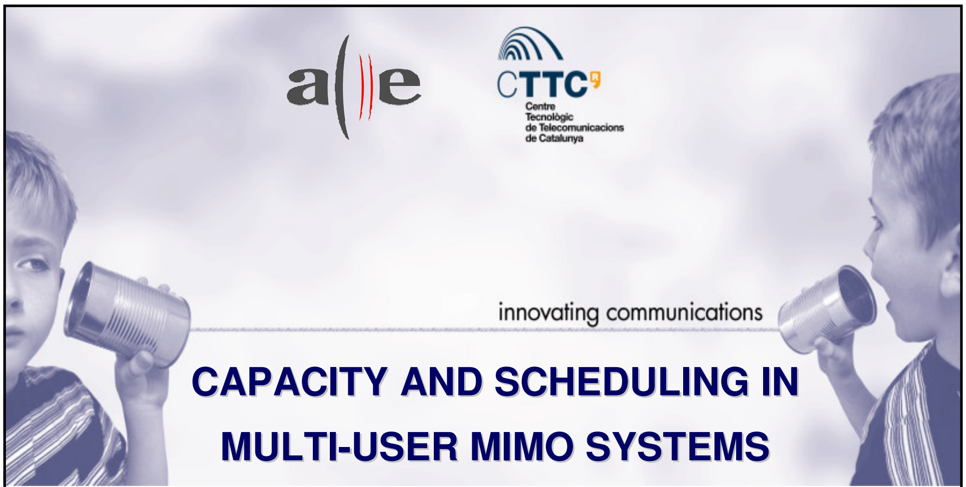

CAPACITY AND SCHEDULING IN MULTI-USER MIMO SYSTEMS

A cross-layer approach

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ACE Course on *MIMO Communication Systems and Antennas*, KTH, Stockholm, Sept 5-9, 2005.

REFERENCES

The sources of this seminar are mainly:

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MOTIVATION

- Best way for multiple users to transmit over a shared medium? Orthogonal access? Simultaneous?
- Differences between uplink (multiple access) and downlink (broadcast) channels?
- Impact of multiple transmit and/or multiple receive antennas?
- In multi-user systems, can we take advantage of fading?
- Can the scheduling process be enhanced with channel-related information?
- Combined use of queue and channel information for scheduling?
- Information theory approach: keep it general !!

OUTLINE

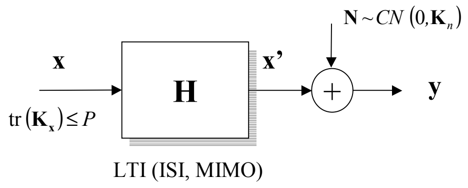
- Motivation
- A review of capacity issues in single-user systems
  - ✓ Definition, Capacity for MIMO systems.
- Capacity issues in multi-user systems:
  - ✓ Broadcast (BC) and Multiple Access (MAC) channels.
  - ✓ Capacity regions for SISO BC & MAC. Sum capacity. Symmetric capacity.
  - ✓ Multi-user diversity. Channel-aware scheduling.
    - ✓ Fairness issues: Proportional Fair Scheduling
    - ✓ Slow-fading channels: Opportunistic Beamforming
- Channel- and queue-aware scheduling
  - ✓ Motivation
- Q&A

OUTLINE

- Motivation
- **A review of capacity issues in single-user systems**
  - **Definition, Capacity for MIMO systems.**

A REVIEW OF CAPACITY ISSUES IN SINGLE-USER SYSTEMS

CAPACITY IN LINEAR TIME INVARIANT SYSTEMS



GAUSSIAN NOISE!!

•Definition of mutual information

$$I(X;Y) = h(X) - h(X|Y) \quad \text{with} \quad h(X) = E_x(-\log f_x(x))$$
$$h(X|Y) = E_{xy}(-\log f_{x|y}(x|y))$$

- *Information capacity* of an AWGN channel with power constraint P:

$$C = \max_{f_x(x)} I(X;Y)$$
$$s.t. \quad \mathrm{tr}(\mathbf{K}_x) \leq P$$

- Mutual information maximized for *GAUSSIAN input*:

$$\mathbf{X} \sim CN(0, \mathbf{K}_x)$$

CAPACITY IN LINEAR TIME INVARIANT SYSTEMS

- In these conditions, maximizing mutual information amounts to:

Signal

$$C = \max_{f_x(x)} I(X;Y) = \max_{\mathbf{K}_x} I(X;Y) = \max_{\mathbf{K}_x} \log \frac{|\mathbf{K}_n + \mathbf{H}\mathbf{K}_x\mathbf{H}^H|}{|\mathbf{K}_n|}$$

Noise + interference

$$s.t. \quad \mathrm{tr}(\mathbf{K}_x) \leq P$$

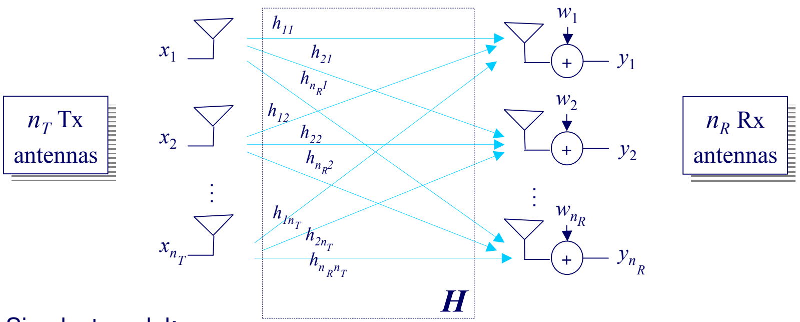
- **Remarks:**
  - In general, $\mathbf{K}_x$ depends on $\mathbf{H}$ and what information is available @ Tx side (partial, full, none).
  - Units: bits/s/Hz…when log = $\log_2$
  - Interpretation (Shannon's Channel Capacity Theorem): For every data rate R…

Information capacity (C) provides an upper bound of the achievable data rates (R)

- Assumptions: Gaussian input symbols & ideal channel coding (and decoding)
- Useful equivalence:

$$C = \max_{\mathbf{K}_x} \log \frac{|\mathbf{K}_n + \mathbf{H}\mathbf{K}_x\mathbf{H}^H|}{|\mathbf{K}_n|} = \max_{\mathbf{K}_x} \log \left| \mathbf{I} + \mathbf{K}_n^{-1}\mathbf{H}\mathbf{K}_x\mathbf{H}^H \right|$$

MIMO CHANNEL MODEL



- Simplest model:
  - Channel: Flat fading (frequency), static / independent Rayleigh fading (time)
  - Noise: Gaussian (spatially) white $\mathbf{N} \sim CN\,(0, \mathbf{K}_n) \rightarrow \mathbf{W} \sim CN\,(0, N_o I_{n_R})$

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_{n_R} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1n_T} \\ h_{21} & h_{22} & \cdots & h_{1n_T} \\ \vdots & \vdots & \ddots & \vdots \\ h_{n_R 1} & h_{n_R 2} & \cdots & h_{n_R n_T} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{n_T} \end{bmatrix} + \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_{n_R} \end{bmatrix} \qquad \mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w}$$

CAPACITY OF MIMO SYSTEMS (LTI)

$$C = \max_{\mathbf{K}_x} \log \left| \mathbf{I} + \mathbf{K}_w^{-1} \mathbf{H} \mathbf{K}_x \mathbf{H}^H \right| \qquad \mathbf{K}_w = N_o \mathbf{I}_{n_R}$$

- **SISO**, Shannon Capacity

$$\mathbf{K}_x = P \quad (\mathbf{K}_w = N_o) \Rightarrow C = \log\left(1 + \frac{P|h|^2}{N_o}\right) = \log(1 + \text{SNR})$$

Asympt growth
LOG in power
i.e. 1 bits/s/Hz every 3 dB

- **MIMO, no CSI at Tx** – Isotropic transmission:

$$\mathbf{K}_x = \frac{P}{n_T}\mathbf{I}_{n_T} \Rightarrow C = \log\left| \mathbf{I} + \frac{P}{N_o n_T}\mathbf{H}\mathbf{H}^H \right|$$

$$C \approx n \log \frac{P}{N_0 n_T} + \sum_{i=1}^{n} \log \lambda_i^2$$

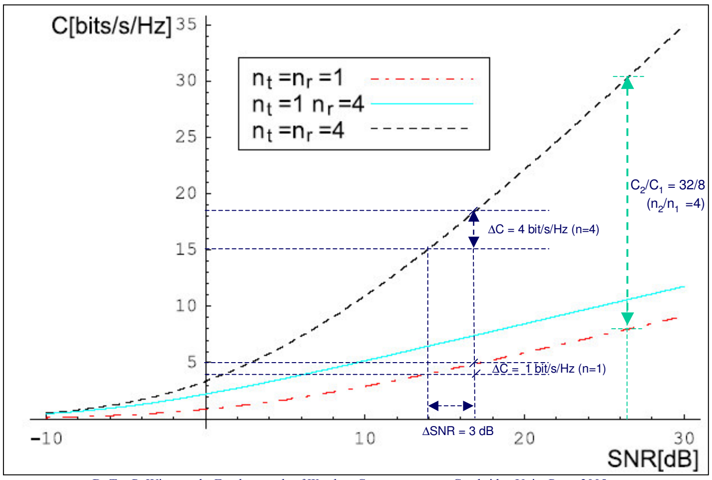
Asympt growth
LOG in power
LIN in antennas
i.e. n bits/s/Hz every 3 dB

- **MIMO, full CSI at Tx** – Waterfilling over channel eigenmodes (SVD):

$$\mathbf{K}_x = \mathbf{V}\,\text{diag}(P_1 \ \ldots \ P_n)\mathbf{V}^H \quad \mathbf{H} = \mathbf{U}\,\text{diag}(\lambda_1 \ldots \lambda_n)\mathbf{V}^H \Rightarrow C = \sum_{i=1}^{n} \log\left[1 + N_0^{-1}\lambda_i^2 P_i\right]$$

Power allocation (Lagrange): $P_i(\lambda_i) = \left(\mu - \frac{N_0}{\lambda_i^2}\right)^+ \quad i = 1 \ldots n \quad \sum_{i=1}^{n} P_i = P \quad n = \min(n_T, n_R)$

CAPACITY OF MIMO SYSTEMS (LTI)



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SISO: LOG in power

i.e. 1 bits/s/Hz every 3 dB

MIMO: LOG in power, LIN in antennas

i.e. n bits/s/Hz every 3 dB

OUTLINE

- Motivation
- A review of capacity issues in single-user systems
  - Definition, Capacity for MIMO systems, time-varying systems.
- **Capacity issues in multi-user systems:**
  - **Broadcast (BC) and Multiple Access (MAC) channels.**
  - **Capacity regions for SISO BC & MAC. Sum capacity. Symmetric capacity.**
  - **Multi-user diversity. Channel-aware scheduling.**
    - **Fairness issues: Proportional Fair Scheduling**
    - **Slow-fading channels: Opportunistic Beamforming**
  - **Capacity regions for MIMO BC & MAC. Duality principle.**

CAPACITY ISSUES IN MULTI-USER SYSTEMS

BROADCAST AND MULTIPLE-ACCESS CHANNELS

Broadcast Channel (BC):

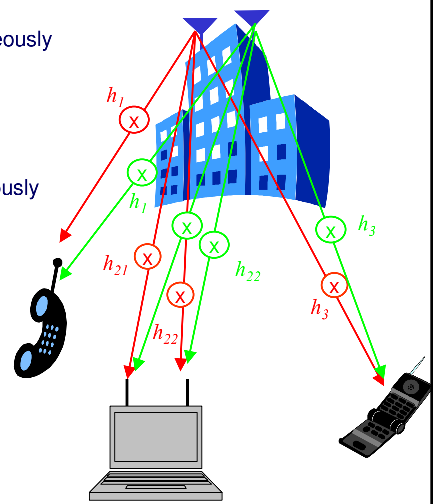
- Downlink
- One transmitter to many receivers simultaneously

Multiple Access Channel (MAC):

- Uplink
- Many transmitters to one receiver simultaneously

Remarks:

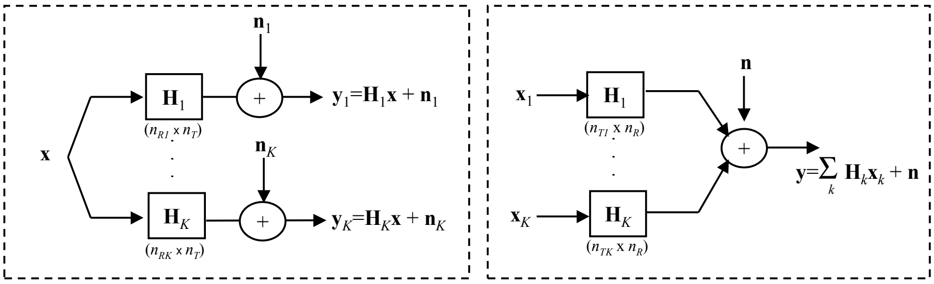
- Users can be regarded as an antenna array in a large area.
- Cooperation among antennas within the SAME location.
- Multiple antennas in one location enable Space Division Multiple Access or stream Multiplexing.



MIMO BC and MAC – CHANNEL MODEL

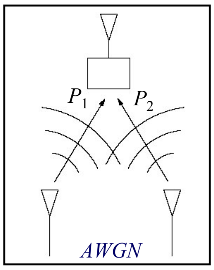
- One base station (BS) equipped with n_T (n_R) antennas
- K user equipments (UE) equipped with n_{Rk} (n_{Tk}) antennas each

BS Shared power constraint | **UE individual power constraints**



Broadcast Channel (BC) | **Multiple Access Channel (MAC)**

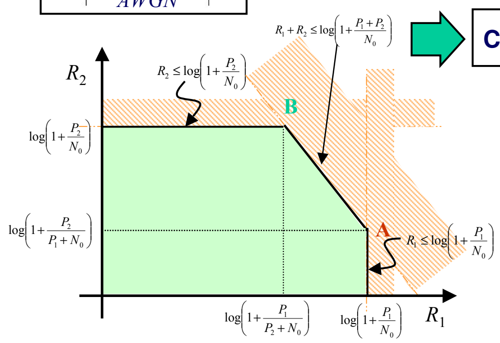
CAPACITY REGION FOR MAC-AWGN



- SISO, MAC, AWGN channel, K=2 users:

$$y[m] = x_1[m] + x_2[m] + w[m]$$

- **Single user:** Rate R achievable iff R<C → C upper perf. bound
- **Multi-user:** UEs communicate with BS in a shared bandwidth → trade-offs turning up!!
  - Set of achievable rates (R_1,R_2) with simultaneous communication??

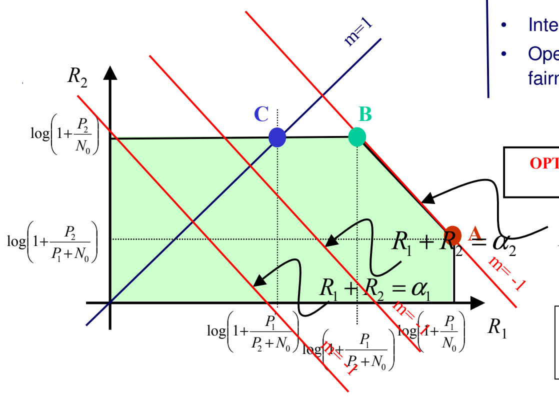


CAPACITY REGION, $\mathcal{C}$!!

- Characterizes *optimal* trade-off achievable by *any* MA scheme.
- User 2 gets R_2>0 while user 1 attains single-user bound (**A**) !!
- HOW? *Successive interference Cancellation* (SIC).
- Reversing detection order leads to different rate split (**B**) - fairness

MEASURES OF INTEREST

- Some performance measures (scalars) for a capacity region:
  - *Sum capacity* $C_{\text{sum}} := \max_{(R_1,R_2)\in C} R_1 + R_2$
    - Reached at **A**,**B** segment (ANY point)
    - Points **A**,**B** achievable via SIC
    - Intermediate points in **AB** via time/freq sharing
    - Operating point TBD according to priorities or fairness constraints



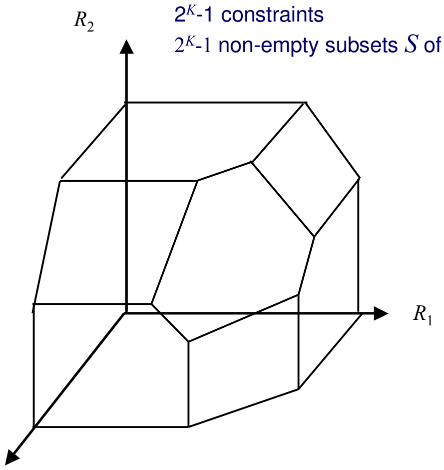
Best policy in MAC-SISO:
ALL users at a time (+ SIC)

- *Symmetric capacity* $C_{\text{sym}} := \max_{(R,R)\in C} R$
  - Reached @ boundary (near/far) - **C**

GENERAL CASE: MAC with K users

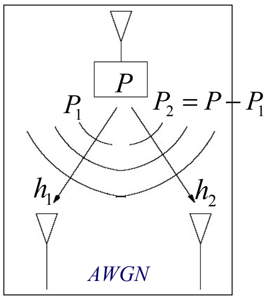
$$\sum_{k\in S} R_k \le \log\left(1+\frac{\sum_{k\in S} P_k}{N_0}\right)$$

2^K-1 constraints
2^K-1 non-empty subsets S of users



$$R_1 \le \log\left(1+\frac{P_1}{N_0}\right)$$
$$R_2 \le \log\left(1+\frac{P_2}{N_0}\right)$$
$$R_3 \le \log\left(1+\frac{P_3}{N_0}\right)$$
$$R_1+R_2 \le \log\left(1+\frac{P_1+P_2}{N_0}\right)$$
$$R_2+R_3 \le \log\left(1+\frac{P_2+P_3}{N_0}\right)$$
$$R_1+R_3 \le \log\left(1+\frac{P_1+P_3}{N_0}\right)$$
$$R_1+R_2+R_3 \le \log\left(1+\frac{P_1+P_2+P_3}{N_0}\right)$$

CAPACITY REGION FOR BC-AWGN



- SISO, BC, AWGN channel, K=2 users:

$$y_1[m] = h_1 x[m] + w_1[m] \qquad y_2[m] = h_2 x[m] + w_2[m]$$

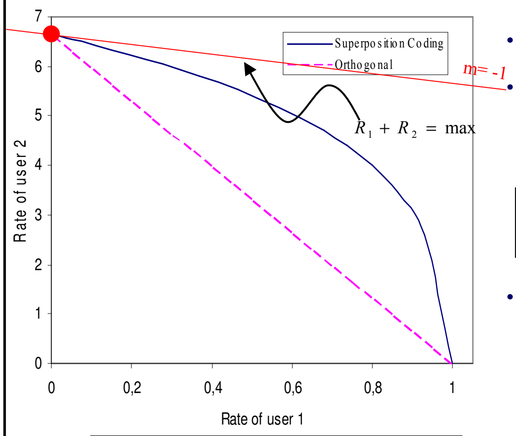
- BS communicates with UE in a shared bandwidth & shared power (P) → trade-offs turning up!!
  - How to MUX data for both users at the BS? $x[m] = ??$
  - Set of achievable rates (R_1,R_2) with simultaneous comms.??
- Assume: User 2 is the "strongest" $\left(|h_2| \geq |h_1|\right)$ and superposition coding $x[m] = x_1[m] + x_2[m]$
- If x_1 decodable at UE_1 (weakest) in the presence of x_2, so is at UE_2 (strongest) for all power splits P_1, P_2 (not possible if reversed order)

$$\mathrm{SNIR}_{x_1 @ \mathrm{UE}_1} = \frac{P_1 |h_1|^2}{(1-P_1)|h_1|^2 + N_0} \leq \frac{P_1 |h_2|^2}{(1-P_1)|h_2|^2 + N_0} = \mathrm{SNIR}_{x_1 @ \mathrm{UE}_2}$$

- So apply SIC at the strongest (UE_2) and

$$\mathrm{R}_1 = \log\left(1 + \frac{P_1 |h_1|^2}{(P-P_1)|h_1|^2 + N_0}\right) \qquad \mathrm{R}_2 = \log\left(1 + \frac{(P-P_1)|h_2|^2}{N_0}\right)$$

CAPACITY REGION FOR BC-LTI (cont'd)



$$\mathrm{R}_1 = \alpha \log\left(1 + \frac{P_1 |h_1|^2}{\alpha N_0}\right) \qquad \mathrm{R}_2 = (1-\alpha)\log\left(1 + \frac{P_2 |h_2|^2}{(1-\alpha) N_0}\right)$$

$$\alpha = \alpha_{\mathrm{opt}} = \frac{P_1}{P_1 + P_2} = \frac{P_1}{P}$$

Orthogonal multiple access

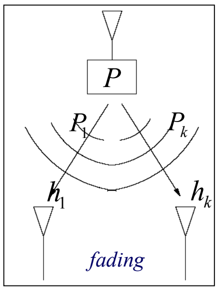
- **SC boundary** given by all P_1/P_2 splits
- **Sum-rate:** allocate ALL power to strongest user (UE_2)
  …at the expense of delays!!

Best policy in BC-SISO: ONE user at a time

(vs. MAC-SISO: ALL users simultaneously)

- **Orthogonal multiple access** strictly suboptimal for all power splits!!
  - SC: low power for strong user (UE_2) is efficiently exploited (x_1 removed) and low interference to weaker (UE_1)
- **Remarks:**
  - Strong assumption: DEGRADED BC
  - MIMO is non degraded.
  - Degradation not needed in UL (centralized Rx & CSI).

BC CHANNEL WITH FADING



- SISO, BC, fading channel, *K* users:

$$y_k[m] = h_k[m]x[m] + w_k[m]$$

- Assumptions:
  - Fading processes ($\{h_k[m]\}$): Independent and identically distributed (symmetric case).
  - Power constraint (pooled power) : $E_H\left[\sum_{k=1}^{K} P_k[m]\right] = P$

- Take the case with CSIT (i.e power allocation possible):
  - AWGN: Sum capacity maximized by transmitting to the BEST user
  - Fading: Schedule the BEST user at EACH time (*greedy* approach). Equivalent point-to-point channel

$$|h|^2_{\text{eq}} = \max_{k=1..K} |h_k|^2$$

- How to allocate power? Temporal waterfilling for the equivalent P2P channel

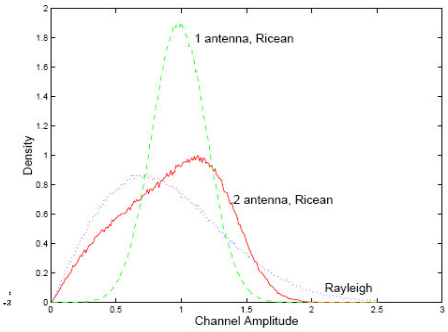
$$P^*(\mathbf{h}) = \left(\frac{1}{\lambda} - \frac{N_0}{\max_{k=1..K}|h_k|^2}\right)^+ \quad \Rightarrow \quad C_{\text{sum}} = \mathrm{E}_h\left[\log\left(1 + \frac{P^*(\mathbf{h})\left(\max_{k=1..K}|h_k|^2\right)}{N_o}\right)\right]$$

MULTI-USER DIVERSITY (MUDiv) GAIN

- With *K* users *FADING INDEPENDENTLY* and OPPORTUNISTIC (*DYNAMIC*) *SCHEDULING*, channel gain improves

$$|h_1|^2 \rightarrow |h|^2_{\text{eq}} = \max_{k=1..K} |h_k|^2$$

Higher gain means higher (sum) rate!!



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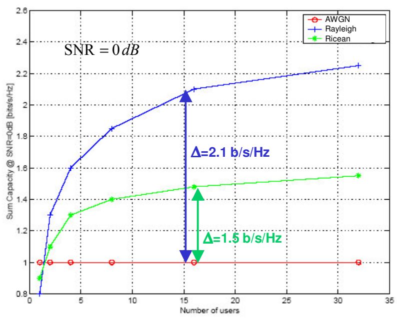

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- Gain wrt AWGN for K>1 (mid-high SNR)
- The amount of MUDiv increases with pdfs' tails: Rayleigh > Rice (κ=5, LOS, less "random")
- MUDiv gain increases with nr. of users (*K*): the stronger is the strongest channel

MULTI-USER vs. CLASSICAL DIVERSITY

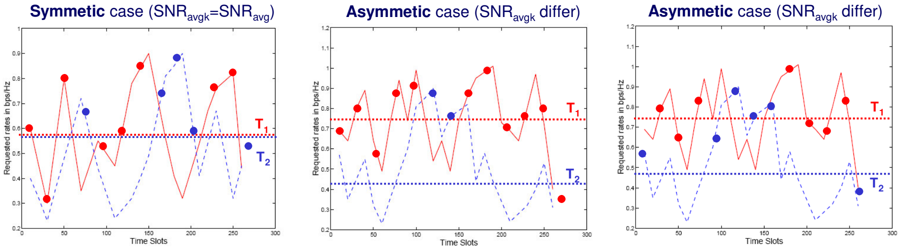
- **Purpose:**
  - Classical (time/frequency/space): Increase link *reliability* (slow fading)
  - MUDiv: Increase *average* cell *throughput* (fast fading)
    …but no rate guarantees in *specific* fading states
- **Means:**
  - Classical: *Counteract* adverse fading effects.
  - MUDiv: *Exploit* independent fading (capture strongest user)
- **Scope:**
  - Classical: Works at the *link* level
  - MUDiv: *System-wide* (active users)

REMARKS ON MUDiv

- **Signalling:**
  - UEs: Track their link quality (common pilot)
  - BS: Access to quality measurements (feedback channel)
- **Delay in the feedback channel** (ass.: delay&error free)
  - Mismatch actual channel-measured channel
  - FIX: ↓ scheduling slots ⇒ ↑ signalling overhead ⇒ selective MUDiv (f/b iff above threshold)
- **Fairness & delay:**
  - Non-homogeneous user set in real-world networks (assumed so far)
    - Different statistics (Rayleigh, Rice,…) average SNRs (near-far).. RESOURCE ALLOCATION ??
  - **FIX: Proportional Fair Scheduler (PFS)**

PROPORTIONAL FAIR SCHEDULING (PFS)

Symmetic case ($SNR_{avgk}=SNR_{avg}$) | **Asymmetic** case (SNR_{avgk} differ) | **Asymmetic** case (SNR_{avgk} differ)



Opportunistic-**greedy** is **FAIR** | Opportunistic-**greedy** is **UNFAIR** | Opportunistic-**PFS** is **FAIR**

- **Proportional Fair Scheduler**: Schedule user with *peak rate with respect to its average rate*

$$k^*[m] = \max_k \frac{R_k[m]}{T_k[m]} \qquad T_k[m] = \begin{cases} (1-1/t_c)T_k[m] + (1/t_c)R_k[m] & k = k^*, \\ (1-1/t_c)T_k[m] & k \neq k^* \end{cases}$$

- **PFS vs. *greedy*** opportunistic schedulers:
  - Both channel-dependent (vs.round-robin, vs. queue-based). PFS implemented in IS-856.
  - Greedy: No *short-term* fairness, captures MUDiv, maximizes *average* sum-rate.
  - PFS: No *short-term* fairness, *long-term* fairness (same # access), captures some MUDiv, loss in average sum-rate.
- Latency time scale (t_c), a design parameter: if larger, larger averaging period, higher latency (schedule when hitting a really high peak)

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REMARKS ON MUDiv

- **Signalling:**
  - UEs: Track their link quality (common pilot)
  - BS: Access to quality measurements (delay-free feedback channel)
- **Delay in the feedback channel** (ass.: delay&error free)
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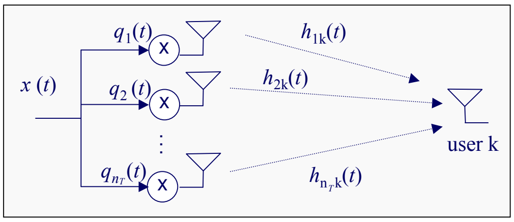
- **Fairness & delay:**
  - Non-homogeneous user set in real-world networks (assumed so far)
    - Different statistics (Rayleigh, Rice,…) average SNRs (near-far).. RESOURCE ALLOCATION ??
  - FIX: **Proportional Fair Scheduler (PFS)**
- **Limited and slow fluctuations** (ass: high & fast)
  - Limited: poor scattering/LOS – Slow : low mobility environment
  - Result: low cell throughput (peaks) - Delay requirements not met.
  - **FIX: Opportunistic beamforming.**

OPPORTUNISTIC BEAMFORMING

- Slow fading hurts: If all users fade slow ⇒ like K=1 user ⇒ no MUDiv
- Limited fluctuation hurts: lower peak rates



$\mathbf{q}[m] = [q_1[m] \ldots q_{n_T}[m]]^T$

$\mathbf{h}_k[m] = [h_{1k}[m] \ldots h_{n_T k}[m]]^T$

with

$\|\mathbf{q}[m]\|^2 = 1$

- **TRICK** (MISO): Induce fast and high fluctuations by transmit beamforming with a time-varying common set of random weights (e.g circularly symmetric Gaussian):

$$y_k[m] = \left(\mathbf{h}_k^T[m]\mathbf{q}[m]\right)x[m] + w_k[m] \Rightarrow \mathrm{SNR}_k[m] = \frac{\left|\mathbf{h}_k^T[m]\mathbf{q}[m]\right|^2}{N_0}$$

??? Random weights

measure at UE_k
feedback to BS

- **When are SNR peaks reached?:** When beam "points" at user *k*

$$\mathbf{q}[m] \,//\, \mathbf{h}_k^*[m] \Rightarrow$$ **"OPPORTUNISTIC BEAMFORMING"**

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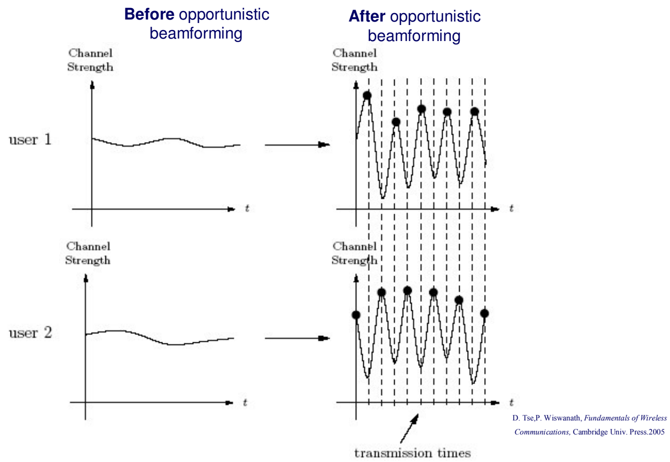
OPPORTUNISTIC BEAMFORMING (cont'd)



- **How fast should $\mathbf{q}[n]$ change?:** Design parameter:
  - *Fast enough* to induce fast fading
  - *Slow enough* for reliable channel estimation, timely feedback, stable loop.

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OPPORTUNISTIC BEAMFORMING (cont'd)

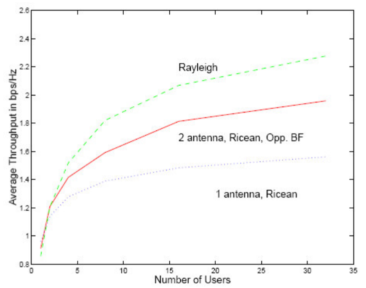
DOES OPPORTUNISTIC BEAMFORMING ALWAYS HELP?

- Slow fading $h_k[m]=h_k$: Constant $\rightarrow$ $\left|h_k^*\mathbf{q}[m]\right|^2$: Fast & high fluctuation **YES**
- Fast Rayleigh fading: $h_k[m]$: i.i.d. Gaussian $\rightarrow$ $h_k^*\mathbf{q}[m]$: i.i.d. Gaussian **NO**

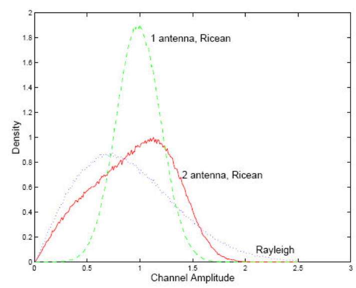
  i.e. identical distribution for ANY distribution of $\mathbf{q}$
- Fast Ricean Fading: $h_k[m]=h_k+h_{kw}[m]$ $\rightarrow$ $\left|\mathbf{h}_k^*[m]\mathbf{q}[m]\right|^2=\left|\mathbf{h}_k^*\mathbf{q}[m]+\mathbf{h}_w^*[m]\mathbf{q}[m]\right|^2$ **YES**

Additional power for FAST fluctuations

No additional fluctuations



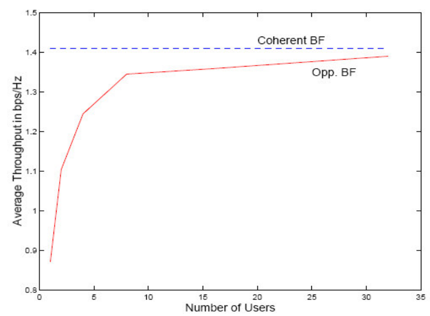
D. Tse,P. Wiswanath, *Fundamentals of Wireless Communications*, Cambridge Univ. Press.2005



D. Tse,P. Wiswanath, *Fundamentals of Wireless Communications*, Cambridge Univ. Press.2005

REMARKS ON OPPORTUNISTIC BEAMFORMING

Opportunistic vs. coherent beamforming:



D. Tse,P. Wiswanath, *Fundamentals of Wireless Communications*, Cambridge Univ. Press.2005

- Performance: Comparable for high *K* (always a user to point at)
- CSIT needs:
  - Opp.: SNR only (Opp.)!!!
  - Coherent: full CSI

Multiple transmit antennas just for inducing fluctuations? Can we do better?

YES

MULTIPLE ORTHOGONAL RANDOM BEAMS

+ Still inducing fast fading
+ Additional spatial multiplexing gain (SDMA)
- Extra overhead for SNR measurements & feedback

OUTLINE

- Motivation
- A review of capacity issues in single-user systems
  - Definition, Capacity for MIMO systems.
- Capacity issues in multi-user systems:
  - Broadcast (BC) and Multiple Access (MAC) channels.
  - Capacity regions for SISO BC & MAC. Sum capacity. Symmetric capacity.
  - Multi-user diversity. Channel-aware scheduling.
    - Fairness issues: Proportional Fair Scheduling
    - Slow-fading channels: Opportunistic Beamforming
- **Channel- and queue-aware scheduling**
  - **Motivation.**
- Q&A

CHANNEL- AND QUEUE-AWARE SCHEDULING

ASSUMPTIONS REVISITED

- **Implicit assumptions so far…**
  - Ass. 1: *Infinite* transmit buffer size:
    - Users can be delayed without bound (to maximize sum-rate).
    - Did not care much about packet arrival rates.
  - Ass.2 : Scheduled user(s) always have data to transmit
- **BUT in realistic scenarios…**
  - *Finite* buffer size:
    - When close to buffer overflow, user should be scheduled regardless of channel conditions.
    - If too many packets arrive, buffer bound to explode.
  - Traffic is *bursty*: no point in scheduling a user with empty buffer!
- **CONCLUSION:** *Channel* and *queue* (buffer) information must be jointly considered in the scheduling process (i.e. cross-layer)

QUESTIONS ?