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Dual-Polarized mm-Wave Antenna Solution for Mobile Phone

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Abstract—This article describes a novel dual-polarized mm-wave antenna for mobile phone devices. The mm-wave antenna module consists of a 4-layer PCB, an extra metallic piece acting as a reflector, and four metallic pins. The four metallic pins are placed on the top layer of the PCB acting as an array of vertically polarized monopoles. On the bottom layer an array of horizontally polarized dipoles are fed using microstrip lines. The two middle layers act as ground. Simulations show very good performance in the 27 to 29.5 GHz range. In this frequency range, the horizontally and vertically polarized arrays provide better than -1.5 dB efficiency, and higher than 11.5 dBi realized gain. Also, the reflection coefficient is mostly below -10 dB in the 27 to 29.5 GHz range for each individual antenna element. Beam-steering is possible up to $\pm 35^\circ$ for both polarizations with a scan loss below 3 dB.

Index Terms—antennas, antenna arrays, 5G, mm-wave frequencies, monopoles, dipoles, reflector.

I. INTRODUCTION

An exponentially increasing amount of devices are connected to each other and to the cloud, creating a need for the advancement of communication networks. It is due to this need, that the 5th generation of mobile communication networks (5G) is being developed. In order to achieve higher data rates and improved capacity, higher frequencies (6–80 GHz), and larger frequency bands are being explored [1], [2]. In particular, the mm-wave band 24.25–29.5 GHz is seen attractive as most of the countries have allocated a sub-band in this range for 5G [3]. In this paper, we demonstrate antenna solutions for the upper part of the whole range.

The use of higher frequencies brings a new set of interesting challenges to mobile phone antenna designers. First of all, mobile phones are very packed structures where the available volume for antennas is scarce. Therefore, new mm-wave antennas should utilize the volume inside the phone efficiently and they should not degrade the performance of currently existing sub-6 GHz antennas. At mm-wave frequencies, the capture area of an isotropic antenna is very small and therefore directive antennas are needed. As mobile devices can be in any orientation with respect to the access point or base station during normal use, dual-polarized operation and beam-steering capabilities are required in order to provide sufficient link reliability. Most of the millimeter-wave antennas support radiation towards the broadside direction of the mobile device [4]–[6]. On the other hand, providing dual-polarized radiation towards the edge of the phone is very demanding since the thickness of PCBs is small compared to the wavelength. This

Fig. 1. Section of the phone model that is used for the mm-wave antenna simulations.

is why most of the current end-fire designs provide only single-polarized operation [7]–[10].

In this paper, we present a simple yet efficient way of designing an end-fire mm-wave module which does not short circuit the metal frame where current sub-6 GHz antennas are implemented. The energy is directed outside of the mobile device through a plastic filled window in the metal frame.

II. PHONE MODEL AND MM-WAVE ANTENNA

A. Phone model

As important as the mm-wave antenna, is the model used for the terminal device. In this design, a relatively realistic phone model is used, since it will directly impact the achievable performance. As shown in Fig. 1, only the front section of the phone is used for simulations, since the rest of the phone has very little effect on the mm-wave performance. Currently used sub-6 GHz antennas are generally implemented in the metal frame of the phone [11], [12]. The clearance between the ground plane and the frame affects directly the achievable performance of both sub-6 and mm-wave antennas. The clearance in this model is set to 2 mm, which is in good agreement with the state of the art designs [13]. In order to radiate towards the end-fire direction, a window or opening must be carved in the metal frame. For robustness and aesthetic reasons this window must be filled with dielectric, and its height is limited. For the 7.5 mm high frame the maximum window height is 5.5 mm, leaving at least 1 mm of metal at each side. Fig. 2 presents the mobile phone model and window dimensions used in this design.

TABLE I
MAIN DIELECTRIC PROPERTIES

Material	Description	ϵ_r	$\tan \delta$
Preperm PPE400	Plastic used to fill the window in the metal frame	4	0.0024
Preperm L700HF	Top and bottom glass covers	7.0	0.005
Megtron7	PCB substrate	3.34	0.003

B. Mm-wave antenna

The mm-wave antenna consists of a 4-layer PCB, circular pins acting as monopoles, and a reflector. Fig. 3 shows the PCB layout. The dielectric used in the PCB is Megtron7, which presents very desirable characteristics at mm-wave frequencies ($\epsilon_r = 3.34$ $\tan\delta = 0.003$) [14]. Implemented on the top layer are the feedlines and the circular pads for the placement of the monopoles. On the bottom layer of the PCB there are microstrip lines which feed broadband, bow-tie shaped dipoles, see Fig. 4. Table 1 shows all the materials used in this design and its main characteristics. Fig. 5 shows the top and bottom views of the simulation model.

1) *Horizontal array*: The horizontally-polarized (H-Pol.) antennas are implemented using classic bow-tie dipoles. Planar dipoles are easy to manufacture. Moreover, dipoles are balanced not requiring a ground plane which could potentially capacitively load or short circuit the sub-6 GHz antennas implemented in the metal frame. However, most of the RF measurement devices are designed to be used with unbalanced structures such as microstrip lines. Therefore, a balanced to unbalanced transition is included providing a 180° phase shift between the arms of the dipole, see Fig. 6 [15]. In this case, no additional reflector is needed, since, the ground plane located on the upper layer serves as such similarly to a Yagi-Uda reflector, see Fig. 3. A transversal cut of the E-field distribution when all the elements are fed simultaneously can be seen in Fig. 7

2) *Vertical array*: The vertically-polarized (V-Pol.) antennas are fed using microstrip lines. These microstrip lines end in a circular pad whose diameter is 0.5 mm. Vertically oriented pins (diameter=0.3 mm) acting as monopoles are placed on top of the pads. In order to modify the otherwise omnidirectional radiation pattern of the monopoles, and to isolate the antennas from the rest of the phone, a reflector is added. The reflector is made from aluminum and it can be precisely screwed into the right position on top of the PCB. Moreover, the reflector presents openings in order to avoid shorting the microstrip lines. Ground plane modifications have been used extensively in order to increase and modify the characteristics of transmission lines and antennas such as monopoles or patch antennas in the past [16]–[19]. In order to increase the operational bandwidth of the monopole the ground plane is modified. As Fig. 3 shows, a small section of the ground plane underneath the monopole is removed, reducing the capacitance and increasing the impedance bandwidth. The current distribution for a single monopole and ground plane can be seen in Fig. 8. Fig. 9 shows the E-field distribution

Fig. 2. Simulated mobile phone model. Dimensions in mm.

Fig. 3. Schematic side view of the PCB used. Dimensions in mm.

Fig. 4. Top and bottom tilted view of the PCB. Dimensions in mm.

when all the vertically-polarized antennas are fed simultaneously.

III. ARRAY PERFORMANCE RESULTS

The main results of the designed antenna array are presented in this section. These results have been obtained using the electromagnetic 3D simulator CST Microwave Studio. Fig. 10 shows the simulated reflection coefficients for horizontally and vertically-polarized antennas. The single-element matching is

Fig. 5. Top and bottom view of the simulation model. The metal and glass covers are removed for clarity.

Fig. 6. Current distribution for the horizontally-polarized antennas and balanced to unbalanced converter.

Fig. 7. E-field transversal cut for the horizontally-polarized array.

Fig. 8. Tilted side view of the current distribution for the vertically-polarized antennas and modified ground plane.

mostly below -10 dB for both polarizations in the 27 to 29.5 GHz range. The V-pol. antennas present a wide bandwidth mainly due to the ground plane modifications. The bow-tie

Fig. 9. E-field transversal cut for the vertically-polarized array.

Fig. 10. Reflection coefficient of the horizontally (as dashed lines) and vertically (as solid lines) polarized antennas.

Fig. 11. Total efficiency of the 4-element array integrated inside the mobile phone.

shape has been optimized for the dipoles. However, the area available for these is limited, thus making it not possible to further increase the bandwidth. The total efficiency and peak realized gain for the 4-element array are presented in Figs. 11 and 12, respectively. The efficiency is well above -1.5 dB for the whole frequency band, while the peak realized gain varies between 11.5 and 13 dBi. The radiation pattern of the array remains fairly similar across the frequency range. As an example, the 3-D radiation pattern of the array at the center frequency of 28 GHz is shown in Fig. 13. The main limiting factors regarding the beam-steering range are the distance between the elements and the dimensions of the window in the metal frame. The chosen distance between the elements is $d = 6$ mm. Since this distance is slightly over $\lambda/2$ at the aimed frequency band, the beam-steering range free of grating lobes is $\sim \pm 42^\circ$ according to [20]:

$$d < \frac{\lambda}{1 + |\cos(\theta_0)|}. \quad (1)$$

Fig. 12. Realized gain of the 4-element array integrated inside the mobile phone.

Fig. 13. Simulated (and combined) 3-D radiation pattern realized gain of the 4-element array at 28 GHz for vertical and horizontal polarizations, respectively. (Realized gain values are in dBi.)

Fig. 14. Realized gain (radiation pattern) for the steered beams of the 4-element array at 28 GHz for horizontal polarization.

The beam-steering capabilities of the designed array at 28 GHz are presented in Figs. 14 and 15. The maximum beam-steering with a scan-loss below 3 dB is $\sim \pm 35^\circ$ for horizontal and vertical polarizations. The horizontal polarization exhibits slightly better performance but the beams steered at larger angles degrade rapidly. The steering performance of the vertically-polarized array is slightly worse due to the more directive individual element patterns.

IV. TOLERANCE STUDY FOR IMPLEMENTATION IN THE MOBILE PHONE

In order to verify the robustness of the design with respect to its practical implementation in a mobile device, some key parameters are studied with a parameter sweep. The most important parameters are the distance from the end of the PCB to the metal frame and the window size. The distance from the

Fig. 15. Realized gain (radiation pattern) for the steered beams of the 4-element array at 28 GHz for vertical polarization.

TABLE II
PARAMETER VALUES IN THE TOLERANCE STUDY

Case	Distance from the PCB to plastic window	Window size	Plastic filled window ϵ_r
Reference	0.5	5.5	4
A	1	5.5	4
B	0	5.5	4
C	0.5	4.5	5
D	0.5	3.5	6.5

Fig. 16. Reflection coefficient of the vertically-polarized antenna element P2 for the parametric sweep.

PCB to the metal frame is varied ± 0.5 mm with respect to the reference value, while the window size is decreased from the initial 5.5 mm to 3.5 mm. Note that when the window size is changed the optimal permittivity value of the plastic inside it changes. Table 2 shows the parameters used for each simulation. Figs. 16 and 17 show the reflection coefficient for the port in the middle of the array (P2) for each polarization. The array performance is robust to small changes in the distance between the PCB and the plastic window. However, decreasing the height of the window will directly affect the performance of the horizontally polarized antennas. Overall, the results are reasonable and the design should tolerate small misalignments during the mm-wave antenna array assembly process.

V. CONCLUSION

A novel dual-polarized mm-wave antenna array inside a realistic metal-frame mobile phone is presented. The antenna

Fig. 17. Reflection coefficient of the horizontally-polarized antenna element P2 for the parametric sweep.

array is designed to work in the 27 to 29.5 GHz frequency band. The required PCB and additional elements to prototype this solution are easy to manufacture and assemble. The vertically placed pins could easily be assembled into their exact location with the aid of a shaped plastic, which could be removed afterwards. Single element reflection coefficient is below -10 dB for the whole frequency band of 27–29.5 GHz, and the 4-element array efficiency is well above -1.5 dB. Due to the promising simulation results and ease of fabrication the authors plan to later manufacture a prototype in order to verify the performance experimentally. This antenna solution is very suitable for upcoming 5th generation mobile communications.

REFERENCES

- [1] "5G Spectrum." Public Policy Position, Huawei, Shenzhen, China, 2018.
- [2] "Looking Ahead to 5G." Nokia, Espoo, Finland, 2014.
- [3] "5G Spectrum Vision." 5G Americas, Bellevue, Washington, USA, 2019.
- [4] J. Kornprobst, K. Wang, G. Hamberger, and T. F. Eibert, "A mm-wave patch antenna with broad bandwidth and a wide angular range," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 8, pp. 4293–4298, Aug. 2017.
- [5] M. Khalily, R. Tafazolli, P. Xiao, and A. A. Kishk, "Broadband mm-wave microstrip array antenna with improved radiation characteristics for different 5G applications," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 9, pp. 4641–4647, Sep. 2018.
- [6] M. Stanley, Y. Huang, H. Wang, H. Zhou, A. Alieldin, S. Joseph, C. Song, and T. Jia, "A dual-band dual-polarised stacked patch antenna for 28 GHz and 39 GHz 5G millimetre-wave communication," in *2019 13th European Conference on Antennas and Propagation (EuCAP)*, Mar. 2019, pp. 1–4.
- [7] J. Kurvinen, H. Kähkönen, A. Lehtovuori, J. Ala-Laurinaho, and V. Viikari, "Co-designed mm-wave and LTE handset antennas," *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 3, pp. 1545–1553, Mar. 2019.
- [8] S. Zhang, X. Chen, I. Syrytsin, and G. F. Pedersen, "A planar switchable 3-D-Coverage phased array antenna and its user effects for 28-GHz mobile terminal applications," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 12, pp. 6413–6421, Dec. 2017.
- [9] N. O. Parchin, M. Shen, and G. F. 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)*, Oct. 2016, pp. 1–4.
- [10] B. Yu, K. Yang, C. Sim, and G. Yang, "A novel 28 GHz beam steering array for 5G mobile device with metallic casing application," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 1, pp. 462–466, Jan. 2018.
- [11] R. Luomaniemi, J. Hannula, R. Kormilainen, A. Lehtovuori, and V. Viikari, "Unbroken metal rim mimo antenna utilizing antenna clusters," *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 6, pp. 1071–1075, June 2019.
- [12] L. Zhang, Y. Ban, C. Sim, J. Guo, and Z. Yu, "Parallel dual-loop antenna for WWAN/LTE metal-rimmed smartphone," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 3, pp. 1217–1226, March 2018.
- [13] J. Choi, W. Hwang, C. You, B. Jung, and W. Hong, "Four-element reconfigurable coupled loop MIMO antenna featuring LTE full-band operation for metallic-rimmed smartphone," *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 1, pp. 99–107, Jan 2019.
- [14] "Matrix Electronics Limited, Circuit board materials, Mississauga, Ontario, Canada." [Online]. Available: <https://www.matrixelectronics.com/products/panasonic/megtron-7/>.
- [15] Yongxi Qian and T. Itoh, "A broadband uniplanar microstrip-to-CPS transition," in *Proceedings of 1997 Asia-Pacific Microwave Conference*, Dec 1997, pp. 609–612 vol.2.
- [16] M. K. Khandelwal, B. K. Kanaujia, and S. Kumar, "Defected ground structure: Fundamentals, analysis, and applications in modern wireless trends," in *Hindawi, International Journal of Antennas and Propagation*, Feb. 2017, p. vol.2017.
- [17] C. Jansri, C. Phongcharoenpanich, and S. Lamultree, "A printed circular monopole antenna with slot and modified ground plane for uwb applications," in *2018 15th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, Jul. 2018, pp. 564–567.
- [18] T. Hong, S. Gong, Y. Liu, and W. Jiang, "Monopole antenna with quasi-fractal slotted ground plane for dual-band applications," *IEEE Antennas and Wireless Propagation Letters*, vol. 9, pp. 595–598, 2010.
- [19] M. A. Antoniadis and G. V. Eleftheriades, "A compact multiband monopole antenna with a defected ground plane," *IEEE Antennas and Wireless Propagation Letters*, vol. 7, pp. 652–655, 2008.
- [20] W. L. Stutzman, and G.A. Thiele, *Antenna theory and design*, 3rd ed. Hoboken, NJ: John Wiley & Sons, Inc., 2012.