A Switchable 3D-Coverage Phased Array Antenna Package for 5G Mobile Terminals

Ojaroudiparchin, Naser; Shen, Ming; Zhang, Shuai; Pedersen, Gert F.

Published in:
I E E E Antennas and Wireless Propagation Letters

DOI (link to publication from Publisher):
10.1109/LAWP.2016.2532607

Publication date:
2016

Document Version
Early version, also known as pre-print

A Switchable 3D-Coverage Phased Array Antenna Package for 5G Mobile Terminals

Naser Ojaroudiparchin, *Student Member, IEEE,* Ming Shen, *Member, IEEE,* Shuai Zhang, and Gert Frølund Pedersen, *Senior Member, IEEE*

***Abstract*—This manuscript proposes a new design of a millimeter-wave (mm-Wave) array antenna package with beam steering characteristic for the fifth generation (5G) mobile applications. In order to achieve a broad 3D scanning coverage of the space with high-gain beams, three identical sub arrays of patch antennas have been compactly arranged along the edge region of the mobile phone PCB to form the antenna package. By switching the feeding to one of the sub arrays, the desired direction of coverage can be achieved. The proposed design has >10 dB gain in the upper spherical space, good directivity and efficiency, which is suitable for 5G mobile communications. In addition, the impact of user's hand on the antenna performance has been investigated.**

***Index Terms*— 5G, beam steering, mm-Wave, patch antenna, phased array antenna.**

I. Introduction

As fourth-generation (4G) mobile communication systems are being deployed, investigation and development of 5G mobile communication systems have been started to meet the expected need for higher data rates in the future. The standardization activity of 5G is going to be finalized in 2016 and also the commercial availability of equipment is expected to be approximately in the early of 2020s [1].

One of the key enabling techniques in 5G systems is the use of millimeter-wave bands along with directional phased array antennas at both the mobile device and base station [2]. Different from the design of antennas for 4G, the use of millimeter-wave spectrum will put challenging requirements on the design of antennas in 5G cellular systems. As show in Fig. 1 (a), typical 4G mobile phones use omnidirectional antennas with moderate radiation gain to achieve coverage in all directions [3]. For 5G mobile phones, however, the directional phased array antenna can only cover part of the space [4]. Even though the coverage issue can be mitigated by steering the beam, it is still very difficult to achieve a coverage range similar to omnidirectional antennas using one array.

In this paper, we propose a 3D-coverage phased array antenna for 5G wireless systems (Fig. 1(a)). The main advantage of the proposed design compared with previous works [4-5], is the switching characteristic of the antenna package to select the desired area of coverage with high gain beams. Furthermore, the proposed design with three sub arrays can operate either in diversity or MIMO mode. The proposed antenna package operates in 21-22 GHz which is one of the candidate bands for 5G mobile communications [6].

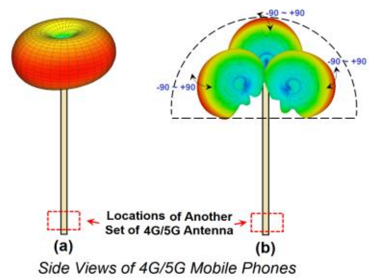

Fig. 1. Radiation patterns of mobile phone antennas, (a) typical 4G antenna, and (b) the proposed 5G antenna package.

The proposed package consists of three sub arrays of microstrip patch antennas. Each of the sub arrays is steerable in the scanning range of -90° to +90° (Theta plane). The three sub-arrays are designed such that their radiation patterns partially overlap on each other but cover different part of the space (Fig. 1(b)). The S-parameters, radiation pattern, efficiency and beam steering characteristics of the proposed design are investigated. The antenna performance in presence of user's hand (Data-Mode) has been discussed as well.

II. Configuration of the 5G Mobile Phone Antenna

The proposed design consists of three sub arrays of patch antennas in different sides of the edge region in PCB (Fig. 2).

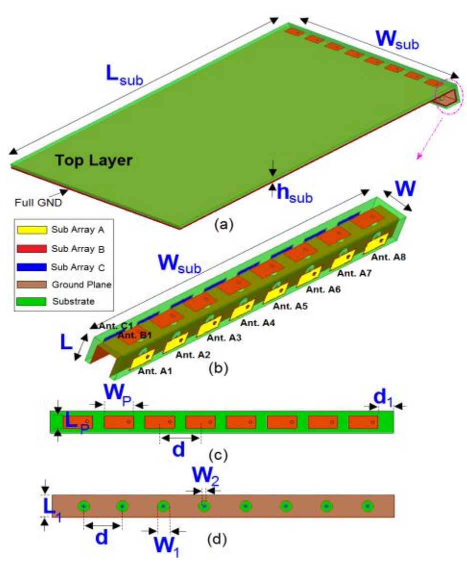

Fig. 2. (a) Side view of the proposed 5G antenna with full ground plane, (b) antenna package configuration with three sub arrays, (c) top layer of each sub-array, and (d) bottom layer of each sub-array.

Authors are with the Antennas, Propagation, and Radio Networking (APNet) Section, Department of Electronic Systems, Faculty of Engineering and Science, Aalborg University, DK-9220, Aalborg, Denmark (e-mails: naser@es.aau.dk; mish@es.aau.dk; sz@es.aau.dk; and gfp@es.aau.dk).

Eight patch antenna elements have been used for each of the sub arrays. The center-to-center distance between the elements (d) is approximately $\lambda/2$, where λ is the wavelength of 21.5 GHz. The antenna is designed on the Nelco N9000 substrate with thickness (h_{sub}), dielectric constant (ε_r), and loss tangent (δ) of 0.787 mm, 2.2, and 0.0009, respectively. The values of the antenna parameters are listed in Table I.

TABLE I. PARAMETER VALUES OF THE 5G ANTENNA PACKAGE

Parameter	W_{sub}	L_{sub}	h_{sub}	W_P	L_P	d
Value (mm)	55	110	0.787	4.32	2	6.5
Parameter	d_1	W	L	W_1	L_1	W_2
Value (mm)	4.5	4.574	3.787	1.72	3	0.5

The main challenge here in the design is to cover at least half of the space for 5G mobile phones (Fig. 1(b)) with high-gain radiation beams. In order to acquire this property, three linear sub arrays of patch antennas have been used at different sides of PCB (Fig. 2.). The proposed antenna package could also be used in the bottom portion of the mobile phone PCB to cover another half of the space [4].

Figure 3(a) illustrates a system architecture in which the proposed antenna package can be used for 5G applications. For operations using time division duplex, the feed network can be implemented using low loss phase shifters (such as HMC933LP4E [7]) for beam steering, and the selection among the sub-arrays can be easily achieved by using a microwave switch (such as SP3T AlGaAs PIN Diode Switches [8]).

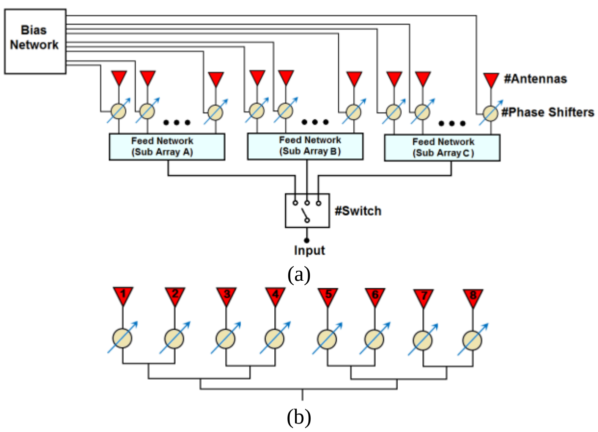

Fig. 3. (a) Phased array architecture for the proposed switchable phased array antenna package, (b) typical 1:8 feed network for a linear phased array antenna.

One of the important system blocks to achieve a functional array antenna is the feed network. In the proposed design, three 1×8 uniform linear array antennas have been used, where each radiating element of them is excited by signals with equal magnitude. There are various feeding network topologies which could be used for this purpose: parallel (such as Wilkinson power divider shown in Fig. 2(b)), series, and etc. According to the mentioned active elements, the quantitative estimation of the insertion loss of the feeding network could be less than 5 dB.

III. RESULTS

A. Single Element Patch Antenna

The type of the antenna elements in this design is microstrip patch antenna which is one of the popular planar antennas for microwave/millimeter-wave wireless links. Microstrip patch antennas (MPAs) can be fed in a variety of ways such as microstrip-line feed, coaxial-probe feed, aperture-coupled feed, and etc [9]. In this paper, the coaxial probe feeding technique has been used for antenna elements. As illustrated in Fig. 4(a), the inner conductor of the coaxial probe feed extends from ground plane through the PCB substrate to reach the radiating element. The simulated S_{11} and radiation pattern characteristics of the patch antenna element are illustrated in Fig. 4. According to the obtained results, the antenna has a good radiation behavior in the frequency range from 21 to 22 GHz.

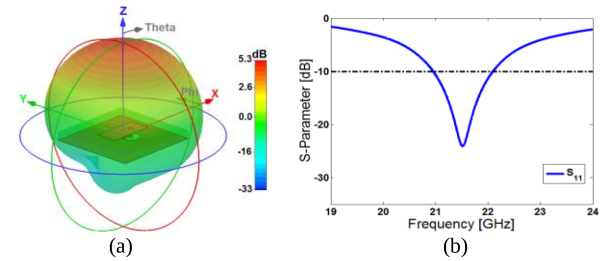

Fig. 4. Simulated (a) radiation pattern, and (b) S_{11} of the single patch antenna.

B. Compact Beam Streeable Antenna package

The radiation patterns of the compact antenna package at 21.5 GHz for single elements and sub arrays for 0° scanning angle are illustrated in Figs. 5(a) and (b). The antenna has good radiation patterns at 21.5 GHz for single elements and sub arrays. Figure 5(c) illustrates the radiation coverage of the sub arrays at 0°. It can be seen that the antenna covers more than half of the space (scanning angle from -90° to 90°) with a minimum realized gain of 10 dB and a maximum gain of 12.5 dB.

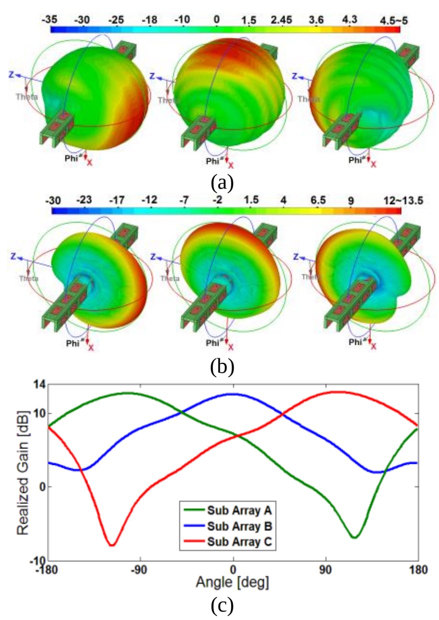

Fig. 5. Radiation patterns of proposed antenna package at 21.5 GHz for, (a) single elements, (b) sub arrays at 0º scanning angle, and (c) converge space of the sub arrays with realized gain values.

C. Proposed Beam Streeable Mobile Phone Antenna

As illustrated in Fig. 1, the antenna package has been used at the edge region of the mobile phone PCB with a full ground plane. The simulated S-parameters for one of the sub-arrays are shown in Fig. 6. As illustrated, the proposed mobile phone antenna has good S-parameters in the frequency range of 21 to 22 GHz. The proposed 5G mobile phone antenna has a dimension of $W_{sub} \times L_{sub} \times h_{sub}$ = 55×110×4.5 mm^3.

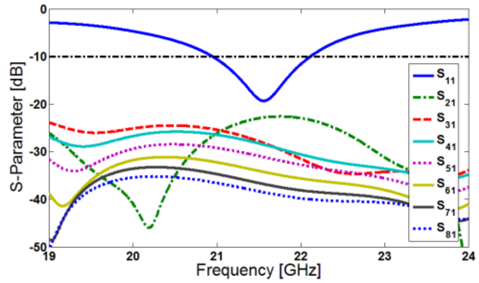

Fig. 6. Simulated S-parameters of the sub array with eight antenna elements.

According to the simulated results, the thickness of the proposed design could be reduced from 4.5 to 3.5 mm. In addition, by using other substrates with low thickness (0.3 mm instead of 0.787 mm) and also by decreasing the width of patch elements (from 2 to 1.4 mm), it is possible to reduce the total thickness of the antenna from 4.5 to 2.5 mm. The highest mutual couplings are found among '*Ant.A1-Ant.A2*', '*Ant.A1-Ant.B1*', and '*Ant.A1-Ant.C1*'. Figure 7 illustrates the maximum mutual couplings among the antenna elements. As seen the antenna exhibits good impedance matching level around operational frequency and low mutual coupling between sub arrays.

The 3D radiation patterns of the antenna with directivity values at different scanning angles for each sub array at 21.5 GHz are shown in Fig. 8. The proposed antenna configuration with three arrays is highly effective in covering the spherical beam coverage for 5G cellular handsets.

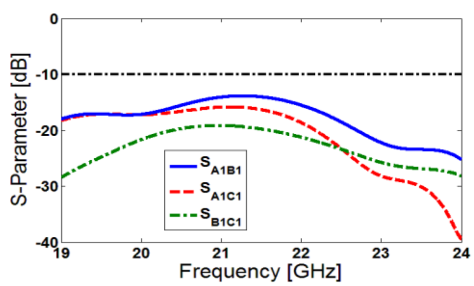

Fig. 7. Mutual couplings for the antenna elements of different sub arrays.

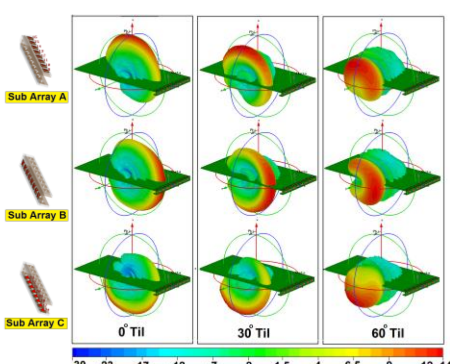

Fig. 8. 3D radiation patterns of each sub arrays at different scanning angles.

The simulated radiation efficiency and total efficiency of the proposed mobile phone antenna package are shown in Fig. 9. The results of the calculations using the *CST Microwave Studio* software [10] indicated that the proposed 5G antenna has good efficiencies. Across the scanning range of 0° to 60°, the radiation efficiency and total efficiency are higher than 95% and 80%, respectively.

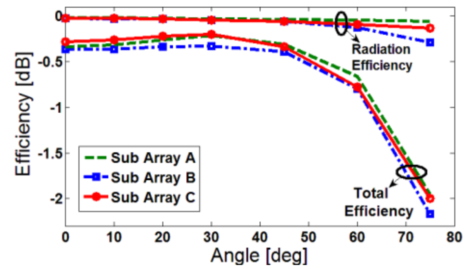

Fig. 9. Simulated radiation and total efficiencies of antenna sub-arrays.

Figure 10 shows the simulated realized gains for different scanning angles. As illustrated, the antenna has a good beam steering characteristic with acceptable gain levels in different scanning angles. The gains are almost constant in the range of 0° to 30° with less than 1dB variation.

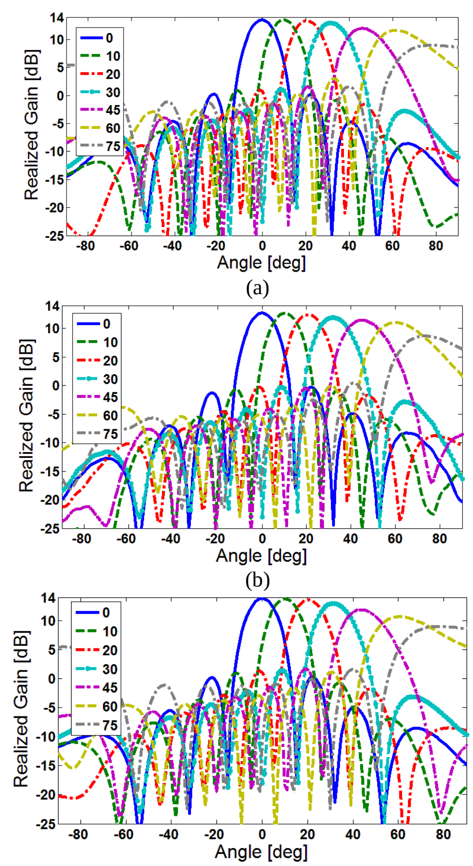

Fig. 10. Realized gains of the sub-arrays at different scanning angles, (a) sub array A, (b) sub array B, and (c) sub array C.

It can be seen that more than 12.5 dB antenna gains have been obtained in the main beam direction for each sub-array. It should be noted that the beam steering characteristic of the antenna for plus/minus (+/-) scanning angles are symmetric. In the fabrication of the proposed antenna package, each sub array could be made separately and by using glue we can connect them together. In addition, it is possible to hold them together using a piece of copper plate as a part of ground plane. As the antenna sub arrays have similar performance, one of them embedded on the mobile phone PCB has been fabricated to validate the performance.

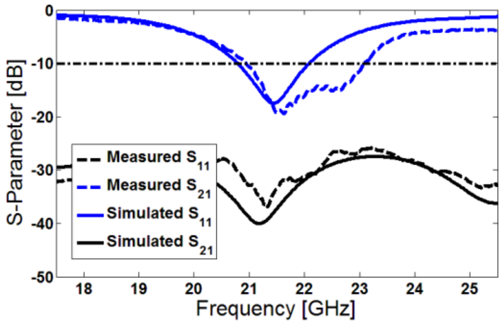

Fig. 11. Measured and simulated S-parameters of two antenna elements.

The measured and simulated S-parameters of two antenna elements (elements at positions 4 and 5) are shown in Fig. 11. As seen, the antenna has a good response in the frequency range of 21 to 22 GHz with -20 dB return loss at 21.5 GHz. In addition, the antenna radiation pattern for a single element of the sub array has been measured which is illustrated in Fig. 12.

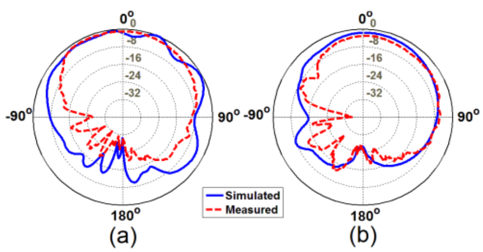

Fig. 12. Measured and simulated radiation patterns of a single element antenna embedded on the mobile phone PCB at 21.5 GHz, (a) E-plane, and (b) H-plane.

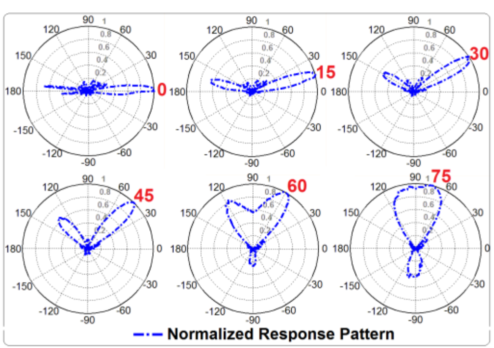

Fig. 13. Synthesized beam patterns from the measured data in Fig. 12 for various scanning angles.

Furthermore, the beam patterns of the fabricated antenna were synthesized using the measured data for the single element (Fig. 12). The results are depicted in Fig. 13 for the scanning range of -90° to 90° [11]. As seen, the synthesized beams have a good steering characteristic in the scanning range form 0° up to 75°.

D. *The Effect of User Hand on the Antenna Performance*

The user's hand is one of the body parts that touches the mobile phone most frequently, and it could have effects on the antenna performance in data mode [12]. Therefore, the antenna behavior in presence of user's hand has been investigated in this work as well. As illustrated in Fig. 14, different placement of the proposed antenna in data mode and also different distance among user's hand and the antenna has been investigated.

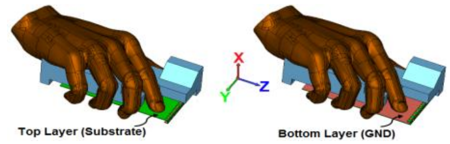

Fig. 14. Different placements of the proposed antenna in data mode.

According to the obtained results from simulations, the total losses of antenna parameters in terms of antenna gain, radiation efficiency, and total efficiency are about 1.5 dB, 15%, and 20%, respectively. In addition, hand's impact on the impedance matching and beam steering characteristics is insignificant.

IV. Conclusion

The design of a phased array antenna package for 5G communications has been presented. The antenna consists of three sub arrays, and each sub-array covers part of the scanning space. The main novelty of this study is the switching characteristic of the antenna to select the desired area of coverage, while maintaining high gain beams. The whole design has been validated by simulation. In addition, experimental verification was done for one sub array and good matching between simulation and measurements has been obtained.

References

[1] T. S. Rappaport, *et al*., "Millimeter wave mobile communications for 5G cellular: It will work!," *IEEE Access*, vol.1, pp. 335-349, 2013.

[2] Y. Azar *et al.*, "28 GHz propagation measurements for outdoor cellular communications using steerable beam antennas in New York city," *2013 IEEE ICC*, pp. 5143–47, 2013.

[3] D. -G. Yang, D. -O. Kim, and C. -Y. Kim, "Design of internal multi-band mobile antenna for LTE700/WCDMA/UMTS/WiMAX/WLAN operation," *PIERS Proceedings*, 27-30 March, Kuala Lumpur, pp. 1490-1493, 2012.

[4] W. Hong, K. Baek, Y. Lee, and Y. G. Kim, "Design and analysis of a low-profile 28 GHz beam steering antenna solution for future 5G cellular applications," *IEEE international microwave symposium*, 1-6 June 2014, Tampa Bay, Florida, 2014.

[5] N. Ojaroudiparchin, M. Shen, and G. F. Pedersen, "A 28 GHz FR-4 compatible phased array antenna for 5G mobile phone applications," *IEEE International Symposium on Antennas and Propagation (ISAP2015)*, Tasmania, 2015.

[6] Y. Wang, *et al.*, "5G mobile: Spectrum broadening to higher-frequency bands to support high data rates," *IEEE Vehicular Technology Magazine*, vol. 9, pp. 39-46, 2014.

[7] HMC933LP4E, "*Analog phase shifter*," Hittite Microwave Company.

[8] SP3T AlGaAs," *PIN diode switch*," M/A-COM Technology Solutions Holding Inc.

[9] K. Phalak, and A. Sebak, "Aperture coupled microstrip patch antenna array for high gain at millimeter waves," *IEEE International Conference on Communication, Networks and Satellite (COMNETSAT)*, 4-5 Nov. 2014, Jakarta, pp. 13-16, 2014.

[10] *CST Microwave Studio.* ver. 2014, CST, Framingham, MA, USA, 2014.

[11] D. Psychoudakis, Z. Wang, and F. Aryanfar, "Dipole array for mm-wave mobile applications," *Antennas and Propagation Society International Symposium (APSURSI)*, 7-13 July 2013, Orlando, Florida, 2013.

[12] J. Ilvonen, *et al.*, "Mobile terminal antenna performance with the user's hand," *IEEE Antenna and Wireless Propagation Letters*, vol. 10, pp. 772-775, 2000.