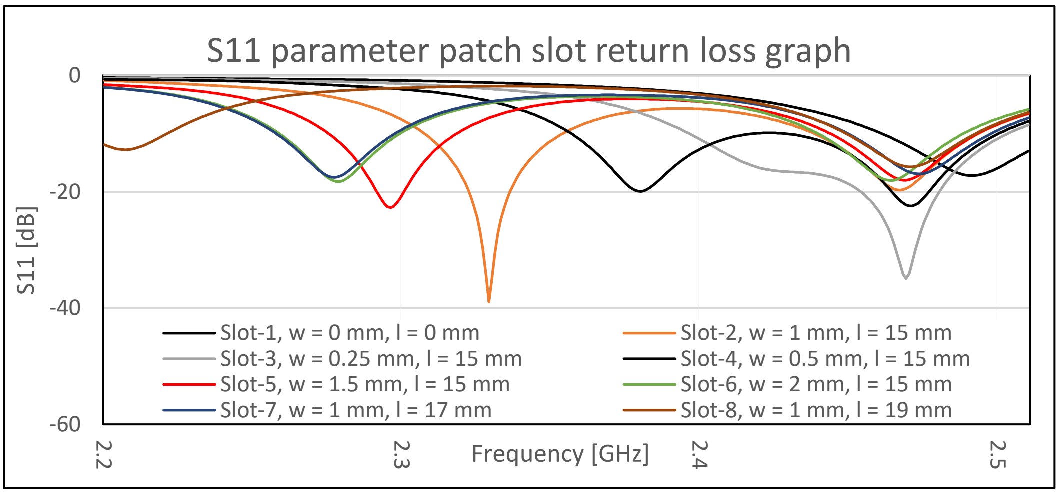

Figure 3: Simulated S11-parameter for variation of patch slot dimension.

Eq. 4 and Eq. 5 shows that resonant frequency of patch antenna is inversely proportional to length and width of the patch. Thus, by decreasing the patch size, the resonant frequency is increased. Therefore, with the reduction in resonant frequency (f2), the reduction of the antenna size is possible while keeping the resonant frequency same. Slot-4 is found to be the best performing antenna for showing dual frequency operations and broad bandwidth (narrow bandwidth is one of the disadvantages of patch antenna). Since bandwidth decreases with increase in polarization or antenna gain therefore Slot-4 (maximum bandwidth) design is considered as basic model for next enhancement techniques. The S11 parameter for Slot-4 are below -10 dB making the entire BW of the antenna workable (hence, combining BW1 and BW2) without any standing waves and power losses.

5.3 Validation

In Figure 4 shows the manufactured prototype to validate the simulation against measurement results. The measurement results are recorded using vector network analyzer and spectrum analyzer from Rohde and Schwarz.

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Figure 4: (left) IGLUNA 2020 slotted patch antenna (reference antenna) CAD design; (right) prototyped hardware

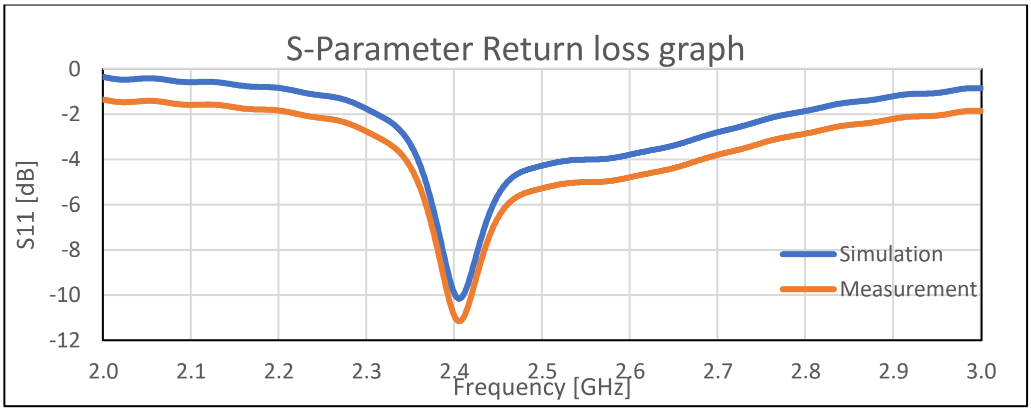

Figure 5: Reference antenna S11 parameter simulation result (left) and test result (right)

In Figure 5, both curves clearly form the central frequency of 2.4 GHz. Also, they indicate dual frequency excitation of antenna due to unsymmetrical return loss (S11) graph verifying simulation results. Additionally, the resonant frequency, offered bandwidth, single or dual frequency operations and return losses of the antenna can be confirmed. The validation of the other performance characteristics would require an anechoic chamber.

The discrepancy between the simulation and experimental results (approx. 1 dB) are mainly implementation losses (losses due to connectivity, internal losses), reflected signal interference and interferences from other signals in the vicinity of the antenna. The experiment setup has ±0.5 dB tolerances (source of error). Additional ±0.5 dB tolerance was measured due to multipath reflection (inter-signal interferences).

6. Enhancement Techniques

The planar rectangular patch antenna shows linear polarization and low gain of 4.09 dBi. After implementing the slotted patch enhancement technique, firstly circular polarization is achieved furthermore, the gain value can be increased to max. 7.15 dBi. Additionally, the antenna also shows dual resonant frequency characteristics making if further useful for multi frequency operations. This makes the slotted patch antenna a good starting point to understand the effect of additional performance enhancement techniques, especially suitable for space applications. Therefore, the following performance analysis will be a combination of additional technique with slotted patch antenna, especially with design parameter of Slot-4. The techniques selected under this study are easily applicable to a PCB based antenna manufacturing design and process.

6.1 Slotted ground plane

The increase in the radiation efficiency is associated with the embedded slot in ground plane. It lowers the form factor thereby, enhancing the flow of the surface current on the patch. The expected performance enhancements are increased bandwidth and polarization of the antenna radiation pattern [1]. The ground plate further reduces quality

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factor of the antenna structure, the obtained impedance bandwidth for a compact design with slotted ground plane can be greater than the conventional antenna design [3]. Owing to reduced fundamental frequency, enhanced polarization and bandwidth, the efficiency of antenna is also increased.

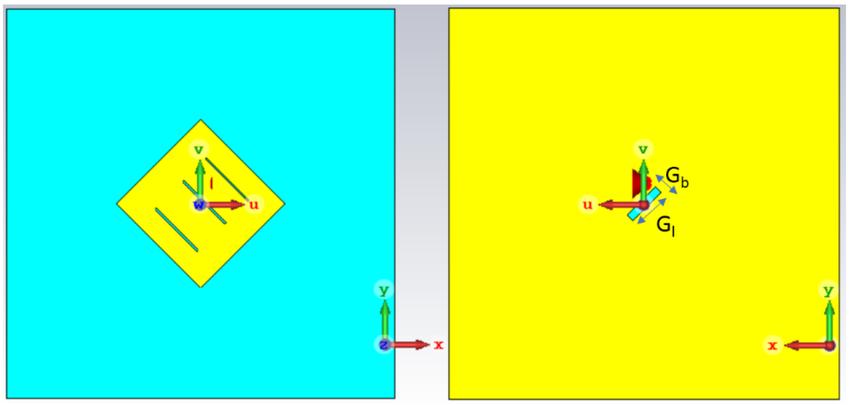

Figure 6: (left) Top view with Slotted patch; (right) bottom view with narrow slit in ground plane

When proper slots are embedded in the ground plane, lowering of the resonant frequency is observed. A related design with meandering in ground plane is shown in this section. A narrow slit (l = 5 mm and b = 2 mm) is meandered into the ground station as shown in Figure 6.

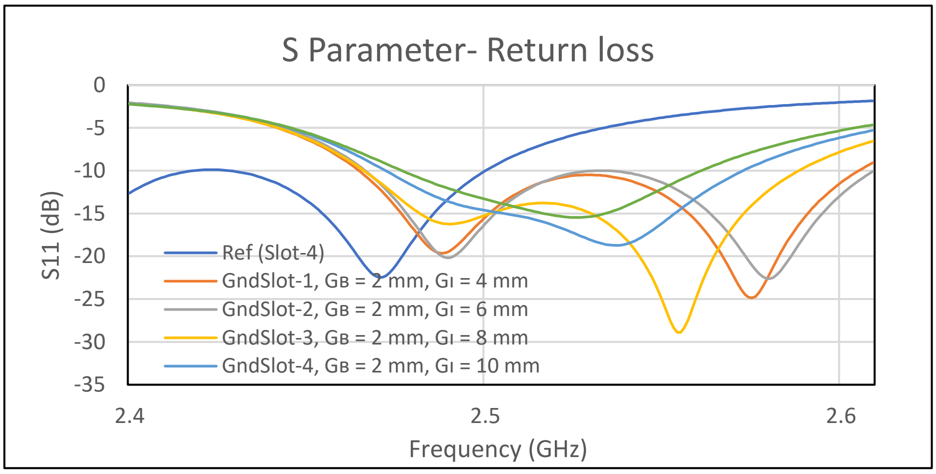

Figure 7: Simulated S11-parameter for variation of ground plane slot dimension.

The slit is just behind the rectangular patch antenna element. The narrow slot is placed exactly at the centreline of the antenna and the radiating patch, slot is at -45° to the antenna's resonant direction (x-axis in this case) to effectively meander the excited surface current. The angle is given to align the surface current flow of the ground plane with that of the radiating patch element.

To analyse the performance effect of meandering the ground plane, the side length of the antenna and the radiating patch is kept constant in all the variations. The feed position is kept the same. The measured return loss is shown in Figure 7. It is observed, that as slot length increases the fundamental resonant frequency decreases. This decrease in the resonant frequency corresponds to an antenna size reduction compared to the regular antenna size. The behaviour is owing to the embedded slots in ground plane, which effectively lowers the quality factor Q of the microstrip antenna. From return loss behaviour (Figure 7) it can also be observed that increasing the Length (G_l) of the slot, decreases the operating frequency (f2). This lowering of operating frequency allows for the possibility of antenna size reduction. The estimated size reduction has been found to be 15% in length and width of the antenna patch.

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Ground plane experiences a reverse current flow as that of radiating patch in patch antennas. Thus, by introducing a slot directly below the radiating element of the antenna, the surface current in the ground plane is forced to go around the ground plane slot [3]. Ground plane slot induces an additional polarization in the antenna performance due to the induced surface current rotation (hence, affecting the power flow) in radiating element. The polarization difference also leads to more efficient antenna performance due to less power leakage into cross polar radiation. It was observed that the polarization difference (LHCP-RHCP) of slotted ground plane rectangular patch antenna design (GndSlot-3 in Table 6) is 20.28 dBi as compared to slotted patch antenna (Slot-4) with just 11.83 dBi polarization difference. Also, the impedance bandwidth shows similar behavior as that of polarization with increase in slot length. GndSlot-3 (G_l= 8mm) is the best design because of the polarization difference and lower resonant frequency (offers antenna compactness).

Table 6: Ground plane slot dimension variation and performance

Antenna number	G_l [mm]	G_b [mm]	Polarization difference [dBi]	f1, f2 [GHz]	BW1, BW2 [MHz]	f2/f1	Abs. Gain [dBi]
Ref (Slot-4)	0	0	11.83	2.4703, 2.3785	73.3, 63.7	1.04	7.09
GndSlot-1	4	2	12.61	2.4650, 2.3780	140.5	1.04	7.11
GndSlot-2	6	2	11.30	2.4724, 2.379	143.1	1.04	7.11
GndSlot-3	8	2	20.28	2.4450, 2.3823	122.2	1.03	7.11
GndSlot-4	10	2	15.89	2.4270	99.9	-	7.13
GndSlot-5	11	2	10.96	2.4160	84	-	7.13

6.2. Resistance Integration

Antenna shorting by pin is another widely known performance enhancement technique for patch antennas however, it is also proposed to use chip resistance instead of pin for antenna shorting [3]. The resistance shorted antennas experience enhanced bandwidth and reduced fundamental resonant frequency [9]. The maximum effects are seen by placing the chip resistor at the edge of the radiating patch making the radiating edge a quarter wavelength of the resonant frequency wavelength [3]. Since, the excited electric field under rectangular patch at fundamental mode has maximum value around the patch edge, chip resistor is placed at the patch edge for maximum effects on the resonant frequency lowering of the rectangular patch antenna.

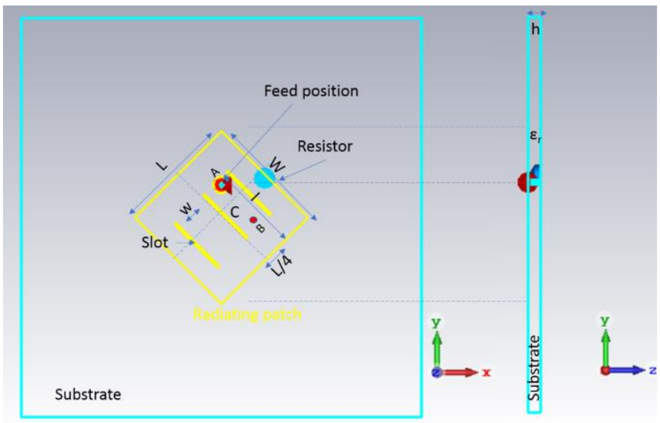

Figure 8: Resistance integrated slotted patch antenna design analogy

This is because the side length of patch acts as radiating element (λ/2) of half wavelength. By inserting a resistor at the mid of radiating edge, makes it (λ/4) quarter wavelength, thus enhancing the bandwidth of the antenna, but at the expense of gain [10]. This is due to increased ohmic loss in the current density of the patch which results in loss in gain of the antenna. Decrease in the gain value and the polarization characteristic of the antenna results in the overall decrease in the efficiency of the antenna. It has been found in this section that, by using resistance loading of lower magnitude, antenna bandwidth

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will be greatly enhanced [9]. To analyze the effects of resistance, the reference antenna design Slot-4 (l = 15 mm, w = 0.5 mm) from section "*Reference antenna*" was taken as design baseline. The geometry of probe feed antenna and the chip resistor has been shown in Figure 8 below. The resistance has been varied in the rage of 0.1 to 15 Ω for simulation.

Table 7:Performance comparison of resistance integrated slotted patch antenna.

Antenna number	Resistance [Ω]	f1 [GHz]	f2) [GHz]	BW [MHz]	f2/f1 [-]	Abs. Gain [dBi]	RHCP [dBi]
Ref (Slot-4)	0	2.3785	2.4703	63.7, 73.3	1.04	7.09	5.73
Resist-1	0.1	2.5090	-	65.3	-	7.12	5.73
Resist-2	0.5	2.5110	-	65.3	-	7.12	5.73
Resist-3	5	2.5151	2.7330	79.1, 92.9	1.09	7.12	5.79
Resist-4	10	2.5242	2.7224	327	1.08	7.12	5.81
Resist-5	15	2.5245	2.7074	329.1	1.07	7.12	5.81

Table 7 lists the respective resonant frequency and impedance bandwidth for resistance variation. The gain remains constant; however, the impedance bandwidth is affected considerably. As the resistance value increases from 0.1 to 15 Ω, the bandwidth BW1 increases from 65.3 to 329.1 MHz. Also, frequency ratio f2/f1 decreases as the resistance magnitude increases. This behavior allows to tune for a desirable secondary resonant frequency for dual frequency applications.

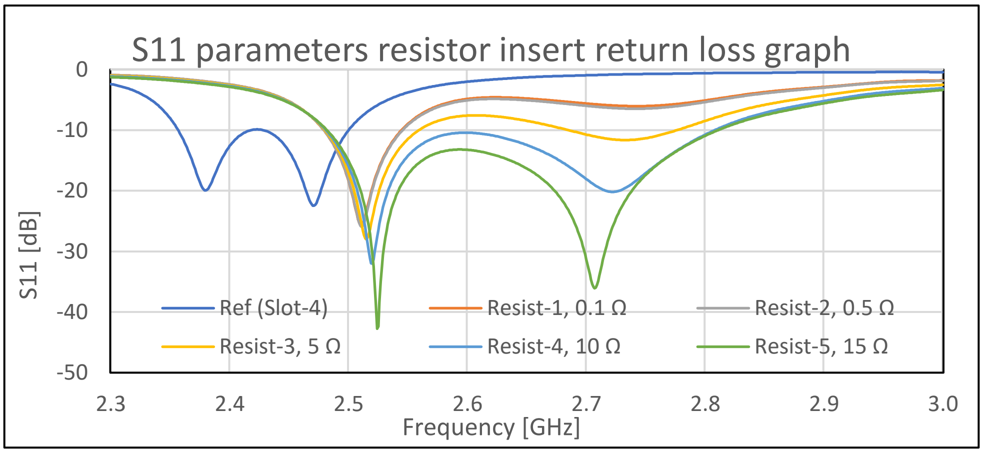

Figure 9: Simulated S11-parameter for variation of resistance values

The return loss plot in Figure 9 shows a shift of resonant frequency f2 (the plot valley around 2.7 GHz) by approx. 300 MHz (currently 2.7 GHz) but remains relatively stable for different resistor values. On the other hand, frequency f1 (the plot valley around 2.5 GHz) has a very considerable effect of changes in resistance magnitude. This behavior implies that by optimizing the resistance value, the frequency f1 can be regulated to a desired value. Antenna integrated with R = 10 Ω and 15 Ω shows max. BW and good property for dual frequency operation. The S11 parameter is below -10 dB in both cases, making the entire BW of the antenna workable without any standing waves and power loses.

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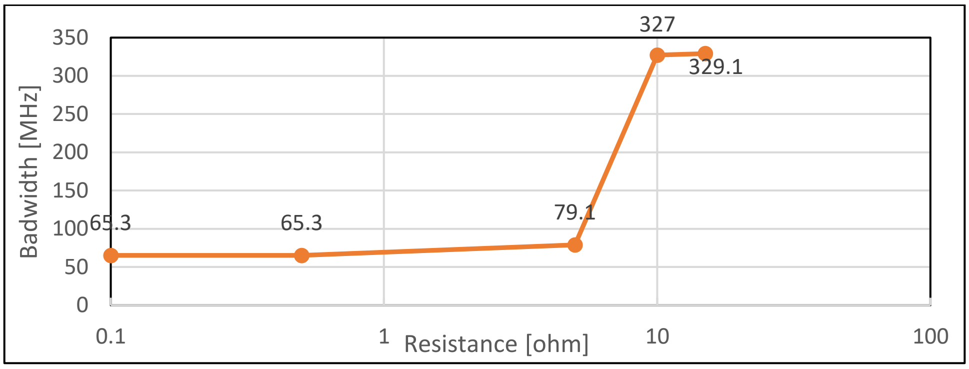

Figure 10: Effect of the resistance magnitude on the impedance bandwidth of the antenna

In Figure 10 shows the trend of impedance bandwidth by changing resistor value. For low resistance values, the increasing rate is very moderate. Above 5 Ω, the impedance bandwidth increases drastically. This is because the antenna surface current and power flow find a power sink and hence, antenna is able to regulate and operate on larger number of frequencies. The sudden rise in the bandwidth is due to the merging of two individual frequencies.

6.3. Capacitor Integration

Antenna feed pin between the ground plane and the patch of the antenna is capacitively coupled [1]. In this section, a chip capacitor along with feed pin is used to control antenna's capacitive reactance. The capacitor enhances the capacitance of the antenna and feed pin by enhancing the surface current in the patch [3]. The capacitance shorted antennas experience changes in the surface waves and space wave patterns. This results in enhanced bandwidth and reduced fundamental frequency [3]. Due to reduced operation frequency, the compact antenna can be obtained with no significant performance variations. The geometry of probe feed antenna and the chip capacitor is shown in Figure 11.

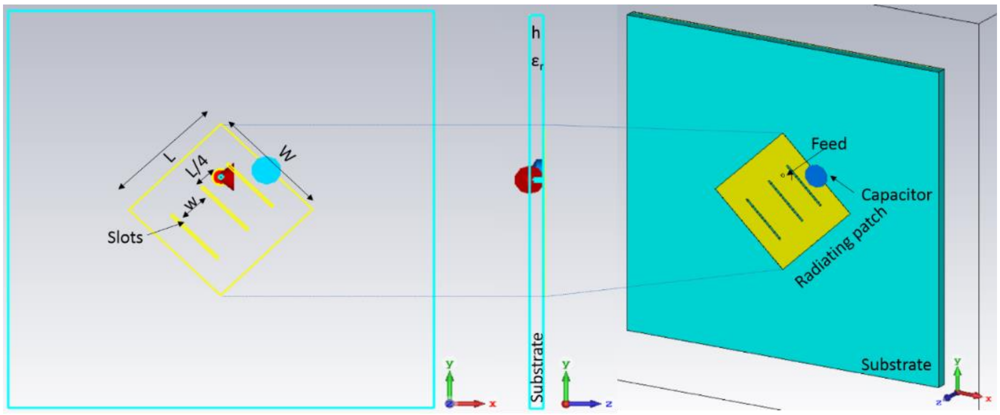

Figure 11: Slotted patch antenna analogy with integrated capacitance

Table 8: Performance comparison of capacitor integrated slotted patch antenna

Antenna number	Capacitance [pF]	f1 & f2 [GHz]	BW [MHz]	Max Gain [dBi]	f2/f1
Ref (Slot-4)	0	2.3785 & 2.4703	63.7 & 73.3	7.09	1.04
Cap-1	0.2	2.3799	80.6	7.05	-
Cap-2	0.3	2.3161 & 2.4842	52.8 & 36.9	7.06	1.07
Cap-3	0.5	2.2463 & 2.4913	42 & 47.6	7.06	1.11
Cap-4	0.8	2.1361 & 2.4962	29.7 & 55.3	7.06	1.17
Cap-5	1	2.0620 & 2.4993	20 & 50	7.06	1.21

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The Table 8 presents the resonant frequency and impedance bandwidth for the slotted patch antenna (Slot-4) integrated with chip capacitor variation from 0 to 1 pF. It shows inversely proportional relation between frequency – capacitance and capacitance - bandwidth. The shift of resonant frequency can be used to the reduce antenna surface area.

Figure 12 shows the inversely proportional relation between capacity and resonant frequency of approx. The equation to give am impression for the slope of variation in resonant frequency due to capacitance variation is mentioned below:

$$f1 = -0{,}384 \cdot cap[pF] + 2.443[MHz]$$

The S11 parameter improves positively correlates with capacity implying increased antenna efficiency.

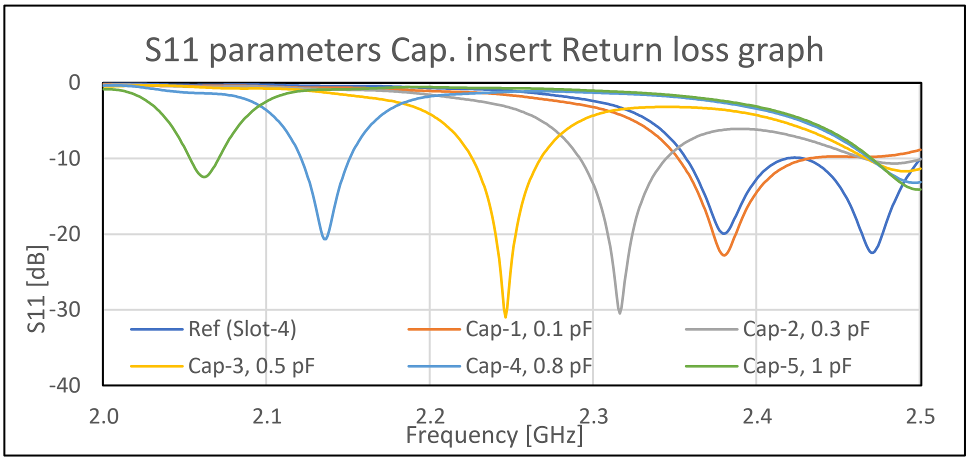

Figure 12: Simulated S11-parameter for variation of capacity

6.4. Parasite patch integration

In the fundamental resonant mode TM_{010}, the electric field perpendicular to the patch radiative edge has a standing wave distribution with a positive and negative node along its axis. The direction of the electric field is reversed after propagating over half-wavelength. Thus, there are two standing waves along the main patch which will force partial power to the parasitic patch located along the radiating edges of the power patch. By carefully adjusting the dimensions and location of power patch and parasitic patches, the magnitude of total radiation fields in the back space can be partially cancelled due to approximately 180 degrees out of phase from power patch and parasitic patch. Moreover, by adjusting the size of both the patches, electric field can be made in phase. Thus, by matching the radiating phase, the radiation in the front-space of the antenna will be greatly enhanced and the high-gain operation is acquired [13].

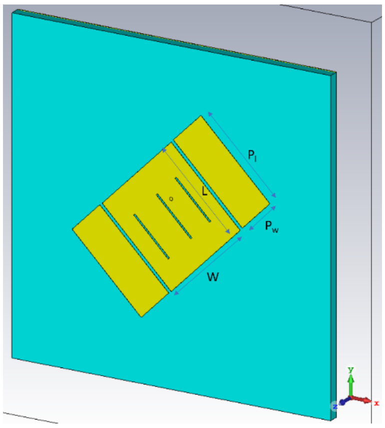

Figure 13: Indirect coupled parasitic patch slotted patch antenna

The capacitive patches are placed at the orthogonal axis of the radiating patch enabling fundamental mode (TM_{010}) of the antenna's radiating edge. Figure 13 shows two indirectly coupled parasitic patch of length 10x15 mm. The parasitic patch is coupled with the radiating edge of the main patch. To get a high gain antenna performance either high-permittivity dielectric superstrate material loading, or amplifier involved active circuitry can be used. Especially small satellites with limited resources can benefit from a better link budget.

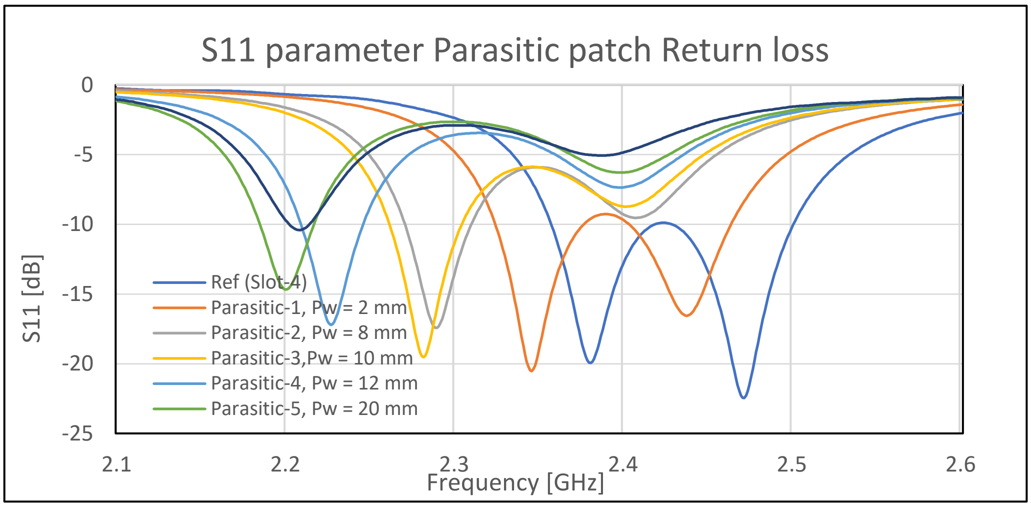

Figure 14: Return loss comparison of parasitic patch (10 x 15 mm) integrated slotted patch antenna

Figure 14 shows return loss behaviour for the reference antenna (Slot-4) with parasitic patch of varying dimensions integrated. The antenna's main operating frequency decreases with increase in length.

The Table 9 lists the resonant frequency and impedance bandwidth. The overall gain of the antenna is improved as the width P_w of the parasitic patch increases since the radiated energy becomes more concentrated. Furthermore, with increase in length, the bandwidth decreases from 63.7 MHz to 12 MHz.

Table 9: Performance comparison of parasitic patch integrated slotted patch antenna

Antenna number	**P_w [mm]**	**P_l [mm]**	**Gain [dBi]**	**f [GHz]**	**BW [MHz]**	**Polarization difference [dBi]**
Ref (Slot -4)	0	0	7.09	2.3785 & 2.4703	63. 7 & 73.3	4.67
Parasitic-1	2	15	7.07	2.345 & 2.437	52.4 & 60.5	12.62
Parasitic-2	8	15	7.17	2.2882	39.3	12.65
Parasitic-3	10	15	7.21	2.2813	42.9	13.11
Parasitic-4	12	15	7.25	2.2260	36.8	8.07
Parasitic-5	14	15	7.30	2.1992	32	5.77
Parasitic-6	20	15	7.40	2.2071	12	8.68

In Figure 15 the four lines show increase in gain almost similarly for all frequencies. This happens due to the more radiating surface area available on the radiating patch. The current from the power patch is induced into the parasitic patch and surface flows in the direction as induced by the current flow from the power patch.

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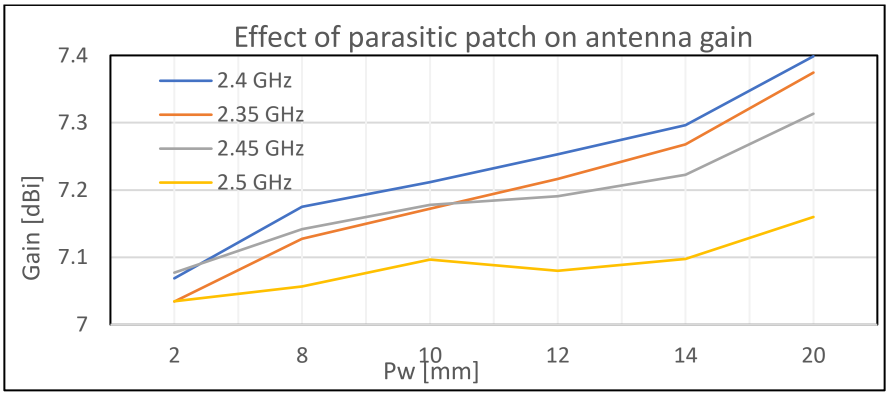

Figure 15: Gain trend of parasitic patch (10x15 mm) integrated slotted patch antenna

7. Combination of performance enhancement techniques

The herein introduced enhancement techniques can be combined to optimize the antenna performance for given application. In the following, a S-band antenna for TT&C link on a 3U Cubesat has been considered as a scenario for combining the techniques. Since Cubesats are highly constrained in volume and power resources, optimization for minimum volume and high gain are the key factors.

A proposed design for this scenario is a patch antenna which incorporates slotted patch, slotted ground plane, capacitance, and parasitic patch. The *slotted patch* technique is responsible for circular polarization, dual frequency optimization and high axial ratio. The *slotted ground plane* increases the polarization thus, increases the antenna efficiency and decreases the bandwidth. The *capacitance* technique increases the bandwidth and reducing the size of antenna by reducing the natural resonant frequency of the antenna. Lastly, the *parasitic patch* contributes in increasing the gain and directivity of the antenna. To summarize the antenna expected out of the combination of these techniques should have high gain, highly polarized and optimum bandwidth performance characteristics while reduced size and thickness.

To analyze the size reduction and gain increase when combining the techniques, two design optimizations were conducted. "Combined design 1" targeted gain maximization while keeping frequency and size comparable to the reference antenna. "Combined design 2" targeted size minimization while keeping frequency and gain comparable. The performance characteristics of the antenna is outlined in Table 10.

Both antennas show wide bandwidth of 286.6 and 216.6 MHz, respectively. Comparing to the Ref. Slot-4 antenna (bandwidth 70 MHz), the combined enhancement technique design shows an increased bandwidth for same antenna thickness. Bandwidth of the antenna is directly proportional to height of substrate layer as shown:

$$B \propto \frac{\varepsilon_r - 1}{\varepsilon_r}\frac{W}{L}h \qquad \text{Eq. 10}$$

This implies, that the thickness can be further reduced for narrow band application (space communications) by employing performance enhancement techniques. Compared to the reference antenna, "Combined design 1" shows a gain increase of 27 % to 8.14 dBi and "Combined design 2" a size reduction of 52 % (from 96 to 46.2 cm^2).

Table 10: Performance of the combination enhancement technique antenna design

Characteristics	Reference Slot-4	Combined design 1	Combined design 2	Units
Central frequency	2.40	2.40	2.40	GHz
Gain	7.09	8.14	7.13	dBi
VSWR	< 2	<2	<2	
Bandwidth	70	286.6	216.6	MHz
Connector type	SMA	SMA	SMA	

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Return loss	-22.4	-21.8	-21.3	dB
Size	98 x 98 x 3.22	98 x 98 x 3.22	68 x 68 x 3.22	mm
Polarization difference	11.17 - RHCP	18.54 – RHCP	13.56 – RHCP	dB
Mass	<70	<70	<50	g

8. Conclusion

Table 11 below summarizes the effect on different performance characteristics of antenna due to respective enhancement technique. It shows that all techniques result in the lowering of the resonant frequency, implying the possibility to reduce the antenna size. The potential applications due to respective enhancement techniques are mentioned in last column of Table 11.

Table 11: Performance enhancement vs Performance comparison result

Enhancement techniques	Gain	Band-width	Operating frequency	Polarization (co and cross)	Size reduction	Performance	Applications
Slotted patch	const.	decr.	f1: const. f2: decr.	incr.	possible	Narrowband with multiple resonant frequency	Radar, array fed waveguide and satellite communications [15]
Slotted ground plane	mild incr.	incr.	decr.	incr.	possible	Highly polarized performance with high radiation efficiency	Aircraft and terrestrial MIMO applications [16]
Resistor	subst. decr.	incr.	mild decr.	decr.	possible	High bandwidth performance at low gain operations	Radar and Medical scanning applications [17]
Capacitor	const.	decr.	decr.	decr.	possible	Decrease in the resonant frequency and highly compact antenna	Mobility and back-haul applications [18]
Parasitic patch	incr.	decr.	decr.	incr.	possible	High gain performance with high axial ratio characteristics	Satellite communications and defense communications [14]

The main outcome of this article is the significant performance increase by combining the techniques. For given 2.4 GHz scenario, following improvement compared to a slotted patch antenna could be achieved:

- Gain enhancement by 27 % (7.09 to 8.14 dBi)
- Percent bandwidth increase by 9 % (70 to 286.6 MHz @2.4 GHz)
- Size reduced by 52% from (96 to 46.2 cm^2)

In future work, the findings of this article can be applied for design optimization of compact antenna arrays by further gain reduction and gain improvement. The planned IoT/M2M (machine to machine) small satellite constellations will demand highly integrated antenna arrays to close the link despite weak ground sensor signals, or active beam forming and multiple beams [21]. Thus, this article's outcome will contribute to further optimizing the efficiency of such communication missions.

Symbols

W	Patch width	H	Height of substrate
L	Patch length	d_p	Feed position
C	Speed of light	f_{100}, f_{300}	Excitation modes
F	Operating frequency	L	Slot length
E	Dielectric constant	W	Slot width
ε_e	Effective dielectric constant	G_l	Ground slot length
G_b	Ground slot width	P_l	Parasitic patch length
P_w	Parasitic patch width		

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