Cooperative Communications

Lecture 10

Thomas Zemen Paolo Castiglione

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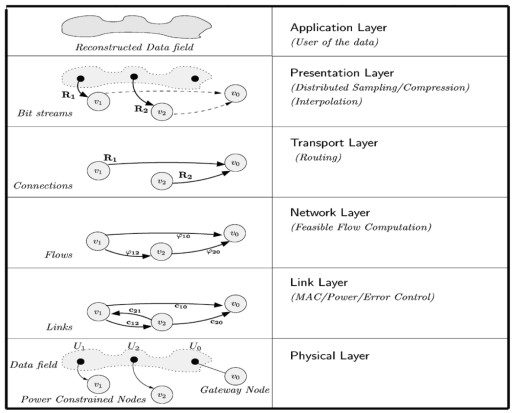
Outline

Today, Lecture 10

- Partner selection algorithms
  - Introduction to cross-layer design for cooperative systems
  - Link level outage performance analysis
  - Partner selection for static cooperative multiple access
  - Lifetime vs fairness

Cooperation: also between OSI layers

more point-to-point links are involved for one transmission:
separation of OSI layers is no longer optimal



PHY+MAC: grouping & partner selection (I)

Layers are inter-dependent if a user (BER etc.) or a network (lifetime etc.) performance metrics need to be optimized

PHY layer:

- cooperative scheme: DF, AF, cooperative beamforming, interference alignment..
- estimation of channel parameters: SNR, channel gain, Doppler and/or delay spread..

MAC layer:

- resource allocation: power, bandwidth, rate, delay..
- grouping and partner selection: which relays for which nodes? which interference alignment cluster?

PHY+MAC: grouping & partner selection (II)

Recalling the *cooperative region* for coded cooperation over time-variant channels (lecture 6):
[collection of mobility (TBP) and channel ($\bar{\gamma}$, p) settings for which coded cooperation is beneficial **in terms of user BER**]

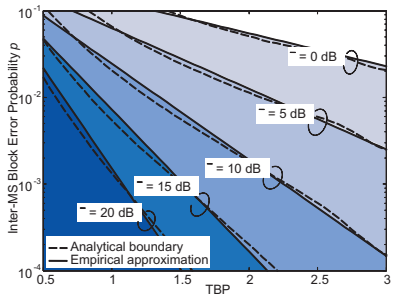


Figure source: [1, Fig. 11]

- Partners must be chosen such that inter-user outage probability p is small (**close partners**) and uplink SNR $\bar{\gamma}$ is critical.
- Velocity (Doppler-spread) indicates if cooperation is advantageous.

PHY+MAC: grouping & partner selection (III)

Mobility asymmetry (β) affects the performance (long-term statistics unbalances are drawbacks for cooperative MICRO-diversity) **partners chosen with similar SNR and velocity values.**

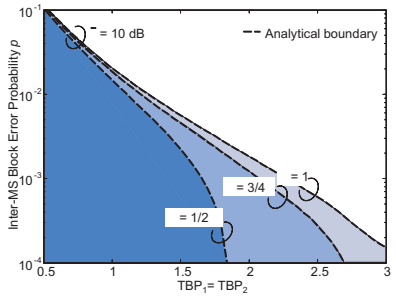


Figure source: [1, Fig. 12]

Literature

First paper on the topic:

- A.Hunter, T.E.; Nosratinia, "Distributed protocols for user cooperation in multi-user wireless networks," *Proceedings IEEE GLOBECOM '04*

Huge literature covering many different types of problems.
Suggested papers:

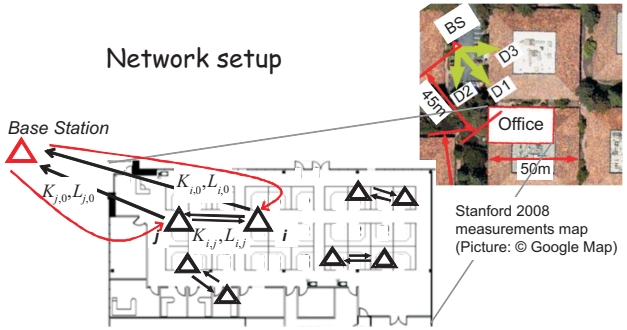
- Z. Lin, E. Erkip, A. Stefanov, "Cooperative regions and partner choice in coded cooperative systems," *IEEE Transactions on Communications*, 2006
- V. Mahinthan, Lin Cai, J.W. Mark, Shen Xuemin, "Maximizing cooperative diversity energy gain for wireless networks," *IEEE Transactions on Wireless Communications*, 2007

Partner selection for static cooperative multiple access

- Measurement network topology and system/channel model
- AF outage analysis over Ricean fading
- Goal and research question
- Energy consumption optimization (based on outage analysis)
- Optimal and suboptimal solutions
- Performance results, optimality degree and robustness

Network and Channel Model

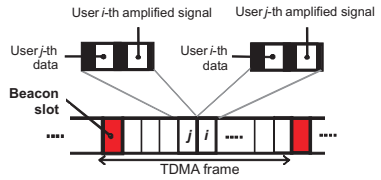
- N battery-powered static indoor nodes communicate to an outdoor BS ($j = 0$).



Modeling from meauserements: Ricean fading $|h_{i,j}|$ on each link (i,j). K-factors and path loss $(K_{i,j}, L_{i,j})$ modeled as *log-normal* random variates with distance dependent means.

System Model

Simple cooperative multiple access scheme: TDMA and AF.



- Node i transmits power ρ_i for the whole slot (also for relaying).
- $\gamma_{i,j} = \rho_i |h_{i,j}|^2 / \sigma^2$: instantaneous SNR on the link (i,j).

Outage Analysis

Direct transmission on the link (i,j)**:** outage probability tightly approximated[1]

$$\Pr[\gamma_{i,j} < \gamma_{\text{th}}^{\text{dir}}] \approx \left[\gamma_{\text{th}}^{\text{dir}} \cdot \sigma^2 / (c_{i,j}\rho_i)\right]^{d_{i,j}}.$$

Ricean fading: diversity $d_{i,j} = 1$ and *coding gain* $c_{i,j}$

$$c_{i,j} = \frac{\exp(K_{i,j})}{L_{i,j}(K_{i,j}+1)}.$$

[1] $\gamma_{\text{th}}^{\text{dir}}$ depends on the target spectral efficiency and the modulation/code.

Estimated Coding Gains from I2O Measurements

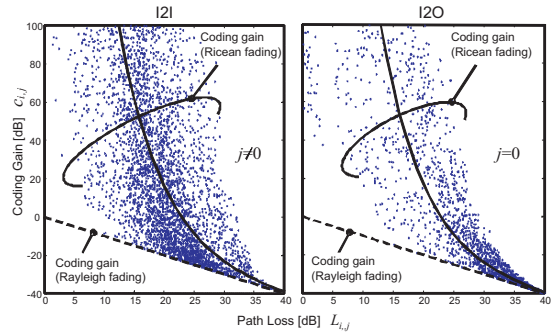


Figure source: [3, Fig. 2]

Real coding gain values highlight the poorness of the Rayleigh fading assumption $c_{i,j} = L_{i,j}^{-1}$.

AF outage anlysis

AF relaying[2]**:** The *dynamic amplification factor* at relay j sets the *effective* SNR for source node i

$$\gamma_{(i,j),0} = \gamma_{i,0} + \left(\frac{1}{\gamma_{i,j}} + \frac{1}{\gamma_{j,0}} + \frac{1}{\gamma_{i,j}\gamma_{j,0}} \right)^{-1}.$$

$$\Pr[\gamma_{(i,j),0} < \gamma_{\mathrm{th}}^{\mathrm{AF}}] \approx \left(\frac{\gamma_{\mathrm{th}}^{\mathrm{AF}} \cdot \sigma^2}{c_{(i,j),0}^{\mathrm{AF}} \cdot \sqrt{\rho_i \rho_j}} \right)^{d_{(i,j),0}^{\mathrm{AF}}},$$

diversity gain $d_{(i,j),0}^{\mathrm{AF}} = 2$; *effective* coding gain $c_{(i,j),0}^{\mathrm{AF}}$:

$$c_{(i,j),0}^{\mathrm{AF}} = \left[\frac{1}{c_{i,0}} \cdot \left(\frac{1}{c_{i,j}} + \frac{1}{c_{j,0}} \right) \right]^{-\frac{1}{2}}.$$

[2] $\gamma_{\mathrm{th}}^{\mathrm{AF}}$ depends on the target spectral efficiency and the modulation/code.

Energy Consumption

- Set by the **target outage probability**, the spectral efficiency and the modulation/coding format.
- Over-head and synchronization aspects translated into additional energy terms.

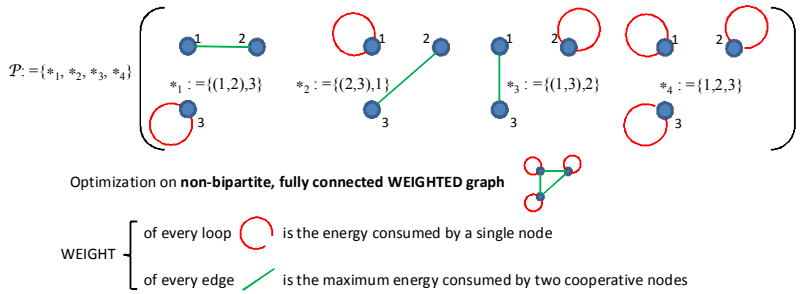
Goal and Research Question

GOAL: to maximize the network lifetime,
i.e. to minimize the maximum energy consumption,
by allowing for a variable number of cooperating pairs of nodes.

QUESTION: which are the optimal
and the low-complexity suboptimal pairing strategies?

Energy Consumption Optimization

$\mathcal{P}$ is the set of candidate pairing sets ξ **(disjoint pairs)**
[EXAMPLE: for $N = 15$ the number of candidate pairing sets $|\mathcal{P}| \simeq 10^7$]



Optimal Solution

Min-max problem: find the pairing set ξ for which the maximum energy consumption $E^{\max}(\xi)$ is minimum.

$$\hat{\xi} = \arg\min_{\xi \in \mathcal{P}} E^{\max}(\xi).$$

Optimal solution to the combinatorial optimizations problem (iterated Gabow algorithm):

- Computational complexity $O(N^5)$: too slow for large networks!
- BS (*genie*) would need to know all the energy consumptions for all paired and single nodes: impracticable!

Suboptimal Solution

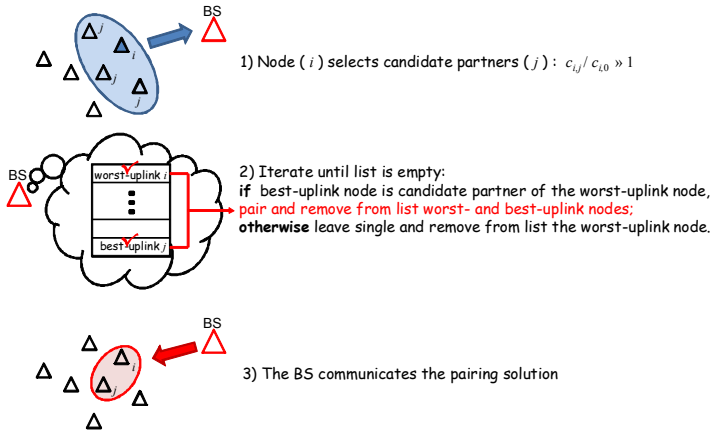
Existing Worst-Link-First algorithms: based on second order statistics (rx powers or signal strenghts, link path loss..)
We call them "Path-Loss based": **WLF-PL**

Novelty in our algorithm: the metric is the uplink coding gain[3].

[3] Furthermore the novel algorithm considers odd N networks.

WLF-CG algorithm

Worst-Link-First Coding-Gain ($c_{i,j}$) based algorithm, $O(N^2)$:



Performance Results

- Network topology similar to the one of the Stanford measurement campaign.
- Results averaged over 5×10^4 scenarios.
  - Target outage probability 10^{-3};
  - spectral efficiency $= 1$;
  - Gaussian code-book.
- For each scenario, $(K_{i,j}, L_{i,j})$ generated according to the I2O stochastic model.

Energy Gains over No-Cooperation

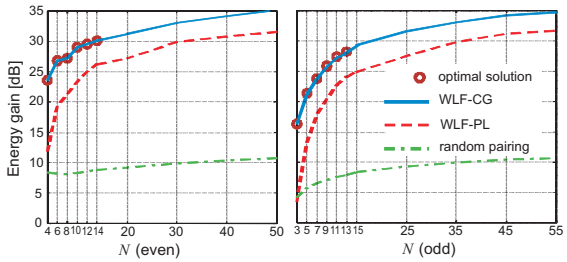


Figure source: [3, Fig. 3]

- Huge energy gains over direct transmission, random pairing and existing algorithms!
- With high probability $c_{i,j} \gg c_{i,0}$: less sensitivity to inter-node channels qualities $\rightarrow$ WLF-CG almost optimal.

K-factor Estimation Errors

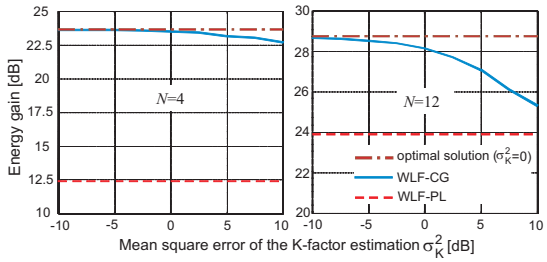


Figure source: [3, Fig. 4]

- For small networks, WLF-CG robust to the K-factor estimation errors.

Summary

- Realistic coding gains, calculated from measurements$\rightarrow$ the Rayleigh fading assumption does not hold in practical I2O scenarios.
- Partner selection algorithm (WLF-CG) exploits the local knowledge of the fading statistics.
- The WLF-CG algorithm gains up to 11dB compared to existing greedy algorithms in static multiple access.
- **What happens though if nodes do not fully tolerate to share their resources to the partners? See next section**

Lifetime vs fairness

- User energy gain and *user-fairness*
- Goal and research question (revisited)
- Energy consumption optimization with user-fairness constraint
- Optimal and suboptimal solutions (revisited)
- Performance results and optimality degree

User energy gain

- Energy consumption $E_{i,0}$ (direct transmission) and $E^{\mathrm{AF}}_{(i,j),0}$ (AF) set by the **target outage probability** and the **spectral efficiency** (and also the modulation/coding format)
- The energy gain or loss $g_{i,j}$ achieved by user i cooperating with partner j

$$g_{i,j} = \frac{E_{i,0}}{E^{\mathrm{AF}}_{(i,j),0}}$$

User-fairness (I)

The energy gain or loss $g_{i,j}$ is constrained by the **user-fairness** $\overline{g}$

$$g_{i,j} = g_{\mathrm{eff}}(R) \times g^{\mu\mathrm{D}} \times g^{\mathrm{MD}}_{i,j} = \frac{E_{i,0}}{E^{\mathrm{AF}}_{(i,j),0}} \geq \overline{g}$$

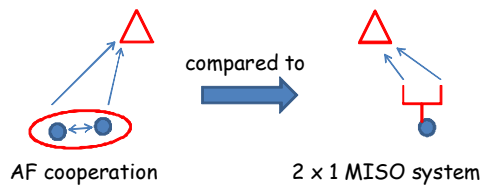
- $g_{\mathrm{eff}}(R) = \left(2^R - 1\right) / \left(2^{2R} - 1\right) < 1$ is the **rate penalty factor**;
- $g^{\mu\mathrm{D}} = (2p)^{1/d^{\mathrm{AF}}_{(i,j),0}} / p = \sqrt{2/p} \geq 1$ is the **micro-diversity gain** (small-scale);
- $g^{\mathrm{MD}}_{i,j} = c^{\mathrm{AF}}_{(i,j),0} / c_{i,0}$ is the **macro-diversity gain** (large-scale). For $c_{i,j} \gg c_{i,0}$: $g^{\mathrm{MD}}_{i,j} \simeq \tilde{g}^{\mathrm{MD}}_{i,j} = \sqrt{c_{j,0}/c_{i,0}}$

User-fairness (II)

User-fairness $\overline{g}$ has here a twofold interpretation:

- a maximum amount of energy loss, compared to the non-cooperative option, can be tolerated by the user ($\overline{g} < 0\mathrm{dB}$);
- a minimum energy gain for the user is introduced as incentive to cooperate ($\overline{g} \geq 0\mathrm{dB}$).

No-coop 2x1 MISO



User-fairness no longer applies.

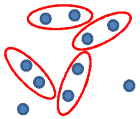
i.i.d. MISO links: only the micro-diversity gain is available (Alamouti)

$$g_{\mathrm{MISO}} = \frac{g^{\mu\mathrm{D}}}{2},$$

where factor 1/2 is due to the power splitting between the antennas

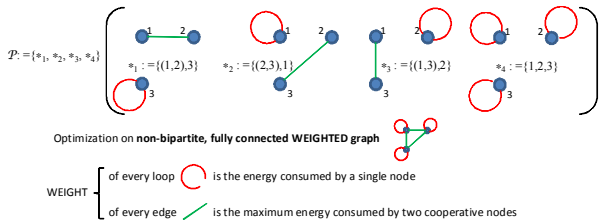
Goal and research question

GOAL: to maximize the network lifetime (same as before),
i.e. to minimize the maximum energy consumption (among the users),
by allowing for a variable number of cooperating pairs of users.



QUESTION: which are the optimal
and the low-complexity suboptimal pairing strategies,
that account for the user-fairness constraint?

Optimal solution



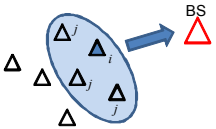
Min-max problem: find the pairing set ξ for which the maximum energy consumption $E^{\max}(\xi)$ is minimum

$$\hat{\xi} = \arg\min_{\xi \in \mathcal{P}} E^{\max}(\xi)$$
$$\text{s.t. } g_{i,j} \geq \bar{g}, \ \forall (i,j) \in \xi$$

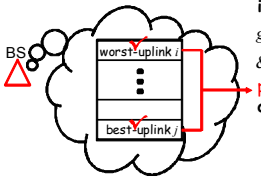
Edges not meeting the user-fairness constraint are discarded:
only a subset of $\mathcal{P}$ fulfills the constraint

Modified WLF-CG algorithm

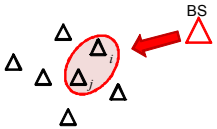
Worst-Link-First Coding-Gain ($c_{i,j}$) based algorithm, $O(N^2)$:



1) Node (i) selects candidate partners (j) : $c_{i,j} / c_{i,0} >> 1$.
[The inter-user channel $c_{i,j}$ will not impact the performance of (i) :
$\longleftrightarrow$ $g_{i,j}^{\mathrm{MD}} \cong \tilde{g}_{i,j}^{\mathrm{MD}}$]



2) Iterate until list is empty:
if best-uplink candidate partner (j) of the worst-uplink node (i) fulfilling:
$g_{\mathrm{eff}}(R) \times g^{\mathrm{MD}} \times \min\left(\tilde{g}_{i,j}^{\mathrm{MD}}, \tilde{g}_{j,i}^{\mathrm{MD}}\right) \geq \bar{g}$ **user - fairness**
& $c_{j,i} >> c_{j,0}$ **(i) also candidate partner for (j)**
pair and remove from list worst- and best-uplink nodes;
otherwise leave single and remove from list the worst-uplink node.



3) The BS communicates the pairing solution

Performance results

- Network topology similar to the one of the Stanford measurement campaign.
- Results averaged over 10^5 scenarios.
  - Target outage probability 10^{-3};
  - spectral efficiency $= 1$;
  - Gaussian code-book;
  - $c_{i,j} > c_{i,0} + 20\mathrm{dB}$ in the WLF-CG.
- For each scenario, $(K_{i,j}, L_{i,j})$ generated according to the I2O stochastic model.

Lifetime gains vs user-fairness

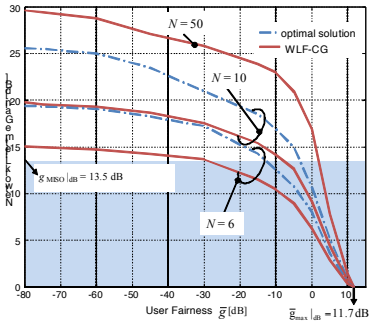


Figure source: [4]

- For less stringent user-fairness requirements ($\bar{g} < 0\mathrm{dB}$), WLF-CG better than Alamouti! Large benefits of *macro-diversity*
- WLF-CG suboptimal, e.g. up to $6\mathrm{dB}$ loss for $N = 10$: due to the conservative rule $c_{i,j} > c_{i,0} + 20\mathrm{dB}$ (necessary for the user-fairness)

Is cooperation attractive?

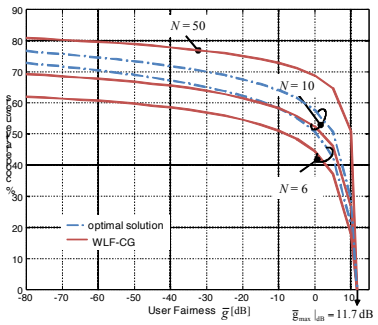


Figure source: [4]

- More severe the user-fairness constraint ($\bar{g} \geq 0\mathrm{dB}$): less likely to cooperate (especially for small N)
- Less stringent constraints ($\bar{g} < 0\mathrm{dB}$): cooperative option becomes more attractive

Summary

- User-fairness: twofold definition in AF cooperation
  1) max energy loss tolerated 2) min energy gain required by the user
- Pairwise grouping (low-complexity algorithm):
  I2O network lifetime increase by 10 compared to Alamouti,
  by 200 compared to single-antenna transmission
  [50 indoor users, tolerance up to $10\mathrm{dB}$ energy loss]
- **Macro-diversity** has a huge impact on performances

References I

[1] P. Castiglione, M. Nicoli, S. Savazzi and T. Zemen,"Cooperative regions for coded cooperation over time-varying fading channels,"*Proc. of Int. ITG/IEEE Workshop on Smart Antennas 2009*

[2] Z. Wang, Member, G. B. Giannakis, "A simple and general parameterization quantifying performance in fading channels," *IEEE Trans. on Comm.*, 2003

[3] P. Castiglione, S. Savazzi, M. Nicoli, T. Zemen, "Impact of fading statistics on partner selection in indoor-to-outdoor cooperative networks", *Proc. of IEEE ICC 2010*

[4] P. Castiglione, S. Savazzi, M. Nicoli, G. Matz, "Partner Selection in Cooperative Networks: Efficiency vs Fairness in Ricean Fading Channels", *Proc. of IEEE ISCCSP 2010*

[5] I. Stanojev, O. Simeone, U. Spagnolini, Y. Bar-Ness, R. L. Pickholtz, "Cooperative ARQ via Auction-Based Spectrum Leasing," *IEEE Trans. on Comm.*, 2010