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Published in:
14th European Conference on Antennas and Propagation, EuCAP 2020

DOI:
10.23919/EuCAP48036.2020.9135839

Published: 01/03/2020

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:
Luomaniemi, R., Salmi, A., Lehtovuori, A., & Viikari, V. (2020). Reducing User Effect on Mobile Antenna Systems with Antenna Cluster Technique. In *14th European Conference on Antennas and Propagation, EuCAP 2020* Article 9135839 (Proceedings of the European Conference on Antennas and Propagation). EurAAP. https://doi.org/10.23919/EuCAP48036.2020.9135839

Reducing User Effect on Mobile Antenna Systems With Antenna Cluster Technique

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***Abstract*—This paper studies the use of antenna cluster technique in mobile antenna systems and especially its use in reducing the user effect. The study is conducted with measurements of two different antenna designs using a hand phantom to represent the user holding the device. The results show that antenna designs based on the antenna cluster technique can retain good performance in the presence of a user. Furthermore, the cluster technique can also be used to reduce the user effect by adapting the cluster operation for different environments.**

***Index Terms*—frequency-reconfigurable, mobile antennas, multifeed antennas, multiple-input multiple-output (MIMO), user effect.**

I. Introduction

The requirements for the smartphone antennas are mainly set by two factors: the constantly increasing amount of data transferred through wireless networks and the requirements for the device appearance set by the users. This means that antennas should cover wide frequency bands and new frequency ranges, such as the 3.5 GHz band, are taken into use to enable the increasing data rates. In addition to increasing the frequency bands used, the data throughput is also increased using the multiple-input multiple-output (MIMO) techniques. On the other hand, the trend of maximizing the size of the touchscreen means that the antennas fulfilling these new requirements should be placed in yet smaller volume.

Frequency tuning and frequency reconfigurability have been popular techniques to improve the performance of mobile antenna systems in many published antenna designs. The frequency tuning or reconfigurability can be realized with, e.g., tunable capacitors [1]–[3], on/off-type switches [4], [5], and switches connected to multiple lumped matching components [6], [7]. These methods are based on using one or more tunable elements to modify the radiating structure or the matching circuits.

A completely different method for frequency reconfigurability has been developed in recent years. The antenna cluster technique, [8], [9], is based on multiple actively fed radiating elements operating collaboratively as one antenna. All feeds are used simultaneously with proper frequency dependent complex weighting to maximize the efficiency of the cluster. Several MIMO antenna designs based on the antenna cluster technique have been proposed in [10]–[12].

Smartphone antennas are typically designed for free-space usage. User effect, meaning the degradation of the performance caused by the user holding the device, is a major problem with these systems. Although the frequency reconfigurable designs have more degrees of freedom than traditional fixed antenna solutions, they also suffer from significant losses due to the user effect. In addition, the reconfigurable elements are hardly ever used to compensate the user or adapt the operation to changing environments.

In this work, we study the antenna cluster technique with the user effect. The technique utilizes tunable amplifiers and phase shifters to feed different elements which makes it possible to adapt the feed signals to the user as well. The measurements of two different prototypes based on antenna cluster technique show that these designs can achieve good performance in the difficult environment and that by re-optimizing the feeding weights, the user effect can be reduced.

II. Theory and Background

The antenna cluster technique, [8], [9], utilizes the operation of multiple distributed feeds used collaboratively. Each port is fed with a proper amplitude and phase to maximize the combined efficiency of the antenna cluster. By changing these feeding weights, the operation frequency of the cluster can be reconfigured.

The operation of a cluster is defined by the radiation matrix $\mathbf{D}$, which can be calculated from the far-field patterns of the antenna elements F_i as [10]

$$D_{ij} = \iint_{4\pi} F_i \cdot F_j^* \, d\Omega. \tag{1}$$

By using the far-field patterns for the calculation of the radiation matrix instead of only S-parameters, all losses of the system, including the user, are taken into account. Therefore, the effect of the user is properly taken into account.

When fed with complex feeding weights $\mathbf{a}$, the efficiency of the cluster is

$$\eta = \frac{\mathbf{a}^{\mathrm{H}}\mathbf{D}\mathbf{a}}{\mathbf{a}^{\mathrm{H}}\mathbf{a}}, \tag{2}$$

where $()^{\mathrm{H}}$ is the conjugate transpose. The maximum efficiency can be calculated as the largest eigenvalue of $\mathbf{D}$

$$\eta_{\text{max}} = \max\left\{\text{eig}\left(\mathbf{D}\right)\right\}, \tag{3}$$

and the feeding weights are the corresponding eigenvector.

Using this theory, the feeding weights can be calculated separately using either the far-field patterns in free space or with the user. This way the optimum performance can be achieved in both cases. In real use, a way of estimating the antenna properties and optimal feeding weights for different scenarios would be needed. In this work, we are assuming that complete far-field properties of the antennas in all cases are known.

In addition to efficiency, the performance of MIMO systems can be evaluated with ergodic capacity. With MIMO, capacity better describes the operation of the whole system than just efficiency. It gives a single figure-of-merit that includes, e.g., the efficiencies and correlations of all antennas. In the results presented in this paper, we evaluate the ergodic capacity following [13] using SNR $= 20\,\mathrm{dB}$ and 10^4 Rayleigh fading channel realizations in the calculations.

All the results in this paper are measured and calculated using the following method. First, the far-field patterns of individual feeds are measured while all the other ports are terminated with $50\,\Omega$ terminations. The patterns of each feed forming one antenna cluster are then combined computationally into the total pattern of the cluster using the complex weights calculated using (3). These total radiation patterns of the clusters are then used to calculate the total efficiency and MIMO capacity. All antennas are measured both in free space and with a Speag SHO3T0110-V3RWC hand phantom. The feeding weights are calculated for both cases to study how the re-calculation of these weights can be used to reduce the user effect.

III. Case I - Switch-reconfigurable MIMO antenna

The first antenna is based on the design originally proposed in [11]. This design uses distributed feeding around the whole metal rim of the device and switches to reconfigure the structure separately for low-band frequencies and high-band frequencies. Fig. 1 shows the antenna structure and the port configurations for the low-band and high-band operations. In the low band, switches in the rim are closed and two larger elements are used as one antenna cluster. The whole rim is then used for two clusters enabling two MIMO antennas in the 700–960 MHz frequencies. In the high-band configuration, the switches are open and larger number of smaller elements can be used. In total, four two-element clusters are used for four MIMO antennas in the 1.7–2.7 GHz and 3–4 GHz bands.

Fig. 2 shows the prototype and the measured total efficiencies are shown in Fig. 3. In the low band, about 30–40 % efficiency is achieved in free space. We have now two different sets of results with the user. First, with original weights meaning that the feeding weights are the same as in the free space case. Secondly, with optimal weights which means that the feeding weights have been re-calculated to maximize the efficiency with the user. Now we can see that for data stream 1, there is a significant difference between these two cases. By re-calculating the feeding weights, up to 3-fold increase in efficiency can be achieved in the low band. With the optimal weights, a flat efficiency with an average of 17 % is achieved. Without the re-calculated weights, the minimum efficiency drops down to 6 %. The second data stream is less affected by the user due to the location of the elements farther away from the hand. An average efficiency of 23 % is achieved in both cases.

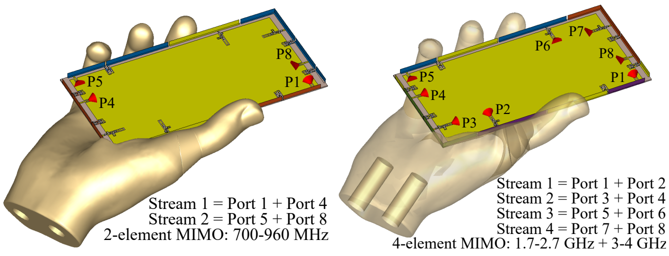


Fig. 1. (a) Low-band operation and (b) high-band operation port configurations and operation bands for the antenna of Case I. The elements of every antenna cluster are marked with same color.

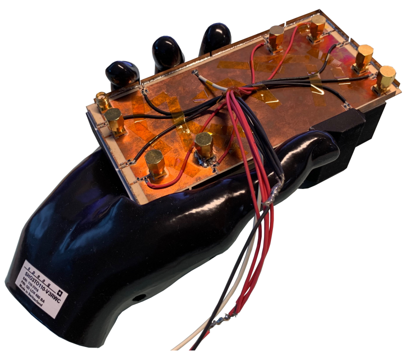


Fig. 2. The measured antenna prototype for Case I and the hand phantom used in the measurements.

The high-band results are more complex to interpret due to the larger number of antenna clusters. However, few important remarks can be made. The results show that while most of the data streams are affected quite significantly by the user, better than 30 % average efficiency can still be achieved. Secondly, similar to the low-band case, also in the higher frequencies we can use the cluster technique to compensate for the user effect. For example, with data stream 1 at around 2.4 GHz, the efficiency would drop to below 10 % but with the re-calculated weights, the efficiency can be kept at around 20 %.

To study the operation of this antenna and the benefits of the cluster technique in more detail, Fig. 4 shows the efficiencies of the data stream 1 cluster and the individual feeds of that cluster in both environments in the low band. Looking at the low-band results, we can see that in free space, the cluster works by combining the operation of two elements with different resonant frequencies. The amplitudes of these feeds show that the power balance between the elements is adjusted to reach the best efficiency across the whole band. With the user, however, element 4 that is closer to the palm is more affected than the other element. Without re-calculating the feeding weights, more power is fed for this element than is actually beneficial. With the re-calculated weights, more power can be fed to the element that works better in the new

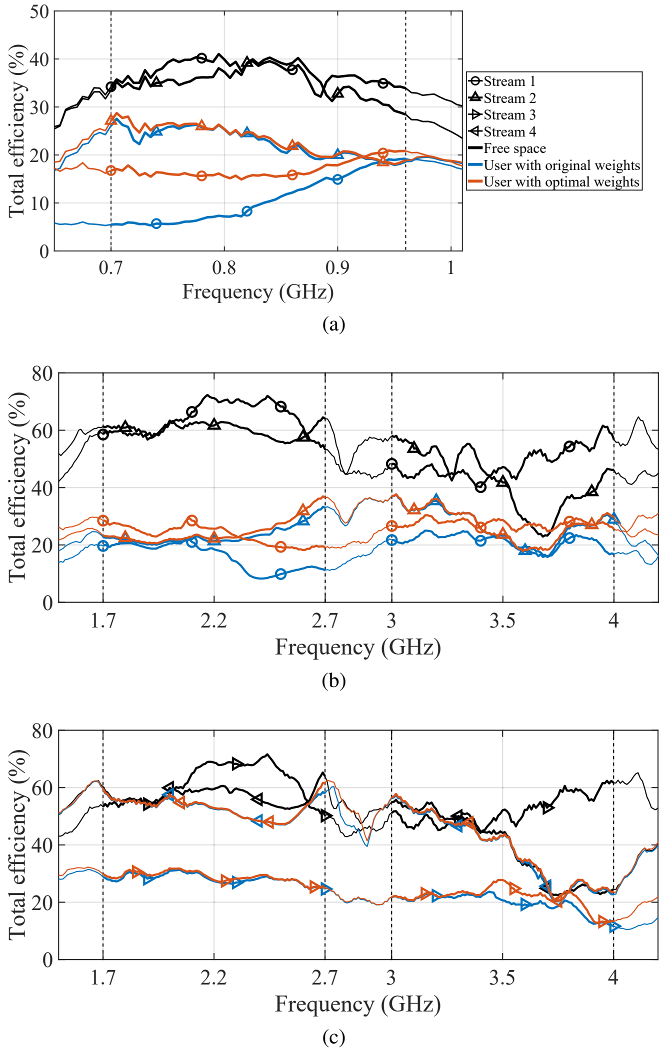


Fig. 3. Measured total efficiencies in free space and with user for Case I for (a) low band, (b) high band streams 1 and 2, and (c) high band streams 3 and 4.

environment.

Similar results for the high band are shown in Fig. 5. The same principle applies also for these results. Based on how the hand is holding the device and how that affects the operation of the antenna elements in different ways, improved efficiency can be achieved with cluster technique by adapting the operation better for changed environment compared to the case where fixed operation in different environments would be used.

Finally, Fig. 6 shows the capacities calculated for the low band and the high band results. The single-input single-output (SISO), 2×2, and 4×4 capacities refer to the maximum ideal capacities that could be achieved in free space with 100 % efficient antennas with zero correlation. The capacity results also confirm that the cluster technique can be used to compensate the user effect. Up to about 20 % and 9 % higher capacities in the low band and the high band, respectively, can be achieved by re-calculating the feeding weights compared to

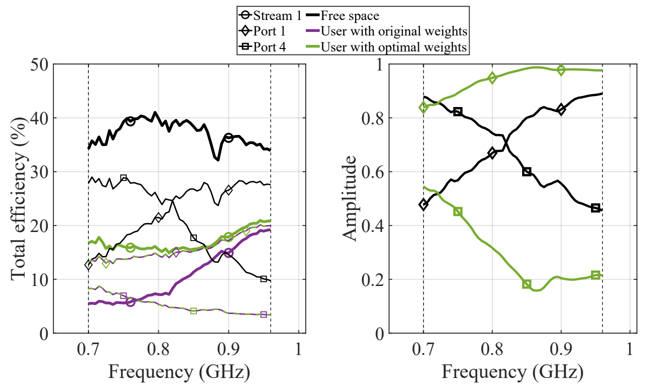


Fig. 4. Efficiencies of the antenna cluster and the individual elements and the amplitudes of the feeding weights in free space and with the user for Case I low-band.

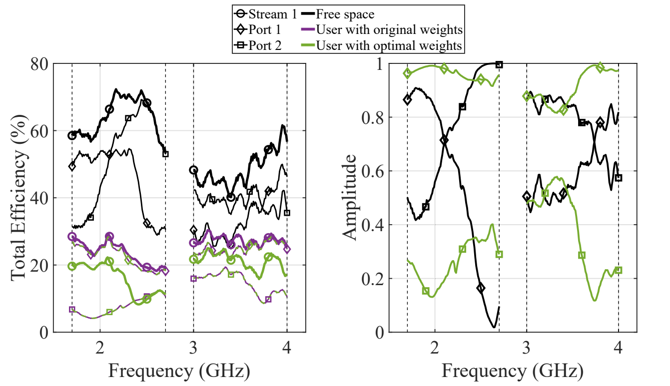


Fig. 5. Efficiencies of the antenna cluster and the individual elements and the amplitudes of the feeding weights in free space and with the user for Case I high-band.

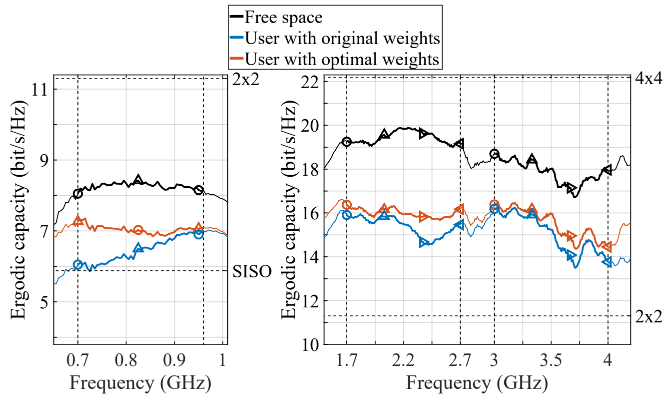
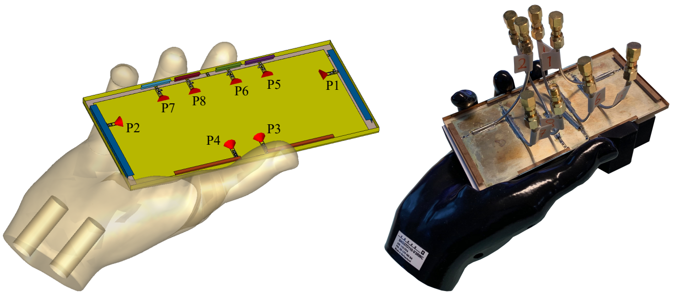


Fig. 6. Capacities calculated for the low-band and high-band results in free space and with the user for Case I.

using the original free-space weights. Also, in the low band, better than the ideal single-antenna capacity is achieved even with the user and in the high band, clearly better than the ideal 2×2 MIMO capacity is achieved.



(a) (b)

Fig. 7. (a) Antenna model and (b) measured prototype with the hand phantom for Case II.

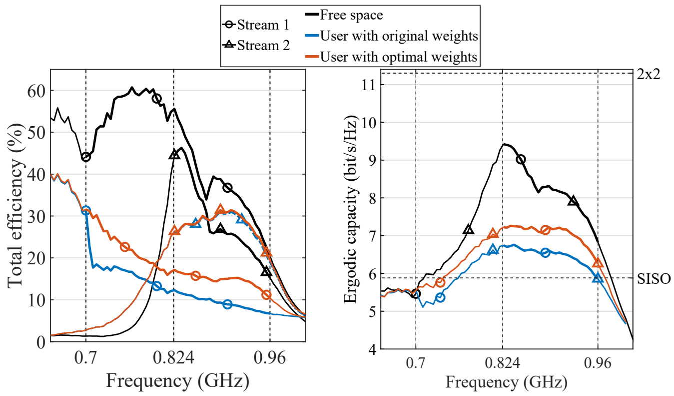


Fig. 8. Measured total efficiencies and calculated capacities for the low-band antennas for Case II.

TABLE I

FREQUENCY BANDS AND PORT CONFIGURATIONS FOR CASE II ANTENNAS

<table>
<tr><th colspan="3">LB</th><th colspan="3">HB</th></tr>
<tr><td rowspan="3">Stream 1</td><td rowspan="3">P1+P2</td><td rowspan="3">700-960 MHz</td><td colspan="3">version 1</td></tr>
<tr><td>Stream 1</td><td>P5+P6</td><td>1.7–5 GHz</td></tr>
<tr><td>Stream 2</td><td>P7+P8</td><td>1.7–5 GHz</td></tr>
<tr><td rowspan="5">Stream 2</td><td rowspan="5">P3+P4</td><td rowspan="5">824-960 MHz</td><td colspan="3">version 2</td></tr>
<tr><td>Stream 1</td><td>P5</td><td>1.7–5 GHz</td></tr>
<tr><td>Stream 2</td><td>P6</td><td>3.4–4.2 GHz</td></tr>
<tr><td>Stream 3</td><td>P7</td><td>1.7–5 GHz</td></tr>
<tr><td>Stream 4</td><td>P8</td><td>3.4–4.2 GHz</td></tr>
</table>

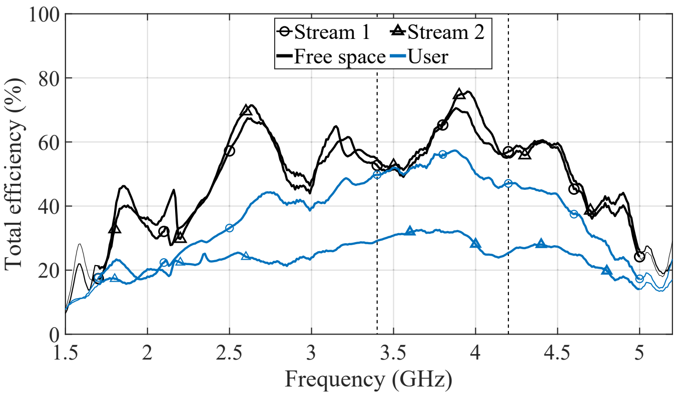


Fig. 9. Measured high-band total efficiency for Case II version 1 antenna.

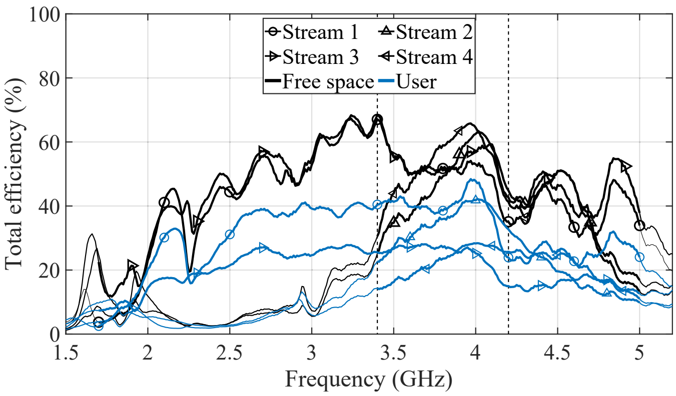


Fig. 10. Measured high-band total efficiency for Case II version 2 antenna.

IV. Case II - Unbroken Metal Rim MIMO Antenna

The second antenna is based on the design originally proposed in [12]. In this case, the metal rim of the device is completely unbroken, which makes the antenna design even more challenging, especially for MIMO antennas, due to the high coupling between different elements. With the antenna cluster technique, this coupling can be utilized and two orthogonal radiation modes in the low band can efficiently be excited [14]. This way, two-element MIMO operation can be utilized in the 824–960 MHz low band and the other cluster can even cover the full 700–960 MHz band.

In the original design, the high-band antennas were designed to cover the 1.7–2.7 GHz and 3.4–3.8 GHz bands. In this work, we extend the study of this design. Because the high-band antenna elements are close to each other, the user's hand affects both elements of an antenna cluster in a similar manner. This can lead to a situation where re-optimization of the feed weights of the clusters does not offer any significant improvement, although the performance level itself can be good [15]. Therefore, the matching networks of the high-band antennas are re-designed for two different versions. In version 1, the four elements form two clusters that are designed to cover a wide bandwidth from 1.7 GHz up to 5 GHz with two MIMO antennas. Version 2 uses these four elements individually so that two of them cover the same bandwidth as in version 1 and the other two elements cover a narrower 3.4–4.2 GHz bandwidth. This version then has two MIMO antennas in the 1.7–5 GHz band and four MIMO antennas in the 3.4–4.2 GHz band. The antenna structures are shown in Fig. 7 and the port configurations and the designed frequency bands of each data stream are presented in Table I.

The low-band total efficiency and capacity results are shown in Fig. 8. Similar conclusions can be drawn from these results as from the low-band results of Case I. Also in this case, one of the data streams benefits by more than 65 % in terms of total efficiency from the compensation by cluster weight re-optimization. The other data stream is much less affected by the user in general due to the different placement of the antenna elements and the current distributions in the metal rim.

The measured total efficiencies for both variations of the high-band antennas are shown in Fig. 9 and Fig. 10. The results show that in this design, the four high-band elements can be used either as two clusters or as four independent antennas depending on the wanted properties of the system. When used independently, four-element MIMO operation can be achieved in the 3.4–4.2 GHz band leading to higher data throughput. However, using the elements as antenna clusters also has benefits. For example, the bandwidths at 40 % total efficiency level in free space for data streams 1 and 2 are 2360 MHz and 2350 MHz for version 1, whereas for the data streams 1 and 3 for version 2, they are 1750 MHz and 1950 MHz. Similarly for the 20 % efficiency bandwidths with the user, the results are 2890 MHz and 2640 MHz for version 1 and 2700 MHz and 1700 MHz for version 2.

The results of Case II show that with the antenna cluster technique, wider bandwidths can be achieved by combining the operation of multiple antennas. Because the elements of an antenna cluster can be tuned to resonate at different frequencies, wide bands can be covered with the combined operation. Also, as the user's hand can affect the individual elements differently depending on the placement of the elements and the grip of the hand, the cluster is more robust against the user effect than individually used antennas.

V. Conclusion

This paper studied the antenna cluster technique and its applications for smartphone MIMO antennas with the user effect. Two different antenna designs have been studied with measurements of prototypes both in free space and with a hand phantom representing the user. The results show that due to the distributed feeding enabled by the cluster technique, the re-optimization of the complex feeding weights of the antenna elements can be used to reduce the user effect in certain cases. Although changing the weights for different operation environment does not always provide improvement in performance, the cluster technique can still be beneficial due to the increased robustness against the user effect offered by the combined operation of multiple antenna elements.

Although the user was not originally taken into account in the design process of the studied designs, they can still retain good performance level when held by the user's hand. To achieve full benefits of the adaptivity offered by the antenna cluster technique, the user effect should be taken into account in the antenna design process in future studies. Also, ways of predicting the needed adjustments in the feeding weights without the need for the full far-field information should be studied.

Acknowledgment

This work was supported in part by the Academy of Finland, under decision 319005.

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