Rate-Splitting for Multi-Antenna Non-Orthogonal Unicast and Multicast Transmission

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Introduction

Non-orthogonal unicast and multicast transmission

- Existing works mainly consider Multi-user Linear Precoding (MU-LP) [1].
- Use Successive Interference Cancellation (SIC) to separate the multicast and unicast messages.
- Known as Layered Division Multiplexing (LDM) in the literature of digital television systems [2].

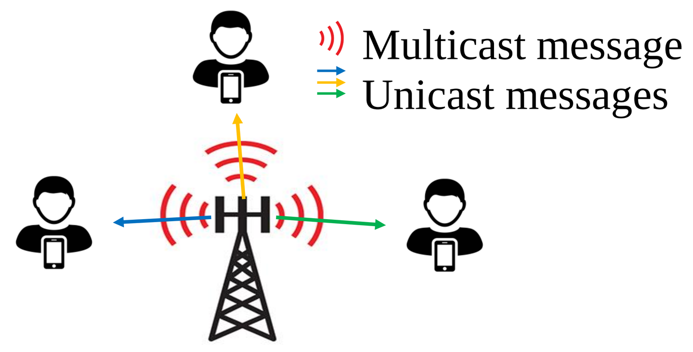

Fig. 1: Non-orthogonal unicast and multicast transmission.

Existing MU-LP beamforming

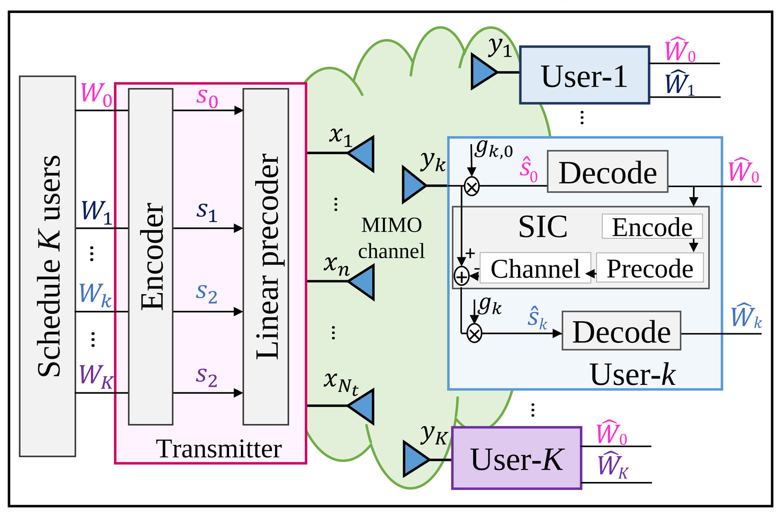

Fig. 2: *K*-user MU-LP assisted multi-antenna non-orthogonal unicast and multicast transmission.

- Transmit signal is:

$$\mathbf{x} = \underbrace{\mathbf{p}_0 s_0}_{\text{multicast stream}} + \underbrace{\sum_{k\in\mathcal{K}} \mathbf{p}_k s_k}_{\text{unicast stream}}$$

- Signal received at user-*k* is:

$$y_k = \underbrace{\mathbf{h}_k^H \mathbf{p}_0 s_0}_{\text{intended multicast stream}} + \underbrace{\mathbf{h}_k^H \mathbf{p}_k s_k}_{\text{intended unicast stream}} + \underbrace{\sum_{j\in\mathcal{K}, j\neq k} \mathbf{h}_k^H \mathbf{p}_j s_j}_{\text{interference among unicast streams}} + n_k.$$

Proposed Rate-Splitting Beamforming

System Model

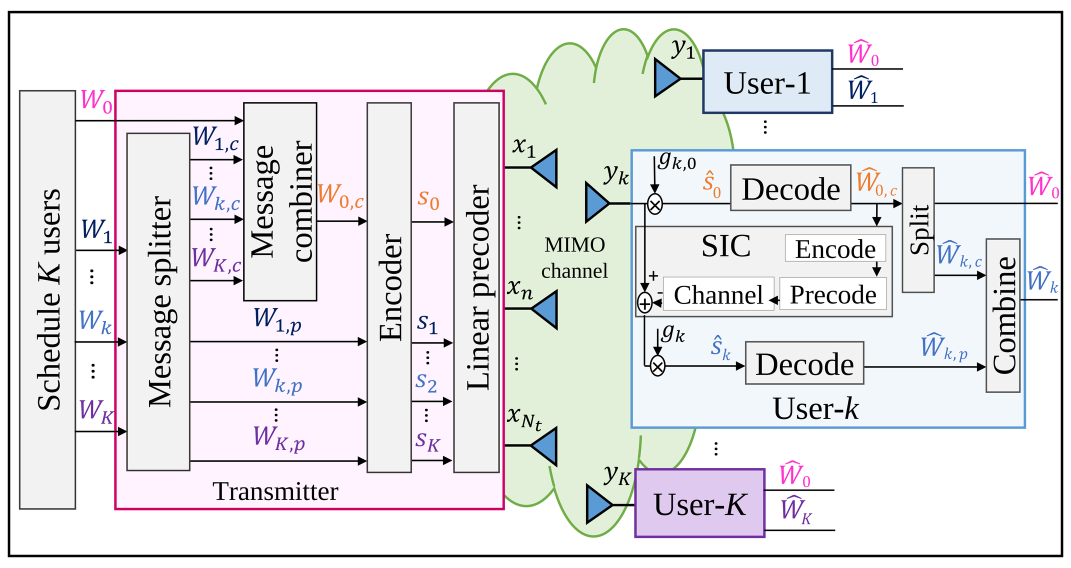

Fig. 3: *K*-user rate-splitting assisted non-orthogonal unicast and multicast transmission.

- ***Message splitting***: the unicast message W_k is split into a common part $W_{k,c}$ and a private part $W_{k,p}$.
- ***Data stream generation***: the common parts of the unicast messages $W_{1,c},\ldots,W_{K,c}$ are encoded along with the multicast message W_0 into a super-common stream s_0. The private parts $W_{1,c},\ldots,W_{K,c}$ are independently encoded into private streams $s_1,\ldots,s_K$.
- ***Transmit signal***: $\mathbf{x} = \underbrace{\mathbf{p}_0 s_0}_{\text{super-common stream}} + \underbrace{\sum_{k\in\mathcal{K}} \mathbf{p}_k s_k}_{\text{private streams}}$.
- ***Signal received at user-k***:

$$y_k = \underbrace{\mathbf{h}_k^H \mathbf{p}_0 s_0}_{\text{super-common stream}} + \underbrace{\mathbf{h}_k^H \mathbf{p}_k s_k}_{\text{intended private stream}} + \underbrace{\sum_{j\in\mathcal{K}, j\neq k} \mathbf{h}_k^H \mathbf{p}_j s_j}_{\text{interference among private streams}} + n_k.$$

SIC is used for dual purpose:
❖ To separate the unicast and multicast streams (as in MU-LP)
❖ To dynamically manage interference among unicast streams

- s_0 is first decoded. The SINR of decoding s_0 at user-*k* is:

$$\gamma_{k,0} = \frac{|\mathbf{h}_k^H \mathbf{p}_0|^2}{\sum_{j\in\mathcal{K}} |\mathbf{h}_k^H \mathbf{p}_j|^2 + 1}.$$

- After s_0 is decoded and removed, s_k is decoded with SINR:

$$\gamma_k = \frac{|\mathbf{h}_k^H \mathbf{p}_k|^2}{\sum_{j\neq k, k\in\mathcal{K}} |\mathbf{h}_k^H \mathbf{p}_j|^2 + 1}.$$

- The achievable rate of s_0 at user-k is: $R_{k,0} = \log_2(1+\gamma_{k,0})$.
- The achievable rates of s_k at user-*k* is: $R_k = \log_2(1+\gamma_k)$.
- To ensure that s_0 is successfully decoded by all users, the achievable rate of s_0 shall not exceed $R_0 = \min\{R_{1,0},\ldots,R_{K,0}\}$.
- R_0 is shared by the rate of transmitting W_0 and $W_{1,c},\ldots,W_{K,c}$. Denote C_0 as the portion of R_0 transmitting W_0 and $C_{k,0}$ as the user-k's portion of R_0 transmitting $W_{k,c}$, the achievable super-common rate is equal to $C_0 + \sum_{k\in\mathcal{K}} C_{k,0} = R_0$.
- The total achievable rate of the unicast message of user-k is: $R_{k,tot} = C_{k,0} + R_k$.

Problem Formulation

For a given weight vector $\boldsymbol{u}=[u_1,\ldots,u_K]$, the weighted sum rate maximization problem of the *K*-user Rate-Splitting (RS) assisted non-orthogonal unicast and multicast is

$$\begin{aligned} \max_{\mathbf{P},\mathbf{c}} \ & \sum_{k\in\mathcal{K}} u_k R_{k,tot} \\ \text{s.t.}\ & C_0 + \sum_{k\in\mathcal{K}} C_{k,0} \leq R_{k,0},\ \forall k\in\mathcal{K} \\ & C_0 \geq R_0^{th} \\ & C_{k,0} \geq 0,\ \forall k\in\mathcal{K} \\ & \mathrm{tr}(\mathbf{P}\mathbf{P}^H) \leq P_t \end{aligned}$$

Optimization Framework

Equivalent WMMSE problem

$$\begin{aligned} \min_{\mathbf{P},\mathbf{x},\mathbf{u},\mathbf{g}} \ & \sum_{k\in\mathcal{K}} u_k \xi_{k,tot} \\ \text{s.t.}\ & X_0 + \sum_{k\in\mathcal{K}} X_{k,0} + 1 \geq \xi_{k,0},\ \forall k\in\mathcal{K} \\ & X_0 \leq -R_0^{th} \\ & X_{k,0} \leq 0,\ \forall k\in\mathcal{K} \\ & \mathrm{tr}(\mathbf{P}\mathbf{P}^H) \leq P_t \end{aligned}$$

Alternating Optimization Algorithm [3]

1. Initialize: $n \leftarrow 0, \mathbf{P}^{[n]}, \mathrm{WSR}^{[n]}$
2. Repeat
3. $n \leftarrow n+1$;
4. $\mathbf{P}^{[n-1]} \leftarrow \mathbf{P}$;
5. $\mathbf{u} \leftarrow \mathbf{u}^{\mathrm{MMSE}}(\mathbf{P}^{[n-1]})$; $\mathbf{g} \leftarrow \mathbf{g}^{\mathrm{MMSE}}(\mathbf{P}^{[n-1]})$;
6. Update $(\mathbf{x},\mathbf{P})$ by solving the left problem.
7. Until $|\mathrm{WSR}^{[n]} - \mathrm{WSR}^{[n-1]}| \leq \epsilon$

Numerical Results

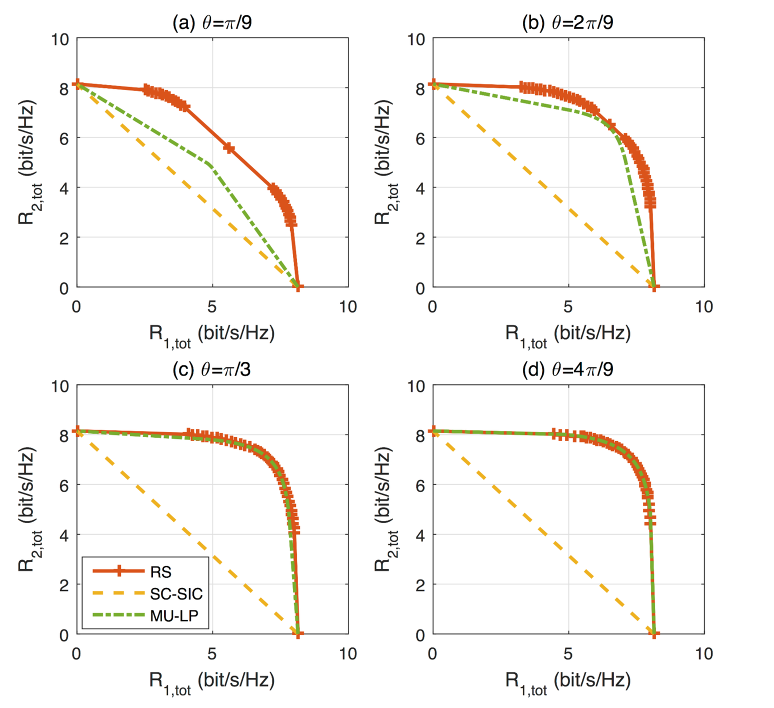

Fig. 4: Achievable rate region comparison of different strategies, $\gamma = 1, R_0^{th} = 0.5$ bit/s/Hz

- In all figures, SNR=20 dB. The transmitter is equipped with 4 antennas serving two single-antenna users.
- Superposition Coding and Successive Interference Cancellation (SC-SIC) is the application of power-domain Non-Orthogonal Multiple Access (NOMA) in the non-orthogonal unicast and multicast transmission.
- Channel model:

$$\mathbf{h}_1 = [1,1,1,1]^H,$$
$$\mathbf{h}_2 = \gamma \times [1, e^{j\theta}, e^{j2\theta}, e^{j3\theta}]^H$$

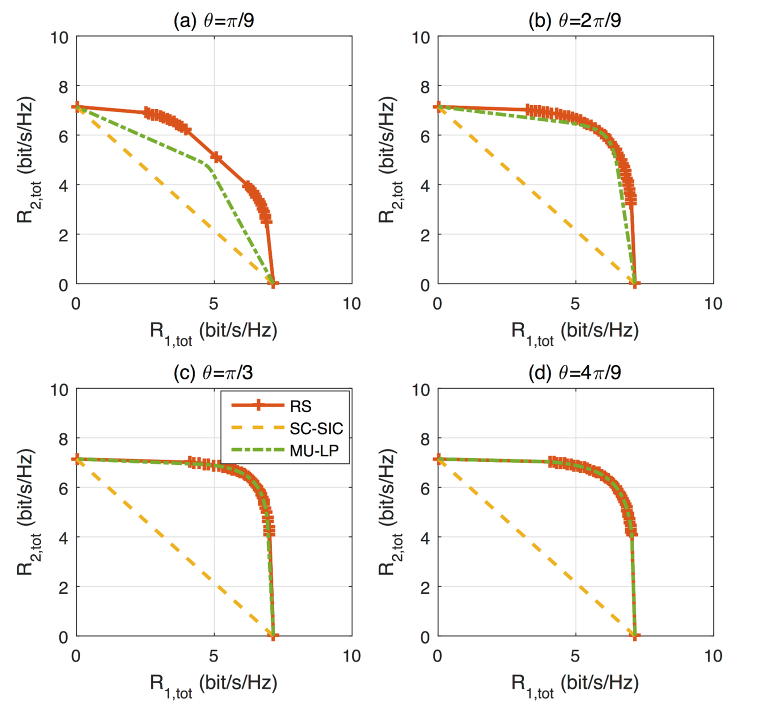

Fig. 5: Achievable rate region comparison of different strategies, $\gamma = 1, R_0^{th} = 1.5$ bit/s/Hz

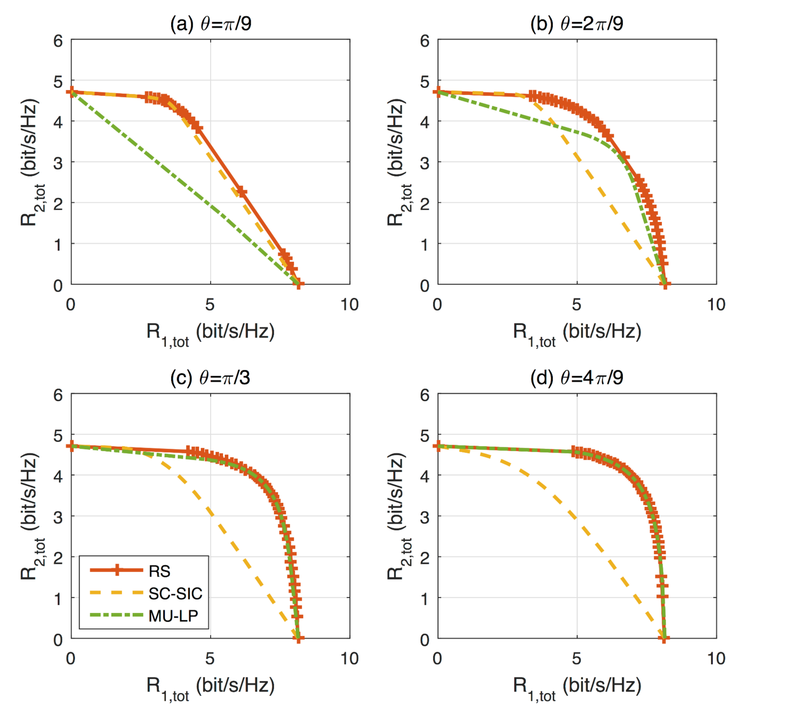

Fig. 6: Achievable rate region comparison of different strategies, $\gamma = 0.3, R_0^{th} = 0.5$ bit/s/Hz

Observations:
❖ RS softly bridges and outperforms MU-LP and SC-SIC in any user deployments.
❖ The rate region gain of RS over MU-LP and SC-SIC increases as the rate threshold of the multicast message decreases.
❖ RS is more robust to a wide range of channel gain difference and channel angles among users.

Conclusions

To conclude, we exploit the benefit of the linearly-precoded RS in the joint unicast and multicast transmission systems by utilizing a super-common stream to encapsulate the multicast message and parts of the unicast messages.

- We propose a RS-assisted unicast and multicast transmission system.
- The merits of the existing one layer of SIC is further exploited. RS uses one layer of SIC to not only separate the unicast and multicast streams but also dynamically manage the multi-user interference.
- We show in the results that the performance of MU-LP and SC-SIC is more sensitive to the channel strength disparity and channel angles among users.
- We show that RS softly bridges and outperforms MU-LP and SC-SIC in any user deployments. The benefit of RS is obtained without any increase in the receiver complexity compared with MU-LP.

References

[1] O. Tervo et al., "Energy-efficient joint unicast and multicast beamforming with multi-antenna user terminals," IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Sapporo, 2017.

[2] L. Zhang et al., "Layered-Division-Multiplexing: Theory and Practice," in IEEE Transactions on Broadcasting, vol. 62, no. 1, pp. 216-232, March 2016.

[3] H. Joudeh and B. Clerckx, "Sum-Rate Maximization for Linearly Precoded Downlink Multiuser MISO Systems With Partial CSIT: A Rate-Splitting Approach," in IEEE Transactions on Communications, vol. 64, no. 11, pp. 4847-4861, Nov. 2016.