Compact Wearable Antenna for Millimeter-Wave (mm-Wave) Fifth Generation

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Abstract

The need for networking, communication, and data sharing capabilities among users of wearable terminal devices has increased, and this has made the new wearable antenna one of the most active research areas. This work presents a wearable antenna for 5G applications based on a microstrip patch antenna operating at 28GHz millimeter-wave (mm-wave). The operating frequency of 28GHz is expected to be appropriate for 5G mm-wave wearable antenna design. The design is made of the semi-flexible Rogers Duroid RO3003 substrate, which has a thickness of 0.75mm, a loss tangent of 0.001 and a relative permittivity of 3. CST Microwave Studio software is used to analyze and evaluate the proposed antenna's performance to other existing designs in terms of return loss, bandwidth, gain, directivity, and point SAR value.

Keywords: 5G, Millimeter-Wave (mm-wave), Wearable Antenna, Specific Absorption Rate (SAR).

1. Introduction

Due to high demand for secure, fast, and large data transmission rates in many recent and advanced applications, such as broadcasting, Internet of Things (IoT), automobiles, smart cities, energy, and wearable devices, global mobile data traffic has grown significantly in recent years. The capacity and performance of each generation of mobile and wireless communication systems have been enhanced to fulfil those expectations [1].

The bandwidth is one important technique to increase capacity and data rates in current and future mobile and wireless generations. The bandwidth is directly proportional to the data rates. Higher data rates are possible because of the increased bandwidth. For current frequency ranges, such as the 1.7 GHz GSM band, the 1.8 GHz 4G/LTE band, the 2.0 GHz 4G/LTE band, the 2.1 GHz LTE band, and the 2.6 GHz band, all have restricted capacity. For 5G applications, high-frequency bands such as 24, 28, 37, and 39 GHz, as well as certain future suggested bands such as 47 GHz and 60 GHz, have recently been explored [1]. These high-frequency bands, also known as millimeter-Wave (mm-Wave) bands, can provide a huge amount of bandwidth, exceeding 500 MHz. The key benefit of mm-Wave technology is that it reduces the volume of devices by having very high resonance frequencies, resulting in a smaller antenna and higher speed and capacity [2]. Despite this, current 5G communication continues to use the sub-6 GHz spectrum which include 3.3 GHz to 4.2 GHz and 4.4 GHz to 5 GHz. In the recent decade, the demand for wearable devices has skyrocketed. Wearable devices that work on many bands, such as 3G, 4G, Wi-Fi, and GPS, are already crowded, but they are getting smarter and smaller. As a result, multiband antennas and smaller antennas are preferred. The propagation losses of mm-wave communications, which operate at high frequencies, are quite large [3]. To reduce propagation losses, the employed antenna should have high directional gain radiation patterns which is directed in the direction of wave propagation. Wearable antennas are one of the most important components of wearable electronics, which are used in a variety of applications from medical to military to entertainment and other everyday wearable devices [4]. Medical equipment for patient monitoring, smartwatches with embedded miniature antennas, military tracking and navigation systems, body-worn camera with Wi-Fi and Bluetooth, glasses for augmented reality, and wearable sporting gear are only a few examples of wearable antennas.

Nonetheless, the wearable antenna's design is crucial, especially for 5G mm-wave and IoT applications, where the manufacturing process and tolerances at higher frequencies have a significant impact on performance. When developing a wearable antenna for 5G applications for use as an integrable element of worn devices, numerous factors must be considered. They must be conformal or flexible, durable, and capable of operating in close proximity to the human body with little performance deterioration. The human body is well recognized for degrading antenna efficiency and gain owing to natural body tissue losses; thus, the implementation environment must be addressed during the design phase to develop a highly stable and durable 5G wearable antenna [5]. As one of the key criteria for such devices, the wearable antenna should be able to work successfully under various bending situations. On the other hand, the materials used as substrates and conductive portions for wearable antennas are critical [6]. They must be carefully designed to give the essential mechanical or physical properties, such as bending, wrapping, and occasionally washing, with little performance impact.

Other than that, wearable antennas are antennas that function within the human body, allowing the human body to absorb part of the radiated energy [5]. Human tissues will be damaged and burned because of the absorption of these waves. Therefore, when wearable antennas are employed, it is essential to decrease the interaction of electromagnetic radiation with human body tissues [3]. A specific absorption rate (SAR) is used to evaluate the absorption of electromagnetic waves in human tissue. SAR calculations may be made using either the point SAR technique or the average of SAR in terms of mass or volume. Point SAR is determined for each grid cell by dividing the absorbed power in each grid by the grid mass. Point SAR is also the value without mass averaging and defines the highest SAR of all the grid cells. For averaged SAR measurements, each point is represented by a cube with a given mass, either 1g or 10 g, and the power loss density is integrated on this cube. The cube's mass is divided by the power loss in integral form at the end [7]. Therefore, the SAR limit is determined by the Standardization Committee and varies by area throughout the world. The Federal Communications Commission (FCC) regulates SAR in the United States, with a maximum allowable value of 1.6 W/kg averaged over 1 gram of tissue at the frequency less than 6 GHz [8]. However, in Europe, the International Commission on Non-Ionizing Radiation Protection (ICNIPR) established a maximum tolerable SAR of 2.0 W/kg averaged over 10 grams of tissue at the frequency of less than 10 GHz. Due to the benefits of low profile, small size, light weight, and ease of manufacturing, the microstrip patch antenna has been selected for the 5G wearable antenna design in this work. The proposed antenna is operated in mm-wave spectrum since its operational frequencies is 28 GHz. Transmission line model calculation was used to determine the size of the patch antenna and inset feed. CST Microwave Studio software is used to simulate the antenna and analyze its parameters including SAR.

2. Related Works

2.1. *Antenna Design*

Fig. 1 shows the geometry of the proposed antenna. The patch antenna with a copper thickness of 0.035 mm is modelled on a semi-flexible Rogers Duroid RO3003 substrate with a relative permittivity of 3.0, a loss tangent of 0.001, and a thickness of 0.75 mm. The patch and ground plane of a microstrip antenna is crucial for designing an antenna since it determines the antenna's bandwidth, size, gain, and efficiency. Table 1 shows all the optimized dimension of the proposed antenna.

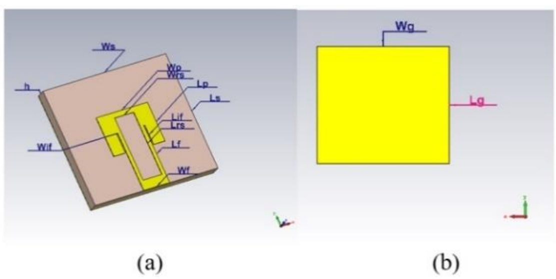

Fig. 1. Geometry of 5G Wearable Antenna Operating at 28GHz: (a) Front View, (b) Rear View.

Table 1. Dimensions of 5G Wearable Antenna Operating at 28 GHz

Parameters	Annotation	Value (mm)
Substrate Width	Ws	9
Substrate Length	Ls	8
Ground Width	Wg	9
Ground Length	Lg	8
Patch Width	Wp	3.75
Patch Length	Lp	2.7
Feed Line Width	Wf	1.9
Feed Line Length	Lf	4
Inset Feed Width	Wif	0.09
Inset Feed Length	Lif	1.35
Slot Width	Wrs	1.4
Slot Length	Lrs	4.35
Substrate Height	h	0.75
Copper Height	ht	0.035

2.2. *Antenna Simulation of Specific Absorption Rate (SAR) Level*

To calculate the SAR value as the antenna is to be worn on the body, a numerical human phantom model has been created in CST Microwave Studio software, as illustrated in Fig. 2. The human phantom model consists of three layers of human tissues: skin, fat, and muscle. Table 2 lists the dielectric properties of human tissues at 28 GHz, and Table 3 lists the tissues' thermal characteristics [7].

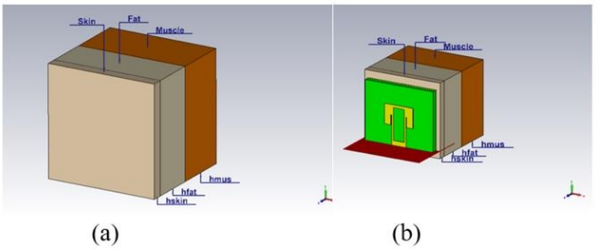

Fig. 2. Numerical Human Phantom Model: (a) Human Tissue Layers, (b) Perspective View.

Table 2. Dielectric Properties of Human Tissues at 28 GHz.

Tissue	Mass Density (kg/m3)	Relative Permittivity (Ɛr)	Conductivity (S/m)
Skin	1109	16.55	25.82
Fat	911	6.09	5.04
Muscle	1090	24.43	33.6

Table 3. Thermal Parameters of Human Tissues.

Tissue Properties	Skin	Fat	Muscle
Heat Capacity (kJ/K/kg)	3.391	2.348	3.421
Thermal Conductivity (W/K/m)	0.37	0.21	0.49
Metabolic Rate (W/m3)	1620	300	480
Thickness (mm)	1	4	6

3. Results and Discussion

In this work, the performance of the 5G wearable antenna was evaluated through the simulation using CST Microwave Studio software. Through the simulation, the S-Parameters, Bandwidth, Gain, Directivity, VSWR, Smith Chart, Surface Current, and SAR analysis of proposed antenna are obtained as shown in below. Fig. 3. shows the simulated return loss of the proposed 5G wearable antenna. From the simulation result, the 5G wearable antenna resonates at 27.995 GHz with a return loss of -21.451 dB and a wide bandwidth covering from 27.221 GHz to 28.738 GHz with respect to -10 dB.

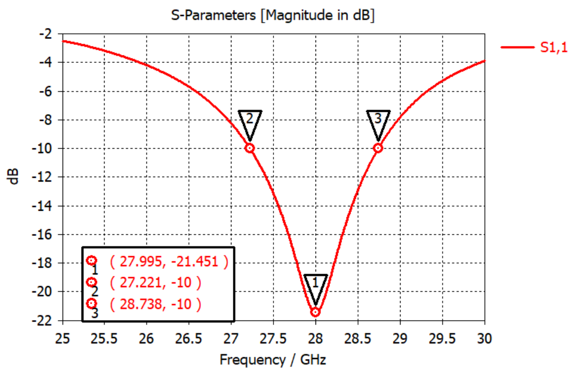

Fig. 3. Simulated Return Loss (S11) of the Proposed Antenna

Fig. 4 shows the simulated gain of the proposed 5G wearable antenna. From the simulation result, the proposed 5G wearable antenna has a gain of 6.671 dB at 27.995 GHz. Fig. 5 illustrates the simulated directivity of the proposed 5G wearable antenna. From the simulation result, the proposed 5G wearable antenna has a directivity of 8.195 dBi at 27.995 GHz.

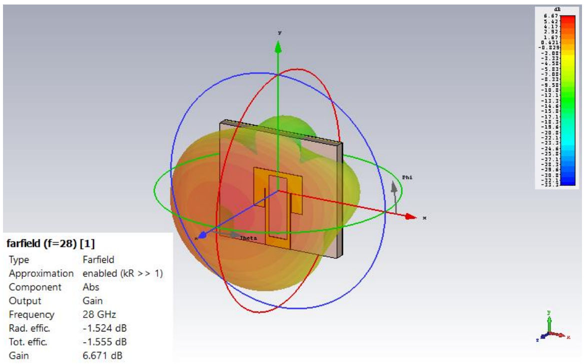

Fig. 4. Simulated Gain of the Proposed Antenna

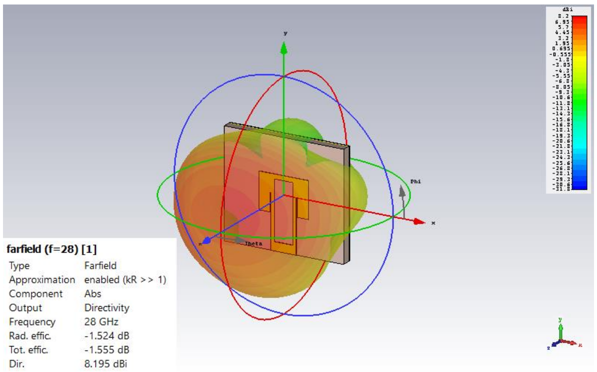

Fig. 5. Simulated Directivity of the Proposed Antenna

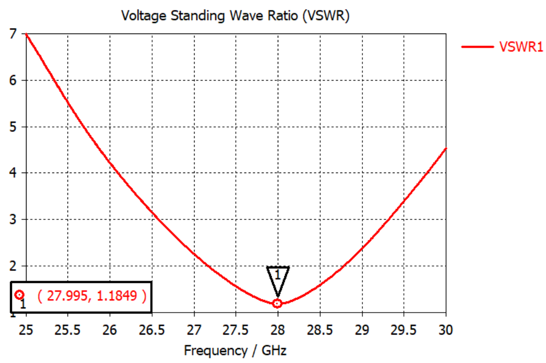

Fig .6. Simulated VSWR of the Proposed Antenna

Fig. 6 illustrates the simulated VSWR of the proposed 5G wearable antenna. It has a good VSWR value of 1.1849 at 27.995 GHz. Fig. 7 displays the surface current of the proposed 5G wearable antenna. From the simulation result, the proposed 5G wearable antenna has a surface current of 921.974 A/m surrounded at the feeding line.

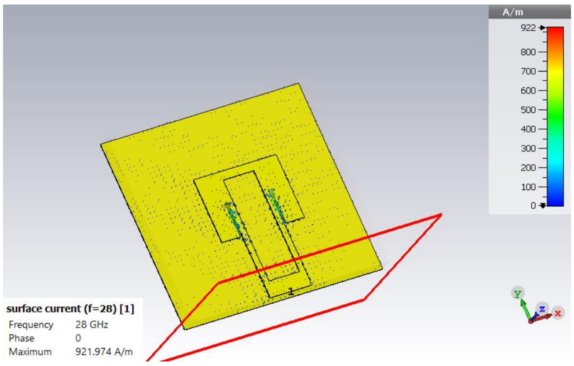

Fig. 7. Surface Current of the Proposed Antenna

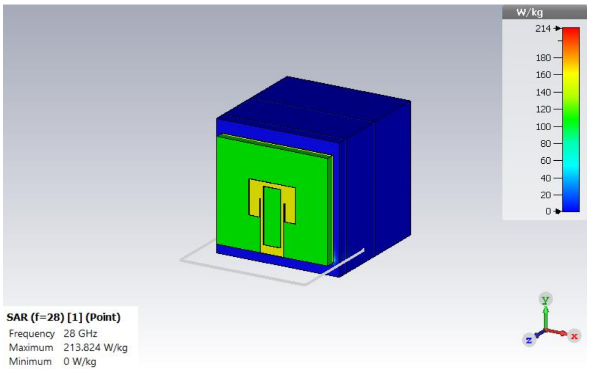

Fig. 8. Simulated Point SAR of the Proposed Antenna

Fig. 8 shows the simulated point SAR of the proposed 5G wearable antenna. The proposed antenna has a point SAR of 213.824 W/kg at 27.995 GHz.

Table 4. Summary of Simulated Results of the Proposed Antenna

Antenna Parameter	Values
Operating Frequency (GHz)	27.995
Bandwidth (GHz)	1.517
Return Loss (dB)	-21.451
Gain (dB)	6.671
Directivity (dBi)	8.195
VSWR	1.1849
Surface Current (A/m)	921.974
Point SAR (W/kg)	213.824

Table 4 shows the summary of the simulated results of the proposed antenna. At the operating frequency of 28 GHz, a return loss of -21.451 dB is achieved with VSWR of 1.1849. In addition, the operating bandwidth for 28 GHz is 1.517 GHz between 27.221 GHz and 28.738 GHz with respect to -10 dB. The proposed antenna achieved with a gain of 6.671 dB, directivity of 8.195 dBi, and surface current of 921.974 A/m. SAR which is employed with wearable antenna, is used to measure how well electromagnetic waves are absorbed by human tissues. To assess he point SAR value of the 5G wearable antenna, a numerical human phantom model was created. The point SAR produced from the proposed antenna is 213.824 W/kg based on the results of the simulation.

Table 5. Comparison of Antenna Parameters between Proposed 5G Wearable Antenna with Other Existing Designs

Paper	Ahmed et.al.[2]	Vivek et.al.[9]	Proposed antenna
Substrate	Ultralam 3850HT	Polycar-bonate	Rogers 3003
Relative Permittivity (Ɛr)	3.14	2.57	3
Operating Frequency (GHz)	38, 60	28	27.995
Bandwidth (GHz)	0.442, 0.657	1.49	1.517
Return Loss (dB)	-13.996, -19.268	-65.76	-21.451
Gain (dB)	2.19, 4.43	8.886	6.671
Directivity (dBi)	-	-	8.195
VSWR	-	1.001	1.185
Surface Current (A/m)	-	-	921.974
Point SAR (W/kg)	-	-	213.824
Average SAR (1g/10g) (W/kg)	0.33/0.15, 0.63/0.35	-	-

Table 5 shows the comparison of antenna parameters between the proposed antenna with other existing designs. In contrast to the design by Ahmed and Ahmed [2], they developed a dual-band flexible wearable antenna enabling modern 5G applications to be incorporated on a smartwatch. The substrate is made of Ultralam 3850HT, which has a low and steady relative permittivity of 3.14 and thin flexible cores. For wearable and high frequency designs, the steady dielectric constant is an important requirement. The frequency range of the mm-waves includes both 38 GHz and 60 GHz, and the antenna can operate at any one of these frequencies. As compared to this paper, the proposed antenna in this work has a greater bandwidth, as a broader bandwidth may effectively function across a wider range of frequencies. The antenna designed by Ahmed and Ahmed has a low average SAR value for SAR analysis of 0.33 W/kg and 0.63 W/kg averaged across 1g and 10g of tissues, respectively, at 38 GHz. As opposed to this, the proposed antenna in this work only has a point SAR value of 213.824 W/kg without averaging across the mass of tissues. For a different design by Vivek, Kumar, and Shambavi [9], they developed a polycarbonate substrate with a relative permittivity of 2.57, thickness of 0.5mm, and a loss tangent of 0.0069 for a 5G wearable antenna. Although the wearable antenna has a peak gain of 8.886 dB and a return loss of -65.76 dB, however the bandwidth is slightly less than the proposed antenna in this work. Moreover, the wearable antenna is lack of SAR analysis, which is important for determining how wearable antennas may affect human.

4. Conclusions

In this paper, a wearable mm-wave antenna with a semi-flexible Rogers Duroid RO3003 substrate is proposed for use in 5G applications. The antenna can operate at 28 GHz with a bandwidth of 1.517 GHz. Within the frequency band of operation, the antenna radiates in a directional pattern with a high gain of 6.671 dB and a high directivity of 8.195 dBi. In addition, the point SAR value on human tissue has been modelled. The proposed antenna in this work is suited to be a wearable antenna due to low return loss, a low point SAR value, compact size, light weight, and ease of manufacturing.

Acknowledgements

This work was supported by the Ministry of Higher Education Malaysia under the Fundamental Research Schemes with project codes of Proj-FRGS/1/2019/TK04/UCSI/02/1 and the UCSI University Research Excellence & Innovation Grant (REIG) with project code of REIG-FETBE-2022/038.

References

1. M. Ikram, K. Sultan, M. F. Lateef, and A. S. M. Alqadami, “A Road towards 6G Communication—A Review of 5G Antennas, Arrays, and Wearable Devices,” Electronics, vol. 11, no. 1, Art. no. 1, Jan. 2022.

2. M. I. Ahmed and M. F. Ahmed, “A Wearable Flexible antenna integrated on a Smart Watch for 5G Applications,” *J. Phys. Conf. Ser.*, vol. 1447, no. 1, p. 012005, Jan. 2020.
3. L. Bariah et al., “A Prospective Look: Key Enabling Technologies, Applications and Open Research Topics in 6G Networks.”, Sep. 09, 2020.
4. N. F. M. Aun, P. J. Soh, A. A. Al-Hadi, M. F. Jamlos, G. A. E. Vandenbosch, and D. Schreurs, “Revolutionizing Wearables for 5G: 5G Technologies: Recent Developments and Future Perspectives for Wearable Devices and Antennas,” *IEEE Microw. Mag.*, vol. 18, no. 3, pp. 108–124, May 2017.
5. S. N. Mahmood et al., “Recent Advances in Wearable Antenna Technologies: a Review,” *Prog. Electromagn. Res. B*, vol. 89, pp. 1–27, 2020.
6. R. Karim, A. Iftikhar, B. Ijaz, and I. Ben Mabrouk, “The Potentials, Challenges, and Future Directions of On-Chip-Antennas for Emerging Wireless Applications—A Comprehensive Survey,” *IEEE Access*, vol. 7, pp. 173897–173934, 2019.
7. T. Hamed and M. Maqsood, “SAR Calculation & Temperature Response of Human Body Exposure to Electromagnetic Radiations at 28, 40 and 60 GHz Mm-Wave Frequencies,” *Prog. Electromagn. Res. M*, vol. 73, pp. 47–59, 2018.
8. K. Zhao, S. Zhang, C.-Y. Chiu, Z. Ying, and S. He, “SAR study for smart watch applications,” in 2014 IEEE Antennas and Propagation Society International Symposium (APSURSI), Jul. 2014, pp. 1198–1199.
9. N. Vivek, S. K. B, and K. Shambavi, “Design of Wearable Antennas for 5G Applications,” *Int. J. Electr. Eng. Technol.*, vol. 12, no. 5, Jun. 2021.

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