ASYMPTOTIC ANALYSIS OF NEAR-FIELD COUPLING IN MASSIVE MISO AND MASSIVE SIMO SYSTEMS

Aniol Martí [1], Jaume Riba [1], Meritxell Lamarca [1], and Xavier Gràcia [2]

[1]Departament de Teoria del Senyal i Comunicacions, Universitat Politècnica de Catalunya (UPC)

[2]Departament de Matemàtiques, Universitat Politècnica de Catalunya (UPC)

Motivation

The increasing demand for higher data rates together with the enormous growth of connected devices have pushed standards to adopt larger antenna configurations and higher carrier frequencies, rising the far field distance to thousands of meters, and making it impossible to operate in it due to the high attenuation of such bands. For this reason, near-field models must be taken into account in 5G and beyond.

In this work, we consider a system communicating in the near field and we focus on the coupling caused by the receiver to the transmitter when a massive array is employed in one of the communication system ends. In order to do so, we leverage *multiport communication theory*.

Multiport Communication

Multiport communication theory is a framework that involves a circuit-theoretic approach where the inputs and outputs of a MIMO communication system are associated with ports of a multiport black box, described by its impedance parameters. For the purpose of this work, we consider the (noiseless) simplified system shown in Figure 1.

Defining vectors $\mathbf{v}_\mathrm{T} = (v_{\mathrm{T},1}, \dots, v_{\mathrm{T},N_\mathrm{T}})^\mathrm{T}$ and $\mathbf{i}_\mathrm{T} = (i_{\mathrm{T},1}, \dots, i_{\mathrm{T},N_\mathrm{T}})^\mathrm{T}$ (and equivalently for all currents and voltages in the figure), the relationship between the port currents, port voltages and the Z-parameter matrix is:

$$\begin{pmatrix}\mathbf{v}_\mathrm{T}\\ \mathbf{v}_\mathrm{R}\end{pmatrix} = \begin{pmatrix}\mathbf{Z}_\mathrm{T} & \mathbf{Z}_\mathrm{TR}\\ \mathbf{Z}_\mathrm{RT} & \mathbf{Z}_\mathrm{R}\end{pmatrix}\begin{pmatrix}\mathbf{i}_\mathrm{T}\\ \mathbf{i}_\mathrm{R}\end{pmatrix}. \quad (1)$$

From circuit analysis, we can obtain the matrix of the (noiseless) input-output relationship $\mathbf{v}_\mathrm{R} = \mathbf{D}\mathbf{v}_\mathrm{G}$:

$$\begin{aligned}\mathbf{D} &= Z_\mathrm{L}(Z_\mathrm{L}\mathbf{I} + \mathbf{Z}_\mathrm{R})^{-1}\mathbf{Z}_\mathrm{RT}(Z_\mathrm{G}\mathbf{I} + \mathbf{Z}_\mathrm{T} - \mathbf{Z}_\mathrm{TR}(Z_\mathrm{L}\mathbf{I} + \mathbf{Z}_\mathrm{R})^{-1}\mathbf{Z}_\mathrm{RT})^{-1}\\ &= Z_\mathrm{L}(Z_\mathrm{L}\mathbf{I} + \mathbf{Z}_\mathrm{R} - \mathbf{Z}_\mathrm{RT}(Z_\mathrm{G}\mathbf{I} + \mathbf{Z}_\mathrm{T})^{-1}\mathbf{Z}_\mathrm{TR})^{-1}\mathbf{Z}_\mathrm{RT}(Z_\mathrm{G}\mathbf{I} + \mathbf{Z}_\mathrm{T})^{-1}.\end{aligned} \quad (2)$$

In many cases, specially in far-field communications, the *unilateral approximation* $\mathbf{Z}_\mathrm{TR} \approx 0$ is used. This assumption simplifies the analysis greatly and leads to the following input-output matrix:

$$\mathbf{D}_\mathrm{UA} = Z_\mathrm{L}(Z_\mathrm{L}\mathbf{I} + \mathbf{Z}_\mathrm{R})^{-1}\mathbf{Z}_\mathrm{RT}(Z_\mathrm{G}\mathbf{I} + \mathbf{Z}_\mathrm{T})^{-1}. \quad (3)$$

This is a coarse approximation. Instead, we propose to verify if the inter-array coupling is much smaller than the intra-array coupling:

$$\left\|\mathbf{Z}_\mathrm{TR}(Z_\mathrm{L}\mathbf{I} + \mathbf{Z}_\mathrm{R})^{-1}\mathbf{Z}_\mathrm{RT}\right\|_\mathrm{F} \ll \|Z_\mathrm{G}\mathbf{I} + \mathbf{Z}_\mathrm{T}\|_\mathrm{F}, \quad (4)$$

or equivalently as

$$\left\|\mathbf{Z}_\mathrm{RT}(Z_\mathrm{G}\mathbf{I} + \mathbf{Z}_\mathrm{T})^{-1}\mathbf{Z}_\mathrm{TR}\right\|_\mathrm{F} \ll \|Z_\mathrm{L}\mathbf{I} + \mathbf{Z}_\mathrm{R}\|_\mathrm{F}, \quad (5)$$

since $\mathbf{D} \approx \mathbf{D}_\mathrm{UA}$ in both cases.

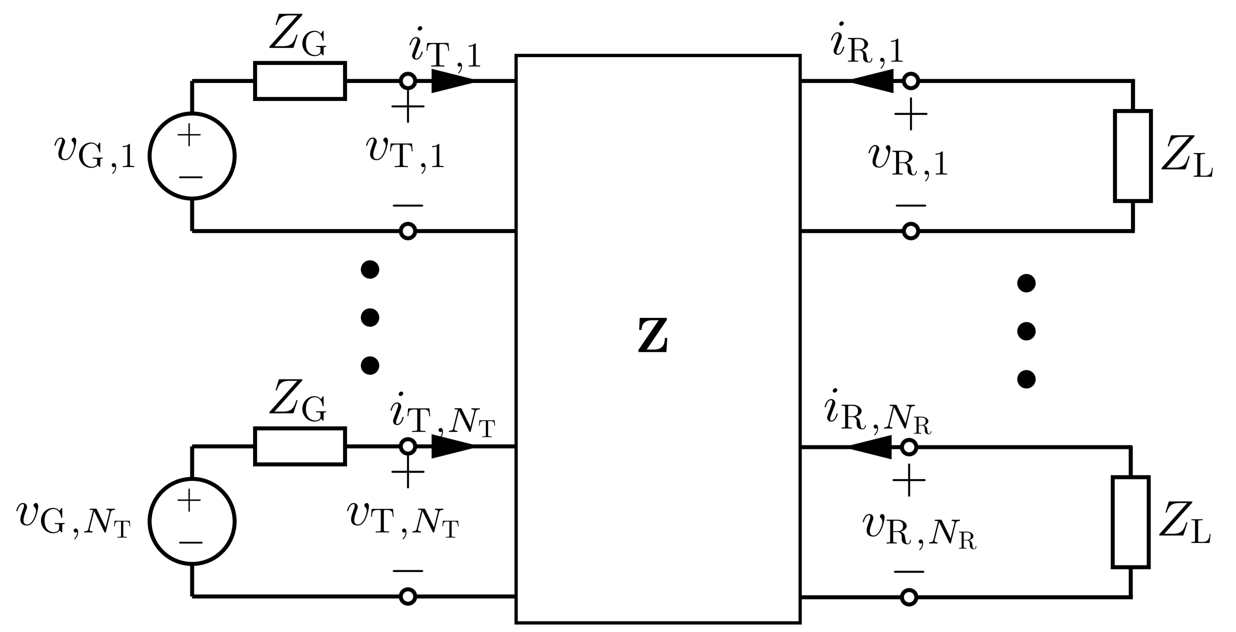

Figure 1. Simplified (noiseless) multiport model of a MIMO system.

System Model

Two complementary wireless communication systems are considered: massive MISO with $N_\mathrm{T} = N$ (downlink), and massive SIMO with $N_\mathrm{R} = N$ (uplink). The array is assumed to be a uniform linear array (ULA) with aperture size D and radiating elements are Hertzian dipoles of length l with a separation d between them. The *intra-array coupling* impedance matrix for this setup is:

$$\begin{cases}[\mathbf{Z}_\cdot]_{m,n} = R_\mathrm{r}, \ m = n, \ 1 \le m, n \le N,\\ [\mathbf{Z}_\cdot]_{m,n} = \frac{3}{2}R_\mathrm{r}\,\mathrm{j}\exp(-\mathrm{j}kd|m-n|)\left(\frac{1}{kd|m-n|} - \frac{\mathrm{j}}{(kd|m-n|)^2} - \frac{1}{(kd|m-n|)^3}\right),\end{cases} \quad (6)$$

where $R_\mathrm{r} = \frac{2}{3}\pi\eta(\frac{l}{\lambda})^2$ is the radiation resistance. Assuming that communication takes place in the *radiative* near field, the Z-parameters of *inter-array coupling* are:

$$[\mathbf{z}_\mathrm{TR}]_n = \mathrm{j}R_\mathrm{r}\frac{\mathrm{e}^{-\mathrm{j}kr_n}}{kr_n}, \quad (7)$$

where r_n is the distance between the single-antenna device and the n-th element in the array.

Study of Coupling Effects

For MISO and SIMO, conditions (4) and (5) become:

$$\frac{\|\mathbf{z}_\mathrm{TR}\|_2^2}{|Z_\mathrm{RL}|} \ll \|\mathbf{Z}_\mathrm{GT}\|_\mathrm{F}, \quad \frac{\|\mathbf{z}_\mathrm{RT}\|_2^2}{|Z_\mathrm{GT}|} \ll \|\mathbf{Z}_\mathrm{RL}\|_\mathrm{F}, \quad (8)$$

where $\mathbf{Z}_\mathrm{GT} = Z_\mathrm{G}\mathbf{I} + \mathbf{Z}_\mathrm{T}$ and $\mathbf{Z}_\mathrm{RL} = Z_\mathrm{L}\mathbf{I} + \mathbf{Z}_\mathrm{R}$. Observe that both conditions are equivalent.

Fixing the *inter-element spacing*:

$$\|\mathbf{Z}_\mathrm{GT}\|_\mathrm{F} \sim O(\sqrt{N}), \quad \lim_{N\to+\infty}\frac{\|\mathbf{z}_\mathrm{TR}\|_2^2}{|Z_\mathrm{RL}|} < +\infty, \quad (9)$$

which means that the unilateral approximation is (asymptotically) valid. Numerical results for this scenario are shown in Figure 2.

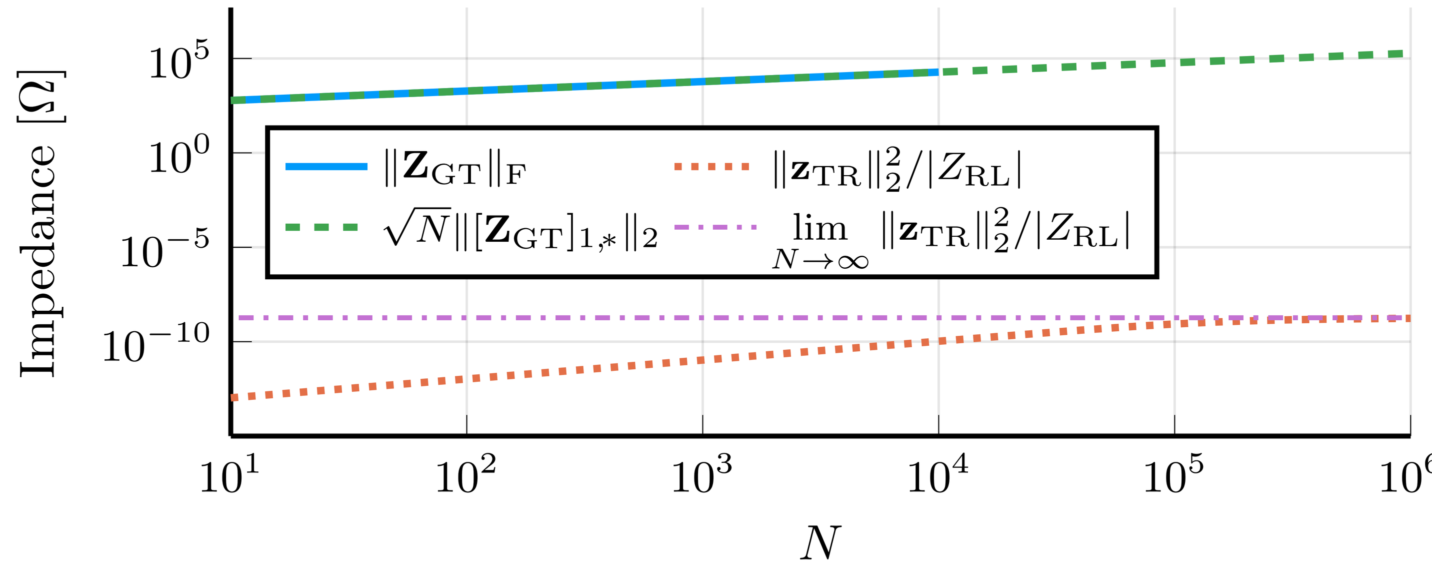

Figure 2. Fixed $d = \lambda/2$ coupling condition as a function of N with $r = 55\,\mathrm{m}$.

Fixing the *array size* by letting $d = \frac{D}{N-1}$,

$$\|\mathbf{Z}_\mathrm{GT}\|_\mathrm{F} \sim O(N^{3.5}), \quad \|\mathbf{z}_\mathrm{TR}\|_2^2 \sim O(N). \quad (10)$$

As $\|\mathbf{Z}_\mathrm{GT}\|_\mathrm{F}$ grows much faster than $\|\mathbf{z}_\mathrm{TR}\|_2^2$, the unilateral approximation is also asymptotically valid when the array size is fixed. The numerical results are shown in Figure 3.

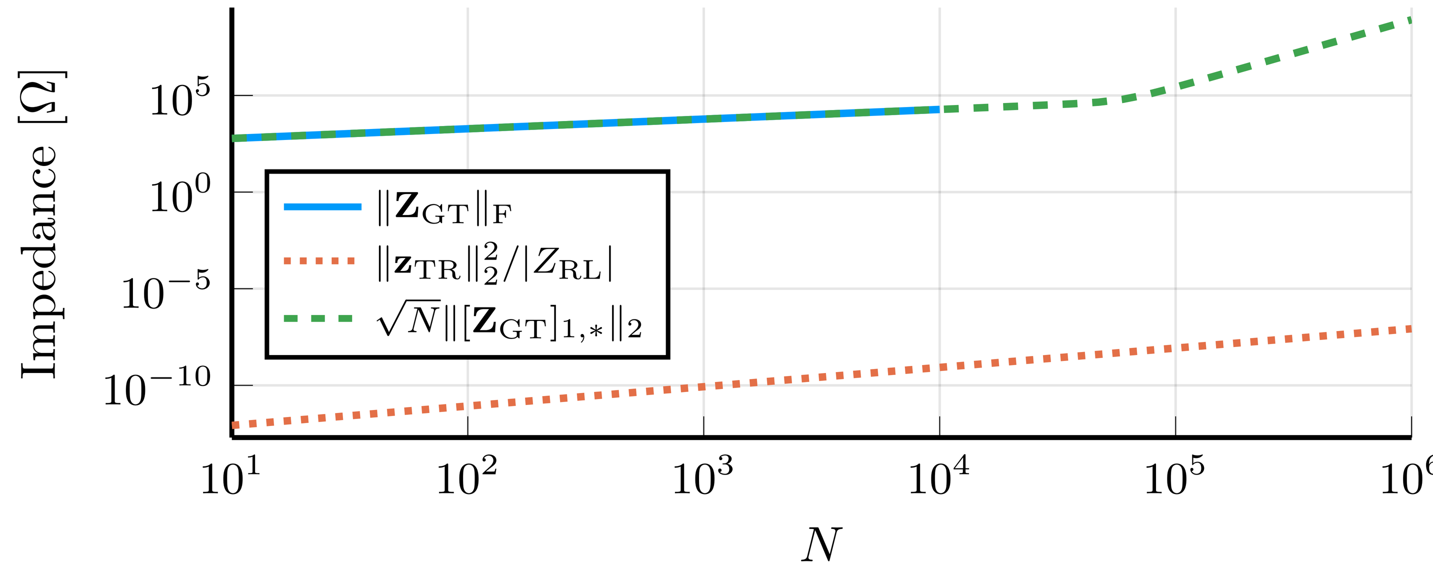

Figure 3. Fixed array size $D = 1\,\mathrm{m}$ coupling condition as a function of N with $r \approx 20\,\mathrm{m}$.

References

[1] A. Martí, J. Riba, M. Lamarca, and X. Gràcia, "Asymptotic Analysis of Near-Field Coupling in Massive MISO and Massive SIMO Systems," *IEEE Communications Letters*, 2024. DOI: 10.1109/LCOMM.2024.3416044.

Acknowledgments

This work was funded by projects MAYTE (PID2022-136512OB-C21) and GeMMFiT (PID2021-125515NB-C21) by MCIU/AEI/10.13039/501100011033 and ERDF "A way of making Europe", grants 2021 SGR 01033 and 2021 SGR 00603 by Department de Recerca i Universitats de la Generalitat de Catalunya and grant 2023 FI "Joan Oró" 00050 by Departament de Recerca i Universitats de la Generalitat de Catalunya and the ESF+.

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Cofinanciado por la Unión Europea

AGENCIA ESTATAL DE INVESTIGACIÓN

Aniol Martí – aniol.marti@upc.edu