

Angular Spread Effect on Spectral and Energy Efficiency of a Hybrid Massive MIMO System

Siti Aisyah, Angela Doufexi, and Simon Armour

University of Bristol, Bristol, BS8 1UB, United Kingdom, <https://www.bristol.ac.uk/>

Abstract—This paper extends a previous study of hybrid beamforming Massive MIMO system with a Uniform Linear Array (ULA) to consider a system with a Uniform Rectangular Array (URA). The ULA Massive MIMO system provides a full degree of freedom for beamforming in the azimuth direction. In contrast, the URA offers more flexible 2D beamforming, both in azimuth and elevation directions, making it better suited for handling multipath scenarios. These two different antenna array structures have been analyzed for fully and partially connected hybrid beamforming systems. This paper shows that the spectral and energy efficiency of the system with a ULA can reach up to $\sim 15\%$ higher than that of the one with a URA for the single-user hybrid beamforming massive MIMO system. The simulation result also shows that the specific angular spread can also increase the spectral and energy efficiency up to $\sim 26\%$ for both ULA and URA hybrid systems.

I. INTRODUCTION

In massive Multiple Input Multiple Output (MIMO), the arrangement of the antenna elements at the transmitter side is crucial to generate narrow beams with small side lobes. Most research studies the uniform linear array (ULA) at the BS for a fully connected hybrid precoding system [1]. However, due to the large dimensions of ULA, it is not feasible for practical used in Massive MIMO. Instead, it is typically applied in areas such as radar, satellite communication, and navigation systems. Several research studies also consider different array configurations such as uniform rectangular array [2]. However, most studies investigated the fully hybrid precoding system [1] [2]. Therefore, this paper investigates the performance analysis of both the fully and partially connected hybrid beamforming massive MIMO system with different types of antenna array, ULA and URA. The spectral efficiency (SE) and energy efficiency (EE) of fully and partially connected structures are presented and the impact of angular spread on those performance metrics is investigated.

II. SYSTEM MODEL

The hybrid beamforming Massive MIMO systems modelled in this paper are equipped with 32 transmit antenna and 8 receive antennas comprised of either Uniform Linear Array (ULA) or Uniform Rectangular Array (URA) and configured as either fully or partially connected. The URA dimensions are 8×4 and 4×2 for transmit and receive antennas, respectively. The single-user Massive MIMO system is assumed to operate in a frequency flat rich scattering channel, in which the path gains are derived from a zero-mean, unit-variance, and complex-value normal distribution.

In this simulation scenario, the Minimum Mean Square Error (MMSE) has been applied to the system as it is assumed

to operate in a noisy environment. The simulation considers several precoder types such as the optimal precoder for both fully and partially connected systems. For a comparison, it also provides sparse and successive interference cancellation (SIC) precoders for fully and partially hybrid structures, respectively. Also, the formula to define spectral and energy efficiency for fully and partially connected hybrid structures referred to our previous definition [3].

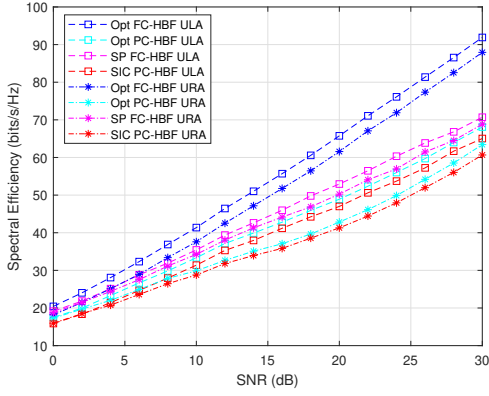
III. SIMULATION RESULT

This section studies and compares the performance of fully and partially connected hybrid beamforming systems with ULA and URA. Fig. 1a shows that the SE value for a hybrid system with ULA is higher than that of URA for all types of precoder. The SE of the ULA hybrid system with AoD and AoA described in TABLE I is up to $\sim 4.5\%$ higher than that of URA for the optimal fully connected precoder and reaches up to $\sim 15\%$ for the optimal partially connected hybrid system. Similarly, Fig. 1b shows that the EE value of the ULA hybrid system exceeds that of the URA across all precoder types. This happened because ULA has a uniform beamforming structure that can achieve high directivity in a specific direction leading to higher spectral and energy efficiency. Whereas the URA, which has antenna placed in both horizontal and vertical dimensions, provides more complex spatial diversity compared to the simpler ULA, which may improve performance in certain scenarios, but it also introduces more complexity in beamforming, which affects the efficiency.

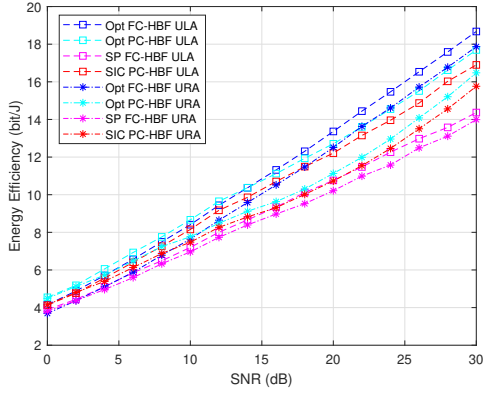
Simulations were performed to analyze the impact of angular spread on SE and EE values, as illustrated in Fig. 2a. Assuming azimuth of AoA and AoD is varied while the elevation angular spread is fixed, the result indicates that the peak SE and EE values vary with various azimuth angular spreads. For an elevation angular spread of 30° , the highest SE value occurs at an azimuth angular spread of 75° for all precoder types, except for fully connected sparse precoders

TABLE I: Simulation Parameter Setup

Parameter	Value
Carrier Frequency	3.5 GHz
Number of Tx antenna elements, N_t	32
Number of Rx antenna elements, N_r	8
Tx and Rx element spacing	$\frac{1}{2}\lambda$
Number of ray multipath	80
Angle of Departure (AoD) differential	az $\in (\pm 45^\circ)$ el $\in (\pm 30^\circ)$
Angle of Arrival (AoA) differential	az $\in (\pm 45^\circ)$ el $\in (\pm 30^\circ)$



(a)

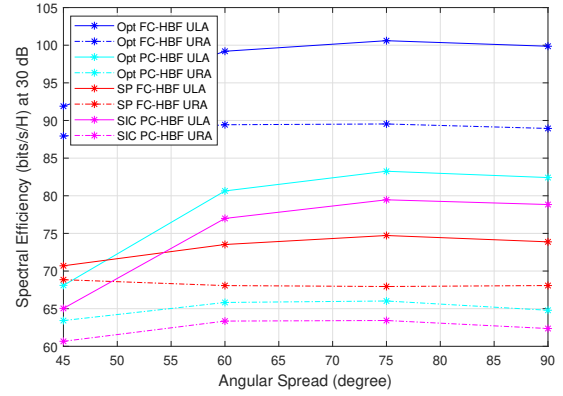


(b)

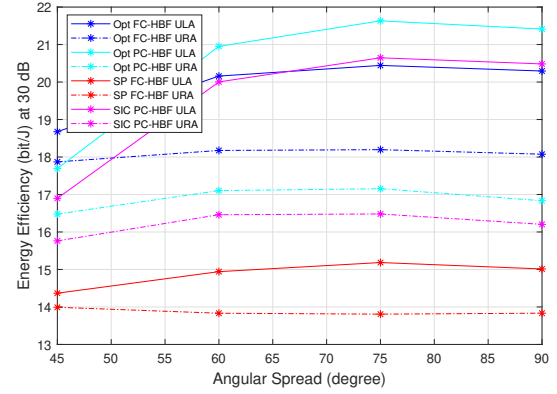
Fig. 1: (a). Spectral efficiency; (b). Energy Efficiency for fully and partially connected hybrid beamforming system using URA and ULA for different precoder types at azimuth angular spread of 45° and elevation angular spread of 30°

with URA, where it is at 45° . The significant increase occurs for a partially connected structure with ULA, where it increases around 22% at azimuth angular spread of 75° compared to that of 45° . This happens because the system is implemented in multipath propagation with many scatterings, where a broader angular spread allows the system to exploit different multipath components to increase capacity without increasing interference. The same trend also applies to EE value shown in Fig. 2b, where the highest EE value of partially connected hybrid architecture occurs at azimuth angular spread of 75° which is approximately $\sim 22\%$ higher than that of 45° .

From the graph in Fig. 2, the highest difference SE value between a hybrid structure with ULA and URA is ~ 17 bps/Hz ($\sim 26\%$) which occurs at azimuth angular spread of 75° of partially connected hybrid structure. The trend of the EE value is the same as that of the SE value. The EE value of a hybrid structure with ULA is up to $\sim 25\%$ (4 bit/J) higher than that of URA which also occurs for a partially connected hybrid structure.



(a)



(b)

Fig. 2: (a). Spectral efficiency; (b). Energy Efficiency for fully and partially connected hybrid beamforming system using URA and ULA with varying azimuth angular spread

IV. CONCLUSION

In this paper, we have presented fully and partially connected hybrid beamforming massive MIMO systems using ULA and URA antenna configurations and investigated the spectral and energy efficiency and the impact of angular spread upon these metrics. The simulation results showed that the spectral and energy efficiency for ULA is approximately 4.5% to 15% higher than the URA system, depending upon precoder type used. It also shows that the increase of up to $\sim 26\%$ spectral and energy efficiency can be achieved when the azimuth angular spread is 75° .

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