Lyu, B., Safdar, G. A., Jamshed, M. A. and Ur Rehman, M. (2022) Flexible Ultra-Wideband Antenna for 5G and Beyond Wearable Applications. In: 1st International Conference on Microwave, Antennas & Circuits (ICMAC 2021), Islamabad, Pakistan, 21-22 Dec 2021, ISBN 9781665400862

(doi: 10.1109/ICMAC54080.2021.9678300)

This is the Author Accepted Manuscript.

© 2021 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

There may be differences between this version and the published version. You are advised to consult the publisher's version if you wish to cite from it.

http://eprints.gla.ac.uk/257561/

Deposited on: 22 October 2021

Enlighten – Research publications by members of the University of Glasgow
http://eprints.gla.ac.uk

Flexible Ultra-Wideband Antenna for 5G and Beyond Wearable Applications

Bowen Lyu*, Ghazanfar A. Safdar†, Muhammad Ali Jamshed*, and Masood Ur-Rehman*

* James Watt School of Engineering, University of Glasgow, Glasgow, UK
†School of Computer Science and Technology, University of Bedfordshire, Luton, UK
Email: muhammadali.jamshed@glasgow.ac.uk

***Abstract*—Millimeter wave frequencies are front running contenders for 5G wireless communications. A wideband antenna that can provide coverage in whole of these frequencies is a well sought off challenge. This paper presents design of a quasi-Yagi antenna consisting of three driven arms and three pairs of spiral directors that efficiently meets this requirement. To satisfy the flexibility demand of wearable applications, the antenna employs liquid crystal polymer LCP as the substrate. The antenna has a small size of $5\times8\times0.202$ mm^3 while covering 24-71 GHz band. The proposed antenna achieves peak gain of 2.85, 6.33 and 8.52 dBi, respectively, and an efficiency of more than 70% in the desired frequency bands. The symmetric structure of the antenna also makes the fabrication easier. The ultra-wideband, radiation characteristics and flexibility of usage makes it a promising candidate for 5G and Beyond wearable applications.**

***Index Terms*—Quasi-Yagi antenna, millimeter wave, wearable applications, Liquid Crystal Polymer, 5G, ultrawideband.**

I. Introduction

With the advent of fifth-generation (5G) communication and internet of things (IoT), wearable wireless devices, including portable healthcare equipment, smartwatch,and other smart devices have occurred a tremendous development [1]. The market size of the wearable application is expected to exceed £44000 million by the end of 2025, with a compound annual growth rate of 16.2% [2]. Antenna is an essential component of the wireless enabled wearable devices. Its operation is crucial and usually defining for the performance of these devices. Wearability brings its own challenges in the antenna design on top of the typical free space requirements and flexibility to conform with the body shape, underneath, is one of them [1]. The attraction for 5G system lies in its inherent features of wider availability, high data rate, increased reliability, low latency, smaller and lightweight components and reduced interference [3] [4]. An antenna design fulfilling all these criteria is a knotty problem. While, modalities for 5G networks are in proposition, the Federal Communication Commission (FCC) has identified millimeter wave (mm-wave) frequencies of 28 GHz, 38 GHz and 60 GHz as a favorite pick for 5G wireless communications [3] [4]. In addition, the Wireless Gigabit (WiGig) Alliance is committed to develop and promote wireless communications technology in the unlicensed 60 GHz frequency band. The WiGig standard requires a fractional bandwidth of more than 22% [5].

Coverage of these different frequency bands in a small wearable device is a labyrinth task. Having multiple antennas in a tiny space makes it bulkier, use of a single antenna covering multiple bands is an efficient alternative [4] [6]. Numerous antenna designs are proposed to meet the vivid demands of 5G wearable wireless applications at mm-wave frequencies [6]- [7]. Patch antennas have emerged as a popular choice for these devices because they offer ease of design, simple integration and low cost. A sector-disk radiator and an elliptical radiator are presented in [8] [9], respectively. Both of them exploit a π-shaped slot to couple with the feed line giving rise to a notched band.

A dual-feed square loop antenna is presented in [10]. Antenna resonates at 38.5 and 73.5 GHz with exhibiting gain values of 2.9 and 3 dBi, respectively. A dual-band microstrip patch antenna has been discussed in [11]. This antenna can achieve the gain of 5.5 dBi and 6 dBi, that corresponds to the resonant frequency of 37 GHz (bandwidth of 14.8%) and 54 GHz (bandwidth of 16%), respectively. Another microstrip patch antenna exploiting the H and E slots to radiate is presented in [12]. The antenna resonates at 26.9 GHz, 35.1 GHz, and 54.7 GHz with bandwidths of 2.92 GHz, 3.13 GHz and 7.62 GHz, respectively. Moreover, the gain of each operating frequency is 5.86 dBi, 4.63 dBi, 6.36 dBi, respectively. Chen et al. have presented a triband quasi-Yagi antenna covering 23–31 GHz, 36–41 GHz and 54–67 GHz frequencies for mm-wave operation at 28 GHz, 38 GHz and 60 GHz bands [13]. The antenna offers gain values of 6.2 dBi, 7.6 dBi, and 9.4 dBi at the three resonant frequencies. Though, these multiband antennas fulfill the basic requirements, the resonant structures constrain the maximum resonant frequency or bandwidth, which limit them to balance the wide bandwidth and extremely high frequency, for example, in the case of WiGig standard. Moreover, flexibility and conformity to the shape of the human user is also not achievable due to rigidity of the substrates used.

This limitation can effectively be eliminated by using antennas with ultra-wide bandwidths (UWB) and flexible substrate. Planar dipoles and bowtie structures offer wideband operation, but they need baluns for efficient performance [14] [15]. Moghaddam et al. have presented a bowtie antenna integrated with a multilayer substrate feeding network [16]. The antenna covers the frequencies of 20-50 GHz with a reflection coefficient better than -8 dB requiring differential excitation in a way similar to magneto-electric dipoles and marchand baluns. Zeng et al. have come up with a microstrip-fed end-fire magnetoelectric dipole antenna design having a -10 dB bandwidth ranging from 22.1 to 41.7 GHz with a peak gain of 6.7 dBi [17]. The antenna utilises an integrated balun covering the whole operating. Wu et al. have proposed an array antenna covering the frequencies of 55-68 GHz [18]. The elemental design consists of a microstrip radiation element and the feeding planar hollow waveguide. Through the use of vias, substrate integrated cavity is formed. Sehrai et al. have proposed a quad element MIMO antenna where the radiating element consists of four arcs to cover mm-wave frequencies of 23 GHz to 40 GHz [7]. These structures are complex, inflexible and do not cover the three bands of interest in mm-wave frequency range.

In this paper, we have proposed a quasi-Yagi antenna to cover the 5G mm-wave bands from 24 to 70 GHz. To ensure flexibility and conformity, liquid crystal polymer (LCP) consisting of polyimide/polyethene terephthalate (PET) is chosen as a substrate. LCP is considered an excellent material to improve the conformal and flexible characteristics enhancing the adaptability of the wearable antennas [19]. Following the introduction, the rest of the paper is organized in three sections. Section II describes the antenna design. Section III presents the numerical results and analysis of the antenna performance. Section IV summarizes the findings and concludes the discussion.

II. Antenna Design

Yagi antenna is conventionally being used for television signal reception for many years. It consists of several pairs of dipoles as driven modules and possess broad bandwidth, straightforward construction, and relatively high gain [13] [20]. We have chosen printed Yagi structure as the basis of our ultrawideband mm-wave antenna design. In the proposed structure, three pairs of drivers and spiral directors are laid on top and bottom sides of the flexible substrate (i.e., Rogers 3850 LCP with dielectric constant of 2.9, loss tangent of 0.0025 and thickness of 0.2 mm). To obtain an overall compact size of $5\times8\times0.202$ mm^3 while having an ultrawideband mm-wave operation, a detailed optimization process is carried out to have optimal dimensions of the driven arms (A1, A2 and A3 in Fig. 1), truncated ground (by adjusting the lengths of S1, S2 and S3), the size of rectangular ground patches, and the dimension of the small open stub.

For 28 GHz operation, the truncated ground is not only for receiving return current but also acts as the reflector of A1 whereas A2 and A3 perform as directors for A1. At 38 GHz, A1, A2 and A3 act as a reflector, driver and director, respectively. For 60 GHz operation, A2 works as a reflector while A3 is the driver element. The directors are realized in the form of spirals as they are more effective than other possible structures (such as I-shaped, L-shaped and U-shaped) for obtaining larger bandwidth and higher gain [21]. The driven arms resonate at 28, 38 and 60 GHz corresponding to

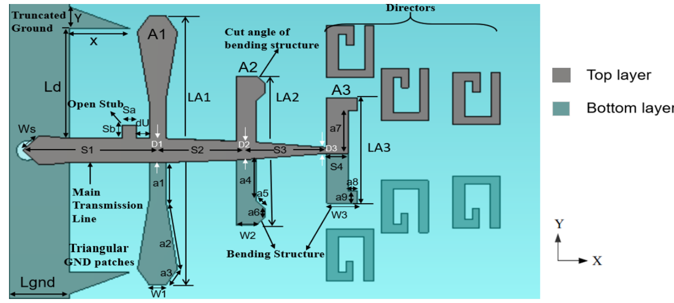

Fig. 1. The configuration of the proposed quasi-Yagi antenna.

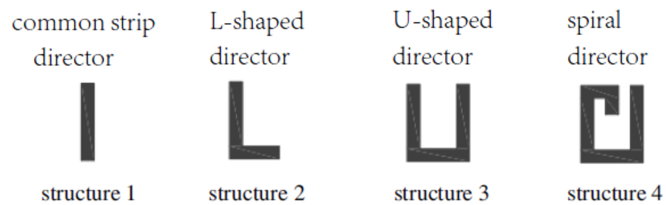

Fig. 2. Four structures for the director.

A1, A2 and A3, respectively. In the design process, length of A2 is approximated first, then, S1, S2, and S3 are determined to match the impedance of A3. Subsequently, A1 and A2 are structured applying similar method. In addition, other elements are utilized for fine-tuning the antenna functionality.

The antenna is fed through a 50 Ω coaxial line. The coaxial line not only acts as a feedline but also provides signal transmission for the dipoles on top and bottom layers. The reference ground is extended to the radiating plane to reduce the power loss of the transmission line (Fig. 3) because the coaxial line encounters serious mismatch when passing through the substrate. There are several ways to achieve the broadband impedance matching including use of ladder networks, multiple stubs, multiple line sections and tapered lines [21]. A combination of the tapered transmission line and multiple stubs is employed to broaden the bandwidth in the proposed design. Especially, the main transmission line is elaborately designed as a tapered line, which can provide impedance matching for A1, A2 and A3 along with the coaxial feedline.

The length of the truncated ground is significant for the current distribution in the proposed antenna because the ground plane acts as a reflector and affects the performance of resonant dipoles. Only when A1 is resonating at 28 GHz, the truncated ground needs to be used as a reflector to enhance directivity. Thereby, the length of the ground plane should be less than S1 but greater than diameter of coaxial feedline. The triangular ground patches can change routes of return current of A1 at 28 GHz, which strengthens the impedance matching of 28 GHz band without affecting that of 38 and 60 GHz. The fine-tuning elements consisting of the open stub, cut angle of bending structure and bending structure (see Fig.1), are important to adjust and improve the impedance matching.

TABLE I
OPTIMIZED GEOMETRICAL PARAMETERS OF PROPOSED QUASI-YAGI ANTENNA.

A1 (mm)		A2 (mm)		A3 (mm)		Other (mm)	
LA1	4.517	LA2	2.504	LA3	1.776	X	0.899
W1	0.259	W2	0.305	W3	0.467	Y	0.363
a1	0.691	a4	0.709	a7	0.727	Ld	1.855
a2	1.119	a5	0.184	a8	0.145	dU	0.185
a3	0.305	a6	0.144	a9	0.21	Sa	0.218
S1	1.289	S2	1.268	S3	1.179	Sb	0.218
D1	0.396	D2	0.296	D3	0.098	Ws	0.325

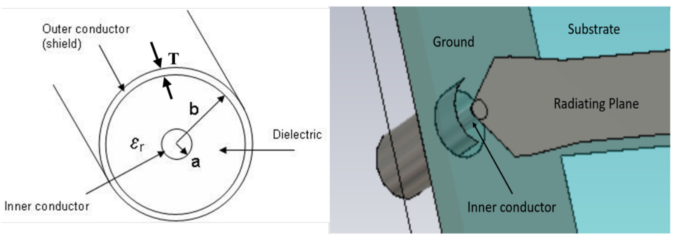

Fig. 3. Configurations of the coaxial feedline.

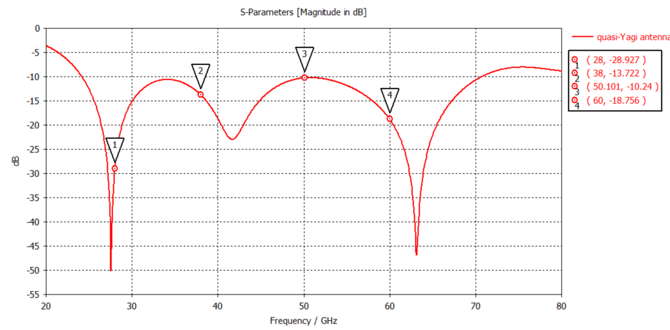

Fig. 4. Reflection coefficient response of the proposed quasi-Yagi antenna.

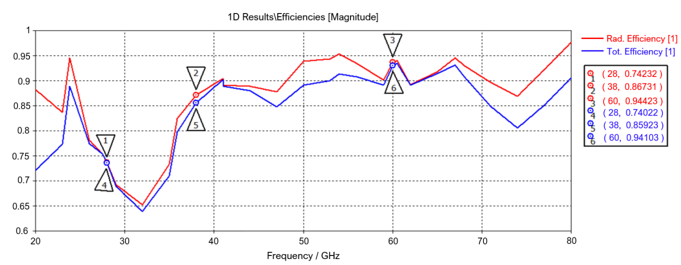

Fig. 5. Radiation efficiency and total efficiency of the proposed quasi-Yagi antenna.

The bowtie shaped edges of A1 arms effectively widen the bandwidth at 28 GHz, that is essential to reach the entire coverage of 5G frequency bands.

Following the matching order of 28 GHz, 38 GHz and 60 GHz, the bending structure contributes to the impedance matching adjustment of A3 while the bending structure with cut angel serves the same purpose for A2 driver. However, it is hard to enhance the impedance matching at 28 GHz. Thereby, the triangular ground patches and open stub are designed to reinforce the impedance matching at 28 GHz. Through numerous calculations, iterations and simulations, the optimal values of different structural parameters for the antenna geometry shown in Fig. 1 are summarized in Table 1.

III. RESULTS AND ANALYSIS

The proposed quasi-Yagi antenna is modelled and analyzed numerically using CST Studio Suite. The antenna performance is studied in terms of reflection coefficient, bandwidth, gain, efficiency, and radiation pattern in the mm-wave frequency range.

A. Reflection Coefficient (S_{11}) Response

The reflection coefficient response of the proposed antenna is shown in Fig. 4. It is evident from the plot that the proposed antenna posses a very good impedance matching in the entire band of interest. The bandwidth covers the whole spectrum from 24 GHz to 70 GHz with strong resonances at 27 GHz, 42 GHz, and 63 GHz frequencies.

B. Antenna efficiency

Figure 5 illustrates the radiation and total efficiency of the proposed quasi-Yagi antenna. The proposed design exhibits an efficiency of more than 70% in the entire mm-wave band of interest supporting the operation at 28 GHz, 38 GHz and 60 GHz frequency with minimum losses.

C. Antenna gain

The antenna peak gain performance is shown in Fig. 6. The antenna realizes good gain vales of 2.9 dBi, 6.3 dBi and 8.5 dBi, respectively, at the three frequencies of 28 GHz, 38 GHz and 60 GHz. Though slightly less at the lower frequencies, in most of the operating bandwidth the gain value is above 6 dBi (ranging from 37 GHz to 70 GHz). Nevertheless, the antenna offers a good peak gain for the ultra-wideband mm-wave operation for 5G and beyond networks.

D. Radiation Pattern

The radiation patterns of the proposed quasi-Yagi antenna at 28 GHz, 38 GHz and 60 GHz are presented in Fig. 7. The

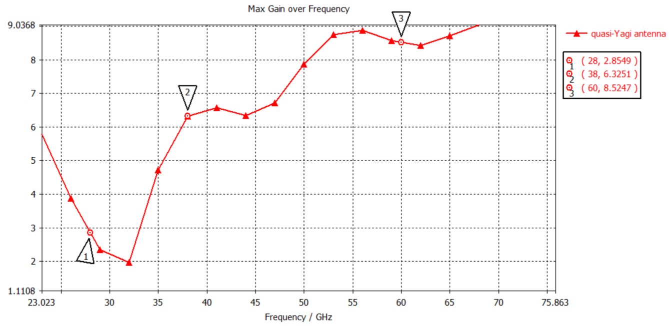

Fig. 6. Gain of the proposed quasi-Yagi antenna.

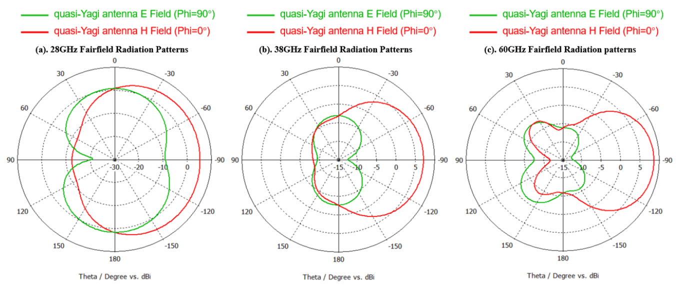

Fig. 7. Radiation patterns of the quasi-Yagi antenna.

xy-plane (Phi = 90°) corresponds to the E-plane while the xz-plane (Phi = 0°) corresponds to the H-plane. The E-field radiation pattern performs like a dipole radiation pattern at 28, 38 and 60 GHz (with slightly distorted shape at 60 GHz). The H-field radiation pattern has a high front-to-back ratio and covers a broader range of angles as compared to the E-field. Overall, the antenna provides good radiation coverage.

IV. Conclusion

A quasi-Yagi antenna for ultra-wideband mm-wave operation has been designed and analyzed numerically in this paper. The proposed antenna makes use of a relatively simple structure and small size to offer a huge -10 dB bandwidth ranging from 24-70 GHz. The antenna employs a flexible LCP substrate to ensure human body conformity while achieving good radiation coverage, high gain (greater than 6 dBi in most of the operating bandwidth) and greater than 70% of efficiency. These features make the proposed antenna a good candidate solution for ultra-wideband operation for 5G and beyond systems working at mm-wave frequencies.

Acknowledgement

This work was supported by Innovative and Collaborative Research Grant under Pakistan UK Education Gateway (ICRG-2020) Project No. 310366 - Deforestation in Pakistan: Combating through Wireless Sensor Networks (DePWiSeN)).

References

[1] Q. H. Abbasi, M. Ur-Rehman, K. Qaraqe, and A. Alomainy, *Advances in body-centric wireless communication: Applications and state-of-the-art*. Institution of Engineering and Technology, 2016, no. 65.

[2] T. Page, "A forecast of the adoption of wearable technology," *International Journal of Technology Diffusion (IJTD)*, vol. 6, no. 2, pp. 12–29, 2015.

[3] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, "Millimeter wave mobile communications for 5g cellular: It will work!" *IEEE access*, vol. 1, pp. 335–349, 2013.

[4] M. U. Rehman and Q. H. Abbasi, "Multiband millimetre-wave antennas for 5g and beyond," *Antennas and Propagation for 5G and Beyond*, p. 101, 2020.

[5] T. Nitsche, C. Cordeiro, A. B. Flores, E. W. Knightly, E. Perahia, and J. C. Widmer, "Ieee 802.11 ad: directional 60 ghz communication for multi-gigabit-per-second wi-fi," *IEEE Communications Magazine*, vol. 52, no. 12, pp. 132–141, 2014.

[6] M. Ur-Rehman, M. Adekanye, and H. T. Chattha, "Tri-band millimetre-wave antenna for body-centric networks," *Nano communication networks*, vol. 18, pp. 72–81, 2018.

[7] D. A. Sehrai, M. Abdullah, A. Altaf, S. H. Kiani, F. Muhammad, M. Tufail, M. Irfan, A. Glowacz, and S. Rahman, "A novel high gain wideband mimo antenna for 5g millimeter wave applications," *Electronics*, vol. 9, no. 6, p. 1031, 2020.

[8] O. M. Haraz, M. M. M. Ali, S. Alshebeili, and A.-R. Sebak, "Design of a 28/38 ghz dual-band printed slot antenna for the future 5g mobile communication networks," in *2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting*. IEEE, 2015, pp. 1532–1533.

[9] A. Kumar and P. Kapoor, "Design and performance evaluation of a dual-band antenna for the 5g mobile communication," in *2016 IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT)*. IEEE, 2016, pp. 2034–2036.

[10] S. Li, T. Chi, Y. Wang, and H. Wang, "A millimeter-wave dual-feed square loop antenna for 5g communications," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 12, pp. 6317–6328, 2017.

[11] Z. Lodro, N. Shah, E. Mahar, S. B. Tirmizi, and M. Lodro, "mmwave novel multiband microstrip patch antenna design for 5g communication," in *2019 2nd International conference on computing, mathematics and engineering technologies (iCoMET)*. IEEE, 2019, pp. 1–4.

[12] G. Amrutha and T. Sudha, "Triple band antenna for 5g applications," in *2018 International Conference on Advances in Computing, Communications and Informatics (ICACCI)*. IEEE, 2018, pp. 1650–1652.

[13] M.-J. Chen, N.-C. Liu, W.-R. Xue, and J.-H. Tarng, "Compact millimeter-wave triband quasi-yagi antenna for 5g and wigig applications," in *2019 PhotonIcs & Electromagnetics Research Symposium-Spring (PIERS-Spring)*. IEEE, 2019, pp. 3359–3364.

[14] H. Raza, A. Hussain, J. Yang, and P.-S. Kildal, "Wideband compact 4-port dual polarized self-grounded bowtie antenna," *IEEE transactions on antennas and propagation*, vol. 62, no. 9, pp. 4468–4473, 2014.

[15] J. P. Doane, K. Sertel, and J. L. Volakis, "A wideband, wide scanning tightly coupled dipole array with integrated balun (tcda-ib)," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 9, pp. 4538–4548, 2013.

[16] S. M. Moghaddam, J. Yang, and A. A. Glazunov, "Ultra-wideband millimeter-wave bowtie antenna," in *2017 International Symposium on Antennas and Propagation (ISAP)*. IEEE, 2017, pp. 1–2.

[17] J. Zeng and K.-M. Luk, "Wideband millimeter-wave end-fire magneto-electric dipole antenna with microstrip-line feed," *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 4, pp. 2658–2665, 2019.

[18] K.-l. Wu, Y. Yao, X.-h. Cheng, J.-s. Yu, T. Yu, and X.-d. Chen, "Analysis and design of novel wideband and high efficiency millimeter-wave antenna arrays for 60-ghz applications," *Frontiers of Information Technology & Electronic Engineering*, vol. 21, no. 1, pp. 128–143, 2020.

[19] W. Farooq, M. Ur-Rehman, X. Yang, and Q. H. Abbasi, "Study of a novel multi-band antenna for body-centric wireless networks," in *2015 IEEE 11th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*. IEEE, 2015, pp. 112–116.

[20] H. Kumar and G. Kumar, "A broadband planar modified quasi-yagi using log-periodic antenna," *Progress In Electromagnetics Research Letters*, vol. 73, pp. 23–30, 2018.

[21] L. Lu, K. Ma, F. Meng, and K. S. Yeo, "Design of a 60-ghz quasi-yagi antenna with novel ladder-like directors for gain and bandwidth enhancements," *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 682–685, 2015.