Partial Feedback-Based Opportunistic Scheduling

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Cross-Layer Design for resource allocation

We consider a network of N independent users communicating with a single access point.

- Resource allocation is done at LINK/MAC layer
- Goal of cross-layer R.A. is
  optimal assignement of resource (power,time,frequency,codes) given channel state information and given certain constraints (e.g. QoS, max power).
- Two schools of thought:
  - Information theory
  - Queuing theory

Multiuser Information Theory

- Establishing multiuser capacity regions (for MAC and BC)
- Devising R.A. schemes allowing to reach *certain* points of the CR
- For instance, the sum capacity point.

Sum capacity of the multiuser MIMO downlink [Caire03][Vishwanath03][Yu03]:

$$C_{sum} = \max_{Q_i, \sum \mathrm{Tr}(Q_i) \leq P} \log_2 \| I + \sum_i H_i Q_i H_i^* \|$$

where H_i is channel matrix of user i, P is total TX power, Q_i is transmit covariance of user i.

sum capacity is achieved by Dirty Paper Coding [Costa].

Multiuser Queuing Theory

Consider a network with N users, exhibiting independent channels $H_i(t)$, with queue of lengths $u_i(t), i = 1..N$ at time t and bit arrival rate A_i.

- Establishing the multiple-access stability region (SR).
  - The set of arrival rates $\{A_i\}$ for which there exists a resource allocation policy that keep all N queues lengths $\{u_i(t)\}$ stable.
- Devising R.A. schemes allowing to reach *certain* point within the SR
- For instance, the optimal throughput under stability point. [Shakkottai][Yeh][Boche]

There are strong connections between capacity and stability region [Yeh 03]

Channel dependent scheduling

A few (of the many) critical issues

- Information theory advocates NON orthogonal access (unlike TDMA,CDMA) in MISO/MIMO case
- Multi-user resource allocation heavily relies of good feedback design
- Improving on fairness/performance trade-off
- Using multiple antennas in the right way (to avoid channel hardening)

On Feedback Design

Primary concerns

- Minimizing the load (hard to send full CSI of all users)
- Guaranteeing high quality of feedback (despite delays)
- Defining proper metrics for MIMO case (SNR not sufficient)

The multiple antenna case

- TDMA is optimal if BTS has one antenna only.
- If multple antennas at BTS, TDMA scheduling capacity is degraded [ISITA04]
- ⇒ Capacity achieving is TD+SDMA like (not TDMA like)!
- Feedback requirements can be heavy!

Solutions:

- Blind multi-user beamforming (Hassibi03)
- Selective multiuser diversity idea can used (extension to SDMA case)

MISO Broadcast Sum Capacity

With full feedback (N_t antennas at BTS, single antenna at mobiles):

$$C_{sum} \approx N_t \log \log N$$

Achieved by superposition coding

- Dirty Paper Coding QR decomposition [Caire, Shamai 00]
- Lattice Strategies [Erez, Shamai, Zamir 00], [Windpassinger et al. 04]
- Trellis Precoding [Yu, Cioffi 01]
- Vector Pertubation [Peel, Hochwald, Swindlehurst 03]
- Greedy ZF beamforming [Tu, Blum 03]

With no feedback: No gain!

Problem: What to do with a little feedback?

see [Sharif, Hassibi Subm. IT 03]

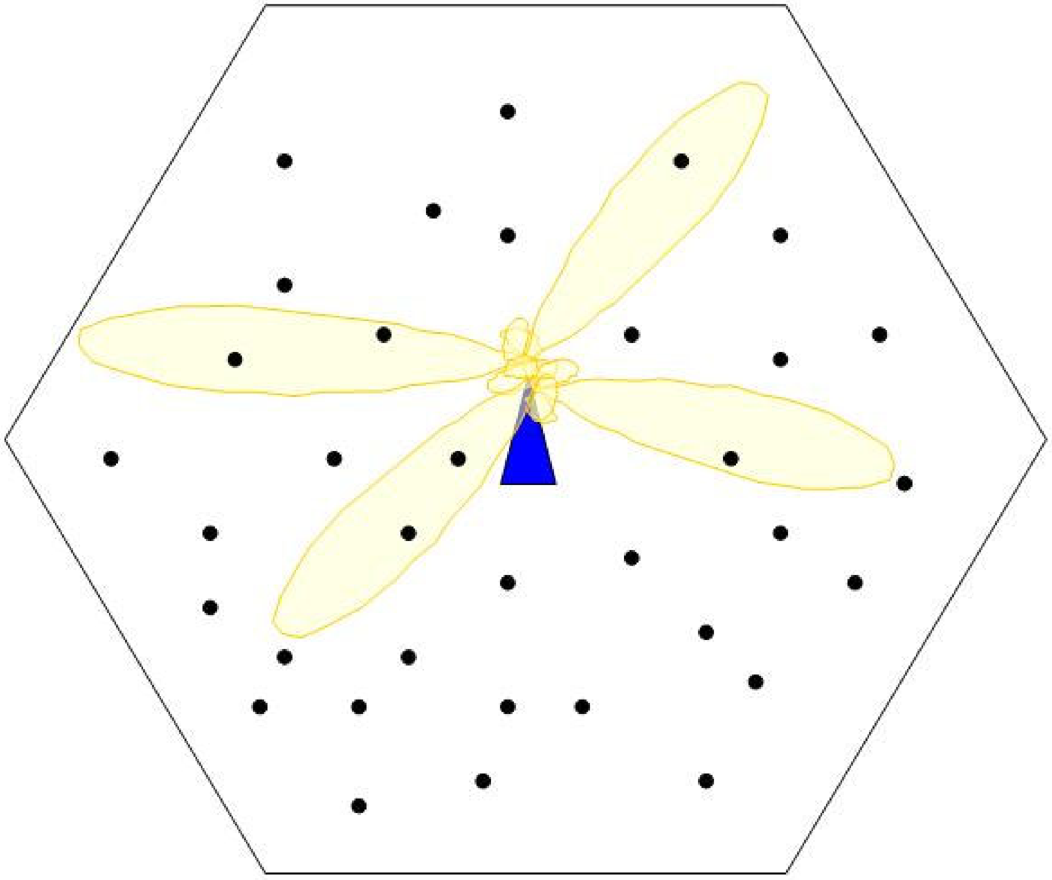
Opportunistic Unitary Beamforming

A low feedback, low complexity multi-user scheduler is obtained from:

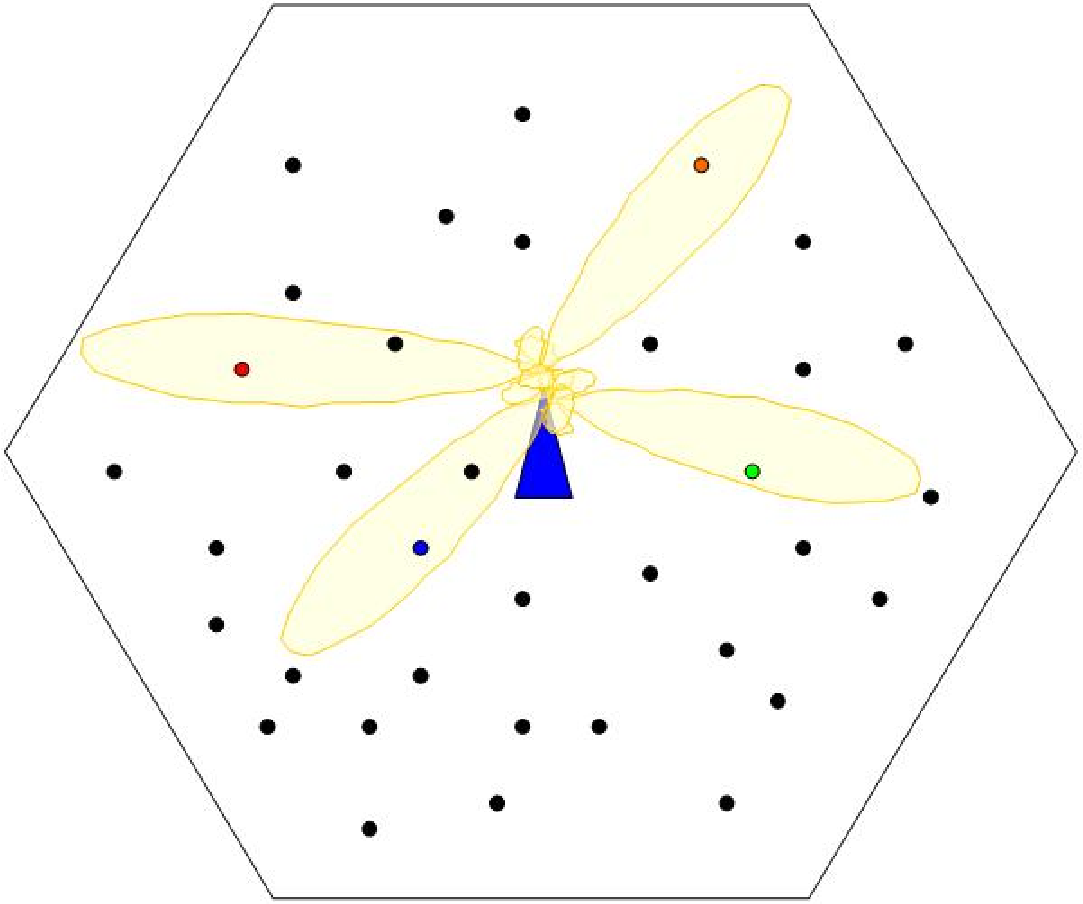
$$C_u = E\left\{\max_{Q,\mathbf{I}} SR(Q, H_{\mathbf{I}})\right\} \tag{1}$$

- Max done over the set of unitary matrices Q and scheduling vectors $\mathbf{I}$.
- SR is the rate summed over the users pointed by the scheduling vector, with combined channel $H_{\mathbf{I}}$

Opportunistic multi-user beamforming (1)



Opportunistic multi-user beamforming (2)



Memory less Opportunistic Beamforming [Sharif, Hassibi]

At time slot t the transmitted signal is

$$s(t) = \sum_{m=1}^{N_t} q_m(t) s_m(t) \tag{2}$$

Received signal is

$$y_k = \sum_{m=1}^{N_t} H_k q_m s_m + n_k, k = 1, \ldots, N \tag{3}$$

SINR calculation:

$$SINR_{k,m} = \frac{\left|H_k q_m\right|^2}{1/\rho_k + \sum_{j \neq m} \left|H_k q_j\right|^2} \tag{4}$$

Sum rate performance:

$$SR \approx E\left\{\sum_{m=1}^{N_t} \log_2(1 + \max_{1 \leq k \leq N} SINR_{k,m})\right\} \tag{5}$$

Memory less opportunistic BF performance

For very large number of users:

- F the sum rate converges to C_u
- The scaling laws of C_u and of C_{sum} (with N_t, N) are identical!

For sparse networks (low number of users):

- Severe degradation
- Blind beamformer does not reach C_u nor C_{sum}.

:-(WHAT TO DO?

Robust opportunistic beamforming for Sparse Networks

- Opportunistic beamforming with beam power control (BPC) [SPAWC 2005]
- Exploiting channel memory [ISIT 2005]

Opportunistic beamformer with beam power control

Key Ideas:

- Random BF Q might not reach 100% target in a sparse network.
- Major source of complexity/feedback is multiuser BF over *entire user set*.
- Q is good at helping detect linearly separable users, with good channel gains.
- Once user set is decided with Q, MU BF can be *refined* at the cost of modest complexity/feedback.
- Refinement can take form of recalculation of optimal BF, or power control over existing BF.

SIR-based beam power control

We assume the transmitter knows all the SIRs $\gamma_{k,m} = |H_k q_m|^2$ and noise level

$$\max_{\mathbf{p}} \sum_{k \in \mathbf{I}^{(r)}} \log\left(1 + \frac{P_m \gamma_{km}}{\sigma^2 + \sum_{j \neq m} P_j \gamma_{kj}}\right)$$

$$\text{subject to } \sum_{i=1}^{N_t} P_i = P$$

We propose

- closed-form solution for 2 antennas
- iterative solution for $N_t > 2$ antennas

Beam power control based on iterative waterfilling

For $n = 1, 2, \dots$ repeat

Step 1 Calculate $\lambda_k = \frac{\gamma_{km}}{\sigma^2 + \sum\limits_{j \neq m} P_j^{(n-1)} \gamma_{kj}}$, for $k \in \mathbf{I}^{(r)}$

Step 2 Let $\mathbf{p^{(n)}}$ be the power allocation solution of:

$max_{\mathbf{p}} \sum\limits_k \log(1 + P_m \lambda_k)$, subject to $\sum\limits_m P_m \leq P$

yielding $P_m^{(n)} = [\mu - 1/\lambda_k]_+$, with $\sum\limits_k [\mu - 1/\lambda_k]_+ = P$

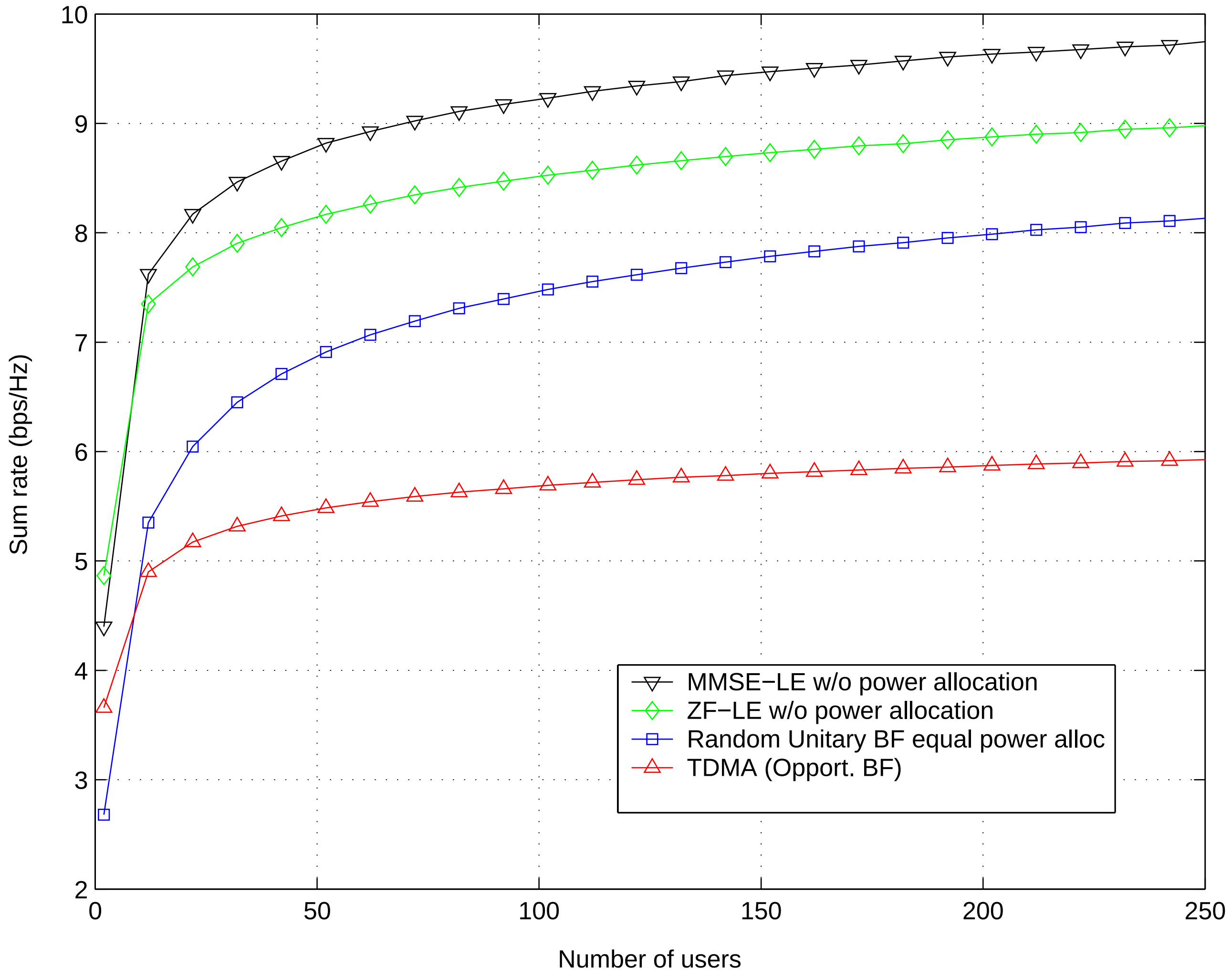
SINR-based beam power control

Here we only use the knowledge of $SINR_{k,m}$.

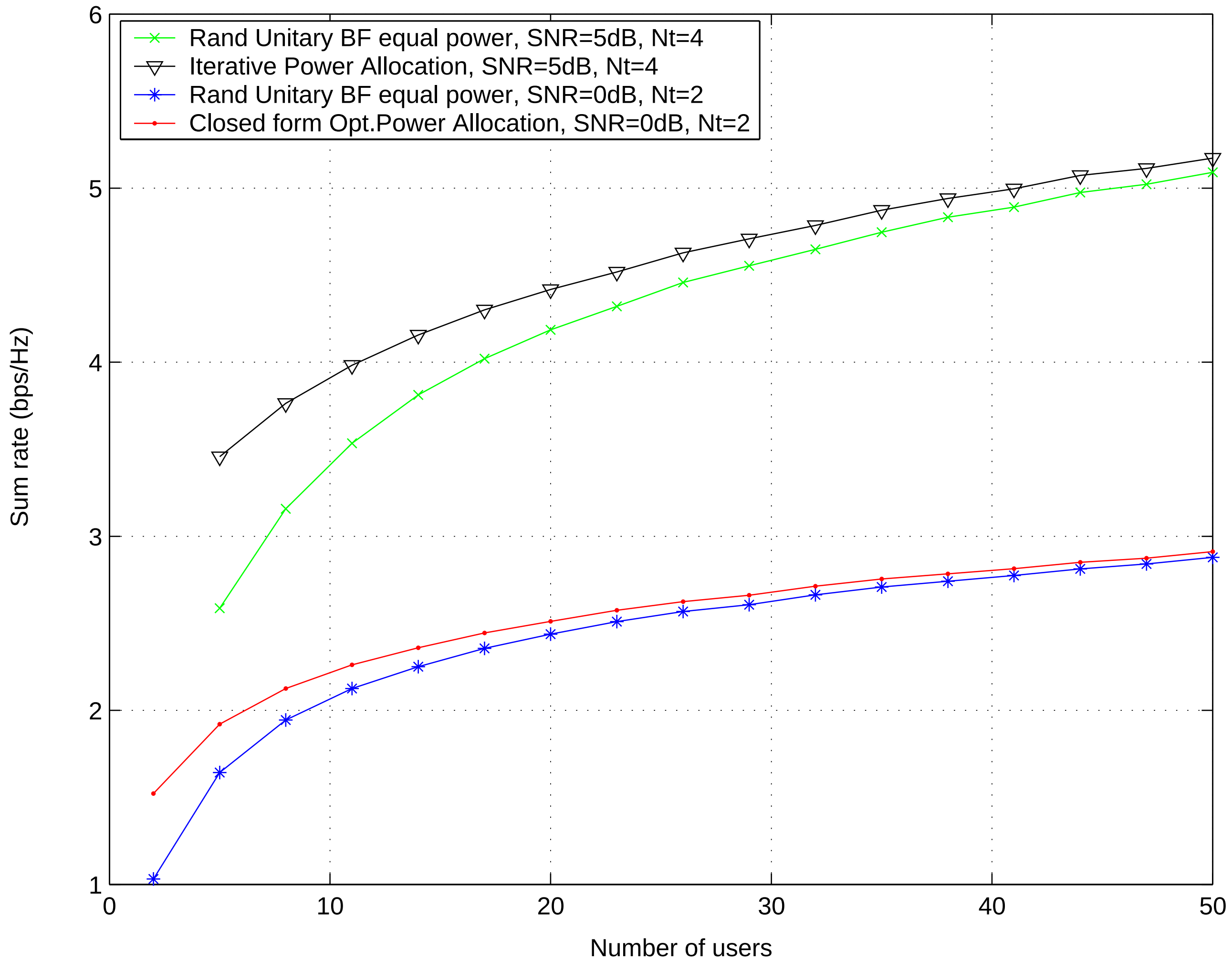
The Beam-on Beam-off (BOBO) algorithm is proposed:

For $N_t = 2$, we compute $\vartheta = SINR_{min}/SINR_{max}$. If ϑ is less than threshold, then worse beam is turned off (with same total power), otherwise is kept on .

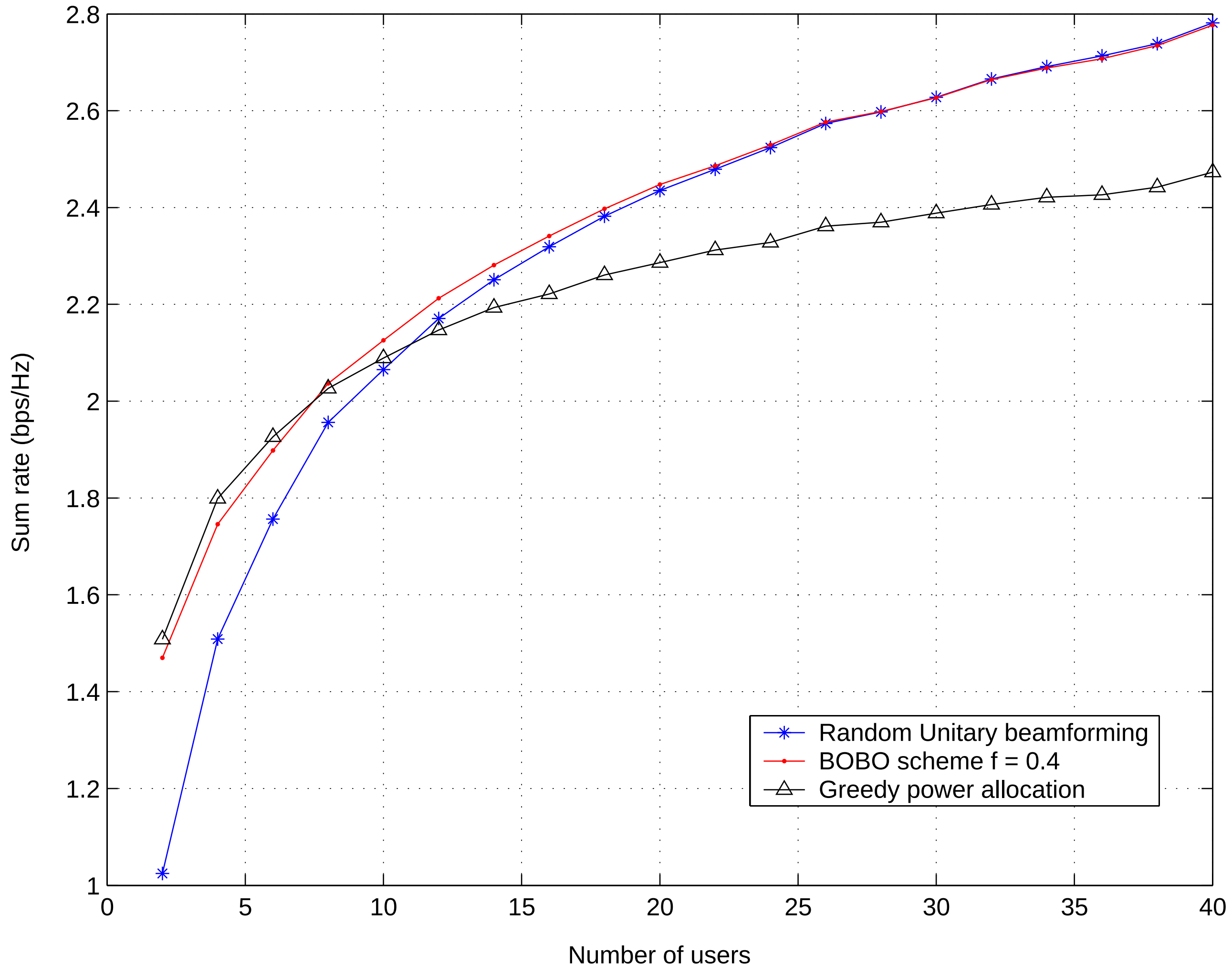
Simulated performance



Simulated performance



Simulated performance



Memory based opportunistic beamformer

Define set of ’preferred’ unitary beamformers

$$\mathbf{Q}_{pref} = [Q_1, Q_2, .., Q_s]$$

At each time slot t,

- Generate a new random Q_{rand},with sum rate $SR(Q_{rand})$
- Select from the Set of ’preferred’ matrices, Q_i*, such that $i* = arg\max_{Q_i} SR(Q_i)$
- If $(SR(Q_{i*}) > SR(Q_{rand}))$ use Q_{i*} , else use Q_{rand}

Second phase (update of the Set)

- If $(SR(Q_{rand}) > SR(Q_{imin}))$, replace Q_{imin} by Q_{rand}, where Q_{imin} is matrix with minimum sum rate ($i_{min} = arg\min_{Q_i} SR(Q_i)$)

Asymptotic performance [ISIT 05]

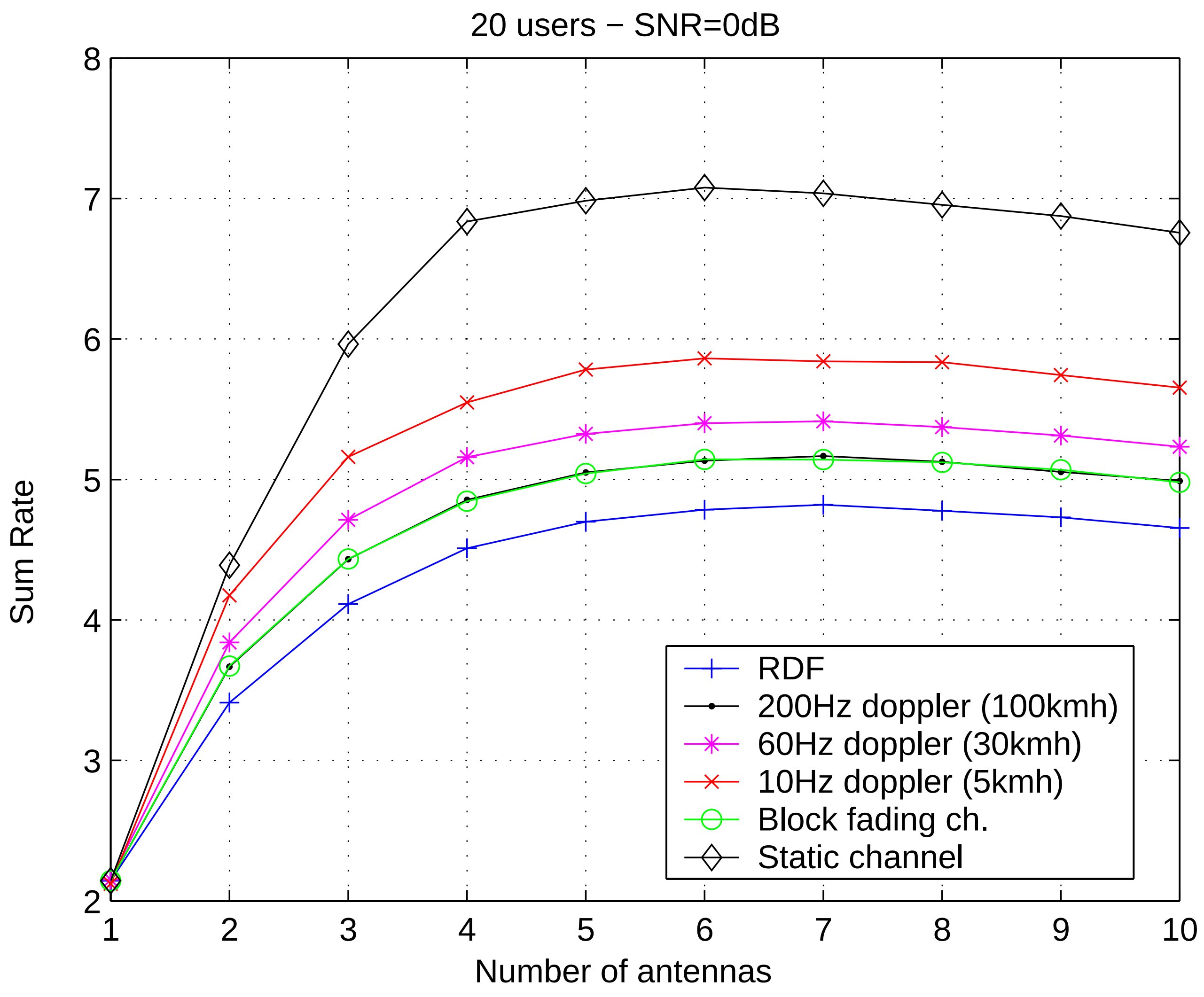
Channel Memory: $M = \frac{T_{coh}}{T_{slot}}$, where T_{coh} is coherence time, T_{slot} is slot duration

Proposition

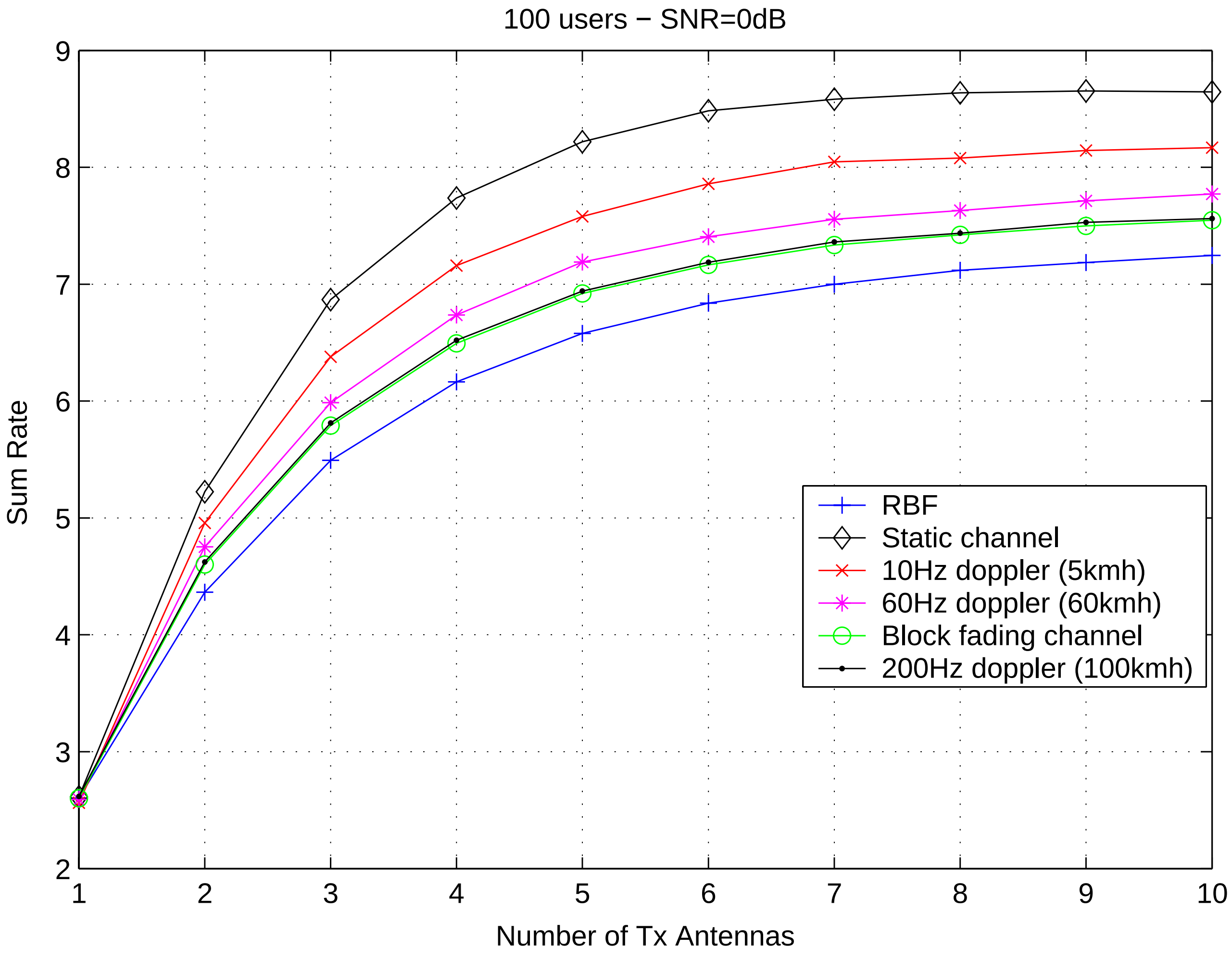
For $M \rightarrow \infty$, the 'best' beamforming matrix of the set, denoted Q_{i*}, converges to the optimal unitary beamforming matrix Q_{opt}.

Rate of convergence Can be analyzed theoretically (to be published)

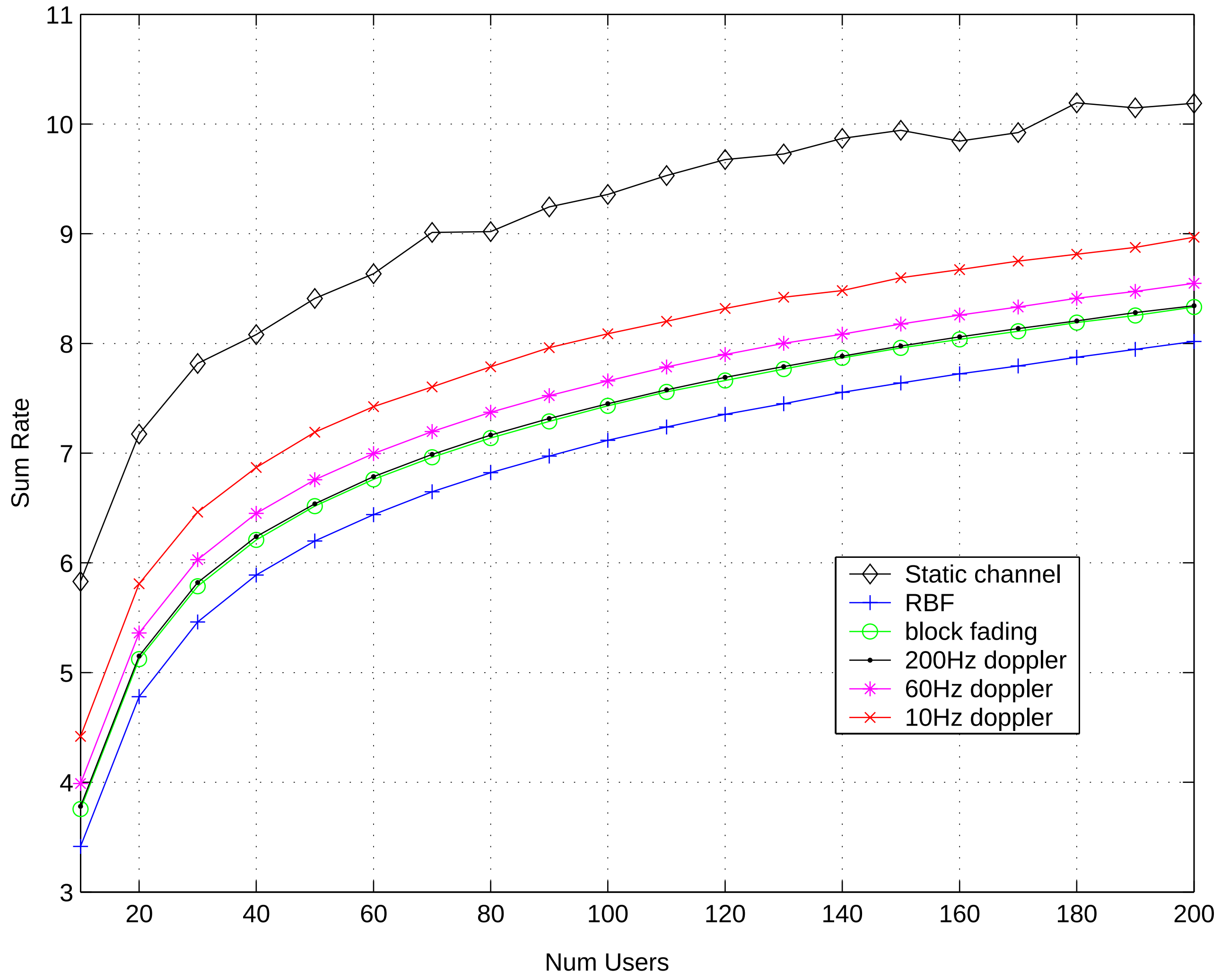
Simulated performance



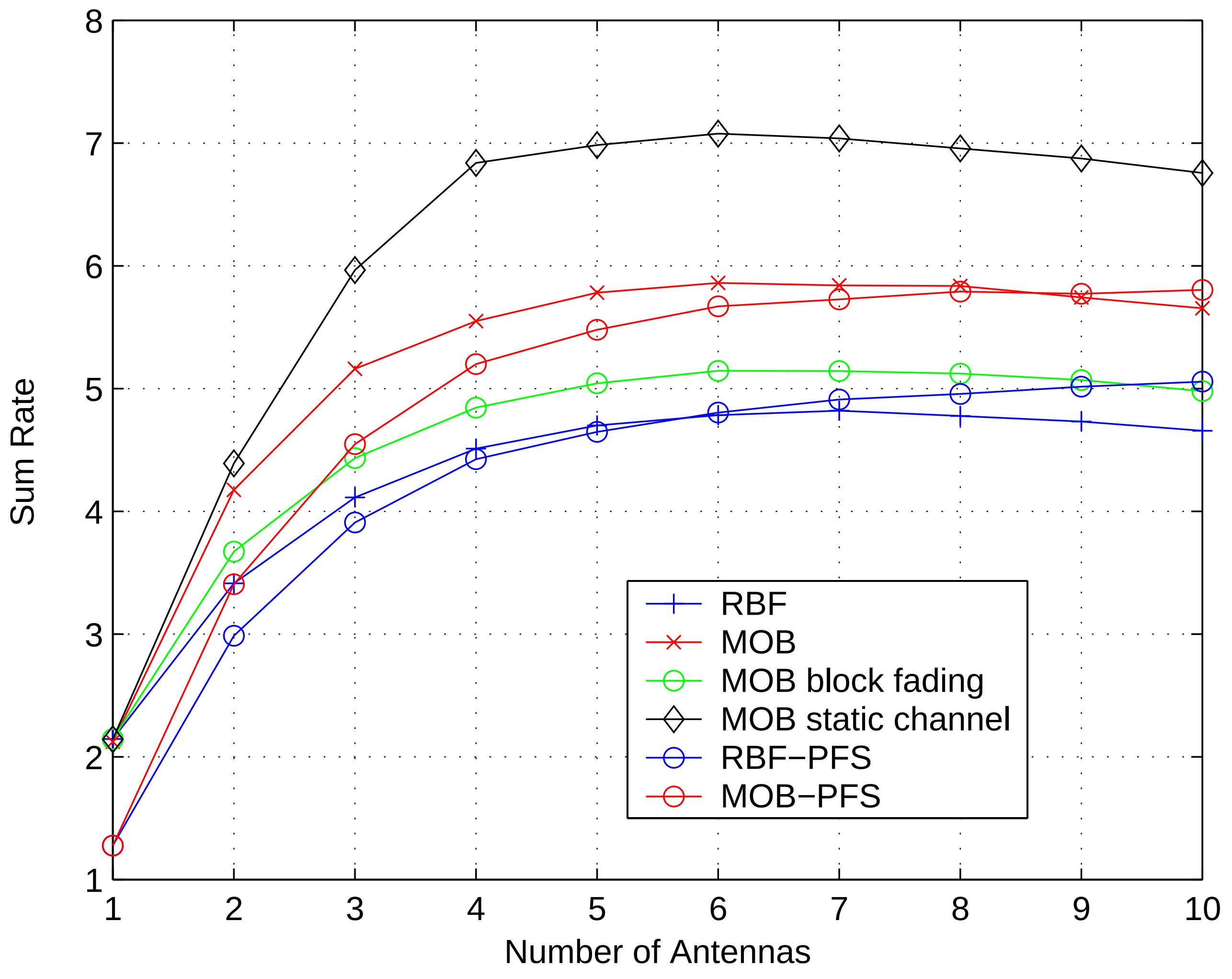
Simulated performance



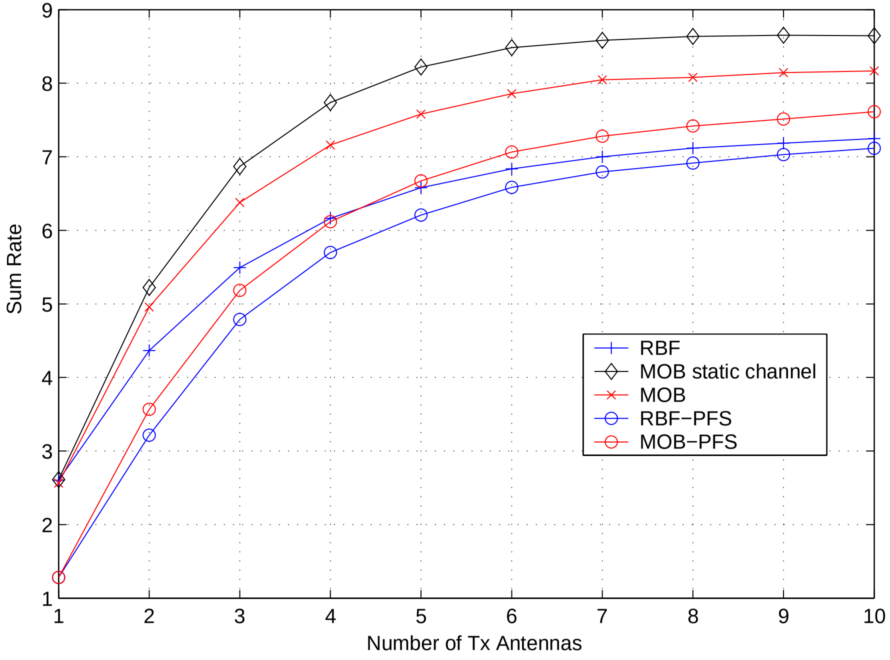
Simulated performance



Simulated performance with multiuser PFS



Simulated performance with multiuser PFS



Conclusions

- Opportunistic multiuser beamforming is promising but rich in open problems
- We showed low-feedback techniques for improving robustness based on
  - Power control (from fine to coarse depending on feedback)
  - memory
- We treated MISO case. Techniques may be extended and analyzed in multi-user *MIMO* case