EXPLOITING LONG-TERM STATISTICS IN SPATIALLY CORRELATED MULTI-USER MIMO SYSTEMS WITH QUANTIZED CHANNEL NORM FEEDBACK

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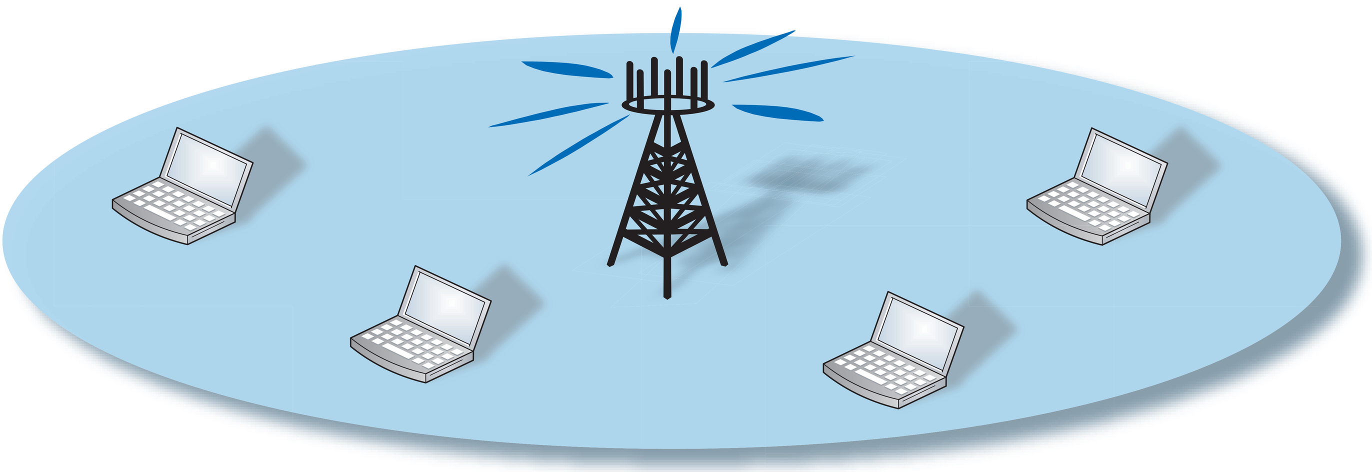
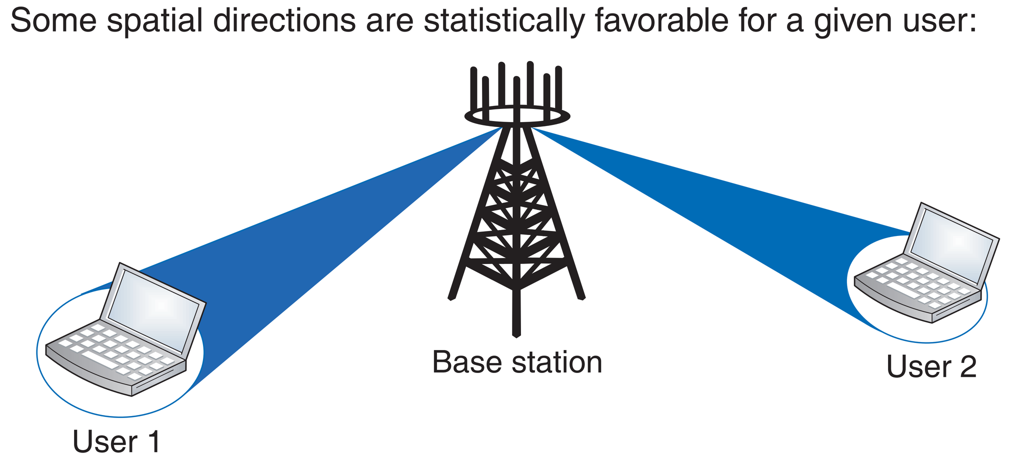


Spatial Correlation

Consider the multi-antenna system

- Elevated base station, n_T antennas.
- Multiple users, n_R antennas.

Some spatial directions are statistically favorable for a given user:



Excellent for simultaneous transmission to several users:

- Spatial division multiple access (SDMA)
- Linear precoding and receive beamforming

System Model

Urban environment with elevated base station:

- Spatially correlated transmitter.
- Independent receive antennas.

Channel model:
Rayleigh fading multi-antenna channel to user k

$$\mathbf{H}_k = [\mathbf{h}_{k,1},\ldots,\mathbf{h}_{k,n_R}]^H \in \mathbb{C}^{n_R \times n_T},$$

with independent rows $\mathbf{h}_{k,i} \in \mathcal{CN}(\mathbf{0},\mathbf{R}_k)$.

Received signal when transmitting s_k to user k:

$$\mathbf{y}_k(t) = \mathbf{v}_k^H \mathbf{H}_k \Big(\underbrace{\sqrt{p_k}\mathbf{w}_k s_k(t)}_{\text{signal}} + \sum_{j \neq k} \underbrace{\sqrt{p_j}\mathbf{w}_j s_j(t)}_{\text{interference}} \Big) + \underbrace{\mathbf{n}_k(t)}_{\text{noise},\sigma_k^2}$$

- Transmit beamformer $\mathbf{w}_k \in \mathbb{C}^{n_T}$, Receive beamformer $\mathbf{v}_k \in \mathbb{C}^{n_R}$.

Available channel state information:

- Transmitter knows the statistics.
- Receiver k knows both the channel realization $\mathbf{H}_k$ and statistics.

Performance and Beamforming

Performance measure: Total data rate of all users.
User rate increases with the signal-to-interference-and-noise ratio:

$$\mathrm{SINR}_k = \frac{p_k \|\mathbf{v}_k^H \mathbf{H}_k \mathbf{w}_k\|^2}{\sum_{i \neq k} p_i \|\mathbf{v}_k^H \mathbf{H}_k \mathbf{w}_i\|^2 + \sigma_k^2}.$$

Tricky performance optimization problem:

- Transmit beamformer $\mathbf{w}_k$ affects all users (fairness).
- Transmitter only knows the channel statistics.
- Receiver is unaware of the other users' channels.

Subspace Cancellation

In order to make robust SINR estimation possible:

- The effect of the receive beamformer $\mathbf{v}_k$ predictable at transmitter.

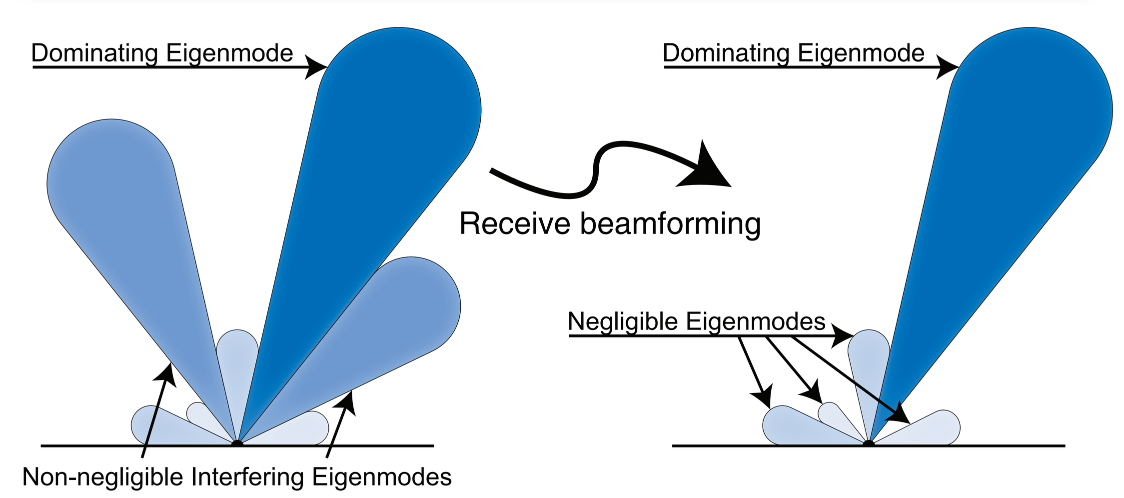
Subspace partitioning of the covariance matrix $\mathbf{R}_k$:

$$\mathbf{R}_k = \left[\mathbf{u}_k^{(D)}\, \mathbf{U}_k^{(I)}\, \mathbf{U}_k^{(0)}\right] \begin{bmatrix} \lambda_1 & & \\ & \ddots & \\ & & \lambda_{n_T} \end{bmatrix} \left[\mathbf{u}_k^{(D)}\, \mathbf{U}_k^{(I)}\, \mathbf{U}_k^{(0)}\right]^H$$

- $\mathbf{u}_k^{(D)}$ dominating eigenvector (largest eigenvalue).
- $\mathbf{U}_k^{(I)}$ eigenvector subspace of non-negligible eigenvalues.
- $\mathbf{U}_k^{(0)}$ eigenvector subspace with eigenvalues close to zero.

Proposed transmission strategy:

- Transmission along dominating eigenvector: $\mathbf{w}_k = \mathbf{u}_k^{(D)}$.
- Interference in $\mathbf{U}_k^{(I)}$ can be mitigated without loss of signal power.
- Receiver cancels out the $n_R - 1$ strongest eigenvalues in $\mathbf{U}_k^{(I)}$.



SINR Estimation and Feedback

Effective channel with the proposed receive beamforming:

$$\tilde{\mathbf{h}}_k^H = \mathbf{v}_k^H \mathbf{H}_k \in \mathcal{CN}(\mathbf{0},\mathbf{Q}_k).$$

- Same eigenvectors in $\mathbf{Q}_k$ as in $\mathbf{R}_k$, but the eigenvalues are

$$[\lambda_1, 0, \ldots, 0, \lambda_{n_R+1}, \ldots, \lambda_{n_T}].$$

Important observations:

- The effective channel $\tilde{\mathbf{h}}_k$ is almost rank one (along $\mathbf{u}_k^{(D)}$).
- The distribution of $\tilde{\mathbf{h}}_k$ is known at the transmitter.

Transmitter needs to estimate signal/interference powers $\|\tilde{\mathbf{h}}_k^H \mathbf{w}_i\|^2$:

- Robust SINR estimation necessary for data rate adaptation.
- Estimation quality can be improved by feedback.
- The channel norm $\|\tilde{\mathbf{h}}_k\|^2$ measures the gain in all directions.

Quantized Channel Norm Feedback

It have been shown before that

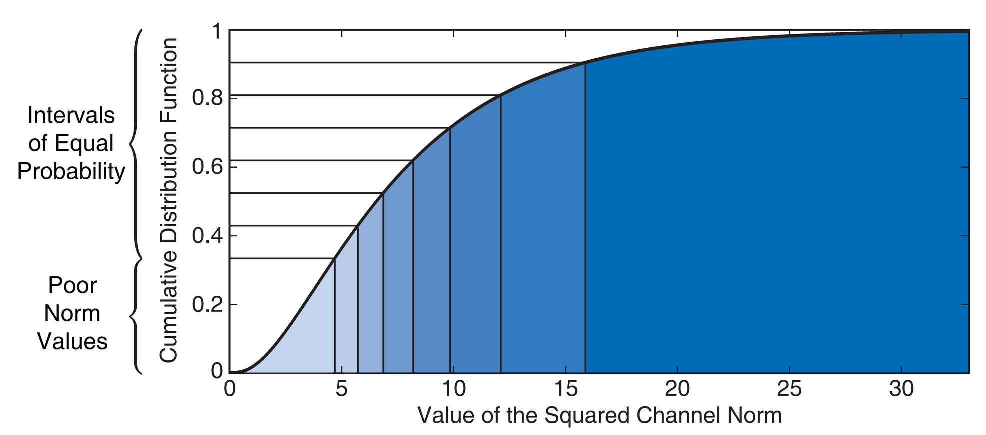
- Feedback of the exact norm $\|\tilde{\mathbf{h}}_k\|^2$ gives good SINR estimation.

What happens when quantization is introduced?

- We have derived an MMSE estimator for signal/interference power.
  - Exploits feedback of the quantized squared channel norm.
  - Closed-form expressions are given for arbitrary quantization.

How to quantize the channel norm optimally?

- Divide the probability density into intervals of equal probability!
  - Should be based on the post-user-selection distribution.
- Proposed quantization (*heuristic*)
  - One interval for really poor channel norms.
  - The rest of the probability density divided equally.



Performance Evaluation

Base station

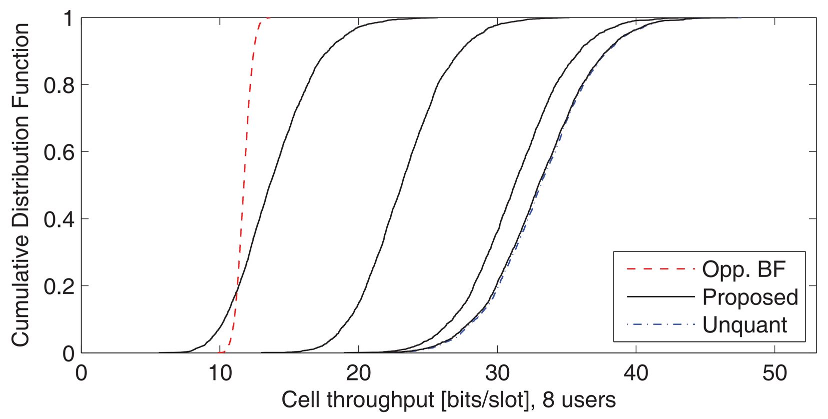
- 8 antennas in a uniform circular array (UCA).
- 15 degrees of angular spread.

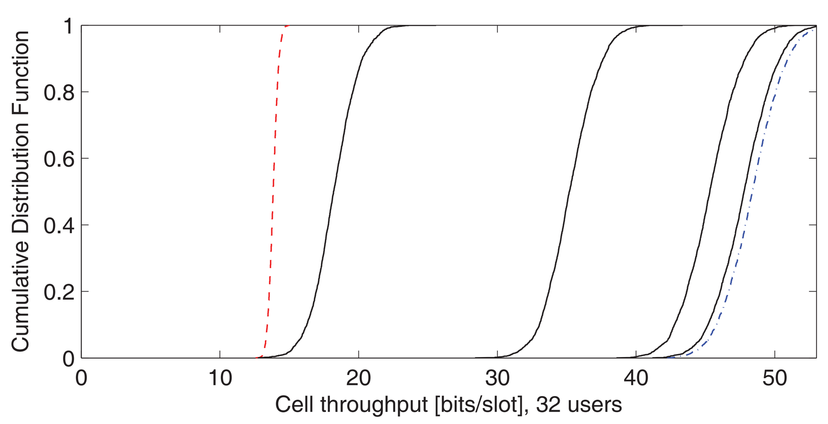
Mobile users

- 4 antennas at each user.
- Uniformly distributed users in the cell.

Transmission properties

- Average signal-to-noise ratio (SNR) at cell boundary of 10 dB.
- Greedy resource allocation with proportional fairness.
- Outage probability of 5% (using SINR estimator with back-off).





Observations

- 1 bit gives 50% of the performance gain, 3 bits give 90%.
- Opportunistic beamforming (exact feedback) is outperformed.

Conclusions and Contributions

- Transmission takes place along the strongest eigenvector.
- Receiver cancels out interference in other eigen-subspaces.
- Feedback of channel norm makes reliable SINR estimation possible.
- Only a few bits are required to capture most of the feedback gain.