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# Co-Designed Handset Antennas with Wide Angular mm-Wave Coverage and LTE MIMO

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**Abstract**— The co-existence of mm-wave and LTE antennas in modern handsets is yet an unsolved challenge in the phone industry and antenna research community. The different antenna types merged together in a shared volume easily hinder each other's performance. This paper extends the work published recently, showing how high-gain mm-wave antennas at 28 GHz can be incorporated in the same volume with LTE MIMO antennas. The results show that with small compromises a decent performance can be achieved at both mm-wave and LTE bands.

**Keywords**— beam-steering, handset antenna, LTE, metal frame, millimeter-wave, multiple-input multiple-output (MIMO)

## I. INTRODUCTION

Fifth generation (5G) mobile networks will utilize millimeter-wave (mm-wave) frequencies for high-speed communications. Especially, the spectrum available at around 28 GHz is under significant interest [1]–[4]. However, the mm-wave bands are only usable for short distances and, thus, the current LTE networks will remain in use.

In order to benefit from the higher frequencies, future mobile devices must be equipped with suitable antennas for such communications. However, finding space for mm-wave antennas is not an easy task. LTE antennas are typically integrated to the metal frame of the handset reserving space from the short ends [2], [5]–[7]. Even though these antenna types operate at frequencies far from each other, especially the LTE performance is easily deteriorated. Metal parts of the mm-wave antenna might short-circuit the LTE antenna if they are located too close to each other. For example, [8] presents a mm-wave design that grounds the metal frame, which would affect the LTE antennas. Furthermore, the requirements for multiple-input multiple-output (MIMO) support at the LTE bands and beam-steering capability with wide angular coverage at the mm-wave band complicate the design process even more. Implementing MIMO only is known to weaken the LTE performance remarkably [5], [9].

Unlike the LTE antennas, the mm-wave antennas need to be directional to obtain reasonable transmission ranges. Thus, the narrow-beam antennas should be beam-steerable to increase the angular coverage. In spite of the beam-steering capability, one array provides only partial cover and, hence, for full coverage the handset should be equipped with several arrays. For example, [1] presents a design that radiates from the short edges and the front and back faces of the phone. Many other

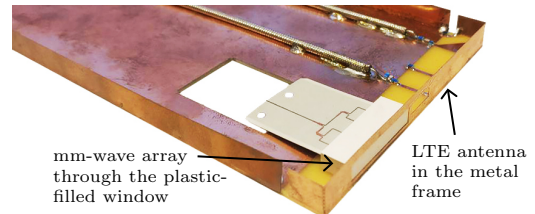


Fig. 1. The prototype used in [13] to demonstrate a way to accommodate mm-wave and LTE antennas in the same shared volume.

proposed solutions only include one or two arrays [3], [8], [10]–[12] leaving some directions uncovered.

In a recent publication [13], we demonstrated with a proof-of-concept prototype how to successfully co-design mm-wave and LTE antennas within a shared volume. The use of plastic-filled window in the metal frame of the handset allowed us to incorporate the two antenna structures together. Previously, co-existing mm-wave and LTE antennas were only designed in [4]. The co-existence of mm-wave and other sub-6 GHz antennas is also studied recently [14].

This paper continues the work of [13] by improving the mm-wave coverage with additional arrays of enhanced gain on each side of the phone and by implementing a diversity antenna to realize MIMO operations at the LTE bands. Whereas [13] was the first paper to incorporate mm-wave and LTE antennas in a shared volume, this paper is the first one to present a complete antenna system. The new simulations show that a sufficient performance level, which compares well to other designs, can be achieved with the same co-design method.

## II. ANTENNA DESIGNS

The used phone model is a simple printed circuit board (PCB) design with size of  $150 \times 75 \times 7 \text{ mm}^3$ , which corresponds to common commercial smartphones. The design includes a metal frame, which is also typical feature in today's devices. The phone is modeled and antennas simulated in electromagnetic 3-D simulator CST Microwave Studio. Required matching networks are designed with Optenni Lab.

The LTE antennas are integrated to the metal frame on the short edges of the phone, and the copper-plated 0.8-mm thick FR-4 ( $\epsilon_r = 4.3$ ,  $\tan \delta = 0.025$ ) substrate acts as the RF-ground. Ground clearance for the antennas is 10 mm in each end of the phone, which is certainly large compared to current devices [2], but this is the first proof-of-concept. The mm-wave arrays are designed on separate 0.101-mm thick PCBs (RO4350B,  $\epsilon_r =$

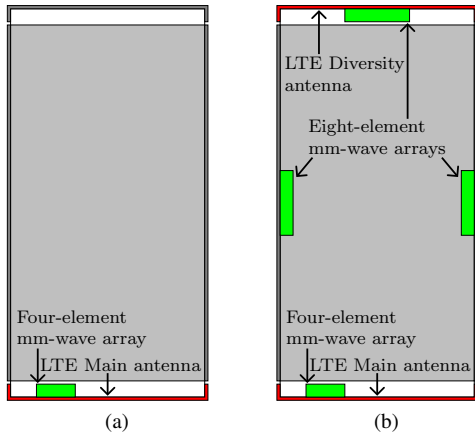


Fig. 2. (a) Co-designed antennas from [13]. (b) Improved system with several extended mm-wave arrays and LTE MIMO.

3.48,  $\tan \delta = 0.0037$ ) and are enclosed by plastic PREPERM L450 ( $\epsilon_r = 4.5$ ,  $\tan \delta = 0.0005$ ) [13].

The mm-wave antenna arrays cover frequencies 25–30 GHz, and the LTE antennas operate at the low band (LB) and the high band (HB) at 700–960 MHz and 1710–2690 MHz, respectively. In [13], a design with one four-element mm-wave module and one LTE antenna was presented. That design lacks gain and angular coverage at the mm-wave band, and does not fulfill MIMO requirements at the LTE bands. Here, we present an improved design, which includes three additional eight-element mm-wave arrays for higher gain and improved coverage, and also an LTE diversity antenna for MIMO support. The difference between these designs is shown in Fig. 2.

#### A. Extended mm-Wave Antenna

The mm-wave antenna is an array of Vivaldi antennas enclosed with RF-optimized plastic PREPERM L450. Vivaldi antennas are simple to implement on a PCB and are able to operate at very wide frequency band. Details and dimensions of the Vivaldi antenna are presented in [13]. The plastic enclosure insulates the metal parts of mm-wave and LTE antennas from each other. In addition, the dielectric improves matching of the mm-wave array and enables smaller structures as the effective wavelength of the mm-wave signal is reduced inside the dielectric.

In [13], we designed a linear four-element array to be incorporated in the same volume with the LTE antenna. To achieve higher realized gain, we extend the array with four additional elements. Fig. 3 shows the structure of the extended Vivaldi array. The eight-element arrays are placed to the middle of the long sides and the other short end of the handset. The size of the plastic-filled window in the metal frame for the larger array is  $42 \times 4 \text{ mm}^2$ . The length of the window is nearly doubled compared to the four-element design.

Beam-steering can be realized with progressive phase shifts between the elements. In this work, we directly modify the input signal in the simulations, but in reality same can be done with phase shifters or vector modulators. By steering the beam

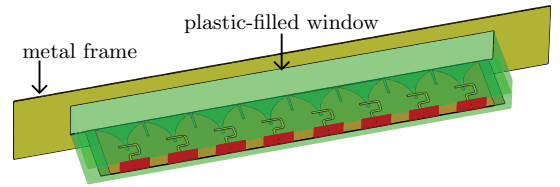


Fig. 3. The extended eight-element Vivaldi array enclosed with PREPERM L450 plastic. The array is based on the design in [13].

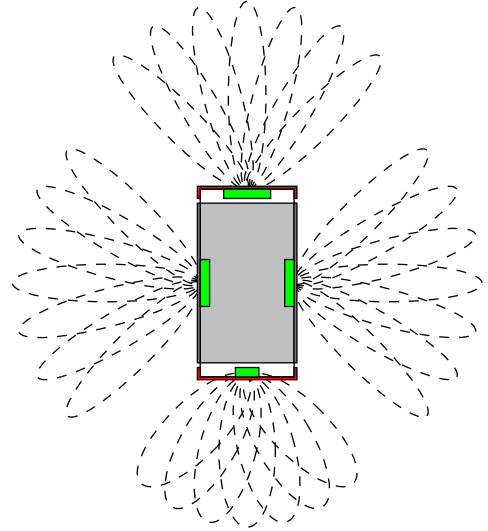


Fig. 4. Several beam-steerable mm-wave elements to have large angular coverage around the phone.

of each array, nearly  $360^\circ$  coverage around the phone can be achieved as Fig. 4 illustrates.

#### B. LTE MIMO Configurations

The LTE antennas are integrated into the metal frame. The frame acts as a capacitive coupling element (CCE), which excites resonating currents in the chassis. Both LB and HB are implemented on the same structure and are fed separately. Dimensions of the main antenna are presented in [13].

The simplest manner to implement MIMO in the proof-of-concept design of [13] would be copying the same design to the other end of the phone. However, having the symmetric MIMO structure is not possible as we extend to the eight-element array. Therefore, the structure of the LTE diversity antenna is redesigned in order to accommodate the extended array within the same shared volume. The mm-wave array is placed to the center of the frame and the low band feeds are moved to the corner, so that the distance between the feeds and the mm-wave block is 2.9 mm. The structure of the diversity antenna with the eight-element array in this asymmetric MIMO configuration is shown in Fig. 5a. For comparison, we also present the results for the symmetric structure, which is equipped with the same four-element array as the main antenna, seen in Fig. 5b.

Ports 1 and 2 in Fig. 5 refer to the feeds for LB and HB in the main antenna, respectively. Similarly, ports 3 and 4 refer to the LB and HB feeds of the diversity antenna, respectively.

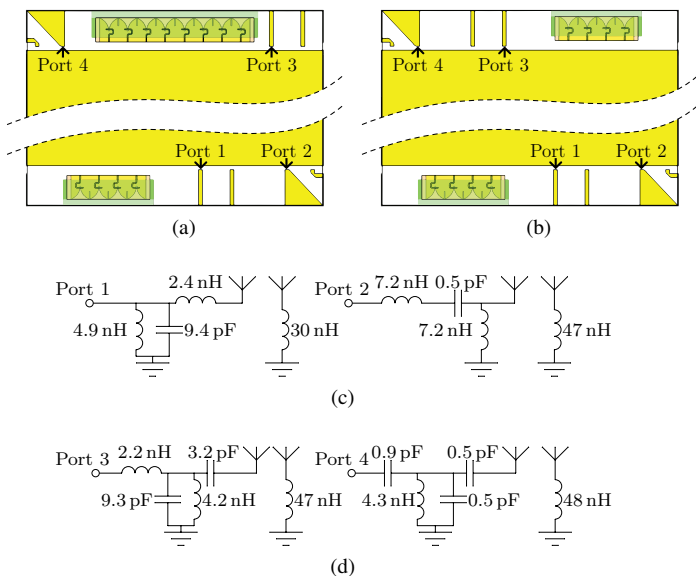


Fig. 5. The two designed MIMO configurations. (a) The asymmetric configuration combines the diversity antenna with the eight-element mm-wave block whereas (b) the symmetric structure has the same design with the four-element mm-wave array in both ends. (c) The matching circuits of the main antennas. (d) The matching circuits of the diversity antenna in (a).

The unmarked feeding strips in Fig. 5 are used for aperture matching components. Fig. 5c shows the matching circuits of the main antennas. In the symmetric configuration, also the matching networks are identical. The diversity antenna in the asymmetric configuration requires different matching network, which is shown in Fig. 5d.

### III. MM-WAVE PERFORMANCE

Fig. 6 shows the realized gain of the eight-element array at different beam-steering angles at 26 and 28 GHz resulting in maximum gains of 10 and 11.5 dBi, respectively. The simulations show that steering the beam roughly  $\pm 45^\circ$  still results in realized gain that is within 3 dB of the peak gain at the broadside direction. However, at 26 GHz we can notice the beam losing its shape as the steering angle increases.

The four-element array also steers the beam roughly  $\pm 40^\circ$ , but naturally with smaller gain. As was shown in [13], the realized gain of the small array peaks at 7 dBi. The difference is expected as the array size doubled in the new design. As the arrays in each side are able to cover a  $80\text{--}90^\circ$  wide cone, nearly  $360^\circ$  coverage around the phone is obtained.

Other published antennas of similar size typically reach peak gain around 12 dBi with slightly larger scanning range [3], [11], [12]. However, our design is quite compact physically and is not tied to any particular location.

### IV. LTE MIMO PERFORMANCE

Fig. 7 shows the  $S$ -parameters of both MIMO configurations. As is expected, the coupling between the LB antennas is quite large, as they couple through the ground plane. In the asymmetric case, coupling is slightly reduced due

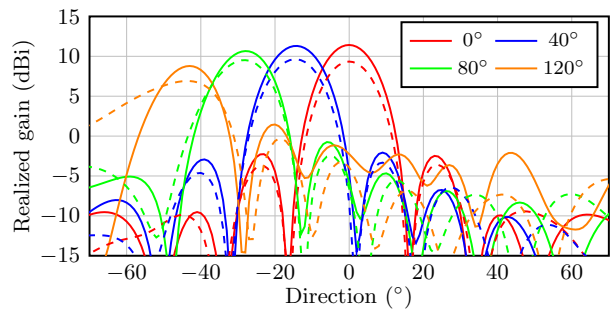


Fig. 6. Realized gain and beam-steering of the eight-element array in the azimuth plane with different progressive phase shift values between the elements. The solid and the dashed lines show the performance at 28 GHz and 26 GHz, respectively.

to different feeding locations and matching circuits between the two ends, compared to the symmetric case. In Fig. 7a, the matching levels of the main antennas are good, generally below  $-6$  dB. The larger mm-wave module clearly affects the performance of the diversity antenna, as the matching of the HB is very peaky. The symmetric configuration provides better than  $-6$  dB matching basically over both bands entirely.

Fig. 8 shows the total efficiencies of both MIMO configurations. The behavior of antennas in both setups is similar to the  $S$ -parameters. In the asymmetric case, the main antenna has very high efficiencies, peaking at 70 and 85 % at LB and HB, respectively. Although the diversity antenna does not reach as high values as the main antenna, it still performs quite well having basically 30–40 % efficiency at LB and 40–70 % at HB. When the diversity antenna is added, the efficiency of the main antenna drops roughly 20 percentage points at the low band compared to [13]. Comparison to other published designs [5], [6], [15] shows that both configurations perform well among them. Benefit of this design is the passive implementation that enables carrier aggregation, whereas, e.g., [5], [6] present reconfigurable designs.

The results show that co-designing mm-wave and LTE MIMO antennas is a trade-off between the antenna types. Now, the LTE diversity antenna performs significantly better in the symmetric design. However, that configuration results in smaller realized gain at the mm-wave band due to the smaller array. On the other hand, if better mm-wave performance is desired, then LTE diversity performance must be sacrificed.

### V. CONCLUSION

This paper presented a handset antenna design that incorporates mm-wave and LTE antennas in the same structure. Placing beam-steerable mm-wave modules on all sides of the phone allows us to achieve nearly  $360^\circ$  coverage around the device. Eight-element Vivaldi arrays enable wideband performance with high realized gain peaking at 11.5 dBi. The two presented LTE MIMO configurations indicate that a successful co-design is a trade-off between mm-wave and LTE antennas as enhancing one's performance hinders the other. However, the overall performance of both antenna types is good in both configurations.

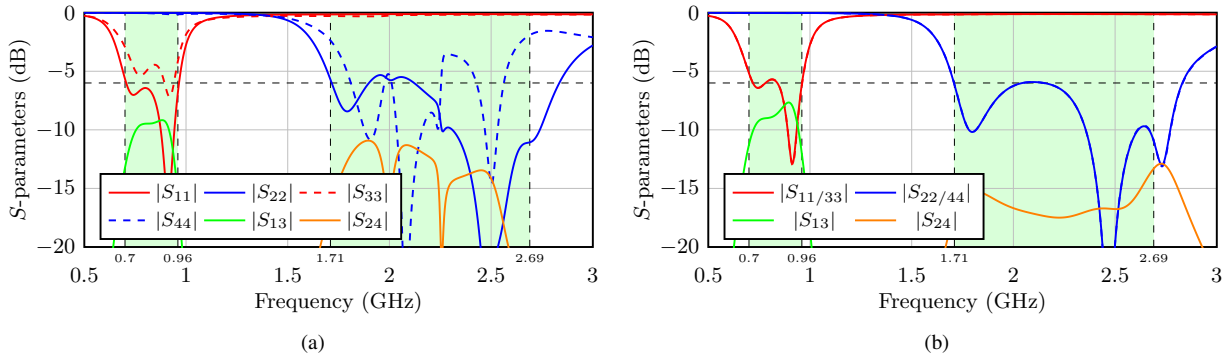


Fig. 7.  $S$ -parameters of the LTE antennas in (a) asymmetric and (b) symmetric MIMO configurations. Dashed black lines show the  $-6$  dB level.

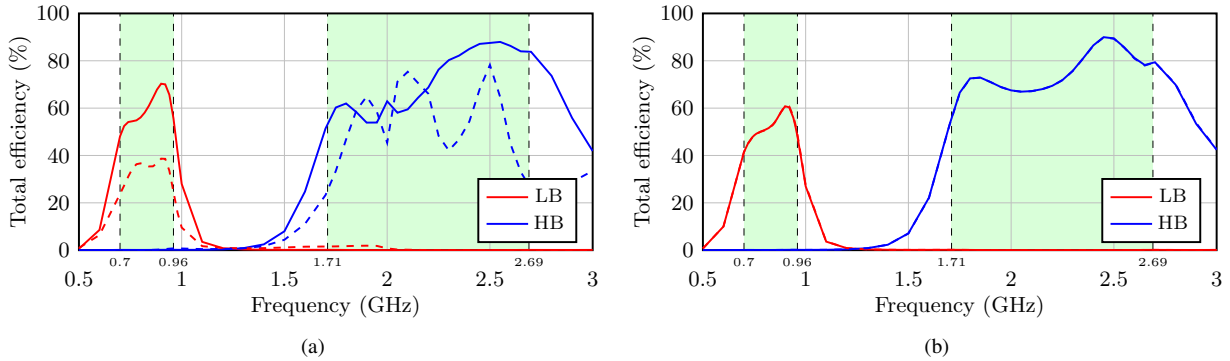


Fig. 8. Total efficiencies of the LTE antennas in (a) asymmetric and (b) symmetric MIMO configurations. In (a) the solid lines are the main antenna and the dashed the diversity antenna.

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