Hannula, Jari Matti; Saarinen, Tapio O.; Lehtovuori, Anu; Holopainen, Jari; Viikari, Ville

Tunable eight-element MIMO antenna based on the antenna cluster concept

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1 Introduction

Increasing expectations for wireless communications demand even better network solutions. Mobile data traffic has grown 18-fold in the past five years and is expected to increase 7-fold during the next five years [1]. To answer to these demands, the fifth generation (5G) of mobile communications is being standardised and developed. The 5G networks should provide 100–1000 times the capacity of the current long-term evolution (LTE)-based fourth-generation networks [2–4]. The 5G communications standard, IMT-2020, is planned to be released by 2020.

To cover future demands, additional frequency bands have been allocated in an agreement signed in WRC15 [5]. For example, 3.4–3.6 GHz has been allocated globally for mobile communications. About 3.6–3.8 GHz is available in some regions, and there are ongoing discussion for allocating the 3.8–4.2 GHz band for mobile use in Europe. All in all, the allocated sub-6 GHz spectrum will be globally more diverse, but also more fragmented, demanding improvements in capacity from improving spectral efficiency of wireless communication via spatial multiplexing. In this work, we design an eight-element MIMO antenna capable of operating at frequencies from 1.7 to 6 GHz.

In this work, we design an eight-element MIMO antenna in a handset form factor. Previously published designs [6–8, 10] are limited to a narrow band. Whereas in this work we design an antenna capable of operating at frequencies from 1.7 to 6 GHz. This operation across a wide bandwidth is enabled by the concept studied in [11, 12], which involves the use of multiple closely spaced antenna elements to form a single antenna cluster. The operating frequency of the cluster can then be changed by weighting the signal fed to each element, somewhat similar to beam-steering an antenna array.

This concept has previously considered only a single cluster. The main contribution of this work is the extension of the antenna cluster theory to MIMO. In this work, we extend the theory to consider all antennas in the vicinity, enabling us to model their effect and to use the concept for MIMO. The strong coupling in an eight-element antenna structure enables using the concept for MIMO. The proposed antenna achieves over 60% efficiency at frequencies above 3 GHz, and the system exceeds the ergodic capacity of the ideal 7 × 7 MIMO in that band.

2 Theory

To understand the operating principle of the proposed antenna, the basic concepts of MIMO and the applied frequency reconfigurability method are discussed.

2.1 Multiple-input–multiple-output

MIMO techniques are a method for improving the spectral efficiency of wireless communication via spatial multiplexing. In theory, the capacity of an $M \times M$ MIMO channel can be $M$ times that of a single-input–single-output channel. However, this result assumes that there exists independent Rayleigh fading among the antennas, i.e. the MIMO channel $H$ is uncorrelated. In practise, the channel is not uncorrelated, reducing the capacity of the system.

In the following, we present the equations characterising the MIMO performance and enabling us to compare the antenna designs. We assume an infinitely rich Rayleigh fading channel, to provide a neutral comparison between different designs. Assuming that the transmitter does not know the channel, the instantaneous capacity $C$ of an $M \times M$ MIMO channel is

$$C = \log_d \det \left( I_u + \frac{\rho_t}{M} HH^H \right)$$

where $I_u$ is an $M \times M$ identity matrix, $\rho_t$ is the signal-to-noise ratio (SNR) and $H$ is the channel matrix. Assuming the Kronecker model, the effect of the receive and transmit antennas can be separated from $H$ with the relation

$$H = R_r^{1/2} H_r R_t^{1/2}$$
where $R_r$ and $R_t$ are the antenna correlation matrices. Assuming Rayleigh fading, the elements of $H_w$ being independent and identically distributed variables, i.e. zero-mean circularly symmetric complex Gaussian random variables. For purposes of evaluating the handset antenna performance in this paper, we designate it as the receiver antenna $R_r$ and assume ideal transmitter antenna, i.e. $R_t = I_M$.

All the correlation is then due to the receive antennas, which are modelled with $R_r$. In addition to the correlation, the antenna efficiency reduces the MIMO performance, by reducing the available SNR. Thus, the overall effect of the receiving antenna on the channel is

$$R_r = \Lambda^{1/2} R_i \Lambda^{1/2} \quad (3)$$

where

$$\Lambda = \text{diag}[\eta_1, \eta_2, \ldots, \eta_M] \quad (4)$$

where $\eta_i$ is the total efficiency of the $i$th antenna and $R_i$ is the normalised correlation matrix

$$R_i = \begin{bmatrix} 1 & \rho_{12} & \cdots & \rho_{1M} \\ \rho_{21} & 1 & \cdots & \rho_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{M1} & \rho_{M2} & \cdots & 1 \end{bmatrix} \quad (5)$$

where the elements on the main diagonal equal one (an antenna is entirely correlated with itself) and $\rho_{ij}$ are the complex correlation coefficients between two distinct antennas [15]. The complex correlation coefficient between antennas $i$ and $j$ can be calculated from the far-field patterns

$$\rho_{ij} = \frac{\int \int F_i F_j^* \, d\Omega}{\sqrt{\int \int F_i F_i^* \, d\Omega \int \int F_j F_j^* \, d\Omega}} \quad (6)$$

where $F_i$ is the far-field pattern of the $i$th antenna. With $R_r$ fully characterised, the ergodic capacity of the channel can be calculated from a large number of Monte Carlo simulations on (1).

The complex correlation coefficient relates to the envelope correlation coefficient (ECC), a commonly used metric for evaluating multiantenna systems. Assuming two narrow band signals following a Rayleigh distribution, the ECC is [16]:

$$\rho_{e, ij} \approx |\rho_{ij}| \quad (7)$$

where $\rho_{ij}$ is the complex correlation coefficient calculated from (6).

### 2.2 Frequency reconfigurable antenna cluster

The antenna design presented in this paper uses the frequency reconfigurability concept in [11, 12], which is also extended here. This section briefly describes the concept to provide the necessary background for the proposed antenna design. The fundamental principle of the method is the simultaneous use of multiple antennas to form an antenna cluster. Each antenna is fed the same data, but with the specific amplitude and phase weighting. By choosing the weights properly, both the mismatch and coupling can be reduced, assuming the antennas are designed in a suitable manner. The weights can then be adjusted to tune the antenna to another frequency. The implementation of the weighing requires a suitable transceiver. The transceiver implementation has been evaluated multiantenna systems. Assuming two narrow band coefficients between two distinct antennas [15]. The complex correlation coefficient (ECC), a commonly used metric for characterising, the ergodic capacity of the channel can be calculated from the eigenvalues of $\delta$. The results published on this topic so far assume that the cluster is the only antenna in the vicinity, and any power that is not reflected is radiated [11, 12]. This is because the weighting coefficients have been calculated from the scattering parameters. Scattering parameters cannot distinguish between radiated power and losses, as it only considers whether the power reflects back to the ports or if it is dissipated inside the network. Thus, the radiation matrix $D$ calculated from the scattering parameters can only be used to minimise the reflected power. When the device has only one antenna cluster and low ohmic losses, this is not a problem. With MIMO, however, the emphasis is also on the other antennas on the device. If the effect of the other antennas is not considered, $D$ gives only the matching efficiency, so ignoring the effect of coupling, which is a significant source of loss in MIMO systems. Additionally, the weighting coefficients might not be optimal for maximising the radiated power. This relates to the idea of uncoupled matching [20], in which one should not aim to minimise the reflections, but also consider the coupling to other antennas.

There are two ways to model the effect of the other antennas. One option is to include every antenna on the device in the scattering matrix. However, we do not want to feed all the antennas simultaneously, because that would combine all the antennas into one overly large cluster and prevent them from being used for MIMO. Therefore, the scattering matrix should only include the columns corresponding to the active antenna elements, i.e. the elements used to form the specific cluster, but also include the rows that describe how the active antennas couple to the other nearby antenna elements.

Alternatively, based on the relationship between the radiation patterns and the scattering matrix [21], the radiation matrix can be calculated from the far-field radiation patterns. The advantage of the far-field approach is that it considers all the losses in the system. There is no need to explicitly include antennas outside the cluster in the radiation matrix, and ohmic losses are also considered. Using far-field patterns, the elements of the radiation matrix can be calculated from [21, 22]

$$D_{i,j} = \frac{1}{4\pi^2} \int \int F_i F_j^* \, d\Omega \quad (11)$$

where $F_i$ is the radiation pattern of the $i$th antenna, normalised such that $D_{i,i}$ equals the total efficiency of that antenna. The distinction between (8) and (11) is that (8) considers the matching efficiency of the cluster, whereas (11) shows the total efficiency. If the antenna structure is lossless, (8) equals (11).
In this section, we show the design procedure for applying the antenna cluster concept for wideband MIMO antenna design. First, the individual cluster with frequency reconfigurable behaviour is designed, according to the principles explained in [12]. Then, the design is multiplied across the volume resulting in eight separate antenna clusters.

### 3.1 Antenna design

The described theory is used to implement an $8 \times 8$ MIMO in a handset form factor. The volume of the chassis is $136 \times 68 \times 6 \text{ mm}^3$, corresponding roughly to that of a modern smartphone. The design includes eight antennas, each with a volume of $15 \times 10 \times 6 \text{ mm}^3$. The antennas are placed along the long edges of the chassis, as shown in Fig. 1. Although the 10 mm side clearance is not compatible with current trends in smartphone design, the proposed antenna can be used to demonstrate the feasibility of $8 \times 8$ MIMO at lower frequencies.

To implement MIMO using the antenna cluster method, the first step is to design the antenna clusters. Since this work is the first implementation of the method, similar clusters are used for all the MIMO antennas. However, one could design different clusters for different locations as well.

In this design, one antenna cluster consists of four antenna elements, each with a different resonant frequency. To take advantage of the full volume allocated for each antenna, the antenna is designed on a substrate block with these dimensions. The design of the individual antenna elements is done starting with the longest element that covers the lowest frequencies of the targeted operation bands. The idea is to route the longest antenna alongside the edges of the block to obtain the required length in a reasonable manner without meandering. A design principle is to keep the elements with approximately the same length as far away from each other as possible. Other elements are then added and spaced accordingly to obtain frequency reconfigurability across the whole band in accordance with the concept in [11]. The dimensions of the antenna elements are given in Fig. 1a. The design is based on the one presented in [12], which has been modified to better take advantage of the height of the antenna.

The ideal number of antenna elements depends on the targeted frequency range and available antenna volume. During the antenna design process, four proved to be the optimal number of antenna elements for covering the entire frequency range. In our simulations, we were unable to cover the entire bandwidth with only three elements. Adding the fifth element was not considered since the specifications were already achieved with four.

The next step after designing a working antenna cluster is to implement MIMO through the use of multiple clusters. In this work, this is done by duplicating the block to eight different locations. Then, the MIMO performance should be optimised. The coupling to the other clusters and the location on the chassis will modify the operation of each cluster. This could be done through even large modifications to the clusters, but in this work, we limit this step to only changing the location of the ‘edge’ clusters, as shown in Fig. 1.

A challenge with the block placement is that obtaining good matching at 1.7 GHz requires that the block is placed as close to the short edge of the ground plane as possible to properly excite the dominant mode in the chassis [23, 24]. However, because the corners are occupied by the four antenna blocks, the remaining four blocks must be placed further away from the corners. Placing the edge cluster closer to the corner improves matching, but reduces the isolation to the corner cluster. Moving the cluster further away has the opposite effect. Thus, the design involves finding the optimal compromise between these two design criteria.

### 3.2 Prototype

The prototype is manufactured on an radio-frequency plastic PREPERM 255 ($\varepsilon_r = 2.55$, $\tan \delta = 0.0008$ at 1 GHz) by Premix (http://preperm.com). The substrate including the antenna blocks is milled to shape from a single piece of the plastic. The ground plane is made from a thin sheet of laser-cut bronze which is attached to the substrate by routing and soldering wires through the via holes. The measurement cables are routed through the back of the device to minimise their impact on the antennas. For effective grounding and rigid connection of the measurement cables, the design includes a ground plane on both sides of the substrate. The two ground planes are connected with several vias, as shown in Fig. 1, to ensure that they are at the same potential. The antenna elements are made using copper-coated Kapton polyimide, on which the antenna shape is created. The polyimide has an adhesive back, so it is cut to shape, placed on the antenna block and then bent to cover the sides of the block.

### 4 Results

In this section, we show the performance results for the MIMO antenna prototype. The results are divided into two categories: intra-cluster results, which show the performance of an individual cluster, and MIMO results, where the operation of the entire antenna system is evaluated.

The analysis in this paper is performed without an actual reconfigurable transceiver. The concept was experimentally verified in [12]. In [17], the feasibility of an integrated transceiver implementation is discussed. As of this moment, no suitable transceivers exist for this concept. Thus, the analysis is performed based on combining individually simulated and measured field data using the theory presented in Section 2.

#### 4.1 Intra-cluster performance

The design includes two types of antenna clusters depending on their location: corner and edge clusters. Fig. 1 shows the locations of the clusters. Owing to symmetry, only two clusters are required.
to characterise the entire antenna. The remaining clusters have identical performance with the only difference being in the orientation of the radiation pattern, which can be changed by mirroring the pattern along the corresponding symmetry plane(s).

Fig. 2 shows the scattering parameters for the corner cluster and Fig. 3 shows the edge cluster. The coloured curves depict the reflections $S_{ii}$ of each port. The coupling $S_{ij}$ between the ports is also relevant for the cluster operation, but the graphs are not shown as not to clutter the figure. Most importantly, the black curve depicts the minimum total active reflection coefficient (TARC), obtained when the cluster is fed with the excitation shown in Figs. 2b and c. Comparing the TARC to the reflection coefficients of ports 1a and 1c shows the benefit of the method.

The excitation is to be generated with the transceiver, and changed according to the operating frequency, thus making the cluster tunable. Depending on the scattering parameters, sometimes the optimal excitation at a port can be zero. This occurs for the corner cluster at around 4.1 GHz, where feeding port one is not necessary since the combined coupling from the other ports cancels itself.

The results show that a very flat matching level is obtained for the corner cluster from 1.8 to 3.2 GHz, and a TARC smaller than −10 dB is reached over most of the frequency range. The exception is around 5 GHz, which none of the elements cover very well.

The far-field patterns of the antenna elements are measured using the MVG StarLab 6 GHz measurement system. Each element is measured separately, with the remaining elements terminated with 50 Ω loads. The radiation matrix is formed from the radiation patterns using (11), and optimal weights are computed from (10). Fig. 4 illustrates the total efficiencies of the corner and edge clusters when the weighted feeds are applied. The simulated and measured efficiencies are in good agreement with each other. Although both clusters resonate at the same frequency, the edge cluster operates with reduced efficiency. The coupling to the lowest chassis mode is the strongest in the corner [23, 24], which improves the performance of the corner cluster. The edge element does not have this advantage, and thus reduced performance is obtained near the lower limit of the design bandwidth.

One of the goals of this work was to investigate whether the isolation between clusters could be improved through weighted feeding, i.e. instead of only improving matching to also improve isolation. However, using the scattering parameters and (8) provides essentially identical results for this design. The intra-cluster coupling appears to be much more significant than the...
Far is the measurement process itself: the far-field approach requires eight measurements, whereas the scattering parameter difference between calculating the weights from the far field or the coupling to the other clusters. As such, there is not much of a

Fig. 6

Simulated sources of loss for a signal fed to the (a) corner, (b) edge clusters. The black curves represent loss due to mismatch (coupling to itself)

coupling to the other clusters. As such, there is not much of a difference between calculating the weights from the far field or the scattering matrix, at least in this structure. In the future, this effect should be considered with different structures. The main benefit so far is the measurement process itself: the far-field approach requires eight measurements, whereas the scattering parameter approach requires 28 measurements with a two-port vector network analyser.

The measurement results in Fig. 4 show that total efficiency of 50% is reached above 2.5 GHz, where the performances of the corner and edge clusters are basically identical. This shows the importance of the chassis mode with regards to the overall performance in the traditional 1.7–2.7 GHz band. Efficient implementation of an 8 × 8 MIMO is, therefore, difficult in that band because only half of the antennas can be placed in the corner.

Once the weighted far-field patterns have been generated, the cluster can be considered an ordinary single-element antenna for the purposes of evaluating the MIMO performance. Thus, the existence of multiple ports is embedded in the cluster itself.

4.2 MIMO performance

With the antenna clusters characterised, the MIMO performance of the antenna is analysed using common metrics of MIMO, as described in Section 2.1. Since only two clusters are measured, the patterns of the remaining clusters are generated by performing corresponding coordinate transformations on the measured patterns.

The first parameter that affects the MIMO performance is the efficiency of antennas, shown already in Fig. 4. To analyse the loss of efficiency further, Fig. 5 shows the matching and coupling of both the corner and edge clusters. The largest source of loss is quite evident from the result: the coupling between the adjacent corner and edge clusters, reaching even −6 dB at some frequencies. Additionally, the edge cluster has mismatch loss in the 1.7 GHz band. The coupling could be reduced by moving the edge clusters further away from the corners, but this comes at the cost of reduced matching efficiency. The chosen placement is a compromise between these two effects.

In the case of high-order MIMO, the effect of the smaller coupling cannot be neglected either. To demonstrate this behaviour, Fig. 6a illustrates the different sources of losses for power fed to the corner cluster #1. This representation emphasises the cumulative effect the coupling has. Although the coupling to the individual non-adjacent clusters is well below −10 dB, the total coupling to them at 1.7 GHz accounts for over 20% of loss in efficiency.

At 1 GHz, almost all powers are lost due to the impedance mismatch. As the frequency increases, the matching improves, but the coupling grows as well. Thus, from 1.7 to 2.5 GHz the total loss remains quite constant. The largest source of coupling also changes: as the coupling to clusters #3–#8 decreases, the improved matching of cluster #2 causes more power to couple to it from cluster #1. The adjacent cluster remains the largest source of loss (almost 30% at 2.5 GHz) all the way to 5 GHz, where its effect finally diminishes.

Fig. 6b depicts the same data for edge cluster #2. The edge cluster shows a similar trend, though with larger overall loss due to the impedance mismatch. The loss curves of both clusters converge at around 3 GHz, as is evident also from the efficiency curves depicted in Fig. 4.

In addition to efficiency, the correlation between the antennas has an effect. Fig. 7 depicts the ECCs calculated from the simulated and measured far-field data. The ECC is under 0.2 in the operating band, with the exception of the correlation between the adjacent edge elements (ρ32). Nevertheless, in the operating band, the ECC is below 0.5, which is considered adequate for MIMO operation [15].

The simulated and measured correlations match to each other fairly well excluding the correlation between clusters #2 and #3. According to simulations, the correlation is above 0.6 below 1.5 GHz and smaller than 0.2 above 2 GHz, whereas the simulated peak correlation is lower, but it remains significant until higher frequencies. We believe that this is mainly due to the feeding cables connected to clusters #1 and #2 slightly distorting the radiation pattern of the edge cluster, which makes the symmetry assumption inaccurate. Simulations that model the measurement cables support this theory, as similar behaviour is seen there as well.
reasonably good performance: above 3 GHz, over 60% efficiency

that presented in [26], where the MIMO capacity is studied by

of antennas in the handset. Above 3 GHz, the antenna enables a

antenna size have been studied in [25]. The results of this work

This demonstrates that the desired improvement in spectral
efficiency can be obtained with high-order MIMO at these

frequencies. However, the results show that though the antennas
can be matched well, obtaining good efficiency with an eight-

element MIMO in the 1.7–2.7 GHz band is challenging due to
coupling. The presented design was based on copying an
individually designed cluster. The performance could be optimised
further by better considering the MIMO performance already
during the individual cluster design.

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Fig. 7 ECCs calculated from

(a) Simulated, (b) Measured far-field patterns

Fig. 8 Calculated ergonomic capacity for both the simulated and measured
antenna parameters when the SNR is 20 dB. The ideal capacity for different
M × M MIMO channels is shown for comparison

Fig. 8 shows the ergonomic capacity, calculated as the mean value of
(1) using 104 random samples at each frequency point. A Rayleigh fading channel is assumed for the propagation
environment. In the calculations, we assume the SNR to be 20 dB
and the number of base station antennas to be equal to the number
of antennas in the handset. Above 3 GHz, the antenna enables a
capacity larger than that of the ideal 7 × 7 MIMO, reaching at best
97% of the ideal capacity of the 8 × 8 MIMO. Below 3 GHz,
the capacity is limited because of reduced efficiency.

The theoretical limitations of MIMO capacity as a function of
antenna size have been studied in [25]. The results of this work
also indicate a limitation on capacity due to the limited chassis
size. Additionally, the behaviour of the capacity curve is similar to
that presented in [26], where the MIMO capacity is studied by
conjugate matching of the antennas at point frequencies.

5 Conclusion
This work presented the first application of the antenna cluster
method for MIMO operation. The proposed method was used to
implement an eight-element MIMO antenna, whose operating
frequency is tunable over a wide bandwidth, from 1.7 to 6 GHz.
Despite only being the first implementation, the antenna has
reasonably good performance: above 3 GHz, over 60% efficiency
is obtained for each antenna, resulting in an ergonomic capacity
exceeding that of the ideal 7 × 7 MIMO. At the highest frequencies,
the achieved ergonomic capacity is 97% of the theoretical maximum.
This demonstrates that the desired improvement in spectral
efficiency can be obtained with high-order MIMO at these

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