Evaluating cross-connection fronthaul redundancy schemes for segmented user-centric distributed massive MIMO under limited capacity links

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***Abstract*— User-centric (UC) distributed massive multiple-input multiple-output (MIMO), also known as cell-free massive MIMO, is a technology designed to maximize user spectral efficiency (SE) and ensure uniform coverage in 6G systems. One way to reduce the deployment complexity of these networks is a segmented fronthaul implementation, which may introduce reliability issues that are compensated in the literature through protection schemes. This paper evaluates cross-connection fronthaul redundancy schemes under limited capacity links. Our findings enhance the understanding of cross-connection schemes, extending what is presented in the literature in limited fronthaul environments.**

***Keywords*— Cell-free massive MIMO, Segmented fronthaul, Cross-connection redundancy schemes, Fronthaul limitations.**

I. Introduction

User-centric (UC) distributed massive multiple-input multiple-output (D-mMIMO), also known as cell-free massive MIMO, is an ultra-dense wireless network where the number of transmission-reception points (TRPs) exceeds the number of users' equipment (UEs). These networks maximize user spectral efficiency (SE) and ensure uniform coverage in 6G systems by coherently transmitting and receiving each UE's signal through multiple TRPs. The signals are jointly processed using fronthaul links to central processing units (CPUs) which coordinate the system and handle baseband functions. Finally, each user is connected to a limited cluster of TRPs based on their conditions and requirements [1].

The deployment complexity of UC D-mMIMO is an open problem in the literature. One proposed solution to simplify the deployment is fronthaul segmentation, which offers scalability by using a compute-and-forward architecture were fronthaul links connect multiple TRPs to a CPU in a serial configuration [2]. However, this structure may bring reliability issues. For instance, certain failures could lead to disconnection of many TRPs and result in significant performance losses. In [3], protection schemes are assessed to address this issue, and cross-connection (CC) between serial chains is identified as a reasonable option for protection.

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Despite this, the CC evaluation in [3] did not consider fronthaul limitations. This consideration is fundamental, as transferring TRPs to a different serial chain through CC will transfer fronthaul load and impact the protection scheme performance. This paper aims to fill this gap by evaluating CC with fronthaul limitations to answer if the scheme can be effective even in practical fronthaul limited scenarios. To this end, the fronthaul limitation model presented in [4] is used.

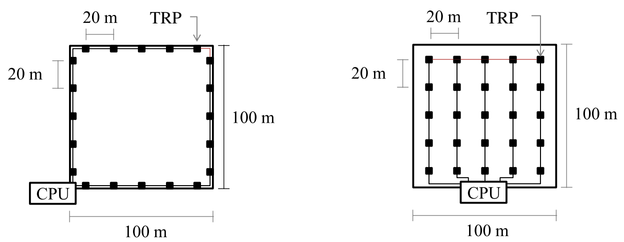
II. System model

It is assumed a UC D-mMIMO system with a fronthaul network that connects TRPs in a serial way, as presented in [3]. The fronthaul limitations are modeled according to the linear quantization approximation described in [4] for a baseband in TRP functional split, which uses the Bussgang decomposition.

III. Numerical Results

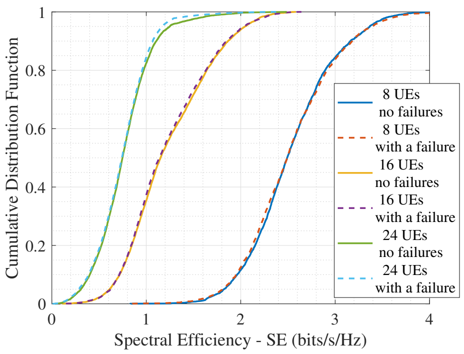
This study examines the downlink spectral efficiency (SE) performance of a segmented UC D-mMIMO network covering an office environment scenario that spans a 100 m × 100 m area based on MR precoding, Rician channels, and the assumptions outlined in [3]. The focus is on cross-connection protection schemes for the fronthaul network structures presented in Figs. 1a and 1b. In both scenarios, each TRP is equipped with four antennas, and the heights of UEs and TRPs are assumed to be 1.65 m and 5 m, respectively.

Limited fronthaul links with capacities of 5 Gbps and 10 Gbps are considered. These configurations represent an optical 10 Gigabit Ethernet network using cheaper SFP+ modules for short-distance transmissions and a system with more limited available fronthaul bandwidth. Furthermore, the evaluated user counts were 8, 16, 24, and 48. The first two were used in both

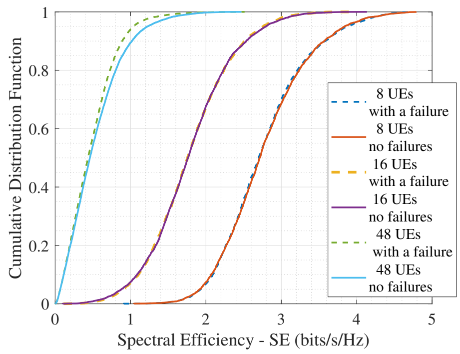


(a) Case/Configuration 1 (b) Case/Configuration 2

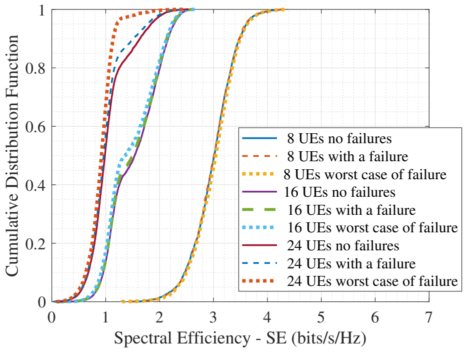
Fig. 1. Illustration of the two scenarios used and how the TRPs are installed and connected each other for the simulations.



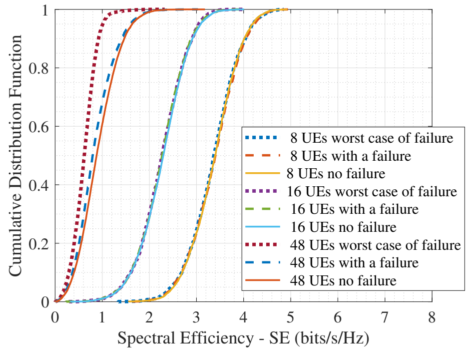
(a) Case 1 with 5 Gbps of fronthaul demand.



(b) Case 1 with 10 Gbps of fronthaul demand.



(c) Case 2 with 5 Gbps of fronthaul demand.



(d) Case 2 with 10 Gbps of fronthaul demand.

Fig. 2. Cumulative Distribution Functions (CDFs) of Spectral Efficiency (SE) across different user counts in the scenarios presented in fig. 1 for fixed fronthaul data capacities of 5Gbps and 10Gbps.

capacities, 24 is used only in 5 Gbps, and 48 is used only in 10 Gbps. The two latter counts are the maximum number of users the system fronthaul can support in the scenario of Figure 1a.

Figs. 2a and 2b show the cumulative distribution function (CDF) of the user SE for the considered fronthaul capacities in systems operating normally and experiencing one failure. The results indicate that the system's SE is not significantly impacted by the activation of the CC protection scheme, suggesting that limited fronthaul is not a major bottleneck for the utilization of these protection schemes. In a denser configuration with 24 and 48 users for the capacities of 5 and 10 Gbps, a more noticeable decrease in SE occurs, but mostly for the best-performing users. Even then, the maximum SE decay due to the protection utilization is only 15%.

Figs. 2c and 2d show the CDF of user SE for different fronthaul capacities in systems operating under normal conditions, experiencing a single failure, and facing a combination of failures that result in the maximum fronthaul requirements. It is noticeable that the SE of failed systems is similar to that of non-failed ones for the 8 and 16 user cases, even under more fronthaul demanding failures. When 24 users are considered in the 5 Gbps capacity, a significant decrease in SE due to CC activation is only observed at the failure configuration that results in the most fronthaul demands, where the 90th percentile SE is reduced by 1 bps/Hz. Similarly, for 48 users with 10 Gbps, a large SE decrease due to CC activation is observed only in the most fronthaul impacting failure configuration, where a reduction of up to 0.6 bps/Hz occurs.

IV. Conclusions

This paper presented an evaluation of CC fronthaul redundancy schemes for a segmented UC D-mMIMO network under hardware failure, considering limited capacity fronthaul infrastructure. The simulation results indicated that the fronthaul overload from the CC scheme activation is not a major bottleneck for the utilization of the protection scheme. Noticiable impacts on the users' SE were only observed in the maximum allowed user count for the considered fronthaul capacities of 5 and 10 Gbps. Even then, the SE reduction was limited to 1 bps/Hz. Future research could consider outdoor scenarios and work with dynamic bit allocation based on Signal-to-interference-plus-noise-ratio (SINR) degradation concerning non-limited fronthaul.

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