Rate-Splitting Multiple Access for Multi-Antenna Multi-Carrier Joint Communications and Jamming

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Outline

Motivation

- With increasing number of systems and applications, RF spectrum has become a congested and contested environment.
- Two challenges for military systems in RF congested and contested environments:
  1. Perform wideband communications to meet the data requirements for advancing applications with high spectral efficiency and under strict reliability and robustness requirements.
  2. Deny the Adversarial Users (AUs) in the environment using the same time and frequency resources of service.

Motivation

- Our target is efficient communications with friendly Information Users (IUs) on the battlefield while denying AUs of service.
  - Wideband communications with multiple antennas and multi-carrier waveforms.
  - Practical and realistic scenario of imperfect Channel State Information at Transmitter (CSIT) for IUs and statistical CSIT for AUs.
- Rate-Splitting Multiple Access (RSMA) is a multiple access technique for multi-antenna systems with efficient interference management capabilities.

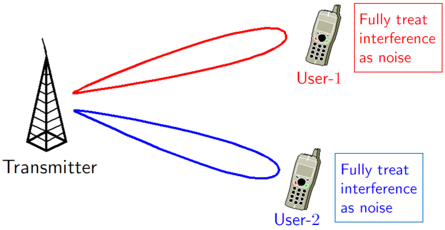
We investigate the performance of RSMA for joint communications and jamming with multi-carrier waveforms under imperfect and statistical CSIT.

Multi-User MIMO Communications

- Multi-User Multiple-Input Multiple-Output (MU-MIMO) Communications : meet the demand for increasing data rate and connectivity in emerging communications standards.
- Efficient use of limited physical resources, such as, time and frequency bands by making use of spatial domain.
- Support large number of users in wireless ad-hoc/centralized networks.
- Key enabling technology in 5G.

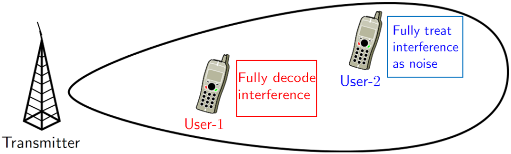
Space-Division Multiple Access

- **Space-Division Multiple Access (SDMA)** : improved sum-rate with perfect Channel State Information at the Transmitter (CSIT).
  - Linear precoding to separate users' streams at the transmitter.
  - Any multi-user interference is treated as noise.
  - Severe performance degradation under interference due to imperfect CSIT.

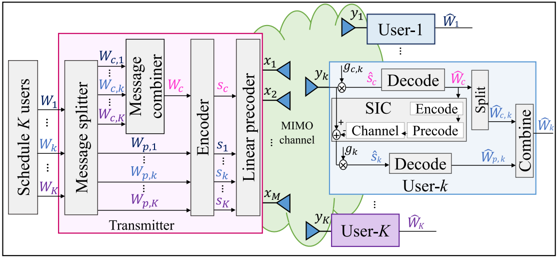


Non-Orthogonal Multiple Access

- **Non-Orthogonal Multiple Access (NOMA)** : based on Superposition Coding (SC) at the transmitter and Successive Interference Cancellation (SIC) at the receivers.
  - Originally considered for the Single-Input Single-Output Broadcast Channel (SISO-BC).
  - Significant Degree-of-Freedom (DoF) loss in multi-antenna unless user channels are aligned and have a disparity of strengths [8].

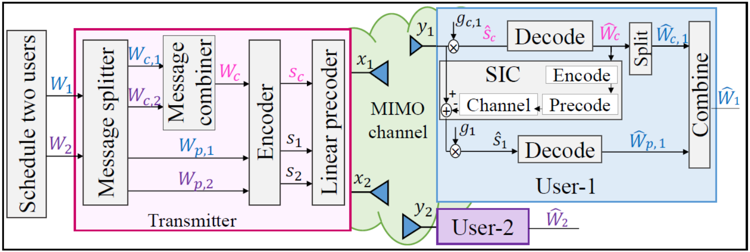


Rate-Splitting Multiple Access



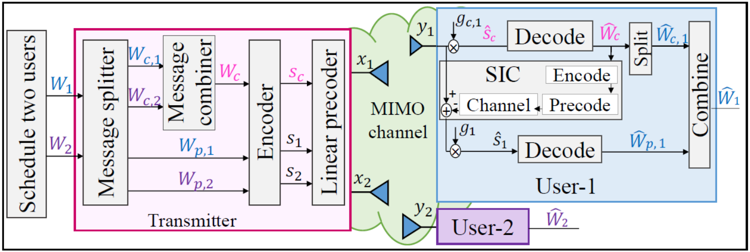
- **Rate-Splitting Multiple Access (RSMA) :** linearly precoded RS at the transmitter and SIC at the receivers [9, 10].
  - Splits the messages into common and private parts.
  - Partially decodes interference and partially treats it as noise.
  - Achieves entire DoF region of K-user Multiple-Input Single-Output (MISO) BC with imperfect CSIT [11, 12].

RSMA - Transmitter (MISO BC, 2 Users)



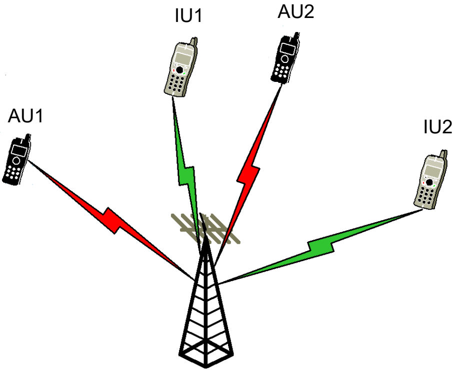
- **Split:** $W_1 \rightarrow \{ \underbrace{W_{c,1}}_{\text{common}}, \underbrace{W_{p,1}}_{\text{private}} \}$, $W_2 \rightarrow \{ \underbrace{W_{c,2}}_{\text{common}}, \underbrace{W_{p,2}}_{\text{private}} \}$
- **Combine:** $\{W_{c,1}, W_{c,2}\} \rightarrow W_c$
- **Encode:** $W_c \rightarrow s_c$, $W_{p,1} \rightarrow s_1$, $W_{p,2} \rightarrow s_2$
- **Transmit signal :** $\mathbf{x} = \mathbf{p}_c s_c + \mathbf{p}_1 s_1 + \mathbf{p}_2 s_2$

RSMA - Receiver (MISO BC, 2 Users)



- **Received signal at user-k:** $y_k = \mathbf{h}_k^H \mathbf{x} + z_k$
- **SIC at receivers:**
  1. Decode s_c by treating s_1 and s_2 as noise, perform cancellation
  2. User-1: Decode s_1 (s_2 as noise), User-2: Decode s_2 (s_1 as noise)
- **Instantaneous rates at user-k:**
  - Common stream : $R_{c,k} = \log_2\left(1 + \frac{|\mathbf{h}_k^H \mathbf{p}_c|^2}{\sum_{i=1}^{2} |\mathbf{h}_k^H \mathbf{p}_i|^2 + 1}\right)$
  - Private stream : $R_k = \log_2\left(1 + \frac{|\mathbf{h}_k^H \mathbf{p}_k|^2}{|\mathbf{h}_k^H \mathbf{p}_i|^2 + 1}\right),\ i \neq k$

System Model



- Transmitter with N_t antennas
- K IUs with single-antenna, imperfect CSIT: $\underbrace{\mathbf{h}_{k,n}}_{\text{channel}} = \sqrt{1-\sigma_{ie}^2}\underbrace{\widehat{\mathbf{h}}_{k,n}}_{\text{CSIT}} + \sigma_{ie}\underbrace{\widetilde{\mathbf{h}}_{k,n}}_{\text{error}}$
  - $\sigma_e^2 = P^{-\alpha}$
  - α : CSIT quality scaling factor
- L AUs with single-antenna, statistical CSIT: $\mathbf{R}_{g_{l,n}} = \mathbb{E}\left\{\mathbf{g}_{l,n}\mathbf{g}_{l,n}^H\right\}$.
- N subcarriers, $\mathcal{S} = \{1, \ldots, N\}$
- N_p pilot subcarriers for AUs, $\mathcal{S}_p$ set of pilot subcarrier indices
- Transmitter has synchronisation with AU transmissions [3, 6, 7] and a perfect knowledge of $\mathcal{S}_p$ [1, 2, 3, 4, 5]
- Pilot subcarrier jamming to disrupt the communication of AUs [1, 2, 3, 4, 5]

System Model

Transmit Signal at Subcarrier-n

$$x_n = \mathbf{p}_{c,n} s^f_{c,n} + \sum_{k=1}^{K} \mathbf{p}_{k,n} s^f_{k,n} + \sum_{l=1}^{L} \mathbf{f}_{l,n} s^e_{l,n}.$$

Received Signal at IU-k and Subcarrier-n

$$y_{k,n} = \mathbf{h}^H_{k,n} \mathbf{x}_n + z_{k,n}.$$

Average Jamming Power at AU-l and Pilot Subcarrier-n

$$\begin{aligned}\bar{\Lambda}_{l,n}(\mathbf{P}_n, \mathbf{F}_n) &\triangleq \mathbb{E}\left\{ |\mathbf{g}^H_{l,n}\mathbf{p}_{c,n}|^2 + \sum_{k\in\mathcal{K}} |\mathbf{g}^H_{l,n}\mathbf{p}_{k,n}|^2 + \sum_{l'\in\mathcal{L}} |\mathbf{g}^H_{l,n}\mathbf{f}_{l',n}|^2 \right\} \\ &= \mathbf{p}^H_{c,n}\mathbf{R}_{g_{l,n}}\mathbf{p}_{c,n} + \sum_{k\in\mathcal{K}} \mathbf{p}^H_{k,n}\mathbf{R}_{g_{l,n}}\mathbf{p}_{k,n} + \sum_{l'\in\mathcal{L}} \mathbf{f}^H_{l',n}\mathbf{R}_{g_{l,n}}\mathbf{f}_{l',n}.\end{aligned}$$

Problem Formulation

- Maximize mutual information $I_k = \log|\mathbf{I} + \mathbf{Z}_k^{-1}\mathbf{H}_k^H\mathbf{P}\mathbf{P}^H\mathbf{H}_k|$ with carrier-non cooperative processing
- $C_{k,n}$: common stream rate for user-k
  $I_{k,n}(\mathbf{P}_n, \mathbf{F}_n)$: private stream mutual information for user-k
  $J_{l,n}^{thr}$: jamming power threshold

Mutual Information Maximization

$$\max_{\mathbf{P},\mathbf{F},\mathbf{c}} \sum_{n\in\mathcal{S}}\sum_{k\in\mathcal{K}} (C_{k,n} + I_{k,n}(\mathbf{P}_n, \mathbf{F}_n))$$

$$\text{s.t.} \sum_{k'\in\mathcal{K}} C_{k',n} \leq I_{c,k,n}(\mathbf{P_n}, \mathbf{F_n}), n\in\mathcal{S}, k\in\mathcal{K}$$

$$\bar{\Lambda}_{l,n}(\mathbf{P}_n, \mathbf{F}_n) \geq J_{l,n}^{thr}, \quad n\in\mathcal{S}_p,\ l\in\mathcal{L}$$

$$\sum_{n\in\mathcal{S}} \mathrm{tr}(\mathbf{P}_n\mathbf{P}_n^H) + \mathrm{tr}(\mathbf{F}_n\mathbf{F}_n^H) \leq \bar{P}_t,$$

$$\mathbf{c} \geq \mathbf{0}.$$

The problem is not convex!

Proposed Algorithm

- Rate-MSE transformation for non-convex objective and rate constraints [12, 13]
- First-order Taylor approximation for non-convex jamming power constraint [14]

MSE Minimization

$$\min_{\mathbf{P},\mathbf{F},\mathbf{x},\mathbf{u},\mathbf{g}} \sum_{n\in\mathcal{S}}\sum_{k\in\mathcal{K}} (X_{k,n}+\xi_{k,n}(\mathbf{P}_n,\mathbf{F}_n)) \quad (2a)$$

$$\text{s.t.} \quad \sum_{k\in\mathcal{K}} X_{k,n}+1 \geq \xi_{c,k,n}(\mathbf{P}_n,\mathbf{F}_n) \quad (2b)$$

$$\bar{\Lambda}^{t}_{l,n}(\mathbf{P}_n,\mathbf{F}_n) \geq J^{thr}_{l,n} \quad (2c)$$

$$\sum_{n\in\mathcal{S}} \mathrm{tr}(\mathbf{P}_n\mathbf{P}_n^H)+\mathrm{tr}(\mathbf{F}_n\mathbf{F}_n^H) \leq \bar{P}_t, \quad (2d)$$

$$\mathbf{x} \leq \mathbf{0}. \quad (2e)$$

SCA-based algorithm

$t \leftarrow 0,\ i \leftarrow 0,\ \mathrm{WSR}^0 \leftarrow 0,\ \hat{\mathbf{P}},\ \hat{\mathbf{F}}$
while $|\mathrm{WSR}^i - \mathrm{WSR}^{i-1}| > \epsilon_r$ **do**
  $\boldsymbol{u}^i \leftarrow$ updateWeights($\hat{\mathbf{P}}$, $\hat{\mathbf{F}}$)
  $\boldsymbol{g}^i \leftarrow$ updateFilters($\hat{\mathbf{P}}$, $\hat{\mathbf{F}}$)
  while $|\mathrm{WMMSE}^t - \mathrm{WMMSE}^{t-1}| > \epsilon_m$ **do**
    $(\mathbf{P}^{t+1}, \mathbf{F}^{t+1}, \mathbf{x}^{t+1}) \leftarrow$ (2) for given $\boldsymbol{u}^i$, $\boldsymbol{g}^i$ and $(\mathbf{P}^t, \mathbf{F}^t)$
    $\mathrm{WMMSE}^{t+1} \leftarrow$ updateWMMSE($\mathbf{P}^{t+1}$, $\mathbf{F}^{t+1}$)
    $t \leftarrow t+1$
  end
  $\hat{\mathbf{P}} \leftarrow \mathbf{P}^t$, $\hat{\mathbf{F}} \leftarrow \mathbf{F}^t$
  $\mathrm{WSR}^{i+1} \leftarrow$ updateWSR($\hat{\mathbf{P}}$, $\hat{\mathbf{F}}$)
  $t \leftarrow 0,\ i \leftarrow i+1$
end
return ($\hat{\mathbf{P}}$, $\hat{\mathbf{F}}$)

Feasibility and Threshold Calculation

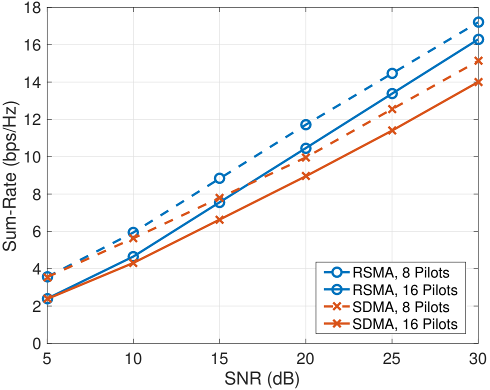
$\Rightarrow$ The jamming thresholds should be set carefully at each subcarrier for maximum jamming power at each AU and feasibility of the problem.

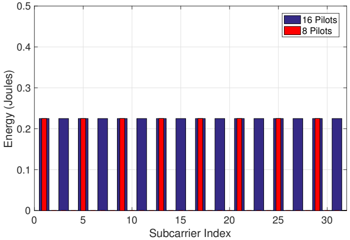
Jamming Threshold at AU-l and Subcarrier-n

$$J_{l,n}^{thr} = \rho \frac{\bar{P}_t}{|S_p| L} \tau_{l,n}, \quad n \in \mathcal{S}_p, \;\; l \in \mathcal{L}.$$

- $\tau_{l,n}$: Largest eigenvalue of channel covariance matrix $\mathbf{R}_{g_{l,n}}$.
- $\rho \in [0, 1]$: Controls the strictness of the jamming power threshold.

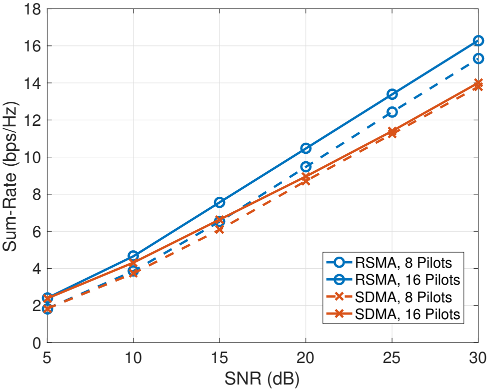
Sum-Rate vs. SNR

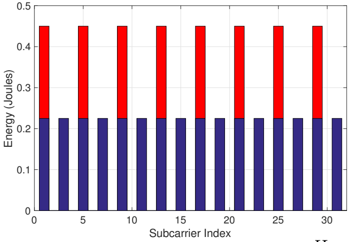




- IU CSIT : $\mathbf{h}_{1,n} = [1, 1, 1, 1]^H$, $\mathbf{h}_{2,n} = [1, e^{j4\pi/9}, e^{j8\pi/9}, e^{j12\pi/9}]^H$
- AU covariance : $\mathbf{g}_{1,n}{=}[1, e^{j\beta}, e^{j2\beta}, e^{j3\beta}]^H$ averaged over $\beta{=}[0, 4pi/9]$
- $\rho = 0.9\frac{|\mathcal{S}_p|}{N/2}$

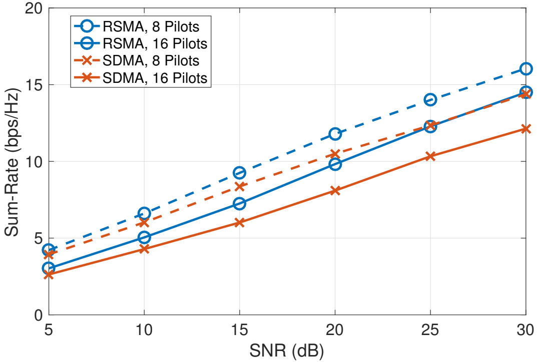
Sum-Rate vs. SNR





- IU CSIT : $\mathbf{h}_{1,n} = [1, 1, 1, 1]^H$, $\mathbf{h}_{2,n} = [1, e^{j4\pi/9}, e^{j8\pi/9}, e^{j12\pi/9}]^H$
- AU covariance : $\mathbf{g}_{1,n}$=$[1, e^{j\beta}, e^{j2\beta}, e^{j3\beta}]^H$ averaged over β=$[0, \ldots, 4pi/9]$
- $\rho = 0.9$

Sum-Rate vs. SNR - Frequency Selective Channel



- 3GPP CDL-A channel model by Quadriga, 100 realizations
- Delay spread of 1200ns, 23 clusters, 20 rays per cluster
- OFDM subcarrier spacing of 60kHz, OFDM Cyclic-Prefix of $10\mu s$
- $\rho = 0.9\frac{|\mathcal{S}_p|}{N/2}$

Conclusion

- We propose a multi-carrier waveform design method for RSMA to perform joint communications and jamming in a multi-antenna network under imperfect and statistical CSIT.
- We show that RSMA can achieve significantly higher sum-rate than SDMA while focusing the same amount of jamming power on AU pilot subcarriers.

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Thank you for listening...