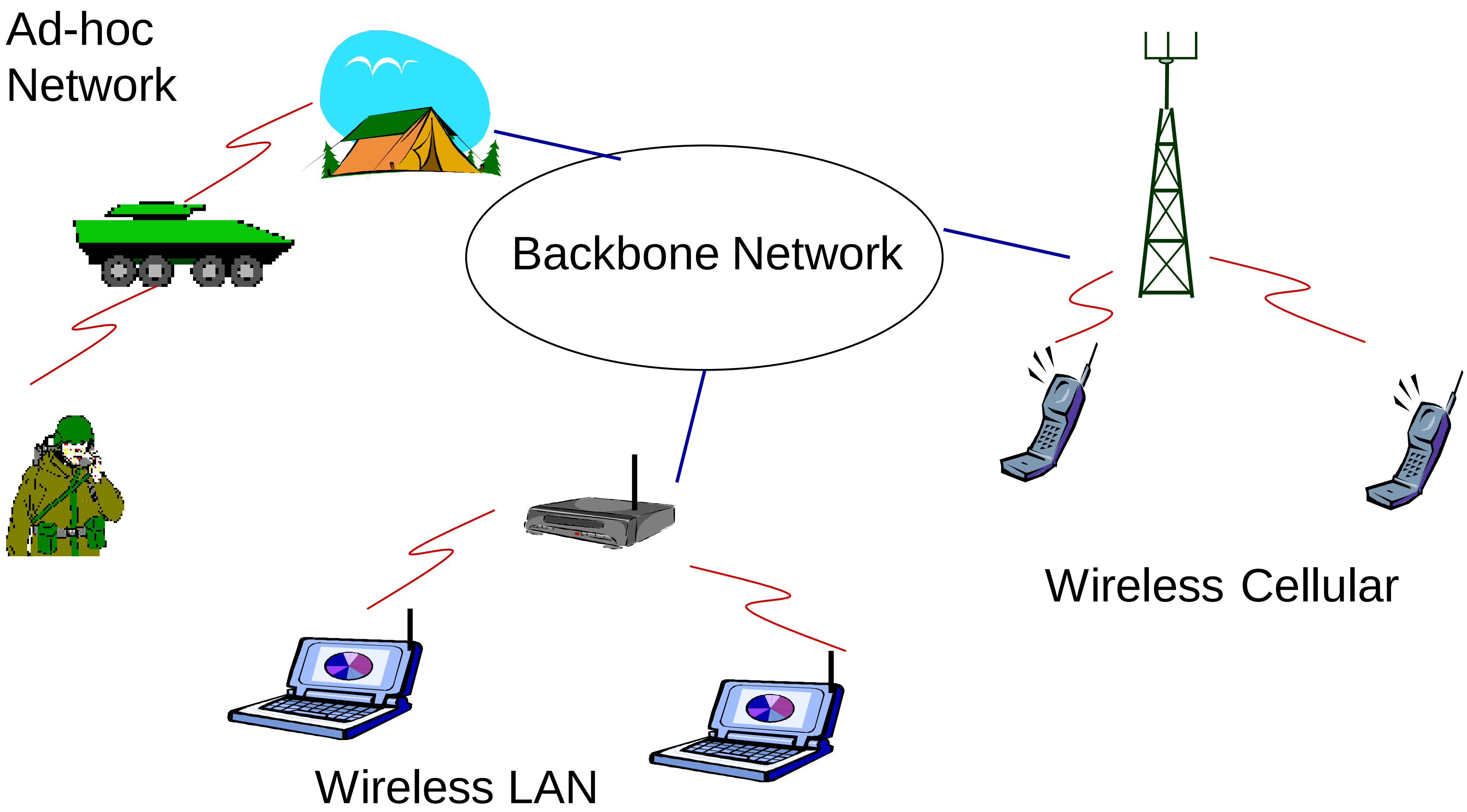
Cooperative Communications in Wireless Systems

Elza Erkip

Wireless Networks

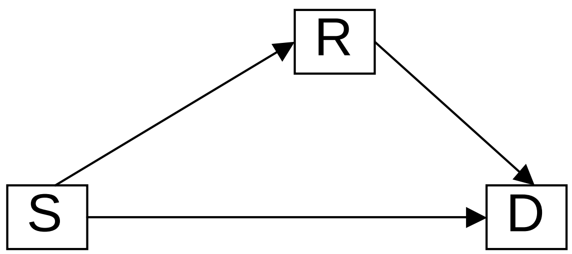


Outline

- Relay channel
  - Relaying in wireless: Use relays for diversity
  - Traditional multihop versus multihop with diversity
- Concept of cooperation: “Virtual” antenna array
- Information theoretic model and analysis
- Cooperative codes

Relay Channel

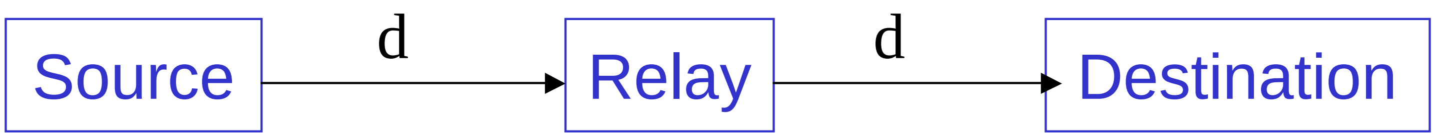
- Introduced by Ven der Meulen (1971)
- Cover and El Gamal (1979): Inner and outer bounds on the capacity; capacity of degraded relay channel



- Multiple relays:
  - Schein & Gallager
  - Gupta & Kumar
  - Xie & Kumar
  - Reznik, Kulkarni & Verdu
  - Gastpar & Vetterli
  - Gastpar, Kramer & Gupta

Multi-hop Wireless Communications

- Multi-hop reduces power requirements and interference

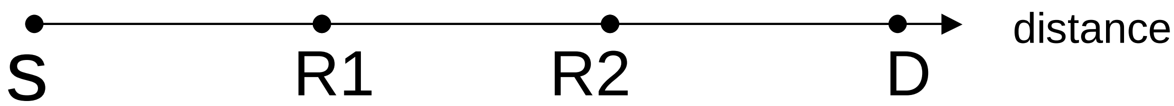


  - § Direct transmission: $P_{total} = P\left(2d\right)^{\alpha} = 2^{\alpha} P d^{\alpha}$
  - § Relayed transmission: $P_{total} = 2Pd^{\alpha}$

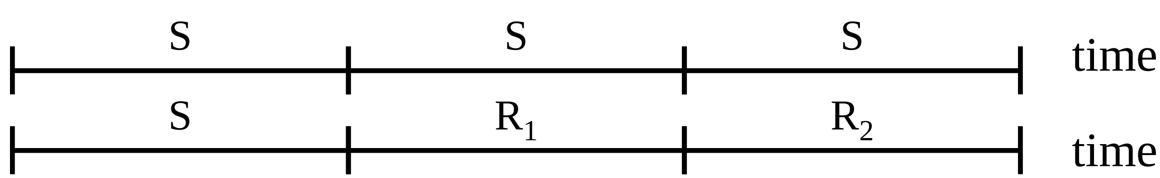
- Current trends:
  - – Only consider path loss
  - – Destination only processes signal from relay
- What about fading? Use multi-hop for diversity.

Diversity in Multihop

- One source/destination, two relays

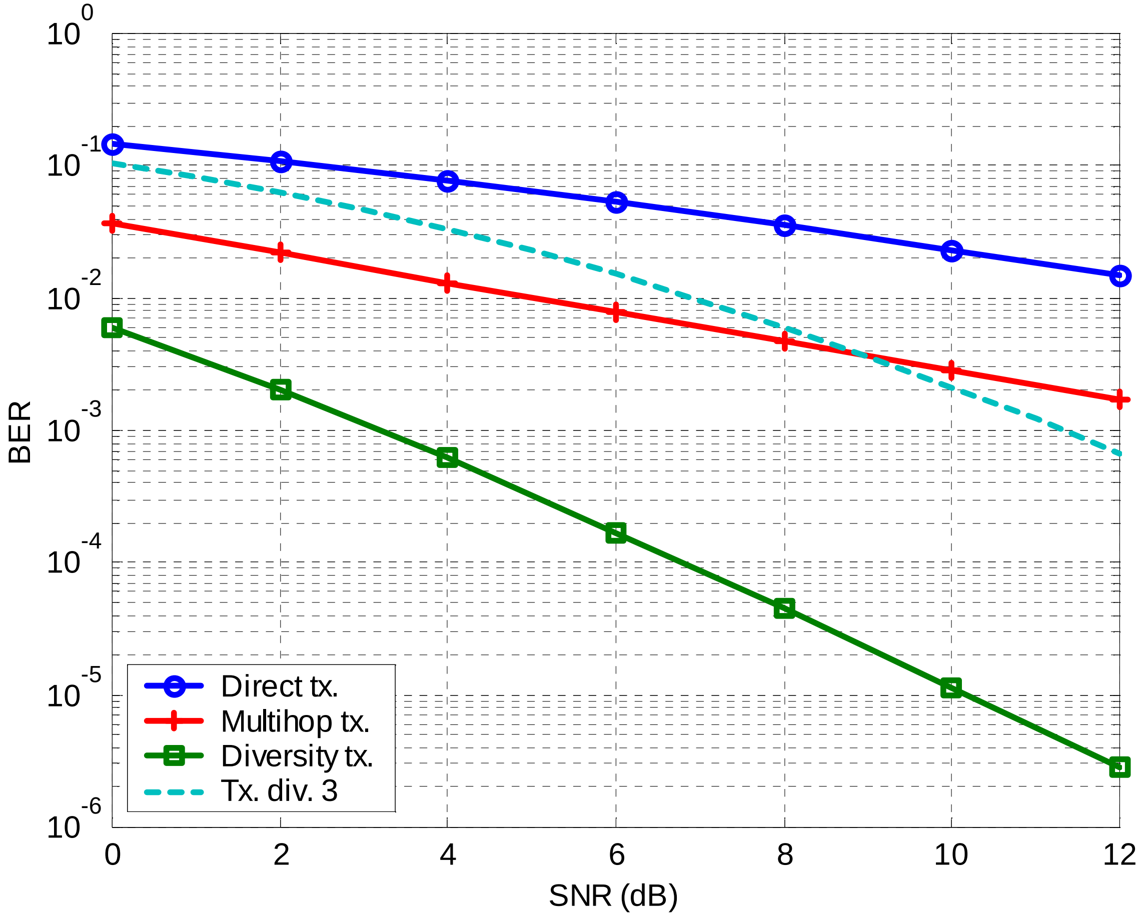


- Path loss and fading
- Uncoded BPSK, bit by bit processing
  - Relays amplify received signal and forward
- Direct
- Via relays



  - Total power divided equally among source and relays

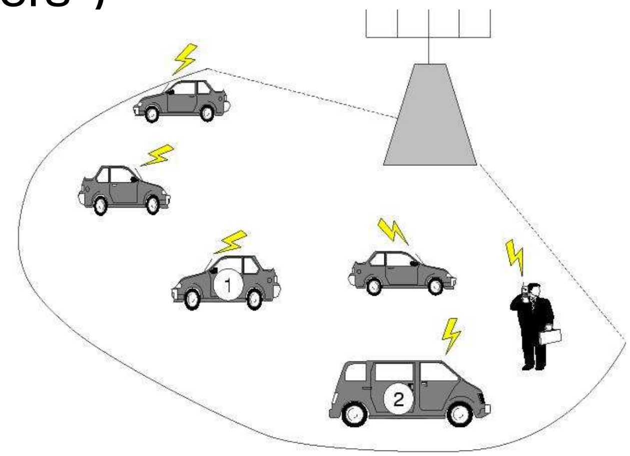
Effect of Multihop Diversity



User Cooperation Diversity

- Diversity through cooperation of mobiles

  (Sendonaris, Erkip, Aazhang)
- Two main ideas
  - Use relays to provide diversity
  - Collaborative scheme: Both mobiles help each other ("partners")



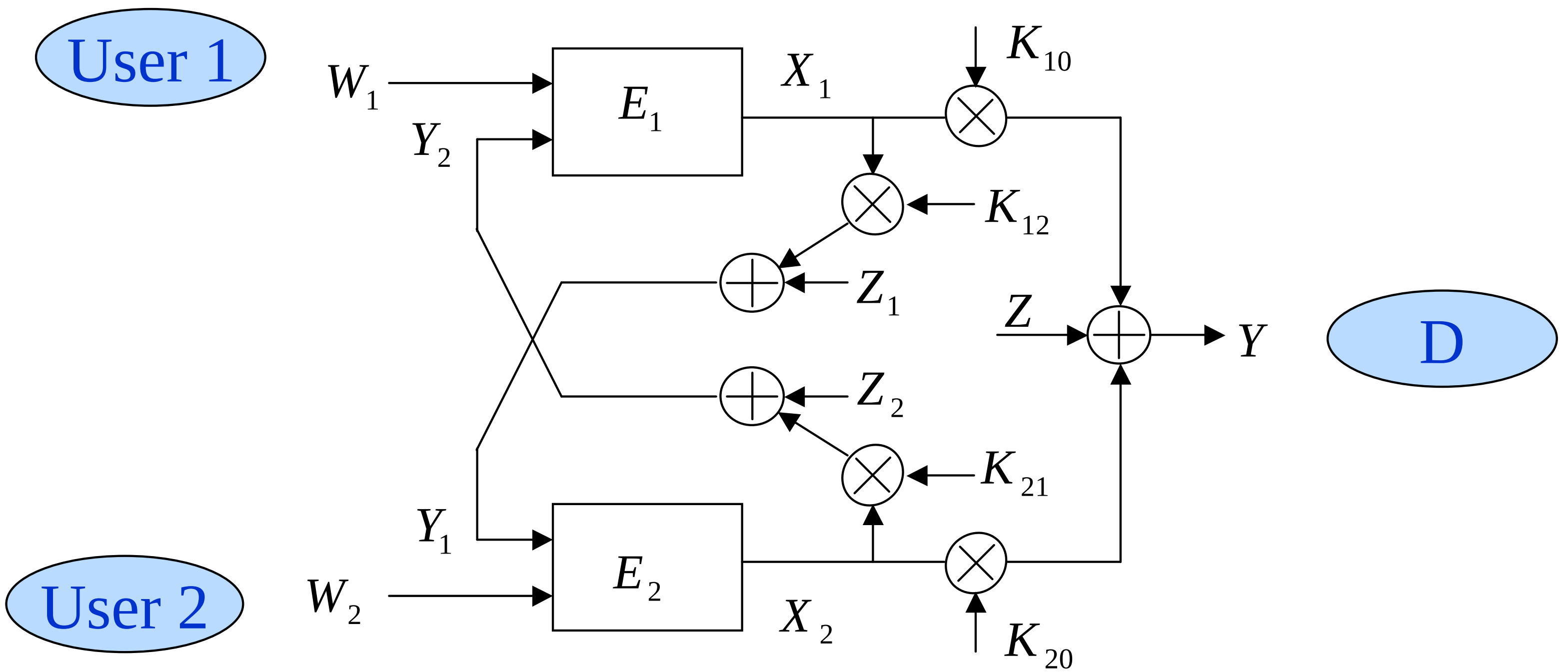
User Cooperation

- Mobile antennas are omnidirectional
  - Signals transmitted towards the destination can be “overheard” at the partner
  - Partners process this overheard information and re-transmit towards the destination
    - Total resources (power, bandwidth) are same as non-cooperative case
  - Destination processes signals from both mobiles
- Spatial diversity through partner’s antenna, a “virtual” antenna array
  - Inter-user channel is noisy!

Approach

- Information theory *(Sendonaris, Erkip, Aazhang)*
  - A general model illustrating that cooperation results in throughput and diversity gains
  - Some idealized assumptions
- Code design *(Stefanov, Erkip)*
  - More realistic assumptions
  - Channel codes that exploit user cooperation gains

Information Theoretic Model



- K_{ij} : Fading amplitudes
- Receivers track the fading parameters, transmitters don't

Capacity Analysis

- Assumptions
  - Partners receive and transmit at the same time (same assumption as classical relay of Cover & El Gamal)
  - Transmitters have phase information: Coherent combining is possible
- Model is similar to multiple access channel with generalized feedback
  - DMC and Gaussian (Carleial, Willems et.al.)
- Achievable region under fading

Transmit Signal Structure

- Information $W_1 = (W_{10}, W_{12})$
- Signal $X_1 = (X_{10}, X_{12}, U_1)$
  - X_{10} : Send W_{10} at rate R_{10} to destination (D)
  - X_{12} : Send W_{12} at rate R_{12} to mobile 2 (also heard at D)
  - U_1 : Cooperative signal based on (W_{12}, W_{12}) to the BS
- Power allocation: $P_1 = P_{10} + P_{12} + P_{U1}$

Achievable Rate Region with Cooperation

The closure of $\{(R_1, R_2) \mid R_1 = R_{10} + R_{12}, R_2 = R_{20} + R_{21}\}$ where

$$R_{k0} < \mathrm{E}\left\{C\left(\frac{K_{k0}^2 P_{k0}}{N}\right)\right\} \quad k = 1,2$$

$$R_{k\tilde{k}} < \mathrm{E}\left\{C\left(\frac{K_{k\tilde{k}}^2 P_{k\tilde{k}}}{K_{k\tilde{k}}^2 P_{k0} + N_k}\right)\right\} \quad k = 1,2$$

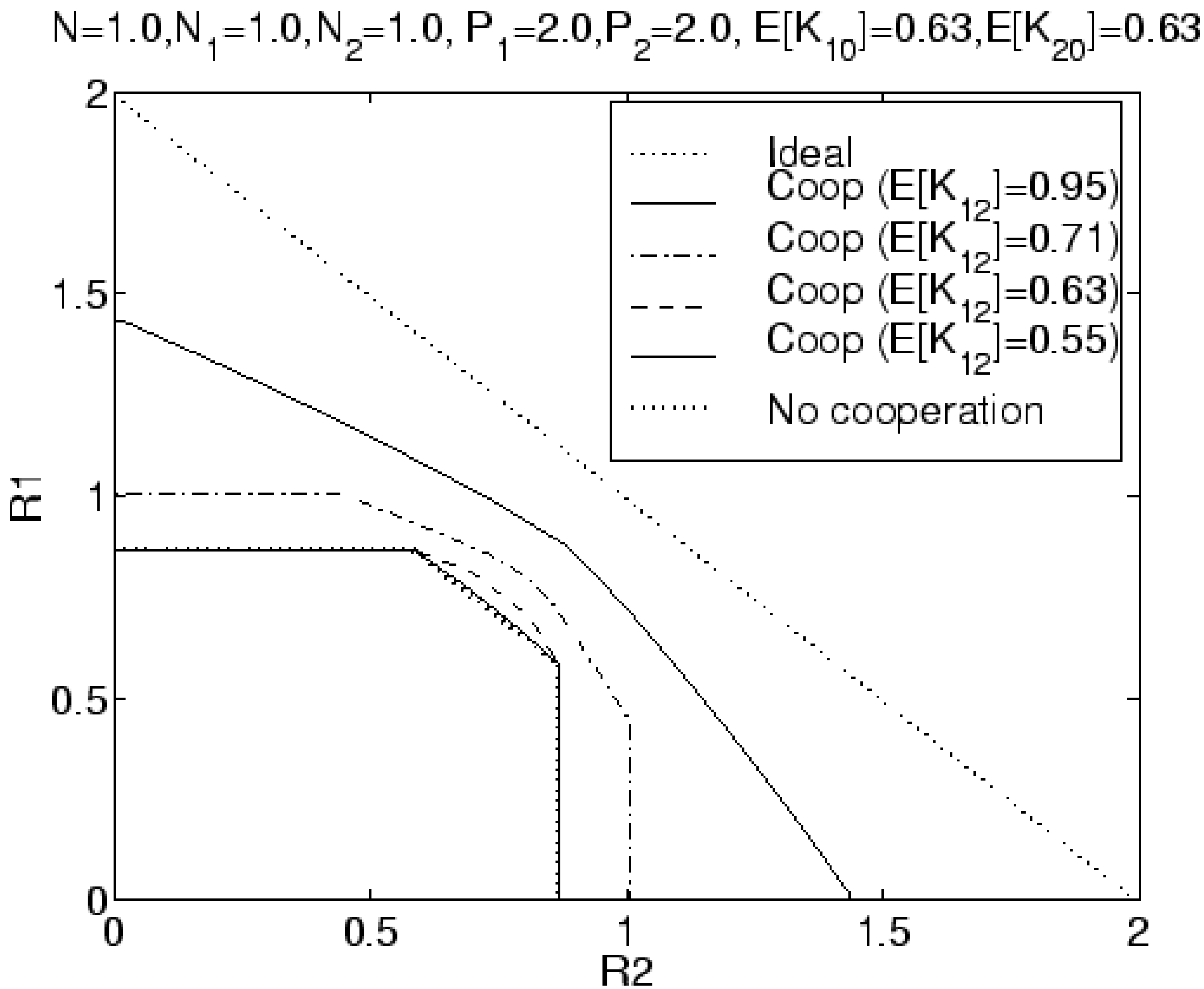
$$R_{10} + R_{20} < \mathrm{E}\left\{C\left(\frac{K_{10}^2 P_{10} + K_{20}^2 P_{20}}{N}\right)\right\}$$

$$R_{10} + R_{20} + R_{12} + R_{21} < \mathrm{E}\left\{C\left(\frac{K_{10}^2 P_1 + K_{20}^2 P_2 + 2K_{10}K_{20}\sqrt{P_{U1}P_{U2}}}{N}\right)\right\}$$

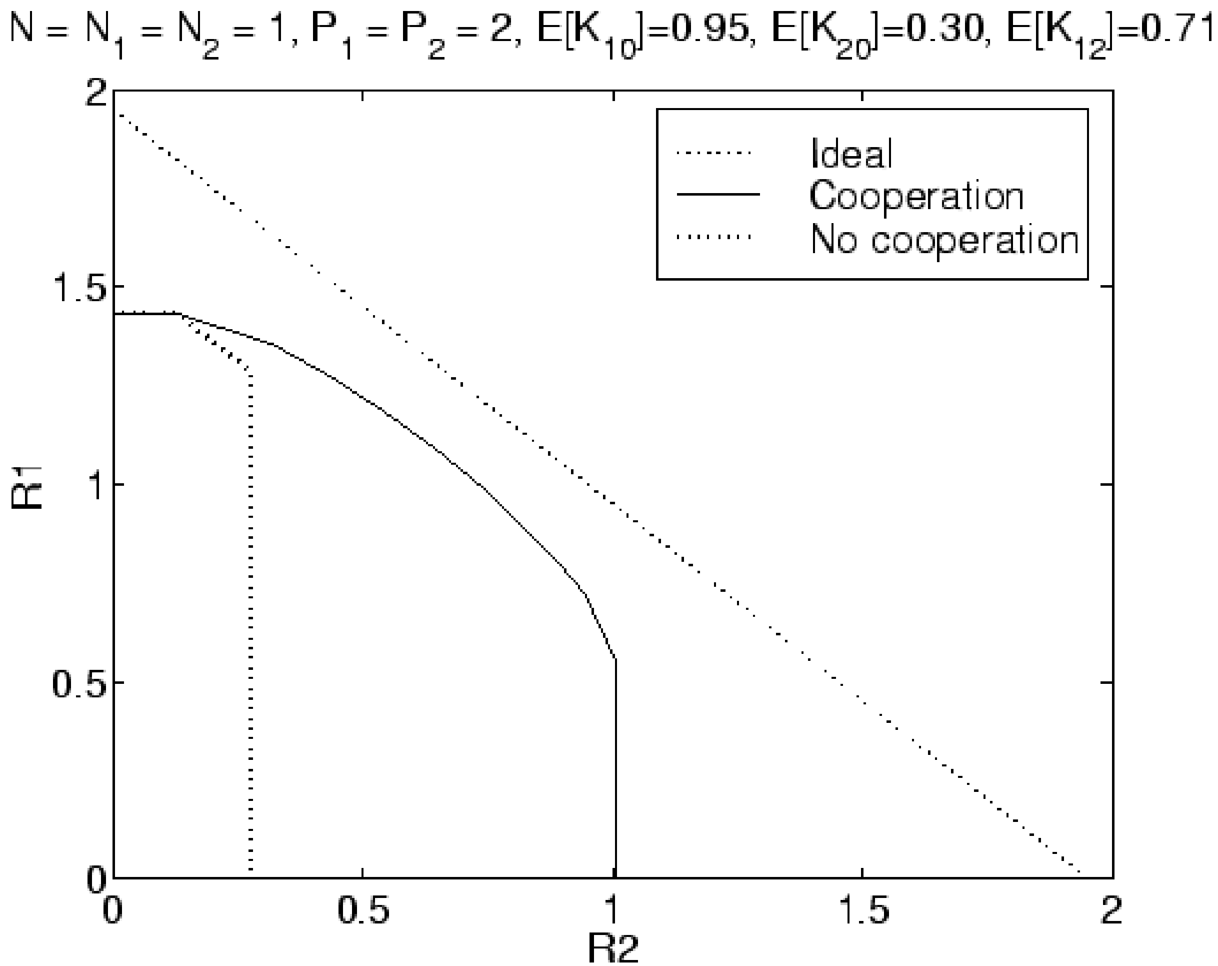
for some power assignment

$$P_1 = P_{10} + P_{12} + P_{U1}, \;\; P_2 = P_{20} + P_{21} + P_{U2}$$

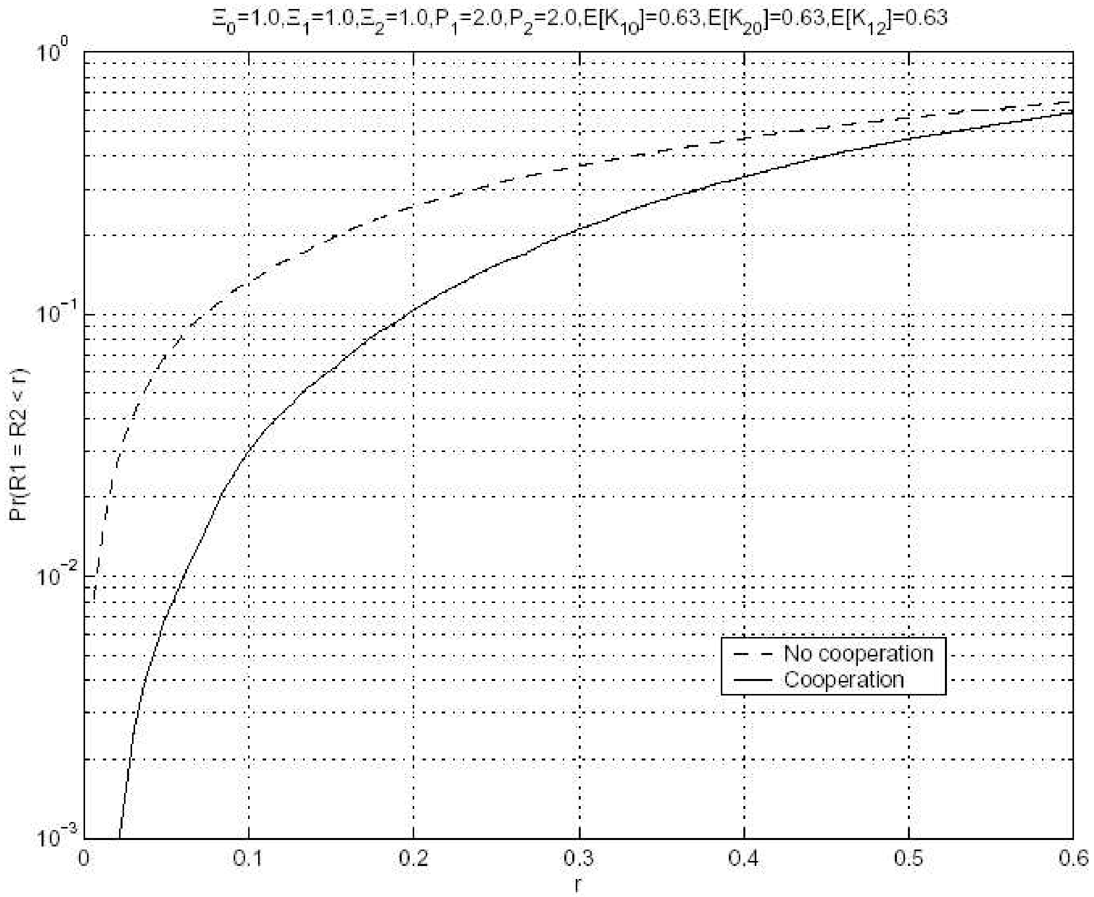
Achievable Rate Region (Symmetric)



Achievable Rate Region (Asymmetric)



Probability of Outage



Benefits of Cooperation

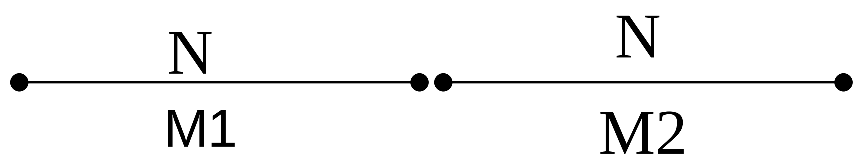
- Higher data rates
- Reduced outage

  } For both mobiles

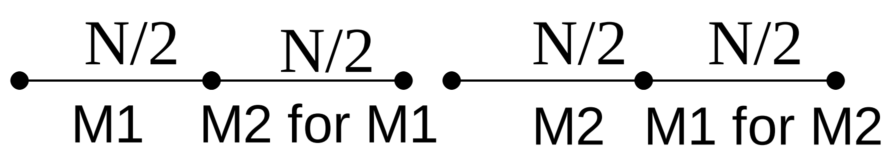
  ➡ Provides an incentive for relaying
- Increased battery life
- Extended coverage for cellular
- Works even when inter-user channel is bad or one user is closer to the base station

Realistic Constraints

- Hard to transmit/receive at the same time
  - Without cooperation



  - With cooperation



Cooperation Using Time-Sharing

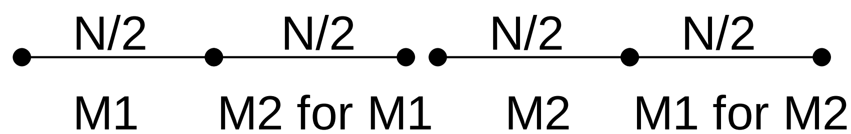
(*Laneman, Tse, Wornell*)

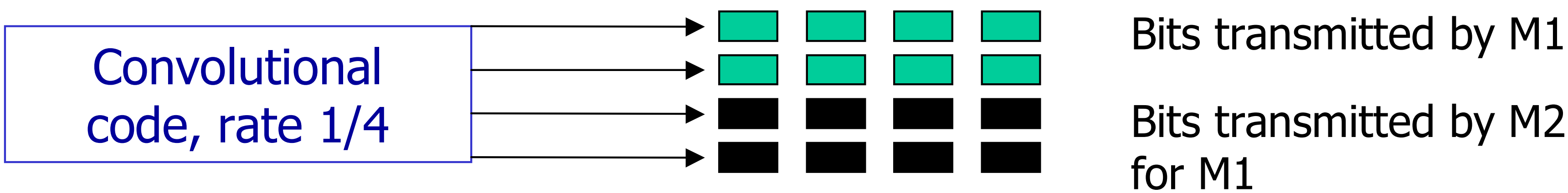
- Works for same/separate receivers
- Outage probability analysis for slow fading
- Partner can
  - Amplify and forward
    - Amplifies noise, two level diversity
  - Decode and forward
    - Perfect decoding is a strict constraint, one level diversity
  - Adaptive decode and forward
    - Partner decodes only when it can, two level diversity
- Channel codes for cooperation?

Channel Coding for Cooperation

(Stefanov, Erkip)

- With cooperation

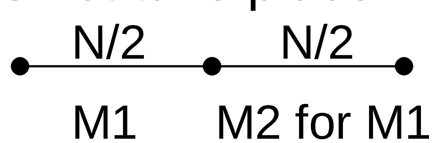




- To cooperate, M1 only transmits half of its coded bits.
- This is received at M2 and at the destination.
- M2 decodes M1's information, re-encodes and transmits remaining half of the coded bits.
- M2 forwards only when it has correct information (checked by CRC), otherwise M1 continues.
  - Protocol similar to *Hunter & Nosratinia.*

Block Fading Model

- Quasi-static channels
  - Block fading when cooperation takes place
- Can use codes designed for block fading channels *(Knopp & Humblet)*
  - Maximize diversity and coding advantages
- Additional constraints
  - First half of the code has to be good in the quasi-static inter-user channel
  - Code has to be good in the quasi-static channel when cooperation does not take place



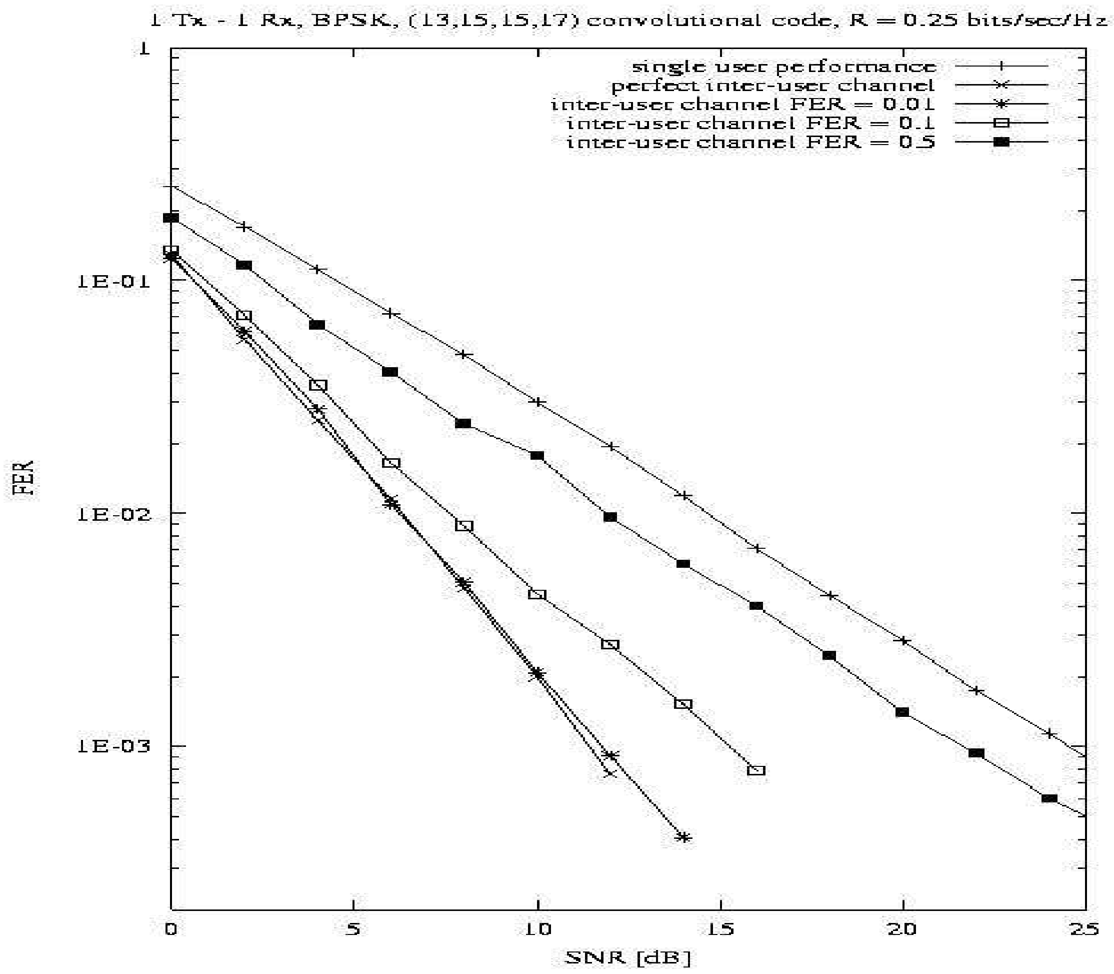
Cooperative Coding Performance Analysis

- Frame error rate with the above cooperation protocol

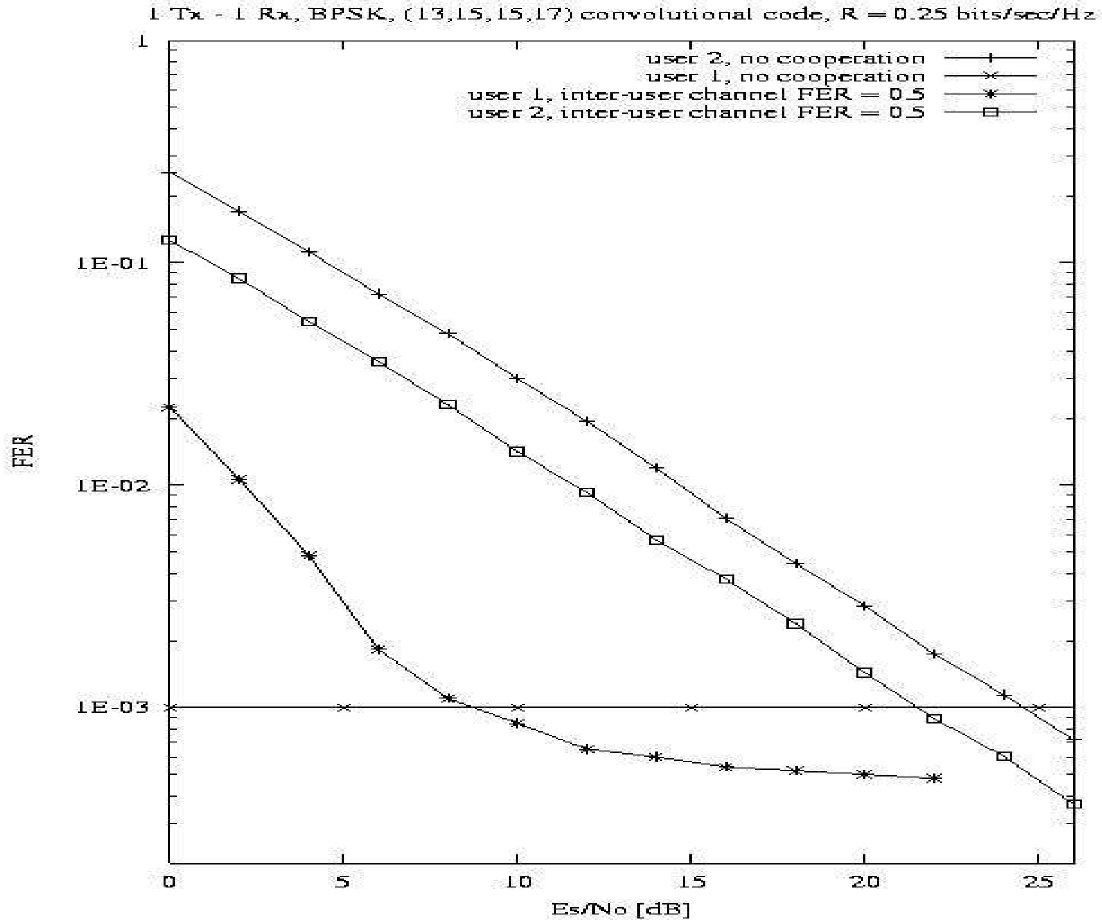
$$
\begin{aligned}
P_f^C &= (1 - P_f^{in}) P_f^{BF} + P_f^{in} P_f^{QS} \\
&\le P_f^{BF} + P_f^{in} P_f^{QS} \\
&\le \frac{K_{BF}}{SNR_1 SNR_2} + \frac{K_{in}}{SNR_{in}} \frac{K_{QS}}{SNR_1}
\end{aligned}
$$

  - P_f^C : FER for the cooperative protocol
  - P_f^{in} : FER for inter-user channel
  - P_f^{BF} : FER for the block fading channel resulting from cooperation
  - P_f^{QS} : FER for the direct (non-cooperative) channel
  - SNR_i: Received SNR for user i at the destination, i=1,2
  - SNR_{in}: Received SNR in the inter-user channel
  - K: Code parameters

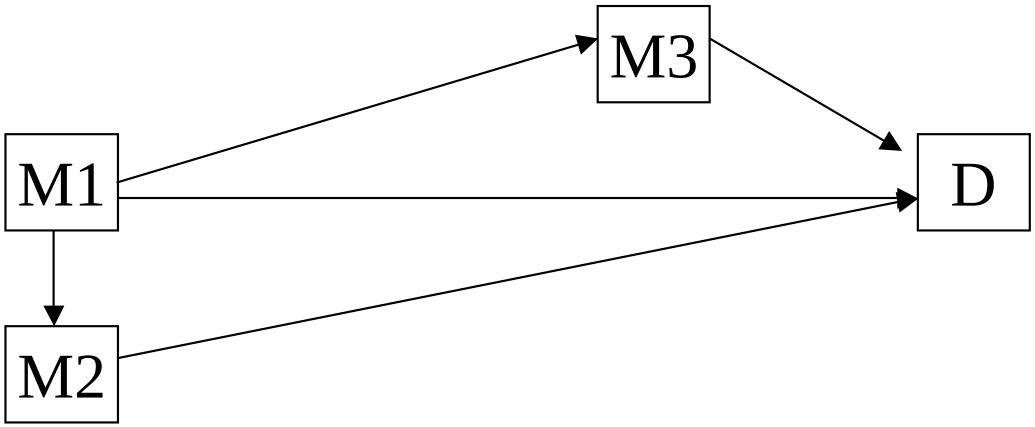
Cooperative Coding (Similar users)



Cooperative Coding (Asymmetric case)

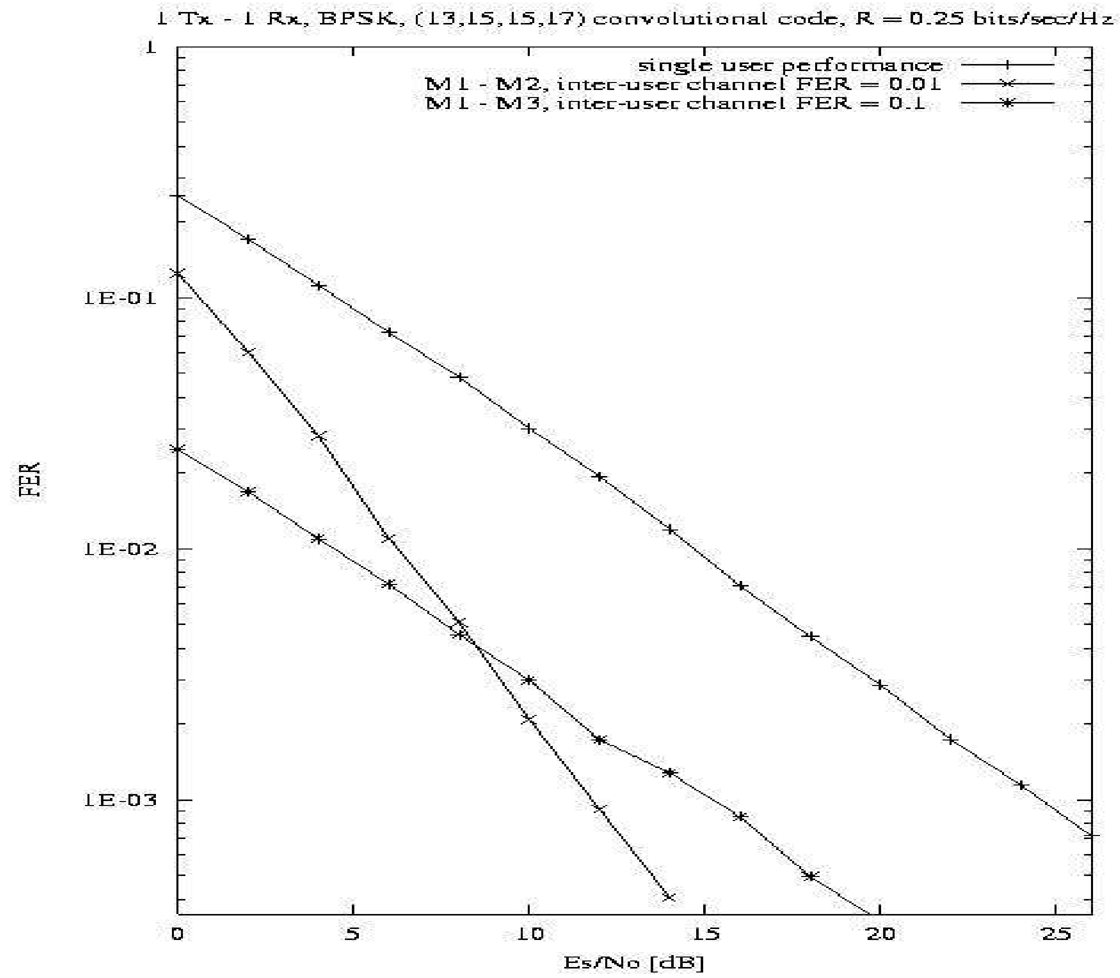


Effect of Cooperation on Routing



- Traditional routing
  - Only path loss is considered: Choose M3 as relay
- Cooperative diversity
  - For medium-high SNR, M2 results in lower error rate
  - Good inter-user channel dominates

Routing with Cooperative Diversity



Other Related Projects at Poly

- Cooperative space-time coding *(Stefanov, Erkip)*
  - Cooperative codes for mobiles with multiple antennas
  - Asymmetric: Cooperation among mobiles with different number of antennas (overlay codes)
- Choice of partners: Geometry of cooperation *(Lin, Erkip, Stefanov)*
- Diversity in relaying protocols *(Yuksel, Erkip)*
- Visit our web page: eeweb.poly.edu/~elza

References

1. A. Sendonaris, E. Erkip and B. Aazhang, “User cooperation diversity-part I: System description.” To appear, *IEEE Transactions on Communications.*

2. A. Sendonaris, E. Erkip and B. Aazhang, “User cooperation diversity-part II: Implementation aspects and performance analysis.” To appear, *IEEE Transactions on Communications.*

3. A. Stefanov and E. Erkip, “Cooperative coding for wireless networks.” In *Proceedings of IEEE Conference on Mobile and Wireless Communications Networks,* Stockholm, Sweden, September 2002.

4. A. Stefanov and E. Erkip, “On the performance analysis of cooperative space-time coded systems.” To appear *IEEE Wireless Communications and Networking Conference (WCNC 2003),* New Orleans, Lousiana, March 2003.

5. A. Stefanov and E. Erkip, “Cooperative space-time coding for wireless networks.” To appear, *2003 Information Theory Workshop*, Paris, France, April 2003.