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Department of
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Multicast beamforming and admission control for UMTS-LTE and 802.16e

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Parts of the talk

- Part I:
  - QoS + max-min fair multicast beamforming
- Part II:
  - Joint QoS multicast beamforming and admission control

Motivation

- Multicasting increasingly important (network TV, streaming media, software updates, network management)
- Increasingly over wireless for last hop
- PHY-layer multicasting – exploits wireless “broadcast advantage” + CSI-T [SidDavLuo:04-06]
- Complements packet-level multicasting → higher efficiency

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Motivation: E-MBMS / UMTS-LTE

- Evolved Multimedia Broadcast/Multicast Service (E-MBMS) in the context of 3GPP / UMTS-LTE
- Motorola Inc., "Long Term Evolution (LTE): A Technical Overview," Technical White Paper:
  http://business.motorola.com/experiencelte/pdf/LTE%20Technical%20Overview.pdf

2. Multicast Traffic Channel (MTCH)
(DL point-to-multipoint channel for transmission of MBMS data)

EVOLVED MULTICAST BROADCAST MULTIMEDIA SERVICES (E-MBMS)

There will be support for MBMS right from the first version of LTE specifications. However, specifications for E-MBMS are in early stages. Two important scenarios have been identified for E-MBMS: One is single-cell broadcast, and the second is MBMS Single Frequency Network (MBSFN).

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Prelude

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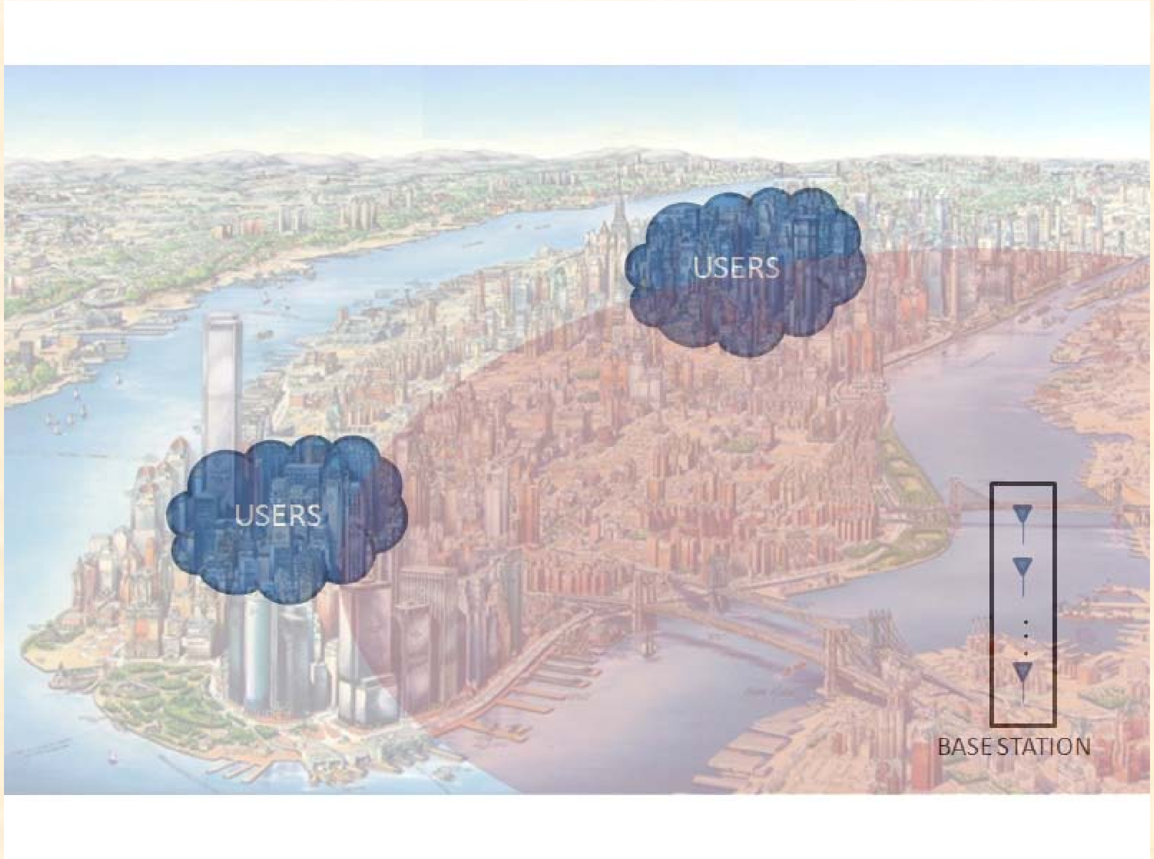
Broadcast



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Multicast beamforming

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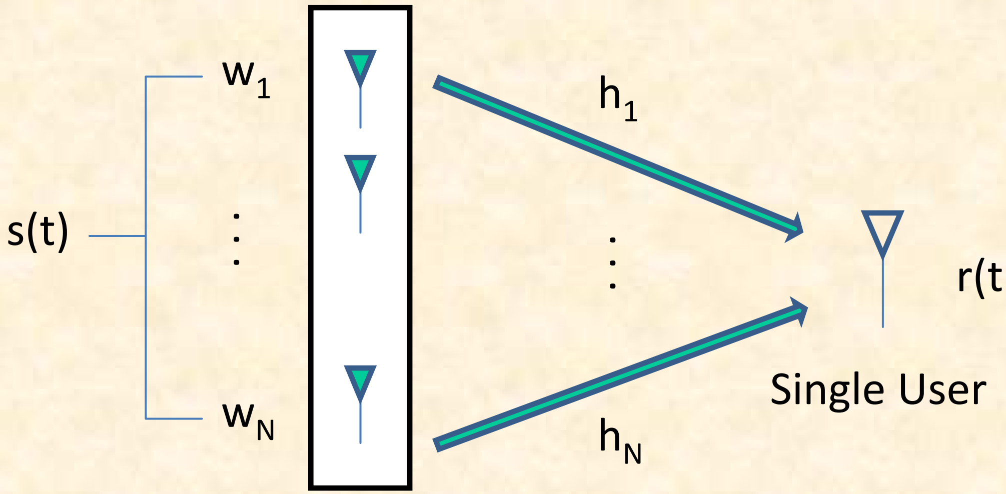
Beamforming



$r(t)=s(t)\cdot\sum w_i \cdot h_i$ + noise

Transmission power
$P = ||\mathbf{w}||^2$

Useful signal power
$P = |\mathbf{w}^T\mathbf{h}|^2$

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Part I: Transmit Beamforming for Multicasting

- Joint work w/ Tim Davidson, Tom Luo, Lefteris Karipidis
- Problem statement:
  - Transmit beamforming for multicasting to multiple co-channel groups
- QoS formulation
- NP-hardness
- Multicast power control
- Max-min-fair version
- The Vandermonde case
- Robust formulations

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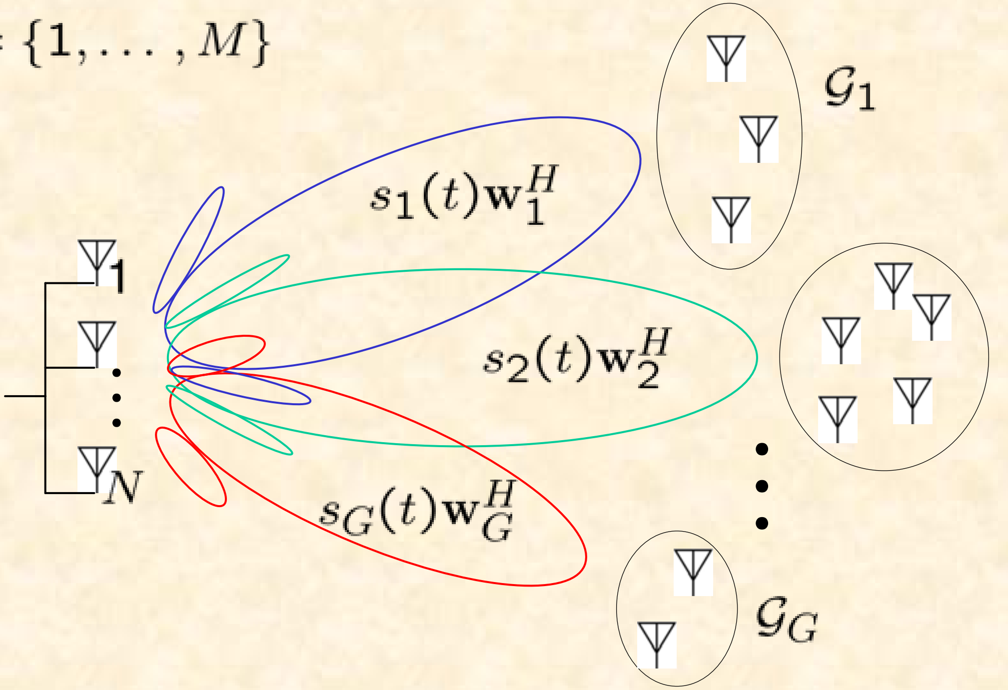
Problem Setup

- Downlink Transmission: BS has N antenna elements
- M single-antenna intended mobile receivers
- $1 \leq G \leq M$ co-channel multicast groups $\mathcal{G}_k$, $k \in \{1, \ldots, G\}$,

  $\mathcal{G}_k \cap \mathcal{G}_l = \emptyset, l \neq k, \cup_k \mathcal{G}_k = \{1, \ldots, M\}$
- $s_k(t)$: modulated signal,

  sent to group $\mathcal{G}_k$,

  $\sum_{k=1}^{G} s_k(t)\mathbf{w}_k^H$: Tx signal



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QoS formulation

- Optimal joint design of transmit beamformers (full CSI at Tx)
- QoS formulation: Minimize total Tx power, subject to meeting prescribed lower bounds on the received SINRs

$$\mathcal{I}: \quad \min_{\{\mathbf{w}_k \in \mathbb{C}^N\}_{k=1}^G} \sum_{k=1}^{G} \|\mathbf{w}_k\|_2^2$$

$$s.t.: \quad \frac{|\mathbf{w}_k^H \mathbf{h}_i|^2}{\sum_{l \neq k} |\mathbf{w}_l^H \mathbf{h}_i|^2 + \sigma_i^2} \geq \gamma_i, \ \forall i \in \mathcal{G}_k, \ \forall k \in \{1, \ldots, G\}$$

- Special cases:
  - multiuser downlink ($G = M$) is SOCP (Bengtsson & Ottersten);
  - broadcasting ($G = 1$) (Sidiropoulos, Davidson, Luo)
  - middle ground

Single multicast group (G=1)

$$\min_{\mathbf{w} \in \mathbb{C}^N} \|\mathbf{w}\|_2^2$$

$$s.t. : \frac{|\mathbf{w}^H \mathbf{h}_i|^2}{\sigma_i^2} \geq \gamma_i, \ \forall i$$

- Seems benign …
- … but non-convex, and in fact NP-hard!
- Contains *partition* (Sidiropoulos, Davidson, Luo ‘06)

Hence …

$\mathcal{I}:$

$$\min_{\{\mathbf{w}_k \in \mathbb{C}^N\}_{k=1}^{G}} \sum_{k=1}^{G} \|\mathbf{w}_k\|_2^2$$

$$s.t.: \quad \frac{|\mathbf{w}_k^H \mathbf{h}_i|^2}{\sum_{l \neq k} |\mathbf{w}_l^H \mathbf{h}_i|^2 + \sigma_i^2} \geq \gamma_i, \ \forall i \in \mathcal{G}_k, \ \forall k \in \{1, \dots, G\}$$

→ NP-hard in general ☹

Recasting to isolate non-convexity

- Equivalent reformulation for $\mathbf{Q}_i := \mathbf{h}_i \mathbf{h}_i^H$ and $\mathbf{W}_k := \mathbf{w}_k \mathbf{w}_k^H$

$\mathcal{R}$:

$$\min_{\{\mathbf{W}_k \in \mathbb{C}^{N\times N}\}_{k=1}^{G},\ \{s_i \in \mathbb{R}\}_{i=1}^{M}} \sum_{k=1}^{G} \text{trace}(\mathbf{W}_k)$$

$$\begin{aligned} \textit{s.t.}: \quad & \text{trace}(\mathbf{Q}_i \mathbf{W}_k) - \gamma_i \sum_{l \neq k} \text{trace}(\mathbf{Q}_i \mathbf{W}_l) - s_i = \gamma_i \sigma_i^2, \\ & \forall i \in \mathcal{G}_k,\ \forall k \in \{1, \ldots, G\}, \\ & s_i \geq 0,\ \forall i \in \{1, \ldots, M\}, \\ & \mathbf{W}_k \succeq \mathbf{0},\ \forall k \in \{1, \ldots, G\} \end{aligned}$$

$$\text{rank}(\mathbf{W}_k) = 1,\ \forall k \in \{1, \ldots, G\}$$

- $\mathcal{R}$ is *SDP* : lin. cost func. & M lin. eq., M nonneg., G psd constraints
- Lagrange bi-dual interpretation

Algorithm [KarSidLuo:TSP08]

- *Relaxation*: Solve the SDP Problem $\mathcal{R}$, denote solution $\{\mathbf{W}_k\}_{k=1}^{G}$
- *Randomization / Scaling Loop*: For each k, generate a vector in the span of $\sqrt{\mathbf{W}_k}$, using the Gaussian randomization technique, and solve multicast power control problem (LP) for given configuration; If feasible, then feasible solution for original problem
- Repeat, select best configuration (minimum Tx power)
- If $\text{rank}(\mathbf{W}_k) = 1, \ \forall k, \ \Rightarrow$ Problem $\mathcal{R}$ *equiv* to $\mathcal{I}$
- Quality of approximate solution: $\dfrac{\min(\sum_{k=1}^{G} \beta_k p_k)}{\sum_{k=1}^{G} \text{trace}(\mathbf{X}_k)}$

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Multi-group Multicast Power Control

- If Problem $\mathcal{I}$ feasible $\Rightarrow$ Problem $\mathcal{R}$ feasible (converse, not true in general)
- Solution blocks of relaxed problem, not rank-one in general
- *Randomization*: generate candidate beamforming vectors
- Ensure constraints of Problem $\mathcal{I}$ $\Rightarrow$ solve $\mathcal{MGPC}$
- LP ☺

$$a_{k,i} := |\mathbf{w}_k^H \mathbf{h}_i|^2$$

$$\beta_k := \|\mathbf{w}_k\|_2^2$$

p_k power boost factor for multicast group k

$\mathcal{MGPC}$:

$$\min_{\{p_k \in \mathbb{R}\}_{k=1}^G} \sum_{k=1}^{G} \beta_k p_k$$

s.t. :

$$\frac{p_k a_{k,i}}{\sum_{l \neq k} p_l a_{l,i} + \sigma_i^2} \geq c_i,$$

$$\forall i \in \mathcal{G}_k, \ \forall k \in \{1, \ldots, G\},$$

$$p_k \geq 0, \ \forall k \in \{1, \ldots, G\}.$$

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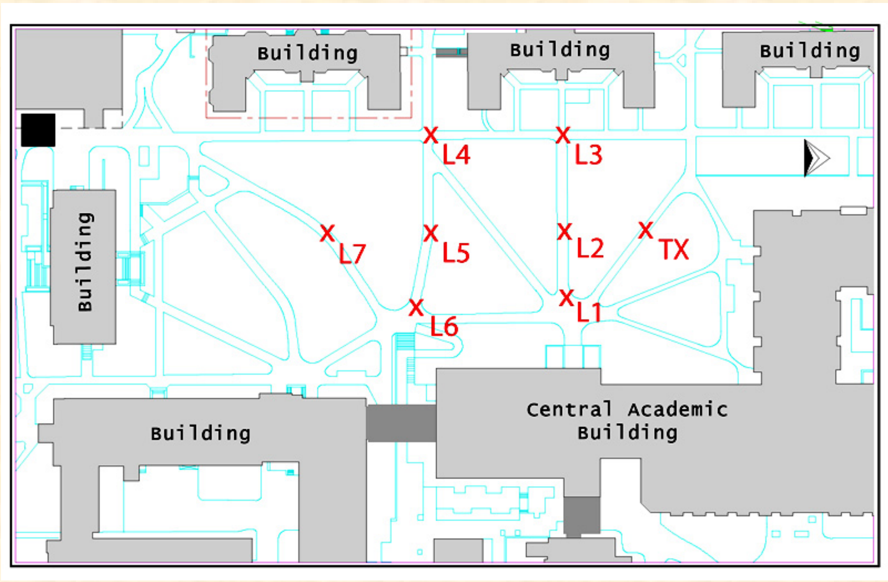
Experimental results



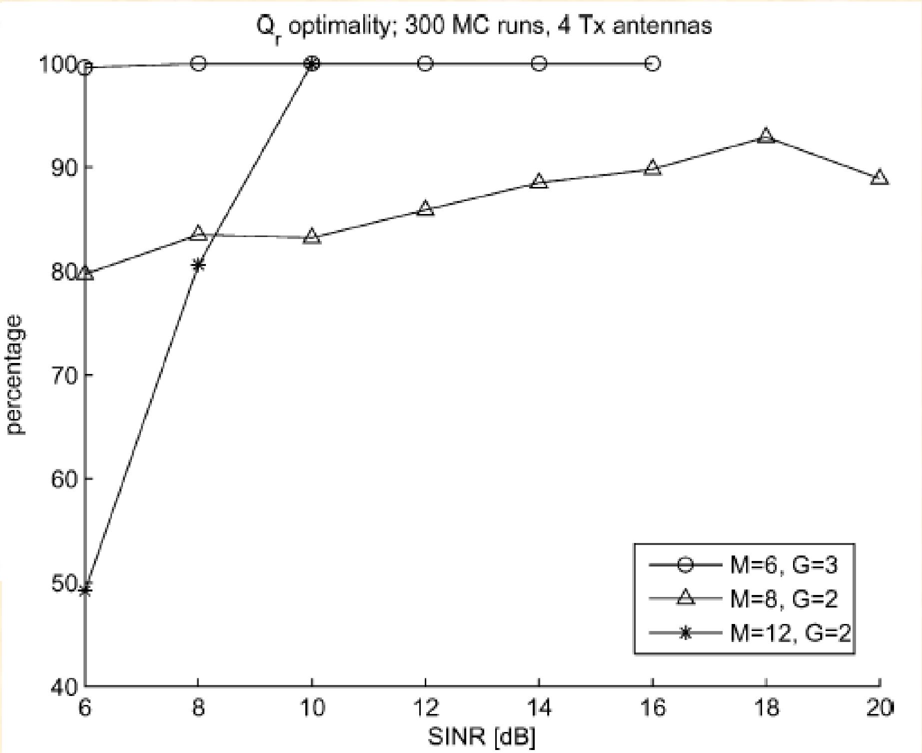


Fig. 4. Q_r optimality; 300 MC runs, 4 Tx antennas.

http://www.ece.ualberta.ca/~mimo/

Often optimal, despite relaxation;

Not far from optimal (3-4dB) in most cases

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Analytical Approximation Performance Guarantees

Result (LuoSidTseZha SIOPT): Let v_o denote the optimum value of the single-group multicast beamforming problem (which is NP-hard), and v_r denote the optimum value of the associated SDR. Then, in the complex case,

$$v_r \leq v_o \leq 8Mv_r$$

(M is the total number of subscribing receivers) and Gaussian randomization with $\sim$ 50 samples generates a feasible approximate solution that satisfies this bound with very high probability.

- (Usually pessimistic: $c << 8M$ often the case in practice)

Max-min-fair version

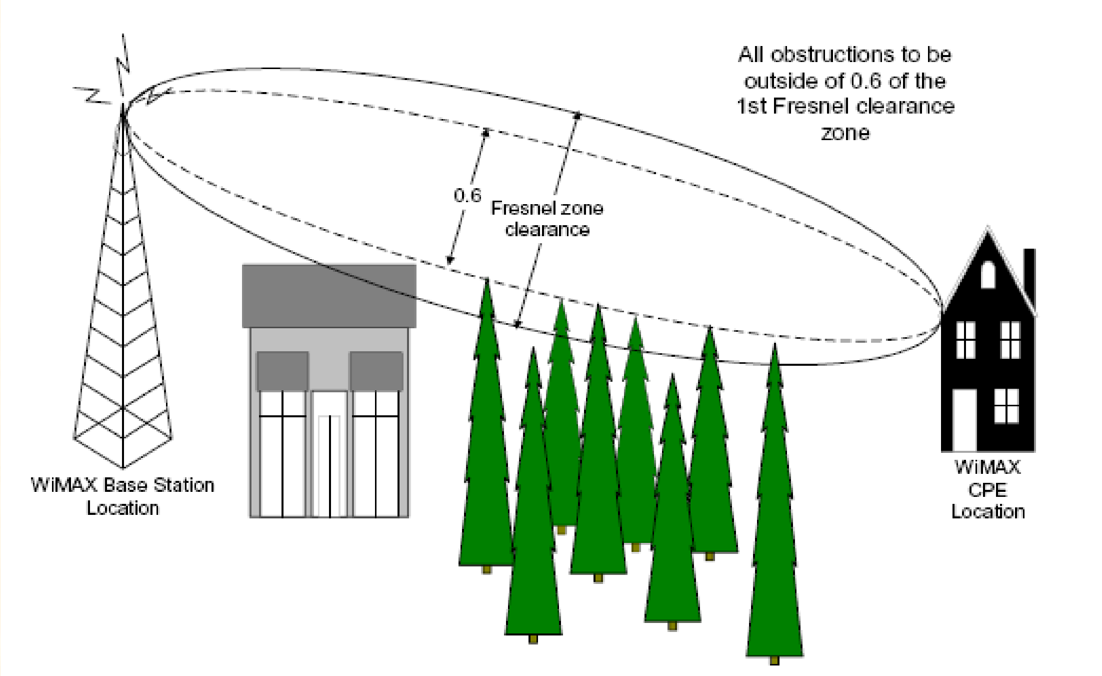
$\mathcal{F}:$

$$\max_{\{\mathbf{w}_k \in \mathbb{C}^N\}_{k=1}^G} \min_{k \in \{1,\ldots,G\}} \min_{i \in \mathcal{G}_k} \frac{|\mathbf{w}_k^H \mathbf{h}_i|^2}{\sum_{\ell \neq k} |\mathbf{w}_\ell^H \mathbf{h}_i|^2 + \sigma_i^2}$$

$$\text{s.t.}: \quad \sum_{k=1}^{G} \|\mathbf{w}_k\|_2^2 \leq P.$$

Exact Globally Optimal Solution in the Vandermonde Case (1)

- Motivation: fixed wireless LoS communications, e.g., WiMAX



Exact Globally Optimal Solution in the Vandermonde Case (2)

- For ULA, far-field / LoS (or, single-path) scenario
  → Vandermonde channel vectors $\mathbf{h}_i = [1 \; e^{j\theta_i} \; e^{j2\theta_i} \; \dots \; e^{j(N-1)\theta_i}]^T$
- Numerical observation: SDR consistently rank-1!
  Suggests: Problem not NP-hard, in fact convex in this case?
- Rx signal power at user *i* from beam *k* : $\left|\mathbf{w}_k^H \mathbf{h}_i\right|^2 = \sum_{\ell=-(N-1)}^{N-1} r_k(\ell) e^{j\theta_i \ell}$
- Autocorrelation fun.: $r_k(\ell) = \sum_{m=1}^{N-\ell} w_k(m) w_k^*(m+\ell), \quad 0 < \ell \leq N-1$
- Conjugate-symmetric about the origin: $r_k^*(-\ell) = r_k(\ell)$

Exact Globally Optimal Solution in the Vandermonde Case (3)

- $\mathbf{r}_k := [r_k(-N+1), \cdots, r_k(-1), r_k(0), r_k(1), \cdots, r_k(N+1)]^T,$

  $\mathbf{f}_i := [e^{-j\theta_i(N-1)}, \cdots, e^{-j\theta_i}, 1, e^{j\theta_i}, \cdots, e^{j\theta_i(N-1)}]^T$

  $\left|\mathbf{w}_k^H \mathbf{h}_i\right|^2 = \mathbf{f}_i^T \mathbf{r}_k \qquad r_k(0) = \mathbf{r}_k(N) = \sum_{m=1}^{N} w_k(m) w_k^*(m) = ||\mathbf{w}_k||_2^2$
- Equivalent reformulation:

$$\min_{\{\mathbf{r}_k\}_{k=1}^G} \sum_{k=1}^{G} \mathbf{r}_k(N)$$

$$\text{s.t.}: \quad \mathbf{f}_i^T \mathbf{r}_k \geq \gamma_i \sum_{\ell \neq k} \mathbf{f}_i^T \mathbf{r}_\ell + \gamma_i \sigma_i^2, \; \forall i \in \mathcal{G}_k, \; \forall k \in \{1, \ldots, G\},$$

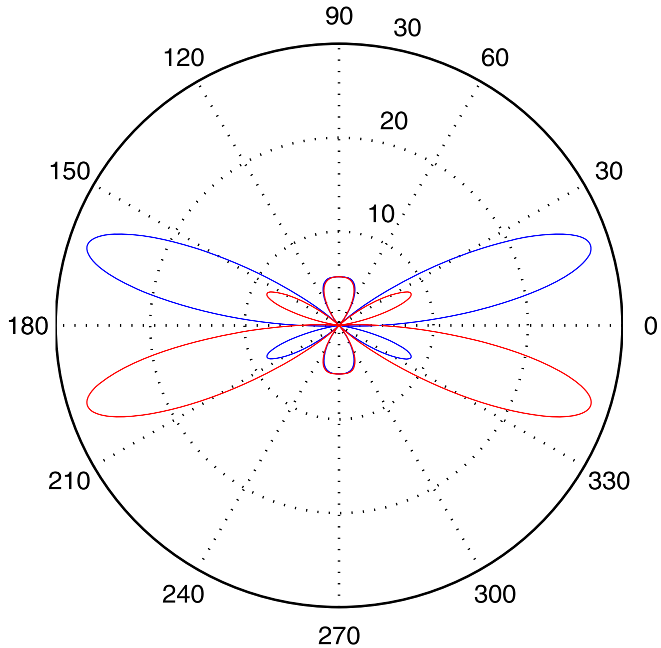
$$\mathbf{r}_k : \text{autocorrelation vector}, \; \forall k \in \{1, \ldots, G\}$$

- Autocorrelation constraints equivalent to LMIs [AlkVan02] → SDP
- ACS → spectral factorization → optimal beamvectors

Example

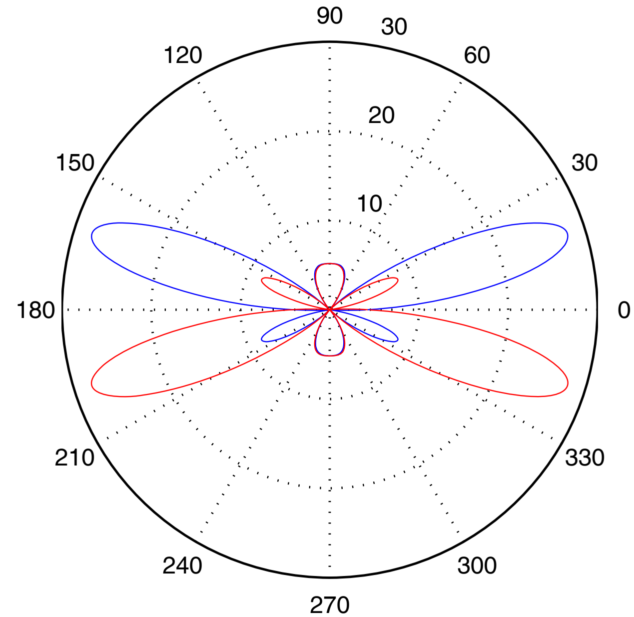
- $N = 4, \sigma_i^2 = \sigma^2 = 1, \gamma_i = \gamma = 10\text{dB}$

Algorithm 1: SDR + Randomization + MGPC



24 users in 2 groups, spaced 10 deg apart

Algorithm 2: SDP + Spectral factorization



24 users in 2 groups, spaced 10 deg apart

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Robust Multicast Beamforming for imperfect CSI

- Perfect CSI: $\tilde{\mathbf{h}}_i := \mathbf{h}_i / \sqrt{\gamma_i \sigma_i^2}$

$$\mathcal{ONRB}: \quad \min_{\mathbf{w} \in \mathbb{C}^N} \|\mathbf{w}\|_2^2 \quad s.t.: \quad |\mathbf{w}^H \tilde{\mathbf{h}}_i|^2 \geq 1, \quad \forall\, i \in \{1, \ldots, M\}.$$

- Robust version for imperfect CSI:

$$\mathcal{RB}: \quad \min_{\mathbf{w} \in \mathbb{C}^N} \|\mathbf{w}\|_2^2 \quad s.t.: \quad |\mathbf{w}^H \tilde{\mathbf{h}}_i|^2 \geq 1,\ \forall\, \tilde{\mathbf{h}}_i \in \mathsf{B}_\epsilon(\bar{\mathbf{h}}_i),\ \forall\, i \in \{1, \ldots, M\}.$$

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Robust Multicast Beamforming

→ Result: Let $\mathbf{w}'$ be an exact solution of $\mathcal{RB}$.
Then $\mathbf{w}'/(1+\epsilon||\mathbf{w}'||)$ is an exact solution of ONRB.
Conversely, if $\mathbf{w}_o$ is an exact solution of ONRB,
then $\mathbf{w}_o/(1-\epsilon||\mathbf{w}_o||)$ is an exact solution of $\mathcal{RB}$.

Multicast Beamforming: Recap

- Multi-group multicast transmit beamforming under SINR constraints is NP-hard in general [KarSidLuo,SidDavLuo]
- Good & efficient approximation algorithms via SDR
- In the important special case of Vandermonde steering vectors it is in fact SDP – can be solved exactly & efficiently!
- For general steering vectors, exact solutions of the robust and non-robust versions of the single-group (broadcast) problem related via simple one-to-one scaling transformation!
- For Vandermonde steering vectors, robust version of the multi-group multicast problem is convex as well! [KarSidLuo]

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Part II: Joint Multicast Beamforming and Admission Control

- Joint work w/ Vivi Matskani, Tom Luo, Leandros Tassiulas
- Inter-group interference and/or power constraint → infeasibility → admission control
- Joint multicast beamforming and admission control: MDR
- Single multicast group: important special case, in view of UMTS-LTE / E-MBMS
- MDR works for multiple co-channel multicast groups; will focus on single group for brevity
- In this case, infeasibility arises due to Tx power constraint

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Infeasibility and Admission Control

- Often *infeasible* $\rightarrow$ *admission control*
- Goal: max # users served @ pre-specified SNR levels for a given P.
- Two stages:

$$S_o = \text{argmax}_{S \subseteq \mathcal{U}, \{\mathbf{w} \in \mathbb{C}^N\}} |S|$$
$$\text{subject to}: \|\mathbf{w}\|_2^2 \leq P,$$
$$\frac{|\mathbf{w}^H \mathbf{h}_i|^2}{\sigma_i^2} \geq c_i, \forall i \in S,$$

$\rightarrow$

$$\min_{\mathbf{w} \in \mathbb{C}^N} \|\mathbf{w}\|_2^2$$
$$\frac{|\mathbf{w}^H \mathbf{h}_i|^2}{\sigma_i^2} \geq c_i, \ \forall i \in S_o.$$

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Single-stage reformulation

$$\min_{\mathbf{w}\in\mathbb{C}^N,\{s_i\in\{-1,+1\}\}_{i\in\mathcal{U}}} \epsilon\|\mathbf{w}\|_2^2+(1-\epsilon)\sum_{i\in\mathcal{U}}(s_i+1)^2$$

$$\text{subject to}: \|\mathbf{w}\|_2^2\leq P,$$

$$\frac{|\mathbf{w}^H\mathbf{h}_i|^2+\delta^{-1}(s_i+1)^2}{\sigma_i^2}\geq c_i,\ \forall i\in\mathcal{U}.$$

Result: (Cf. [MatSidLuoTas:07-08]) For $\delta\leq\min_{i\in\mathcal{U}}\frac{4c_i^{-1}}{\sigma_i^2}$ and $\epsilon<\frac{1}{P/4+1}$, the reformulated problem is always feasible, and its solution simultaneously maximizes the number of users served and minimizes the power required to serve them.

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Getting 'close' to a convex problem

$\mathbf{W} := \mathbf{w}\mathbf{w}^H$, $\mathbf{S}_i := \mathbf{s}_i\mathbf{s}_i^T$, where $\mathbf{s}_i := [s_i \quad 1]^T$, and $\mathbf{H}_i := \mathbf{h}_i\mathbf{h}_i^H$; rewrite as

$$\min_{\mathbf{W}\in\mathbb{C}^{N\times N},\{\mathbf{S}_i\in\mathbb{R}^{2\times 2}\}_{i\in\mathcal{U}}} \epsilon\,\mathrm{Tr}(\mathbf{W})+(1-\epsilon)\sum_{i\in\mathcal{U}}\mathrm{Tr}(\mathbf{1}_{2\times 2}\mathbf{S}_i)$$

$$\text{subject to}: \mathrm{Tr}(\mathbf{W}) \le P,$$

$$\frac{\mathrm{Tr}(\mathbf{H}_i\mathbf{W}) + \delta^{-1}\mathrm{Tr}(\mathbf{1}_{2\times 2}\mathbf{S}_i)}{\sigma_i^2} \ge c_i,\ \forall i \in \mathcal{U},$$

$$\mathbf{W} \ge 0, \mathrm{rank}(\mathbf{W}) = 1,$$

$$\mathbf{S}_i \ge 0, \mathrm{rank}(\mathbf{S}_i) = 1, \mathbf{S}_i(1,1) = \mathbf{S}_i(2,2) = 1,\ \forall i \in \mathcal{U}.$$

Semidefinite Relaxation (SDR)

Drop rank-1 constraints → convex

$$\min_{\mathbf{W}\in\mathbb{C}^{N\times N},\{\mathbf{S}_i\in\mathbb{R}^{2\times 2}\}_{i\in\mathcal{U}}} \epsilon\mathrm{Tr}(\mathbf{W})+(1-\epsilon)\sum_{i\in\mathcal{U}}\mathrm{Tr}(\mathbf{1}_{2\times 2}\mathbf{S}_i)$$

$$\text{subject to}: \mathrm{Tr}(\mathbf{W}) \leq P,$$

$$\frac{\mathrm{Tr}(\mathbf{H}_i\mathbf{W}) + \delta^{-1}\mathrm{Tr}(\mathbf{1}_{2\times 2}\mathbf{S}_i)}{\sigma_i^2} \geq c_i, \ \forall i \in \mathcal{U},$$

$$\mathbf{W} \geq 0,$$

$$\mathbf{S}_i \geq 0, \mathbf{S}_i(1,1) = \mathbf{S}_i(2,2) = 1, \ \forall i \in \mathcal{U}.$$

MDR- Algorithm

1. $\mathcal{U} \leftarrow \{1, ..., K\}$
2. Solve the relaxed problem and let $\check{\mathbf{W}}$ denote the resulting transmit covariance matrix
3. $\check{\mathbf{w}}$ = principal component of $\check{\mathbf{W}}$, scaled to power $Tr(\check{\mathbf{W}})$.
4. For each $i \in \mathcal{U}$, check whether

$$\frac{|\check{\mathbf{w}}^H \mathbf{h}_i|^2}{\sigma_i^2} \geq c_i.$$

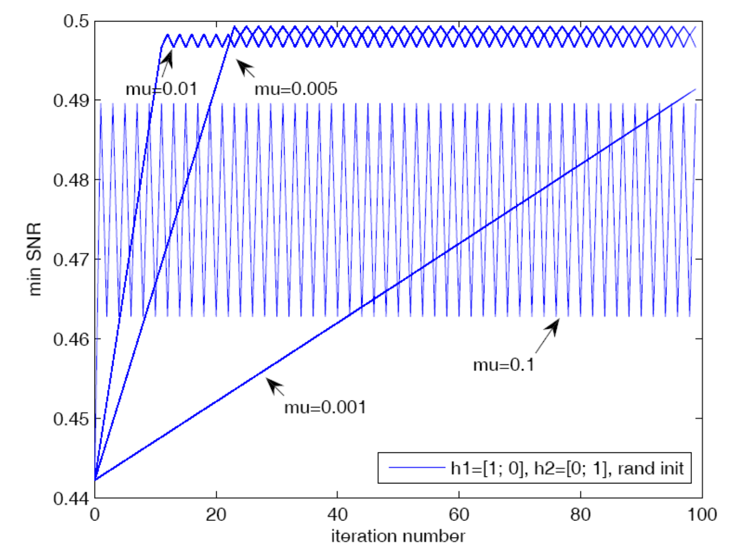
If true for all $i \in \mathcal{U}$, stop (a feasible solution has been found); else pick the user with largest gap to its target SNR, remove from $\mathcal{U}$ and go to step 2.

Lozano's Algorithm

1. Init: $\mathbf{w} = [1\ 0\ \cdots 0]^T$
2. Compute $SNR_i(t-1) = P\mathbf{w}_{t-1}^H \mathbf{H}_i \mathbf{w}_{t-1},\ \forall i \in \mathcal{U}$
3. Sort $SNR_i(t-1),\ \forall i \in \mathcal{U}$.
4. Drop a fixed proportion of users with lowest attained $SNRs$.
5. Find weakest link among remaining ones ($\rightarrow k$)
6. Take step in its direction: $\mathbf{w}_t = \mathbf{w}_{t-1} + \mu \mathbf{H}_k \mathbf{w}_{t-1}$; then $\mathbf{w}_t = \mathbf{w}_t / \|\mathbf{w}_t\|_2$
7. Repeat until no significant change in minimum SNR.

Issues w/ Lozano's algorithm

- Simple algorithm, but intricate convergence behavior
- No guidelines for choosing μ
- We show via toy counter-example:
  - May shut-off users completely (no chance of admission) – fairness issue
  - May not converge
  - Can exhibit limit cycle behavior, even for very small μ



Example of limit cycle behavior of Lozano's algorithm. $N = 2$ Tx, $K = 2$ users, $\mathbf{h}_1 = [1\ 0]^T$, $\mathbf{h}_1 = [0\ 1]^T$ $\sigma_1 = \sigma_2 = P = 1$. Random initialization, $\mu = 0.1$.

Proposed improvement - I: LLI

- [Lopez:2004]: Max average SNR beamformer ←→ pricipal component:

$$\mathbf{H} := [\mathbf{h}_1, \cdots, \mathbf{h}_K] \ (N \times K);$$

$$[\mathbf{U}, \mathbf{S}, \mathbf{V}] = \mathsf{svd}(\mathbf{H}^H); \mathbf{w}_0 = \mathbf{V}(:, 1);$$

- Use this for initialization
- PC can be tracked, e.g., using power method → overall solution remains simple, adaptive
- **LLI**: Lozano with Lopez Initialization

Proposed improvement - II: dLLI

- Simple and effective way to suppress limit cycle behavior: damp μ according to a predefined back-off schedule. This should be balanced against our primary objective, which is to find a good solution

- The weight update of Lozano's algorithm can be interpreted as taking a step in the direction of the *local* subgradient of $\min_{i \in \mathcal{A}_t} SNR_i(t-1)$, where the minimum is taken over the currently active user set $\mathcal{A}_t$.

Proposed improvement - II: dLLI

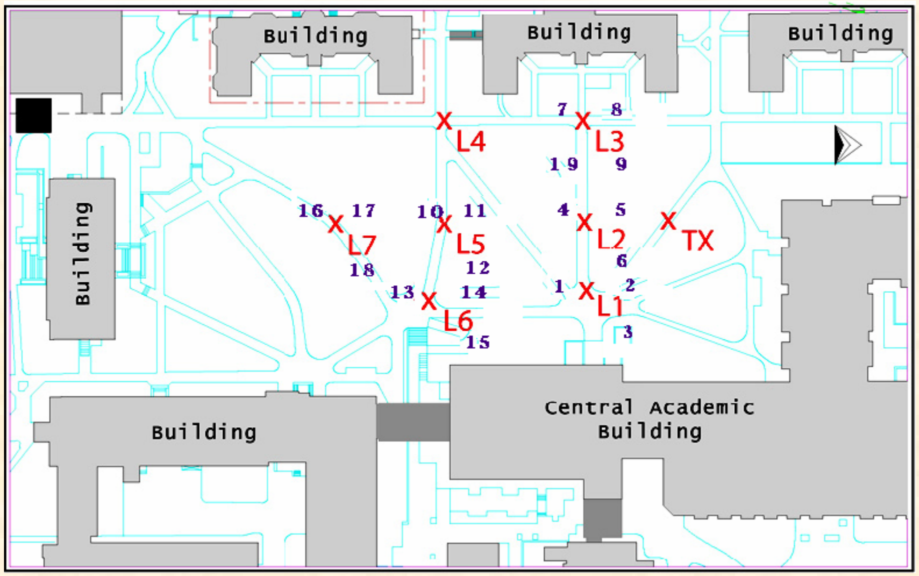
- There are two difficulties here: this is not a subgradient in the usual sense, because it is only a local, not a global under-estimator of $\min_{i \in \mathcal{A}_t} SNR_i(t-1)$; and $\mathcal{A}_t$ can change as iterations progress. These difficulties arise because we are dealing with a non-convex and NP-hard problem.

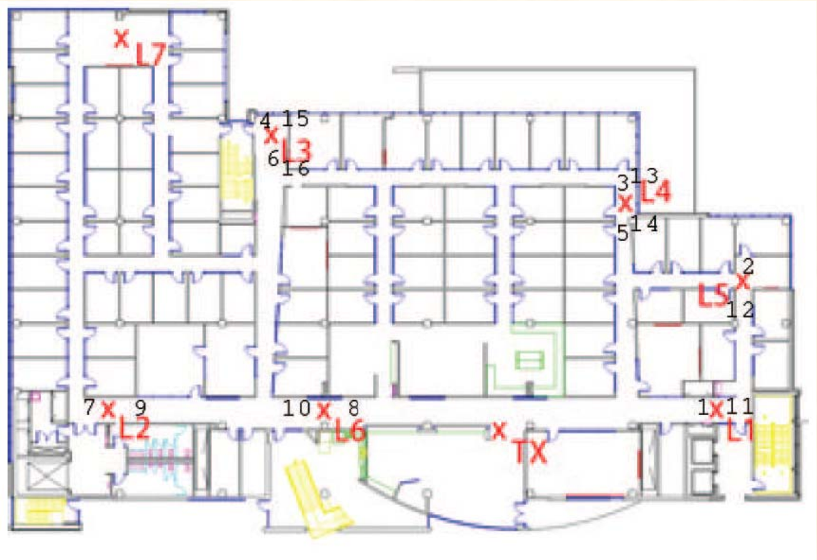
- dLLI: $\mu_t = \frac{\mu_{t-1}}{t/10}$ if t mod $10 = 0$, else $\mu_t = \mu_{t-1}$ (back-off every 10 iterations).

Fair comparison

- MDR fixes min SNR, attempts to optimize coverage
- Lozano and (d)LLI fix coverage, attempt to optimize min SNR
- Proper comparison: min SNR vs. coverage operating characteristic (similar to ROC)
- Using measured channel data
- Benchmark: enumeration over all subsets; for each use SDR
- Per-subset problem is still NP-hard, but
  - enumeration+SDR (‘ENUM’) yields upper bound on min SNR (attainable performance)
  - when SDR returns rank-1 solution for maximal subset, it is overall optimal; this happens in vast majority of cases considered → ENUM yields tight upper bound

Measured channel data





http://www.ece.ualberta.ca/~mimo/

N = 4 Tx antennas

Left: Outdoor

Right: Indoor

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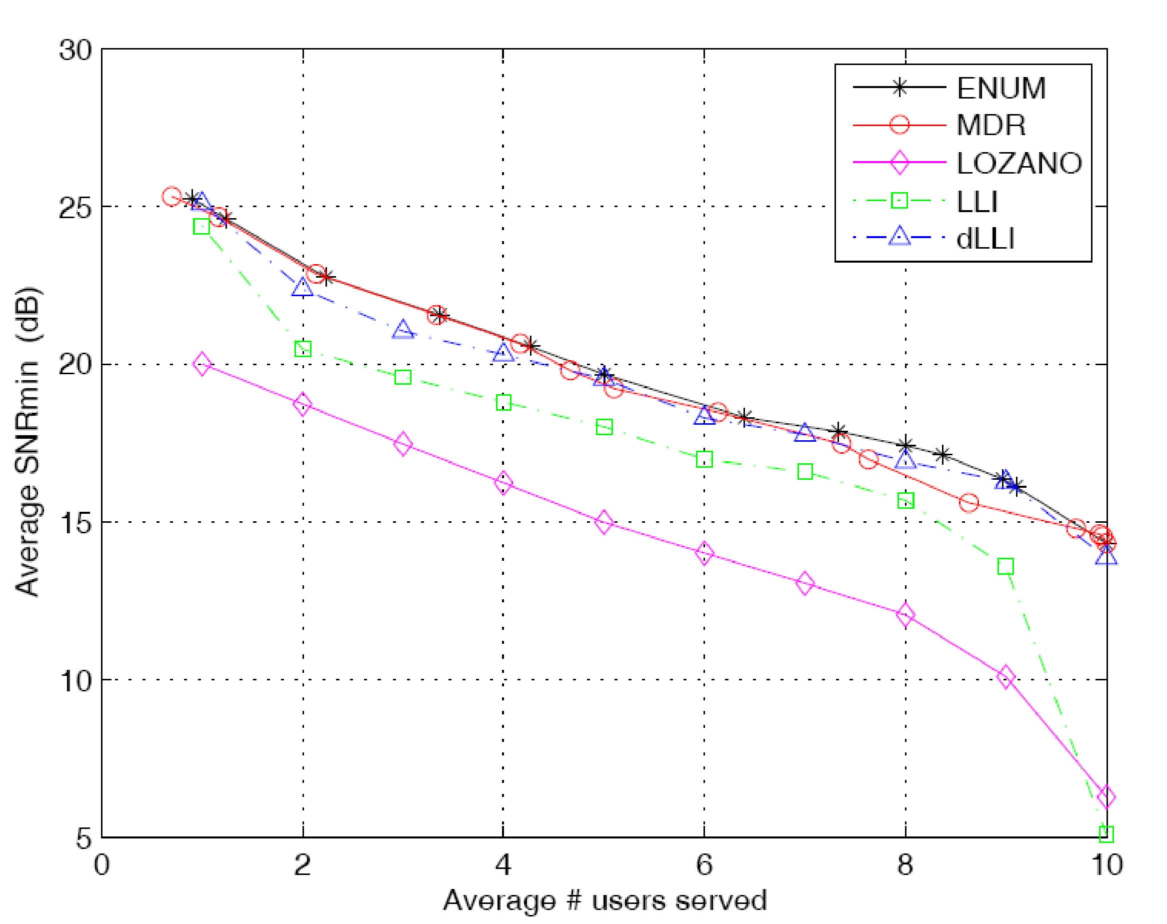
Results – I: Outdoor, I-CSIT

Instantaneous CSI-T.
30 Measured channel snapshots.
$K = 10$ users, $P = 30$,
$N = 4$ Tx, $c_i = c$,
$\sigma_i^2 = \sigma^2 = 1, \forall i$.
MDR: $\epsilon = 10^{-10}$,
$\delta < \min_{i \in \mathcal{U}} 4c^{-1}/\sigma_i^2$.
Lozano's, LLI: $\mu = 10^{-2}$, $accuracy$ (convergence) $= 10^{-3}$.



Complexity (per problem instance):
ENUM: about 2 min
MDR: between 10^{-2} and 1 sec
Lozano's, LLI: between 10^{-2} and 10^{-1} sec.

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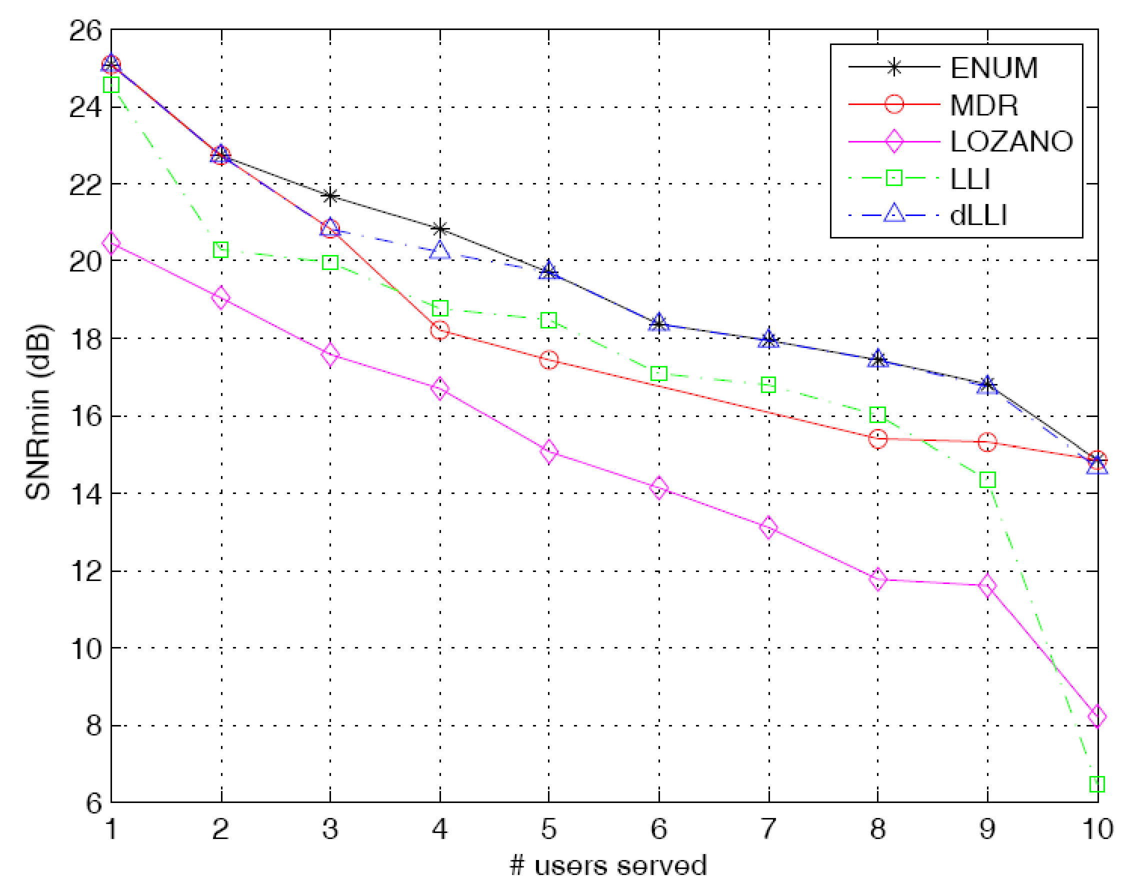
Results – II: Outdoor, LT-CSIT

Long-term CSI-T.
$K = 10$ users, $P = 30$,
$N = 4$ Tx, $c_i = c$,
$\sigma_i^2 = \sigma^2 = 1, \forall i$.
MDR: $\epsilon = 10^{-10}$,
$\delta < \min_{i \in \mathcal{U}} 4c^{-1}/\sigma_i^2$.
Lozano's, LLI: $\mu = 10^{-2}$,
$accuracy$ (convergence)
$= 10^{-3}$.



Complexity:
ENUM: about 2 min
MDR: between 10^{-2} and 1 sec
Lozano's, LLI: between 10^{-2} and 10^{-1} sec.

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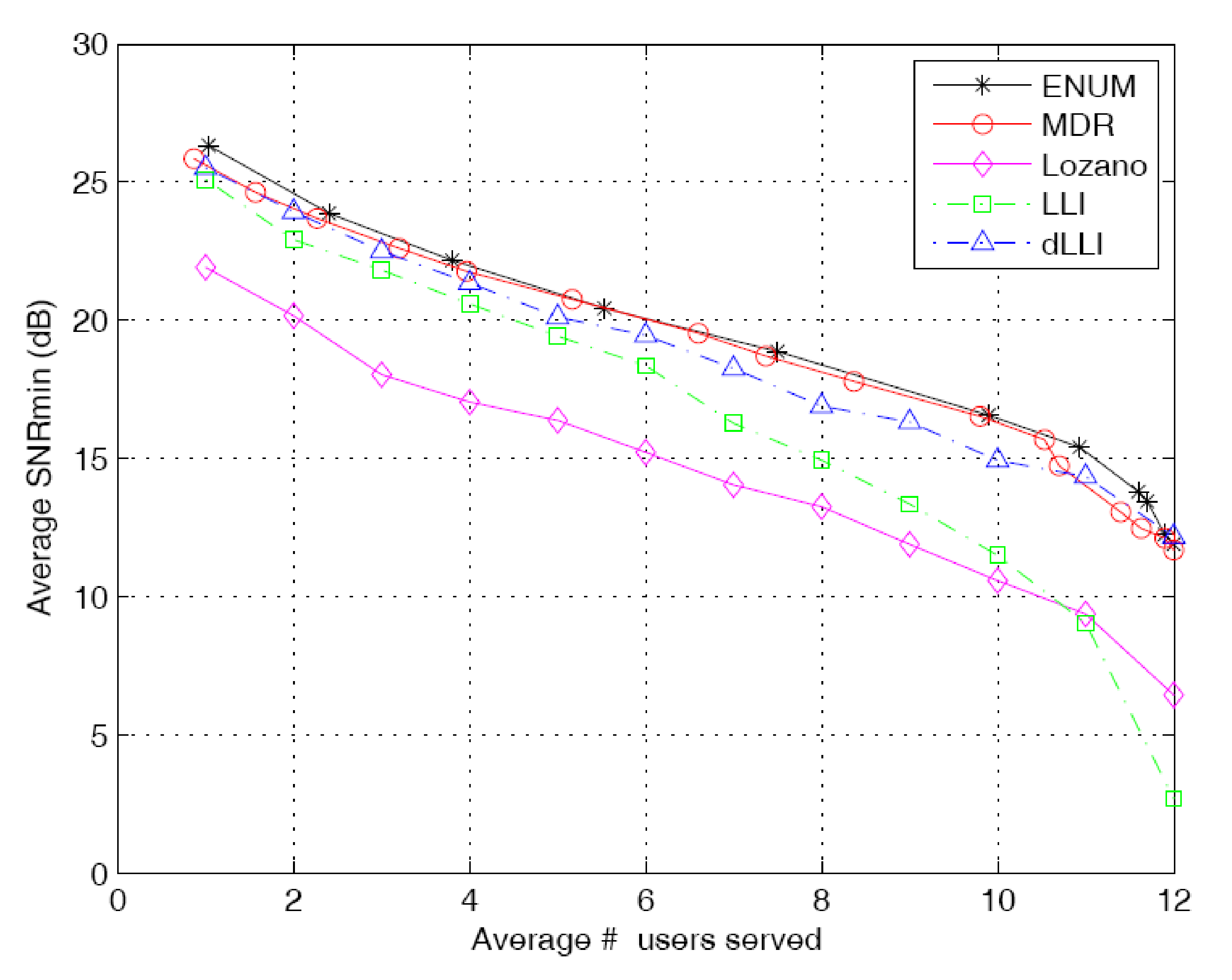
Results – III: Indoor, I-CSIT



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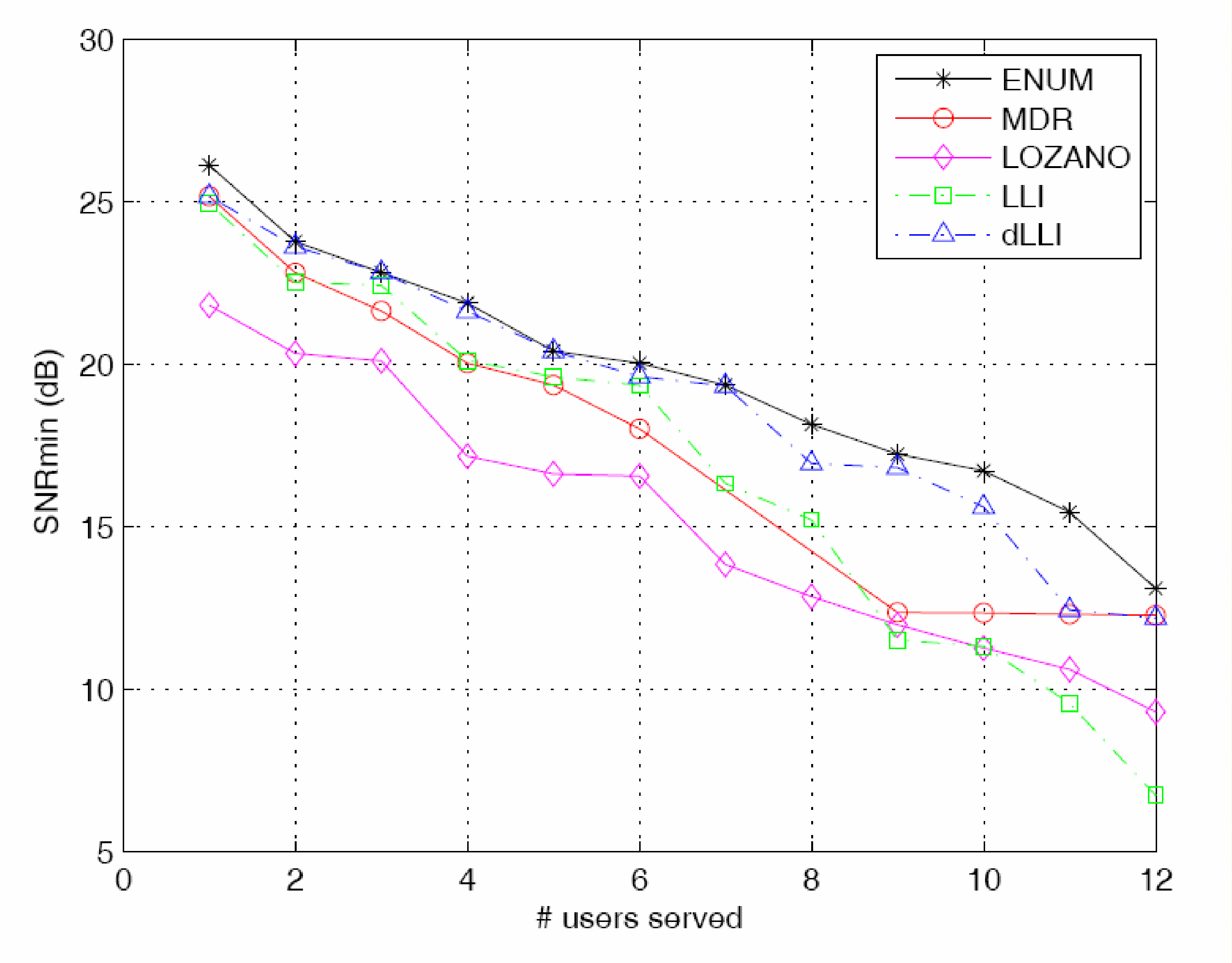
Results – IV: Indoor, LT-CSIT



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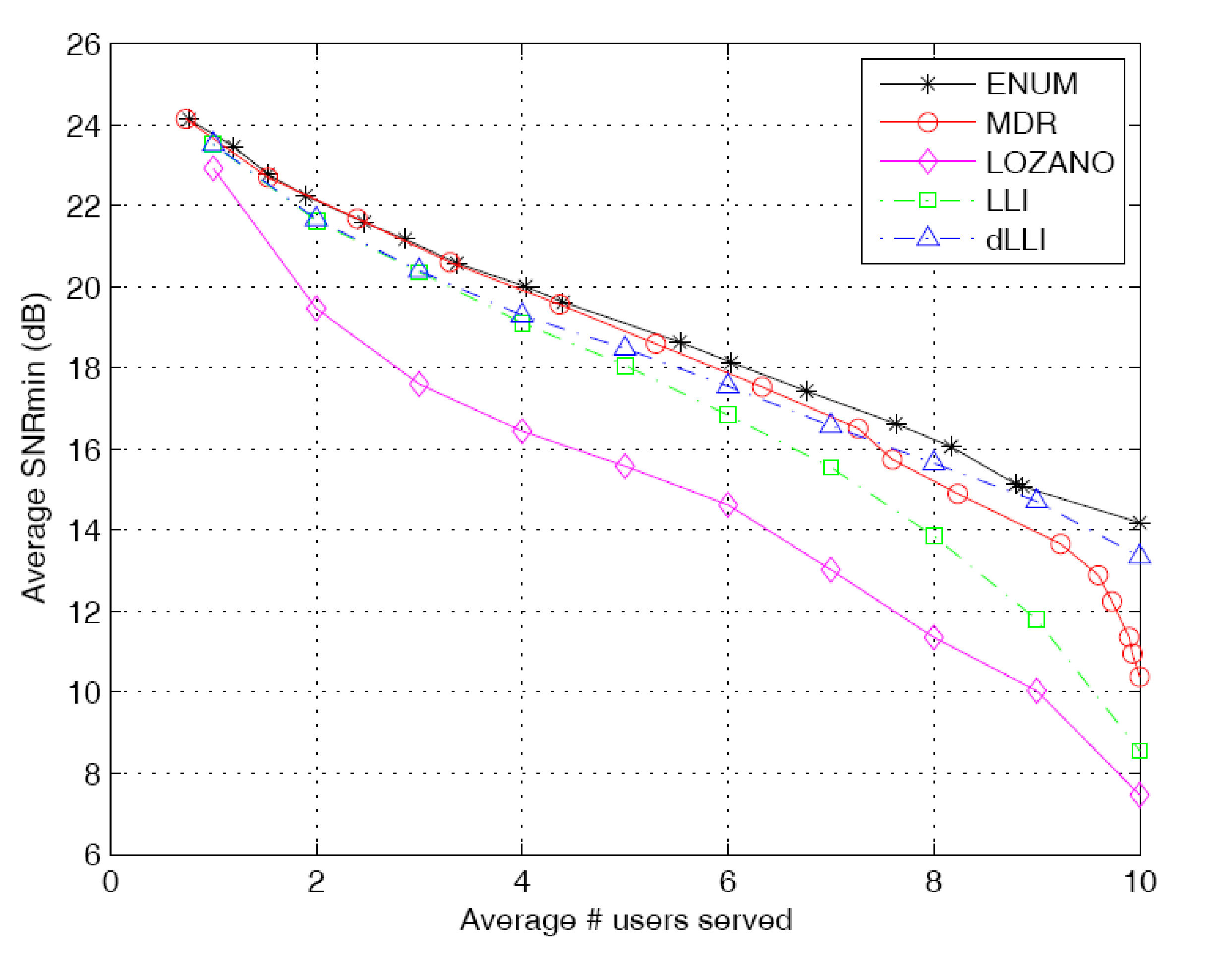
Results – V: iid Rayleigh, I-CSIT



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Conclusions

- ENUM returned rank-1 solutions in all cases except full coverage; complexity exponential in K; prohibitive for large K.
- dLLI and MDR emerge as clear winners
- dLLI best for LT-CSIT
- MDR best in certain I-CSIT cases
- dLLI is simpler and faster than MDR
- … but MDR works for multiple groups
- Both close to optimal
- dLLI : significant improvement over Lozano's original algorithm; due to adaptive nature and only quadratic complexity → ideal candidate for practical implementation in LTE / E-MBMS

Sneak preview:

Multicast beamforming for minimum outage
(Ntranos, Sidiropoulos, Tassiulas, IEEE TWC)

- Assume channel vectors random, drawn from, say, Gaussian
- Max # customers served under power constraint is NP-hard, even if you know their channels exactly.
- For large # customers, can approx. max # served by min P(outage)
- Trivial for single Gaussian – and it doesn't require channel state – only channel statistics!
- NP-hard problem → trivial one! ☺

Sneak preview:

Multicast beamforming for minimum outage
(Ntranos, Sidiropoulos, Tassiulas, IEEE TWC)

- Promising … but *Gaussian mixture* model is far more realistic for multicast

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Sneak preview:

Multicast beamforming for minimum outage: Results

- When # kernels in mixture > # Tx antennas, there's no escape from NP-hardness … ☹
- But for 2-3 kernels (practical), optimal solution is tractable.
- For any number of kernels, effective approximation of very low computational complexity.
- Very interesting because approach requires no CSI, and still delivers (probabilistic) service guarantee
- Respects subscriber privacy concerns; requires no logging
- No reverse-link signaling

Thank you for your attention ☺

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