Low-Cost Radial Line Slot Array Antenna for Millimeter-Wave Backhaul Links

Muhammad U. Afzal*, Nishat Y. Koli†, Karu P. Esselle*,
*School of Electrical and Data Engineering, University of Technology Sydney, NSW 2007.
†School of Engineering, Macquarie University NSW 2109.

***Abstract*—The front-end antennas with a directed narrow beam are essential to establish a robust backhaul network for 5G network. The cost and profile of the antenna are imperative due to the large number of smaller cells envisaged for a millimeter-based 5G communication network. Radial-line slot array (RLSA) antennas are suitable due to their planar and thin height profile and single feed point. A low-cost RLSA is investigated for the millimeter-wave backhaul network without using dielectric materials. The lack of dielectric substantially reduces the fabrication cost of the antenna. The RLSA is made of two metal plates where radiating slots are on a thin-plate at the top. The results predicted through numerical simulations indicate antenna can create a narrow broadside beam without any excessive grating or side lobes.**

***Index Terms*—antennas, backhaul, millimeter, RLSA, high-gain, 5G.**

I. INTRODUCTION

The development of 5G, the fifth generation of wireless standards, is aimed at feeding human and machine-centric data-hungry wireless devices through a wider spectrum of millimeter-wave frequency band [1]–[4]. The lack of ability to penetrate urban infrastructure and other obstacles is, however, one of the major challenges for 5G communication. The development is thus focused on using ultradense cells with smaller coverage areas to maintain the quality of service. The network bottleneck is a backhaul network that will provide connectivity to the core network. A low-profile and low-cost high-gain antenna technology with a directed energy beam and low-side lobes is imperative to realize a dense, robust wireless backhaul [4].

A classic high-gain antenna used for microwave links in existing wireless communication is a reflector dishes [5]. The dishes are bulky for the denser 5G communication backhaul network. A planar alternative to dishes is a 2D array of low-gain antenna elements. These arrays are though aesthetically attractive but suffer from other limitations such as feed losses [6]. A radial-line slot array antenna, on the other hand, is thin with a planar height profile and do not suffer from feed losses similar to the arrays [7]–[11].

A single-layered RLSA comprises a radial waveguide that is formed between two metal plates. The top plate has an array of radiating slots, while the bottom plate is solid and acts as the ground plane of the antenna. The waveguide is typically filled with dielectrics or other slow-wave structure so that the guided wavelength inside the waveguide is smaller than the free-space wavelength. Therefore, most of RLSAs are realized by printing radiating slots on commercial dielectric laminates. In a large aperture RLSA, the cost of the dielectric is substantial and thus makes this antenna technology relatively expensive for applications such as 5G backhaul network.

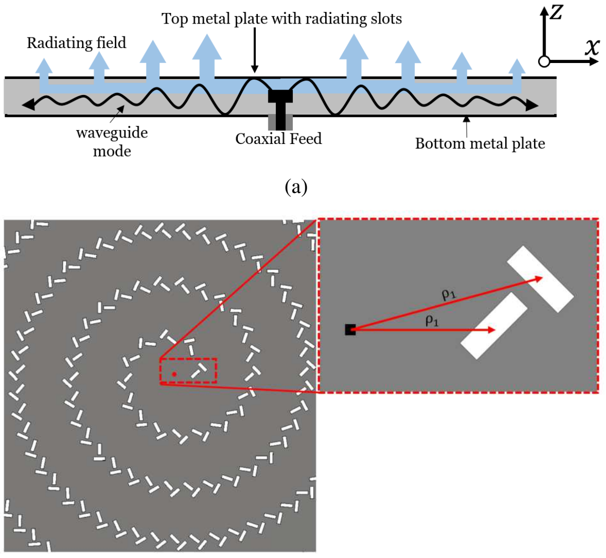
The paper investigates a low-cost CP RLSA antenna design for 5G backhaul network by completely removing the dielectric material from the radial waveguide. The design is inspired from a recently reported all-metal RLSA design [12]. However, instead of using about $0.95\lambda_0$ (where λ_0 is the free-space wavelength at operating frequency) spacing between slots rings used in [12], this paper uses the about λ_0 spacing between the rings of slots. The antenna can be designed with only two thin sheets of metal plates where radiating slots can be stamped in one of the plates through low-cost manufacturing processes. The antenna does not suffer from a major grating or side lobes and has a narrow broadside beam. The peak gain and aperture efficiency of the antenna can be improved further by optimizing slots sizes on the top radiating plate. The paper is organized such that first, a brief description of RLSAs is given in Section II. The design example is discussed in Section III. Results predicted through numerical simulations are included in Section IV and the paper is concluded at the end.

II. CONFIGURATION OF RADIAL-LINE SLOT ARRAY ANTENNAS

RLSAs are planar and thin high-gain antennas suitable for point-to-point communication links. These antennas can be designed for both linear and circularly polarized applications. The theory of RLSAs is thoroughly covered in the literature [12]–[19] and is not detailed here for brevity. However, salient features of the class of RLSA used for the proposed design are summarized.

A classical single-layered RLSA comprises a radial waveguide, which is fed at the center with a coaxial probe, as pictorially depicted in Fig. 1. The waveguide is formed between two metal plates. The top metal has all the radiating slots and the bottom plate is solid and acts as a ground plane. The probe excites the outward travelling radial TEM waveguide mode at the center of the waveguide. The energy from the travelling wave inside the waveguide is coupled into the free space through radiating slots in the top plate.

The orientation of slots controls the polarization of the antenna and the radial distance from the center of aperture change the excitation phase of the radiated field. In broadside radiating CP RLSAs, the slots are arranged in a spiral pattern, as shown in Fig. 1. The fundamental element is a pair of two slots, as shown



(a)

(b)

Fig. 1. (a) A pictorial depiction of the RLSA cross-section. The radially outward travelling TEM waveguide are radiated through slots in the top metal plate. (b) Arrangement of radiating slots on an aperture of hypothetical CP RLSA.

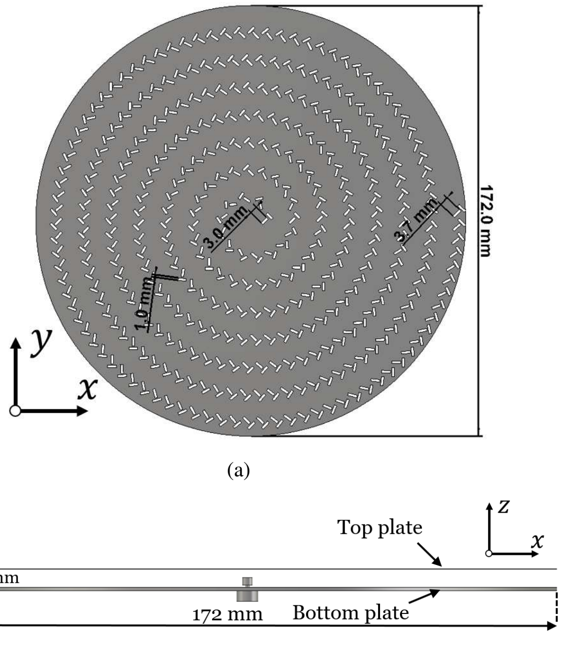
in the figure inset, which is analogous to a CP antenna. The difference in the radial distances of the two slots in the pair is set to the quarter of the guided wavelength ($\rho_2 - \rho_1 = \lambda_g/4$) to have an excitation phase difference of 90^o. The slots are arranged such that they are orthogonal to each other and thus radiate two orthogonal field components. The slots width is kept constant and the length is varied as a function of radial distance:

$$l = \delta + (\rho \times \alpha) \tag{1}$$

where $\rho \times \alpha$ is the coupling factor, which is adjusted by the coefficient α.

III. DESIGN EXAMPLE

A dielectric-less CP RLSA antenna was designed and reported in this paper. The antenna was designed at the center operating frequency of 27 GHz. The top metal plate was a 0.035 um thin sheet of metal, while the bottom plate was a 1 mm thick metal plate that provides mechanical stability to the structure. The antenna has a circular aperture with a maximum diameter of 172 mm or $15.5\lambda_0$, where λ_0 is the free-space wavelength at the operating frequency. The radiating slots were arranged in seven rings of a spiral as shown in Fig. 2. The width of the slots was fixed to 1 mm throughout the aperture, while the length was varied using (1). The value of α and δ are set to 0.008 and 5.5, respectively. The center of the first slot is at a radial distance of about 5.5 mm and thus have a slot length of 3 mm. The length of the slots close to the edges is around 3.7 mm. The spacing between two slot pairs in the radial direction was set to 11 mm (or $0.99\lambda_0$), whereas the spacing between two slot pairs in the spiral direction was set to 5.5 mm.



(a)

(b)

Fig. 2. Model of the RLSA used for full-wave simulations. (a) Top view with layout of radiating slots and (b) Side view.

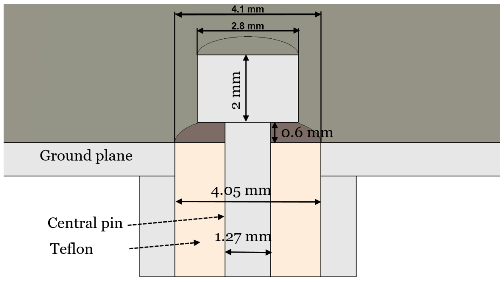
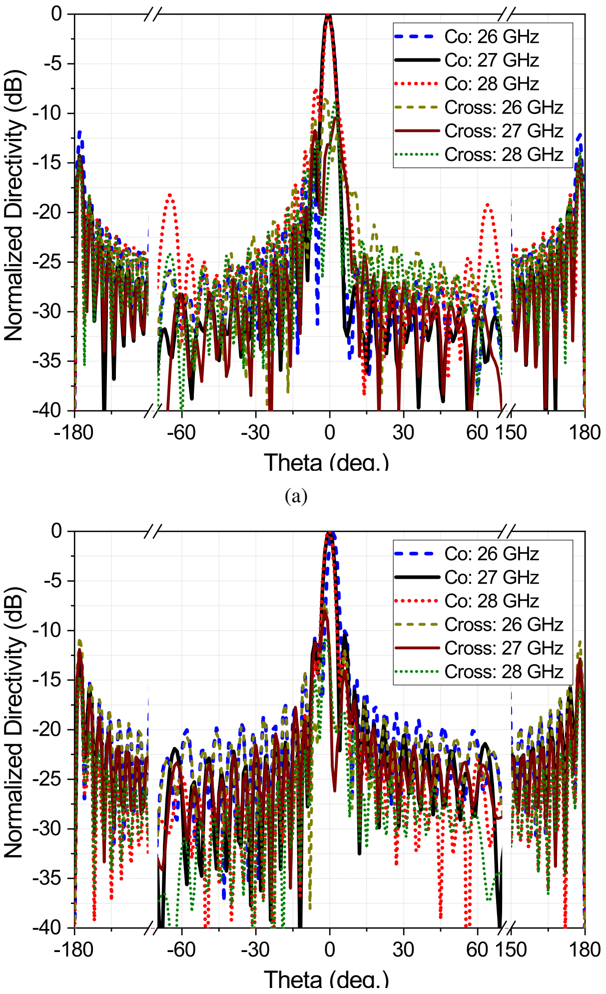


Fig. 3. An enlarged cross-section with key dimensions of the feeding probe modelled for the RLSA.

The slot layout, generated through a custom-built macro, is shown in Fig. 2. The feeding probe was made from an SMA connector that has an extended frequency range of around 27 GHz. In prototyping, SMA 2.9(K) or Rosenberger RPC-2.92 can be used to improve the efficiency of the system [20], [21]. A disk head was created on top of the connector to improve the impedance matching. An enlarged cross-section of the feeding probe with key dimensions is shown in Fig. 3. The bottom of the probe is a standard connector that has a conductive pin at the center and a Teflon ring around the pin. The ring of Teflon isolates the center pin from the ground plane. The central pin protrudes into the radial waveguide and the disk head is attached on top of the pin. The disk head was a circular disk of diameter 2.8 mm that has a height of 2 mm.

IV. PREDICTED RESULTS

The RLSA was simulated with a Transient solver in CST Microwave Studio in a frequency band between 26 GHz and



(a)

(b)

Fig. 4. Pattern cuts taken at azimuth angles (a) $\phi = 0^o$ and (b) $\phi = 90^o$ taken at three frequencies in the operating band.

28 GHz. The antenna has a peak gain of 21.5 dBic at 28 GHz. The normalized far-field directivity pattern cuts of the right-hand circularly polarized (RHCP) field components taken at azimuth angle $\phi = 0^o$ and $\phi = 90^o$ are plotted in Fig. 4. The antenna has a narrow directed beam with a 3dB beamwidth of less than 4^o within the operating frequency band. There are no major side lobes and even the grating lobes around 90^o elevation angles are 20 dB less than the beam peak. The antenna also has a reasonable cross polar rejection with cross-polar component at least 10 dB less than the co-polar component in the main beam direction. The cross-polar discrimination can be increased further through improved design as demonstrated in [12]. The front-to-back gain ratio of the co-polar component is low at 26 GHz, which is mainly due to the residual power that is radiated and leaks from the edges of the radial waveguide. This problem of residual power exists only in small-to-medium aperture RLSAs and is not significant when the aperture of RLSAs is increased for high-gain (gain>30 dB) applications. To improve the front-to-back gain ratio in low-to-medium gain antennas, either slots' sizes can be increased close to the maximum permitted value that increase the radiated power and hence reduce the residual power, or a ring of RF absorbers can be used to absorb leftover leaving the edges of the RLSA waveguide.

The overall maximum height of the antenna, excluding the SMA connector protruding out of the ground plane, is 6 mm. The aperture efficiency and gain of the antenna can be improved through optimal slots size and spacing. The manufacturing cost of the antenna is extremely low because apart from the feeding connector, no other commercial part or component is used in the antenna design. The slot pattern in our previous prototypes [12] was created through laser cutting. The pattern can be created through metal stamping for large scale manufacturing, which is an extremely low-cost and mature manufacturing process already being used in the industry. The thin and flat profile of the antenna makes it suitable to be deployed in ultradense 5G cells in urban areas by concealing it in the building façade. The weight of the antenna is extremely low and can be reduced further using lighter and thinner metal sheets.

V. CONCLUSION

A low-cost high-gain radial-line slot array antenna (RLSA) can be designed without dielectrics in the RLSA TEM waveguide. The antenna can substantially reduce the fabrication cost and suitable for 5G backhaul network to provide a point-to-point communication link. The total height of the antenna is less than 1 cm and, more importantly, has a planar height profile. The flat panel can be integrated into existing infrastructure. There are no major grating lobes in the visible region between elevation angles $\pm 90^o$. The antenna beam is directed narrow and has a 3dB beamwidth less than 4^o.

REFERENCES

[1] K. Al-Amoodi, M. M. Honari, R. Mirzavand, J. Melzer, D. G. Elliott, and P. Mousavi, "Circularly-polarised end-fire antenna and arrays for 5g millimetre-wave beam-steering systems," *IET Microwaves, Antennas Propagation*, vol. 14, no. 9, pp. 980–987, 2020.

[2] R. K. Saha, "Licensed countrywide full-spectrum allocation: A new paradigm for millimeter-wave mobile systems in 5g/6g era," *IEEE Access*, vol. 8, pp. 166612–166629, 2020.

[3] P. Ramanujam, C. Arumugam, R. Venkatesan, and M. Ponnusamy, "Design of compact patch antenna with enhanced gain and bandwidth for 5g mm-wave applications," *IET Microwaves, Antennas Propagation*, vol. 14, no. 12, pp. 1455–1461, 2020.

[4] Olli Kursu, Marko Leinonen, Giuseppe Destino, Nuutti Tervo, Marko Sonkki, Timo Rahkonen, Aarno Pärssinen, Saila Tammelin, Marko Pettissalo, and Aki Korvala, "Design and measurement of a 5g mmw mobile backhaul transceiver at 28 ghz," *EURASIP Journal on Wireless Communications and Networking*, vol. 2018, 12 2018.

[5] A. Harmouch, K. Mawass, F. Shakra, and C. El Mouccary, "Enhancement of directional characteristics of circularly polarized dish parabolic antennas using metallic scatters," in *The 2nd Middle East Conference on Antennas and Propagation*, 2012, pp. 1–5.

[6] Aqeel Naqvi and Sungjoon Lim, "Review of recent phased arrays for millimeter-wave wireless communication," *Sensors*, vol. 18, pp. 3194, 09 2018.

[7] K. Kelly and F. Goebels, "Annular slot monopulse antenna arrays," *IEEE Transactions on Antennas and Propagation*, vol. 12, no. 4, pp. 391–403, Jul 1964.

[8] M. Ando, K. Sakurai, N. Goto, K. Arimura, and Y. Ito, "A radial line slot antenna for 12 GHz satellite TV reception," *IEEE Transactions on Antennas and Propagation*, vol. 33, no. 12, pp. 1347–1353, Dec 1985.

[9] M. Ando, K. Sakurai, and N. Goto, "Characteristics of a radial line slot antenna for 12 GHz band satellite TV reception," *IEEE Transactions on Antennas and Propagation*, vol. 34, no. 10, pp. 1269–1272, Oct 1986.

[10] M. Takahashi, J. I. Takada, M. Ando, and N. Goto, "A slot design for uniform aperture field distribution in single-layered radial line slot antennas," *IEEE Transactions on Antennas and Propagation*, vol. 39, no. 7, pp. 954–959, Jul 1991.

[11] N. Y. Koli, M. U. Afzal, K. P. Esselle, and M. Z. Islam, "Investigation on aperture field distribution of circularly polarised radial line slot array antennas," in *2018 IEEE Asia-Pacific Conference on Antennas and Propagation (APCAP)*, Aug 2018, pp. 462–463.

[12] M. N. Y. Koli, M. U. Afzal, K. P. Esselle, and R. M. Hashmi, "An all-metal high-gain radial-line slot-array antenna for low-cost satellite communication systems," *IEEE Access*, vol. 8, pp. 139422–139432, 2020.

[13] M. E. Bialkowski, "Analysis of a coaxial-to-waveguide adaptor including a descended probe and a tuning post," *IEEE Transactions on Microwave Theory and Techniques*, vol. 43, no. 2, pp. 344–349, Feb 1995.

[14] M. Takahashi, M. Ando, N. Goto, Y. Numano, M. Suzuki, Y. Okazaki, and T. Yoshimoto, "Dual circularly polarized radial line slot antennas," *IEEE Transactions on Antennas and Propagation*, vol. 43, no. 8, pp. 874–876, Aug 1995.

[15] M. Ando, "New DBS receiver antennas," in *1993 23rd European Microwave Conference*, Sept 1993, pp. 84–92.

[16] J. Takada, M. Ando, and N. Goto, "A reflection cancelling slot set in a linearly polarized radial line slot antenna," *IEEE Transactions on Antennas and Propagation*, vol. 40, no. 4, pp. 433–438, Apr 1992.

[17] P. W. Davis and M. E. Bialkowski, "Linearly polarized radial-line slot-array antennas with improved return-loss performance," *IEEE Antennas and Propagation Magazine*, vol. 41, no. 1, pp. 52–61, Feb 1999.

[18] P. W. Davis and M. E. Bialkowski, "Experimental investigations into a linearly polarized radial slot antenna for DBS TV in Australia," *IEEE Transactions on Antennas and Propagation*, vol. 45, no. 7, pp. 1123–1129, Jul 1997.

[19] M. E. Bialkowski and P. W. Davis, "Analysis of a circular patch antenna radiating in a parallel-plate radial guide," *IEEE Transactions on Antennas and Propagation*, vol. 50, no. 2, pp. 180–187, Feb 2002.

[20] Rosenberger, "Rpc-2.92," https://www.rosenberger.com/product/rpc-292/.

[21] Radiall, "Sma / sma-com / sma 2.9 series," https://www.mouser.com/datasheet/2/516/SMA_SMA29%20D1C004XEe-587915.pdf.