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Microstrip antenna design with partial ground at frequencies above 20 GHz for 5G telecommunication systems

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ABSTRACT

This article presents the design of a microstrip patch antenna at different frequencies above 20 GHz that intended to be used for fifth generation (5G) telecommunication system. The design of microstrip patch antenna that has a radiating element with a rectangular shape and partial ground plane is proposed. The patch antenna is designed using a Rogers RT5880 substrate with dielectric constant, εr of 2.2. The results of the designed antenna design analyzed in terms of the reflection coefficient, bandwidth, gain, and directivity performance. The proposed patch antennas at design frequencies of 25.875 GHz, 38.75 GHz, 43 GHz, 46.25 GHz, 48.7 GHz, 51.5 GHz, 71 GHz, and 83.5 GHz have a fractional bandwidth, gain and directivity that respectively greater than 10.2 %, 2.159 dB and 2.562 dBi. All designs and analysis are performed by using the CST Microwave Studio software.

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1. INTRODUCTION

Recently, the transition from the fourth generation (4G) technology to the fifth generation (5G), which is widely denoted as 5G is anticipated to be launched within the next decade. Although the 4G cellular mobile systems are still being rolled out in many countries, the telecommunication industries and researchers have already begun to work on the 5G system. Driven by the perpetual demand for greater network speed and the larger systems capacity, many nations including, United State, China, European Union, Japan, and South Korean have commenced large-scale research and development efforts to launch 5G wireless broadband technology earlier than 2020 [1]. As in the coming years, the total amount of mobile traffic is expected to increase significantly and in order to achieve 5G for commercial availability around 2020, the future 5G should consider the needs of users with reliability and the good service quality in maintaining network performance such as latency, security, reliability, availability, energy performance, and device cost [2-3].

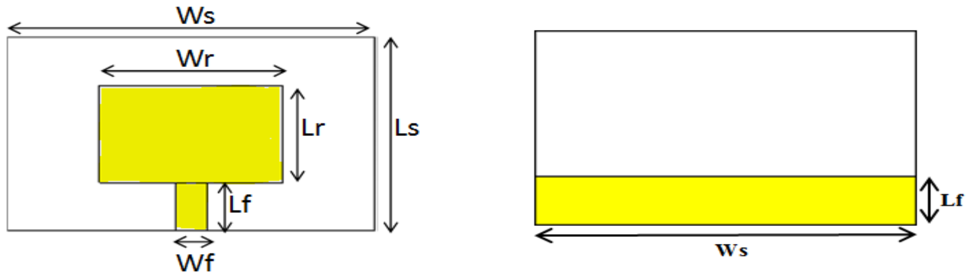
A potential disruptive move is to extend the communication spectrum to include frequency bands above those used today by 4G for mobile and wireless communication systems, which typically located below 6 GHz [4-5]. International Mobile Telecommunications (IMT)-Advanced specifications of fourth generation (4G) terrestrial mobile telecommunication were approved by the International Telecommunication Union Radio Standards Sector (ITU-R) in January 2012 [5]. Based on [6], it is possible of allocation in the frequency range between 24.25 GHz and 86 GHz for the mobile services on primary basis in the development of IMT for 2020 and beyond [5-6]. The 2015 World Radiocommunication Conference has considered that IMT is intended to provide the protection services, which the band is allocated on the primary basis for 5G telecommunication systems.

Hence, one of the main components in wireless communication, which is antenna needed a careful design as the operating frequency is higher than 20 GHz, which facing more challenges. The microstrip patch antenna is selected considering its utilization, which has become diverse due to small size, light weight, and cost-effective fabrication. Inherently microstrip patch antenna has narrow bandwidth and low efficiency and its performance greatly depend on the different frequency used [7]. In addition, as wireless applications require more and more bandwidth; the demand for microstrip patch antenna operating at higher frequencies becomes inevitable. Furthermore, at a higher frequency that greater than 20 GHz, selection of substrate becomes critical, which the low dielectric constant and low loss tangent values exhibit better performance [8].

Thus, this article proposes rectangular-shaped microstrip patch antennas that designed at frequencies above 20 GHz; specifically at 25.875 GHz, 38.75 GHz, 43 GHz, 46.25 GHz, 48.7 GHz, 51.5 GHz, 71 GHz and 83.5 GHz considering the proposed spectrum reported in [6]. The design utilizes Rogers RT5880 substrate, which simulated and optimized via the use of CST Microwave Studio. The analysis is conducted to observe the performance of bandwidth, radiation pattern, gain, and directivity.

2. ANTENNA DESIGN

The designs of a microstrip patch antenna are shown in Figure 1. The microstrip patch antenna consists of a rectangular patch; that serves as a radiating element on the top layer, substrate element on the middle layer and ground plane on the bottom layer. The top layer and bottom layer are consists of copper materials with a thickness of 17 μm that give a good radiating performance. Meanwhile, the middle layer is formed by a Rogers RT5880 substrate that has a dielectric constant, ε_r of 2.2 and thickness of 0.254 mm [9-11], [21].



(a) (b)

Figure 1. CST layout of the proposed microstrip antenna: (a) top view and (b) bottom view

The performance of the microstrip antenna depends on its resonance frequency used and dimension. Thus, the reflection coefficient, radiation efficiency, gain, directivity, and other related parameters are depending on each different resonance frequency. For an efficient radiation, the length of radiating element for the patch antenna, Lr is designed based on the following theoretical expression (1) [12-13]:

$$\mathrm{Lr} = \frac{c}{2f\sqrt{\varepsilon_{eff}}} - 2\Delta l \quad (1)$$

where f is referring to operating frequency used. Meanwhile, Δl and ε_{eff} are an average length and effective relative permittivity of the substrate, respectively. The average length, Δl and effective relative permittivity, ε_{eff} can be computed by using the respective expression (2) and (3) [14-15]:

$$\Delta l = \frac{(0.412h)(\varepsilon_{eff}+0.3)\left(\frac{Wr}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{Wr}{h}+0.8\right)} \quad (2)$$

$$\varepsilon_{eff} = \frac{\varepsilon_{r+1}}{2} + \frac{\varepsilon_{r-1}}{2}\left(1+\frac{10h}{Wr}\right)^{-1/2} \quad (3)$$

where ε_r and h are relative permittivity and the thickness of the substrate, accordingly. Meanwhile, the width of the radiating element for the patch antenna, Wr can be determined from equation (4) [16-17]:

$$\mathrm{Wr} = \frac{c}{2f}\left(\frac{\varepsilon_r+1}{2}\right)^2 \tag{4}$$

where c is the speed of light. Meanwhile, the feeding element has a dimension of width, Wf and length, Lf. Based on the characteristic impedance, Z_0 of 50 ohm, the width of the feeding line, Wf can be computed via the use of (5) [18-19]:

$$\frac{\mathrm{Wf}}{h} = \begin{cases} \frac{8e^{A}}{e^{2A}-2} & , \frac{\mathrm{Wf}}{h} < 2 \\ \frac{2}{\pi}\left[B - 1 - \ln(2B-1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\left\{\ln(B-1) + 0.39 - \frac{0.61}{\varepsilon_r}\right\}\right] & , \frac{\mathrm{Wf}}{h} > 2 \end{cases} \tag{5}$$

where constant A and B are expressed as in the respective equation (6) and (7) [20]:

$$A = \frac{Z_0}{\pi}\sqrt{\frac{\varepsilon_r+1}{2}} + \frac{\varepsilon_r-1}{\varepsilon_r+1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right) \tag{6}$$

$$B = \frac{377\pi}{2Z_0}\sqrt{\varepsilon_r} \tag{7}$$

Afterward, the length of feeding line, Lf is designed initially based on the quarter wavelength, $\lambda_g/4$. Where, λ_g is guide wavelength that can be determined based on formula (8) [21-23]:

$$\lambda_g = \frac{c}{f\sqrt{\varepsilon_{eff}}} \tag{8}$$

Afterward, the ground plane is designed by considering both full and partial ground plane. However, the implementation of a full ground plane has led to degradation of the reflection coefficient and narrow band performance. Thus, the partial ground plane is implemented through optimization that resulting in the final dimension of Lf x Ws, where the length is similar to the length of feeding line, while the width is equal to the width of the substrate. This grounding technique produces the best reflection coefficient result as the radiating element of the antenna is fully radiating [24]. The designs and optimization are conducted through the use of full electromagnetic wave simulator, Computer Simulation Technology (CST) Microwave Studio. The substrate that implemented in the design is Rogers RT5880 with a dielectric constant of 2.2, thickness of 0.254 mm, copper cladding of 0.017 mm and tangent loss of 0.0004. The optimized and finalized dimensions of all antennas that designed referring the intended 5G operating bands are listed in Table 1.

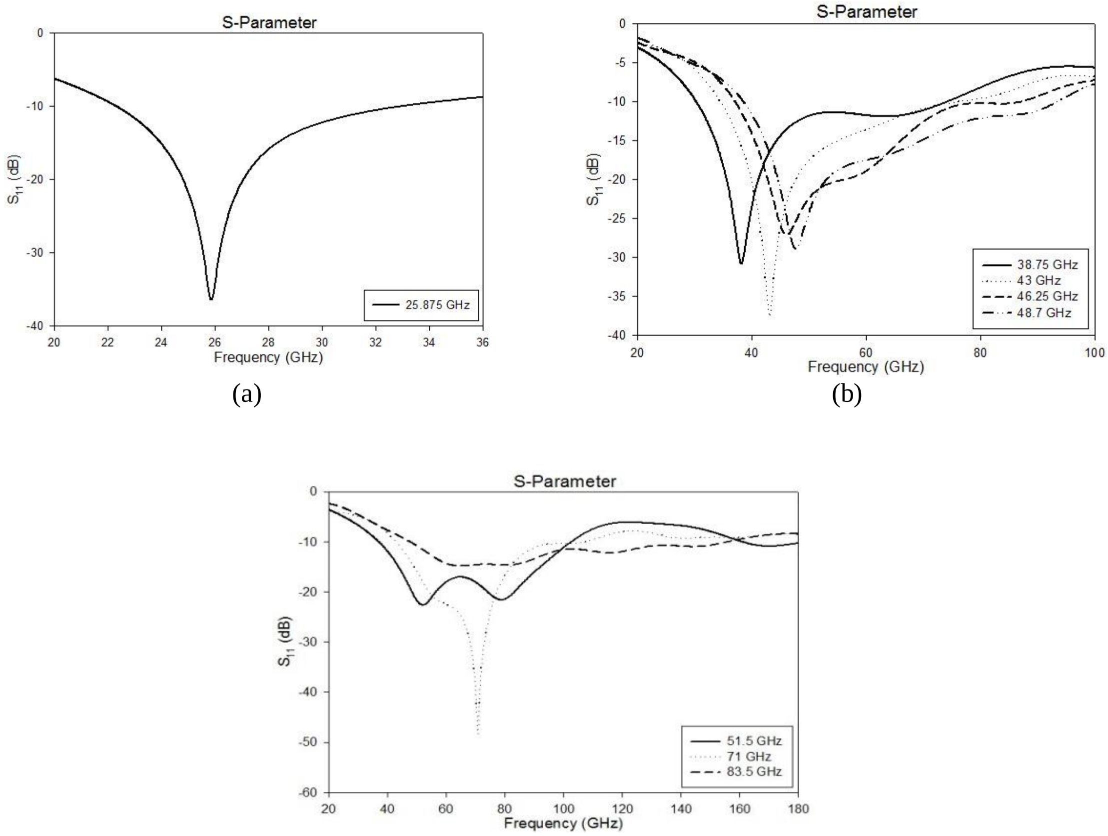
Table 1 shows that all optimized dimensions of the proposed microstrip patch antennas with the partial ground plane and simple microstrip feeding line are depending on the specific 5G designated operating frequency range [25]. Afterward, the performances of the proposed antennas are analyzed in terms of the reflection coefficient, bandwidth, gain and directivity performance as presented in the next section.

Table 1. The Optimized and Finalized Dimensions of Microstrip Patch Antenna at Each Specific 5G Designated Operating Frequency Range

Parameters	Designated Frequency Range (GHz)							
	24.25-27.5	37-40.5	42.5-43.5	45.5-47	47.2-50.2	50.4-52.6	66-76	81-86
Centre / design frequency, f_0 (GHz)	25.875	38.75	43	46.25	48.7	51.5	71	83.5
Width of substrate, Ws (mm)	8.400	5.800	5.954	5.592	5.352	4.600	4.600	3.116
Length of substrate, Ls (mm)	5.380	3.600	2.800	4.458	2.400	2.400	1.600	1.862
Width of radiating element, Wr (mm)	4.200	2.900	2.977	2.796	2.676	2.300	2.300	1.558
Length of radiating element, Lr (mm)	2.660	1.800	1.400	1.200	1.200	1.200	0.800	0.931
Width of feed element, Wf (mm)	0.761	0.761	0.761	0.761	0.761	0.761	0.761	0.761
Length of feed element, Lf (mm)	1.345	0.900	0.700	1.115	0.600	0.600	0.400	0.466

3. RESULTS AND ANALYSIS

The proposed microstrip rectangular-shaped patch antennas with the partial ground plane that had the finalized dimensions as summarized in Table 1 are simulated and analyzed via Computer Simulation Technology (CST) Microwave Studio according to eight different designated frequencies between 24 to 86 GHz. The reflection coefficient, S_{11} results for each designed antenna are referring to the requirement of less than -10 dB to ensure minimal reflected power. Hence, the antenna bandwidth performance is determined by using this -10 dB reflection coefficient specification [26]. The reflection coefficient, S_{11} results of the proposed antennas with eight different design frequencies above 20 GHz are shown in Figure 2.



(a) (b)

(c)

Figure 2. Reflection coefficients, S_{11} of the proposed patch antennas that designed at specific frequencies of: (a) 25.875 GHz, (b) 38.75, 43, 46.25 and 48.7 GHz, and (c) 51.5, 71 and 83.5 GHz

The best reflection coefficient, S_{11} of -48 dB can be observed from the 71 GHz antenna compared to the worst reflection coefficient, S_{11} of -15 dB that demonstrated by the 83.5 GHz antenna. Referring to the plotted results in Figure 2, it is can be noted that all designed antennas have quite wide bandwidth performance especially two antennas that designed at 51.5 GHz and 83.5 GHz, which are having the respective bandwidth of 67.34 GHz and 108.17 GHz. The broadest bandwidth performance is 108.17 GHz that corresponds to 106.4% of fractional bandwidth shown by the 83.5 GHz antenna. Meanwhile, the narrowest bandwidth performance is 10.585 GHz (38.4%) that depicted by the 25.875 GHz antenna. These performances are summarized in Table 2. Furthermore as seen from Figure 2 and Table 2, the antenna designed at the design frequency of 46.25 GHz has a bandwidth performance that operates from 37.07 GHz to 86.876 GHz, which actually sufficient to cover the designated frequencies of 38.75 GHz, 43 GHz, 46.25 GHz, 48.7 GHz, 51.5 GHz, 71 GHz and 83.5 GHz.

The microstrip patch antenna design produces a nearly omnidirectional far-field radiation pattern as can be noticed in the polar plots at eight different design frequencies shown in Figure 3. From this assessment of radiation pattern, the gains and directivities of the proposed antennas are summarized in Table 2. The best antenna gain of 3.018 dB is demonstrated by the antenna that designed at 48.7 GHz compared to the worst antenna gain performance of 2.159 dB shown by 38.75 GHz and 71 GHz antennas.

Nonetheless, these two antennas with worst antenna gain offer the best directivity performance of 4.860 dBi (the 71 GHz antenna) and the worst directivity of 2.562 dBi (the 38.75 GHz antenna). Hence, the proposed antennas have the gain and directivity that higher than 2.159 dB and 2.562 dBi, accordingly.

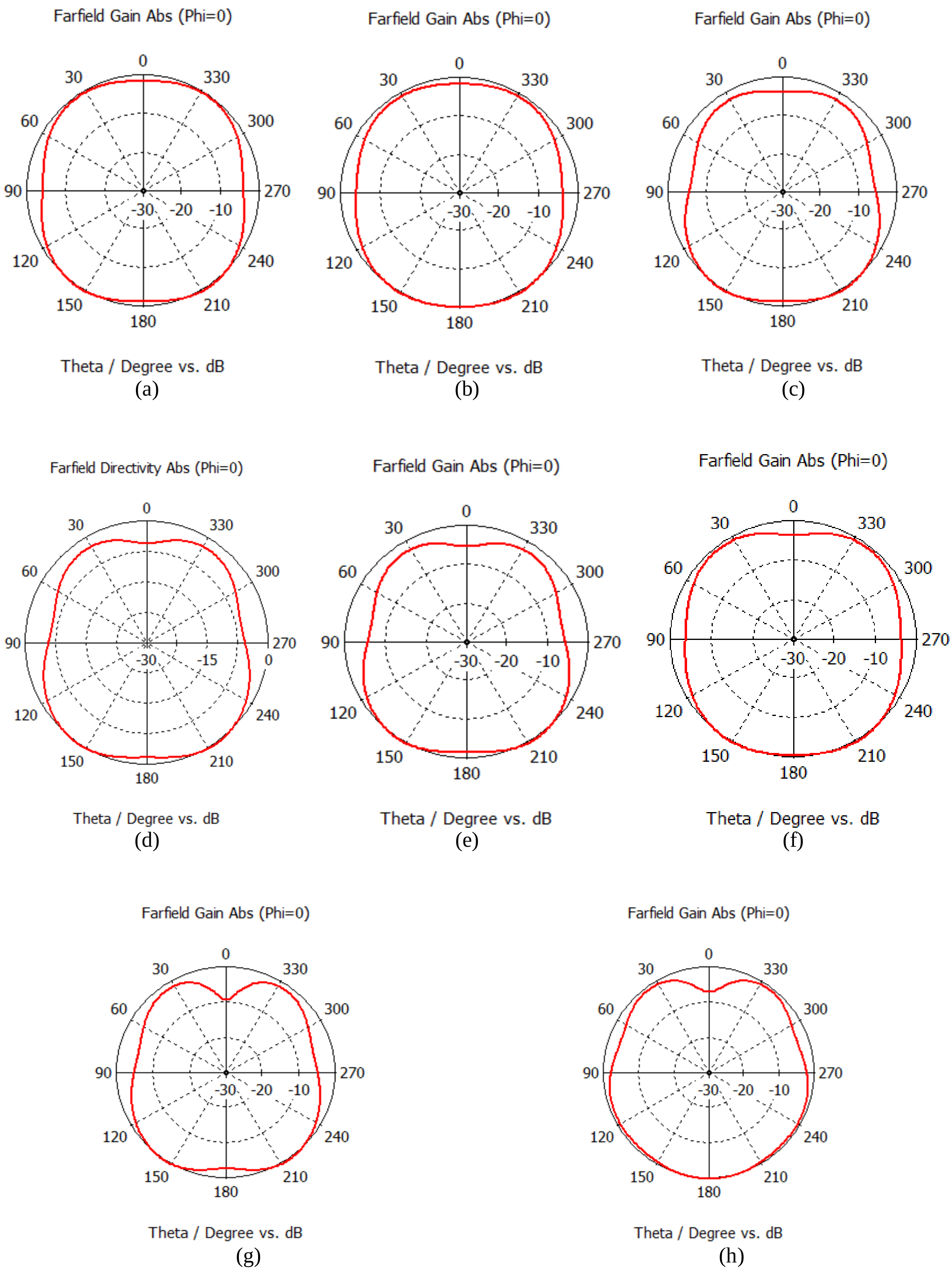


Figure 3. Simulated radiation patterns in polar plot at frequencies of: (a) 25.875 GHz, (b) 38.75 GHz, (c) 43 GHz, (d) 46.25 GHz, (e) 48.7 GHz, (f) 51.5 GHz, (g) 71 GHz and (h) 83.5 GHz

Table 2. The Characteristics of Microstrip Patch Antenna for Each Specific Operating Frequency

Parameters	Designated Frequency Range (GHz)							
	24.25-27.5	37-40.5	42.5-43.5	45.5-47	47.2-50.2	50.4-52.6	66-76	81-86
Centre / design frequency, f_0 (GHz)	25.875	38.75	43	46.25	48.7	51.5	71	83.5
S_{11} (dB)	-36	-31	-38	-27	-29	-23	-48	-15
Operating Frequency (GHz)	22.288-32.873	30.365-74.029	34.366-74.476	37.07-86.876	38.328-92.772	36.79-104.13	43.187-99.798	47.578-155.76
Bandwidth (GHz)	10.585	43.664	42.11	49.806	54.444	67.34	56.611	108.17
Fractional Bandwidth (%)	38.4	83.7	73.7	80.4	83.1	95.6	79.2	106.4
Gain (dB)	2.814	2.159	2.789	2.290	3.018	2.501	2.159	2.833
Directivity (dBi)	2.916	2.562	3.542	3.970	3.799	3.109	4.860	3.454

The summary of results on the characteristics of the proposed patch antenna such as reflection coefficient, bandwidth, gain and directivity for each operating frequency are represented in Table 2. The gain of the antenna must be greater than 2 dB in order to radiate well for the antenna design. This requirement is achieved by the proposed antenna that has the gain in the range between 2.159 dB and 3.018 dB. Meanwhile, the directivity is between 2.562 dBi and 4.860 dBi. The best value reflection coefficient is observed to be -48 dB at 71 GHz, while -15 is the worst at 83.5 GHz. Other than that, the bandwidth of the proposed patch antenna is greater than 38.4 % shown by 25.875 GHz antenna. The antenna that designed at 83.5 GHz depicts the broadest bandwidth of 106.4 %. As the proposed antenna has nearly omnidirectional beam, this design seems to be suitable for mobile applications at frequency range above 20 GHz for 5G technology.

4. CONCLUSION

The design of the microstrip patch antenna with partial ground plane has been presented at different ranges of frequencies above 20 GHz, which expected to be used in future 5G technology. The antenna design, optimization, and analysis have been conducted through CST Microwave Studio simulator. Throughout this study, microstrip patch antennas have been designed and simulated concerning expected 5G bands of 24.25-27.5 GHz, 37-40.5 GHz, 42.5-43.5 GHz, 45.5-47 GHz, 47.2-50.2 GHz, 50.4-52.6 GHz, and 81-86 GHz. The results from each antenna are analyzed in terms of reflection coefficient, bandwidth, gain, directivity, and radiation pattern performance. In higher frequencies, all parameter involved in the design of microstrip patch antenna must be accurately computed to minimize the error and loss that could be occurred. Then, the optimization has been performed to determine the best length and width that needed to offer optimal antenna performance. The proposed patch antenna has depicting the performances of fractional bandwidth, gain, and directivity that respectively greater than 38.4 %, 2.159 dB and 2.562 dBi. These good performances and the plotted radiation patterns guarantee the suitability of the proposed patch antenna for mobile applications in higher frequencies that greater than 20 GHz.

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