5G Wearable Devices

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One potential way of enhancing capacity and data rates in the current and future mobile and wireless generations is the bandwidth. The data rates are directly proportional to the bandwidth. The higher bandwidth provides higher data rates. However, current frequency bands, i.e., 1.7 GHz GSM band, 1.8 GHz 4G/LTE band, 2.0 GHz 4G/LTE band, 2.1 LTE band, and 2.6 GHz band, provide limited bandwidth. Recently, high-frequency bands including 24 GHz (n258), 28 GHz (n257 and n261), 37 GHz (n260), and 39 GHz (n260) in addition to some future recommended bands, i.e., 47 and 60 GHz, have been considered for 5G applications.

Keywords: 5G ; wearable Devices ; antennas

1. 5G Wearable Antennas

The demand for wearable devices has grown tremendously in the last decade. The number of connected wearable electronic devices has increased by more than 100% in the last 4 years, rising from 325 million in 2016 to about 720 million in the year 2019 [1][2][3][4][5]. As technology continues growing at a high rate, these devices are expected to reach 1.1 billion by 2022 [3]. A wearable antenna is one of the essential elements of the wearable electronics that are utilized for several wearable applications ranging from medical to military to entertainment and other daily-use wearable devices [4], as can be seen in **Figure 1**. A few examples that include wearable antennas are medical devices and monitoring patient health, smartwatches with incorporated small antennas, military tracking and navigation systems, body-worn camera with WiFi and Bluetooth, and wearable athletic devices, etc. [6][7][8][9][10][11]. Nevertheless, the design of the wearable antenna is critical, particularly for 5G mm-Wave and IoT applications in which the manufacturing process and tolerances at higher frequencies have a huge effect on its performance. There are also several aspects that need to be taken into account when designing a wearable antenna for 5G applications for the utilization as an integrable part of worn devices [4]. They need to be conformal/flexible, robust, and operate with minimum performance degradation in close vicinity with the human body. It is well-known that the human body tends to degrade antenna efficiency and gain due to the natural losses of the body tissues, and thus the implementation environment needs to be considered during the design process to achieve a highly stable and robust 5G wearable antenna [12]. The wearable antenna should also effectively operate under different bending conditions as part of the important requirements for such devices. On the other hand, the utilized materials as substrates and conductive parts for the wearable antennas are very important [13]. They must be chosen carefully to provide the required mechanical/physical features such as bending, wrapping, and sometimes washing while maintaining minimal influence on the performance [14].

Figure 1. Illustration of wearable antenna applications.

In the following subsections, we go through the state-of-the-art of 5G wearable antennas, which includes a summary of the presented structures, techniques, materials substrates, and performances. In fact, there are a plethora of different kinds of wearable antennas that have been utilized for numerous wearable electronic devices, as can be found in the literature [12][15][16][17][18]. However, these antennas are mainly proposed for 4G, 3G, and older technologies. The recent progress on wearable antennas for 5G applications is limited to a few works. This is due to the fact that the 5G and future 6G technologies are still recent and the classical optimization methods of wearable antennas are not always suitable to achieve the requirements of these advanced technologies.

2. Sub-6 GHz 5G Wearable Antennas

A conventional modified microstrip patch antenna is designed on a thin (0.125 mm) layer of polyethylene terephthalate (PET) substrate for 5G applications [19]. The conductive part of the antenna was made of silver nanoparticles using inkjet printer technology. The overall dimensions of the reported antenna are 60 × 75 mm^2. The antenna operates at around 5 GHz and over the X-band region and demonstrated a maximum gain of 5dBi and about 38% radiation efficiency. The utilized polymer substrate and silver nanoparticles conductive ink technologies with the presented antenna in [19] is of great interest for wearable antennas as it is compatible for wearing and has sufficient flexibility, efficiency, and robustness. However, the antenna dimensions are quite large for integration with compact wearable devices, and further optimization techniques to miniaturize the overall size of the antenna are demanded.

A conformal dielectric resonator wristwatch-like wearable antenna for sub-6 GHz 5G and IoT applications is described in [20]. The 3D structure of the dielectric resonator antenna allows the excitation of various operating modes in one antenna and thus makes it feasible to suit different applications. The other advantages of the dielectric resonator techniques are also the operating wideband and high gain and efficiency characteristics. However, the 3D structure and commonly high-profile features of this type of antenna are not favorable for flexible/wearable antennas. A modified coplanar feeding technique has been utilized in [20] to provide good isolation between the radiating aperture and the platform. The isolation is achieved by a metal plane that acts as a barrier and hence minimizes the unfavorable interferences from the platform and users. It can be noticed that the presented conformal dielectric resonator antenna demonstrated a significant alteration in its performance, including radiation patterns and realized gain, under different bending angles and when it was placed on different parts of the body. These results explain the less existing conformal dielectric resonator antennas for wearable applications in the literature.

In [21], a multiband textile-based rectangular microstrip patch antenna for sub-6 GHz 5G communication application is presented. The antenna is employed with annular and U-Shaped slots etched on the center and edge of the patch, respectively, to achieve the multiband operating frequencies at 0.85, 2.2, and 3.5 GHz. The desired surface current distributions and bandwidth enhancement are obtained by utilizing a meandering ground plane on the rear side of the antenna. While the work did not include measured results for verification, the utilized algorithm of the Coral Reef's optimization technique has demonstrated promising numerical results, which encourage the antenna designers to use such algorithms and artificial intelligence (AI) [22] optimization techniques to tune and optimize 5G wearable antennas for obtaining an efficient and high-performance wearable antenna.

A conductive graphene-based conformal and low-profile dual-band Vivaldi antenna is reported in [23] for 5G WiFi applications. The antenna configuration is shown in **Figure 2**a,b, which comprises an open circuit half-wave and split-ring-resonator to obtain the dual-band operating frequencies at 2.4–2.45 and 5.51–7 GHz. The antenna achieved a maximum measured gain of 6.8 dBi, as can be seen in **Figure 2**c. As mentioned earlier, the important features of the wearable antenna are the stable performance with minimum degradation of operating frequency and radiation patterns when the antenna is bent or twisted. This antenna demonstrated a similar operating frequency with minimal shift and stable radiation patterns under different bending conditions, as can be seen from the measured results in **Figure 2**d,e.

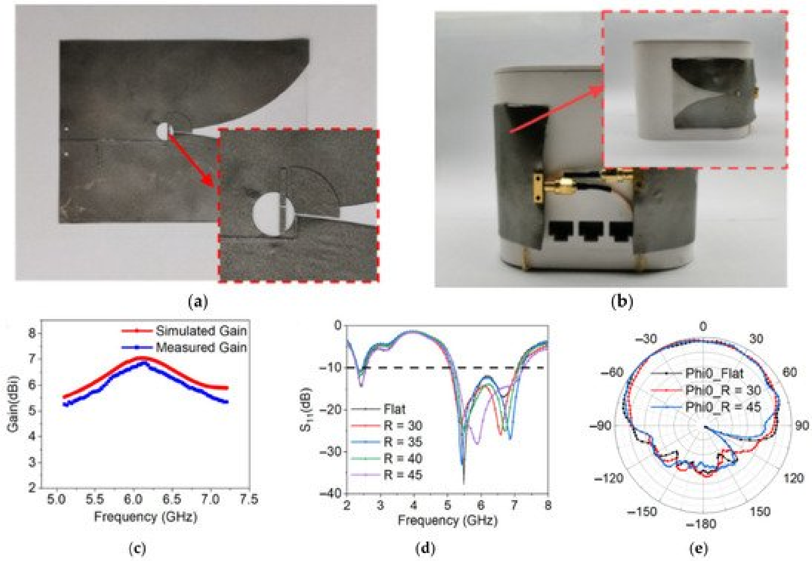

Figure 2. (**a**,**b**) Fabricated prototype and (**c**–**e**) some results of the conductive graphene-based conformal dual-band Vivaldi antenna [23].

A transparent polymer-based and compact multiple-input multiple-output (MIMO) antenna is presented in [24] for 5G smart wearable and remote devices. The antenna has utilized new promising nanotechnology of Nickel metallic mesh as a conductor. The antenna featured a compact size with a transparent look, high conductivity of nano-nickel metallic mesh, and high mechanical stability. The antenna has achieved 93% efficiency and below −20 dB isolation over the operating frequency band of 4.4–5 GHz. The utilization of such new flexible conductive materials at nanoscale particles and flexible transparent dielectrics are encouraging and could lead to highly efficient wearable smart antennas for next-generation technologies. There are a few other antennas that are based on transparent polymer substrates that were reported in [25][26][27].

3. mm-Wave 5G Wearable Antennas

The limitation of the spectrum at the lower microwave frequencies calls for the utilization of the available spectrum at higher mm-wave frequencies for 5G technology, including 5G wearable antennas [4]. Nevertheless, the utilization of such high frequencies will result in greater propagation losses. Therefore, 5G wearable antennas are required to be highly directive with higher gain to minimize this issue and to ensure the mm-wave wearable antennas have the required operating competence. In this subsection, an overview of exiting mm-wave 5G wearable antennas is presented.

An early work on mm-wave antenna for off-body 5G application is described in [28]. The 60-GHz mm-wave band was selected to investigate the electromagnetic exposure of body-mounted antennas and their effect on the human body. The work includes the analysis of antenna array with three different feeding structures on the human body and compared their performances and user exposure. It concluded that the presence of a metal ground plane reduced the electromagnetic exposure by 70 and 8 times in terms of peak and averaged levels. It also helps to reduce the sensitivity of the reflection coefficient when the antenna is mounted on a human body. Though this investigation utilized a conventional rigid antenna, it has emphasized several important factors that need to be considered when designing a highly sensitive mm-wave wearable antenna. These include safety aspects and limitations of some traditional techniques due to the higher sensitivity of the mm-wave antennas to the human body. A flexible reconfigurable MIMO mm-wave wearable antenna that can be controlled to operate at selected frequencies between 26.5–40 GHz is introduced in [29]. The presented antenna is comprised of a T-shape radiating element fixed in a rectangular cut aperture on the ground plane. The radiating element is incorporated with two slots on each side and electronic switches. The antenna was manufactured using inkjet printing technology on a thin flexible polyethylene-terephthalate film. The free-space measured results of the described mm-wave MIMO antenna showed a stable reflection coefficient and a radiation pattern with peak gain of 6.2 dBi and isolation below −20 dB between the two elements. Despite the stable performance on the free-space environment, the performance of the antenna was not tested in close vicinity of a human body to verify the antenna performance stability for actual implementation.

S. Jilani et al. [143] introduced a wideband mm-wave liquid crystal polymer-based flexible antenna array for 5G wireless network application. The antenna comprised two-element arrays of rectangular side-tapered patches fed using coplanar-waveguide-fed (CPW) and corporate transmission line techniques. To achieve appropriate coupling and attain good impedance matching, two additional small stubs were introduced on the CP. The antenna was manufactured using an advanced method of laser-milling and inkjet printing technologies on a thin flexible polymer film. The measurement result of reflection coefficients shows that the antenna exhibits a wideband over 26–40 GHz with a maximum gain of 11 dBi at 35 GHz. However, there are no verifications on the performance of the antenna in close vicinity with the human body. A similar fabrication inkjet printing technology is utilized with a conventional structure dipole array antenna for emerging 5G medical applications and is described in [144]. The reported antenna operates at 23–30 GHz. Though there was obvious variation between simulated and measured results due to the fabrication tolerances as mentioned by the authors, the performance of the antenna in terms of gain, radiation patterns and reflection coefficient is satisfactory. Further investigation and analysis of the safety aspect and bending and twisting when the antenna is close to the human body is required.

EL Wissem et al. [30] reported a conformal mm-wave textile-based antenna operating at 26 GHz for 5G cellular applications. The antenna was incorporated with an electromagnetic bandgap (EBG) structure that was placed around the patch. The EBG has improved the gain and efficiency of the antenna by 2.5 dB and 7% compared to without EBG. The EBG structure also reduced the specific absorption rate (SAR) by 70% to within the acceptable safe level exposure.

A circularly polarized mm-wave wearable antenna for 5G wearable application is introduced by Ubaid et al. [31]. The antenna was based on a straight microstrip transmission line printed on one side, and the EM energy is coupled to a square patch on the other side through a V-shape slot aperture. The circular polarization feature is achieved by parallel alignment of the patch edges to each arm of the V-shape slots with orthogonal arms. This configuration results in a compact size antenna with a wideband and high gain CP antenna operating at the frequency band of 27.2–30.5 GHz. The antenna also achieved a stable 3-dB axial ratio bandwidth over 27.3–29.7 with a maximum gain of 11 dBi and 90% efficiency. The antenna also attained stable and directional electromagnetic radiations. Despite the compact topology and good performance, this work is missing an SAR analysis to evaluate the energy exposure for safety purposes. More recently, a textile-based mm-wave wearable antenna was introduced in [32]. The antenna operates at higher-order mode covering the frequency band of 24.9–31 GHz. The antenna demonstrated a measured gain of 8.2 dBi. An array of 13 × 13 elements was also evaluated to explore the efficacy of receiving power, and the numerical results illustrated the potential for up to six times higher power reception compared to a conventional patch.

References

1. Wearable Technology Market Size Analysis Report 2028. Available online: https://www.grandviewresearch.com/industry-analysis/wearable-technology-market (accessed on 3 December 2021).
2. Gartner Forecasts Global Spending on Wearable Devices to Total $81.5 Billion in 2021. Available online: https://www.gartner.com/en/newsroom/press-releases/2021-01-11-gartner-forecasts-global-spending-on-wearable-devices-to-total-81-5-billion-in-2021 (accessed on 3 December 2021).
3. Global Connected Wearable Devices 2016–2022|Statista. Available online: https://www.statista.com/statistics/487291/global-connected-wearable-devices/ (accessed on 2 December 2021).
4. Aun, N.F.M.; Soh, P.J.; Al-Hadi, A.A.; Jamlos, M.F.; Vandenbosch, G.A.; Schreurs, D. Revolutionizing Wearables for 5G: 5G Technologies: Recent Developments and Future Perspectives for Wearable Devices and Antennas. IEEE Microw. Mag. 2017, 18, 108–124.
5. Wang, G.; Hou, C.; Wang, H. Flexible and Wearable Electronics for Smart Clothing; Wiley: Hoboken, NJ, USA, 2020.
6. Soh, P.J.; Vandenbosch, G.A.; Mercuri, M.; Schreurs, D.M.P. Wearable Wireless Health Monitoring: Current Developments, Challenges, and Future Trends. IEEE Microw. Mag. 2015, 16, 55–70.
7. Sultan, K.; Mahmoud, A.; Abbosh, A.M. Textile Electromagnetic Brace for Knee Imaging. IEEE Trans. Biomed. Circuits Syst. 2021, 15, 522–536.

8. Alqadami, A.S.M.; Zamani, A.; Trakic, A.; Abbosh, A. Flexible Electromagnetic Cap for Three-Dimensional Electromagnetic Head Imaging. IEEE Trans. Biomed. Eng. 2021, 68, 2880–2891.
9. Alqadami, A.S.M.; Stancombe, A.E.; Bialkowski, K.S.; Abbosh, A. Flexible Meander-Line Antenna Array for Wearable Electromagnetic Head Imaging. IEEE Trans. Antennas Propag. 2020, 69, 4206–4211.
10. Alqadami, A.S.M.; Nguyen-Trong, N.; Stancombe, A.E.; Bialkowski, K.; Abbosh, A. Compact Flexible Wideband Antenna for On-Body Electromagnetic Medical Diagnostic Systems. IEEE Trans. Antennas Propag. 2020, 68, 8180–8185.
11. Alqadami, A.S.; Nguyen-Trong, N.; Mohammed, B.; Stancombe, A.E.; Heitzmann, M.T.; Abbosh, A. Compact Unidirectional Conformal Antenna Based on Flexible High-Permittivity Custom-Made Substrate for Wearable Wideband Electromagnetic Head Imaging System. IEEE Trans. Antennas Propag. 2020, 68, 183–194.
12. Mahmood, S.N.; Ishak, A.J.; Saeidi, T.; Alsariera, H.; Alani, S.; Ismail, A.; Soh, A.C. Recent Advances in Wearable Antenna Technologies: A Review. Prog. Electromagn. Res. B 2020, 89, 1–27.
13. Karim, R.; Iftikhar, A.; Ijaz, B.; Mabrouk, I.B. The Potentials, Challenges, and Future Directions of On-Chip-Antennas for Emerging Wireless Applications—A Comprehensive Survey. IEEE Access 2019, 7, 173897–173934.
14. Tsolis, A.; Whittow, W.G.; Alexandridis, A.A.; Vardaxoglou, J.C. Embroidery and Related Manufacturing Techniques for Wearable Antennas: Challenges and Opportunities. Electronics 2014, 3, 314–338.
15. Yan, S.; Soh, P.J.; Vandenbosch, G.A. Wearable Ultrawideband Technology—A Review of Ultrawideband Antennas, Propagation Channels, and Applications in Wireless Body Area Networks. IEEE Access 2018, 6, 42177–42185.
16. Zhu, H.; Shen, Y.; Li, Y.; Tang, J. Recent advances in flexible and wearable organic optoelectronic devices. J. Semicond. 2018, 39, 11011.
17. El Gharbi, M.; Fernández-García, R.; Ahyoud, S.; Gil, I. A Review of Flexible Wearable Antenna Sensors: Design, Fabrication Methods, and Applications. Materials 2020, 13, 3781.
18. Chandravanshi, A.; Rai, A.; Chaitanya, G. Wearable antenna: A critical review. In Proceedings of the 11th International Conference on Industrial and Information Systems, ICIIS 2016, Roorkee, India, 3–4 December 2016.
19. Tighezza, M.; Rahim, S.K.A.; Islam, M.T. Flexible wideband antenna for 5G applications. Microw. Opt. Technol. Lett. 2017, 60, 38–44.
20. Boyuan, M.; Pan, J.; Wang, E.; Yang, D. Wristwatch-Style Wearable Dielectric Resonator Antennas for Applications on Limps. IEEE Access 2020, 8, 59837–59844.
21. Camacho-Gomez, C.; Sanchez-Montero, R.; Martinez-Villanueva, D.; Lopez-Espi, P.L.; Salcedo-Sanz, S. Design of a Multi-Band Microstrip Textile Patch Antenna for LTE and 5G Services with the CRO-SL Ensemble. Appl. Sci. 2020, 10, 1168.
22. Nakmouche, M.F.; Allam, A.M.; Fawzy, D.E.; Lin, A.D.-B. Development of A High Gain fss Reflector Backed Monopole Antenna using Machine Learning For 5G Applications. Prog. Electromagn. Res. M 2021, 105, 183–194.
23. Hu, Z.; Xiao, Z.; Jiang, S.; Song, R.; He, D. A Dual-Band Conformal Antenna Based on Highly Conductive Graphene-Assembled Films for 5G WLAN Applications. Materials 2021, 14, 5087.
24. Qiu, H.; Liu, H.; Jia, X.; Jiang, Z.-Y.; Liu, Y.-H.; Xu, J.; Lu, T.; Shao, M.; Ren, T.-L.; Chen, K.J. Compact, Flexible, and Transparent Antennas Based on Embedded Metallic Mesh for Wearable Devices in 5G Wireless Network. IEEE Trans. Antennas Propag. 2020, 69, 1864–1873.
25. Yu, B.-Y.; Wang, Z.-H.; Ju, L.; Zhang, C.; Liu, Z.-G.; Tao, L.; Lu, W.-B. Flexible and Wearable Hybrid RF and Solar Energy Harvesting System. IEEE Trans. Antennas Propag. 2021.
26. Shakhirul, M.S.; Ain, M.F.; Ahmad, Z.; Abidin, I.S.Z.; Ali, M.Z. Stretch analysis of polydimethylsiloxane composite microstrip patch antenna for 5G application. AIP Conf. Proc. 2021, 2339, 020117.
27. Du, C.; Li, X.; Zhong, S. Compact Liquid Crystal Polymer Based Tri-Band Flexible Antenna for WLAN/WiMAX/5G Applications. IEEE Access 2019.
28. LeDuc, C.; Zhadobov, M. Impact of Antenna Topology and Feeding Technique on Coupling with Human Body: Application to 60-GHz Antenna Arrays. IEEE Trans. Antennas Propag. 2017, 65, 6779–6787.
29. Jilani, S.F.; Rahimian, A.; Alfadhl, Y.; Alomainy, A. Low-profile flexible frequency-reconfigurable millimetre-wave antenna for 5G applications. Flex. Print. Electron. 2018, 3, 035003.
30. Jilani, S.F.; Munoz, M.O.; Abbasi, Q.H.; Alomainy, A. Millimeter-Wave Liquid Crystal Polymer Based Conformal Antenna Array for 5G Applications. IEEE Antennas Wirel. Propag. Lett. 2018, 18, 84–88.

31. Li, E.; Li, X.J.; Seet, B.-C.; Lin, X. Ink-printed flexible wideband dipole array antenna for 5G applications. Phys. Commun. 2020, 43, 101193.
32. Wissem, E.M.; Sfar, I.; Osman, L.; Ribero, J.M. A Textile EBG-Based Antenna for Future 5G-IoT Millimeter-Wave Applications. Electronics 2021, 10, 154.
33. Ullah, U.; Al-Hasan, M.; Koziel, S.; Ben Mabrouk, I. A Series Inclined Slot-Fed Circularly Polarized Antenna for 5G 28 GHz Applications. IEEE Antennas Wirel. Propag. Lett. 2021, 20, 351–355.
34. Mohamed, M.; Hilton, G.S.; Weddell, A.; Beeby, S. Millimeter Wave Power Transmission for Compact and Large-Area Wearable IoT Devices based on a Higher-Order Mode Wearable Antenna. IEEE Internet Things J. 2021.