Cell-Free Massive MIMO with Rate Splitting and Low-Resolution ADCs

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Abstract

This paper studies the sum spectral efficiency (SE) performance of a rate splitting (RS) assisted cell-free (CF) massive multiple input multiple output (mMIMO) with low-resolution analog-to-digital converters (ADCs). We consider the downlink of a CF mMIMO, where the access points (APs) and user equipment (UEs) are equipped with low-resolution ADCs. We show that RS CF mMIMO achieves higher sum SE over conventional CF mMIMO in the presence of quantization noise and pilot contamination.

Ⅰ. Introduction

Cell-free (CF) massive multiple input multiple output (mMIMO) involves deploying large number of access points (APs) distributed geographically and serves several users in the same time-frequency resources. CF mMIMO has shown improved data rate results over collocated mMIMO systems [1]. Rate splitting (RS) multiple access (RSMA) on the other hand is a promising technology for next generation communication that is robust against interference resulting from user mobility and feedback delay [2]. RS splits original messages into common and private parts, encodes the common and private streams, precode and then superimposes the signal for transmission. The huge number of APs in CF mMIMO requires the deployment of additional RF chains which in effect increase the hardware cost and power consumption. Low-resolution ADCs have been proposed for massive MIMO systems to reduce the high-power consumption but comes at the cost of quantization noise (QN) which affects the system performance [3]. This paper studies the performance of a CF mMIMO with low-resolution ADCs, where RS is utilized for DL data transmission.

Ⅱ. System model

Consider a CF mMIMO network with L APs where each AP is equipped with N antennas and are connected to a CPU via error free backhaul links and serve K single-antenna DL users. The APs apply rate splitting technique in the downlink and both APs and UEs are equipped with low-resolution ADCs. We assume Rayleigh fading and assuming a coherence interval τ_c, τ_p slots are reserved for channel estimation and the remaining time slots (i.e., $\tau_s = \tau_c - \tau_p$), are utilized for data transmission. The channel between the l-th AP and the k-th user is modeled as $\boldsymbol{h}_{lk} = \sqrt{\beta_{lk}}\boldsymbol{g}_{lk}$, where $\boldsymbol{g}_{lk} \in \mathbb{C}^{N\times 1}$ denotes the small-scale fading whose elements are distributed as $\mathcal{CN}(0, 1)$ and β_{lk} denotes the large-scale fading coefficient. We modify the similar channel model in [4] to obtain the channel estimates as $\widehat{\boldsymbol{h}}_{lk}$. The signal sent by the l-th AP is given as

$$\boldsymbol{z}_l = \sqrt{p_c}\,\mu_{c,l}^{1/2}\boldsymbol{u}_{c,l}s_c + \sum_{k=1}^{K}\sqrt{p_p}\,\mu_{lk}^{1/2}\widehat{\boldsymbol{h}}_{lk}s_k, \quad (1)$$

where $\boldsymbol{u}_{c,l} \in \mathcal{C}^{N\times 1}$ and $\widehat{\boldsymbol{h}}_{lk} \in \mathcal{C}^{N\times 1}$ are the common and private precoding vectors. $p_c = \rho P$ and $p_P = (1-\rho)P$ represent the power allocated to the common and private streams, respectively where $\boldsymbol{\rho}$ is the ratio that splits downlink power P available at the AP between the common and private streams. $\mu_{c,l} = 1/\mathbb{E}\{\|\boldsymbol{u}_{c,l}\|^2\}$ and $\mu_{lk} = 1/\mathbb{E}\{\|\widehat{\boldsymbol{h}}_{lk}\|^2\}$ are the power control coefficients for the common and private streams respectively. Maximum ratio transmission is adapted to precode the private streams where the channel estimates $\widehat{\boldsymbol{h}}_{lk}$ are used. The common precoder is given as $\boldsymbol{u}_{c,l} = \sum_{i=1}^{K}\boldsymbol{a}_{li}\widehat{\boldsymbol{h}}_{li}$ [5] where we assume common precoding weights $\boldsymbol{a}_{li} = \mathbf{1}$. The received signal at the k-th user is given as

$$y_k = \sum_{l=1}^{L}\boldsymbol{h}_{lk}^{h}\boldsymbol{z}_l + w_k, \quad (2)$$

where $w_k \sim \mathrm{CN}(0, 1)$ is the additive noise at the k-th user. The resulting signal after quantization at user k is given by,

$$\tilde{\boldsymbol{y}}_{\boldsymbol{k}} = \boldsymbol{\alpha}_{\boldsymbol{k}}y_k + n_k, \quad (3)$$

where α_k expresses the accuracy of the ADC and n_k is the quantization noise which is uncorrelated with y_k and given by $\boldsymbol{\alpha}_{\boldsymbol{k}}(1-\boldsymbol{\alpha}_{\boldsymbol{k}})E\{|y_k|^2\}$.

Ⅲ. Spectral Efficiency Analysis

We derive the SE for the common and private streams as (4) and (5) respectively,

$$R_c^k = \frac{\tau_c - \tau_p}{\tau_c}\log_2(1 + S_c^k), \quad (4)$$

$$R_p^k = \frac{\tau_c - \tau_p}{\tau_c}\log_2(1 + S_p^k), \quad (5)$$

where S_c^k and S_p^k are the signal to interference noise ratio for decoding the common and private streams respectively and defined as

$$S_c^k = \frac{D_c^k}{IP_p^k + BU_c^k + \alpha_k^2 + q_c^k} \text{ and } S_p^k = \frac{D_p^k}{IP_p^k - D_p^k + \alpha_k^2 + q_p^k}.$$

The terms $D_c^k = \boldsymbol{\alpha}_K^2 p_c\left|\mathbb{E}\{\sum_{l=1}^{L}\mu_{c,l}^{1/2}\boldsymbol{h}_{lk}^H\boldsymbol{u}_{c,l}\}\right|^2$,

$IP_p^k = \boldsymbol{\alpha}_K^2 p_p\sum_{i=1}^{K}\mathbb{E}\{\left|\sum_{l=1}^{L}\mu_{li}^{1/2}\boldsymbol{h}_{lk}^H\widehat{\boldsymbol{h}}_{li}\right|^2\}$,

$BU_c^k = \boldsymbol{\alpha}_K^2 p_c\mathbb{E}\{\left|\sum_{l=1}^{L}\mu_{c,l}^{1/2}\boldsymbol{h}_{lk}^H\boldsymbol{u}_{c,l}\right|^2\} - D_c^k$,

$q_c^k = \boldsymbol{\alpha}_k(1-\boldsymbol{\alpha}_k)E\{|y_k|^2\}$, $q_p^k = \boldsymbol{\alpha}_k(1-\boldsymbol{\alpha}_k)E\{|y_k^p|^2\}$,

$D_p^k = \boldsymbol{\alpha}_K^2 p_p\left|\mathbb{E}\{\sum_{l=1}^{L}\mu_{lk}^{1/2}\boldsymbol{h}_{lk}^H\widehat{\boldsymbol{h}}_{lk}\}\right|^2$, are defined as the common signal power, interference due to the private streams, interference due to the common stream and beamforming uncertainty gain for decoding the common stream, covariance of the quantization noise due to the common and private streams and private signal power where $y_k^p = \sum_{l=1}^{L} \boldsymbol{h}_{lk}^h \boldsymbol{z}_l^p + w_k$ with $\boldsymbol{z}_l^p = \sum_{k=1}^{K} \sqrt{p_p}\, \mu_{lk}^{1/2} \hat{\boldsymbol{h}}_{lk} s_k$.

We let $R_c = \min(R_c^k)$, the sum SE of the RS CF mMIMO is the given by

$$R = R_c + \sum_{k=1}^{K} R_p^k \ . \qquad (6)$$

From (6), R is a monotonic function of ρ and we adapt the bisection method to find the optimal ρ to maximize R.

IV. Simulation Results

Results are obtained using the parameters τ_c=200, τ_p=10, L=100, N=2, K=10, P=30 dBm and noise power of -92 dBm. Simulation results are obtained over 10^3 iterations in a square area of size 500m x 500m. We assume the same ADC bit resolution at all users and $\boldsymbol{\alpha_k}$ is obtained from [6, Table 1]. Fig. 1 shows the cumulative distribution function (CDF) of the DL sum SE of CF mMIMO and RS CF mMIMO, for different quantization bits. In all instances of the different quantization bits utilized, RS outperforms conventional CF mMIMO. The performance of the system decreases as the quantization bits increases. For instance, at the median CDF, a performance loss of 31.55% and 63.78% is realized over conventional CF mMIMO when b is set to 2 and 1, respectively. Applying RS however can decrease the loss to 25.32 and 60.31% respectively.

Fig. 2 compares sum SE between RS and non-RS schemes versus different number of APs M. Simulation results are obtained by using (6). We can observe from Fig. 2 that increasing L, the SE gradually increases when there is perfect quantization, however it rapidly saturates when there is high QN at b = 1. In all instances, the sum SE of RS outperforms the conventional CF mMIMO setup. RS provides enhanced performance at high quantization noise due to its ability to dynamically allocate power to the common and private streams in the event of high quantization noise to ensure enhanced SE gains.

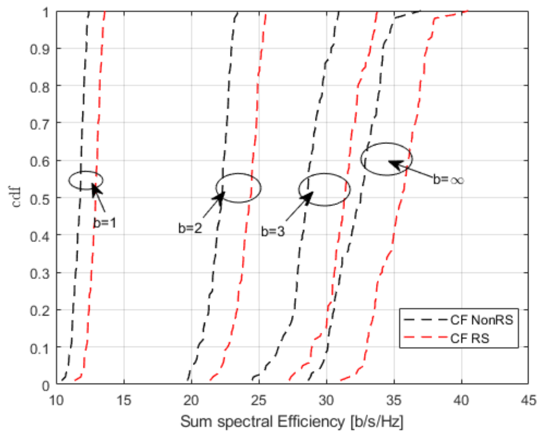

Fig. 1. CDF of DL sum SE for CF mMIMO and RS assisted CF mMIMO

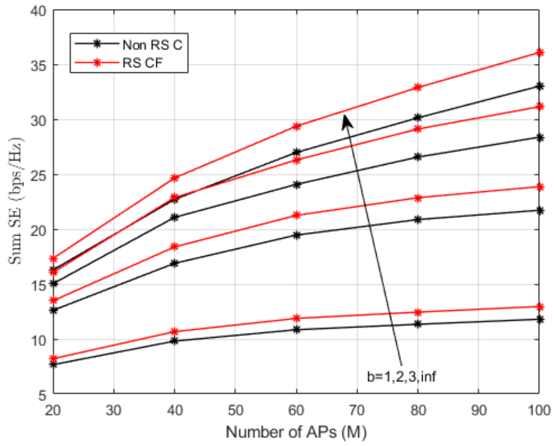

Fig. 2. Sum SE versus number of APs

V. Conclusion

This paper has analyzed the DL sum SE of the CF mMIMO system in the presence of QN and imperfect channel state information. We propose RS by using bisection method to split power between common and private messages to improve the sum SE. It is shown that RS assisted CF mMIMO achieves higher sum SE than conventional CF mMIMO systems. RS can compensate for the performance loss due to quantization noise to some degree.

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REFERENCES

[1] J. Wang and L. Dai, "Asymptotic Rate Analysis of Downlink Multi-User Systems with Co-Located and Distributed Antennas," in *IEEE Trans on Wireless Commun.*, vol. 14, no. 6, pp. 3046-3058, Jun. 2015.

[2] O. Dizdar, Y. Mao and B. Clerckx, "Rate-Splitting Multiple Access to Mitigate the Curse of Mobility in (Massive) MIMO Networks," in *IEEE Transactions on Communications*, vol. 69, no. 10, pp. 6765-6780, Oct. 2021.

[3] X. Hu, C. Zhong, X. Chen, W. Xu, H. Lin and Z. Zhang, "Cell-Free Massive MIMO Systems with Low Resolution ADCs," in *IEEE Trans. on Commun.*, vol. 67, no. 10, pp. 6844-6857, Oct. 2019.

[4] P. Anokye, R. K. Ahiadormey and K. -J. Lee, "Full-Duplex Cell-Free Massive MIMO With Low-Resolution ADCs," in *IEEE Trans. Veh. Technol.*, vol. 70, no. 11, pp. 12179-12184, Nov. 2021.

[5] M. Dai, B. Clerckx, D. Gesbert and G. Caire, "A Rate Splitting Strategy for Massive MIMO With Imperfect CSIT," in *IEEE Transactions on Wireless Communications*, vol. 15, no. 7, pp. 4611-4624, Jul. 2016.

[6] P. Anokye, R. K. Ahiadormey, H. -S. Jo, C. Song and K. -J. Lee, "Low-Resolution ADC Quantized Full-Duplex Massive MIMO-Enabled Wireless Backhaul in Heterogeneous Networks Over Rician Channels," in *IEEE Trans. Wireless Commun.*, vol. 19, no. 8, pp. 5503-5517, Aug. 2020.