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Design of mmWave Multi-sector array Using Bowtie Antenna Elements for 5G Mobile Base Stations

***Abstract**. This paper proposes a compact multi-sector array structure based on bowtie antenna elements. The designed array consists of three (1×8) linear arrays to cover 360°. The array is designed to operate at 28 GHz on an RT/Duroid 5880 substrate to meet the high-frequency specifications with a thickness of 1.575 mm and a dielectric constant of 2.2, while the dissipation factor is (0.0009). Each array sector has a dimension of 30.17 mm as width and 6.4 mm as length. A beam steering performance is proved with the capability of switchable beams to offer directional/omnidirectional choices. Simulations results showed that the proposed array exhibits excellent reflection coefficient characteristics along with a high gain of up to 13.5 dBi and high radiation efficiency. Two configurations of array sectors are presented to introduce a flexible control of the array beams.*

Streszczenie.** W artykule zaproponowano kompaktową, wielosektorową strukturę macierzy opartą na elementach antenowych typu bowtie. Zaprojektowana macierz składa się z trzech (1×8) liniowych szyków pokrywających 360o. Macierz jest zaprojektowana do pracy z częstotliwością 28 GHz na podłożu RT/Duroid 5880 w celu spełnienia specyfikacji wysokiej częstotliwości przy grubości 1,575 mm i stałej dielektrycznej 2,2 przy współczynniku rozproszenia (0,0009). Każdy sektor tablicy ma wymiar 30,17 mm szerokości i 6,4 mm długości. Skuteczność sterowania wiązką została udowodniona dzięki możliwości przełączania wiązek w celu oferowania wyborów kierunkowych/wszechkierunkowych. Wyniki symulacji wykazały, że proponowana matryca wykazuje doskonałe właściwości współczynnika odbicia wraz z wysokim wzmocnieniem do 13,5 dBi i wysoką wydajnością promieniowania. Przedstawiono dwie konfiguracje sektorów matrycy w celu wprowadzenia elastycznego sterowania wiązkami matrycy.* (Projektowanie wielosektorowej macierzy mmWave z wykorzystaniem elementów anteny Bowtie dla mobilnych stacji bazowych 5G***)

Keywords: 5G, Bowtie Antenna, Multi-sector Antennas, mmWave, Mobile Base Stations.
Słowa kluczowe:. Aantena 5G, antena multisektorowa, mmWave

Introduction

Recent years have been investing significant research efforts to develop the fifth-generation (5G) communication system by improving the channel capacity and achieving shorter latency and higher data rates. This development was motivated by the ever-growing traffic in mobile communication and to meet the current requirements imposed by modern wireless communication systems. The aim is to achieve a data rate up to 5-50 Gbps to expand the channel bandwidth and support device-to-device communication as well as to reduce the power consumption significantly (thousands of times) [1]. To this end, the antenna techniques used in previous generations will not be able to fully cope with the new technology and antenna arrays have been employed in the 5G systems. Several frequency bands have been proposed for 5G. The 28 GHz frequency is among them with a bandwidth that could reach 1 GHz. Antenna arrays are not a new technology and have been utilized in radar many years ago, however, designing arrays for mobile communication still needs a lot to be developed and adapted [2].

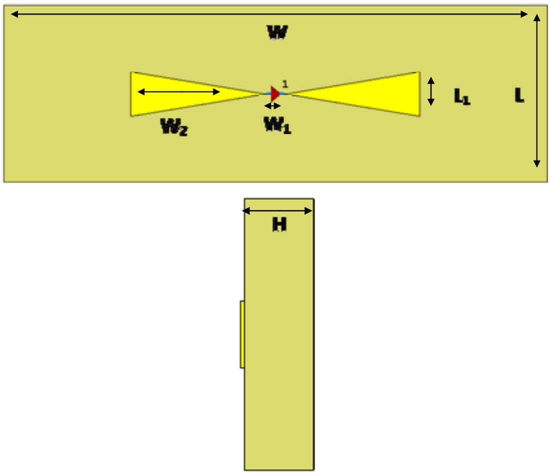
Adopting antenna arrays for 5G mobile networks have been extensively explored recently by utilizing various antenna structures operating at different frequency bands. For example, at the sub-6 GHz band, dipoles [3], ultrawide band antennas (UWB) [4-7] and crossed-bowties [8][9] are widely used at this frequency band by exploiting the wideband properties offered by these structures. Furthermore, additional techniques were previously employed to improve the antenna performance, such as metasurfaces [10], electromagnetic band gap (EBG) metamaterial [11], frequency selective surfaces (FSSs) [12] [13] [14], and forming a multi-sector antenna array [15]. However, at this relatively low frequency, the achieved bandwidth doesn't fulfil the rapid development of modern wireless systems. Thus, a need for higher frequency techniques has urgently emerged.

After the recent announcement of the Federal Communication Committee (FCC) to license three millimeter-wave (mmWave) bands for the 5G mobile networks [23], many antenna array designs have been proposed operating at different frequencies within this band such as 22 GHz [16], 26 GHz [17], 28 GHz [18-22], 37-40 GHz [8] and 60 GHz [23]. Additionally, some works have proposed dual-band structures to cover both the 28 GHz and 38 GHz frequency bands [24, 25]. It is expected that the 5G communication systems operating at mmWave frequencies will offer a 1Gbps data rate anywhere for high mobility devices and pedestrians. However, two important obstacles still need to be addressed: the sufficient coverage area and the flexible mobility even with non-line of sight (NLOS) environments [1].

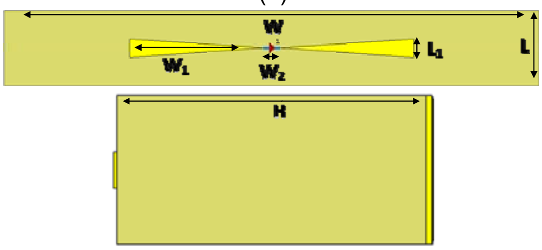
In this work, a mmWave multi-sector Bowtie-based antenna array has been designed operating at 28 GHz. Phased arrays play an important role in realizing point-to-point communication between the device and the base station. This can be achieved by paying attention to the critical factors affecting the array performance, such as adjusting the distance between the antenna elements, which directly influence the scanning properties [26] [27]. Antenna arrays are critical to enable high gain performance and overcome the shortcomings of employing a single directive antenna at the mmWave frequency band [28]. Multi-sector arrays are in high demand for 5G as they help provide high throughput and reduced latency by reducing the signal interference plus noise ratio (SINR) [21]. In addition, they demonstrate wide scanning angles besides the gain stability and the low level of side lobes.

Single Element Bowtie Antenna

Bow-tie antennas have proven excellent performance in many wireless communication applications due to their wide bandwidth and impedance matching possibilities. Thus, it has been chosen in this work with few modifications to improve the radiation properties. Firstly, a traditional bow-tie dipole antenna is designed and simulated. RT/Duroid 5880 substrate has been used to meet the high-frequency specifications. The substrate Thickness is chosen for the standard case is (0.508 mm) and the dielectric constant is 2.2, while the dissipation factor is (0.0009). The conventional bowtie dipole antenna has a radiation pattern with a large back lobe that affects the antenna performance in these types of applications. This issue needs to be addressed without affecting other antenna characteristics such as gain, bandwidth, and impedance matching. To this end, a modified Bowtie antenna has been proposed by backing the substrate with a full background and increasing the substrate height. Fig.1 shows the traditional and the modified bowtie antenna structures, whereas Table 1 summarizes the structure dimensions. By adopting the modified Bowtie structure, the reflection coefficient (S11) of the proposed antenna has been improved from (-22.4 dB) to (-32.65 dB) as shown in Fig.2.



(a)



(b)

Fig. 1. Bowtie dipole antenna: (a) traditional bowtie and (b) proposed Bowtie

Table 1. Structural dimensions for both Bowtie antennas

Antenna dimensions in (mm)	W	W1	W2	L	L1	H
Traditional bowtie	6.1	0.2	1.53	2	0.5	0.508
Modified bowtie	6.4	0.2	1.6	0.9	0.2	1.575

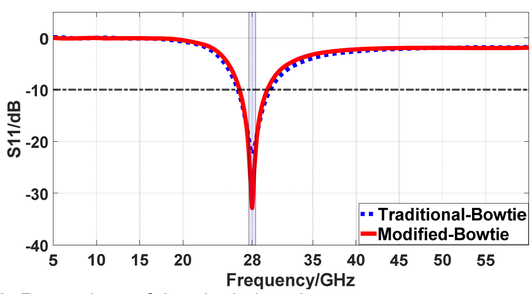


Fig.2: Return loss of the single bowtie antenna.

For the proposed modified Bowtie antenna, the main beam is in the direction perpendicular to the antenna surface. The antenna gain has been enhanced from (2.18) to (4.9) dB. Also, the front-to-back ratio has been improved from (0.08) to (4.45) at 28 GHz. Fig.3 compares the radiation pattern for both antennas, whereas Fig.4 illustrates the gain and efficiency of the proposed modified Bowtie antenna.

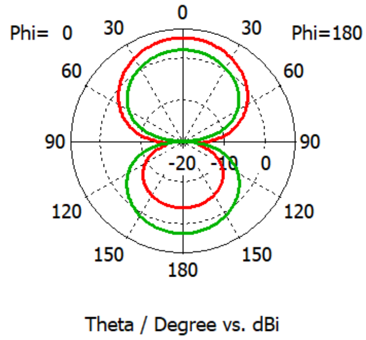


Fig.3. The radiation pattern of the traditional (green) and modified (red) Bowtie antennas

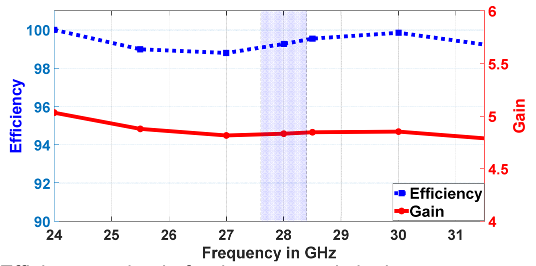


Fig.4. Efficiency and gain for the proposed single antenna

It is clearly seen from Fig.4 that the proposed modified Bowtie antenna exhibits high radiation efficiency and an acceptable gain that reaches around 5 dBi within the selected mmWave frequency band. These promising characteristics make this structure a good candidate for designing a multi-sector antenna array for 5G base stations.

Optimization Procedure For The Proposed Modified-Bowtie

For the modified Bowtie antenna, increasing the substrate thickness and adding background on the other side will definitely change the antenna characteristics. Thus, few geometrical optimizations are needed to improve the impedance matching at 28 GHz and enhance the antenna efficiency and gain. To this end, the Bowtie width and length have been altered and the reflection coefficient (S11) is recorded to observe their impact on the antenna performance. Figs. 5 and 6 show the effect of changing the width (W2) and length (L1) on the reflection coefficient for the proposed Bowtie antenna.

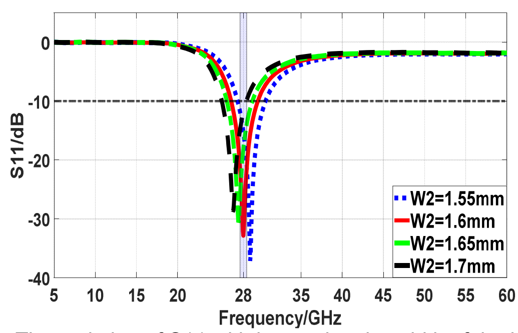


Fig. 5. The variation of S11 with increasing the width of the bowtie

A closer look at Fig.5 reveals that the resonant frequency decreases with increasing the bowtie width (W2) and the optimum value to achieve a 28 GHz operating frequency is 1.6 mm. In contrast, Fig.6 clearly shows that the bowtie length (L1) has a similar impact on the antenna performance where varying L1 from 0.01 mm to 0.3 mm has reduced the resonant frequency 31 GHz to around 26 GHz. The optimum value for achieving a 28 GHz resonant frequency is 0.2 mm. These structural dimensions will be adopted throughout the rest of the paper.

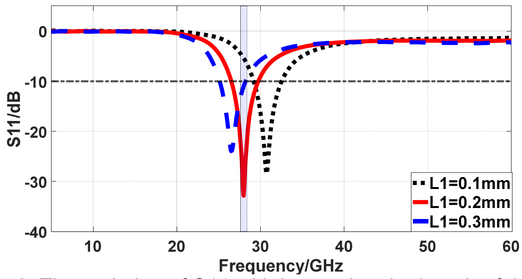


Fig. 6: The variation of S11 with increasing the length of the bowtie

Bowtie-Based Linear Array

A 1×8 linear array based on the proposed Bowtie antenna is constructed and simulated. The spacing between two adjacent elements has been chosen to be (λ/2 =3.61 mm), which is the optimal spacing that gives the ideal performance of the antenna array and improves the controlling of the beam steering capabilities. Fig.7 shows the array structure, the array width = 30.17 mm, length = 6.4 mm and height = 1.575 mm. The 3D radiation pattern of the proposed antenna array is illustrated in Fig.8, whereas Fig.9 shows the simulated gain and efficiency.

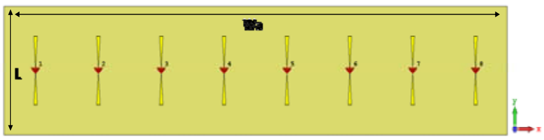


Fig. 7. The constructed 1×8 linear array based on the proposed bowtie antenna

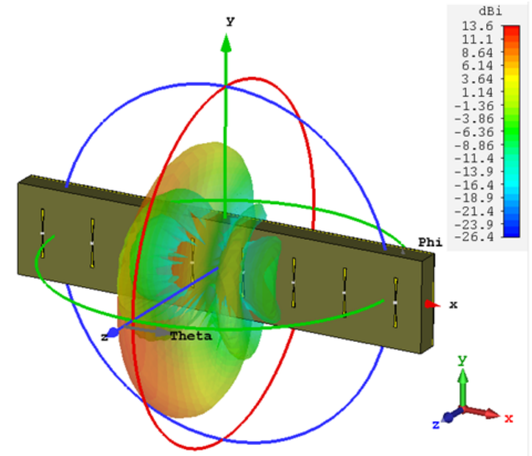


Fig. 8. 3D radiation pattern of the proposed antenna array

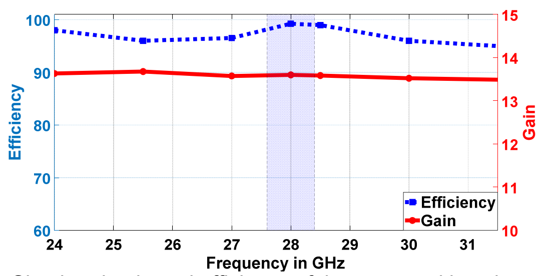


Fig. 9. Simulated gain and efficiency of the proposed bowtie array

As seen in Fig. 8, the antenna array has a main beam that is wide and perpendicular to the array axis with an acceptable level of back and side lobes. These characteristics make this array a preferable choice for 5G base stations at mmWave frequencies. It can also be seen from Fig. 9 that the proposed Bowtie antenna array exhibits an excellent radiation efficiency that reaches more than 95 % over a wide range of mmWave frequencies with peak efficiency at 28 GHz. On the other hand, it is noticed that the array shows a stable gain over the selected range of frequencies with a peak achieved gain is 13.5 dB.

The beam steering capabilities of the designed bowtie array have been tested and three angles (±15o, ±30o, and ±45o) were chosen to this end. The beam steering has been performed by determining the relative phased weight of each element in the array as given by Eq. 1.

$$\varphi = \frac{2\pi d}{\lambda} \sin \theta \quad (1)$$

where d is the space between two adjacent elements, λ is the relative wavelength and θ is the desired steering angle.

Figs. 10 and 11 demonstrate the beam steering flexibility of the designed array in 2D and 3D forms, respectively.

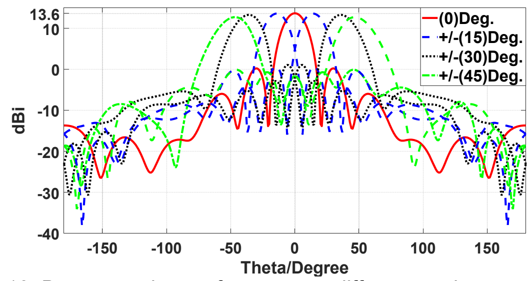


Fig. 10. Beam steering performance at different angles

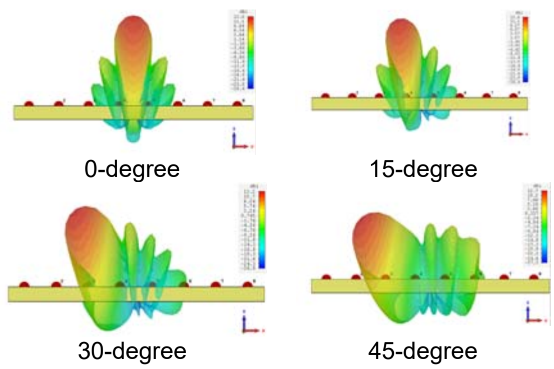


Fig. 11. 3D beam steering performance at different angles

From both figures, it is clearly shown that the proposed bowtie array has perfect directing and beam steering capabilities with keeping the back and side lobes at their minimum levels. Indeed, the antenna maintains its gain for different steering cases around (13 dBi).

Multi-Sector Bowtie Antenna Array

The previous simulation results of the Bowtie single element and linear bowtie array are promising and motivating to form a multi-sector antenna array. The proved radiation pattern and the beam steering tested ability is a very important point to validate the aim of this work and move a step forward to implement a 3-sector antenna array as shown in Fig.12. The proposed 3-sector antenna array is designed to a full 360o coverage area around the array as illustrated in Fig.12. Each sector of the proposed array is designed to cover 120o with keeping a high gain that is no less than 13 dBi at the three minims caused by the radiation pattern overlapping of the three sectors as illustrated in Figs. 13 and 14.

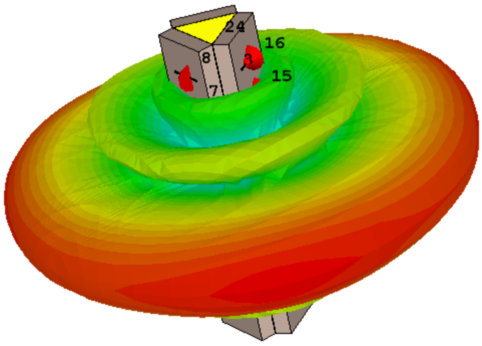


Fig. 12. The 3D radiation pattern of the 3-sector proposed bowtie array

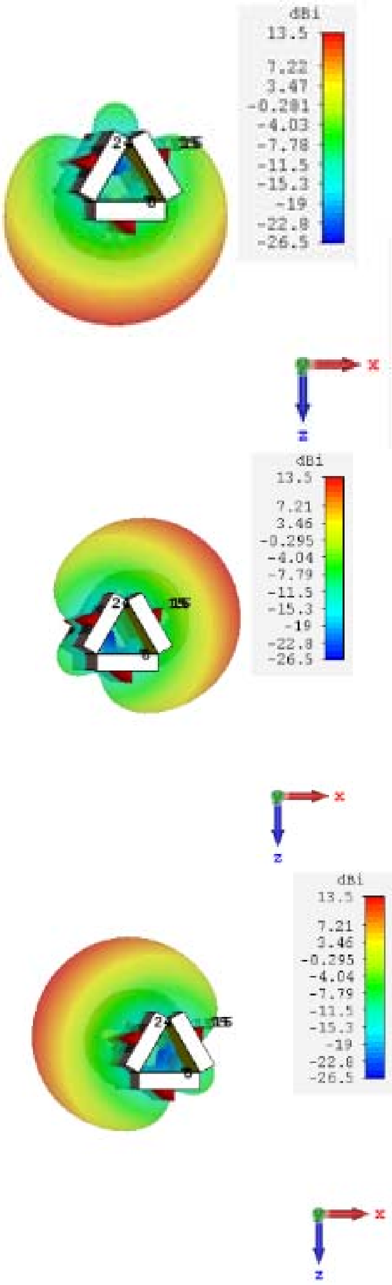


Fig. 13. 3D radiation pattern of each sector in the proposed bowtie array

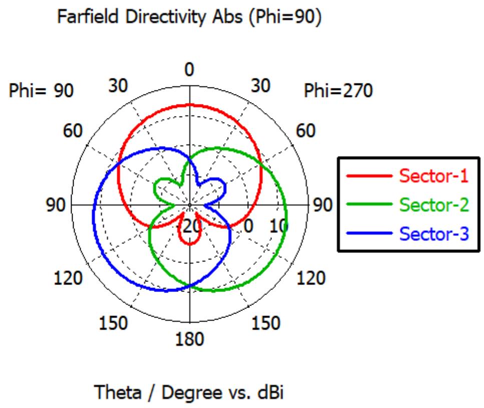


Fig. 14. The coverage area of the three sectors showing the intersection points

Another configuration of the array sectors is also proposed with the horizontal arrangement (shown in Fig.15) to provide vertical beam steering ability as shown in Fig.16.

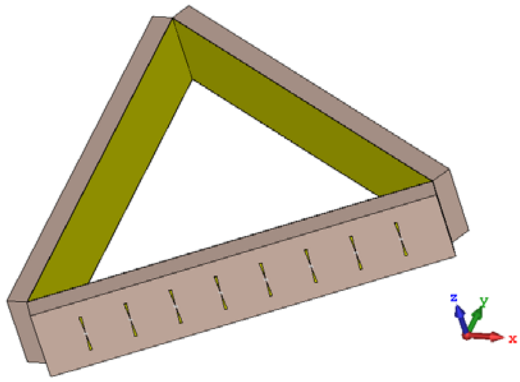
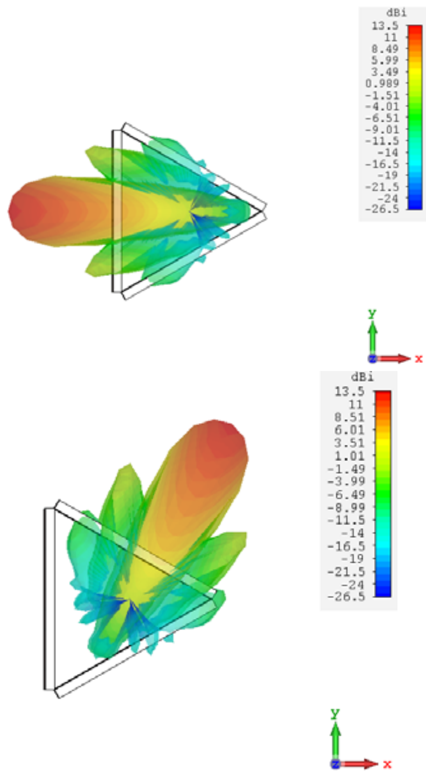


Fig. 15. The horizontal configuration of the array sectors



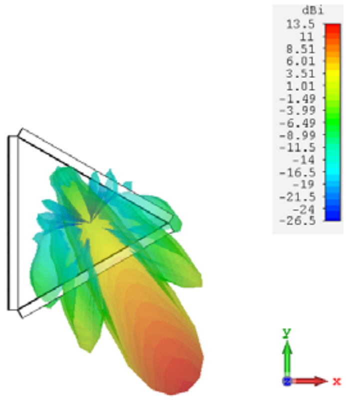


Fig. 16. The 3D radiation pattern of each sector in the horizontal sectors of the bowtie array

The S-parameters of the designed array are shown in Fig. 17. It can be clearly seen that the array exhibits excellent impedance matching characteristics at the frequency of resonance with acceptable isolation between array elements. In addition, Fig. 18 illustrates how the designed array exhibits a stable performance in terms of beam tilting against changing the frequency over the operation bandwidth.

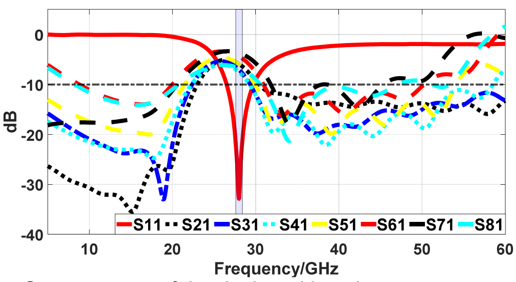


Fig. 17. S-parameters of the designed bowtie antenna array

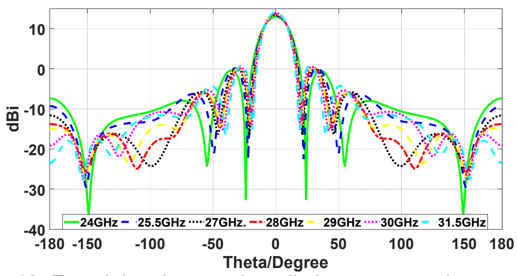


Fig. 18. Examining the array's radiation pattern aginst varying the frequency within the operation bandwidth

Conclusion

In this paper, a new compact size 3-sector phased array is proposed based on dipole bowtie antennas for mmWave 5G base stations. The design contained three (1×8) linear arrays forming a multi-sector phased array. The array is designed to operate at 28 GHz and has a bandwidth of around 3GHz with a gain of 13.5 dBi and high radiation efficiency. The proposed array exhibited a good reflection coefficient while radiating the maximum power arriving at all elements. The array also showed a stable gain over the operating bandwidth with no beam tilting occurred due to the frequency variation. The simulation results have proven that the proposed array can provide a 360o coverage area with a minimum level of side lobes. In addition, a horizontal configuration is also proposed offering another degree of freedom to control the beam steering capability for the array. Finally, the proposed array has great potential in the field of future wireless communication systems.

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REFERENCES

[1] Roh, Wonil, Ji-Yun Seol, Jeongho Park, Byunghwan Lee, Jaekon Lee, Yungsoo Kim, Jaeweon Cho, Kyungwhoon Cheun, and Farshid Aryanfar. "Millimeter-wave beamforming as an enabling technology for 5G cellular communications: Theoretical feasibility and prototype results." IEEE communications magazine 52, no. 2 (2014): 106-113.
[2] Kamaruddin, R.A.A., Ibrahim, I.B.M., Al-Gburi, A.J.A., Zakaria, Z., Shairi, N.A., Rahman, T.A. and Purnamirza, T., "Return Loss Improvement of Radial Line Slot Array Antennas on Closed Ring Resonator Structure at 28 GHz," Przegląd Elektrotechniczny, vol. 1, no. 5, pp. 65–69, 2021.
[3] Peng, Mingming, and Anping Zhao. "High performance 5G millimeter-wave antenna array for 37–40 GHz mobile application." In 2018 International workshop on antenna technology (iWAT), pp. 1-4. IEEE, 2018.
[4] Al-Gburi, A.J.A., Ibrahim, I.M., Zakaria, Z., Zeain, M.Y., Alwareth, H., Ibrahim, A.M. and Keriee, H.H., "High Gain of UWB CPW-fed Mercedes-Shaped Printed Monopole Antennas for UWB Applications," Prz. Elektrotechniczny, no. 5, pp. 70–73, 2021.
[5] A. J. A. Al-gburi, I. Bin, M. Ibrahim, Z. Zakaria, N. Farzana, and B. Mohd, "Wideband Microstrip Patch Antenna for Sub 6 GHz and 5G Applications," Przegląd Elektrotechniczny, no. 11, pp. 26–29, 2021.
[6] A. J. A. Al-Gburi, I. M. Ibrahim, and Z. Zakaria, "An Ultra-Miniaturised MCPM Antenna for Ultra-Wideband Applications," J. Nano Electron. Phys., vol. 13, no. 5, pp. 05012-1-05012–4, 2021.
[7] A. J. A. Al-gburi, I. M. Ibrahim, and Z. Zakaria, "Gain Enhancement for Whole Ultra-Wideband Frequencies of a Microstrip Patch Antenna," J. Comput. Theor. Nanosci., vol. 17, pp. 1469–1473, 2020.
[8] Chen, Yikai, Jiacheng Zhao, and Shiwen Yang. "A novel stacked antenna configuration and its applications in dual-band shared-aperture base station antenna array designs." IEEE Transactions on Antennas and Propagation 67, no. 12 (2019): 7234-7241.
[9] Cui, YueHui, RongLin Li, and HuanZhan Fu. "A broadband dual-polarized planar antenna for 2G/3G/LTE base stations." IEEE transactions on antennas and propagation 62, no. 9 (2014): 4836-4840.
[10] Guo, Jiayin, Feng Liu, Luyu Zhao, Yingzeng Yin, Guan-Long Huang, and Yingsong Li. "Meta-surface antenna array decoupling designs for two linear polarized antennas coupled in H-plane and E-plane." IEEE Access 7 (2019): 100442-100452.
[11] A. J. A. Al-Gburi, I. Ibrahim, Z. Zakaria, and A. D. Khaleel, "Bandwidth and Gain Enhancement of Ultra-Wideband Monopole Antenna Using MEBG Structure," ARPN J. Eng. Appl. Sci., vol. 14, no. 10, pp. 3390–3393.
[12] A. J. A. Al-gburi, I. M. Ibrahim, K. S. Ahmad, Z. Zakaria, M. Y. Zeain, M. K. Abdulhameed, and T. Saeidi "A miniaturised UWB FSS with Stop-band Characteristics for EM Shielding Applications," Przegląd Elektrotechniczny, no. 8, pp. 142–145, 2021.
[13] A. J. A. Al-gburi et al., "High Gain of UWB Planar Antenna Utilising FSS Reflector for UWB Applications," Comput. Mater. Contin., vol. 70, no. 1, 2022.
[14] Zhu, Yufeng, Yikai Chen, and Shiwen Yang. "Integration of 5G rectangular MIMO antenna array and GSM antenna for dual-band base station applications." IEEE Access 8 (2020): 63175-63187.
[15] Al-Tarifi, Monjed A., Mohammad S. Sharawi, and Atif Shamim. "Massive MIMO antenna system for 5G base stations with directive ports and switched beamsteering capabilities." IET Microwaves, Antennas & Propagation 12, no. 10 (2018): 1709-1718.
[16] [8] N. Ojaroudiparchin, Ming Shen and G. F. Pedersen, "8×8 planar phased array antenna with high efficiency and insensitivity properties for 5G mobile base stations," 2016 10th

European Conference on Antennas and Propagation (EuCAP), 2016, pp. 1-5.
[17] Jia, Qinyin, Hongcheng Xu, M. F. Xiong, Binzhen Zhang, and Junping Duan. "Omnidirectional solid angle beam-switching flexible array antenna in millimeter wave for 5G micro base station applications." IEEE Access 7 (2019): 157027-157036.
[18] Yang, Qingling, Steven Gao, Qi Luo, Lehu Wen, Yong-Ling Ban, Xue-Xia Yang, Xiaofei Ren, and Jian Wu. "Cavity-backed slot-coupled patch antenna array with dual slant polarization for millimeter-wave base station applications." IEEE Transactions on Antennas and Propagation 69, no. 3 (2020): 1404-1413.
[19] Hong, Wonbin, Kwanghyun Baek, Yoon Geon Kim, Youngju Lee, and Byungchul Kim. "mmWave phased-array with hemispheric coverage for 5 th generation cellular handsets." In The 8th European Conference on Antennas and Propagation (EuCAP 2014), pp. 714-716. IEEE, 2014.
[20] Ishfaq, Muhammad Kamran, Tharek Abd Rahman, Yoshihide Yamada, and Kunio Sakakibara. "8× 8 Phased series fed patch antenna array at 28 GHz for 5G mobile base station antennas." In 2017 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC), pp. 160-162. IEEE, 2017.
[21] Rebato, Mattia, Michele Polese, and Michele Zorzi. "Multi-sector and multi-panel performance in 5g mmWave cellular networks." In 2018 IEEE Global Communications Conference (GLOBECOM), pp. 1-6. IEEE, 2018.
[22] Tariq, Salahuddin, Dimitris Psychoudakis, Oren Eliezer, and Farooq Khan. "A new approach to antenna beamforming for millimeter-wave fifth generation (5G) systems." In 2018 Texas Symposium on Wireless and Microwave Circuits and Systems (WMCS), pp. 1-5. IEEE, 2018.
[23] Parchin, N. Ojaroudi, H. Jahanbakhsh Basherlou, Y. Al-Yasir, A. M. Abdulkhaleq, R. A. Abd-Alhameed, and P. S. Excell. "60 GHz Multi-Sector Antenna Array with Switchable Radiation-Beams for Small Cell 5G Networks." International Journal of Information and Communication Engineering 14, no. 2 (2020): 50-54.
[24] Parchin, Naser Ojaroudi, Yasir Al-Yasir, Ahmed M. Abdulkhaleq, Issa Elfergani, Ashwain Rayit, James M. Noras, Jonathan Rodriguez, and Raed A. Abd-Alhameed. "Frequency reconfigurable antenna array for mm-Wave 5G mobile handsets." In International Conference on Broadband Communications, Networks and Systems, pp. 438-445. Springer, Cham, 2018.
[25] Parchin, Naser Ojaroudi, Ming Shen, and Gert Frelund Pedersen. "End-fire phased array 5G antenna design using leaf-shaped bow-tie elements for 28/38 GHz MIMO applications." In 2016 IEEE International Conference on Ubiquitous Wireless Broadband (ICUWB), pp. 1-4. IEEE, 2016.
[26] Younus, K. M. and K. H. Sayidmarie, “A tri-band frequency reconfigurable slot antenna for wireless applications,” ACES Journal Applied Computational Electromagnetics Society, Vol. 35, No. 2, 194–200, 2020.
[27] K. H. Sayidmarie and Karam Younus, K. M., "Analysis and Design of Two-Slot Antennas for Wireless Communication Applications," Progress In Electromagnetics Research C, Vol. 104, 115-128, 2020.
[28] Wu, Zehai, Biqun Wu, Zhenhua Su, and Xiuyin Zhang. "Development challenges for 5G base station antennas." In 2018 International Workshop on Antenna Technology (iWAT), pp. 1-3. IEEE, 2018