Metamaterial Based Multiband Microstrip Patch Antenna for 5G Wireless Technology-enabled IoT Devices and its applications

John Colaco1, and R.B. Lohani2

1Department of Electronics and Telecommunication Engineering, Goa College of Engineering Farmagudi-Goa Ponda, Goa, Indi.,
2Department of Electronics and Telecommunication Engineering, Goa College of Engineering, Farmagudi-Goa Ponda, Goa, India.

E-mail: j_7685@yahoo.com

Abstract. In the present era of the digital world, demand for IoT based smart devices has seen tremendous growth. These devices involve real-time human-to-machine communication and interaction. Communication of uninterrupted quality depends on the high bandwidth and speed of the internet. The development of 5G wireless network technology is the response to the crucial factors that lead to this demand, because of its ability to provide extremely fast internet speed, high bandwidth, high performance, reduced latency, and high reliability. In this research work, the authors have developed a metamaterial-based multi-band microstrip rectangular shape patch antenna with a wide high-performance bandwidth because of the demand. The proposed design has a low dielectric constant of 2.2, which is of Rogers RT/Duroid substrate, and a dielectric loss tangent of 0.0010. The design has a resonant frequency of 26 GHz. The simulations carried out using FEKO software has been analyzed for performance. The simulation and analysis reveal a good return loss of -34.4 dB at 26 GHz, -13.49 dB at 40 GHz, -13.63 dB at 53.5 GHz, high bandwidth of 5.368 GHz at 26 GHz, 3.76 GHz at 40 GHz, 2.88 GHz at 53.5 GHz, desirable voltage standing wave ratio, 1⩽VSWR⩽2, high gain of 10 dBi at 26 GHz, 5 dB at 40 GHz, and high antenna radiation efficiency of 99.7 % at 26 GHz, and 61% at 40 GHz, 50% at 53.5 GHz. The bandwidth, return loss, antenna radiation efficiency and power density indicate an improvement of 5.368 GHz to 5.630 GHz, -34.82 dB to -57.10 dB, 99.7 % to 99.8 % and 2208 kW/m2 to 2800 kW/m2 respectively after loading and incorporating artificial magnetic split-ring resonator-based metamaterial on the patch. Further improvement is also seen at other frequencies. The proposed design has immense benefits for humanity due to its improved capacity to manage larger connected IoT devices in the fields of Industrial 4.0, Healthcare 4.0, Autonomous Vehicles, Agriculture 4.0, Education, Climate Change, Sustainability, and Oceanography.

Keywords: Metamaterial, Multi-Band, SRR, Microstrip antenna, 5G, IoT, Millimetre-wave band, Power density
1. Introduction

The innovation to 5G wireless technology-enabled IoT devices at a millimetre-wave band will revolutionize the electronics and telecommunication field [1]. This innovation of wireless communications technology is one of the biggest human achievements in terms of 5G and IoT technology. 5G technology and IoT technology thinking will become reality for smart devices [2]. It could be a big dream come true or a game-changer for humans particularly in the field of education, health, agriculture, autonomous vehicles, industry 4.0, and many other related applications. So, in this proposed work, authors have designed a multiband microstrip antenna by engraving two rectangular vertical slots and further loading metamaterial compatible for various 5G enabled advanced IoT Devices. IoT-based smart devices are expanding their support for Internet access (broadband) beyond devices, such as smart/mobile phones, laptops, and so on. The IoT based smart devices have been amalgamated with cutting-edge technology to manage and communicate smoothly using 5G wireless technology. 5G wireless technology grasps an important role in setting up the platform for real-time communications of IoT devices due to its potential to offer greater bandwidth with millimetre bands compared with 4G or 3G wireless technology. 5G wireless network technology combines the spectrum and access networks to meet the customer’s capacity and coverage needs [3]. The internet of everything specifies the synchronisation of various smart electronic devices such as tablets, smartphones, laptops, multiple machines such as smart vehicles equipped with sensors with IoT communication, and wireless or wired connection of consumer appliances connected through the internet [3]. 5G technology will provide massive support for IoT devices as a useful part of the human digital world as the digital population is growing more than the human population. The latest 5G enabled IoT smart device’s trends are extending to sensor-based IoT competencies to actuators, robots, and drones for distributed synchronization. The biggest challenge facing 5G enabled IoT devices is cybersecurity as hackers proliferate and infiltrate and target the server's proxy. Hence secured communication of a machine to a machine has a dynamic role in emerging IoT smart devices [4]. In light of the COVID-19 epidemic, this advancement would also allow real-time video and audio quality data for patient data analysis and wireless uninterrupted communication of detected health parameters. In this research, two vertical rectangular slots are engraved on the radiating microstrip rectangular patch antenna for effective multi-band operation useful for 5G based IoT devices and applications. These slots generate currents in the patch to obtain multiple resonances and thus increases the bandwidth at a resonance frequency of 26 GHz. In our further research, we have loaded the metamaterial SRR structure on the microstrip patch to boost the performance. The performance is then analysed in comparison with and without loading metamaterial SRR structure.

A Metamaterial is a material that is artificially engineered to acquire unconventional electromagnetic, thermal, acoustic, and mechanical properties that are not found in other naturally occurring materials because of its extraordinary unusual and unique kind of properties such as negative permeability ($\mu<0$) and negative permittivity ($\varepsilon<0$) [5]. When the values of permeability($\mu$) and negative permittivity ($\varepsilon$) are simultaneously negative, then the electric field, magnetic field, and the propagation vector form left-handed medium materials in a double-negative region and wave propagation are moving curiously in reverse signifying material has negative refractive index [5,6]. Various studies and researches are being carried out by scientists and researchers all over the world that will benefit humanity through the use of this metamaterial. The metamaterial electromagnetic properties are best defined by maxwells equations given as [6]. For travelling plane waves, the magnetic and electric fields are given as [6]. The preferences of using metamaterials in the design of the microstrip antenna are to minimize the size and increase other parameters such as bandwidth, gain, and return loss [6]. This will enable us to apply and adapt physics concepts to innovations in microstrip antenna designs from laboratories for practical applications of engineering with a good contract [6]. Since the mu-negative material, the unit cell split-ring resonators are the most used structure used as metamaterials. The metamaterial has varied budding applications such as smart antenna, medical devices, optical devices, smart sensors, smart IoT devices, smart solar power, radomes, optical lenses, invisible submarines, radar, etc. The metamaterial structures have significant roles in the above-said applications for boosting their performance in terms of power or energy.
harvesting, bandwidth, and gain enhancement, squeezing the size of the devices for optimum performance and other benefits. The decree for microstrip patch antenna design in the various field of electronics, communication, information technology, and electrical has enormously increased owing to its high characteristics such as bandwidth, return loss, etc. This extended research work aims at providing a multi-frequency band and improvement in the performance of the previously proposed antenna applicable for various 5G enabled IoT smart Devices for interrupted quality services. This research work, therefore, provides all the necessities required to fulfil the demand for next-generation IoT devices.

A detailed survey and analysis of architecture, challenges, and applications are carried out with metamaterials on transmission lines used for antenna design [5]. Using the FR-4 substrate, the concept of metamaterial and microstrip antenna is combined to maximize the performance of an ordinary patch antenna [8]. A detailed survey has been conducted by the authors briefing the significance of IoT in 5G wireless technology [9]. A dual-band antenna design using the FR-4 substrate with circularly polarized split ring resonators fed inside the truncated square slot is presented for various wireless communication [10]. Using the RT/Duroid substrate, the tri-band microstrip patch antenna is presented using HFSS and IE3D software for 5G applications only [11]. The triple-band microstrip patch antenna with H and E slots operating at 26.92 GHz, 35.08 GHz, and 54.74 GHz is proposed for 5G applications [12]. A brief survey in the evolution of IoT technology for 5G wireless networks is presented [13]. The authors describe a study of potential directions for research, challenges, 5G with IoT-enabled smart healthcare employment [14]. Researchers described that 5G wireless technology will meet the demand for next-generation IoT devices, such as improved data rates, increased capacity, and reduced latency [15].

2. Design methodology for a proposed antenna with slots

Below Table 1 shows the descriptions of various parameters used for the design. Fig. 1 depicts the proposed Multi-frequency band microstrip patch antenna geometry.

| Symbols  | Description                      | value (mm) |
|----------|----------------------------------|------------|
| Wₛ       | Substrate width                  | 8.00       |
| Lₛ       | Substrate length                 | 8.00       |
| h        | Substrate thickness              | 0.65       |
| L_F      | Microstrip line-feed length      | 3.4        |
| W_F      | Microstrip line-feed width       | 0.6        |
| L_P      | Length of the patch              | 3.5        |
| W_P      | Width of the patch               | 4.6        |
| L₁       | Length of the Vertical Slot 1    | 1.0        |
| W₁       | Width of the Vertical Slot 1     | 0.2        |
| L₂       | Length of the Vertical Slot 2    | 1.0        |
| W₂       | Width of the Vertical Slot 2     | 1.0        |
2.1. Findings and Analysis

The performance of microstrip patch antenna in terms of return loss which is a positive quantity and negative reflection coefficient depends upon the high amount of power transmitted by the antenna for inputted power to that of the amount of power reflected because the minimum necessary return loss for 5G wireless technology-enabled IoT devices should have at least -10 dB or greater than -15 dB to radiate at least 90% of power [16,17,18]. For example, if the return loss is 0 dB or 1 dB, then radiation of power will be either 0% for 0 dB or 20% for 1 dB and reflection will be 100% for 0 dB or 80% for 1 dB respectively then the performance of the antenna will be very poor as voltage standing wave ratio will be either infinite or very high which is not suitable [16]. Therefore, as seen in Fig.2, it has been observed and analysed that the return loss of our proposed work with slots is -38.05 dB at 26 GHz, -13.42 dB at 40 GHz, -15.66 dB at 53.6 GHz, which means the proposed antenna will radiate more than 90% of incident power indicating excellent impedance matching. Also, the bandwidth at 26 GHz is 5.368 GHz, at 40 is 7.66 GHz, and at 53.5 GHz is 2.88 GHz which signifies that at the 20 GHz-60 GHz range of frequencies the antenna will efficiently radiate electromagnetic energy at a good rate.

Now in the case of Voltage standing wave ratio which is also related to return loss by the equation in [19], this ratio value should lie in the range $1 \leq VSWR \leq 2$ for showing good impedance matching [1,17,18]. Therefore, as seen in Fig.3, it has been observed and analysed that the desired voltage standing wave ratio is within the above-said range and maximum power (energy) will be delivered to the antenna for maximizing the radiation of the antenna. If this ratio value is above 2, then there will be a higher mismatch and degradation of power efficiency.

Fig.4 and Fig.5 and Fig.6 is showing a gain of the proposed antenna at 26 GHz, 40 GHz and 53.5 GHz frequency respectively illustrating the intensity of the emitted power in a specific direction in comparison to an isotropic antenna. The proposed antenna signifies a maximum gain of 10 dBi at 26 GHz and 5 dBi at 40 GHz and 5 dBi at 53.5 GHz which is very much required for 5G wireless technology for efficient operations of IoT devices and their application. Similarly, Fig.7, Fig.8 and Fig.9 show the 2-D radiation pattern showing very good angular separation at 3 dB points occurring at 26 GHz which is 72.12 deg at Phi= 90 deg and 118.688 deg at Phi= 0 deg, at 40 GHz is 134.340 GHz at phi=90 deg, 33.62 at phi=0 deg, and respectively. This angular separation is from the main lobe measured in degrees where the radiated power decreases to half of its maximum value at -3dB beamwidth, termed as half-power beam-width [16,17,19].

![Figure 1: Geometry of proposed microstrip rectangular patch antenna](image-url)
Figure 2. Return Loss

Figure 3. Voltage standing wave ratio

Figure 4. 3D radiation pattern showing total gain at 26 GHz

Figure 5. 3-D radiation showing total gain at 40 GHz

Figure 6. Radiation showing total gain at 53.5 GHz

Figure 7. 2-D radiation pattern showing HPBW at 26 GHz
Figure 8: 2-D radiation showing HPBW at 40 GHz

Figure 9: 2-D radiation graphical view at 53.5 GHz

Figure 10: Power density at 26 GHz

Figure 11: Antenna radiation efficiency

Fig. 10 is showing the power radiation density of 35.8 kW/m² at 26 GHz accompanying with electromagnetic densities and is defined using instantaneous Poynting vector as the product of instantaneous electric and magnetic field intensity. Hence, this power density of 2208 kW/m² determines the high-power radiation from the antenna per unit area in all directions [19].

Below Fig. 11 shows the antenna radiation efficiency. The movement of electrical charges creates the current and charge densities on the patch surface which gives rise to the radiation of the proposed antenna [17,18]. These densities are due actually to the fringing field acting on the edge of the patch as they add up in phase thereby helping the proposed microstrip antenna to get high radiation efficiency of 99.7 % at 26 GHz.
3. Design methodology for a proposed antenna with SRR based Metamaterial

3.1. Findings and Analysis unit cell of SRR

In this section, the authors have designed circular magnetic split-ring based metamaterial made of copper having thickness 0.035 mm at 26 GHz as seen in fig. 12 and incorporated it on the above-proposed antenna to boost the performance of the antenna in terms of return loss, bandwidth and power radiation density. Table 2 illustrates the designed parameters used.

Table 2. Design parameters.

| Symbols | Description                                      | value (mm) |
|---------|--------------------------------------------------|------------|
| d       | Gap between two concentric rings                 | 0.1        |
| r₁      | Radius of the outer concentric ring              | 0.65       |
| r₂      | Radius of the inner concentric ring              | 0.45       |
| w       | Width of the concentric rings                    | 0.2        |
| g       | Gap for each of the concentric ring              | 0.53       |
| h       | Substrate thickness                              | 0.65       |

Above fig. 13 shows the top view of circular artificial magnetic split-ring resonator unit cell placed on the Rogers RT Duroid 5880 substrate with copper wire of perfect electric conductor and plane wave is incident on this double negative media to view the effect of negative permittivity and permeability as shown in fig. 14. These parameters specify the ability of the Split-ring resonator-based metamaterial to polarize the electric field and magnetize the magnetic field when incorporated into the substrate and loading on the microstrip patch antenna. Both are substantial in electromagnetism. Polarization and magnetization simulation of Lossy Drude models in the frequency domain gives the effect of permeability and permittivity that often not found in other materials and thus it will be thought of as engineered material [20]. Further, these models are implemented into the finite-difference time-domain through accompanying electric and magnetic current densities as shown in fig 17 [20]. The equations that administer their time-based behaviour are given in [20]. The said densities give rise to the Poynting vector which is the power density.
This split-ring resonator-based metamaterial has high sensing and absorbing capability that absorbs 85\% electromagnetic waves as depicted in fig.15. This absorptivity is due to the 0.15 magnitude of reflection and zero magnitude of transmission coefficient and is obtained using equation [21]. This absorption will improve the sensing capability, reduce the size and enhance the bandwidth of the proposed antenna.

3.2. Comparative Analysis of proposed microstrip patch antenna with SRR based metamaterial and without SRR

Figure 18 depicts the top view of the proposed microstrip patch antenna with SRR loaded on the patch.
Figure 18. Top 3D view design of microstrip triangular patch antenna with SRR.

Figure 19. Comparison of Return and bandwidth with SRR based metamaterial and without SRR.

Figure 20: Power density with SRR and without SRR.

Figure 21: Improvement of Current density with SRR based metamaterial.

From figure 19, it is seen and observed that the return loss increased from -34.82 dB to -50.39 dB, and bandwidth increased from 5.368 GHz to 5.630 GHz at 26 GHz after incorporating and loading SRR based metamaterial. Similarly, power density and current density increased from 2205 kW/m$^2$ to 2800 kW/m$^2$ and 300 A/m to 360 A/m respectively. Table 3. shows the comparative analysis of performance in the proposed antenna with slots and SRR and without SRR.
4. Conclusion and future scope
The proposed work of metamaterial-based design of multi-band microstrip rectangular patch antenna is effectively designed and implemented at the same resonance frequency of 26 GHz with additional sub-GHz frequencies applicable for 5G wireless technology-enabled IoT based smart devices and their various applications. The same is simulated, compared and analyzed for the performance of various characteristics using FEKO software. Thus, from table 3, by incorporating and loading circular split-ring resonator-based metamaterial the bandwidth increased by 262 MHz, and return loss by -15.57. Additionally, improvement is also seen at other frequencies as well as current and power densities. Further research is to work on a linear MIMO array or circular MIMO array at the same resonant frequency for improving gain.

5. References
[1] John Colaco and R.B. Lohani 2021 J. Phys.: Conf. Ser. 1921 012032JD.
[2] Helena, A. Ramos, T. Varum, and J. N. Matos 2020 Antenna Design Using Modern Additive Manufacturing Technology: A Review IEEE Access, vol. 8, pp. 177064-177083.
[3] GSMA, G., 2019 5G the internet of things and wearable devices: radiofrequency exposure, GSMA Public Policy.
[4] J W. Ejaz, A. Anpalagan, M.A. Imran, M. Jo, M. Naem, S. Bin Qaisar, and W. Wang, 2016 Internet of Things (IoT) in 5G Wireless Communications, IEEE Access, pp. 10310–10314, 2016.
[5] M. Alibakhshikenari et al., 2020 A Comprehensive Survey of Metamaterial Transmission-Line Based Antennas: Design, Challenges, and Applications, IEEE Access, vol. 8, pp. 144778-144808, Jan.2020.
[6] Wojciech Jan Krzysztofik, and Thanh Nghiem Cao (November 5th, 2018). Metamaterials in Application to Improve Antenna Parameters, Metamaterials and Metasurfaces, Josep Canet-Ferrr, IntechOpen.
[7] Datasheet of Rogers Corporation, rt-Duroid-5880-laminates.
[8] G.Geetharamani and T.Athmanesan, 2020 Design of Metamaterial Antenna for 2.4 GHz WiFi Applications, International Journal of Wireless Personal Communications, Vol.113.
[9] J.M. Khurpade, and D. Rao, P.D. Sanghavi, 2018 A Survey on IoT and 5G Network in International Conference on Smart City and Emerging Technology, Mumbai, India: IEEE, 2018, pp.1-3.
[10] K. Krishnamurthy, M.Basudev, M. Jayanta, and K.P. Ray 2016 Dual-band circularly polarized Split Ring Resonators Loaded Square Slot Antenna, IEEE Transactions on Antennas and Propagation, Vol.64, no.8.
[11] A.N. M. S. Kamal, M. J. Islam, M. J. Uddin, and A. Z. M. Imran, 2018 Design of a Tri-Band Microstrip Patch Antenna for 5G Application in International Conference on Computer,
[12] G. M. Amrutha and T. Sudha, 2018 Triple Band Antenna for 5G Applications in 2018 International Conference on Advances in Computing, Communications and Informatics, Bangalore, India: IEEE, 2018, pp. 1650–1652.

[13] L. Chettri, and R. Bera, 2020 A Comprehensive Survey on Internet of Things (IoT) Toward 5G Wireless Systems, IEEE Internet of Things Journal, Vol.7, pp.16-32, Jan. 2020,

[14] Ahad, M. Tahir, and K. A. Yau, 2020 5G-Based Smart Healthcare Network: Architecture, Taxonomy, Challenges and Future Research Directions IEEE Access, vol. 7, pp. 100747-100762.

[15] M.M. Alsulami, and N. Akkari 2018, The role of 5G wireless networks in the internet-of-things (IoT) in International Conference on Computer Applications & Information Security, Riyadh, Saudi Arabia: IEEE, pp 1-8.

[16] https://antennatestlab.com/antenna-education-tutorials/return-loss-vswr-explained.

[17] J. Colaco, and R. Lohani 2020 High Performance and Efficient Microstrip Square Patch Antenna Design for 5G Wireless Network Technology Useful for Smart TV Applications at IEEE Bangalore humanitarian technology conference, Bangalore, October 8-10, 2020.

[18] J. Colaco, and R. Lohani 2020 Design and Implementation of Microstrip Circular Patch Antenna for 5G Applications in Proc.2nd International Conference on Electrical, Communication and Computer engineering, Istanbul, Turkey: IEEE, 2020, pp. 1-4.

[19] C.A. Balanis. Antenna Theory: Analysis and Design, 3rd ed. A John Wiley & Sons, Inc., Publication, Hoboken, NJ, 2005.

[20] N.Engheta, and R.W.Ziolkowski, METAMATERIALS: Physics and Engineering Explorations, John Wiley, IEEE express.

[21] Y. Xu, B. Zhang, J. Duan and Y. Tian, 2018 Design of Broadband Metamaterial Absorber for C Band and X Band IEEE International Conference on Computer and Communication Engineering Technology (CCET), Beijing, China, 2018, pp. 159-163.