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MIMO Antennas for Radiative Near-Field Links: A Comparative Study at 300 GHz

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***Abstract*—This paper presents a comparative study of different Multiple Input Multiple Output (MIMO) array architectures to realize high-capacity Point-to-Point (PtP) wireless links for potential use in future 6G backhauling applications. This study focuses on the 220-320 GHz band, defined by the new IEEE 802.15.3d standard. Both phased array and focal plane array architectures are studied, considering the link to operate in the radiative near-field. The theoretically achievable capacities are presented based on the channel matrix estimated in the radiative near-field and the application of Shannon's capacity formula. It is found that capacities well above Tbps rates can theoretically be realized, even without the use of interference cancellation techniques.**

I. Introduction

As data traffic in cellular networks keeps increasing, extremely high backhauling speeds will be essential for future 6G applications. Studies are predicting that Tbps links are necessary to support this growth [1]. It is possible to reach these capacity levels using PtP wireless links by exploiting MIMO antenna architectures and by exploiting wide spectral bandwidths. The band defined by the IEEE 802.15.3d standard has 70 GHz spectral bandwidth, between 250-320 GHz, which is sufficient for this application [2]. However, there are demanding challenges in exploiting this spectral bandwidth and the high frequency carriers due to the limited performance of integrated technology [3]; therefore, new communication system architectures, based on low radio frequency power levels and basic signal processing techniques, are mandatory for the practical exploitation of this frequency band. On the other hand, these higher frequencies make it possible to realize extremely high antenna gains with moderate (electrically large) physical dimensions and for short to medium link distances (hundreds of meters) the antenna arrays will operate in the radiative near-field. These two effects of operating at high frequencies allow for the design of high radiated energy efficient MIMO systems.

Line of Sight (LoS) [4,5] and Orbital Angular Momentum (OAM) [6] MIMO architectures have been proposed to realize PtP high-capacity wireless links. In these phased arrays, directive antennas are properly distributed to increase the channel capacity via relative phase shifts and summations of the received signals or by using precoding techniques. When moving to >100 GHz frequency ranges, these types of MIMO architectures pose strict demands on the phase coherence of the analog array front-ends in terms of stability and linearity of active devices. These demands are typically not achievable with high frequency electronics and the realizable data rates are therefore limited.

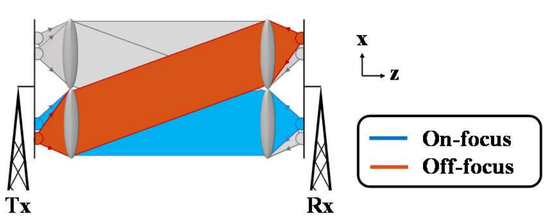

Fig. 1. The subset at the bottom right shows the cross-section of the QO MIMO architecture. Both direct (on-focus) and tilted (off-focus) beams are exploited to reach a 16x16 MIMO system.

In this comparative study a Quasi-Optical (QO) MIMO architecture, proposed in [7], is included. Its geometry is shown in Fig. 1. This is an incoherent array where nearly independent data streams are sent and detected directly via focal plane arrays (FPAs) without the need for interference cancellation.

In this work we study the feasibility of combining the three previously mentioned MIMO architectures with wide spectral bandwidth front-ends in the 220-320 GHz band. The comparison is based on the evaluation of the channel matrix in the radiative near-field and is made in terms of achievable MIMO spectral capacity.

II. Results

The QO MIMO architecture proposed in [7] was designed for a link distance of 100m, having array dimensions of 1m by 1m. To effectively compare the three MIMO architectures, the LoS and OAM arrays have identical overall array dimensions. For all three architectures the largest possible aperture diameters were chosen to obtain the highest possible coupling between the transmit (Tx) and receive (Rx) arrays. The studied geometries are shown in Fig. 2.

To evaluate the channel matrix in the near-field the analysis of antennas in reception is applied, similar to [8]. From the channel matrix the Signal-to-Noise-Interference Ratio (SNIR) per Rx antenna element is derived by

$$SNIR_i = \frac{P_{tx}^i \times |h_{ii}|^2}{N_0 + P_{tx}^i \times \sum_{j=1}^{M} |h_{ij}|^2} \text{ [dB]},$$

where P_{tx}^i is the transmitted power per antenna element (-20

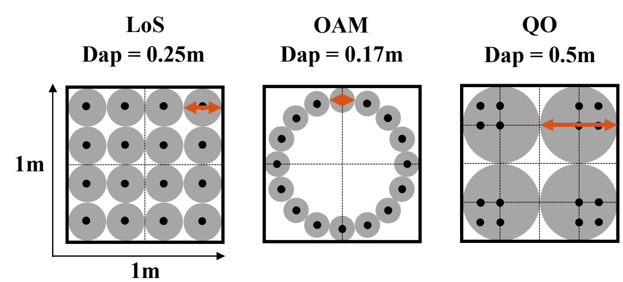

Fig. 2. Geometries of the 16x16 MIMO arrays. The total array dimensions have been fixed to 1m by 1m. Due to this size constraint the aperture diameters are different for each architecture: 0.25m for Los, 0.17m for OAM and 0.5m for QO.

dBm divided equally among the antenna elements), N_0 is the noise level (assumed to be -59 dBm corresponding to a noise figure of 10 dB), h_{ii} are the diagonal entries of the channel matrix which represent the co-coupling, h_{ij} are the non-diagonal channel matrix entries which represent the interference contributions, and M is the amount of antenna elements in the array. From the SNIR the capacity is derived through

$$C = M \times \log_2(1 + SNIR_i) \text{ [bit/Hz/s]}.$$

These spectral capacities are shown in Figs. 3 and 4 as a function of the link distance and the operational frequency, respectively. Due to the diagonal nature of the QO channel matrix, inherent to its geometry, its capacity is higher than that of the LoS and OAM MIMO architectures when no interference cancellation is applied. The LoS and OAM MIMO architectures need interference cancellation in the form of beam forming weights to achieve high capacities. These weights can be derived from the channel matrix using the Singular Value Decomposition method as in [9]. For the capacities with beam forming, shown in Figs. 3 and 4, we assumed that the amplitude and phase of the array weights are realizable at any range and frequency.

By assuming ideal beam forming schemes, the capacity of the LoS and OAM MIMO architectures have increased substantially. On the other hand, for the QO MIMO architecture, since the interference levels are already low, beam forming enhances the capacity less significantly. It is worth noting that the QO MIMO architecture reaches similar capacity levels without beam forming as the ones achieved by LoS and OAM MIMO architectures with beam forming. By integrating over the lower part of the operational bandwidth (235-270 GHz), a capacity of 4.66, 3.82 and 3.03 Tbps is obtained for the QO, LoS, and OAM MIMO architectures with interference cancellation, respectively. Without interference cancellation, a capacity of 3.67, 0.47 and 0.22 Tbps is obtained for QO, LoS, and OAM MIMO architectures, respectively.

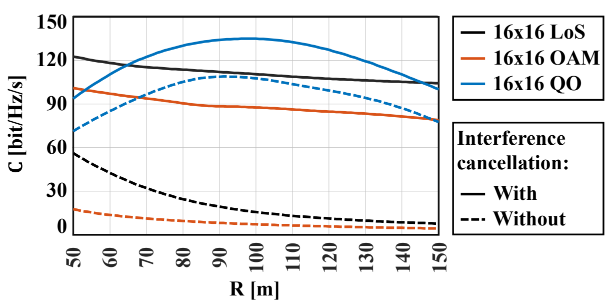

Fig. 3. Theoretical capacities for the three MIMO architectures with and without interference cancellation versus link distance at 270 GHz. A total transmit power of -20 dBm and a noise level of -59 dBm (corresponding to a noise figure of 10 dB) are assumed here.

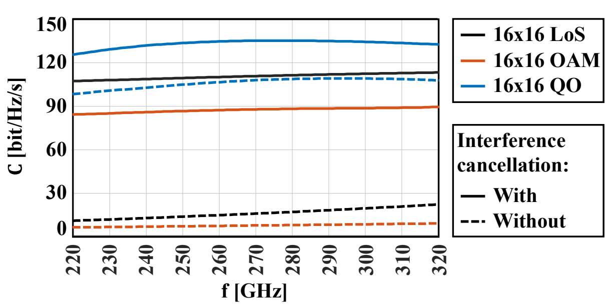

Fig. 4. Theoretical capacities for the three MIMO architectures with and without interference cancellation versus frequency at a 100m.

III. Conclusions

To be able to reach Tbps capacity levels for PtP wireless links, wide spectral bandwidths and MIMO architectures are necessary. At high frequencies, PtP links in the radiative near-field can be used to enable MIMO architectures to operate over large bandwidths. By exploiting architectures based on FPAs, incoherent MIMO systems can be employed with potential data rates in line with the ones achievable by coherent MIMO arrays without the need for beam forming.

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