2024 IEEE Microwaves, Antennas, and Propagation Conference (MAPCON) | 979-8-3503-7969-3/24/$31.00 ©2024 IEEE | DOI: 10.1109/MAPCON61407.2024.10923314

A Novel Bi-directional Dipole Antenna Array for UAV-Based Back-haul Link at C-band Frequency Range

1st Pallav Kumar Sah
Department of Electrical and Computer Engineering
The University of Texas at Dallas
Richardson, TX, USA
Pallav.Sah@utdallas.edu

2nd Ifana Mahbub
Department of Electrical and Computer Engineering
The University of Texas at Dallas
Richardson, TX, USA
Ifana.Mahbub@utdallas.edu

***Abstract*—A novel aperture-efficient bi-directional antenna is proposed to support a back-haul link for unmanned aerial vehicles (UAVs) in the C-band frequency range. The bi-directional antenna radiation is achieved through a double-sided E-dipole structure. This E-dipole combines two vertical stubs on both sides of the antenna. The stubs are slanted at 45 degrees, making them perpendicular to each other and forming an L-shaped structure when viewed from the top, thereby achieving elliptical polarization (EP). The proposed 5G antenna array is designed for dual resonating frequency bands n79 and n96, with fractional bandwidths (FBW) of 20% (4.2-5.12 GHz) and 35% (5.2-7.37 GHz), respectively. Unlike traditional designs that utilize dipole elements, the optimized dipole antenna array can attain a bi-directional distribution of broadside gains of 25.1 dBi, while maintaining a smaller size of $41 \times 41\ cm^2$ ($5.47\lambda \times 5.47\lambda$) with a side lobe level (SLL) better than 21 dB maintaining radiation efficiency more than 80%.**

***Index Terms*—Bidirectional, unmanned aerial vehicle (UAV), back-haul link, C-band, elliptical polarization, dipole, microstrip patch antenna, dual-band, n79, n96, side lobe level (SLL).**

I. INTRODUCTION

The demand for mobile traffic has surged significantly over the past decades and is expected to continue rising with the advancement of next-generation (5G) wireless networks. Despite the high demand for cellular coverage in rural areas, many people still have limited access because cellular coverage in numerous rural regions remains inconsistent. Mobile operators might be reluctant to invest in costly network infrastructure for areas with low demand. As a result, new solutions are being developed for the swift deployment of base stations in regions where operator infrastructure is either lacking or has been compromised [1]. The use of UAVs integrated with 5G bidirectional antennas for data relays or back-haul links offers considerable potential to provide on-demand connectivity.

Bi-directional antennas, known for their dual-directional radiation patterns with high gain, mitigate multipath interference and enhance link efficiency. This UAV-based back-haul connectivity system would improve public safety services and assist in recovery efforts following the failure of communication infrastructure due to natural disasters and low network coverage areas, as shown in Fig 1. However, bi-directional

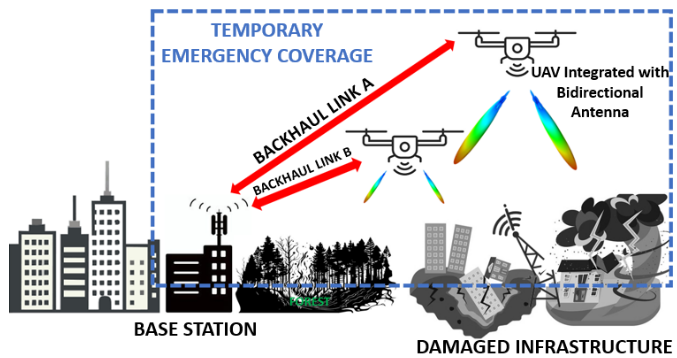

Fig. 1. UAV-based back-haul link system for damaged communication service

antennas are being widely utilized in narrow, elongated, and linear communication environments, including long bridges, subways, tunnels, railways, highways, mega-structures, and corridors [2], [3]. The traditional approach to obtaining bi-directional radiation involves positioning two antenna arrays back-to-back. Previous studies have achieved dual-radiation patterns by orienting two identical antenna arrays in opposite directions [4]. In [5], a stacked director design utilizing multi-layered microstrip antennas is described. However, this design features a large cross-sectional area and a multilayered structure, making it unsuitable for UAVs or confined spaces due to unfavorable wind effects. Some pattern-reconfigurable end-fire antennas have been proposed to achieve bi-directional radiation by alternating beams in two opposite directions [6], [7]. However, these designs are unable to generate two main beams in opposite directions simultaneously.

The C-band frequency range is superior to millimeter-wave (mm-wave) frequency bands for air-to-ground (A2G) and air-to-air (A2A) applications as the mm-wave frequency signal suffers from higher atmospheric attenuation compared to the C-band. The C-band demonstrates excellent signal propagation qualities, particularly in non-line-of-sight (NLOS) conditions, establishing dependable communication channels. As the proposed frequency range is a licensed band currently under review by the Federal Communications Commission

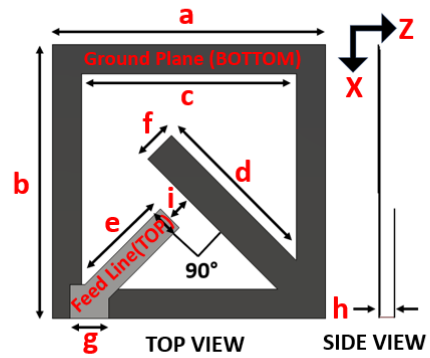

Fig. 2. Geometry for the proposed Unit-cell

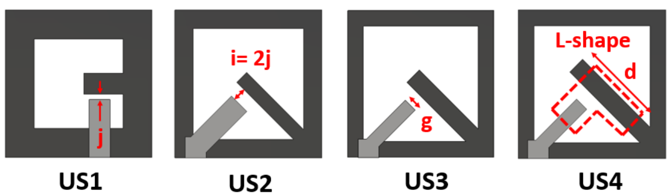

Fig. 3. Development of proposed Unit-cell

(FCC) for prospective use in UAV communications, it ensures that spectrum will be available. This frequency range also provides improved signal propagation and broader coverage, resulting in high efficiency for A2G and A2A communications. Previous research involves the development of effective mm-wave antenna array designs tailored for use in UAV applications. Despite their considerable gain, these configurations are susceptible to atmospheric attenuation, which notably impacts their operational effectiveness in real-world settings, primarily due to their operation within mm-wave frequency bands [8], [9].

To address these challenges, an EP antenna proves to be a fitting solution. Due to their superior mobility and ability to penetrate weather conditions more effectively than linearly polarized (LP) antennas, EP antennas are increasingly favored in wireless communication systems. Consequently, EP reduces power loss caused by Faraday rotation and multi-path effects. In prior work [10], the proposed antenna design exhibits bi-directional radiation, though it is not EP or circularly polarized (CP). EP can be achieved by introducing square slots, ring slots, or dual feeding systems positioned orthogonally relative to each other [11]–[16].

In this article, a novel dipole structure is proposed to achieve simultaneous bi-directional radiation beams for UAV-based back-haul link applications. The presented antenna structure offers the following contributions: (a) The designed antenna uses an E-dipole structure printed on both sides, generating a dual-radiation beam with a maximum gain of 25.1 dBi, making the array an aperture-efficient structure; (b) A narrow 3 dB beam width of 7.3° and a side lobe level exceeding 21 dB add an extra layer of security to the communication link, making it difficult for unauthorized receivers to intercept the signal during various applications, such as telecommunications, broadcasting, military, and aerospace communications; and (c) The designed array achieves a radiation efficiency of more than 85% with elliptical polarization, reducing power loss due to scattering and multi-path effects.

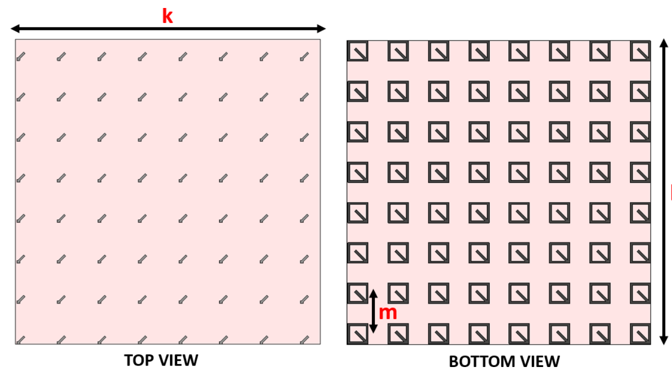

Fig. 4. Geometry of proposed 8×8 array

TABLE I
SPECIFICATION OF PROPOSED ANTENNA (UNIT: MM)

Spec	Value	Spec	Value	Spec	Value
a	28.0	e	10.2	j	1.38
b	28.0	f	3.4	k	410.0
c	22.0	g	2.7	l	410.0
d	18.0	i	2.8	m	27.0

The manuscript is structured as follows: Section II delves into the detailed design architecture of the E-dipole unit cell and its 8×8 array. The simulation outcomes for both the unit cell and the array are presented in Section III, and the paper concludes with the research findings and future works in Section IV.

II. Unit Cell and 8×8 Array Design

Fig. 2 depicts the geometry of the bi-directional dipole antenna presented in this study. The unit cell is a one-layer microstrip structure, with an E-dipole antenna printed on both sides of the FR4 substrate (with a relative permittivity ϵ = 4.4 and a thickness, h of 0.8 mm). The proposed dipole consists of a feed line at $45°$ on the left side of the substrate top and a square-slotted ground with an extended stub at $45°$ on the right-hand side of the unit cell. A gap is introduced between the feed line and the extended ground stub to minimize the coupling, resulting in a dual radiation pattern. To realize a wide-band antenna, the dipole is designed to resonate at 4 GHz, and the extended stub is designed for 6 GHz resulting in a frequency bandwidth of 3.83 GHz (3.87 GHz to 7.7 GHz) as shown in Fig. 5(a). However, the EP with an axial ratio (AR) under 10 dB (Fig. 5(b)) is achieved by the orthogonal placement [16] of the feed line and stub as shown in Fig. 2.

Fig. 3 illustrates the evolution of the proposed antenna, highlighting its impedance matching and EP performance (AR). Four different unit cell structures are examined here, i.e., US1, US2, US3, and US4 (Unit Cell [US]). However, the array (shown in Fig.4) is created for the final proposed unit cell i.e., US4, and the impact of each analysis for all four US is covered in Section III, presented in presented in Fig. 5(a) and (b). US1 is the basic dipole antenna structure with

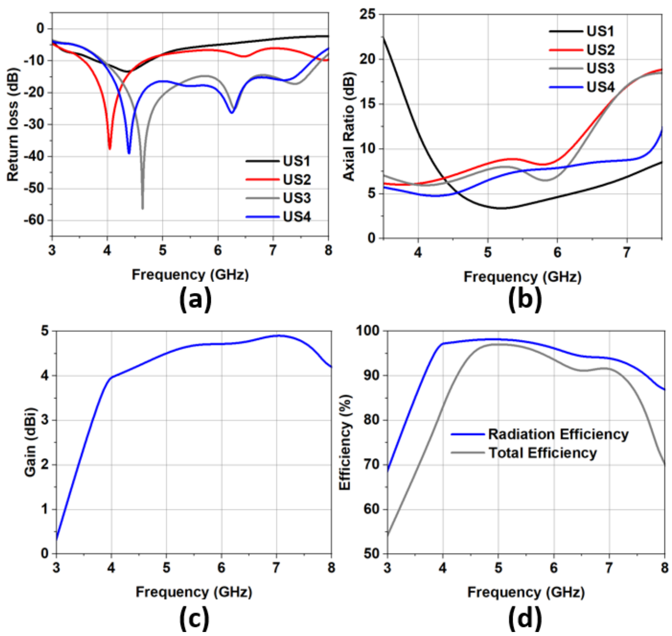

Fig. 5. (a) Simulated return loss and (b) Axial ratio for US1, US2, US3, and US4 for parameter shift j, i, g, and d, respectively; (c) Gain and (d) Radiation & total efficiency for proposed unit cell (US4).

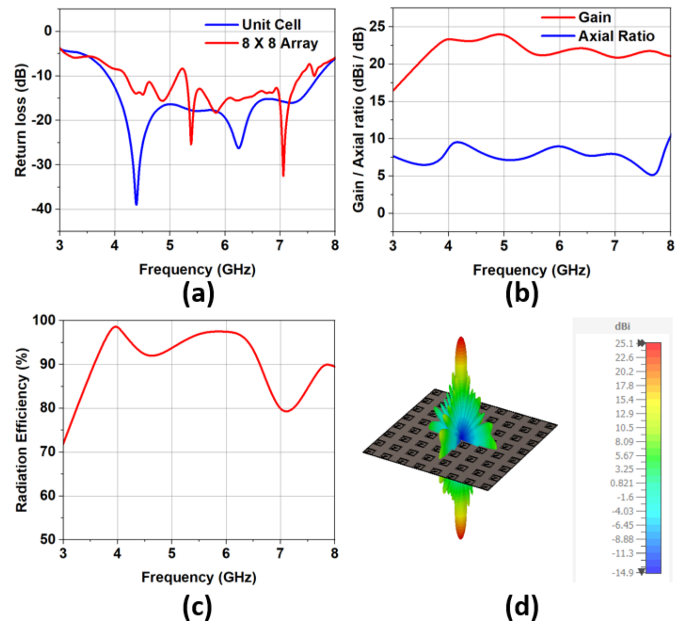

Fig. 6. (a) Simulated return loss for unit cell and array, (b) Gain and axial ratio of the array, (c) Radiation efficiency of the array, and (d) 3-D radiation pattern for array at 5 GHz.

feed and stub placed at an orthogonal position achieving EP. Further, to improve the impedance matching and maintain the EP, in US2, the feed line, and stub are moved to a diagonal position with reduced coupling in between them, making a L-shaped structure at the center. In the US3, the frequency bandwidth is enhanced by introducing a second resonating point through the adjustment of the feed line width. In US4, the impedance over the frequency BW is further improved by stub length analysis for a maximum gain of 4.95 dBi at 7 GHz with radiation and total efficiency above 90% over the band, as shown in Fig. 5(c) and (d), respectively.

However, the antenna array consisting of 64 elements is proposed to increase the gain, arranged in a uniform 8×8 matrix pattern. Each unit cell is placed at a distance of 0.5 λ, optimized for lower SLL and higher gain using the tuning method. The proposed array is limited to 64 elements or fewer, as adding more elements results in decreased overall efficiency and limited improvement in gain. CST Studio Suite 2022 is used to design the antenna. Table I, presents all the final dimensions of the unit cell as well as the 8×8 array as per the design parameters labeled in Fig. 2, 3, and 4. The overall dimension of the proposed array is 41×41 cm^2.

III. Simulation Results

Simulations are conducted separately for each design to assess the performance of each antenna element, specifically for the unit cell and the 8×8 array. The parametric analysis for US1, US2, US3, and US4 are presented in Fig. 5(a) and (b). The dipole structure in US1, designed with orthogonally placed feed and stub, achieves EP (AR= 3.6 dB) with narrow 10 dB BW of 1 GHz and poor matching (S_{11}= -13 dB). Further to improve the impedance matching, the feed line and ground stub in US2 are moved to a diagonal position resembling a 90° phase shift at the center of the unit cell achieving an EP (AR$<$ 10 dB). Increasing the gap between the feed line and ground stub by twice the original distance in US1 improves impedance matching by 184% at 4.04 GHz, thereby reducing coupling between the feed and ground. Now, to improve the impedance bandwidth, a second resonating point is introduced around a higher frequency (at 6 GHz) with the feed line width reduced by 1.6 times, as shown in US3. Finally, in US4, the length of the ground stub is further increased by 1.12 times to achieve better impedance matching of over 35 dB, resulting in a wide bandwidth of 3.83 GHz for EP with AR$<$ 10 dB.

For the proposed antenna array of 8×8 elements arranged at 0.5λ, the achieved BW is divided into dual bands of 4.2-5.12 GHz (n79 band) and 5.2-7.37 GHz (n96 band) compared to the unit cell's (US4) achieved BW as shown in Fig 6(a). The achieved FBW is 20% and 35% for n79 and n96, respectively, with a maximum gain of 25.1 dBi, presented in Fig. 6(b). Where the axial ratio and radiation efficiency of the array are well under 10 dB and above 85%, respectively, as presented in Fig. 6(b) and (c). Fig.6(d), illustrates the 3D presentation of a bi-directional antenna radiation pattern at 5 GHz. However, the 1-D radiation pattern at 5 GHz and 5.5 GHz, for the proposed array is presented in Fig. 7 illustrating a very narrow 3 dB beam width of 7.3° with SLL of 23 dB and 6.3° with SLL of 21.8 dB, respectively. Table II, presents a comparison between the proposed work and prior studies. The proposed antenna exhibited remarkable capabilities in terms of its FBW, showcasing a substantial enhancement of 37.25%. Moreover, its gain significantly surpassed all previously mentioned configurations, demonstrating an impressive 164.2%

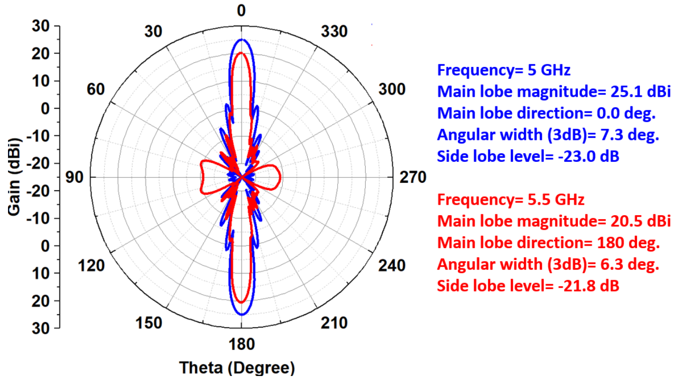

Fig. 7. Array 1-D radiation pattern at 5 GHz and 5.5 GHz band.

TABLE II
COMPARISON OF PROPOSED STRUCTURE WITH PRIOR WORKS.

Parameters	[17]	[18]	[19]	[20]	Proposed work
Frequency (GHz)	5.8	5.5	5.5	2.4	4.2-7.37
Bi-directional property	Yes	Yes	Yes	Yes	Yes
Bi-directional gain (dBi)	6.6	7.6	8	9.5	25.1
FBW (%)	11.3	7.3	25.5	11.4	20 / 35
Length (λ_0)	2	3.33	1.7	2.46	5.47

improvement. These results underscore the antenna's superior performance characteristics compared to existing designs.

IV. CONCLUSION

This article proposes an innovative dipole structure designed to achieve simultaneous bi-directional radiation beams for UAV-based back-haul link applications. The simultaneous dual-beam radiation is produced by a printed dipole structure on the top and bottom layer, arranged in an orthogonal pattern to achieve EP. The dipole array achieves broadside gains of 25.1 dBi simultaneously in both directions. Compared to conventional array designs, the proposed antenna would be a good candidate for use in back-haul applications and narrow network coverage regions. Furthermore, the proposed antenna can also be integrated with the electronic beam steering system to perform beam-forming, making the system efficient.

ACKNOWLEDGMENT

This paper is based upon work supported by the National Science Foundation under Grant number CNS 2148178.

REFERENCES

[1] ITU, "Measuring digital development: Facts and Figures 2023," www.itu.int/itu-d/reports/statistics/facts-figures-2023/, 2023.
[2] K. Cho and T. Hori, "Bidirectional rod antenna composed of narrow patches," Proceedings of IEEE Antennas and Propagation Society International Symposium and URSI National Radio Science Meeting, Seattle, WA, USA, 1994, pp. 174-177 vol.1.
[3] T. Hori, K. Cho and K. Kagoshima, "Dual-polarized bidirectional rod antenna for diversity reception at street microcell base stations," Proceedings of PIMRC '96 - 7th International Symposium on Personal, Indoor, and Mobile Communications, Taipei, Taiwan, 1996, pp. 526-530 vol.2.
[4] J. Zhang, X. M. Zhang, J. S. Liu, Q. F.Wu, T. Ying, and H. Jin, "Dual-band bidirectional high gain antenna for WLAN 2.4/5.8 GHz applications," Electron. Lett., vol. 45, pp. 6–7, Jan. 2009.
[5] T. Jia and X. Li, "A compact stacked bidirectional antenna for dual polarizedWLANapplications," Prog. Electromagn. Res. C, vol. 44, pp. 95–108, 2013.
[6] F. Liu, Z. Zhang,W. Chen, Z. Feng, andM. F. Iskander, "An endfire beamswitchable antenna array used in vehicular environment," IEEE Antennas Wireless Propag. Lett., vol. 9, pp. 195–198, 2010.
[7] C. H. Ko, I. Y. Tarn, and S. J. Chung, "A compact dual-band pattern diversity antenna by dual-band reconfigurable frequency-selective reflectors with a minimum number of switches," IEEE Trans. Antennas Propag., vol. 61, no. 2, pp. 646–654, Feb. 2013.
[8] P. Sah and I. Mahbub, "A High Gain SIW Elliptically Polarized Antenna for Millimeter-Wave Applications," 2023 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (USNC-URSI), Portland, OR, USA, 2023, pp. 1903-1904.
[9] P. Sah and I. Mahbub, "A 38° Wide Beam-Steerable Compact and Highly Efficient V-band Leaky Wave Antenna with Surface Integrated Waveguide for Vehicle-to-Vehicle Communication," 2023 IEEE Texas Symposium on Wireless and Microwave Circuits and Systems (WMCS), Waco, TX, USA, 2023, pp. 1-5, doi: 10.1109/WMCS58822.2023.10194262.
[10] J. -C. S. Chieh and A. -V. Pham, "A Bidirectional Microstrip X-Band Antenna Array on Liquid Crystal Polymer for Beamforming Applications," in IEEE Transactions on Antennas and Propagation, vol. 61, no. 6, pp. 3364-3368, June 2013, doi: 10.1109/TAP.2013.2249032.
[11] J. Pourahmadazar, C. Ghobadi, J. Nourinia, N. Felegari, and H. Shirzad, "Broadband CPW-fed circularly polarized square slot antenna with inverted L-strip for UWB applications," IEEE Antennas Wireless Propag. Lett., vol. 10, pp. 369–372, May 2011.
[12] J. Y. Sze, J. C. Wang, and C. C. Chang, "Axial-ratio bandwidth enhancement of asymmetric-CPW-fed circularly-polarised square slot antenna," Electron. Lett., vol. 44, no. 18, pp. 1048–1049, Aug. 2008.
[13] R. L. Jefferson and D. Smith, "Dual circular polarised microstrip antenna design for a passive microwave transponder," in Proc. 7th Int. Conf. Antennas Propag. (ICAP), York, U.K., Apr. 1991, pp. 141–143.
[14] J.-Y. Jan, C.-Y. Pan, K.-Y. Chiu, and H.-M. Chen, "Broadband CPW-fed circularly polarized slot antenna with an open slot" IEEE Trans. Antennas Propag., vol. 61, no. 3, pp. 1418–1422, Mar. 2013.
[15] J. Pourahmadazar and V. Rafii, "Broadband circularly polarised slot antenna array for L and S-band applications," Electron. Lett., vol. 48, no. 10, pp. 542–543, May 2012.
[16] S. Wang, D. Yang, W. Geyi, C. Zhao, and G. Ding, "Polarizationreconfigurable antenna using combination of circular polarized modes," IEEE Access, vol. 9, pp. 45622–45631, 2021.
[17] R. Wang, B. Z. Wang, G. F. Gao, X. Ding, and Z. P. Wang, "Low-profile pattern-reconfigurable vertically polarized endfire antenna with magneticcurrent radiators," IEEE Antennas Wireless Propag. Lett., vol. 17, no. 5, pp. 829–832, May 2018.
[18] D. Tian et al., "Low-profile high-efficiency bidirectional endfire antenna based on spoof surface plasmon polaritons," IEEE Antennas Wireless Propag. Lett., vol. 17, no. 5, pp. 837–840, May 2018.
[19] S. Y. Chen, "Broadband slot-type Bruce array fed by a microstrip-toslotlineT- junction," IEEE AntennasWirelessPropag. Lett., vol. 8, pp. 116– 119, 2009.
[20] W. D. Liu, Z. J. Zhang, Z. J. Tian, and Z. H. Feng, "A bidirectional high-gain cascaded ring antenna for communication in coal mine," IEEE Antennas Wireless Propag. Lett., vol. 12, pp. 761–764, 2013.