User Selection with Interference Alignment for MU-MIMO Networks

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Motivation

Motivated by user selection in MIMO BC, where each BS opportunistically selects users in the corresponding cell
To obtain better performance in terms of sum-rate, some communication links are switched off instead of keeping all-on state

Key aspects of the study

Investigate sum-rate of multi-user network as a function of number of active links
Consider different user selection schemes
System model

- $M \times M$ MIMO network with $N$ links (users)
- Single data stream at each link
- Rayleigh fading channel with no pathloss
- Equal transmit power at each Tx (P)
- Use of reciprocal network concept to do BF

Figure: The MU-MIMO Network
The filtered signal at the $l$th Rx:

$$\hat{x}_l = g_l^H y_l = g_l^H H_{ll} q_l x_l + \sum_{j=1}^{L} \sum_{j \neq l} g_l^H H_{lj} q_j x_j + g_l^H n_l,$$

where

- $y_l$: the received signal at the $l$th Rx,
- $x_l$: the transmit signal of the $l$th Tx,
- $g_l$: the interference suppression vector at $l$th Rx,
- $H_{lj}$: the complex channel gain from $j$th Tx to $l$th Rx,
- $q_j$: the precoding vector at $j$th Tx,
- $n_l$: the complex Gaussian noise at the $l$th Rx with power $P_N = N_0 B$. 

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The signal to interference plus noise ratio (SINR) of \( l \)th Rx:

\[
SINR_l = \frac{Pg_l^H H_{ll} q_l^H H_{ll}^H g_l}{g_l^H Q_l g_l + P_N g_l^H g_l},
\]

(2)

where the interference covariance matrix \( Q_l = \sum_{j=1}^{L} PH_{lj} q_j q_j^H H_{lj}^H \) (sum of signal power).

Objective: maximize sum-rate

\[
R_{\text{sum-rate}} = \sum_{l=1}^{L} \log(1 + SINR_l).
\]

(3)
Problem description

• If we use a BF algorithm to improve the performance in terms of interference cancelation, the maximum number of links given $M$ is $2M - 1$.
  
  $M$ antennas can cancel $M - 1$ interferers at most $\Rightarrow 2L(M - 1)$ DoF $\geq L(L - 1)$ interferers.

• Simulation result show that iterative ML-IA and MMSE can achieve the maximum number of links given $M$ if one data stream is transmitted at each link.

• $2M - 1$ links instead of all links will be selected to transmit simultaneously if we want to cancel all interferers.
Problem description (cont.)

- User selection: $L$ links are selected among $N$ links for simultaneous transmission through a certain criterion.

- Beamforming: non-iterative algorithms
  - MMSE
  - MS-IA: ZF+MS for $M - 1$ links, and then minimizing interference (or ZF, if possible) for the remaining $L - M + 1$ links.

- What is the value of the optimal $L$ to maximize the sum-rate when non-iterative algorithm is used?
Single-antenna system

- $M = 1$, $q_l = 1$ and $g_l = 1 \Rightarrow$ no BF.

- When $L = 1$, the achievable rate averaged over Rayleigh fading channels is

$$R = \mathbb{E} \left[ \log \left( 1 + \frac{P|h_{11}|^2}{P_N} \right) \right],$$

where $\mathbb{E}[x]$ denotes the expectation of $x$. $H_{ij} = h_{ij}$ is a scalar in this case. $R$ is linearly increasing with $P$ in dB. When $P \rightarrow \infty$, $R_1 \rightarrow \infty$.

- When $L \geq 2$, the sum-rate averaged over Rayleigh fading channels is

$$R_{\text{sum-rate}} = \mathbb{E} \left[ \sum_{i=1}^{L} \log_2 \left( 1 + \frac{P|h_{ii}|^2}{P|\sum_{j=1, j\neq i}^{L} h_{ij}|^2 + P_N} \right) \right],$$

$$= \mathbb{E} \left[ \sum_{i=1}^{L} \log_2 \left( 1 + \frac{|h_{ii}|^2}{|\sum_{j=1, j\neq i}^{L} h_{ij}|^2 + \frac{P_N}{P}} \right) \right].$$

$R_{\text{sum-rate}}$ is monotonically increasing with $P$. 

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The average sum rate of an $L$-user SISO system with Rayleigh fading channels is

$$R_{\text{sum-rate}} = L \ln 2 \int_0^{\infty} r^{2r} e^{\frac{(1-2r)P_N}{P}} \frac{[(L-1)\left(\frac{P}{P_N} + 2r - 1\right) + 1]}{\frac{P}{P_N}[(L-1)(2r - 1) + 1]^2} dr,$$

where $P$ and $P_N$ are the transmit power and the noise power at each link, respectively.

$$\lim_{P \to \infty} R_{\text{sum-rate}} = L \frac{\ln 1 - \ln(L-1)}{1 - (L-1)},$$

$$= L \cdot \frac{1}{L-1} \cdot \frac{\log_2 \frac{1}{L-1}}{1 - \frac{1}{L-1}} \cdot \left(\frac{\ln S - \ln I}{S-I}\right).$$
When $P \to \infty$, the sum-rate is

$$\lim_{P \to \infty} R_{\text{sum-rate}} = \frac{L \ln(L-1)}{(L-2) \ln 2}. \quad (8)$$

Especially,

$$\lim_{P \to \infty, L \to 1} R = \infty, \quad (9)$$

and

$$\lim_{P \to \infty, L \to 2} R_{\text{sum-rate}} = \frac{2}{\ln 2}. \quad (10)$$
Sum-rate of SISO network \((P \to \infty)\)

- \(N = 1, R = \infty\).
- When \(N \geq 2\),
  - Power of interference sum:
    \[
    P_I = P|\sum_{j=1,j\neq i}^{L} h_{ij}|^2. \tag{11}
    \]
  - \(N \uparrow, R_{\text{sum-rate}} \uparrow\).
  - Sum of interference power:
    \[
    P_I = P \sum_{j=1,j\neq i}^{L} |h_{ij}|^2. \tag{12}
    \]
  - \(N \uparrow, R_{\text{sum-rate}} \downarrow\).
Sum-rate of SISO network (cont.)

SISO system with sum of interference power

SISO system with power of interference sum

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User selection schemes

- Random selection: select $L$ links from $N$ links randomly.
  - RS-MMSE
  - RS-MS-IA

- Large gain selection: select $L$ links with the largest channel gains among $N$ links.
  - LG-MMSE
  - LG-MS-IA 1: ZF+MS at $L-1$ links with larger channel gains, and then ZF at the remaining link.
  - LG-MS-IA 2: ZF+MS at $L-1$ links with smaller channel gains, and then ZF at the remaining link.
4 × 4 MIMO network with 100 links in total ($M = 4, N = 100$)

Select 4 links to transmit simultaneously ($L = 4$)

One stream per transmitter

Uniform power allocation

Independent Rayleigh fading

Performance measure → averaged sum-rate over 1000 trials of multipath fading
Compared with RS scheme, LG selection improves the performance using both BF algorithms.

The performance of LG-MS-IA 1 are almost the same as that of LG-MS-IA 2.
$\Delta R = R_{\text{max}} - R_{\text{min}}$, where $R$ is the individual rate of each link.

Variance of $\Delta R$ achieved by RS-MMSE and LG-MMSE is the same.

Variance of $\Delta R$ achieved by LG-MS-IA 2 is smaller than that of LG-MS-IA 1 with the same sum-rate.
Future work

- Investigate the optimal number of active links in MIMO networks.
- Consider better (fair or/and distributive) user selection schemes.
- Extend to multiple streams at each link.
- Application to the multi-antenna cellular network with single antenna at each user.