A Fairer Comparison of Processing Implementations in User-Centric Distributed Massive MIMO Systems

Michael A. S. da Costa, Marx M. M. Freitas, Thaissa T. R. Ueoka, Daynara D. Souza,
A. L. P. Fernandes, André M. Cavalcante, Roberto M. Rodrigues, and João C. W. A. Costa

***Abstract*— This paper performs a new comparison between distributed and centralized processing implementations of user-centric distributed massive multiple-input multiple-output (D-mMIMO) systems, also known as cell-free mMIMO. The impacts of processing capacity limitations and inter-central processing unit (CPU) coordination are considered to perform a fairer comparison. The analysis includes two radio unit (RU) selection methods, varying levels of inter-CPU coordination, and different processing capacity restrictions. Simulation results indicate that processing capacity limitations affect spectral efficiency (SE) more in centralized implementations than in distributed ones. Moreover, centralized implementations may require more inter-CPU coordination to improve SE.**

***Keywords*— Cell-free massive MIMO, computational complexity, processing implementations, user-centric approach.**

I. Introduction

User-centric (UC) distributed massive multiple-input multiple-output (D-mMIMO) systems, commonly referred to as cell-free (CF) mMIMO, are promising technologies for next-generation mobile communication networks (6G and beyond) [1]. These systems employ several distributed radio units (RUs) that cooperate to serve the user equipments (UEs) in the coverage area, offering several advantages over traditional cellular systems, such as a more uniform service and a better coverage probability [2].

The physical implementation of UC D-mMIMO systems is inherently distributed, but processing can be either centralized or distributed [3]. In the implementation of centralized processing, the signal processing tasks are performed in central processing units (CPUs), while in the distributed one, the processing takes place at the RUs [4]. The literature advocates that centralized processing yields higher spectral efficiency (SE) and may even require less fronthaul signaling [3]. However, these insights were achieved without considering essential aspects of D-mMIMO systems, such as multiple CPUs [5], limited computational complexity (CC) [6], and inter-CPU coordination [7]. This paper addresses this issue by presenting fairer comparisons, considering all those aspects to show a fairer overview of these two implementations.

II. System Model

We consider a D-mMIMO system composed of J CPUs, L RUs and K UEs both equipped with a single antenna, as Fig. 1 illustrates. The system operates on the time-division duplex (TDD) protocol and assumes reciprocity for the uplink (UL) and downlink (DL) channels. We focus on DL transmissions and assume that the propagation channels follow a Rician fading defined as in [7]. We assume that each RU can serve only a limited number of UEs to ensure scalability. This prevents the CC from increasing with the number of UEs [2].

To investigate the impacts of inter-CPU coordination and limitation of CC in each processing implementation, we rely on the approaches from [6], [7]. In a nutshell, these works present strategies that modify the RU clusters of the UE to limit the CC of the system [6] and mitigate the effects of inter-CPU coordination [7]. By using these strategies, it is possible to evaluate the performance of UC D-mMIMO systems under different levels of CC and inter-CPU coordination.

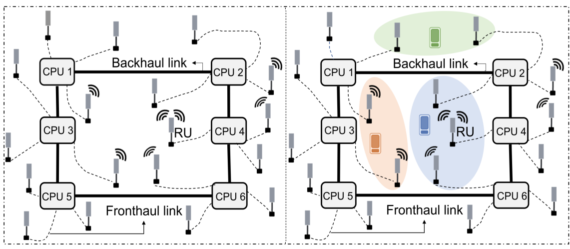


Fig. 1: UC D-mMIMO system with multiple CPUs.

In [6], the CPUs analyze the RU cluster of each UE and states that only the C_{max} RUs presenting the strongest channel gains will serve the UE. This strategy prevents the CC of UC D-mMIMO systems from growing with the number of RUs. In [7], each UE is associated with a primary CPU and a subset of RUs. Then, the remaining CPUs (named non-primary CPUs) may drop the UE of some RUs if it presents a poor channel condition. The non-primary CPUs name the UE as inter-coordinated UE. In [7], each CPU can serve only a limited number of inter-coordinated UEs, denoted as K_{int}.

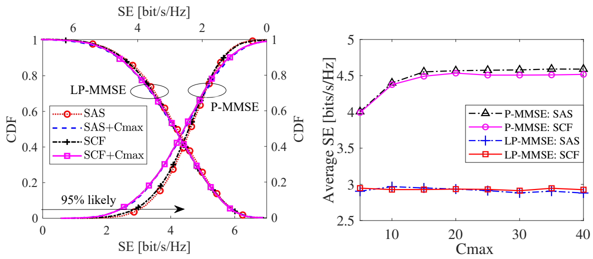
III. Numerical Results

We consider a D-mMIMO network composed of $L = 100$ RUs, where each RU can serve up to 10 UEs [2]. The values of K and K_{int} may vary and are specified throughout the results. The UEs are uniformly distributed across a square area of 1 km $\times$1 km, while the distribution of the RUs follows a hard core point process (HCPP) [8]. The SE is computed as in [2] and the remaining simulation parameters, like radio and propagation ones, follow [7]. The CC is expressed in terms of the number of complex multiplications needed to perform channel estimation and generate the combining

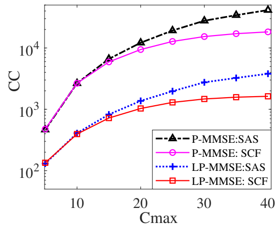
Michael A. S. da Costa[1], Marx M. M. Freitas[1], Thaissa T. R. Ueoka[1], Daynara D. Souza[1], A. L. P. Fernandes[1], André M. Cavalcante[2], Roberto M. Rodrigues[1], and João C. W. A. Costa[1]. [1]Applied Electromagnetism Laboratory, Federal University of Pará - UFPA, Belém, Brazil, [2]Ericsson Research, Ericsson Telecomunicações Ltda., Indaiatuba, Brazil. E-mails: michael.costa@itec.ufpa.br marx@ufpa.br; thaissa.ueoka@itec.ufpa.br; daynara@ufpa.br; andrelpf@ufpa.br; andre.mendes.cavalcante@ericsson.com; rmr@ufpa.br jweyl@ufpa.br. This work was partially supported by Ericsson Telecomunicações Ltda, CNPq and CAPES.

vectors in each coherence block [2]. Monte Carlo simulations are employed to account for different channel realizations and RU/UE positions, and the RU selection schemes of [2], [4] were adopted. Hereafter we name the schemes of [4] and [2] as scalable access point selection (SAS) and scalable cell-free (SCF) as the authors adopt similar terminologies. We have adopted the local partial MMSE (LP-MMSE) precoding for the distributed implementation and partial MMSE (P-MMSE) for the centralized one [4].

Fig. 2 illustrates the impacts of limiting the CC in centralized and distributed processing implementations. In Fig. 2a, the cumulative distribution function (CDF) of the SE is more affected by a small value of C_{max} in the centralized implementation than in the distributed one. For instance, the SE of the 95% likely UEs decreases by approximately 20% when using the P-MMSE scheme, whereas the LP-MMSE may experience a slight increase in SE. This is because centralized processing usually benefits more from RU clusters comprising more RUs than the distributed [8].



(a) CDF, $C_{max} = 10$ (b) Average SE

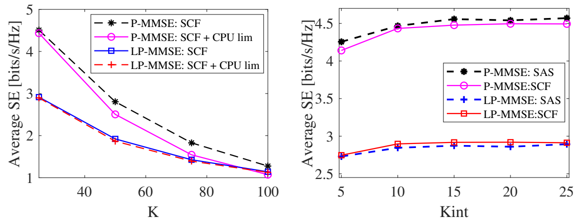


(c) Average CC

Fig. 2: Impacts of limiting the CC in each processing implementation. Parameters setting: $L = 100$, $K = 25$.

In Fig. 2b, the average SE of the P-MMSE scheme does not suffer considerable degradation when $C_{max} = 20$. However, note that the CC increases by approximately 350% when C_{max} grows from 10 to 20, as depicted in Fig. 2c. This suggests that the centralized implementation requires more processing capacity to achieve its total SE, differing from the distributed one that nearly reaches its total SE with $C_{max} = 10$.

Fig. 3 presents the average SE versus the number of UEs K and K_{int}. The term *CPU lim* is utilized jointly with the name of the RU selection scheme to denote the systems that reduce the effects of inter-CPU coordination. One can note that the average SE of the LP-MMSE scheme suffers only a small degradation when the system employs inter-CPU coordination reduction [7]. On the other hand, the SE of the P-MMSE decays when the system mitigates inter-coordination effects, especially when the number of UEs K grows. For example, the SE decays about 15% for $K = 75$. Moreover, when analyzing the variation of K_{int} in Fig. 3b, it is noticeable



(a) Average SE, $K_{int} = 10$ (b) Average SE, $K = 25$

Fig. 3: Impacts of inter-CPU coordination in each processing implementation. Parameters setting: $L = 100$.

that the centralized implementation can achieve greater SEs by increasing K_{int}. However, the impact of varying K_{int} is not as impressive as the variation of C_{max} since a larger K_{int} can provide only marginal gains to the SE. Therefore, despite the centralized implementation requiring higher inter-coordination among CPUs compared to the distributed implementation, the CC was the factor that most differentiated these two implementations throughout this study.

IV. Conclusions

This paper presented a new comparison between the distributed and centralized processing implementations of UC D-mMIMO systems. Simulation results reveal that the processing capacity limitation affects much more centralized implementation than the distributed ones. For instance, the centralized implementation may require an increase of approximately 350% in the CC to achieve its total SE. Besides, the centralized one may need more inter-CPU coordination to reach its total SE, but the gains in SE from increased inter-CPU coordination are marginal. Throughout this study, the CC emerged as the primary distinguishing factor between these two implementations. These results can inspire future works on the theme and lay the foundation for further comparisons between centralized and distributed implementations. Future works include extending our analysis to other network aspects, such as fronthaul limitations and UE mobility.

References

[1] I. F. Akyildiz *et al.*, “6G and beyond: The future of wireless communications systems,” *IEEE Access*, vol. 8, pp. 133 995–134 030, Jul. 2020.

[2] E. Björnson and L. Sanguinetti, “Scalable cell-free massive MIMO systems,” *IEEE Trans. Commun.*, vol. 68, no. 7, pp. 4247–4261, Jul. 2020.

[3] E. Björnson and L. Sanguinetti, “Making cell-free massive MIMO competitive with MMSE processing and centralized implementation,” *IEEE Trans. Wireless Commun.*, vol. 19, no. 1, pp. 77–90, Jan. 2019.

[4] Ö. Demir, E. Björnson, and L. Sanguinetti, *Foundations of User-Centric Cell-Free Massive MIMO*. Foundations and Trends in Signal Processing Series, Now Publishers, 2021.

[5] V. Ranjbar *et al.*, “Cell-free mMIMO support in the O-RAN architecture: A PHY layer perspective for 5G and beyond networks,” *IEEE Commun. Stand. Mag.*, vol. 6, no. 1, pp. 28–34, 2022.

[6] M. M. M. Freitas, D. D. Souza, A. L. P. Fernandes, D. B. da Costa, A. M. Cavalcante, L. Valcarenghi, and J. C. W. A. Costa, “Scalable user-centric distributed massive MIMO systems with limited processing capacity,” in *Proc. IEEE Int. Conf. Commun. (ICC)*, 2023, pp. 1–7.

[7] M. M. M. Freitas, D. D. Souza, D. B. da Costa, A. M. Cavalcante, L. Valcarenghi, G. S. Borges, R. Rodrigues, and J. C. W. A. Costa, “Reducing inter-CPU coordination in user-centric distributed massive MIMO networks,” *IEEE Wireless Commun. Lett.*, pp. 1–5, 2023.

[8] M. Freitas, D. Souza, G. Borges, A. M. Cavalcante, D. B. da Costa, M. Marquezini, I. Almeida, R. Rodrigues, and J. C. W. A. Costa, “Matched-decision AP selection for user-centric cell-free massive MIMO networks,” *IEEE Trans. Veh. Technol*, pp. 1–16, Jan. 2023.