CHALMERS
UNIVERSITY OF TECHNOLOGY

Towards a Generic Model for MU-MIMO Analysis Including Mutual Coupling and Multipath Effects

Citation for the original published paper (version of record):

Amani, N., Wymeersch, H., Johannsen, U. et al (2019)
Towards a Generic Model for MU-MIMO Analysis Including Mutual Coupling and Multipath Effects
13th European Conference on Antennas and Propagation, EuCAP 2019, 2019

Towards a Generic Model for MU-MIMO Analysis Including Mutual Coupling and Multipath Effects

N. Amani[1,2], H. Wymeersch[1], U. Johannsen[2], A. B. Smolders[2], M. V. Ivashina[1], and R. Maaskant[1,2]
[1]Department of Electrical Engineering, Chalmers University of Technology, Gothenburg, Sweden,
anavid@chalmers.se
[2]Electromagnetics Group, Eindhoven University of Technology (TU/e), The Netherlands,
n.amani@tue.nl

***Abstract*—A network model which accounts for antenna mutual coupling and multipath effects in a wireless channel is proposed as a tool to qualitatively evaluate the performance of a multi-user multiple-input multiple-output (MU-MIMO) system. The system performance is assessed when a zero-forcing (ZF) beamformed conventional uniform linear array (ULA) and a sparse array are employed as one sector of a base station antenna (BSA) in a single-cell network. It is shown that highly correlated user equipments (UEs) in a line-of-sight (LOS) scenario can be decorrelated to some extents, by a scattering environment in a non-line-of-sight (NLOS) scenario. This occurs due to increase of the spatial variation by a multipath effect. Furthermore, in both environments a sparse array realized by an increased inter-element spacing is also capable for correlation reduction among users due to the narrower beams.**

***Index Terms*—Base station antenna, multi-user multiple-input multiple-output (MU-MIMO), network theory, sparse array.**

I. INTRODUCTION

Ultra-fast and low latency communication, as promised by the fifth-generation of wireless communication, necessitates for space-division-multiple-access (SDMA) technology where individual beams from the base station antennas (BSAs) serve multiple simultaneous users [1]. In this scheme, the quality-of-service is principally constrained by the amount of the interference of which the correlation among users is one of the contributors [2]. Hereupon, in a multi-user multiple-input multiple-output (MU-MIMO) system the BSA capability to differentiate simultaneous users is critical.

Massive MIMO operating at mm-wave frequencies with a very large number of antenna elements (M) at the BSA has been recently proposed as an enabling technology [3]. However, increasing M arises many system level challenges, both in hardware and software implementations. Therefore, a new multidisciplinary design tool is required. A network approach, based on the impedance (Z-matrix) representation, is proposed to model a MU-MIMO scenario [4], [5]. Within the proposed scheme both the antenna and channel effects are considered simultaneously to generate a more realistic channel matrix for signal processing purposes.

In this paper, the performance of both a zero-forcing (ZF) beamformed uniform linear array (ULA) and a sparse array with reduced field-of-view (FOV) of 30°, as one sector of a BSA, are compared through the network model. The multipath effect is incorporated in the model by the reaction concept assuming randomly localized scatterers between the TX and RX antennas. A sparse array is realized by multiplying the inter-element spacing (d) by a sparsity factor (SF). In [6], with the assumption of a flat-top radiation pattern for the antenna element, an upperbound on d is defined which guarantees no grating lobes inside the FOV. Since the radiation pattern of a real element cannot immediately drop outside the FOV, two guard bands at both sides of the FOV are considered, within which grating lobes are not admitted. Here, a multi-layer stacked patch antenna with enhanced directivity and reduced side lobe level (SLL) is proposed to suppress the grating lobes of a sparse array above the guard bands. Afterwards, the performance of the system employing both a conventional ULA and a sparse array are evaluated in a line-of-sight (LOS) as well as a none-line-of-sight (NLOS) scenario with the help of the network model.

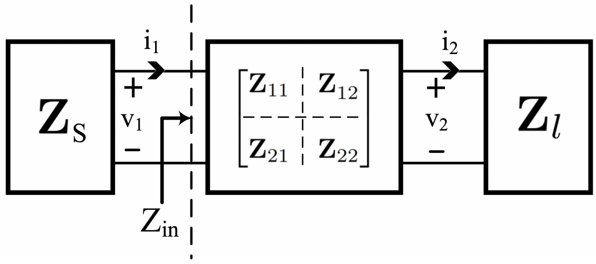


Fig. 1: Network model of a MU-MIMO scenario including mutual coupling and multipath effects.

Section II describes the wireless network model. A multi-layer stacked patch antenna, as an element of both arrays, is proposed in Sec. III. Afterwards, a comparison of the system performance employing both a conventional ULA and a sparse array in different environments is made in this section through simulations. Finally, the conclusions are drawn in Sec. IV.

II. NETWORK MODEL INCLUDING MUTUAL COUPLING AND MULTIPATH EFFECTS

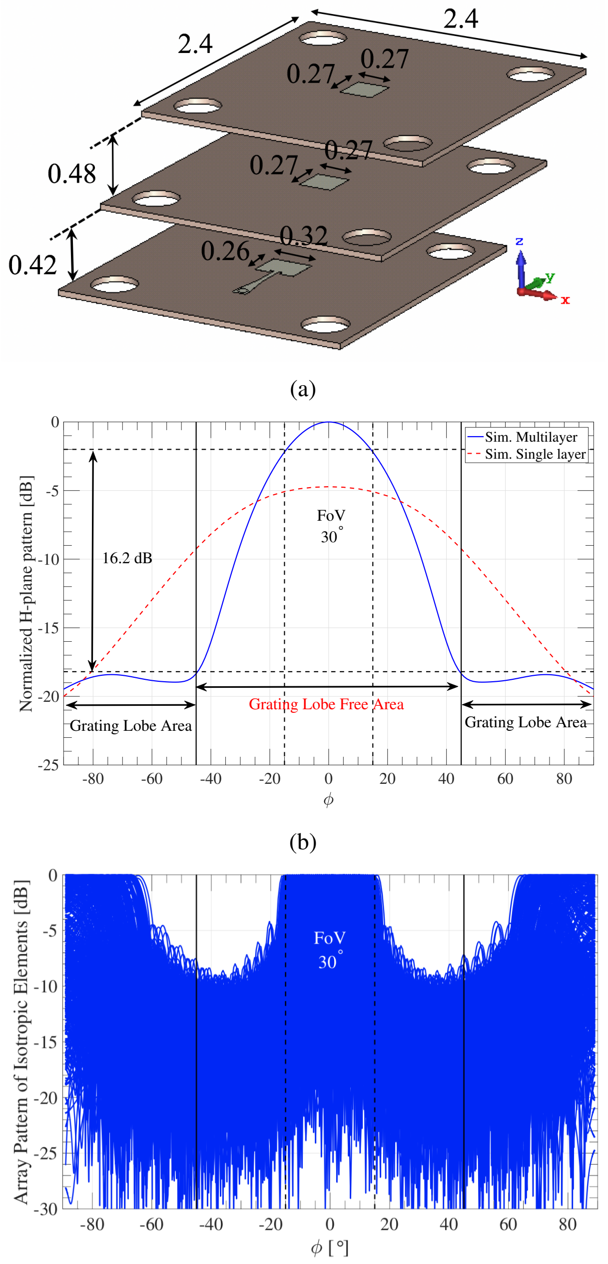
A circuit theoretic multiport concept is presented in [4] for a communication system. Also, [5] employs a network model as a link budget analyzer in the presence of mutual coupling in the BSA. As a further development of the network model, the multi-path effect needs to be included in the network model in order to be able to evaluate the performance of a MU-MIMO system in a NLOS scenario. Traditionally, a highly idealized model of a uniform scattering environment, introduced by Clarke [7], models the multipath in a wireless channel which results in a Rayleigh fading channel. However, multipath components often arrive in clusters in a real environment and therefore a wireless channel may deviate from a Rayleigh fading one [8].

Due to the uncertainty in the exact shape and material properties of the scatterers, we are interested in the qualitative performance figures and trends. In this way, we assume a few number of scatterers gathered in a randomly localized cluster of scatterers (CoS) through a Monte Carlo simulation where the performance metric of the system can be analyzed in a statistical sense. In a NLOS environment, $r_{knm} = r_{kn} + r_{nm}$ represents the link distance between the k-th user, n-th scatterer in the wireless channel and m-th element at the BSA. Hence, $\mathbf{Z}_{12} \in \mathbb{C}^{K\times N\times M}$ in Fig. 1 is a three-dimensional matrix in a NLOS environment whose entries in all three dimensions can be computed by the reaction concept [9], [5, Eq. 2]. The reflection coefficient of each scatterer (Γ_n) needs to be considered; however, for the sake of simplicity it is assumed to be unity for all scatterers. Afterwards, due to the linearity in the system, adding up the entries in the dimension of scatterers (N) includes all constructive and destructive interference effects by the scatterers and models the two-dimensional $\mathbf{Z}_{12}$ in the network model. Computing all network parameters, the channel matrix which relates the input and output voltage vectors of the network model can be computed by [5, Eq. 5] and afterwards a ZF precoder can be applied to compute the required weight vector.

III. CASE STUDY AND SIMULATION RESULTS

In this section, a MU-MIMO system employing either ULA or sparse arrays as a BSA are analyzed. The FOV is assumed to be 30°. The problem of grating lobes by a sparse array can be addressed by a proper selection of d and the element pattern. A multilayer-stacked patch antenna, as shown in Fig. 2(a), is proposed as an element for both the ULA and the sparse arrays. The antenna element is designed on 0.75 mm-thick Rogers RO3003 substrate. Employing two layers of superstrates, as illustrated in Fig. 2(b), the directivity of the element at broadside in the H-plane is increased from 7.6 dB to 12.4 dB while its half-power beamwidth (HPBW) reduced from 75° to 36°. Afterwards, a 20-element conventional ULA ($d = 0.5\lambda$) and a sparse array ($d = 0.85\lambda$) employing the same proposed element are considered. Both of them are H-plane arrays.

In Fig. 2(c) the array pattern (of isotropic radiators) of a sparse array is repeatedly extracted through a Monte Carlo simulation (500 runs) while two users are randomly located inside the FOV and ZF beamforming is applied. BSA mutual coupling is neglected at this stage. The d in the sparse array



(a)

(b)

(c)

Fig. 2: (a) Proposed multilayer-stacked patch antenna with enhanced directivity and reduced SLL (dimensions are in wavelengths), (b) simulated normalized H-plane radiation patterns of the proposed element and single layer patch antenna, (c) 500 array patterns of isotropic elements produced by a sparse array $d = 0.85\lambda$ through a Monte Carlo simulation with random localization of two users while ZF precoding is applied.

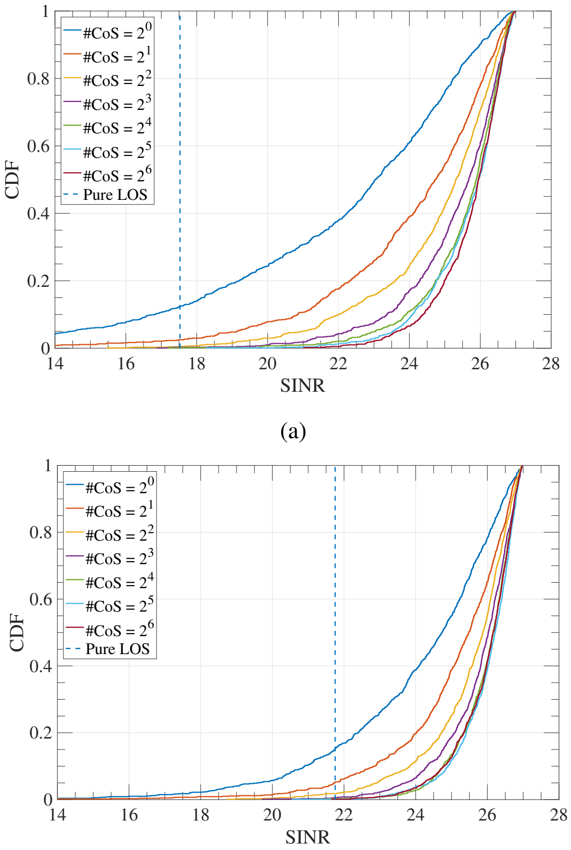
is selected in such a way that the grating lobes appear above the guard bands at both sides of the FOV, termed 'grating lobe areas' in Fig. 2(b). Therefore, the grating lobes in the sparse array are suppressed in the grating lobe areas at least 16.2 dB below the minimum radiation inside the FOV by the element pattern, see Fig. 2(b). Afterwards, the embedded element patterns and $\mathbf{Z}_{11}$ of both arrays, which includes the inter-element BSA mutual coupling effects, are extracted from the CST simulations [10] and imported into the network model for further processing.

In order to evaluate the performance of a MU-MIMO system in the presence of multi-path effects, 2^6 number of scatterers are assumed to be spread in different number of CoS. The number of CoS increases from one to 2^6, in intervals of power-of-two. One CoS means that all scatterers are gathered in one cluster with close proximity to each other. On the other hand, there is only one scatterer in each cluster when the number of CoS equals to 2^6. All network parameters can be computed as explained in the preceding section. Upon applying ZF precoder at the BSA, and by assuming a required SNR of 20 dB for the UEs, the acquired SINR at each UE terminal is computed by [11]

$$\mathrm{SINR}_k = \frac{|\mathbf{h}_k^T \mathbf{w}_k|^2}{\sum_{k' \neq k}^{K} |\mathbf{h}_k^T \mathbf{w}_{k'}|^2 + (1/\mathrm{SNR})} \tag{1}$$

where $(.)^T$ indicates the transpose operation. Meanwhile, $\mathbf{h}_k$ and $\mathbf{w}_k$ represent the k-th UE channel vector and the corresponding weight vector, respectively. In order to ensure equal transmit powers from the BSA in different simulation scenarios, the weight matrix $\mathbf{W} = \mathbf{H}^\dagger(\mathbf{H}\mathbf{H}^\dagger)^{-1}$ is normalized by $\sqrt{\mathrm{tr}(\mathbf{W}\mathbf{W}^\dagger)}$, where tr(.) and $(.)^\dagger$ represent trace of a matrix and Hermitian operator, respectively.

We assumed a specific case of two close-by UEs where the angular separation between them is only 1° and they both have the same distance to the BSA. Then, the location of CoS are randomly defined in each Monte Carlo simulation run. SINR of a UE is computed and its CDF function is plotted in Fig. 3 when a conventional ULA or a sparse array is employed at the BSA. In a pure LOS environment, a step-like function is observed in a CDF plot due to the absence of the scatterers. By cross-comparing the SINR CDF plots achieved by both antennas in a pure LOS environment, in Figs. 3(a) and (b), it can be seen that a sparse array due to the narrower beams from an increased d reduces the correlation between the channel vectors and increases the SINR. However, in a NLOS environment the correlation between UEs depend on the richness of the scattering environment. The trend of the CDF plots in a NLOS scenarios show that when the scatterers get more freedom to be spread into space the spatial variation increases and decorrelate two close-by UEs. Even in a NLOS scenario, the sparse array is advantageous for further correlation reduction and thus increases the SINR.



(a)

(b)

Fig. 3: CDF plot of a UE SINR when two equi-distant UEs are located closed-by with 1° angular separation through a Monte Carlo simulation with random localization of scatterers employing a (a) conventional ULA ($d = 0.5\lambda$), (b) sparse array ($d = 0.85\lambda$).

IV. CONCLUSION

The performance of a MU-MIMO system has been evaluated employing a network model which accounts for both the mutual coupling and multipath effects. It has been shown that a rich scattering environment in a NLOS scenario decorrelates the channel vectors of close-by UEs. Furthermore, a sparse array has shown to be capable of reducing the correlation further due to the spatial resolution enhancement attributed to narrower beams. Meanwhile, the grating lobe problems of the sparse arrays have been mitigated by a proper inter-element spacing and element pattern selection.

ACKNOWLEDGMENT

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 721732.

REFERENCES

[1] C. Sun, X. Gao, S. Jin, M. Matthaiou, Z. Ding, and C. Xiao, "Beam division multiple access transmission for massive mimo communications," *IEEE Transactions on Communications*, vol. 63, no. 6, pp. 2170–2184, 2015.

[2] A. Alshammari, S. Albdran, and M. Matin, "The effect of channel spatial correlation on capacity and energy efficiency of massive mimo systems," in *Computing and Communication Workshop and Conference (CCWC), 2017 IEEE 7th Annual*. IEEE, 2017, pp. 1–5.

[3] T. L. Marzetta, "Noncooperative cellular wireless with unlimited numbers of base station antennas," *IEEE Transactions on Wireless Communications*, vol. 9, no. 11, pp. 3590–3600, 2010.

[4] M. T. Ivrlac and J. A. Nossek, "Toward a circuit theory of communication," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 57, no. 7, pp. 1663–1683, 2010.

[5] N. Amani, R. Maaskant, A. A. Glazunov, and M. Ivashina, "Network model of a 5G MIMO base station antenna in a downlink multi-user scenario," *European Conference on Antennas and Propagation*, 2018.

[6] N. Amani, A. A. Glazunov, M. Ivashina, and R. Maaskant, "Per-antenna power distribution of a zero-forcing beamformed ula in pure los mumimo," *IEEE Com. Letters*, 2018.

[7] R. Clarke, "A statistical theory of mobile-radio reception," *Bell system technical journal*, vol. 47, no. 6, pp. 957–1000, 1968.

[8] M. Peter *et al.*, "Measurement results and final mm-Magic channel models," *Deliverable D2*, vol. 2, 2017.

[9] P.-S. Kildal, *Foundations of antenna engineering: a unified approach for line-of-sight and multipath*. Artech House, 2015.

[10] CST, "CST 2018," *https://www.cst.com/*, 2018.

[11] H. Q. Ngo, *Massive MIMO: Fundamentals and system designs*. Linköping University Electronic Press, 2015, vol. 1642.