Performance Analysis of Full-Duplex Massive MIMO Systems with RSMA

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Abstract

This paper investigates the performance comparison of the spectral efficiency (SE) of a full-duplex (FD) massive multiple-input multiple-output (mMIMO) system with rate splitting multiple access (RSMA) and compares it to conventional multi-user linear precoding, i.e., space division multiple access (SDMA). Simulation results show improved uplink (UL) and downlink (DL) SE compared to SDMA.

Ⅰ. Introduction

The need for wireless connectivity has grown significantly, necessitating improvements in communications technologies. Massive multiple-input multiple-output (mMIMO) is crucial for next-generation wireless communication systems, including enhanced mobile broadband, ultra-reliable low latency communications, and massive machine type communications. Full-duplex (FD) communications can also potentially double the spectral efficiency (SE). This paper explores an FD mMIMO system, integrating rate splitting multiple access due to its better interference management and power control strategy for both uplink (UL) and downlink (DL) transmission. The study shows that the FD-RSMA technique offers superior UL and DL rates compared to traditional multi-user linear precoding schemes.

Ⅱ. System Model

We consider an FD mMIMO base station (BS) and K FD user equipment (UEs) that communicate on the same time-frequency resources, simultaneously. We use the standard block fading model. The BS has massive transmit antennas (M_t) and a few receive antennas while each UE employs massive transmit antennas (N_t) and a single receive antenna. We assume all the channels undergo Rayleigh fading due to the rich scattering environment. Let us define the UL channel and the DL channel, respectively, as $\mathbf{G} = \overline{\mathbf{G}}\,\dot{\mathbf{D}}^{\frac{1}{2}}$ and $\mathbf{H} = \overline{\mathbf{H}}\,\ddot{\mathbf{D}}^{\frac{1}{2}}$, where $\overline{\mathbf{G}} \in \mathbb{C}^{N_t\times K}$ and $\overline{\mathbf{H}} \in \mathbb{C}^{M_t\times K}$ represent the small-scale fading with elements distributed as $\mathcal{CN}(0,1)$. $\dot{\mathbf{D}}$ and $\ddot{\mathbf{D}}$ denote the large-scale fading coefficients.

The coherence interval is T symbols long and we use τ_p of these for training while the remaining timeslot, i.e., $T-\tau_p$ are used for transmitting data. We employ similar UL and DL estimation used in [1] and [2].

In the DL, the BS splits each user's message into a common part (s_c) and private part (s_k). The common parts of all UEs are encoded into a single common stream and is drawn from a public codebook such that it can be decoded by all users. The private messages are superimposed over the common message and then transmitted with linear precoding. The resulting transmitted signal is written as

$$\mathbf{x}^b = \sqrt{P_c}\mathbf{w}_c s_c^b + \sum_{i=1}^{K}\sqrt{P_i}\mathbf{w}_i\, s_i^b, \qquad (1)$$

where $\boldsymbol{w_c}$ is the precoding vector of the common message. The power allocated to the common message and private message is given, respectively, as $P_c = P_{\rm dl}(1-t_{dl})$ and $P_k = P_{\rm dl}\,t_{dl}/\,K$ where $t_{dl} \in [0,1]$ represents the DL power allocation factor.

As for UL RS, for simplicity we consider that each UE splits its message into two sub-data streams, $s_{k,l}^s, \forall k, \forall l \in \mathcal{L} \triangleq 1,2.$ These streams are then precoded and sent to the BS. The transmitted signal by the k-th UE is the given as

$$\mathbf{x}_k^s = \sum_{l=1}^{2}\sqrt{\rho_{k,l}}\;\mathbf{w}_k^s s_{k,l}^s, \quad \forall k, \qquad (2)$$

where the power allocated to sub-data 1 and sub-data 2 is given as $\rho_{k,1} = \rho_{\rm ul}\;t_{\rm ul}$ and $\rho_{k,2} = \rho_{\rm ul}\;(1-t_{\rm ul}), \forall k \in K$, respectively; $\rho_{\rm ul}$ is the total power available at the UEs and $t_{\rm ul} \in [0,1]$ is the UL power allocation factor. The precoder used by the k-th UE is given as $\mathbf{w}_k^s$.

The DL received signal at the k-th user is given as

$$\begin{aligned} y_k^s &= \sqrt{P_c}\mathbf{h}_k^H\mathbf{w}_c s_c^b + \sum_{i=1}^{K}\sqrt{P_i}\,\mathbf{h}_k^H\mathbf{w}_i s_i^b + \sum_{l=1}^{2}\sqrt{\rho_{k,l}}\,\mathbf{q}_{s,k}\mathbf{w}_k^s \\ & s_{k,l}^s + \sum_{i\neq k}^{K}\sum_{l=1}^{2}\sqrt{\rho_{i,l}}\,\mathbf{q}_{c,ki}\mathbf{w}_i^s s_{i,l}^s + n_k^s, \end{aligned} \qquad (3)$$

where $\mathbf{q}_{s,k} \in \mathbb{C}^{1\times N_t}$ and $\mathbf{q}_{c,ki} \in \mathbb{C}^{1\times N_t}$ denote the SI channel at the k-th UE and UE-UE interference channel, respectively. The k-th receiver antenna noise is modeled as $n_k^s \sim \mathcal{CN}(0,1)$. The elements of $\mathbf{q}_{s,k}$ and $\mathbf{q}_{c,ki}$ are distributed as $\mathcal{CN}\left(0,\eta_{s,k}^2\right)$ and $\mathcal{CN}\left(0,\eta_{c,ki}^2\right)$, respectively. The variances $\eta_{s,k}^2$ and $\eta_{c,ki}^2$ represent the strength of the SI at the k-th UE and UE-UE interference channel, respectively.

The UL received signal at the BS k-th receive antenna is given by

$$\begin{aligned} y_k^b &= \sum_{l=1}^{2}\sqrt{\rho_{k,l}}\,\mathbf{g}_k^H\mathbf{w}_k^s s_{k,l}^s + \sum_{i\neq k}^{K}\sum_{l=1}^{2}\sqrt{\rho_{i,l}}\,\mathbf{g}_k^H\mathbf{w}_i^s s_{i,l}^s \\ & +\mathbf{q}_{m,k}\left(\sqrt{P_c}\mathbf{w}_c s_c^b + \sum_{i=1}^{K}\sqrt{P_i}\,\mathbf{w}_i s_i^b\right) + n_k^b, \end{aligned} \qquad (4)$$

where $\mathbf{q}_{m,k} \in \mathbb{C}^{1\times M_t}$ and $n_k^b \sim \mathcal{CN}(0,1)$ represent the SI channel and noise at the k-th receive antenna of the BS, respectively. The entries of $\mathbf{q}_{m,k}$ are modeled as $\mathcal{CN}\left(0,\eta_{m,k}^2\right)$, where $\eta_{m,k}^2$ denotes the SI level at the BS.

III. Spectral Efficiency Analysis

For DL, each user decodes first the common message by treating all private messages as noise. After eliminating the decoded common message by successive interference cancellation (SIC), each user decodes their own private messages.

The DL SE, utilizing the approach in [3], for the common stream and private stream are given respectively as

$$\mathrm{SE}_c^s = \frac{T-\tau_p}{T}\log_2\left(1+\min_k\left(\frac{\mathbb{D}_{c,k}}{\mathbb{V}_{c,k}+\mathbb{I}_{c,k}+\mathbb{L}_{s,k}+\mathbb{C}_{s,k}+1}\right)\right), \quad (5)$$

$$\mathrm{SE}_{p,k}^s = \frac{T-\tau_p}{T}\log_2\left(1+\frac{\mathbb{D}_{p,k}}{\mathbb{V}_{p,k}+\mathbb{I}_{p,k}+\mathbb{L}_{s,k}+\mathbb{C}_{s,k}+1}\right), \quad (6)$$

where $\mathbb{D}_{c,k} \triangleq P_c|\mathbb{E}\{\mathbf{h}_k^H\mathbf{w}_c\}|^2$, $\mathbb{D}_{p,k} \triangleq P_k|\mathbb{E}\{\mathbf{h}_k^H\mathbf{w}_k\}|^2$, $\mathbb{V}_{c,k} \triangleq P_c \operatorname{var}(\mathbf{h}_k^H\mathbf{w}_c)$, $\mathbb{V}_{p,k} \triangleq P_k \operatorname{var}(\mathbf{h}_k^H\mathbf{w}_k)$, $\mathbb{I}_{c,k} \triangleq \sum_{i=1}^K P_i\, \mathbb{E}\{|\mathbf{h}_k^H\mathbf{w}_i|^2\}$, $\mathbb{I}_{p,k} \triangleq \sum_{i=1,i\neq k}^K P_i\, \mathbb{E}\{|\mathbf{h}_k^H\mathbf{w}_i|^2\}$, $\mathbb{L}_{s,k} \triangleq \sum_{l=1}^2 \rho_{k,l}\, \mathbb{E}\{|\mathbf{q}_{s,k}\mathbf{w}_k^s|^2\}$, and $\mathbb{C}_{s,k} \triangleq \sum_{i=1,i\neq k}^K \sum_{l=1}^2 \rho_{i,l}\, \mathbb{E}\{|\mathbf{q}_{c,ki}\mathbf{w}_i^s|^2\}$ denote the power of the desired common stream, desired private stream, common stream gain error, private stream gain error, private streams interference, multi-user interference, SI, and UE-to-UE interference, respectively.

The DL sum SE is then given as

$$\mathrm{SE}^s = \mathrm{SE}_c^s + \sum_{k=1}^K \mathrm{SE}_{p,k}^s. \quad (7)$$

For UL, we assume $|\mathbf{g}_k| > |\mathbf{g}_{k+1}|$ for $d_k < d_{k+1}$, where d_k is the distance between k-th UE and the BS. Therefore, the BS decodes the message of the k-th UE first and we treat indexes greater than k as purely noise. The UL SE for the sub-data 1 and sub-data 2 are given, respectively, as

$$\mathrm{SE}_{k,1}^b = \frac{T-\tau_p}{T}\log_2\left(1+\frac{\mathbb{D}_{1,k}}{\mathbb{V}_{1,k}+\mathbb{I}_{1,k}+\mathbb{I}_{2,k}+\mathbb{L}_{b,k}+1}\right), (8)$$

$$\mathrm{SE}_{k,2}^b = \frac{T-\tau_p}{T}\log_2\left(1+\frac{\mathbb{D}_{2,k}}{\mathbb{V}_{2,k}+\mathbb{I}_{1,k}+\mathbb{I}_{2,k}^*+\mathbb{L}_{b,k}+1}\right), (9)$$

where $\mathbb{D}_{1,k} \triangleq \rho_{k,1}|\mathbb{E}\{\mathbf{g}_k^H\mathbf{w}_k^s\}|^2$, $\mathbb{D}_{2,k} \triangleq \rho_{k,2}|\mathbb{E}\{\mathbf{g}_k^H\mathbf{w}_k^s\}|^2$, $\mathbb{V}_{1,k} \triangleq \rho_{k,1} \operatorname{var}(\mathbf{g}_k^H\mathbf{w}_i^s)$, $\mathbb{V}_{2,k} \triangleq \rho_{k,2} \operatorname{var}(\mathbf{g}_k^H\mathbf{w}_i^s)$, $\mathbb{I}_{1,k} \triangleq \sum_{i>k}^K \rho_{i,1}\, \mathbb{E}\{|\mathbf{g}_k^H\mathbf{w}_i^s|^2\}$, $\mathbb{I}_{2,k} \triangleq \sum_{i\geq k}^K \rho_{i,2}\, \mathbb{E}\{|\mathbf{g}_k^H\mathbf{w}_i^s|^2\}$, $\mathbb{I}_{2,k}^* \triangleq \sum_{i>k}^K \rho_{i,2}\, \mathbb{E}\{|\mathbf{g}_k{}^H\mathbf{w}_i^s|^2\}$, and $\mathbb{L}_{b,k} \triangleq P_c\mathbb{E}\{|\mathbf{q}_{m,k}\mathbf{w}_c^b|^2\} + \sum_{i=1}^K P_i\, \mathbb{E}\{|\mathbf{q}_{m,k}\mathbf{w}_i^b|^2\}$ denote the power of the desired sub-data 1, desired sub-data 2, sub-data 1 gain error, sub-data 2 gain error, sub-data 1 multi-UE interference, sub-data 2 interference, sub-data 2 multi-UE interference, and SI, respectively. Hence, the UL sum SE from the UEs to the BS is given as

$$\mathrm{SE}^b = \sum_{k=1}^K \left(\mathrm{SE}_{k,1}^b + \mathrm{SE}_{k,2}^b\right). \quad (10)$$

IV. Simulation Results

The simulation result is obtained for $\eta_{\mathrm{SI}}^2/N_0 = 50\ \mathrm{dB}, N_0 = -94\ \mathrm{dBm},\ p_\tau = 10\ \mathrm{dBm},\ P_{\mathrm{dl}} = 35\ \mathrm{dBm}, P_{\mathrm{ul}} = 10\ \mathrm{dBm}, T = 200, \tau_p = 2K,\ M_t = 150,\ N_t = 50$.

We plot the DL SE versus the number of UEs and examine its impact on the system using (7) in Fig. 1(a). As the number of UE increases, the SE increases due to the spatial multiplexing gains for both RSMA and SDMA. It can be observed that there is a performance gain of RSMA over SDMA, however the SE gain declines as K increases in the DL. This is as a result of the increase in multi-user, SI and UE-UE interferences

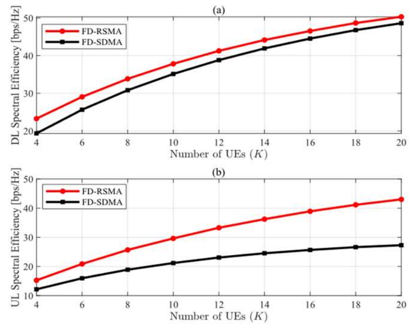

Fig 1: (a) DL spectral efficiency versus number of UEs. (b) UL spectral efficiency versus number of UEs.

and also, from the additional constraint set to common rate to ensure all UEs decode the common stream successfully, thus using the minimum common rate among the UEs. Fig. 1(b) shows the UL SE versus the number of UEs K. Similar to the plot in Fig. 1(a), RSMA outperforms SDMA. However, unlike the DL, all the sub-data of each UE contribute to the UL SE thereby increasing K increases the performance gain of RSMA over SDMA.

V. Conclusion

It is shown that RSMA can provide significant SE gain over SDMA in the UL as the number of UEs increases and in the DL, RSMA shows better performance for fewer UEs. This indicates the robustness of RSMA in managing interference in FD mMIMO systems.

ACKNOWLEDGMENT

This work was supported in part by the Institute of Information & Communications Technology Planning & Evaluation (IITP) grant through Korea Government (MSIT) under Grant 2021-0-00841 (Rate-splitting multiple access based cell-free extremely massive MIMO full-duplex transmission systems), and the ICAN (ICT Challenge and Advanced Network of HRD) program (IITP-2024-RS-2022-00156212).

REFERENCES

[1] B. D. Antwi-Boasiako, P. Anokye, D. K. P. Asiedu, R. K. Ahiadormey, K. -J. Lee and A. F. Molisch, "Multi-Stream Transmission in Massive MIMO Systems With Full-Duplex Bi-Directional Communication Links," in *IEEE Transactions on Vehicular Technology*, vol. 72, no. 9, pp. 12367-12372, Sept. 2023.

[2] P. Anokye, R. K. Ahiadormey, C. Song and K. -J. Lee, "Achievable Sum-Rate Analysis of Massive MIMO Full-Duplex Wireless Backhaul Links in Heterogeneous Cellular Networks," in *IEEE Access*, vol. 6, pp. 23456-23469, 2018.

[3] A. Mishra, Y. Mao, C. K. Thomas, L. Sanguinetti and B. Clerckx, "Mitigating Intra-Cell Pilot Contamination in Massive MIMO: A Rate Splitting Approach," in *IEEE Transactions on Wireless Communications*, vol. 22, no. 5, pp. 3472-3487, May 2023.