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MIMO Channel Capacity Gains in mm-Wave LOS Systems with Irregular Sparse Array Antennas

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***Abstract*— This paper investigates potential advantages of linear irregular sparse antenna arrays over their regular counterparts in a mm-wave line-of-sight (LOS) multiple-input multiple-output (MIMO) scenario. The comparison is based on numerical computations of MIMO eigenvalues of the corresponding channel matrices and the resulting channel capacity. Identical linear antenna arrays are assumed at the transmitter and the receiver sides. The compared regular and irregular arrays have an equal aperture length. Mutual coupling between elements within an array is assumed negligible due to the array sparsity. A 4×4 MIMO channel is studied, where we change the position of the two inner elements to obtain irregularly spaced arrays. It is shown that for some specific distances between TX and RX, the irregular array distribution can significantly improve the channel capacity in LOS. This observation opts for reconfigurable array designs.**

Keywords*— *Channel capacity, Irregular array, LOS multiple-input-multiple-output (MIMO), 5G.

I. Introduction

The dramatic increase of wireless data traffic in the upcoming years will require higher network throughput. This can be achieved, e.g., with larger signal bandwidths and by employing massive multiple-input-multiple-output (MIMO) systems. Miniaturization and bandwidth challenges urge for the development of new antenna technologies at millimeter wave frequencies. Large irregular array antennas have been suggested as one of the many potentially attractive antenna technologies leading to enhanced cost-efficiency in 5G wireless systems [1]. They have been extensively used in other applications such as Radio Astronomy and SATCOM [2], [3], since such arrays can reduce the electronic circuit complexity, the weight, and the power consumption of the antenna system.

In this paper, a 4×4 MIMO system in a mm-wave line-of-sight (LOS) channel is analyzed. As a starting point, we consider a uniform linear array of isotropic radiators optimized for a specific distance between the transmitter (TX) and the receiver (RX). The eigenvalue plot of the channel matrix illustrates significant variations for the other TX-RX separations below the optimum distance [4]. Since the utilization of the same hardware architecture for different fixed wireless access (FWA) scenarios is hugely favorable, the irregularity and reconfigurability notions can come together in MIMO array synthesis to compensate the channel capacity degradation. The performance of the irregular array antenna

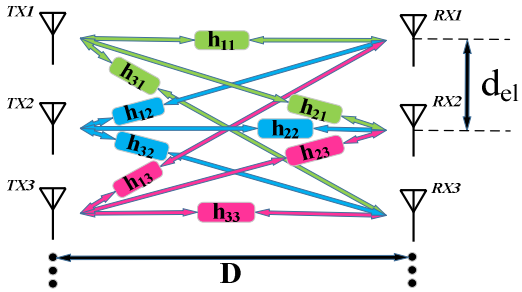

Fig. 1. MIMO channel model with the same number of antennas at both TX and RX. The channel matrix entries are computed using the ray tracing algorithm.

is examined by varying the positions of the two inner elements in the four-element array, while keeping the TX and RX aperture lengths constant. It is pointed out that the elements in the arrays are typically several wavelengths apart and therefore mutual coupling between elements can be neglected. We found that the overall channel capacity at some TX-RX separations can be improved through optimal placement of the two inner elements, relative to its regular counterpart.

An optimal inter-element spacing exists for uniform linear arrays separated by a fixed distance in a LOS channel [4]. The novel contribution of this work is to create a foundation for the developments of optimal irregular array architectures for different TX-RX separation distances in a MIMO system. It can also open up for several new technologies, e.g., reconfigurable antennas and beamforming networks.

II. Problem Setup

Fig. 1 shows a schematic representation of the studied LOS MIMO channel, with uniform TX and RX linear arrays. The following assumptions are made in our simulations:

1- The TX and RX arrays are identical, employing N elements with inter-element distance d_{el}. Hence, the aperture length of both arrays is $L = (N-1)d_{\mathrm{el}}$.
2- The array antenna elements are assumed to be isotropic radiators.

Based on the above assumptions, an entry h_{mn} of the symmetric channel matrix **H** is assumed to be given by the corresponding distance R_{mn} between the elements m and n at the TX and RX sides, respectively, i.e., $h_{mn} = \exp(-j\omega R_{mn}/c)$, with c the speed of light and ω the radial frequency. The irregularly

spaced arrays are obtained by changing the positions of the two inner elements in each four-element array. For a fixed TX-RX distance D, the elements are moved symmetrically from the edges of the array toward the array center, where d_{offset} is the distance from either inner element to its adjacent edge element.

The capacity is then evaluated by using the MIMO classical formula for non-informed transmitters [5] through the eigenvalues λ_i of $\mathbf{HH}^H$, where $(.)^H$ denotes the Hermitian transpose operator. In order to compare irregular to regular arrays, we define the capacity gain as

$$G_C(D) = C_{\text{irregular}}(D) / C_{\text{regular}}(D) \quad (1)$$

where $C_{\text{irregular}}$ and C_{regular} are the calculated MIMO capacities for specific TX-RX separation D.

III. Simulation Results

We consider a 4×4 MIMO system operating at 30 GHz. The maximum reference distance $D_{\max} = 400$ m, which is the approximate size of urban-macro cells [6]. The inter-element spacing of the uniform linear array is then $d_{\text{el}}=100\lambda$, using the design procedure in [4]. Hence, the aperture length is $L = 3$ m. The MIMO channel matrix is computed for 25 m < D < 450 m, after which the channel eigenvalues are extracted.

Fig. 2 (Top) shows significant fluctuations in eigenvalues as a function of D. It is worthwhile to note that, at some distances, for instance, $D = 80$ m, the channel capacity is maximum since all four eigenvalues are equal and MIMO multiplexing is a better option than producing a single beam [5]. However, the situation is totally different for, e.g., $D = 100$ m, where one eigenvalue dominates over the other three. Thus, depending on D, different transmit strategies will provide optimal performance.

Next, we aim at compensating the channel capacity degradation at $D = 100$ m. Fig. 2 (Bottom) shows the capacity gain (in dB) as a function of d_{offset}, for $D = 100$ m. The maximum capacity gain (red star) defines the optimal irregular array configuration for which $d_{\text{offset}} = 18\lambda$.

Fig. 3 (Top) shows the eigenvalues corresponding to the obtained irregular array as a function of D. As can be seen, the irregular distribution of the antenna elements results in more equal eigenvalues, and thus the channel capacity is improved significantly compared to the regular array performance at this specific distance ($D = 100$ m).

Fig. 3 (Bottom), shows the capacity gain in dB corresponding to the optimized irregular array as a function of D. As can be seen from Figs. 2 and 3 (Bottom), the implementation of the optimized irregular array can increase the channel capacity by 4-5 dB at a high SNR regime for the targeted TX-RX separation distance. It is worthwhile to note that the capacity of the optimized irregular array at $D = 100$ m corresponds to the maximum capacity for a 4×4 MIMO system in LOS.

IV. Conclusions

The effect of antenna array irregularity on the channel capacity of a mm-wave LOS MIMO system has been studied. The results show that when the channel capacity for a regular array architecture degrades at some specific TX-RX distances, a (reconfigurable) irregular array can be deployed to compensate for this degradation. This initial study forms the basis for the irregular array architecture synthesis framework to be developed in the future.

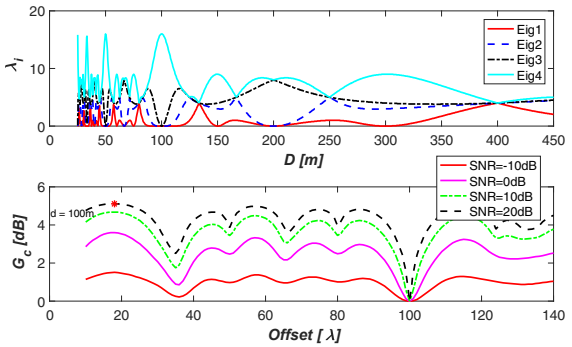

Fig. 2. (Top) Eigenvalues of $\mathbf{HH}^H$ as a function of D for a 4×4 MIMO channel with a regular array structure at both TX and RX; (Bottom) Capacity gain as a function of d_{offset} at $D = 100$ m.

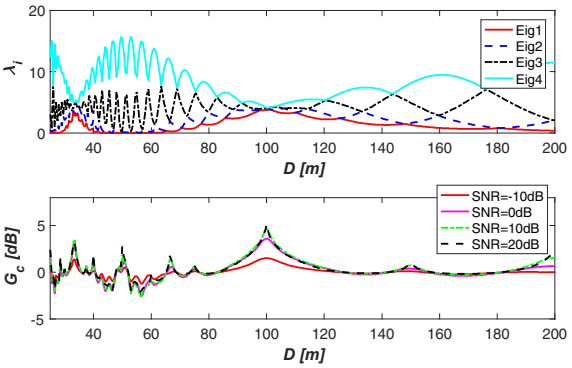

Fig. 3. (Top) Eigenvalues of $\mathbf{HH}^H$ as function of D for a 4×4 MIMO with optimized irregular array structure at both TX and RX for $D = 100m$; (Bottom) Capacity gain as a function of D.

V. Acknowledgment

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