


Design Equation for Operating Frequency of Patch Antenna with a Rectangular Tuning Stub at Early Phase 5G Bands

*¹Barış Gürcan Hakanoğlu, ²Şekip Esat Hayber, ³Mustafa Türkmen


¹Kırşehir Ahi Evran University, Department of Electronics and Automation, 40300, Kaman, Kırşehir,

bghakanoglu@ahievran.edu.tr, 

²Kırşehir Ahi Evran University, Department of Electrical and Electronics Engineering, 40100, Bağbaşı, Kırşehir,

sehayber@ahievran.edu.tr, 

³Erciyes University, Department of Electrical and Electronics Engineering, 38039, Talas, Kayseri,

turkmen@erciyes.edu.tr, 

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Abstract

In this paper, microstrip patch antennas with rectangular tuning stubs are analyzed, and variations of the resonant frequency depending on the dimensions of the stub have been studied. According to these variations, a design equation has also been proposed for the antennas. The operating frequencies are selected from the early phase 5G bands (700, 2300, 3500, and 4700 MHz), but the equation validity is tested for additional frequencies as 6500 MHz and 8500 MHz which are randomly selected. To identify the material effects, analyses are conducted for two different dielectrics, FR4 and Rogers RT/Duroid 5880. The calculations have been performed for twelve different reference antennas and twelve stub-placed modified antennas. It has been shown that the patch antennas with rectangular tuning stubs pave the way to tune the antenna resonance up to 7.5%-27.6% of its reference design frequency. For example, the proposed structure designed for 700 MHz can shift the resonant frequency up to 511.5 MHz for FR4 and 507 MHz for Rogers RT/Duroid 5880. Moreover, the shifting in frequency at 8500 MHz can reach 7950 MHz for FR4 and 7865 MHz for Rogers RT/Duroid 5880 with reasonable S_{11} levels.

Keywords: Microstrip Antenna, Rectangular Patch Antenna, Early 5G, Tuning Stub, Design Equation.

1. INTRODUCTION

Microstrip patch antennas have many advantages, such as being lightweight, cost-effective, and having compatible dimensions with various surfaces, circuits, and devices. However, the major shortcoming of such antennas is their limited bandwidth which makes the input impedance very fragile to fabrication errors and dielectric material tolerances. So, causing changes in the effective length of the patch, manual tuning can adjust the operating frequency. It has been shown that the resonant frequency of a patch antenna can be fine-tuned by placing a tuning stub on one edge of the antenna with the tuning range dependent on the length and the width of the stub [1]. Tunable frequency microstrip antennas can also be realized using RF microelectromechanical systems (MEMS) technology [2]. Tuning and miniaturizing can be performed simultaneously by etching slots in the patch and using thin posts placed near the edge [3]. Besides, it has been demonstrated that a microstrip patch antenna can be tuned on a liquid crystal substrate using a DC bias. The simulated and measured tuning ranges have been found at 8% and 4%, respectively [4]. A microstrip patch antenna on a tunable electromagnetic

band-gap (EBG) structure is proposed with the feature of performing the tuning through a diode-loaded EBG substrate [5]. Another application area for tuning stubs is to obtain triple frequency operation and circular polarization [6, 7]. Moreover, stubs are proposed to enhance the patch's bandwidth and make the whole structure more compact [8, 9].

The motivation for the design frequencies of the antennas in this paper is the early phase 5G bands. Three regions, such as the low range up to 3 GHz, mid-range between 3 GHz-6 GHz, and the high range above 6 GHz, are studied [10]. These bands are still under consideration for some countries, but some have already completed the frequency assignments. Many countries in Europe decided to utilize the 3400-3800 MHz range for the early phase of 5G. The United States launches out 3550-3700 MHz band for a new Citizens Broadband Radio Service to accommodate various commercial services on a shared basis. As a different part of the spectrum, the 4400-5000 MHz band is concerned by Japan and China. Japan has assigned 4400-4900 MHz band for 5G trials, and China defined 4800-5000 MHz band for 5G [11]. Besides, the 2300 MHz band is also released to be

*¹Corresponding author: Kırşehir Ahi Evran University, Department of Electronics and Automation, 40300, Kırşehir, Turkey
bghakanoglu@ahievran.edu.tr

a candidate for 5G communication in Sweden and United Kingdom [12]. Moreover, the Radio Spectrum Policy Group of the European Commission reveals that the 700 MHz band also needs to be operated in practice to make possible nationwide and indoor 5G coverage [13].

This study performs a detailed parametric analysis of the rectangular tuning stub (RTS) effect on the resonant frequency of microstrip patch antenna (MPA) and formulates a design equation. Microstrip patch antenna with rectangular tuning stub will be called MPA-RTS throughout the paper. RTS is placed on the top edge of the patch. The variations of stub edge dimensions result in different ways on the resonant frequencies and reflection coefficient levels. While the width of the stub variation causes a slight shift in resonant frequency and not so much change in reflection coefficient levels, the length of the stub variation produces a significant change in frequency shifting and reflection coefficient levels.

Moreover, the amount of frequency shifting varies according to the operating band. While an MPA-RTS is operating at 700 MHz shifts the resonant frequency up to 511.5 MHz for FR4 and 507 MHz for Rogers RT/Duroid 5880, an 8500 MHz operating MPA-RTS shifts the resonant frequency up to 7950 MHz for FR4 and 7865 MHz for Rogers RT/Duroid 5880 with reasonable return loss levels.

2. DESIGN

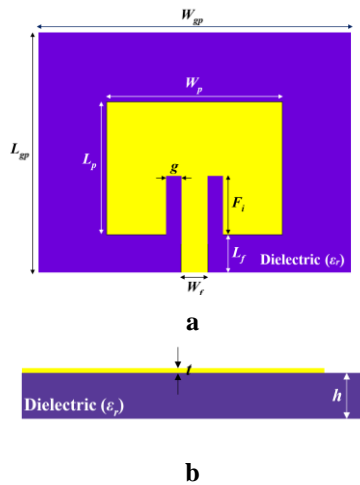


Figure 1. a. Top view of MPA b. Side view of MPA.

The reference antennas are designed for early phase 5G and frequencies outside the 5G bands using the proposed Equations 1-4 derived from the patch antenna's transmission line model [14]. Also, to observe the material effects, two different dielectrics with different heights are used for the

substrates, FR4 and Rogers RT/Duroid 5880, with the permittivity, ϵ_r of 4.4 and 2.2, respectively. The heights of the substrates are 1.5 mm for FR4 and 0.787 mm for RT5880. Figure 1a shows the top view of an example design for the antenna, and Figure 1b shows the side view of the structure. All antennas are designed with the same procedure. First, with Equation 1, the width of the patch, W_p is calculated based on the following parameters: f_r , ϵ_r , and h , where f_r is the resonant frequency, ϵ_r is the relative permittivity, and h is the substrate height. After that, Equation 2 enables us to obtain the effective permittivity, ϵ_{eff} , which should be known to calculate the length extension, ΔL_p due to the fringing field with the condition of $W_p/h > 1$ (Equation 3). Finally, with Equation 4, the patch length, L_p , can be calculated.

$$W_p = \frac{v_0}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}} \tag{1}$$

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 12 \frac{h}{W_p} \right)^{-\frac{1}{2}} \tag{2}$$

$$\frac{\Delta L_p}{h} = 0.412 \frac{(\epsilon_{eff} + 0.3) \left(\frac{W_p}{h} + 0.264 \right)}{(\epsilon_{eff} - 0.258) \left(\frac{W_p}{h} + 0.8 \right)} \tag{3}$$

$$L_p = \frac{v_0}{2f_r \sqrt{\epsilon_{eff}}} - 2\Delta L_p \tag{4}$$

There are no specific rules for the dielectric substrate dimensions. It is recommended that the length of the substrate, L_{gp} , and the width of the substrate, W_{gp} , should be greater than $6h + L_p$ and $6h + W_p$, respectively [15]. We performed a parametric analysis and an optimization about the edge dimensions of the substrate and took the values at which we obtain the reasonable S_{11} levels. The radiating part is modeled as a lossy conductor, and its thickness, t , is set to 0.035 mm (Figure 1b). The feeding is performed through a microstrip feed line with a width of W_f and the length of L_f together with an inset feeding part with the dimensions of the length F_i and the width g . For each design, W_f is taken as 3 mm for fabrication and impedance matching conditions for 50 ohms SMA (SubMiniature version A) connector. Due to the same reason, the width of the inset feeding, g , is calculated together with W_f , h , and ϵ_r to match 50 ohms. The length of inset feeding, F_i , is obtained through parametric analyses until we have the lowest S_{11} levels. The optimized parameters of the MPAs are summarized in Tables 1 and 2.

Table 1. The optimized parameters of the MPAs for FR4 ($\epsilon_r=4.4$), $h=1.5$ mm.

Parameters (mm)	Frequency (GHz)					
	0.7	2.3	3.5	4.7	6.5	8.5
W_{gp}	233.66	71.81	47.46	34.81	25.83	19.85
L_{gp}	182.90	55.75	36.57	26.80	19.49	14.75
W_p	130.32	39.66	26.06	19.41	14.03	10.73
L_p	101.95	30.76	20.02	14.74	10.44	7.78
F_i	35.30	11.70	8.20	6.40	4.60	3.50
g	0.68	0.21	0.14	0.11	0.08	0.06
L_f	38.89	11.84	7.78	5.79	4.19	3.20
W_f	3.00	3.00	3.00	3.00	3.00	3.00

Table 2. The optimized parameters of the MPAs for Rogers RT/Duroid 5880 ($\epsilon_r=2.2$), $h=0.787$ mm.

Parameters (mm)	Frequency (GHz)					
	0.7	2.3	3.5	4.7	6.5	8.5
W_{gp}	314.19	95.95	63.20	47.16	34.19	26.22
L_{gp}	255.41	77.65	50.96	37.88	27.31	20.79
W_p	169.05	51.52	33.86	25.21	18.23	13.94
L_p	144.07	43.60	28.51	21.12	15.14	11.45
F_i	35.30	16.20	11.10	8.60	6.20	4.80
g	0.95	0.29	0.19	0.14	0.11	0.08
L_f	38.89	11.83	7.78	5.79	4.19	3.20
W_f	3.00	3.00	3.00	3.00	3.00	3.00

According to the above results, reference antennas are modeled using Computer Simulation Technology Microwave Studio (CST MWS) [16]. To tune the resonant frequency, an RTS has been placed on the top edge of the patch with the dimensions of L_{RTS} for the length and W_{RTS} for the width. Figure 2 shows an example model for MPA-RTS. This figure shows that with the help of the RTS, it is possible to design antennas occupying less room. The dimensions of the RTS affect the resonant frequency and reflection

coefficient levels of the antennas. So, a detailed parametric analysis should be performed about L_{RTS} and W_{RTS} .

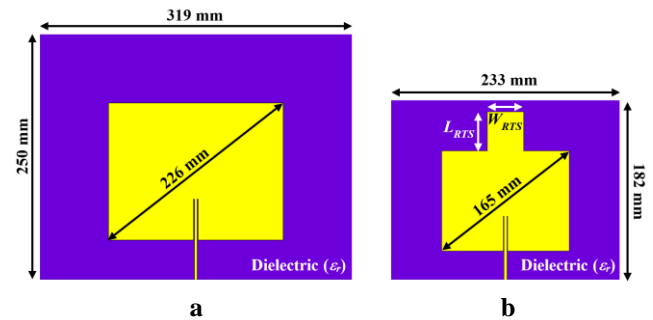


Figure 2. MPAs operating at 511.5 MHz a. without RTS b. with RTS.

3. RESULTS AND DISCUSSIONS

The effects of the variation of the stub parameters on the resonance frequency, f_r , and reflection coefficient parameters, S_{11} , are investigated using time-domain analysis for wideband or multiband antennas in CST MWS based on finite integration technique (FIT). For the study, FR4 material is preferred for dielectric substrate, and the results are also confirmed for a different dielectric material such as Rogers RT/Duroid5880. Other sized antennas are selected at quite different frequency values in addition to 5G frequencies. Thus, the obtained approximate model is valid for a wide range.

3.1. Effect of RTS parameters

MPA-RTS structures are obtained by adding RTSs to MPAs operating at early phase 5G frequencies such as 700, 2300, 3500, 4700 MHz. In addition to these frequencies, antennas are also analyzed at 6500 and 8500 MHz to confirm the validity of the obtained equation. In each case, the parametric analysis starts with $W_{RTS} \times L_{RTS} = 0.5 \text{ mm} \times 0.5 \text{ mm}$ until they reach at the near endpoints of the patch for W_{RTS} and of the substrate for the L_{RTS} . The variation path along the L_{RTS} can be called dielectric substrate distance (DSD). 0.5 mm is chosen as the step size for both parameters of RTS. The results of the FIT-based time-domain analysis for wideband or multiband antennas in CST MWS obtained from 4700 MHz are shown in Figure 3 as an example. All of the results obtained for the other frequencies examined in this study have similar characteristics to those for 4700 MHz which will be shown in the next section as an approach for the MPA-RTS.

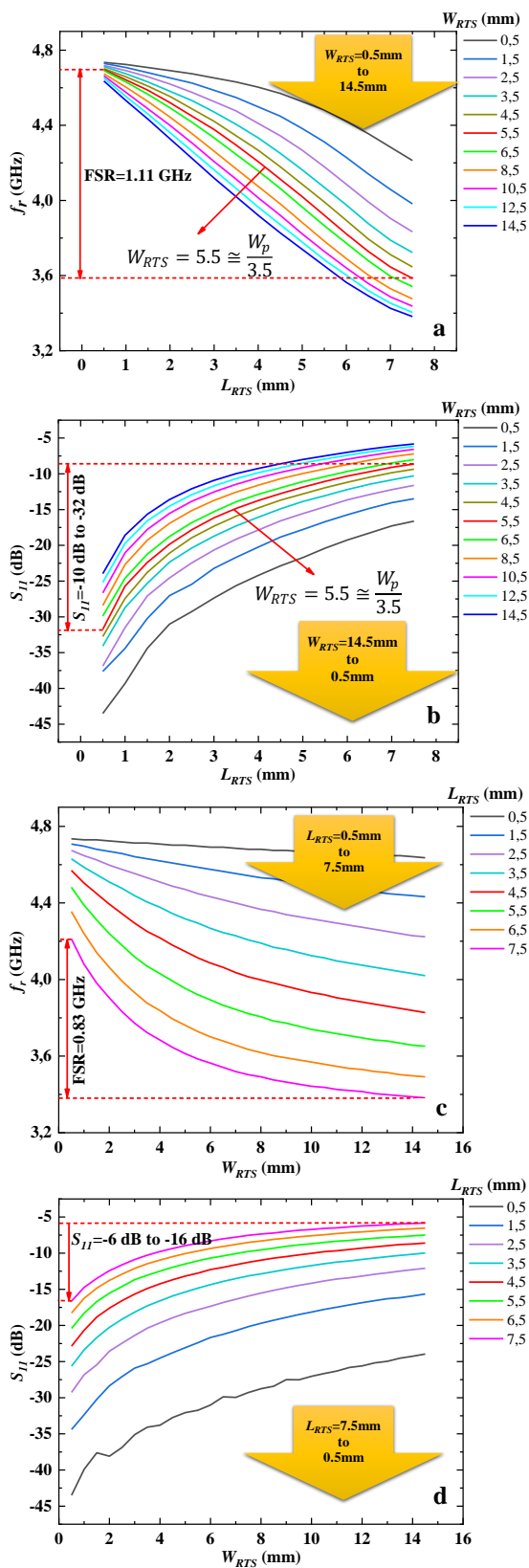


Figure 3. The effect of RTS parameters on the operating frequency and S_{11} of the MPA-RTS **a.** f_r versus L_{RTS} **b.** S_{11} versus L_{RTS} **c.** f_r versus W_{RTS} **d.** S_{11} versus W_{RTS}

Figure 3a-3d shows the variation of resonance frequencies and related S_{11} parameters when L_{RTS} and W_{RTS} change simultaneously along the dielectric and the width of the patch, respectively. It can be seen from Figure 3a that the increase of L_{RTS} and W_{RTS} result in shifting the resonances downwards, beginning from 4700 MHz at which the antenna was initially designed. The frequency shifting range called FSR is 1110 MHz from 4700 MHz to 3590 MHz in Figure 3a, where the S_{11} levels are acceptable. Figure 3b shows that when W_{RTS} decreases, S_{11} levels increase in a negative direction up to -32 dB, which is desirable for these parameters. However, S_{11} levels are not at desired levels for all W_{RTS} values. From Figure 3a and Figure 3b, we should find a particular value for W_{RTS} at which we get a wide shifting range of frequencies and reasonable S_{11} levels at the same time. From the plots, this optimal value is reached at the point when $W_{RTS}=5.5\text{mm}$ or $1/3.5$ of W_p , which can also be expressed as follows,

$$W_{RTS} = W_p/3.5 \quad (5)$$

Figure 3c and Figure 3d show that the effect of W_{RTS} on the frequency and S_{11} parameters for different L_{RTS} values. However, both the amount of change in FSR and the values of S_{11} are not at desired levels. Hence, we can say that the main effect on resonance is due to L_{RTS} . As a result, by placing RTS, microstrip antennas will operate at different frequencies according to variations of the length of the stub.

The effects of the variation of L_{RTS} on the frequency are given in Figure 4 by taking the W_{RTS} as constant for the antenna at each frequency as in Equation 5. Here, the limit value of L_{RTS} is the size of the dielectric substrate. Analyzes were performed for more values by decreasing the operating frequency and thus increasing the antenna dimensions. In Figure 4, while the solid purple line shows the L_{RTS} - frequency change for the FR4 substrate, the light blue solid line shows the L_{RTS} - frequency change for the RT5880 substrate. The change of the reflection coefficient parameters of the antenna with the increase of L_{RTS} is given in the graphs as inset figures. Thus, it can be seen in which values the reflection coefficient parameters fall below -10dB due to the frequency effect of L_{RTS} . Then, an equation is formed with these parametric analysis results, which is explained in Section 3.2.

3.2. An Approach for Patch Antenna with RTS

A mathematical approach that does not require multiple simulation processes is developed in this section. When the condition of $W_{RTS}=W_p/3.5$ is met, $f_{RTS} \propto \exp(-0.7L_{RTS}/W_p)$ can be derived. So, design simplicity is established. Equation 6 shows the expressions for the operating frequency of the regression analysis ($R^2=0.98$) on the time domain analysis for wideband or multiband antennas in CST MWS. It can also be calculated with this equation the results with different W_p , L_{RTS} , and ϵ_r values from the MPA-RTS structures satisfying the condition $W_{RTS}=W_p/3.5$.

$$f_{RTS} = \frac{v_0}{2W_p} \sqrt{\frac{2}{\epsilon_r + 1}} \times e^{-\left(\frac{0.7L_{RTS}}{W_p}\right)} \tag{6}$$

$$= f_r \times e^{-\left(\frac{0.7L_{RTS}}{W_p}\right)}$$

The lower limit of Equation 6 approaches Equation 1, which is valid for conventional MPAs. The lower limit is expressed as follows:

$$\lim_{L_{RTS} \rightarrow 0} f_{RTS} = f_r \tag{7}$$

Similarly, the upper boundary condition of Equation 6 tends to reduce the resonance frequency of the antenna by about 24%.

$$\lim_{L_{RTS} \rightarrow (DSD)} f_{RTS} \cong 0.76 \times f_r \tag{8}$$

Moreover, percentage error values are shown in Figure 5. Percentage error values differ according to the frequency values and substrate material. In this context, according to the graphs for $f_i=700$ MHz, 2300 MHz, 3500 MHz, and 4700 MHz, the percentage error values for RT5880 are slightly higher than for FR4 in general. Similarly, according to the graphs for 6500 MHz and 8500 MHz, it was seen that the percentage error value in FR4 is higher than in RT5880. In other words, the performance of Equation 6 is better for antennas built with RT5880 at high frequencies. It can be concluded that the error values average is 2% for the first

four frequency values, and the highest value rises to 4.5% in a very narrow region. Moreover, the average error value for 6500 MHz is 2.87%, which is 3.76% for 8500 MHz. Considering all frequencies and two types of substrate materials, the most common percentage error average was calculated as 2.44%.

Table 3. Comparison of similar studies in the literature with the current study.

	Structure	Frequency GHz	Tuning Range	Formed Equation
[1]	Rectangular patch antenna with rectangular tuning stubs	2.95	3.33%	No
[17]	Circular patch antenna with rectangular tuning stubs	1.695	9%	No
[18]	Tunable stacked patch PIFA	0.745	10%	No
This work	Rectangular patch antenna with a rectangular tuning stub	0.7	27%	Yes
	Rectangular patch antenna with a rectangular tuning stub	3.5	17%	Yes

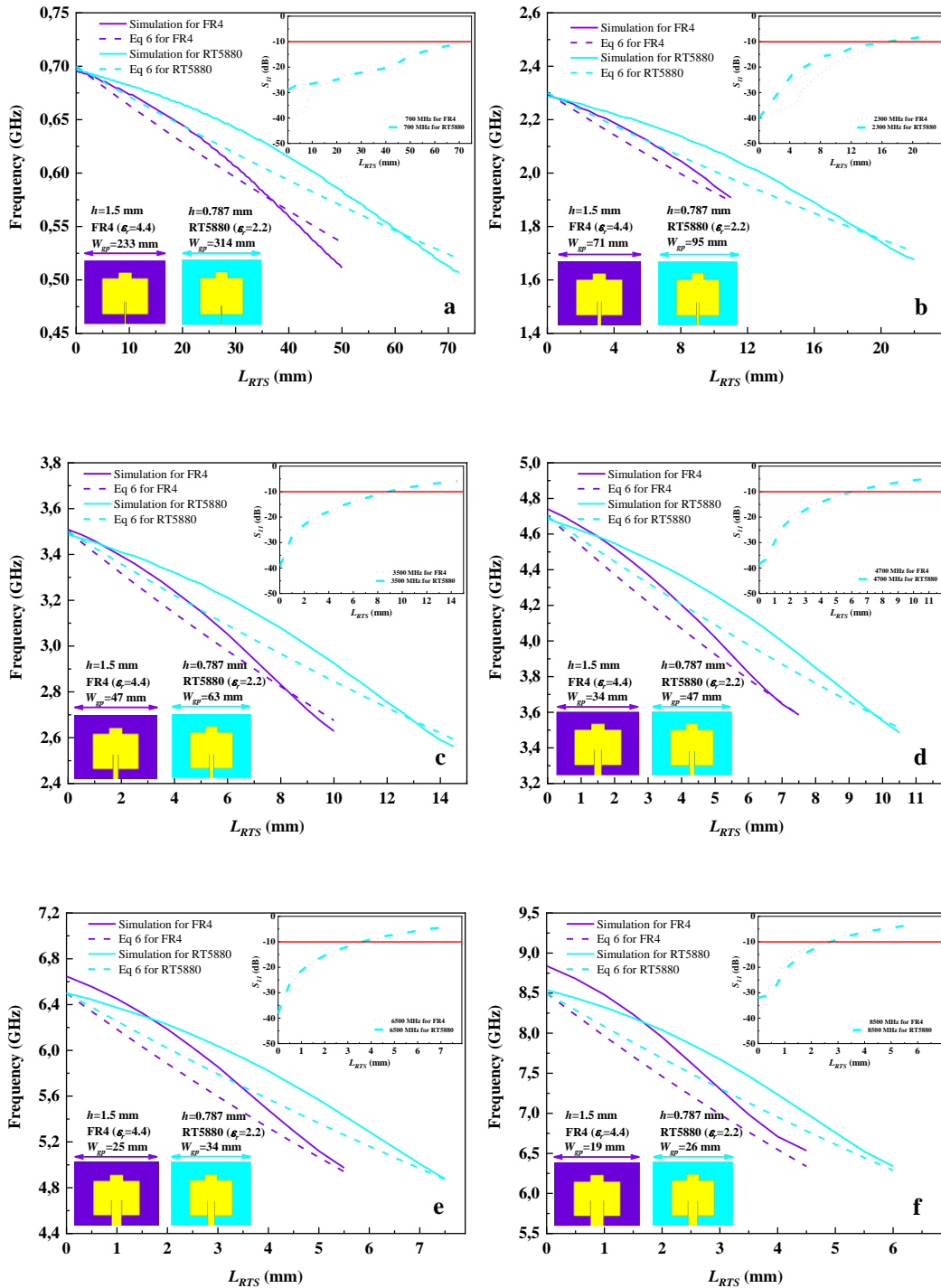


Figure 4. Comparisons of operating frequencies of MPA-RTSs with simulation and Equation 6 for FR4 and Rogers RT/Duroid 5880 **a.** $f_r=700$ MHz **b.** $f_r=2300$ MHz **c.** $f_r=3500$ MHz **d.** $f_r=4700$ MHz **e.** $f_r=6500$ MHz **f.** $f_r=8500$ MHz effect of RTS parameters on the operating frequency and S_{11} of the MPA-RTS **a.** f_r versus L_{RTS} **b.** S_{11} versus L_{RTS} **c.** f_r versus W_{RTS} **d.** S_{11} versus W_{RTS} .

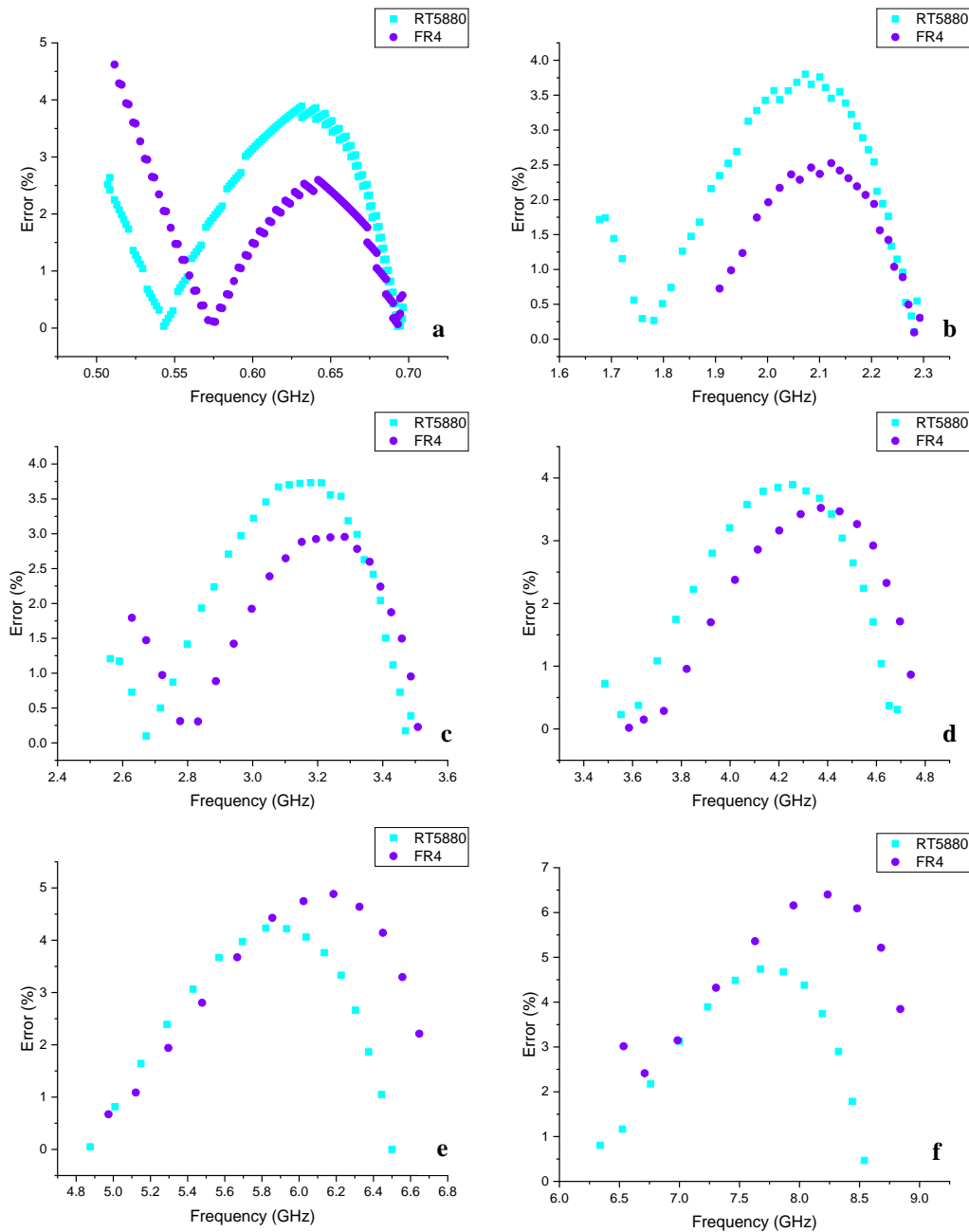


Figure 5. Percentage error values according to the simulation results of the developed formula for different frequencies, **a.** $f_r=700$ MHz **b.** $f_r=2300$ MHz **c.** $f_r=3500$ MHz **d.** $f_r=4700$ MHz **e.** $f_r=6500$ MHz **f.** $f_r=8500$ MHz.

There are microstrip antennas with tuning stubs in the literature. The comparison of some of these with our study is given in Table 3. The general purpose of adding tuning stubs, as is known, is to adjust the antenna around a specific operating frequency. The typical features of the compared studies are that they have more complex geometries and require time-consuming simulations for each size variation. However, in this study, both the adjustment range has been extended, and an analytical model has been developed that gives approximately 2% accurate results. Thus, there is no

need for repeated long simulation processes for each geometric value.

4. CONCLUSIONS

Patch antennas with rectangular tuning stubs operating at early phase 5G bands are designed and simulated. The effects on the radiation characteristics are analyzed by performing a multi-parameter analysis. It has been shown that the edge dimension variations of the stub directly affect the resonant frequency of the antenna and reflection coefficient levels. Also, for an optimal value of the stub width, the frequency shift amount and reflection coefficient levels are reasonable,

1/3.5 of the patch width. After performing a detailed parametric analysis for the stub length, a design equation is proposed. This equation relates the antenna's resonant frequency to the stub length, with the condition of stub width having a definite optimal value.

REFERENCES

- [1]. Du Plessis, M., and John Cloete. "Tuning stubs for microstrip-patch antennas." *IEEE Antennas and Propagation magazine* 36.6 (1994): 52-56.
- [2]. Erdil, Emre, et al. "Frequency tunable microstrip patch antenna using RF MEMS technology." *IEEE transactions on antennas and propagation* 55.4 (2007): 1193-1196.
- [3]. Sheta, Abdel-Fattah, and Samir F. Mahmoud. "A widely tunable compact patch antenna." *IEEE Antennas and Wireless Propagation Letters* 7 (2008): 40-42.
- [4]. Liu, L., and R. J. Langley. "Liquid crystal tunable microstrip patch antenna." *Electronics Letters* 44.20 (2008): 1179-1180.
- [5]. Liang, Jing, and HY David Yang. "Microstrip patch antennas on tunable electromagnetic band-gap substrates." *IEEE transactions on antennas and propagation* 57.6 (2009): 1612-1617.
- [6]. Sung, Y. "Axial Ratio-Tuned Circularly Polarized Square Patch Antenna with Long Stubs." *International Journal of Antennas and Propagation* 2018 (2018).
- [7]. Hasan, Wanis Alfitouri, et al. "Design and fabrication of triple frequency microstrip patch antenna by attaching tuning stub element." *2016 10th International Conference on Telecommunication Systems Services and Applications (TSSA)*. IEEE, 2016.
- [8]. Arya, Ashwini K., Rao Shahid Aziz, and Seong-Ook Park. "Planar ultra-wideband printed wide-slot antenna using fork-like tuning stub." *Electronics Letters* 51.7 (2015): 550-551.
- [9]. Bokhari, S. A., et al. "A small microstrip patch antenna with a convenient tuning option." *IEEE Transactions on antennas and Propagation* 44.11 (1996): 1521-1528.
- [10]. 5G Americas, (2017). *5G Spectrum Recommendations*. https://www.5gamericas.org/wp-content/uploads/2019/07/5_GA_5G_Spectrum_Recommendations_2017_FINAL.pdf (Accessed: 02.01.2020).
- [11]. Lee, Juho, et al. "Spectrum for 5G: Global status, challenges, and enabling technologies." *IEEE Communications Magazine* 56.3 (2018): 12-18.
- [12]. Global Mobile Suppliers Association, (2018). *Spectrum for Terrestrial 5G Networks: Licensing Developments Worldwide*. <https://gsacom.com/paper/5g-spectrum-terrestrial-networks/> (Accessed:02.01.2020).
- [13]. RSPG19-036 FINAL, Strategic Roadmap Towards 5G For Europe, Radio Spectrum Policy Group of European Commission, Brussels, 2019.
- [14]. Balanis, Constantine A. "Antenna Theory Analysis And Design", New Jersey John Willey & Sons." Inc, Publication (2005).
- [15]. Joler, Miroslav, and Josko Kucan. "Impact of Slot Parameters on the Three Resonant Frequencies of a Rectangular Microstrip Antenna: Study of the impact of the slot length, width, and position." *IEEE Antennas and Propagation Magazine* 57.4 (2015): 48-63.
- [16]. Computer Simulation Technology (CST) Microwave Studio, Framingham, MA, USA, 2017.
- [17]. Ray, K. P., and Kumar, G. "Tuneable and dual-band circular microstrip antenna with stubs." *IEEE transactions on antennas and propagation*, 48(7), 1036-1039, (2000).
- [18]. Karmakar, N. C., "Shorting strap tunable stacked patch PIFA." *IEEE Transactions on Antennas and Propagation*, 52(11), 2877-2884, (2004).