Supplementary Material

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Abstract

This document is the supplementary material for the article "Reconfigurable Massive MIMO: Precoding Design and Channel Estimation in the Electromagnetic Domain".

I. A Comparison Between RmMIMO and TmMIMO Architectures

Fig. 1 presents a comparison of four different structures: (a) Traditional fully-digital array (referred to as TmMIMO in this paper); (b) Reconfigurable fully-digital array (referred to as RmMIMO in this paper); (c) Traditional hybrid array [R1]; and (d) Reconfigurable hybrid array.

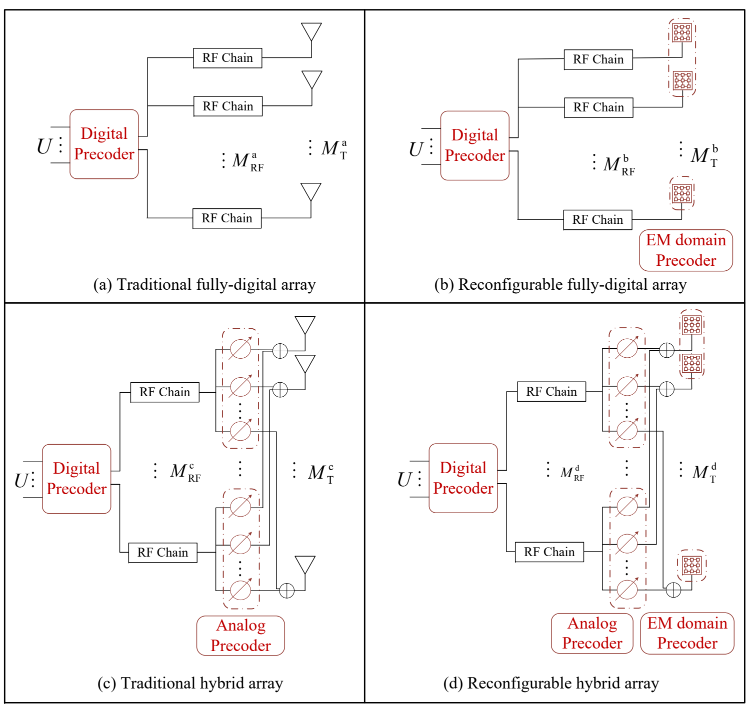

Fig. 1. A comparison of traditional fully-digital/hybrid arrays and their reconfigurable conunterparts in this paper.

Fig. 1 demonstrates that the primary difference between the reconfigurable and traditional arrays lies in the antenna configuration. This paper compares configurations (a) and (b) to assess the additional benefits provided by reconfigurable antenna radiation patterns. We define the ability to customize radiation patterns as EM domain precoding, distinguishing it from traditional digital and analog precoding. Furthermore, our architecture, although distinct from the traditional hybrid array (c), remains compatible with it. Specifically, by replacing the antennas in the traditional hybrid array with reconfigurable antennas, we derive structure (d).

To ensure a fair comparison between the performance of the proposed framework and existing architectures, it is crucial to maintain consistency in certain dimensions. We consider the following two cases:

(1) All architectures have the same number of antennas $(M_{\mathrm{T}}^{a} = M_{\mathrm{T}}^{b} = M_{\mathrm{T}}^{c} = M_{\mathrm{T}}^{d})$:

- Based on our simulation results in the manuscript, structure (b) outperforms structure (a) in terms of SE. Additionally, existing research has confirmed that structure (a) outperforms structure (c) in SE when the number of antennas is the same [R1], as hybrid arrays typically employ fewer RF chains than antennas. Therefore, the relative SE performance is $b > a > c$.
- Similarly, with the same number of antennas, and due to the higher degrees of freedom (DoF) in a fully digital array compared to hybrid beamforming, we have $b > d$. Furthermore, the introduction of additional EM domain DoFs by RmMIMO naturally results in $d > c$, leading to an overall relationship of $b > d > c$.
- The relative performance between (a) and (d) depends on various factors, such as the number of user equipment (UEs), the design DoF of the antenna radiation pattern, and the adopted precoding algorithm. This issue requires further research and is beyond the scope of this paper.

(2) All architectures have the same number of RF chains $(M_{\mathrm{RF}}^{a} = M_{\mathrm{RF}}^{b} = M_{\mathrm{RF}}^{c} = M_{\mathrm{RF}}^{d})$:

- Similar to the previous analysis, the potential SE performance bound is determined by the design DoF. Thus, we have $d > b > a$ and $d > c > a$.
- Next, we compare the performance of structures (b) and (c). In this case, the number of antennas in the proposed structure (b) equals the number of RF chains (i.e., $M_{\mathrm{T}}^{b} = M_{\mathrm{RF}}^{b}$), while the number of antennas in the traditional structure (c) exceeds the number of RF chains (i.e., $M_{\mathrm{T}}^{c} \geq M_{\mathrm{RF}}^{c}$). From an SE perspective, directly comparing architectures (b) and (c) would be influenced by the adopted hybrid precoding algorithms. Therefore, we compare their performance indirectly.

  Figure 2 compares architectures (a) and (b) with the same number of RF chains (and

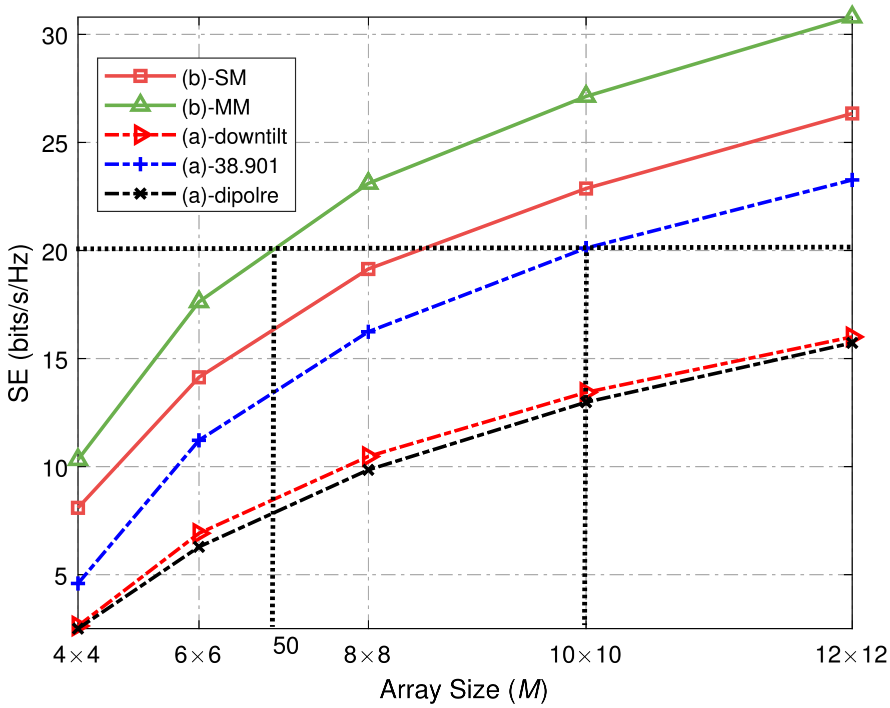

Fig. 2. SE versus array size M for architecture (a) and (b) when $U = 6, K = 100, \mathrm{SNR}_u = 10\mathrm{dB}, \mathrm{SNR}_d = 15\mathrm{dB}$.

the same number of antennas). The simulation results indicate that, to achieve the same SE, architecture (b) requires fewer antennas than architecture (a). For instance, at an SE of 20 bits/s/Hz, architecture (b)-MM with approximately 50 antennas achieves equivalent performance to architecture (a)-38.901 with a 10×10 antenna configuration. On the other hand, for architecture (c)-38.901 with 50 RF chains and a 10×10 antenna configuration, its performance is evidently inferior to that of architecture (a)-38.901 with the same number of antennas. Thus, it can be inferred that if we were to plot the performance curves of architecture (c)-38.901 with different numbers of antennas (but a fixed number of RF chains at 50), when the number of antennas M_T^c exceeds 50, the SE performance curve should be no higher than that of architecture (a)-38.901. **This also confirms that, with the same number of RF chains, architecture (b) can at least match the performance of architecture (c) with more antennas. The relative SE performance relationship can be inferred from Fig. 2.**

II. VISUALIZATION OF OPTIMIZED RADIATION PATTERNS

Following a progressive process from simple to complex channel scenarios, we compared the visual results of the optimized radiation patterns for multiple-user transmissions.

- In Fig. 3, we consider a single-mode (SM), line-of-sight (LoS)-dominant (the Rice factor is set to 15 dB) scenario for 3-UE transmission, examining differences in radiation patterns for various values of K. The optimized radiation pattern is shown in Fig. 14. The colored arrows denote the angle of departure at the BS for different UEs. In this case, it is evident that the pattern optimization strategy primarily focuses on energy harvesting, aiming to gather as much channel energy as possible from the UEs' main multipath directions. As K increases, the radiation pattern exhibits greater directivity, enabling finer beam steering towards corresponding users and enhancing the received energy for each path.

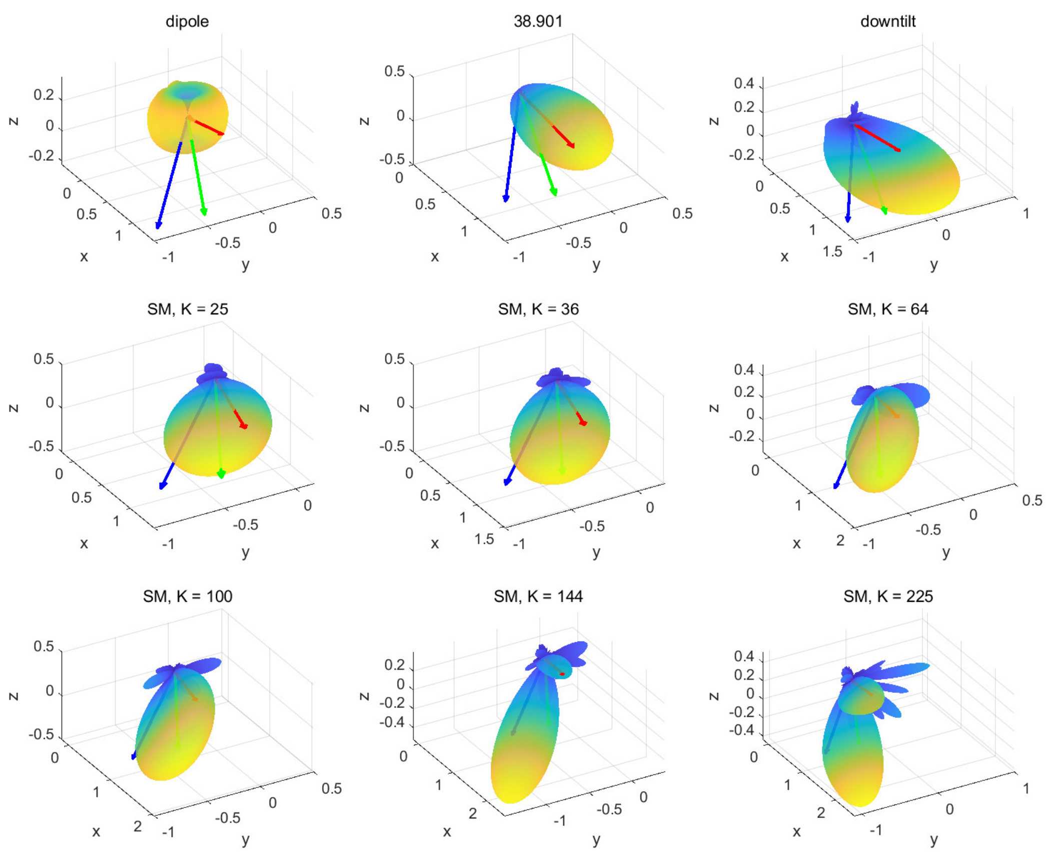

Fig. 3. Optimized patterns for a 3 UE, SM, LoS-dominated transmission scenario.

- In Fig. 4, we investigate the multi-mode(MM), LoS-dominated scenario, comparing radiation pattern differences across various antennas. It is observed that the radiation patterns on different antennas focus on different paths, thereby achieving better overall receiving energy across all directions.

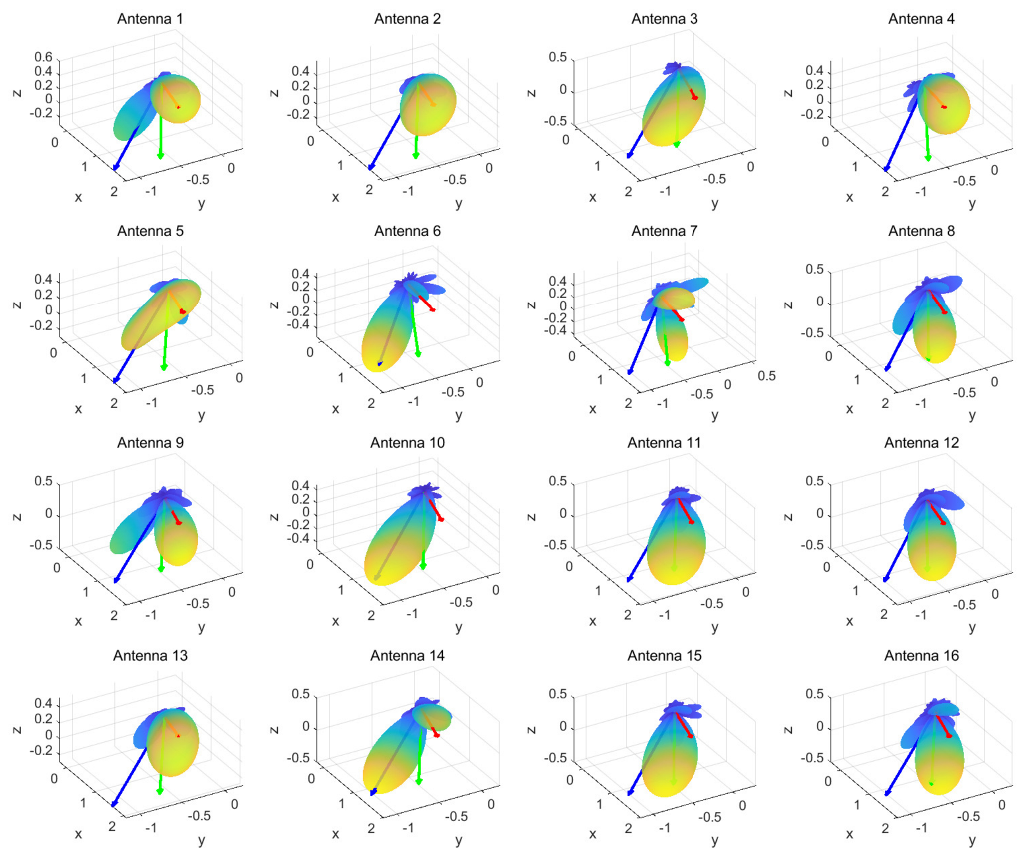

Fig. 4. Optimized pattern for a 3 UE, MM, LoS-dominated transmission scenario, where the BS is equipped with a 4×4 RmMIMO.

- In Fig.5, we analyze the SM, non-line-of-sight (NLoS) transmission, assuming each UE has 8 paths, for 2-UE transmission. In this context, the design of the radiation pattern does not consider all paths for each UE but selectively focuses on certain paths. Additionally, as K increases, the beam's directivity progressively strengthens.

Overall, the proposed scheme for optimizing radiation patterns is an energy harvesting strategy. For LoS-dominated propagation scenarios, whether in SM or MM cases, the radiation pattern is optimized to capture as much energy as possible from all user main paths. The higher the order of spherical harmonics, the stronger the directivity of the designed beam. For MM scenarios, different antennas' radiation patterns focus on different receiving path angles. For NLoS scenarios, since there is no obvious main path, the optimized radiation pattern selectively

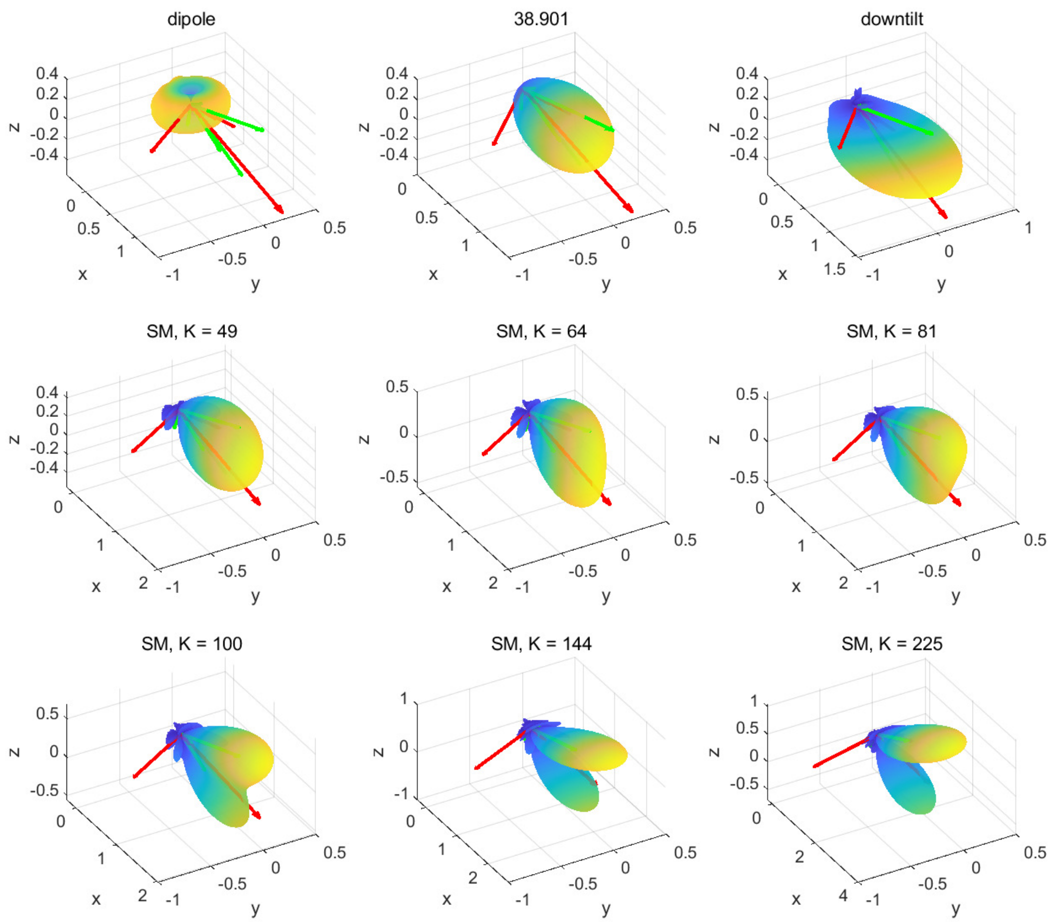

Fig. 5. Optimized patterns for a 2 UE, SM, NLoS transmission scenario.

receives part of the paths rather than considering all of them. Similarly, as the order of spherical harmonics increases, the directivity of the designed beam also strengthens.

REFERENCES

[R1] A. Alkhateeb and R. W. Heath, “Frequency selective hybrid precoding for limited feedback millimeter wave systems,” *IEEE Trans. Commun.*, vol. 64, no. 5, pp. 1801-1818, May 2016.