Rate Analysis of Local Protective Partial Zero Forcing for Full-Duplex Cell-Free Massive MIMO with Low-resolution ADCs

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Abstract

This paper analyzes the sum spectral efficiency (SE) of a full-duplex (FD) cell-free (CF) massive multiple-input multiple-output (MIMO) system with low-resolution analog-to-digital converters (ADCs) at the access points (APs) and downlink users (DL). Local protective partial zero forcing (PPZF) is utilized to decode the Uplink (UL) information and precode data for DL users.

Ⅰ. Introduction

Cell-free (CF) massive multiple-input multiple-output (MIMO) has been considered as a promising solution for future generation of communications system due to its potential to provide higher spectral efficiency, uniform quality of services, and does not require handover in cell areas. Full-duplex (FD) systems allow simultaneous data transmission and reception on the same time-frequency resources unlike half-duplex (HD) systems. However, using FD leads to self-interference (SI). FD system has the potential to double the spectral efficiency (SE) relative to the HD at the expense of self-interference (SI). This paper aims at analyzing the SE performance of protective partial zero forcing (PPZF) processing for FD CF massive MIMO with low resolution analog-to-digital converters (ADCs).

Ⅱ. System Model

We consider a CF massive MIMO system in which single antenna K_u Uplink (UL) and K_d downlink users (DL) user equipments (UE) are jointly served by M FD access points (APs) connected via error-free backhaul links to a central processing unit (CPU). Each AP has L_{rx} receive and L_{tx} transmit antennas. Each AP suffers from SI and inter-AP interference (IAI), and the DL users also suffer from UL-to-DL interference (UDI) caused by other UL UEs. All APs and DL users utilize low-resolution ADCs for quantization, which results in quantization noise (QN). Let's define the channel between i-th UL and the k-th DL users to the m-th AP as $\boldsymbol{g}_{mi} = \sqrt{\beta_{mi}}\bar{\boldsymbol{g}}_{mi}$ and $h_{mk} = \sqrt{\zeta_{mk}}\ \bar{\boldsymbol{h}}_{mk}$ respectively where $\bar{\boldsymbol{g}}_{mi} \in \mathbb{C}^{L_{rx}\times 1}$ and $\bar{\boldsymbol{h}}_{mk} \in \mathbb{C}^{L_{tx}\times 1}$ indicate the small scale fading model as $\mathbb{CN}(0,1)$. β_{mi} and ζ_{mk} denote the large-scale fading coefficients. The coherence interval is τ_c symbols long and we use τ_u and τ_d of these on uplink and downlink pilots respectively, leaving $\tau_s = \tau_c - \tau_u - \tau_d$ for uplink and downlink data transmission. Let $i_i \in \{1,\dots,\tau_u\}$ and $i_k \in \{1,\dots,\tau_d\}$ be the index of the pilot sequence used by the UL user i and DL user k respectively which is denoted by $\phi^u_{i_i} \in \mathbb{C}^{\tau_u\times 1}$ and $\phi^d_{i_k} \in \mathbb{C}^{\tau_d\times 1}$. The UL and the DL channel estimation are same as in [1]. The received quantized pilot signal at the m-th AP is the same as expressed in [1].

III. Performance Analysis

A. Local Protective Partial Zero Forcing

The principle behind this scheme is that each AP suppresses only the interference of the strongest UEs using full-pilot zero forcing (FZF) while tolerating the interference of the weakest UEs. We adopted similar grouping principle as in [3]. At AP l, all the UEs are divided into two disjoint groups: S_m gathers strong UEs whiles W_m gathers the weak UEs. Utilizing PPZF, the local combining vector for UE $i \in S_l$ at m-th AP is given as [2]:

$$w^{PZF}_{mi} = s_{mi}\delta_{mi}\bar{G}_m\boldsymbol{E}_{\boldsymbol{S}_m}\left(E^H_{S_m}\bar{\boldsymbol{G}}^{\boldsymbol{H}}_m\,\bar{\boldsymbol{G}}_m\,\bar{G}_m\boldsymbol{E}_{\boldsymbol{S}_m}\right)^{-1}\varepsilon_{j_{m,i}}$$

where $s_{mi} = \sqrt{p_\tau}\beta_{mi}\nu^{-1}_{mi}$, $\nu^{-1}_{mi} = p_\tau\tau_u\sum_{t\in P^u_i} p_t\,\beta_{m,t} + 1$. $\bar{\boldsymbol{G}}_{\boldsymbol{m}}$ is defined as $\bar{G}_m = \overline{\mathrm{R}^{\mathrm{p}}_{\mathrm{m}}}\Phi^u, \Phi^u = \left[\phi^u_1,\phi^u_2,\dots,\phi^u_{\tau_u}\right]$ and $\delta_{mi} = \mathrm{E}\{|\bar{\boldsymbol{G}}_{\boldsymbol{m}}\mathrm{e}_{\mathrm{i_i}}|\}$. e_{i_i} represent the i_i – column of I_{τ_u}. $\boldsymbol{E}_{\boldsymbol{S}_m}$ and $\varepsilon_{j_{m,i}}$ is obtained similarly as described in [2].

The local PPZF precoding vector used by m-th AP to the $k \in S_l$ given as [3]:

$$\mathrm{f}^{\mathrm{PZF}}_{\mathrm{mk}} = \frac{\bar{\boldsymbol{H}}_{\boldsymbol{m}}\boldsymbol{E}_{\boldsymbol{S}_m}\left(\boldsymbol{E}^{\boldsymbol{H}}_{\boldsymbol{S}_m}\bar{\mathrm{H}}^{\mathrm{H}}_{\mathrm{m}}\,\bar{\boldsymbol{G}}_m\bar{\boldsymbol{H}}_{\boldsymbol{m}}\boldsymbol{E}_{\boldsymbol{S}_m}\right)^{-1}\varepsilon_{j_{m,k}}}{\sqrt{\mathbb{E}\left\{\left\|\bar{\boldsymbol{H}}_{\boldsymbol{m}}\boldsymbol{E}_{\boldsymbol{S}_m}\left(\boldsymbol{E}^{\boldsymbol{H}}_{\boldsymbol{S}_m}\bar{\boldsymbol{H}}^{\boldsymbol{H}}_{\boldsymbol{m}}\,\bar{\boldsymbol{G}}_m\bar{\boldsymbol{H}}_{\boldsymbol{m}}\boldsymbol{E}_{\boldsymbol{S}_m}\right)^{-1}\varepsilon_{j_{m,k}}\right\|^2\right\}}}$$

$\bar{\boldsymbol{H}}_{\boldsymbol{m}}$ is defined as $\bar{\boldsymbol{H}}_{\boldsymbol{m}} = \overline{\boldsymbol{Y}^p_m}\Phi^d, \Phi^u = \left[\phi^d_1,\phi^d_2,\dots,\phi^d_{\tau_d}\right]$ and e_{i_k} represent the i_k – column of I_{τ_d}.

The APs uses protective maximum ratio combining (MRC) and maximum ratio transmission (MRT) to decode and precode data for UEs in W_m. It guarantees full protection to the strong UEs by forcing weak UEs to take place in the orthogonal complement of $\bar{\boldsymbol{H}}_{\boldsymbol{m}}\boldsymbol{E}_{\boldsymbol{S}_m}$ [3]. Let $B_m = I - \bar{\boldsymbol{H}}_{\boldsymbol{m}}\boldsymbol{E}_{\boldsymbol{S}_m}\left(\boldsymbol{E}^{\boldsymbol{H}}_{\boldsymbol{S}_m}\bar{\boldsymbol{H}}^{\boldsymbol{H}}_{\boldsymbol{m}}\,\bar{\boldsymbol{G}}_m\bar{\boldsymbol{H}}_{\boldsymbol{m}}\boldsymbol{E}_{\boldsymbol{S}_m}\right)^{-1}\boldsymbol{E}^{\boldsymbol{H}}_{\boldsymbol{S}_m}\bar{\boldsymbol{H}}^{\boldsymbol{H}}_{\boldsymbol{m}}$, denote the projection onto the orthogonal complement of $\bar{\boldsymbol{H}}_{\boldsymbol{m}}\boldsymbol{E}_{\boldsymbol{S}_m}$. The protective MRT precoding vector from AP m to the UEs $\in W_m$ is given as $\mathrm{w}^{\mathrm{PMRT}}_{\mathrm{mk}} = \frac{\boldsymbol{B}_{\boldsymbol{m}}\bar{\boldsymbol{H}}_{\boldsymbol{m}}e_{i_k}}{\sqrt{\mathbb{E}\{\|\boldsymbol{B}_{\boldsymbol{m}}\bar{\boldsymbol{H}}_{\boldsymbol{m}}e_{i_k}\|^2\}}}$.

With PPZF, the MRC used at AP m for UEs in W_m is given as $\boldsymbol{w}_{mi}^{PMRC} = s_{mi}\delta_{mi}\boldsymbol{B_m}\bar{\boldsymbol{G}}_m e_{i_i}$ [2].

B. Spectral Efficiency Analysis

The quantized received signal obtained for the i-th UL user and the k-th DL user is given as:

$$\tilde{r}_i = \sqrt{p_u}\sum_{m=1}^{M} a_m\, \boldsymbol{w}_{mi}^{H}\, \boldsymbol{g}_{mi}\, s_i^u + \sqrt{p_u}\sum_{i\neq j}^{K_u}\sum_{m=1}^{M} a_m\, \boldsymbol{w}_{mj}^{H}\, \boldsymbol{g}_{mj}\, s_j^u + \sum_{n=1}^{M}\sum_{m=1}^{M} a_m\, \boldsymbol{w}_{mj}^{H}\, \boldsymbol{Q}_{mn}\, x_n^d + \sum_{m=1}^{M} a_m\, \boldsymbol{w}_{mj}^{H}\, \boldsymbol{z}_m + \sum_{m=1}^{M} \boldsymbol{w}_{mj}^{H}\, \tilde{\boldsymbol{z}}_m \quad (1)$$

$$\tilde{y_k} = \sqrt{p_d}\epsilon_k \sum_{m=1}^{M}\sqrt{\eta_{mk}}\, \boldsymbol{h}_{mk}^{H}\, \boldsymbol{f}_{mk}\, s_k^d + \sqrt{p_d}\epsilon_k \sum_{k\neq t}^{K_d}\sum_{m=1}^{M}\sqrt{\eta_{mt}}\, \boldsymbol{h}_{mt}^{H}\, \boldsymbol{f}_{mt}\, s_t^d + \sum_{i=1}^{\mathrm{Ku}} q_{ki} x_i^u + \epsilon_k n_k + \tilde{n_k} \quad (2)$$

where $Q_{mn}, z_m, \tilde{z}_m$ and a_m denote the SI/IAI, noise, QN, and the ADC resolution at the m-th AP, respectively.

$q_{ki}, \tilde{n_k}$ and ϵ_k denote the UDI, QN and ADC resolution at the k-th DL user. s_i^u and s_k^d denote the transmit symbols form the i-th UL user and m-th AP, respectively. p_u, p_d and η_{mk} denote the transmit power at the i-th UL user, the m-th AP and the normalization factor, respectively. The first terms in (1) and (2) describes the desired signal for the i-th UL user and the k-th DL user respectively, and the remaining terms denote the effective noise.

The UL and DL achievable rate for the m-th AP and k-th DL user is written as:

$$\tilde{R_i^u} = \frac{\tau_s}{\tau_c}\ \log_2\left(\frac{p_u\left|\mathbb{E}\{\sum_{m=1}^{M} a_m\, \boldsymbol{w}_{mi}^{H}\, \boldsymbol{g}_{mi}\}\right|^2}{C_i^u + I_{ij}^u + S_i^u + Z_i^u + Q_i^u} + 1\right) \quad (3)$$

Where $C_i^u \cong p_u\, var(\sum_{m=1}^{M} a_m\, \boldsymbol{w}_{mi}^{H}\, \boldsymbol{g}_{mi})$, $I_{ij}^u \cong p_u \sum_{i\neq j}^{K_u} \mathbb{E}\{\left|\sum_{m=1}^{M} a_m\, \boldsymbol{w}_{mj}^{H}\, \boldsymbol{g}_{mj}\right|^2\}$, $S_i^u \cong p_d \sum_{k=1}^{Kd}\sum_{n=1}^{M}\sum_{m=1}^{M} a_m^2 \eta_{mk} \mathbb{E}\{\left|\sum_{m=1}^{M} \boldsymbol{w}_{mi}^{H}\boldsymbol{Q}_{mn}\, \boldsymbol{f}_{nk}\right|^2\}$, $Z_i^u \cong \sum_{m=1}^{M} a_m^2 \mathbb{E}\{\left|\sum_{m=1}^{M} \boldsymbol{w}_{mj}^{H}\ \right|^2\}$ and $Q_i^u = \mathbb{E}\{\left|\sum_{m=1}^{M} \boldsymbol{w}_{mj}^{H}\tilde{\boldsymbol{z}}_m\ \right|^2\}$

denote the beamforming uncertainty gain (BUG), multi-user interference (MUI), SI/IAI, noise and QN, respectively.

$$\tilde{R_k^d} = \frac{\tau_s}{\tau_c}\ \log_2\left(\frac{p_d\epsilon_k^2\left|\mathbb{E}\{\sum_{m=1}^{M}\sqrt{\eta_{mk}}\, \boldsymbol{h}_{mk}^{H}\, \boldsymbol{f}_{mk}\}\right|^2}{\epsilon_k^2 + C_k^d + I_{kt}^d + U_{ki}^d + \tilde{N}_K} + 1\right) \quad (4)$$

where $C_i^u \cong p_d\epsilon_k^2\, var(\sum_{m=1}^{M}\sqrt{\eta_{mk}}\, \boldsymbol{h}_{mk}^{H}\, \boldsymbol{f}_{mk})$, $I_{kt}^d \cong p_d\epsilon_k^2 \sum_{k\neq t}^{K_d} \mathbb{E}\{\left|\sum_{m=1}^{M}\sqrt{\eta_{mt}}\, \boldsymbol{h}_{mt}^{H}\, \boldsymbol{f}_{mt}\ \right|^2\}$, $U_{ki}^d = p_u\epsilon_k^2 \sum_{i=1}^{Ku} \mathbb{E}\{|q_{ki}|^2\}$ and $\tilde{N}_K = E\{|y_k|^2\}$

represent the power of BUG, MUI, UDI and QN at the k-th user, respectively.

IV. Simulation Results

The simulation results are obtained for $K_u = K_d = 10, \tau_u = \tau_d = 7, L_{rx} = L_{tx} = 8, \tau_c = 200, p_u = p_\tau =$ 20dBm, $p_d =$ 23.01dBm and residual SI = $40\ dBm$.

The simulation results are plotted using (1) and (2). Fig. 1 shows a graph of UL/DL sum rate against number of APs for ∞ ADC resolution. PPZF and FZF performs better than MRC/MRT due to their ability to cancel interference. However, PPZF outperforms FZF due to its larger array gain. Fig. 2 compares the SE of MRC/MRT, FZF and PPZF against ADC resolution bit. The UL/DL sum SE grows with increase in ADC resolution bit. MRC, FZF and PPZF requires 4, 7 and 7 bits to converge to the perfect case configuration in the UL. However, DL sum SE for MRT, FZF and PPZF approach ideal case when the ADC resolution bits are 7, 8 and 8 respectively.

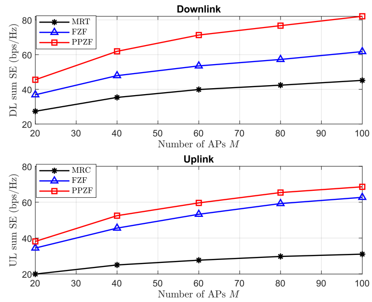

Fig 1: UL and DL sum rate vs Number of APs

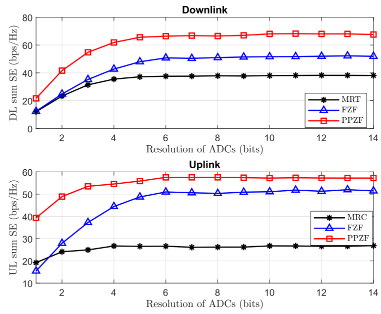

Fig 2: Sum rate vs resolution bit

IV. Conclusion

It is shown that PPZF can provide significant sum-rate performance gains as compared to FZF and MRC/MRT cases.

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