Viikari, Ville; Luomaniemi, Rasmus; Ala-Laurinaho, Juha; Kurvinen, Joni; Kahkonen, Henri; Lehtovuori, Anu; Leino, Mikko

5G antenna challenges and opportunities

Published in:
ISWCS 2019 - 16th International Symposium on Wireless Communication Systems

DOI:
10.1109/ISWCS.2019.8877314

Published: 01/08/2019

Document Version
Peer reviewed version

Please cite the original version:
Viikari, V., Luomaniemi, R., Ala-Laurinaho, J., Kurvinen, J., Kahkonen, H., Lehtovuori, A., & Leino, M. (2019). 5G antenna challenges and opportunities. In *ISWCS 2019 - 16th International Symposium on Wireless Communication Systems* (pp. 330-334). [8877314] (International Symposium on Wireless Communication Systems). IEEE. https://doi.org/10.1109/ISWCS.2019.8877314

5G Antenna Challenges and Opportunities

Ville Viikari, Rasmus Luomaniemi, Juha Ala-Laurinaho, Joni Kurvinen, Henri Kähkönen, Anu Lehtovuori, Mikko Leino
Department of Electronics and Nanoengineering
Aalto University School of Electrical Engineering
Espoo, Finland
ville.viikari@aalto.fi

***Abstract*—Antenna is one of the most important single part of a wireless communications system and significantly affects the total energy consumption. Current mobile antennas can be inefficient in both converting radio energy to radiating waves and also focusing the radiated waves. The upcoming 5G introduces additional challenges to antennas but could also provide opportunities to use RF energy more efficiently. This paper discusses 5G antenna challenges and presents two potential antenna solutions for 5G mobile devices and one for mm-wave access points.**

Keywords—5G, base station antenna, beam steering, handset antenna, millimeter-wave.

I. INTRODUCTION

Wireless technology has a substantial ecological footprint. Wireless access networks alone were estimated to account 0.3-1.7 % of the global electricity consumption in 2015 [1]. A significant portion of that energy is used for generating radio waves: 40-75 % in wireless access points for instance [2]. One of the most important single part affecting the RF energy efficiency in the whole network is the antenna. In the following, we explain the current antenna challenges and estimate potential of RF energy efficiency improvement through better antennas.

There are two important antenna characteristics affecting RF energy efficiency: antenna efficiency, and antenna's ability to focus the available energy to the right direction. Let us first consider the (total) antenna efficiency, that is, the ratio between the radiated RF energy and the available RF energy at its feed. Currently the largest improvement potential is related to the antennas of mobile devices. Their efficiency can be 30-40 % (-5.2...-4.0 dB) in ideal conditions and as low as 1 % (-20 dB) in real use [3], [4]. The need for RF energy is directly proportional to the antenna efficiency: increasing efficiency of a mobile antenna from 1 % to 100 % would theoretically reduce the needed RF energy (and energy needed for generating RF) to one hundredth.

There are currently two main reasons for the low efficiency: 1) small volume used by one antenna, and 2) antenna's inability to adapt to a particular use case. Let us first consider the effect of antenna size. It is well known that ultimately antenna size limits the highest obtainable efficiency and bandwidth [5]. At low frequencies (<1 GHz), the antenna of a mobile device is merely a coupling element exciting radiating currents on the mobile device. Although the size of the actual antenna is somewhat challenging to determine, the same trade-off between the antenna size and efficiency applies: the smaller the antenna (or coupling element), the lower the bandwidth or efficiency.

Currently, mobile antennas do not use the available volume as efficiently as they could. This is because the total antenna volume is divided between many antennas possibly operating at different frequencies. Depending on the operation frequency, only part of the antennas are active while antennas operating at other frequencies are unused. Therefore, only a fraction of the total volume reserved for antennas is used at a time, leading to lower efficiency than could be obtained by actively utilizing all the volume.

Second challenge is that antennas are fixed and unable to adapt their operation to a given use case. Rather than being an independent radiator, a mobile phone antenna is a coupling element exciting certain current distribution on the device. The excited current distribution is the source for radiating fields. Antennas can generally excite a well-radiating current distribution in one use-case (for example a device in free space), but user's proximity can alter the current distribution and collapse the radiation efficiency. Currently used antennas are mainly fixed and unable anyhow alter the excited current distribution.

The so-called antenna cluster technique, originally presented in [6], could potentially make it possible to efficiently use the volume reserved for antennas and also adapt the current distribution to the given use case. We will later shortly review this technique and discuss its potential.

In addition to radiation efficiency, antennas' ability to direct RF energy affects strongly the total RF energy efficiency. Due to physical limitations, radio waves can not be intensely directed from mobile devices at frequencies near a few GHz. However, moving to mm-wave frequencies allocated for 5G makes directive antennas possible. With directive antennas, radio energy could be transferred much more efficiently than currently with non-directive antennas. For instance, increasing frequency from 2.8 GHz to 28 GHz and keeping the antenna sizes unchanged at both ends of the link, could theoretically make the transferred RF energy 100-fold.

While the potential of directing energy accurately in mm-wave 5G is high, there are also additional challenges related to antenna efficiency. Transmission line losses tend to increase with the frequency, and therefore it is highly essential to integrate active electronics in immediate vicinity of radiating elements. Further, millimeter-wave antennas should not hinder the performance of legacy low-frequency antennas in a mobile phone, nor should they require additional volume as it could make the device less attractive to the user.

We will discuss the challenges of locating the mm-wave and low-frequency antennas in the shared volume in a mobile device and also review one potential way for doing it.

Furthermore, we will present a potential way of integrating active elements in the immediate vicinity of radiating elements in millimeter-wave arrays.

Integrating even more antennas to the same system sets new constrains and requires new design methods. In this paper, we introduce three ways to tackle the challenge: 1) multiport optimization technique to find new flexible designs 2) utilizing shared volume to mm-wave and LTE handset antennas and 3) integration of waveguide based mm-wave antennas and electronics.

II. MULTI-FEED ANTENNAS

The antenna cluster technique [6]–[8] utilizes multiple feeds and multiple antenna elements collaboratively to improve the performance of the whole system. By feeding the antenna elements with properly weighted signals, the reflected power can be minimized and thus, the radiated power maximized. By adjusting the amplitude and phase of the feed signals, the antenna cluster can be tuned to operate at different frequencies and wide bandwidths can be covered. This type of frequency reconfigurability is realized with multichannel transceivers that can produce the required complex feeding weights for different operation frequencies.

Designing antenna systems for mobile devices relies heavily on EM simulations. Complex antenna systems with multiple antennas for MIMO operation require large number of these time consuming simulations. In addition, finding new and innovative antenna structures is very difficult. Many optimization tools are appropriate to fine-tune structures that are already relatively close to the final design. Optimizing completely new and complicated structures is extremely difficult and requires often impractically long simulation times.

We have developed and tested a novel antenna design method [9], which requires only one EM simulation. Therefore, it can be used to study a large number of different antenna structures in a short time. The basic idea of the new design method is presented in Fig. 1, where we demonstrate it for a metal-rimmed mobile device. First, the antenna structure is discretized by dividing the metal rim of the device with unit antenna elements. Each one of these elements have one port for feeding and another for connecting the adjacent elements. The multiport S-parameter model of the antenna is used together with circuit simulation tools to find the optimal antenna structure and form antenna clusters.

We evaluate all possible combinations by setting the ports to be either open or short circuits or feeds. With multi-feed antennas, both matching and coupling between the elements in a cluster affect the performance differently than with traditional single-feed antennas. Therefore, the matching efficiency, which takes both of these into account with a single parameter, is used as the optimization goal.

This work was supported in part by the Academy of Finland under the decision 289320, by Nokia Bell Labs, and by the 5G TRx project funded by Business Finland, Nokia Bell Labs, Huawei Technologies Finland, RF360, Pulse Electronics Finland, and Sasken Finland.

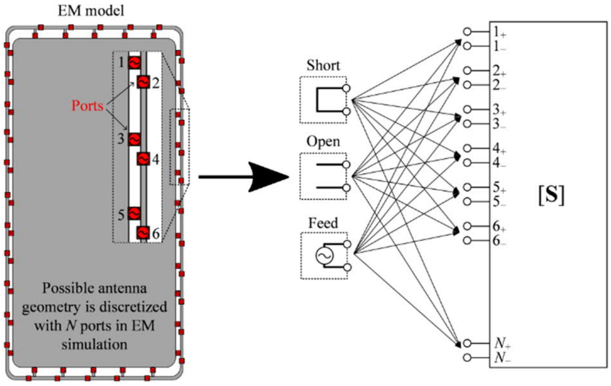

Fig. 1. Basic principle of transforming a multiport EM simulation model into a circuit optimization problem.

The antenna structure can be optimized separately for the 700-960 MHz low band and for the 1.7-2.7 GHz and 3-4 GHz high band. If one of the bands requires a short circuit to form larger antenna elements and the other prefer an open circuit, switches can be used to change the structure for each band and to make design adaptive. In this way, the low band can use larger elements and at the high band, we use larger number of smaller elements for higher order MIMO. The volume available for the antennas is always utilized as efficiently as possible.

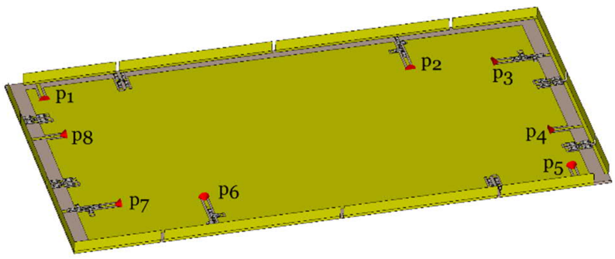

Fig. 2. Multi-feed antenna structure optimized with the new method.

An example of an antenna system designed with this method is shown in Fig. 2. The system has 2x2 MIMO capability in the low band and 4x4 in the high band. Each cluster has two feeds and there are six PIN diode switches in the metal rim and four diodes for the feeds that are only used in the high band. As a result of the optimization, the feeds of the antenna clusters are distributed around the entire metal rim at a novel way. The detailed information is given in [9].

To evaluate the performance of the whole system, including e.g., the efficiency of the antennas and the radiation patterns and correlations, the MIMO capacity in a Rayleigh fading environment with 20 dB SNR is calculated using the simulated and measured far-field patterns of the antennas. Fig. 3 shows the resulting capacities and the ideal capacities corresponding to 100 % efficient antennas with zero correlation for comparison. The capacities are about 8 bit/s/Hz at the low band and 17-20 bit/s/Hz at higher frequencies.

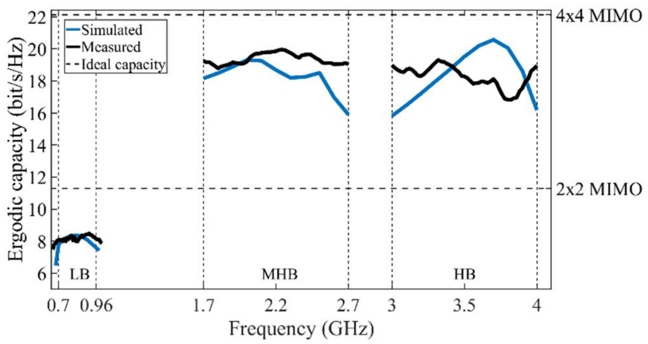

Fig. 3. Capacity calculated using the simulated and measured antenna properties for the multi-feed antenna system.

III. CO-DESIGNED MM-WAVE AND LTE HANDSET ANTENNAS

The coming 5G standard allocates new mm-wave frequencies, but also LTE and other sub-6 GHz antennas remain in use. The most important unsolved issue is how to collocate mm-wave and sub-6 GHz antennas within a shared volume. Although the frequency bands are far apart from each other, the close proximity of other antennas might deteriorate the performance especially at the LTE low band. Another major challenge is the increasing screen-to-body-ratio in mobile devices. Very narrow clearances leave only a little space for antennas, as the devices are packed with other electronics as well.

The available volume for antennas in a mobile phone is very limited, and hence, the different antennas must share volume. We have demonstrated co-designing mm-wave and LTE antennas in [10]. The presented proof-of-concept design is the first one to incorporate mm-wave and LTE antennas in a shared volume. The design consists of a four-element Vivaldi array and a capacitive coupling element as the mm-wave and LTE antennas, respectively. The structure is shown in Fig. 4. The detailed information is given in [10].

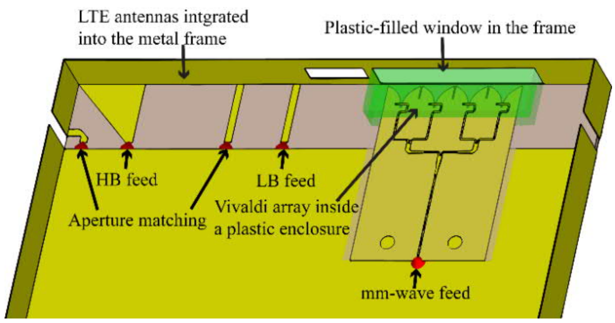

Fig. 4. mm-Wave antenna array sharing the same volume with an LTE antenna.

The LTE antenna operates at 700-960 MHz and 1.71-2.69 GHz. Both bands utilize the same part of the metal frame but are individually fed. The frame acts as the coupling element. The Vivaldi array locates in very close proximity and is enclosed by plastic. The whole module affects the impedance of the LTE antenna and restricts how the LTE feeds and aperture matching components can be placed.

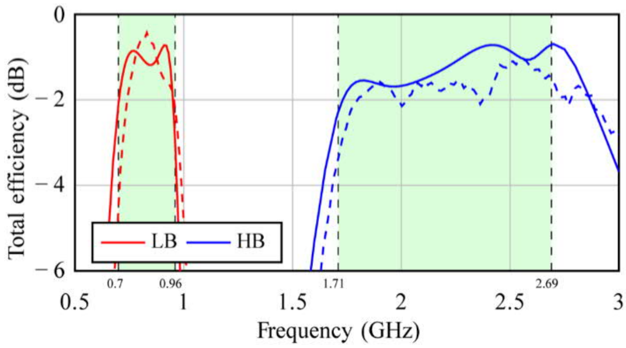

Fig. 5. Total efficiency of the LTE antenna. Solid lines show the simulated values and dashed the measured ones.

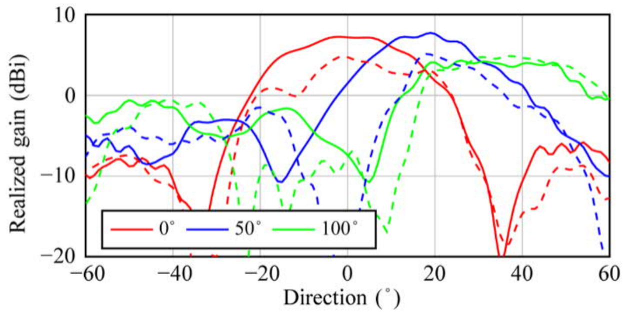

Fig. 6. Realized gain of mm-wave array at 28 GHz with three different progressive phase shift values between the elements. Solid lines show the simulated values and dashed the measured ones.

The operational band of the Vivaldi array is 25-30 GHz. Its beam-steering capability is realized with progressive phase shifts between the elements. For efficient radiation, a window needed in the metal frame is filled with the plastic enclosure of the antenna. The enclosure is a visual aspect but it also improves the matching of the antenna and reduces the effective wavelength of the signal allowing slightly smaller structures.

Critical issue for the coexistence of mm-wave and LTE antennas is that the mm-wave antenna does not short-circuit the LTE antenna. In [10], the plastic enclosure insulates the two antennas from each other, which enables us to achieve only very small interaction between them. Fig. 5 shows that the LTE antenna has total efficiency over -2 dB across both of its operational bands with very good agreement between simulations and measurements.

Fig. 6 shows the demonstrated beam-steering capability of the mobile Vivaldi antenna at 28 GHz. It has sufficient realized gain of 5-7 dBi with ability to steer nearly +/- 40deg. The results show that mm-wave and LTE antennas can coexist and share volume without greatly sacrificing either's performance. The proof-of-concept method presented in [10] can also be applied in other locations with other type of mm-wave antennas.

IV. WAVEGUIDE-BASED MILLIMETER-WAVE ANTENNA WITH INTEGRATED ELECTRONICS

Volume available for mm-wave antennas in base stations is not such a challenging issue as in mobile devices. However, base station antennas are typically electrically much larger for high directivity. For instance, there can be hundreds or thousands elements in a mm-wave phased array. This introduces some challenges.

First, a high-gain antenna can cover only a narrow angular region at a time. Therefore, the antenna needs to be able to steer the beam to be able to provide access to mobile terminals and to communicate with other base stations in different directions. Such an electronically beam-steerable phased array is typically realized on printed-circuit board using 4- or 8-channel vector modulator-based RF phase-shifter chips, see e.g., [11]. PCB transmission-line feed network is used to distribute the signal to phase shifters, which each feed 4 or 8 antenna elements. Phase shifters typically have Rx/Tx-switches for TDD (time domain duplexing) operation and PAs and LNAs to compensate for possible feed network and antenna losses.

This kind of phased antenna architecture is relatively straightforward, but may not provide the highest possible RF performance. Losses due to the RF feed network on PCB are typically significant for large arrays, PCB antennas are often relatively narrow band, they do not inherently allow very wide beam scanning range, they may suffer from active impedance mismatch at certain beam steering angles and their radiation efficiency may be relatively low.

Very low-loss and high-performance phased millimeter wave antenna arrays have been realized from injection molded plastic structures that are subsequently metallized (for instance the SENCITY® Matrix by Huber+Suhner). These structures can accommodate a low-loss waveguide-based RF feed networks together with broadband and efficient 3D-shaped antenna elements. However, these arrays do not provide electronic beam steering as they do not accommodate integration of active, element-specific electronics.

We have recently demonstrated how this kind of antenna and feed network structures can be integrated with active electronics, such as phase shifters on single PCB [12]. Fig. 7 illustrates the proposed solution. Waveguide feed network carries the RF signal to different phase shifters on PCB. A coupling probe on PCB is used to capture the signal propagating in the waveguide. The signal is further fed to phase shifter chip on PCB, from which is coupled forward to another waveguide. Finally horn antennas are used as array elements. All the active electronics on single PCB is integrated to the antenna by stacking the PCB between two 3D-structures.

As an example, Fig. 8. shows the measured (top) and simulated (bottom) 2D-radiation pattern of a 4x4 array at 71 GHz when the beam is steered to -25 in azimuth plane. The shapes of the simulated and measured beams agree well and the simulated total efficiency is -0.25 and the measured one -1.9 dB. The approach is widely usable at different mm-wave frequency bands and we have also demonstrated similar kind of antenna structure with active phase shifters at 28 GHz [13].

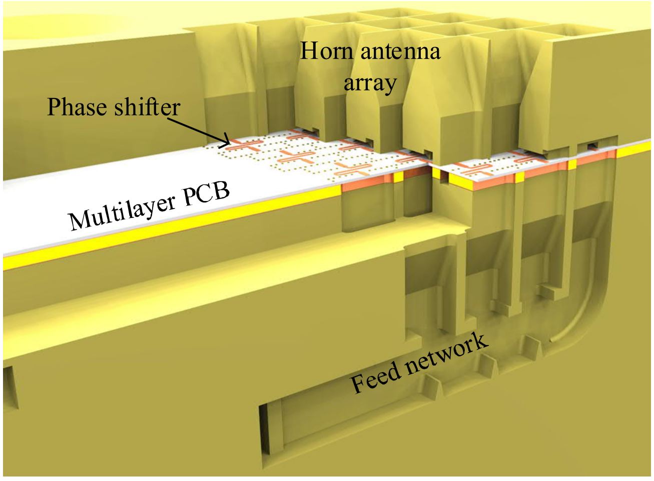

Fig. 7. 3D model cutaway picture of the waveguide-based antenna array with integrated electronics on PCB.

V. Conclusions

Antenna is one of the most important single part of a mobile communications system largely defining the efficiency of RF energy use. Current mobile antennas often convert RF energy inefficiently to radiating waves and also focus the radiated waves poorly. The coming 5G introduces additional challenges to antennas, but also provides opportunities such as possibility to focus RF energy more strongly.

Current mobile antennas are unable to adapt their operation to environment and are therefore inefficient in normal use. We introduced a potential way of making a mobile antenna adaptive to its environment by using multiple radiating elements operated collaboratively.

We have shown that it is possible to integrate directive beam-steerable mm-wave antennas in a shared volume with low frequency LTE antennas in a mobile device. We have also introduced a way to integrate active electronics with low-loss waveguide feed networks and antenna arrays to realize very large mm-wave arrays for 5G access points.

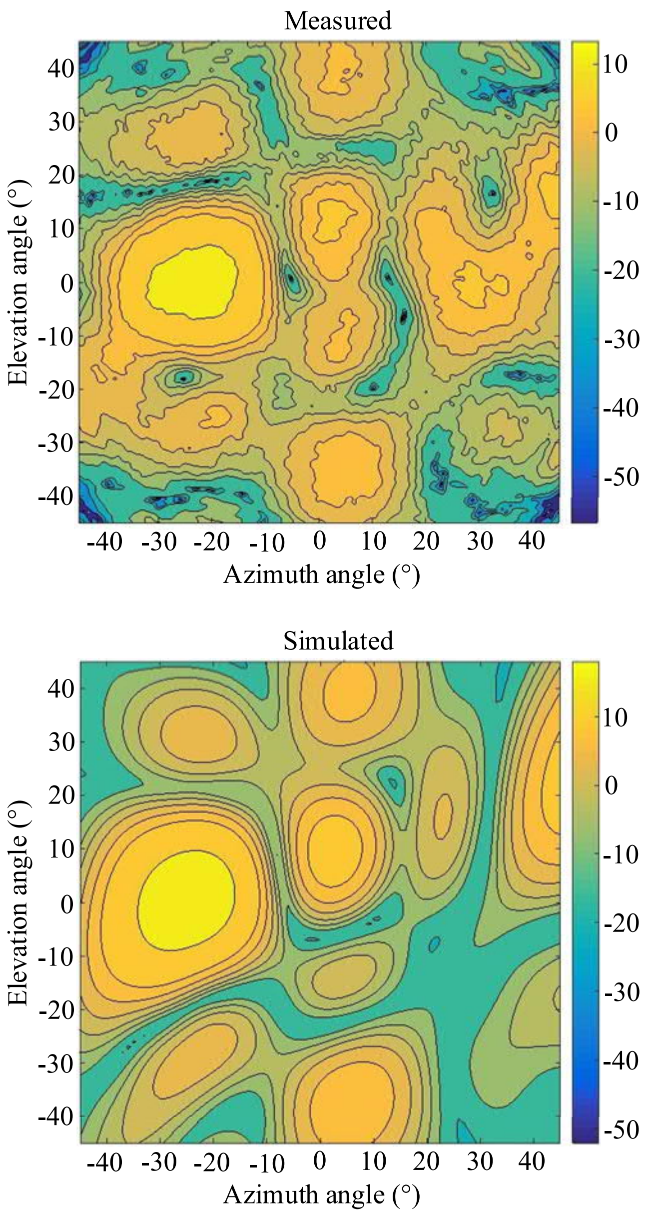

Fig. 8. The measured (top) and simulated (bottom) two-dimensional radiation pattern of the waveguide-based array at 71 GHz when the main beam is steered to -30° in azimuth.

REFERENCES

[1] A. S. G. Andrea and T. Edler, “On global electricity usage of communication technology: trends to 2030,” *Challenges*, vol. 6. no. 1, pp. 117 – 157, 2015.

[2] O. Blume, D. Zeller, and U. Bach, “Approaches to energy efficient wireless access networks,”*Proceedings of the 4th International Symposium on Communications, Control and Signal Processing, ISCCSP 2010*, Limassol, Cyprus, 3-5 Mar. 2010.

[3] G. F. Pedersen, ”Mobile Phone Antenna Performance 2016,” Report, Aalborg University, Denmark, 2016. http://vbn.aau.dk/files/240065248/Mobile_Phone_Antenna_Performance_2016.pdf

[4] J. Krogerus, J. Toivanen, C. Icheln, and P. Vainikainen, ”Effect of the human body on total radiated power and the 3-D radiation pattern of mobile handsets,” *IEEE Transactions on Instrumentation and Measurement*, vol. 56, no. 6, pp. 2375 – 2385, Dec. 2007.

[5] L. J. Chu, “Physical limitations of omni-directional antennas,” *Journal of Applied Physics*, vol. 19, no. 12, pp. 1163–1175, Dec. 1948.

[6] J. Hannula, J. Holopainen and V. Viikari, "Concept for Frequency-Reconfigurable Antenna Based on Distributed Transceivers," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 764-767, 2017.

[7] J.-M. Hannula, T. Saarinen, J. Holopainen, and V. Viikari, ”Frequency reconfigurable multiband handset antenna based on a multichannel transceiver,” *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 9, pp. 4452 – 4460, Sept. 2017.

[8] J.-M. Hannula, T. O. Saarinen, A. Lehtovuori, J. Holopainen, and V. Viikari, “Tunable eight-element MIMO antenna based on the antenna cluster concept,” *IET Microwaves, Antennas & Proapgation*, Feb. 2019.

[9] R. Luomaniemi, J.-M. Hannula, A. Lehtovuori, and V. Viikari, ”Switch-Reconfigurable Metal Rim MIMO Handset Antenna With Distributed Feeding," *IEEE Access*, vol. 7, pp. 48971-48981, 2019.

[10] J. Kurvinen, H. Kähkönen, A- Lehtovuori, J. Ala-Laurinaho, and V. Viikari, ”Co-designed mm-wave and LTE handset antennas,” *IEEE Trans. Antennas Propag.*, vol. 67, no. 3, pp. 1545 – 1553, Mar. 2019.

[11] K. Kibaroglu, M. Sayginer, T. Phelps and G. M. Rebeiz, "A 64-element 28-GHz phased-array transceiver with 52-dBm EIRP and 8-12-Gb/s 5G link at 300 meters without any calibration," *IEEE Transactions on Microwave Theory and Techniques,* vol. 66, no. 12, pp. 5796 – 5811, Aug. 2018.

[12] M. Islam, M. Leino, R. Luomaniemi, J. Song, R. Valkonen, J. Ala-Laurinaho, and V. Viikari, ”E-band beam-steerable and scalable phased antenna array for 5G access point,” *Int. J. Antennas Propag.*, vol. 2018, Article ID 4267053, 10 pages, 2018.

[13] M. Leino. R. Montoya Moreno, J. Ala-Laurinaho, R. Valkonen, and V. Viikari, ” Waveguide-based phased array with integrated element-specific electronics for 28 GHz,” accepted to *IEEE Access*, 2019.