

# COOPERATION IN CELLULAR NETWORKS: TAKING A NEW LOOK AT INTERFERENCE

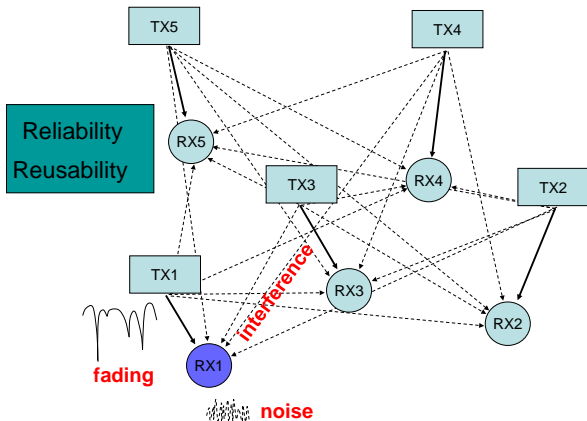
KEYNOTE SPEECH  
ISWCS'10 CONFERENCE, YORK  
21ST SEPTEMBER 2010

David Gesbert, EURECOM

With thanks to R. Zakhour, M. Kountouris, A. Papadogiannis

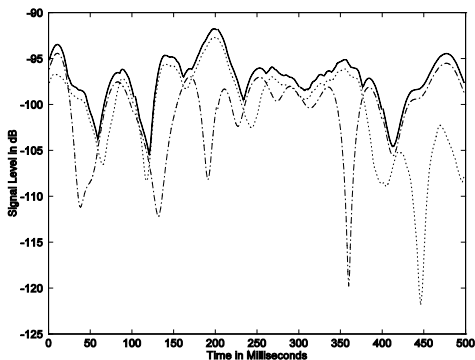
September 21, 2010

# WHY AREN'T WIRELESS COMMUNICATIONS BETTER ?



## CERTAIN PROBLEMS CAN BE TURNED AROUND...

Exploiting **fading** using multi-user diversity **scheduling**



What about **interference**?

# OUTLINE

- **Part 1:** Some traditional approaches to interference control
- **Part 2:** Emerging approaches:
  - Cooperation
  - Coordination
- **Part 3:** The role of information exchange

# CLASSICAL INTERFERENCE CONTROL

- **Avoidance** : *orthogonalizing* transmit resources in time, frequency, space, codes...
- **Containment** : *Leaking* just enough interference to meet a QoS constraint
- **Rejection** : Advanced *receiver-based* processing (beamforming, iterative decoding,..)

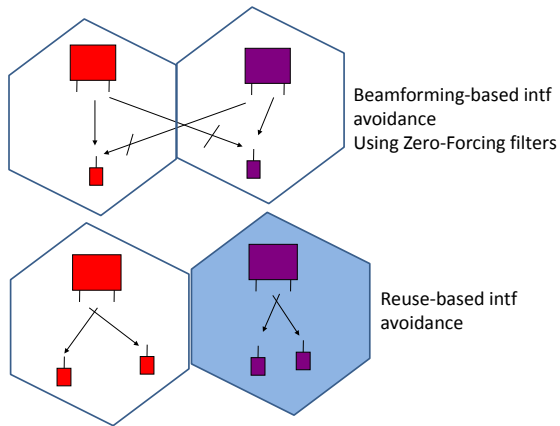
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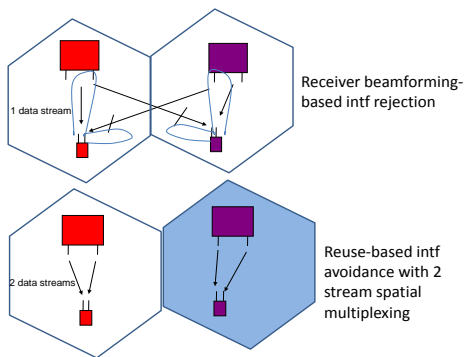
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# THE INEFFICIENCY OF ORTHOGONALIZATION: REUSE VS. BEAMFORMING

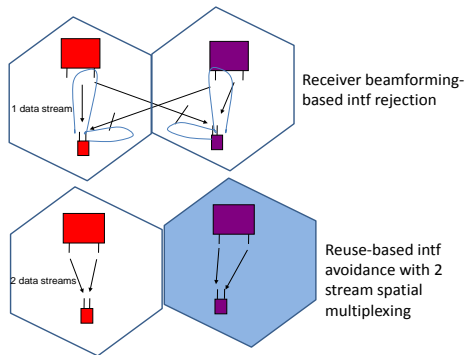


# THE INEFFICIENCY OF REJECTION



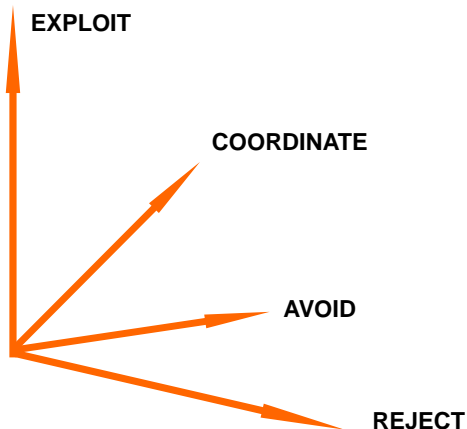
- Avoidance and rejection are **not free**: consume receiver's **degrees of freedom**
- Are there better ways to handle interference?

# THE INEFFICIENCY OF REJECTION



- Avoidance and rejection are **not free**: consume receiver's **degrees of freedom**
- **Are there better ways to handle interference?**

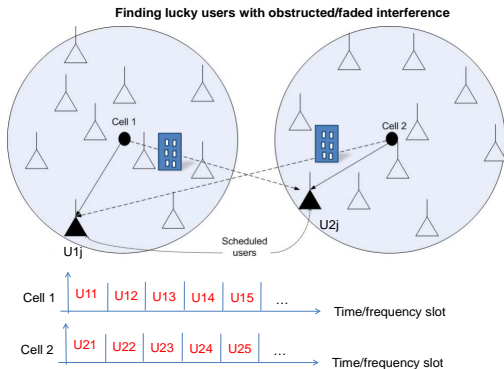
# THE DIMENSIONS OF INTERFERENCE MANAGEMENT



# INTERFERENCE COORDINATION

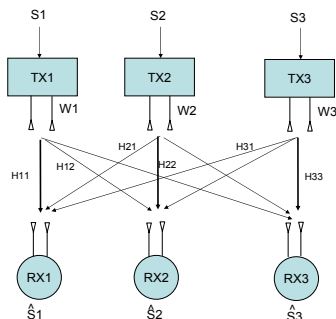
- Softer approach to reducing interference
- Non zero interference is leaked from the transmitter
- Choice of **transmission parameter(s)** is **coordinated** across devices
  - total transmit power
  - time slot
  - subcarrier
  - beam
  - user
  - ...

# COORDINATION USING RESOURCE ALLOCATION



- Exploits the **variability** (fading) of interference
- Power control/beamforming couples the decisions at all cells

# COORDINATION USING MULTIPLE ANTENNA: ALIGNMENT



**Interference Alignment  
Conditions with Nr=2:**

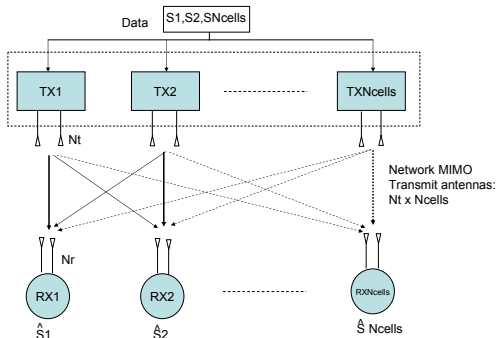
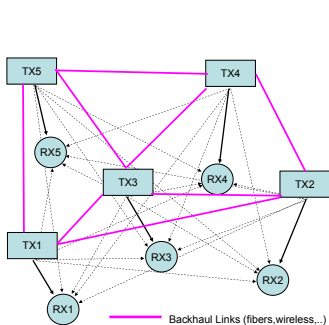
$$H_{21}W_2 \propto H_{31}W_3$$

$$H_{12}W_1 \propto H_{32}W_3$$

$$H_{13}W_1 \propto H_{23}W_2$$

[Maddah-Ali, Motahari, Khandani, *Trans IT 2008*] [Cadambe, Jafar, *Trans IT 2008*]

# MULTI-CELL MIMO COOPERATION



Use standard MIMO techniques with per-base power constraints..

[Hanly et al 1993, Shamai et al. 2001, ...]

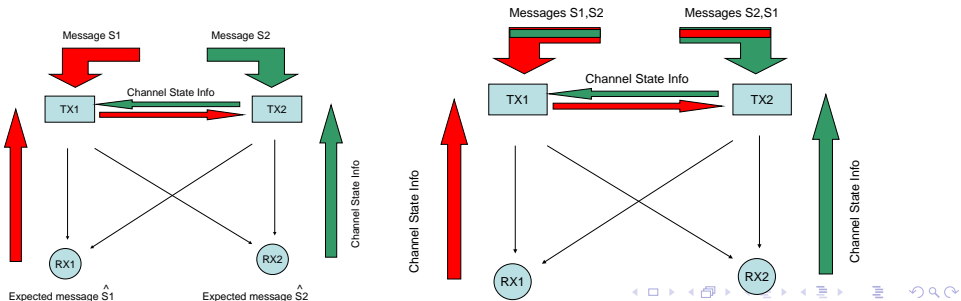
## COORDINATION/COOPERATION: GAIN VS. PAIN

Interference **coordination** requires:

- Sharing of CSI

Interference **exploitation** requires:

- Sharing of CSI
- Sharing of user data



# ON THE COOPERATION GAIN VS. INFORMATION EXCHANGE TRADE-OFF

- Promising research topic
- Just a few guidelines about the trade-off:
  - Backhaul capacity must grow proportional to over-the-air capacity
  - CSI accuracy must grow proportional to SNR
  - Information overhead needs to be mitigated through distributed designs

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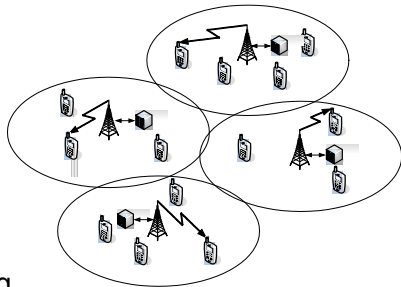
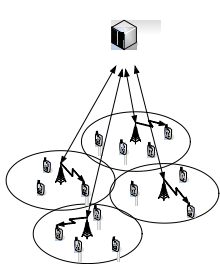
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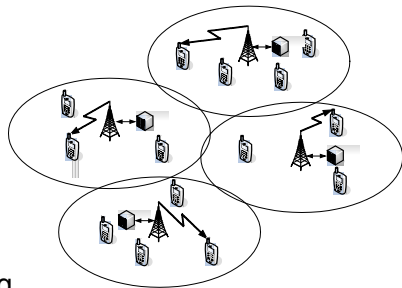
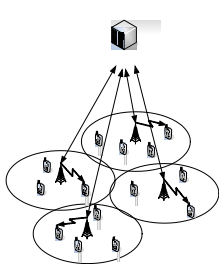
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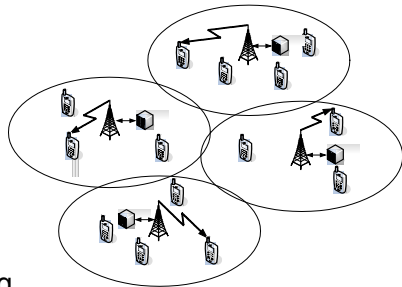
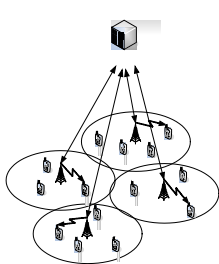
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- MIMO cooperation with clustering
- Partial CSI sharing
- Partial user data sharing

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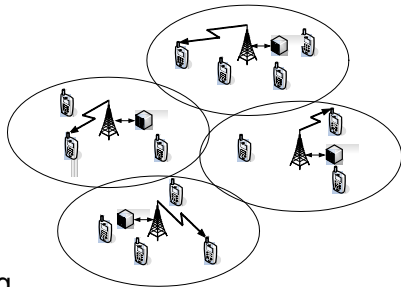
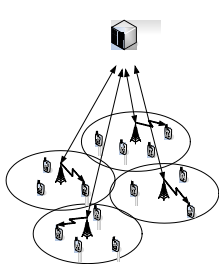
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# COORDINATED SCHEDULING OVER $N$ CELLS WITH $U \gg 1$ USERS

**Definition :** A *scheduling vector*  $\mathbf{U}$  for a given resource slot contains the set of users simultaneously scheduled across all cells:

$$\mathbf{U} = [u_1 \ u_2 \ \cdots \ u_n \ \cdots \ u_N] \quad 1 \leq u_j \leq U$$

**Definition :** A *transmit power vector*  $\mathbf{P}$  contains the transmit power values used by each transmitter towards its respective user:

$$\mathbf{P} = [P_{u_1} \ P_{u_2} \ \cdots \ P_{u_n} \ \cdots \ P_{u_N}]$$

where  $[\mathbf{P}]_n = P_{u_n} = \mathbb{E}|X_{u_n}|^2 \leq P_{\max}$ .

## OPTIMAL SCHEDULING AND POWER CONTROL

The SINR for the user selected in cell  $n$  is

$$\Gamma([\mathbf{U}]_n, \mathbf{P}) = \frac{G_{u_n, n} P_{u_n}}{\sigma^2 + \sum_{i \neq n} G_{u_n, i} P_{u_i}}, \quad (1)$$

The system capacity **under single user decoding** is

$$C(\mathbf{U}, \mathbf{P}) \triangleq \frac{1}{N} \sum_{n=1}^N \log \left( 1 + \Gamma([\mathbf{U}]_n, \mathbf{P}) \right). \quad (2)$$

$$\text{Problem: } (\mathbf{U}^*, \mathbf{P}^*) = \arg \max_{\substack{\mathbf{U} \in \Upsilon \\ \mathbf{P} \in \Omega}} C(\mathbf{U}, \mathbf{P}), \quad (3)$$

# UPPER BOUND AND LOWER BOUND ON CAPACITY

Assuming **no** interference:

$$C(\mathbf{U}^*, \mathbf{P}^*) \leq C^{ub} = \frac{1}{N} \sum_{n=1}^N \log \left( 1 + \max_{u_n=1..U} \{G_{u_n,n}\} P_{max} / \sigma^2 \right). \quad (4)$$

Assuming **full-powered** interference:

$$C(\mathbf{U}^*, \mathbf{P}^*) \geq C^{lb} = \frac{1}{N} \sum_{n=1}^N \log \left( 1 + \max_{u_n=1..U} \left\{ \frac{\{G_{u_n,n}\} P_{max}}{\sigma^2 + \sum_{i \neq n}^N G_{u_n,i} P_{max}} \right\} \right). \quad (5)$$

## CAPACITY SCALING FOR LARGE NUMBER OF USERS

**Theorem 1:** The upper bound on capacity behaves like:

$$E(C^{ub}) \approx \frac{\epsilon}{2} \log U \text{ for large } U \quad (6)$$

**Theorem 2:** The lower bound on capacity behaves like:

$$E(C^{lb}) \approx \frac{\epsilon}{2} \log U \text{ for large } U \quad (7)$$

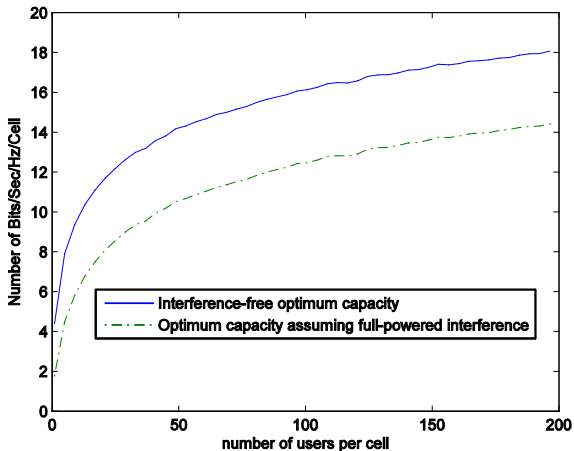
**Corollary :**

$$E(C(\mathbf{U}^*, \mathbf{P}^*)) \approx \frac{\epsilon}{2} \log U \quad (8)$$

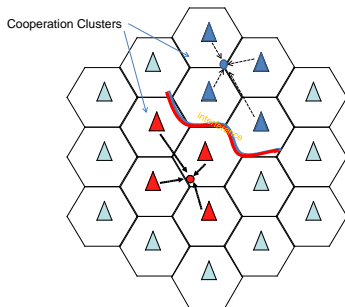
- Interference creates vanishing loss for large number of users
- **No big price paid for looking for small intf users!**

*[Gesbert Kountouris Trans IT 2010]*

# CAPACITY SCALING FOR 4 CELL NETWORK



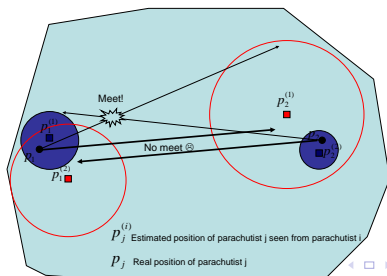
# MULTI-CELL MIMO WITH CLUSTERING



- However our intuition is that the **degree of cooperation** should **vary continuously** with distance...
- Schemes with **continuous** range of cooperation?

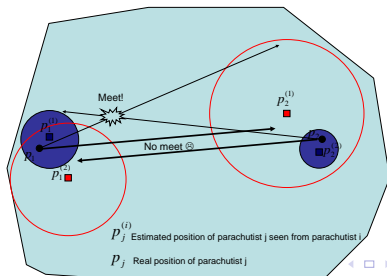
# TEAM DECISION PROBLEM: THE DISTRIBUTED RENDEZ-VOUS PROBLEM

- Two paratroopers are launched over unknown city.
- They have **different** and **imprecise** information about their own and each other's position.
- **Problem:** *Pick a direction to walk into, so as to meet a quickly as possible*



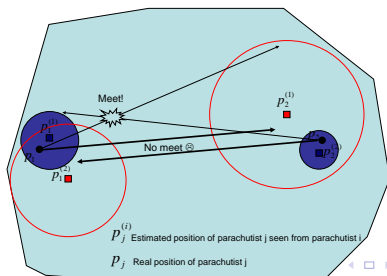
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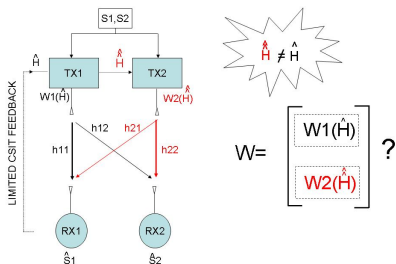


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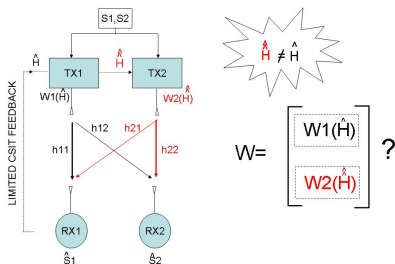


# THE DISTRIBUTED MIMO PRECODING PROBLEM



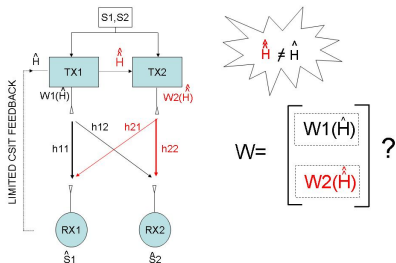
- Each TXer observes the global channel state through a unique limited-feedback channel
- All TXers must choose precoding solution approximating a global optimization solution, based on local info.
- It is a **team decision** problem.

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# THE TEAM DECISION MIMO PROBLEM

The optimal thing to do:

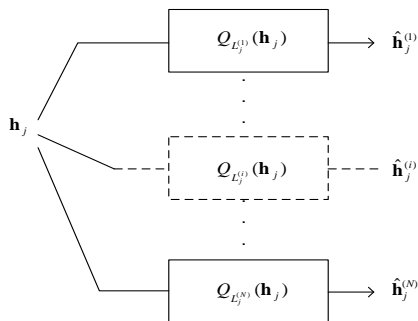
$$\max_{\{\mathbf{w}_1, \dots, \mathbf{w}_N\}} E \sum_{j=1}^M \log(1 + \text{SNR}_j(\mathbf{w}_1(\hat{\mathbf{h}}_1^{(1)}, \dots, \hat{\mathbf{h}}_M^{(1)}), \dots, \mathbf{w}_N(\hat{\mathbf{h}}_1^{(N)}, \dots, \hat{\mathbf{h}}_M^{(N)}))) \quad (9)$$

The (slightly) easier thing to do:

$$\forall i \max_{\{\mathbf{w}_i\}} E_i \sum_{j=1}^M \log(1 + \text{SNR}_j(\mathbf{w}_1(\hat{\mathbf{h}}_1^{(1)}, \dots, \hat{\mathbf{h}}_M^{(1)}), \dots, \mathbf{w}_N(\hat{\mathbf{h}}_1^{(N)}, \dots, \hat{\mathbf{h}}_M^{(N)}))) \quad (10)$$

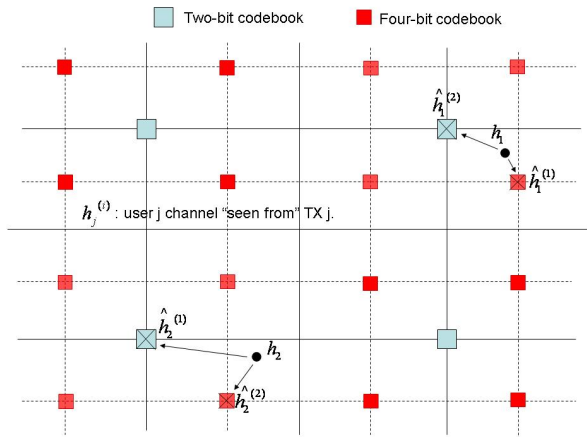
where  $E_i$  denotes the expectation over all channels, conditioned on CSI at TXer  $i$ , i.e.  $\hat{\mathbf{h}}_1^{(i)}, \dots, \hat{\mathbf{h}}_M^{(i)}$ . The **information structure**  $\{\mathbf{h}_j^{(i)}\} \rightarrow \{\hat{\mathbf{h}}_j\}$  determines the difficulty of the problem

# A QUANTIZATION MODEL OF DISTRIBUTED CSI



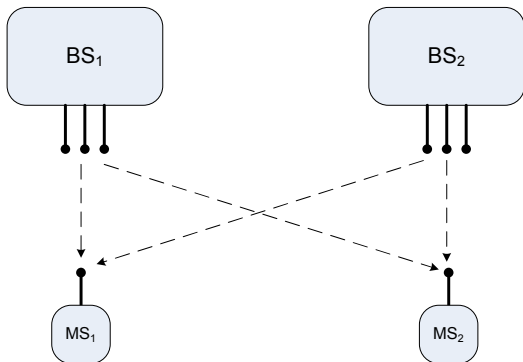
- We assume feedback link between user  $j$  and base  $i$  has decodable rate  $L_j(i)$  bits.
- All codebooks and feedback rates known at all bases.
- Model encompasses *perfect CSIT*, *limited CSIT* as particular cases.

# NESTED CSIT VIA HIERARCHICAL CODEBOOKS



Hierarchical codebooks allows some bases to (partially or totally) reconstruct feedback information at other bases.

# EXAMPLE: SYMMETRIC CSIT



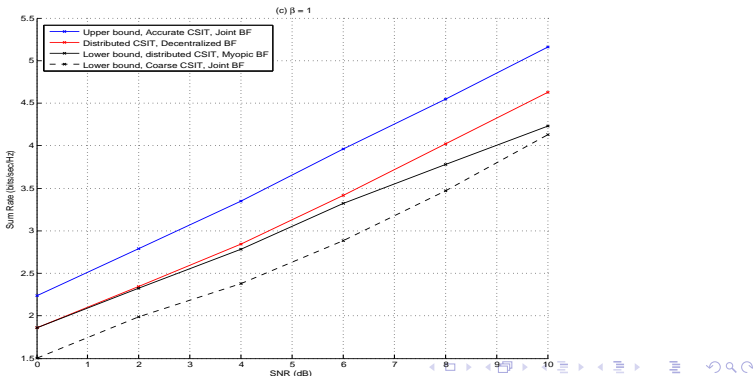
## OTHER SCHEMES

What to do with unequal, imperfect channel estimates?

- **Myopic**: Just look at your own estimates and pretend other transmitters have the same.
- **Cautious**: Only exploit coarse channel estimates, to guarantee consistency.
- **Optimistic**: Exploit finer channel estimates at all transmitters (not practical, just an upper bound)

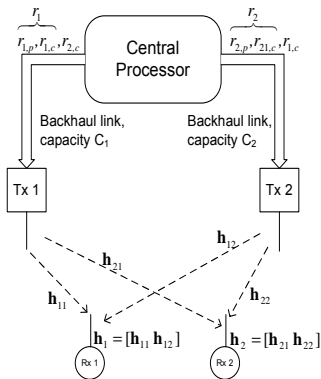
# PERFORMANCE EVALUATION: STRONG INTERFERENCE ( $\beta = 1$ ) TWO SINGLE-ANTENNA BASES AND USERS.

CSI is quantized respectively using  $L_1(2) = L_2(1) = 2$  bits and,  
 $L_1(1) = L_2(2) = 4$  bits



# BRIDGING THE INTERFERENCE AND MIMO CHANNELS

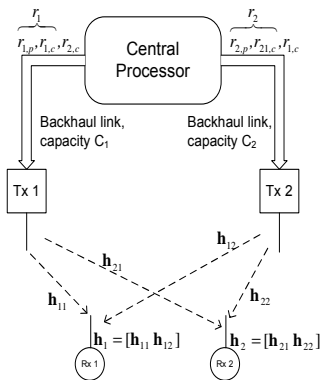
## Partial user data sharing with fully shared CSI



- Rate of user  $i$ ,  $r_i$ , is split into two parts:
  - Private message, from Tx  $i$  alone,  $r_{i,p}$
  - Shared message, from both Txs,  $r_{i,c}$ .
- Extreme cases:
  - $r_{i,c} = 0 \Rightarrow r_i = r_{i,p}$ : IC.
  - $r_{i,p} = 0 \Rightarrow r_i = r_{i,c}$ : BC (network MIMO).

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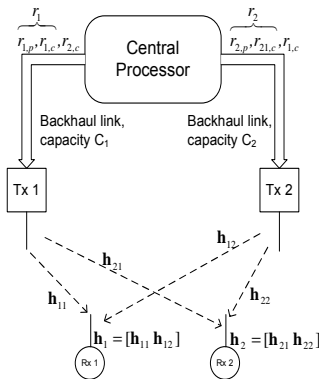
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## SIGNAL MODEL

Linear beamforming on private and common messages:

$$\mathbf{x} = \begin{bmatrix} \mathbf{w}_{1,c} & \mathbf{w}_{2,c} \end{bmatrix} \begin{bmatrix} s_{1,c} \\ s_{2,c} \end{bmatrix} + \begin{bmatrix} \mathbf{w}_{1,p} \\ \mathbf{0} \end{bmatrix} s_{1,p} + \begin{bmatrix} \mathbf{0} \\ \mathbf{w}_{2,p} \end{bmatrix} s_{2,p}, \quad (11)$$

Subject to power constraints:

$$\|\mathbf{D}_i \mathbf{w}_{1,c}\|^2 + \|\mathbf{D}_i \mathbf{w}_{2,c}\|^2 + \|\mathbf{w}_{i,p}\|^2 \leq P_i, \quad i = 1, 2. \quad (12)$$

# ACHIEVABLE RATES

**Theorem:** The following rates are achievable (Slepian-Wolf)

$$r_{i,p} \leq \log_2 \left( 1 + \frac{|\mathbf{h}_{ii}\mathbf{w}_{i,p}|^2}{\sigma_i^2} \right),$$

$$r_i = r_{i,p} + r_{i,c} \leq \log_2 \left( 1 + \frac{|\mathbf{h}_{ii}\mathbf{w}_{i,p}|^2 + |\mathbf{h}_i\mathbf{w}_{i,c}|^2}{\sigma_i^2} \right) \quad (13)$$

where

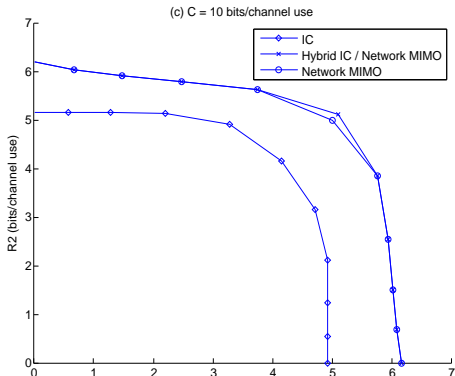
$$\sigma_i^2 = \sigma^2 + \left| \mathbf{h}_{ii}\mathbf{w}_{i,p} \right|^2 + \left| \mathbf{h}_i\mathbf{w}_{i,c} \right|^2 \quad (14)$$

[Zakhour, Gesbert 2010]

# NUMERICAL RESULTS

## SAMPLE RATE REGION BOUNDARY

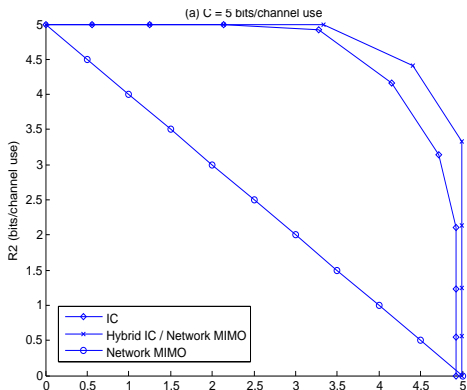
### Generous backhaul ( $C=10$ Bits/Sec/Hz)



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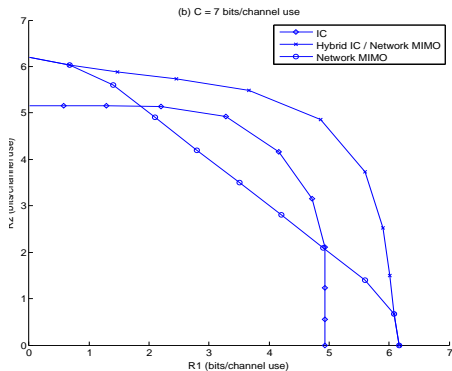
### Restricted backhaul ( $C=5$ Bits/Sec/Hz)



# NUMERICAL RESULTS

## SAMPLE RATE REGION BOUNDARY

Intermediate backhaul ( $C=7$  Bits/Sec/Hz)



# PERSPECTIVES

- Cooperation: the ultimate weapon against interference?
- Difficulty lies more in the **data exchange issues** than in the computational or hardware complexity
- Key theoretical problems yet to solve:
  - Just how much information of any given channel/user data is needed at each cooperating device?
  - Robust precoding designs needed to cope with partial information sharing
  - Architecture design: How to best disseminate limited information exchange? (feedback topologies)
- More details and references:

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- Difficulty lies more in the **data exchange issues** than in the computational or hardware complexity
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