Evaluation of a Compact Antenna Concept for UWB Massive MIMO

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Abstract—A compact antenna concept for ultra wideband massive MIMO is proposed and evaluated. The concept is based on the simultaneous excitation of different Characteristic Modes on each element of the multi element antenna. Thereby, a 484 port antenna with low port to port correlation having only 121 physical antenna elements is generated. Its performance for MIMO systems is evaluated by link-level capacity simulations.

Keywords—Massive MIMO, UWB, Characteristic Modes, Link-level Capacity

I. INTRODUCTION

Optical fibres can provide fast internet access currently enabling data rates of up to 100 GBit/s. The bottleneck in bringing this data rate to mobile users is the wireless link from the indoor base station to the mobile devices. Wireless Local Area Networks working in the IEEE 802.11.ac standard can provide data rates up 867 MBit/s and data rates above 10 GBit/s have been demonstrated in lab experiments. Data rates of 100 GBit/s and beyond are desired for future applications but today there is no technology available which is capable of realizing this need.

The achievable data rate of a communication system is basically a function of the frequency bandwidth used and the bandwidth efficiency realized by the system. In principle, there are two options to increase the bandwidth efficiency of a power limited system, namely the use of ultra wide bandwidth (UWB) or the application of MIMO technology (Multiple Input Multiple Output).

The frequency range below 10 GHz offers good propagation conditions and a rich multipath channel enables the application of MIMO. In the US the FCC (Federal Communications Commission) opened the spectrum from 3.1 GHz to 10.6 GHz for unlicensed use at low spectral power density (-41.3 dBm/MHz EIRP). In other countries this band is further restricted, e.g. in Europe only the band from 6 GHz to 8.5 GHz is available indoors at the same spectral power density.

In order to achieve 100 GBit/s within the bandwidth of 2.5 GHz a bandwidth efficiency of 40 bit/s/Hz has to be realized, which is quite challenging and requires a large scale MIMO system. As the number of uncorrelated antennas that can be realized on a small mobile terminal is limited to a few elements the base station has to provide a huge amount of antennas. Such a system is typically denoted as Massive MIMO. Although size constraints on the base station seem to be less restrictive compared to the mobile terminal the huge amount of antennas needed calls for a compact antenna concept for the base station as well.

In this paper we present a compact antenna concept for the base station and perform some link-level simulations in order to evaluate the MIMO performance of the antenna.

II. ANTENNA CONCEPT

A. Basic Concept

The proposed Multi-Mode Multi Element Antenna (M³EA) aims at realizing multiple uncorrelated antenna ports on each element of the MEA [1]. The multiple uncorrelated ports are obtained by the excitation of different Characteristic Modes [2] on each antenna element. The basic concept is illustrated in Fig. 1. The base station antenna consists of M rows and N columns of physical elements. As each element is supposed to contain K uncorrelated antenna ports this results in $M \times N \times K$ effective antenna ports of the M³EA.

Fig. 1. Concept of a Multi-Mode Multi Element Antenna (M³EA).
B. Multi Mode Antenna Element

Fig. 2 shows a 4-port antenna element based on the multi-mode concept outlined in the previous section.

![Multi-mode antenna element (Fig. 2)](image1)

The antenna element itself contains the 8 slots shaped in such a way that they provide good impedance matching throughout the desired band. The outer dimensions of the element in Fig. 2 are $0.85 \lambda(f_c) \times 0.85 \lambda(f_c)$.

C. Massive Multi-Mode Multi Element Antenna

Based on the simulation model in Fig. 2 a total amount of 121 multi-mode elements have been produced in an external workshop. They are arranged to generate an $11 \times 11$ elements array having 484 antenna ports.

The prototype is shown in Fig. 3. The spacing between the different antenna elements is chosen such that the mutual coupling to neighboring elements within the array is $s_{nn} \leq -20$ dB. In addition the isolation between neighboring elements within the array is improved by using a choke wall of $h_{choke} = \lambda(f_c)/4$ between the elements (see Fig. 3). The choke walls are realized by vertical metal strips located between the elements. The separation distance between the elements of the array is $\Delta_{elements} = 0.58 \lambda(f_c)$.

![Prototype of an 11 x 11 array of multi-mode elements having 484 antenna ports (Fig. 3)](image2)

The $s$-parameters of the center element as shown in Fig. 4 are measured using a four-port network analyzer. It can be observed that the matching of all 4 antenna ports is $s_{ii} \leq -10$ dB in almost all of the desired frequency band of $6 \leq f [\text{GHz}] \leq 8.5$. The mutual coupling between the antenna ports is $s_{ij} \leq -20$ dB in the entire frequency band.

![Measured s-parameters of the center element of the 11 x 11 multi-antenna system (Fig. 4)](image3)

Fig. 4. Measured $s$-parameters of the center element of the $11 \times 11$ multi-antenna system.

Fig. 5 shows the measured mutual coupling between the center element (element $nm = 66$) and one of its direct neighbor elements (element $nm = 76$). It can be observed that the mutual coupling between any of the port is $s_{ij} \leq 25$ dB and therefore fulfills the requirement.

![Measured mutual coupling between the center element (element nm = 66) and one of its direct neighbors (element nm = 76) of the 11 x 11 array (Fig. 5)](image4)

Fig. 5. Measured mutual coupling between the center element (element $nm = 66$) and one of its direct neighbors (element $nm = 76$) of the $11 \times 11$ array.

III. LINK-LEVEL CAPACITY SIMULATION

In order to examine the channel capacity for the M'EA concept, this section provides numerical results of link-level channel capacities obtained by Monte Carlo simulations. Beneath the various channel models that are available for this purpose, geometric, ray-based channel models are an appropriate choice. These models enable the direct incorporation of array geometries and radiation patterns to include the effects of spatial, angular and polarization diversity inherently. In this contribution the WINNER II channel model
has been implemented [3]. In general the model creates a channel matrix according to the summation of clustered rays between the individual elements of a base station (BS) and a mobile station (MS), respectively. The model is the result of excessive measurement campaigns and specifies statistical distributions for the rays’ temporal, angular and power distributions, together with path loss models and field component based weighting and rotation on the physical channel.

Although the center frequency of 7.25 GHz is beyond the specified frequency range of the model, we assume that the properties of the angular distributions will not be fundamentally different. Additionally, although the path loss models may change for the higher frequency, this investigation uses normalized channel matrices that eliminate the influence of long-term fading. In the context of a low-range access network the indoor scenario A1 with non-line-of-sight (NLOS) conditions has been chosen. For the investigation in this contribution, it is assumed that the BS is equipped with the M³EA studied above. Because of the anticipated mounting of the BS on a wall and the reflective backplate, the orientation of the BS array is fixed and is pointing towards the MS with the elements’ z-axis in the simulation setup. It is assumed that the ports of the MS and BS are perfectly decoupled, which is justified by the mutual coupling behaviour from Section II.

It is assumed that the physical channel can be modelled as a flat-fading channel due to any channel orthogonalization scheme like OFDM. In that case, any orthogonal sub-channel can be written in matrix form as

$$y = Hx + w.$$  \hspace{1cm} (1)

The elements of the noise vector $w$ is assumed to be taken from a circularly symmetric zero-mean Gaussian distribution. Assuming a Gaussian distribution of the channel input $x$, the ergodic capacity is given by

$$C = \mathbb{E} \left\{ \log_2 \left( \det \left[ I_{N_{r,\text{eff}}} + \frac{\text{SNR}}{N_{t,\text{eff}}} H H^H \right] \right) \right\},$$  \hspace{1cm} (2)

where $N_{t,\text{eff}} = MNK$ is the number of effective transmit ports, $N_{r,\text{eff}}$ is the number of effective receive ports, $\mathbb{E}\{\cdot\}$ is the expectation and $H$ is the instantaneous channel realization. The formulation used is suitable for the downlink, but is analogue for the uplink.

Figure 6 shows the capacity for an increasing array size with 100000 realizations for each size sample. The SNR is chosen to be 30 dB. The investigation is conducted for the case that the MS is equipped with a single multi-mode element or two elements, yielding 4 or 8 effective ports, respectively.

For comparison, the capacity for independent identically distributed (IID) Rayleigh fading has been included. The graph shows that the M³EA follows the trend of the IID Rayleigh fading case, where each channel coefficient is perfectly uncorrelated.

$$C_{\text{asymptotic}} \approx \log_2 \left( \det \left[ I_{N_{r,\text{eff}}} + \text{SNR} I_{N_{r,\text{eff}}} \right] \right) = N_{r,\text{eff}} \cdot \log_2 \left( 1 + \text{SNR} \right).$$  \hspace{1cm} (4)

It can be seen that the performance for both cases saturates in a similar manner. This behaviour shows that in fact the MS is the limiting factor in the system. The M³EA provides enough degrees of freedom to serve more ports or more users.

The maximum mutual coupling studied in Section II and the used physical space can be taken as boundary values to compare the M³EA to a generic array with crossed dipoles that takes the same physical space and has the same maximum mutual coupling. For that case the array would consist of $121 \lambda/2 \times \lambda/2$ sized elements that have a distance of $\lambda$. This configuration yields an effective number of 242 ports. Please note that the system with crossed dipoles is also restricted to a single physical element for the MS, so that is has only 2 ports at the MS.
In Fig. 7 the ergodic capacity of the compared systems is shown for an increasing SNR. For the given configuration the multi-mode system outperforms the system using crossed dipoles. Firstly, the M³EA provides more degrees of freedom and secondly the asymptotic capacity is larger due to the higher number of ports for MS equipped with a single element.

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