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# Performance evaluation and design of 5G communication-based millimeter wave antenna

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## Abstract

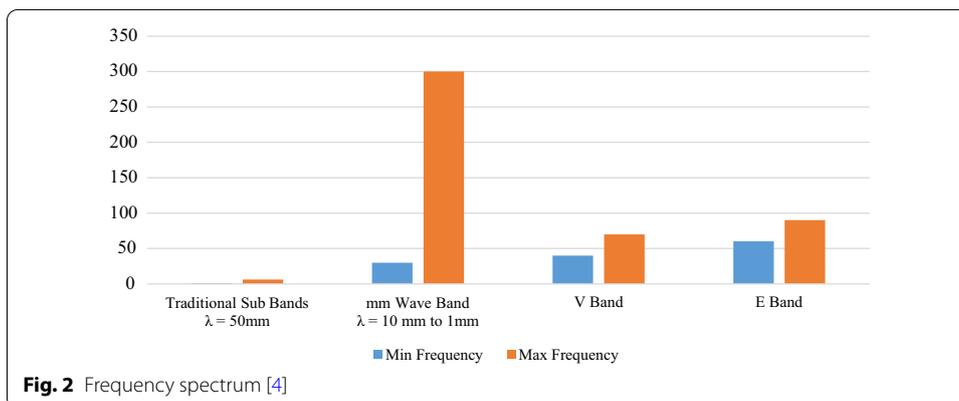
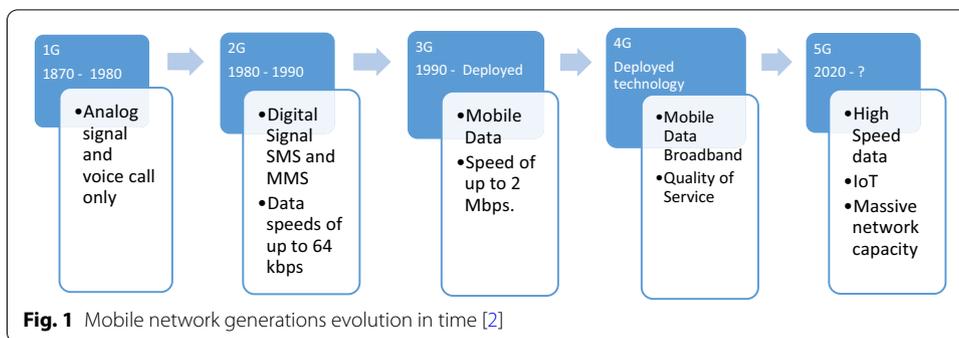
Multiple categories of electronic devices have been introduced recently in response to the demands and developments in the industry. Around 5.19 billion telecom services subscribers today have a significant effect on the allocation and utilization of bandwidth, and hence, there is extensive need to use higher-frequency bands, e.g., mm band to achieve the required quality of service since there is extensive need to shift the paradigm to the next generation. For 5G networks, antenna structuring and designing is an integral part of the communication system. In antenna theory, improving antenna gain is important to attain isotropic antenna, antenna gain can be improved by the controlled behavior of frequencies, beam forming and choosing the right antenna fabric. Through antenna design using different substrates thickness, the propagation losses are examined in order to determine the variation with radiation characteristics. In this way, the examination of the 5G mm-wave spectrum with comparative analysis of input impedance, gain and radiation efficiency is shown through mathematical modeling. Using this approach, the antenna efficiency is improved by up to 20% with increase in substrate thickness. Different antenna arrays have been designed for effective improvement in reflection coefficients. The results are obtained using simulation of antenna in CST and high-frequency structure simulator.

**Keywords:** Antenna array, Beam forming, Gain, Propagation loss, 5G

## 1 Introduction

With the extensive use of wired and wireless communication devices according to Statista reports, 1.5 billion smart phones have been sold during recent years [1]. Mobile communication markets have been growing tremendously according to GSMA, 5.19 billion subscribers in the world have access to the limited bandwidth resources, which is also a motivating factor toward adoption of new technology trends. Since data rate is one of the essential performance parameters in antenna theory in which a better performing transmitter, channel and receiver work in coordination in a communication system. Hence, the improved elements leads to the development of next generation as shown in Fig. 1.

The upcoming 5G technology not only provides greater reliability, higher data rates up to 20 Gbps and reduced power consumption to meet the massive increase in connected devices but also promises to increase the visions of emerging technologies such as virtual



reality and smart cities [3]. To continue deployment and operation in limited frequency bands is not a feasible solution, hence International Telecommunication Union (ITU) till mid of 2018 made certain standards to launch 5G thus millimeter frequency bands will be allocated for 5G backhaul links in order to fulfill the 5G expectations where large bandwidths are required. These are illustrated in Fig. 2.

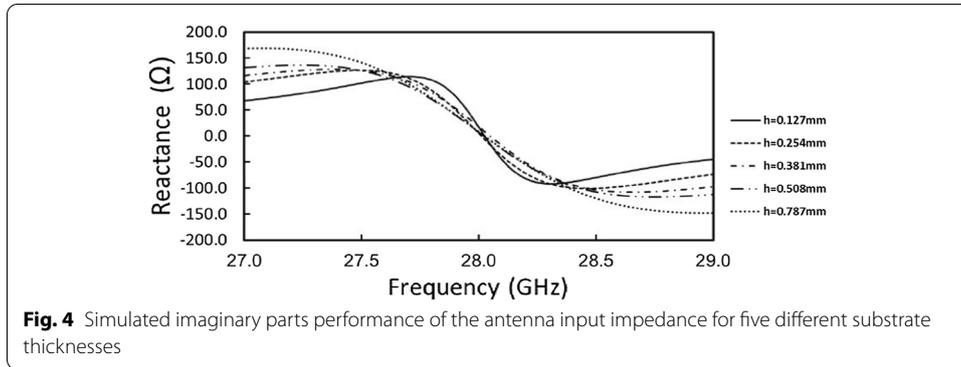
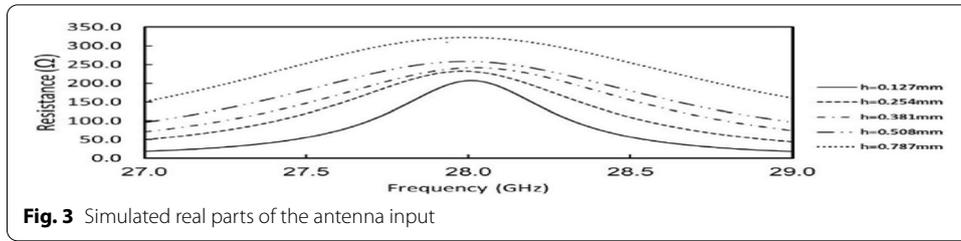
In order to operate over a frequency band, the antenna should be compliant with certain standards supported by regulatory bodies such as European Telecommunications Standards Institute (ETSI) [5] and the United States Federal Communications Commission (FCC). These standards have limitations on different characteristics of the antenna, such as its minimum gain and maximum effective isotropic radiated power (EIRP). Also, the antenna radiation pattern should be accommodated with a radiation pattern envelope (RPE) of a certain class. The class of RPE to be supported depends on the local regulators. The goal of these requirements is to avoid interference within a network and control the effects on other networks operating in the neighboring bands [6].

Hence in the modern era, the prominent increase of wireless devices, insufficient bandwidth and limited channel capacity has substantially promoted efforts to develop advanced standards for communication networks. Consequently, the development of next generation means much better channel capacity and higher data rates by using a millimeter spectrum to characterize the performance of antennas to meet the above-mentioned objectives for which certain parameters should be kept in mind while designing antennas. Antenna parameters can be classified into two categories, firstly the antenna parameters according to the field point of view which include the radiation

pattern, beam width, directivity, gain, bandwidth and the polarization, and the remaining antenna performance parameters are according to the circuit point of view which include input impedance, radiation resistance and reflection coefficient, return loss, VSWR and bandwidth [7–9]. Authors in [10] have worked on various channel models for diverse applications thus with the proper beamforming approaches for enhanced coverage. Current techniques have been presented by authors in [11] for enhancing the performance parameters of patch antennas for 5G implementation at mmW frequencies with performance parameters including gain, bandwidth among antenna elements for MIMO systems. Since the design considerations are vital in terms of an extended semi-circular structure which is also beneficial in enhancing the directional radiation of the antenna [12], the need for evaluating multiplexing performance in 5G Ultra Dense networks for interference suppression rate as a relation of signal of interest (SOI) to signal not of interest (SNOI) with preliminary angular separation has been considered in [13]. For guaranteeing effective coverage in mmW communication systems, the distributed antenna systems and cooperative multi-hop relaying with designing of antenna arrays have been presented in [14]. Hence to achieve an optimized antenna, antenna designing parameters are the key factor in improving antenna performance and that is why the antenna substrate is kept in observation. In [15] with the selection of  $\varnothing_n = \text{un}$  would result in deterministic width  $W$  for which the scaling properties can be thoroughly examined in detail according to the representation with the use of Poisson summation formula. In [16] the entropies of Shannon, Renyi and Kolmorov are examined in detail and with their comparative performance along with pre-fractal shape, the antennas are evaluated since the entropy is interdependent on the fractal geometrical shape and the physical performance of the antennas. The authors in [17] have worked on the model of joint time-frequency-shape management of discrete-time signals using discrete shapelet transform (DST) which makes it possible to realize the time support of frequencies along with investigating the shape simultaneously thus making it possible to synchronize applications in a diversity of fields in signal processing. In [18] the authors have presented a wavelet expansion theory for positive definite distributions on the real line and derived a fractional derivative operator thus the computation of Gabor–Morlet wavelet with its main characteristics. Since the broadband applications are significant so authors in [19] have developed and verified a broadband planar Sierpinski fractal antenna for multiband applications which according to its defined dimensions results in optimal return losses, radiation patterns and gain of the proposed antenna. With the importance of investigating the general implementation of the Sierpinski gasket through the harmonic metric in line with the geometric configuration of small antennas thus its performance is evaluated with the associated entropy.

## 2 Methods and experimentation

**Substrate thickness** We have chosen a low-loss Teflon-based material from the CST STUDIO SUITE library for the study of the impact of the substrate thickness on antenna performance. This substrate has a dielectric constant and  $\epsilon_r = 2$  and loss tangent  $\tan = 0.0007$ . An edge-fed microstrip patch antenna was used in the study as shown in Figs. 3 and 4. The antenna dimensions were slightly adjusted for each substrate thickness so that the antenna resonates at 28 GHz. It can be seen from Fig. 3 that as the



substrate thickness increases from 0.127 to 0.787 mm, the real part of the input impedance increases from 207 to 322 at 28 GHz. This increase in the real part of the antenna impedance can be recognized to an increase in the antenna radiation efficiency. The real part of the antenna input impedance can be written as

$$R_A = R_r + R_{loss}$$

where  $R_A$ , the total real part of the antenna input impedance;  $R_r$ , Radiation resistance which represents the part of the input power of the antenna that is transferred into radiated electromagnetic waves;  $R_{loss}$ , the part of the antenna input resistance (conductor losses, dielectric losses, surface waves, etc.).

### 3 Designing rectangular microstrip antenna

Designing a rectangular microstrip antenna involves choosing the material of substrate with thickness “ $h$ ,” target center resonant frequency “ $f_r$ ” in Hz and the dielectric permittivity constant “ $\epsilon_r$ ,” we determine the antenna dimensions: antenna width  $W$ . This can be calculated in the following steps [20].

*Step 1:* For efficient radiator, calculate the width  $W$  from Eq. (1).

$$W = \frac{C}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}} \tag{1}$$

where “ $C$ ” is the free space light velocity. From the expression we find that that width of the antenna substrate has inverse relation with the resonant frequency, but an optimized substrate thickness can be determined by considering multiple values of thickness.

*Step 2:* The effective dielectric constant  $\epsilon_{eff}$  or the effective relative permittivity can be approximated by using Eq. (2).

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2\sqrt{1 + 12\frac{h}{W}}} \quad (2)$$

The above expression is an empirical expression of the material property  $h/W$ , where “ $W$ ” is the width of the strip and “ $h$ ” is the substrate thickness.

*Step 3:* Determine the incremental length  $\Delta L$  generated by the fringing fields from Eq. (3), due to the fringing effect the patch of the antenna seems larger as compared to its physical dimensions. Hence,  $\Delta L$  can be given as:

$$\Delta L = 0.412h \frac{\left(\varepsilon_{\text{eff}} + 0.3\right)\left(\frac{h}{W} + 0.264\right)}{\left(\varepsilon_{\text{eff}} - 0.258\right)\left(\frac{h}{W} + 0.8\right)} \quad (3)$$

*Step 4:* Determine the effective length  $L_{\text{eff}}$  of the patch using Eq. (4) showing its dependence on  $C$ , i.e., free space light velocity, effective dielectric constant  $\varepsilon_{\text{eff}}$  and resonant frequency  $f_r$ , then determine the actual length  $L$  of the patch using Eq. (5)

$$L_{\text{eff}} = \frac{C}{2f_r\sqrt{\varepsilon_{\text{eff}}}} \quad (4)$$

$$L = L_{\text{eff}} - 2\Delta L \quad (5)$$

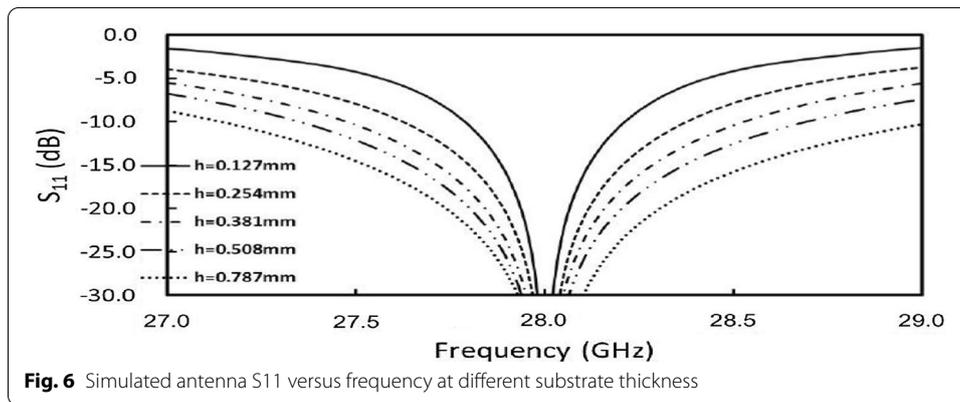
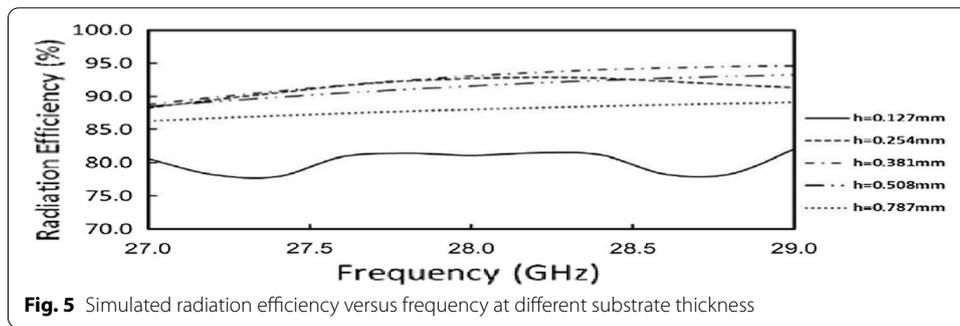
Using these relations, the antenna can be simulated using simulation tools such as ADS Agilent, CST or high-frequency structure simulator (HFSS) and its performance parameters can be adjusted in order to obtain optimum operational characteristics.

#### 4 Discussion on performance evaluation and results

*Substrate thickness* A low-loss Teflon-based material was chosen from the CST STUDIO SUITE library for the study of the impact of the substrate thickness on antenna performance. This substrate has a dielectric constant and  $\varepsilon_r = 2$  (6) and loss tangent  $\tan = 0.0007$ . An edge-fed microstrip patch antenna was used in the study as shown in Figs. 3 and 4. Figures 3 and 4 present the simulated real and imaginary parts of an antenna input impedance for five different substrate thicknesses, respectively. The simulated input impedance is referenced at ref. plane 1 (see Fig. 3). The antenna dimensions were slightly adjusted for each substrate thickness so that the antenna resonates at 28 GHz. It can be seen from Fig. 3 that as the substrate thickness increases from 0.127 to 0.787 mm, the real part of the input impedance increases from 207 to 322 at 28 GHz. This increase in the real part of the antenna impedance can be recognized to an increase in the antenna radiation efficiency. The real part of the antenna input impedance can be written as

$$R_A = R_r + R_{\text{loss}} \quad (7)$$

where  $R_A$ , the total real part of the antenna input impedance;  $R_r$ , radiation resistance which represents the part of the input power of the antenna that is transferred into



radiated electromagnetic waves;  $R_{loss}$ , the part of the antenna input resistance (conductor losses, dielectric losses, surface waves, etc.).

The simulated radiation efficiency is presented in Fig. 5. It can be seen from the figure that the radiation efficiency rises from 81 to 92.8% with the change of substrate thickness from 0.127 mm to substrate thickness of 0.381 mm respectively. This increase in radiation efficiency explains the increase in antenna resistance from 207  $\Omega$  at 0.127 mm substrate thickness to 241  $\Omega$  at 0.381 mm substrate thickness.

The efficiency then starts to decrease again and reaches an efficiency of 88.2% at a substrate thickness of 0.787 mm.

As the microstrip patch is very close to the ground plane which means low thickness that's why the low efficiency at 0.127 mm substrate thickness is observed. Therefore, the electric field lines are strongly attached to the ground plane.

The simulated S11 (referenced at ref. plane 2) is presented in Figure 6. It is clear from the results that the as the substrate thickness increases the antenna supported bandwidth also increases. The bandwidth increases due to the decrease in the antenna quality factor ( $Q$ ) either due to the increased radiation resistance or increased losses in the antenna (Table 1).

To justify our results multiple arrays of same material and structures have been designed such as 4 by 1, 8 by 1 and 16 by 1 with corporate feeding, the total field of the array is determined by the vector addition of the field radiated by the individual elements. The input parameters of three different designs such as 4 by 1, 8 by 1 and 16 by 1 array are enlisted in Table 2. For 5G applications, the antenna needs to have high gain

**Table 1** Simulated antenna parameters at different substrate thicknesses

(mm)	(MHz)	Fractional bandwidth	% Efficiency at 28 GHz
0.127	424	1.51	81
0.254	745	2.7	92
0.381	961	2.4	92
0.508	1170	4.2	91
0.787	1893	6.8	88

**Table 2** Designed parameters for multiple arrays

Design no	Frequency band	No of antenna in an array	Reflection coefficient (dB)	Relative permittivity $\epsilon_r$
Design 1	Mm band 45 GHz	4 × 1	− 37	2.2
Design 2	Mm band 45 GHz	8 × 1	− 18	2.2
Design 3	Mm band 45 GHz	16 × 1	− 6	2.2

of > 12 dB and directive beam that can be steered in a certain direction [21]. It might be hard to achieve such high gain using single small antenna. However, several small antennas can be grouped together in an antenna array to achieve such high gain directive pattern that can be electronically scanned in a certain direction. Shaping the array radiation pattern can be achieved by appropriate element to element spacing and appropriate excitation adjustment of the magnitude and phase of the currents feeding individual elements of the array in CST Studio Suite.

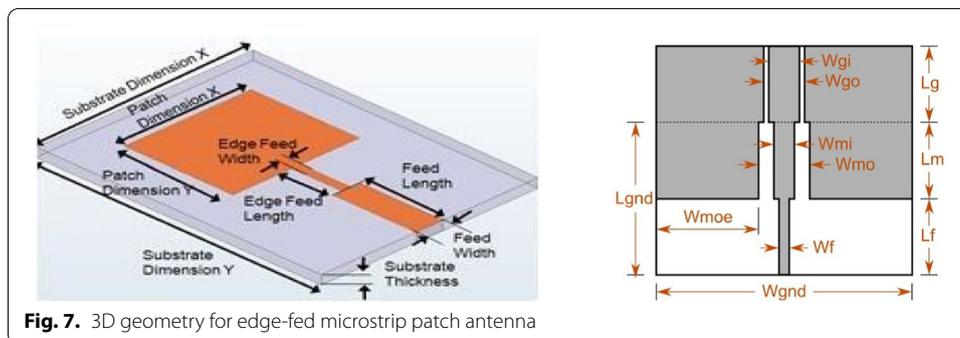
**5 Conclusions**

5G gains the recommendations in terms of high data rates, i.e., 20 Gbps downlink and 10 Gbps uplink as well the support for IoT. That is possible only when we have efficiently designed antenna according to supported millimeter wave spectrum. Among many performance evaluation components, this paper precisely focuses on the selection of antenna material. We find an optimized substrate thickness for an antenna such as going above the values of 0.787 mm and going below 0.127 mm which is critical, the results are shown through graphs by using high-frequency structure simulator. Denser substrate will result in increase in radiation losses, and the surface waves would make the problem worse. A thinner height is more effective in suppressing the higher mode and reducing the radiation losses. Additionally, the thinner substrate with good flexibility is recommendable for the conforming antenna. That’s why this is a good candidate toward implementation of 5G.

**Appendix 1**

Geometry for rectangular edge-fed microstrip patch (performance evaluation of 5G communication-based millimeter wave antenna with the perspective of substrate thickness).

See Fig. 7.



**Fig. 7.** 3D geometry for edge-fed microstrip patch antenna

### Abbreviations

EIRP: Effective isotropic radiated power; FCC: Federal Communications Commission; HFSS: High-frequency structure simulator; ITU: International Telecommunication Union; MIMO: Multiple-input multiple-output; RPE: Radiation pattern envelope; SOL: Signal of interest.

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### Authors' contributions

MS was responsible for overall implementation of the work. MA contributed in the findings and preparation of the manuscript, and SA has worked on research design, working of antennas. US formulated the problem, and Rafay has evaluated the parameters-based results. All authors read and approved the final manuscript.

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### Availability of data and materials

Not applicable.

### Declarations

#### Competing interests

The authors declare that they have no competing interest and hence policy of the journal followed for required processing.

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