Opportunistic beamforming

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- The ordering of the users clearly matters in such a procedure and needs to be optimized in the capacity computation
- For latency reasons (M<K). Then the throughput can be further optimized with respect to the active user set

- All channel knowledge is needed

Caire&Shamai
IT, July03

Ergodic capacity

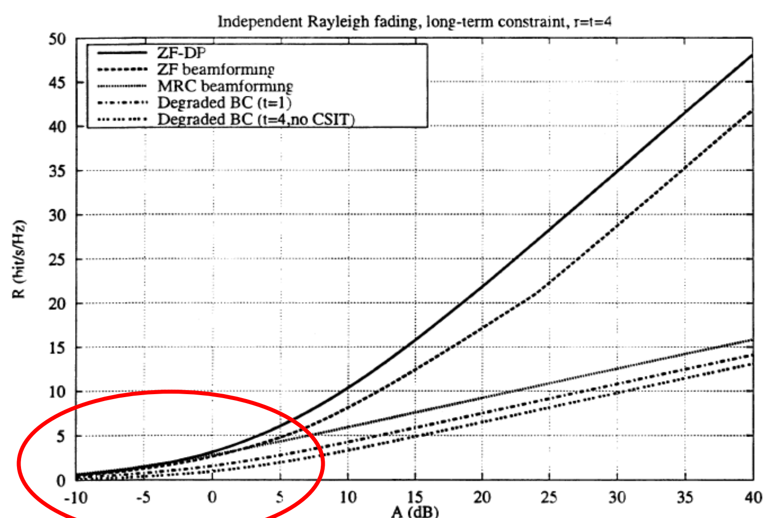


Fig. 5. Throughput versus SNR comparison for a system with independent Rayleigh fading and long-term input constraint, ZF-DP, ZF, MRC with $t = 4$, $r = 4$, the degraded GBC with $t = 1$, $r = 4$, and the degraded GBC without channel state information at the transmitter (no CSIT), $t = 4$ and arbitrary r.

Transmit beamforming: Problem Statement

The goal is $$C^{DP} = \sum_k \log\left(1 + SNIR_k\right)$$

The general space-time linear transmitter is $\mathbf{B} = \mathbf{U_T}.\mathbf{P}^{1/2}.\mathbf{V}^{\mathbf{H}}$ nt & N users

Under the multiple beam approach ($B=U_TP^{1/2}$)

$$\mathbf{x}_{nt\,xN} = \mathbf{Bu} = \sum_{m=1}^{nt} \mathbf{b}_m u_m$$

Let us consider rx with 1 antenna

The ith rx knows (Hi bm) m=1..nt (by training). Therefore, the ith rx can compute the following nt SINRs by assuming that the um is the desired signal and the other interference as follows

$$SINR_{i,m} = \frac{\left|\mathbf{H_i b_m}\ u_{im}\right|^2}{1/SNR + \sum_{u\neq m}\left|\mathbf{H_i b_m}\ u_{im}\right|^2} \quad m = 1..nt$$

user

beam

Transmit beamforming: Assymptotic optimality

Note that on average the SINRs behave like

$$SINR_{i,n} \approx \frac{1}{\frac{1}{SNR} + (nt-1)} \approx \frac{1}{nt-1}$$

Therefore if the beams are assigned randomly, the rate or throughput will be

$$R = E\left\{\sum_{i=1}^{nt} \log\left(1 + SINR_{i,m}\right)\right\} \le nt \log\left(1 + \frac{1}{nt-1}\right) \approx 1$$

No nt-fold increase in the throughput → CSIT is crucial

As an alternative Hassibi presented an scheme where nt orthogonal beams are assigned to nt users depending on the fedback SINR's

$$R = E\left\{\sum_{m=1}^{nt} \log\left(1 + \max_{1\le i\le Ntot} SINR_{i,m}\right)\right\} \approx ntE\left\{\log\left(1 + \max_{1\le i\le Ntot} SINR_{i,m}\right)\right\}$$

$\log \log Ntot$

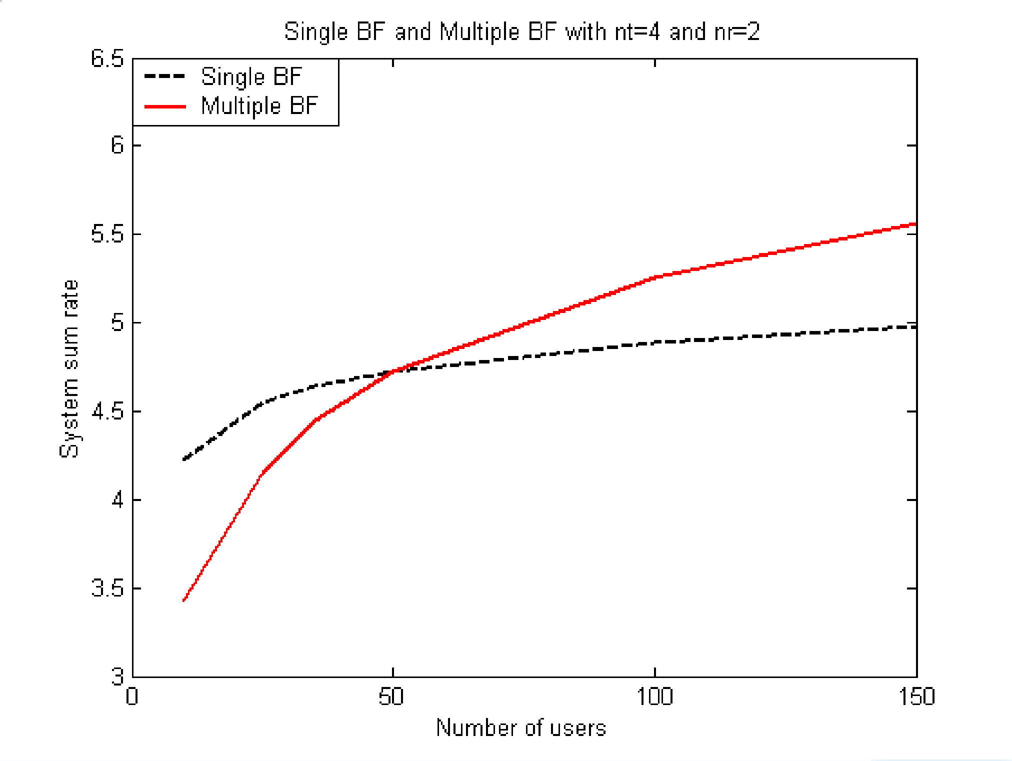
N goes to inf.

Partial CSIT

Transmit beamforming: Multiuser diversity

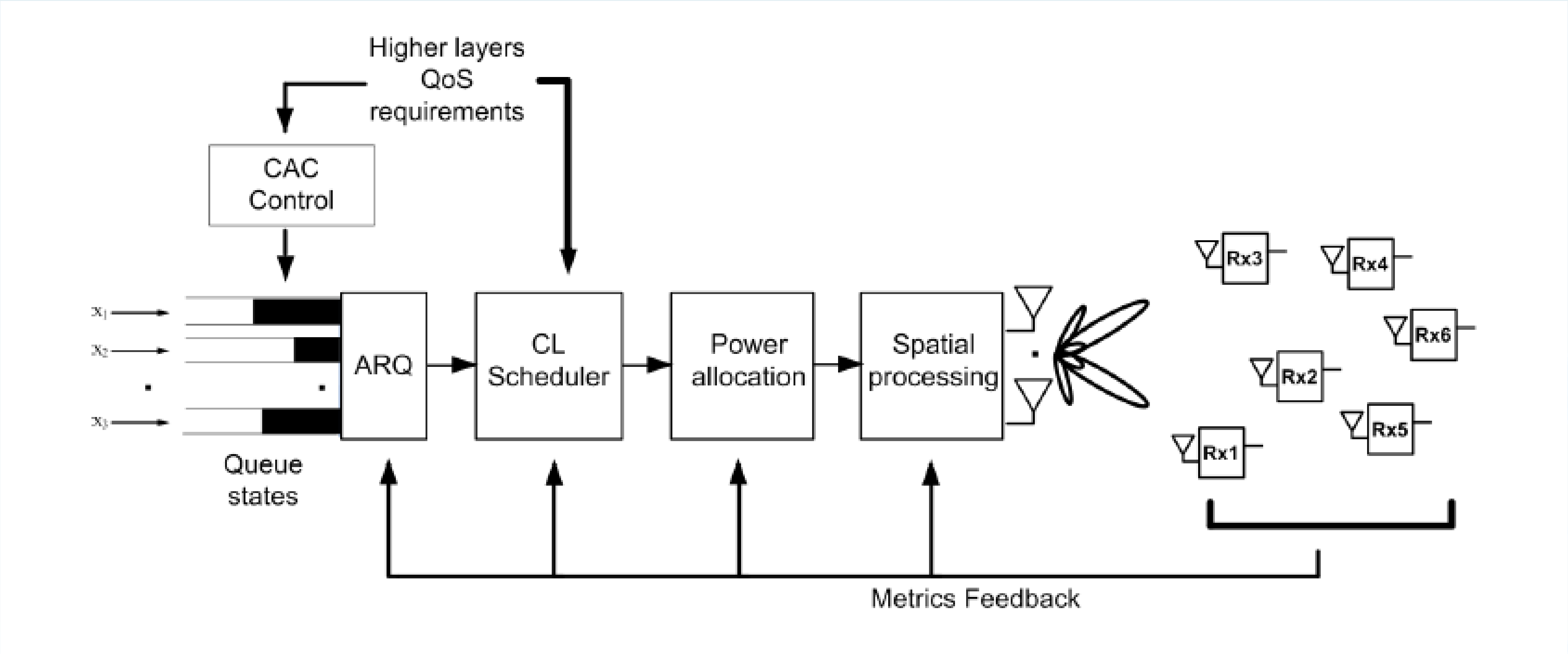
The DPC achieves the same sum capacity $$\lim_{N\to\infty} C_{DP} = n_t \log\log n_t N$$

Intuitively, if the number of users is large the probability of finding nt users placed at the point directions of the nt orthogonal beams is high, thus almost "nulling" the interference among them



Transmit beamforming: Multiuser diversity

Notice that this scheme not only provides a transmission scheme, but also a user selection approach over all the available users in the system: the BS only needs SNR information



Cross-layer system aspects come into play in a "natural way"

Multiuser diversity through the Opportunistic strategy

Opportunistic or “riding the peaks” strategy: choose the best one(s)

An opportunistic decision is not:

A deliverate or goal oriented decision (costly)

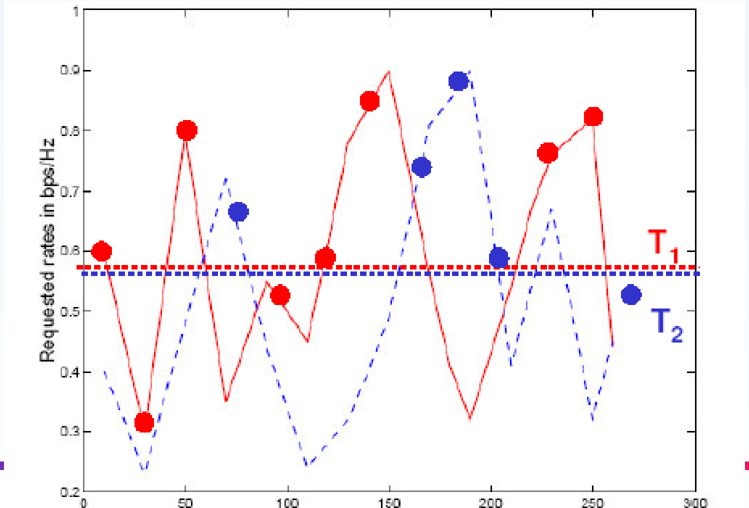
Nor

-A reactive decision (dead-end)

Nor

-A procedural decision (redundant)

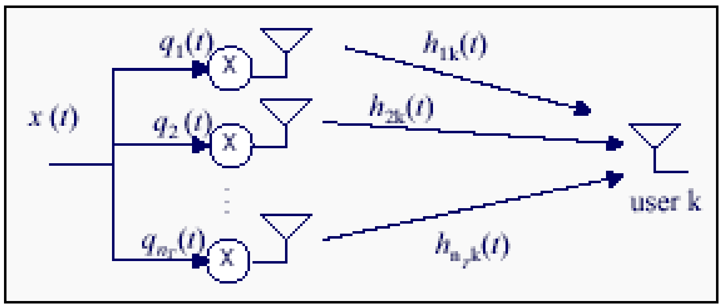
Initially it was thought for single user and single antenna set-up



Opportunistic beamforming (1 beam)

Goal: Design beamformers that require low CSI and that achieve high system sum rate in a multiuser Rayleigh fading channel

- 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):

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

??? — Random weights

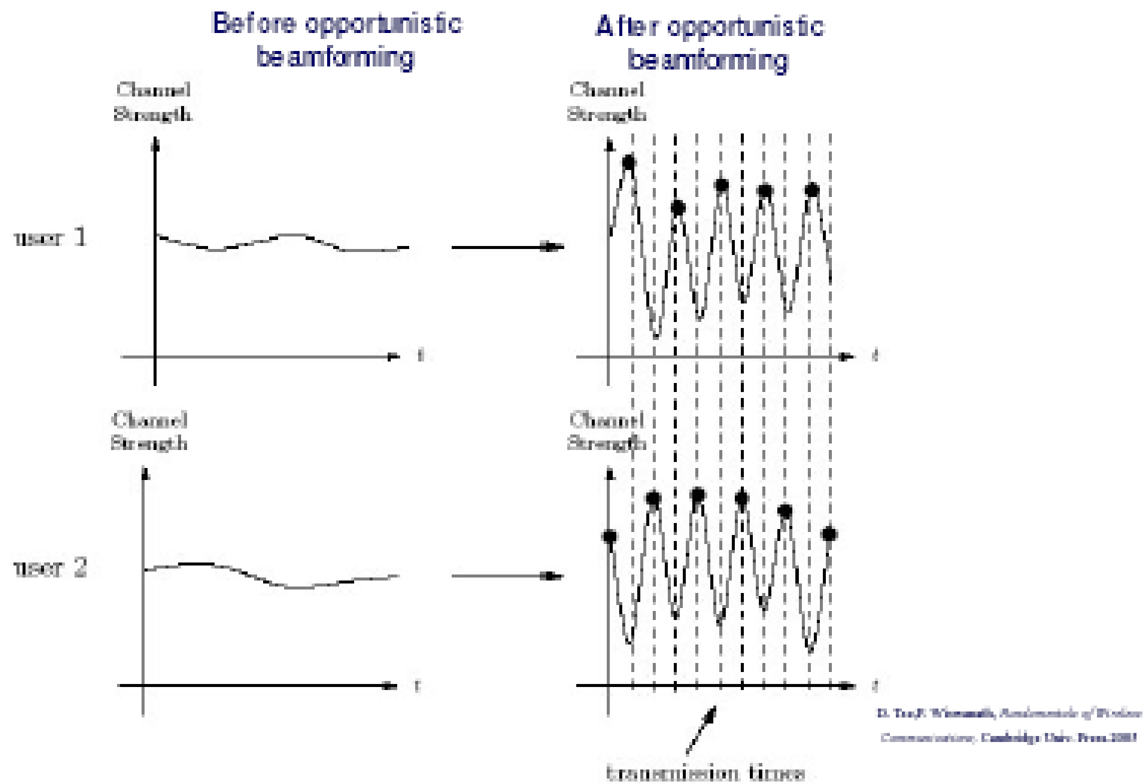
measure at UE$_k$
feedback to BS

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

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

AND with more than one user?

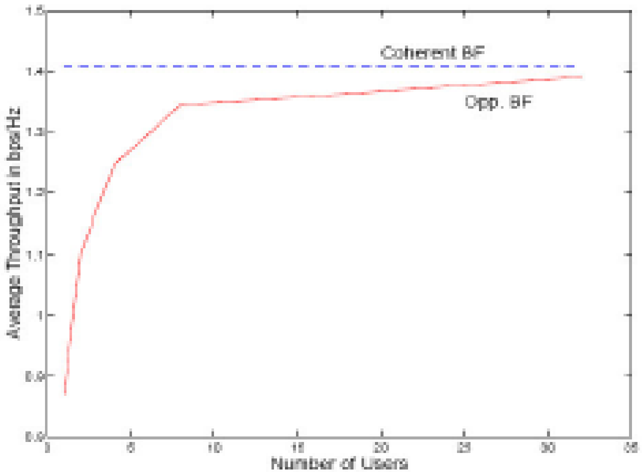
Opportunistic beamforming (1 beam)



- 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.

Opportunistic beamforming (1 beam)

Opportunistic vs. coherent beamforming:



- 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

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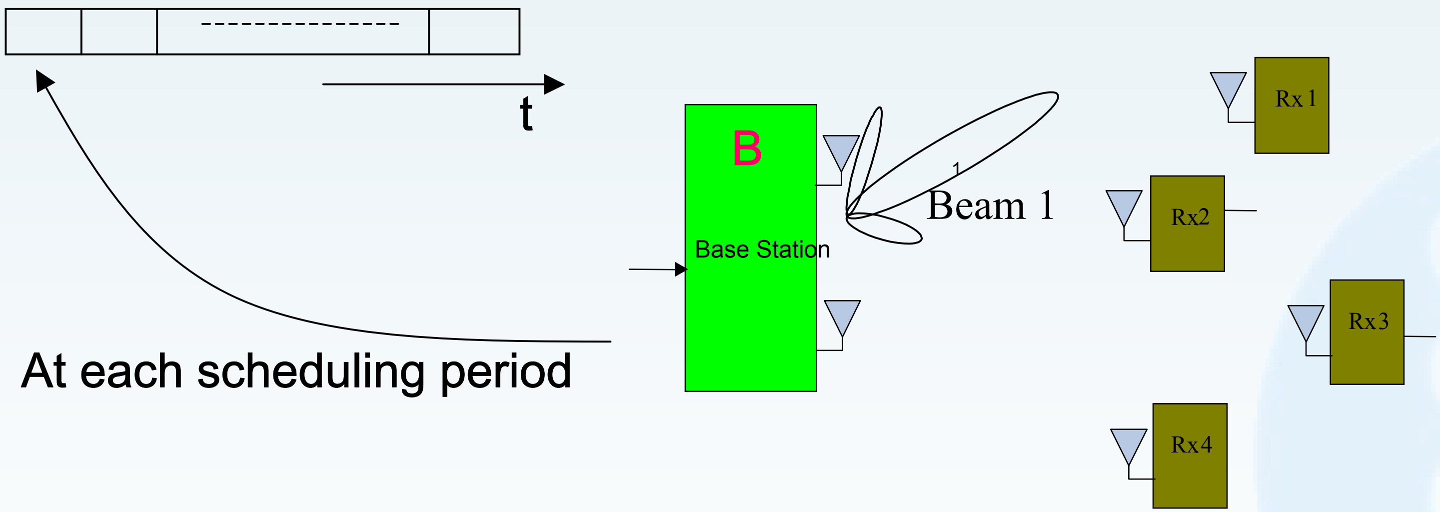
Multiuser Opp. Beamforming (MOB)

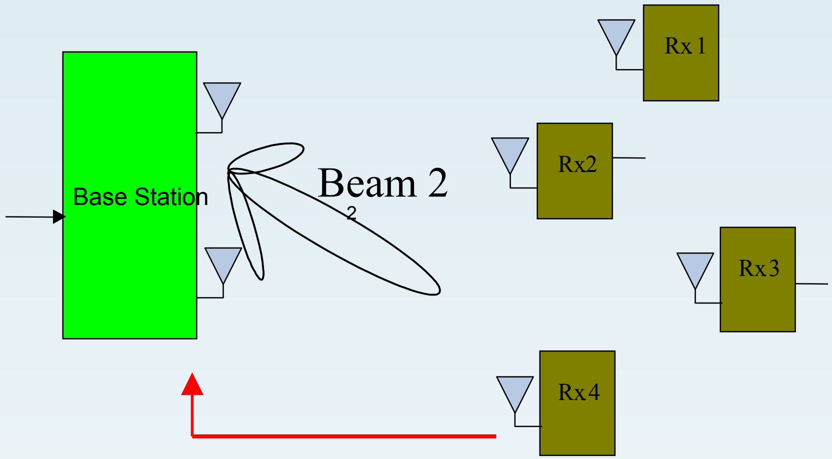
The first step in MOB is the user acquisition, where the BS scheduler sends a training sequence previously known to all users in the cell. And this training process has to be sequentially carried over each one of the generated beams

B = W (orthonormal randomly generated matrix with isotropic distribution). Ex: B= I (antenna selection, if N is high)



Beam 1 is transmitted

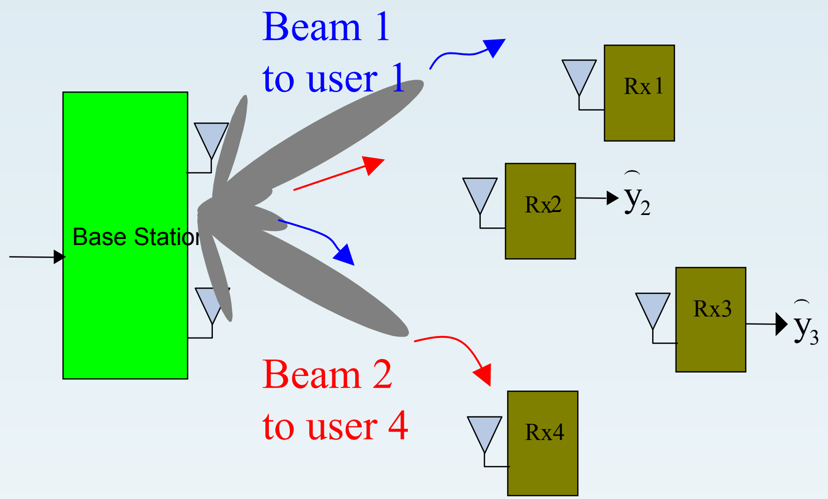
MOB



nt Orthogonal beams are generated without CSIT

Beam 2 is transmitted and each user feeds its SNIR w.r.t. the best beam.

MOB



$$SNIR_{i,m} = \frac{\left|H_i v_m\right|^2}{1 + \sum_{n \neq m} \left|H_i v_n\right|^2}$$

After that, the best users w.r.t. each beam are selected and transmission begins where the transmitted signal encloses the symbols for the selected users

$$\mathbf{x} = \sqrt{\frac{1}{nt}} \sum_{i=1}^{nt} v_i s_i$$

MOB

To sum up, the ORBf technique shows

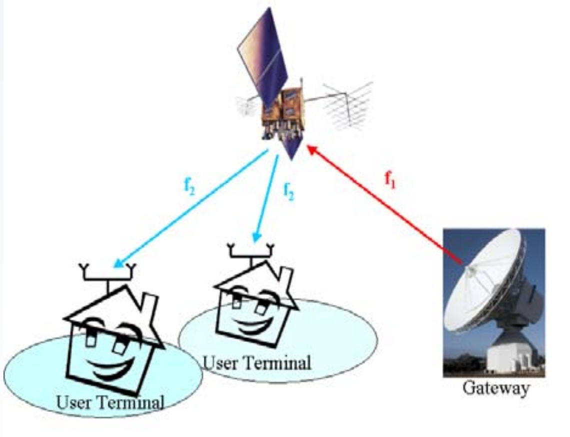
1. Low complexity design. (random beams generation)
2. Moderate feedback load. (best SNIR feedback)
3. Good system performance. (It can reach optimality)
4. Implicit user selection process.
5. Good performance is expected in scenarios with small interference, therefore it presentes outstanding performance at low channel SNR.
6. As it only relies on SNIR information, then it is more robust than full CSIT systems

Therefore, it is proposed as an alternative to more sophisticated precoders, for its implementation in practical systems.

An example: Broadband satellite communications

Broadband interactive scenario

- ***GEO satellite system (DVB-S2)***
  - Multibeam: FL with one GW that manages a cluster of K beams
  - One user per beam is served at a time and users in the same beam are served following a TDMA access scheme
  - The satellite acts as a bent pipe and no OBP is performed
- ***Operating at Ka band (18 to 40 GHz)***
- ***Influence of troposphere phenomena (rain, clouds)***
  - Creates Correlated Areas (CA)
- ***Absence of scatters and strong LOS component***
  - No MIMO through multiple satellite antennas



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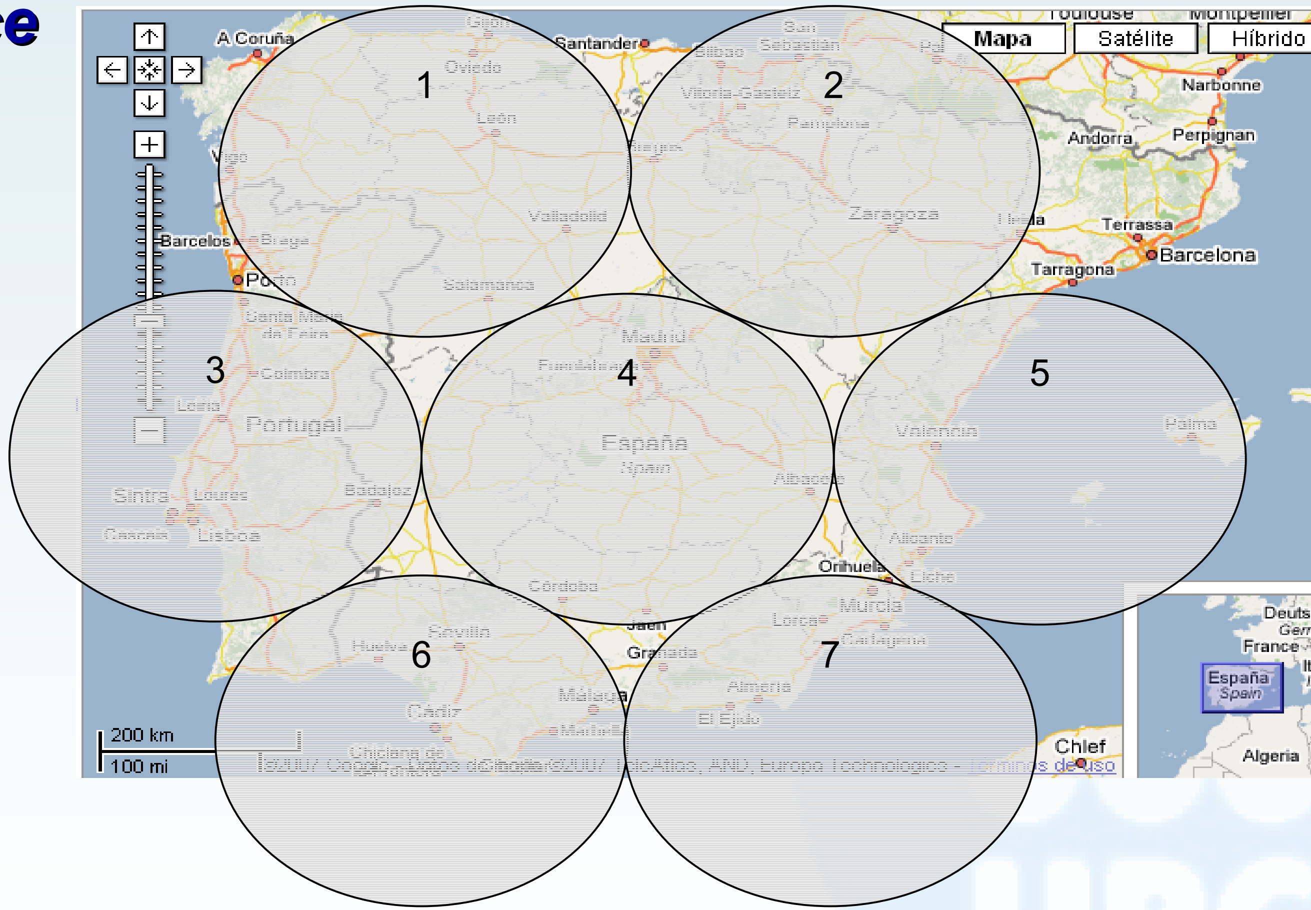


Channel model

- ***In multibeam satellite systems:*** *freq. reuse=1*
  - **Use** **MIMO precoding** **to deal with inter-beam interferences and** increase capacity
- ***Using dual polarization***
  - **Troposphere and antennas introduce cross-polarization components.**

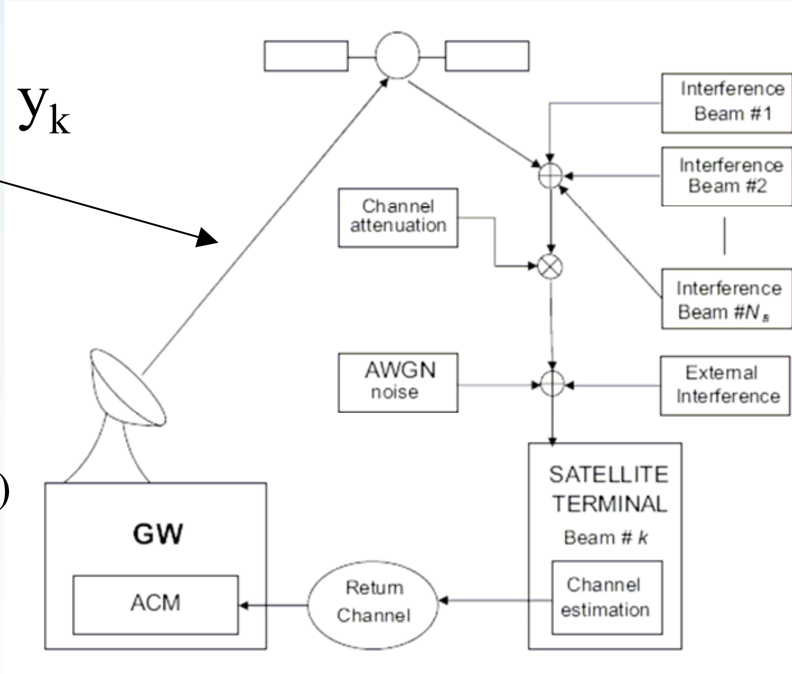
$$\mathbf{y}=\mathbf{Hs}+\mathbf{z}$$

User k: y_k

$$\mathbf{H}=\begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1K} \\ h_{21} & h_{22} & \cdots & h_{11} \\ \vdots & \vdots & \ddots & \vdots \\ h_{K1} & h_{K2} & \cdots & h_{KK} \end{bmatrix}$$

$$\mathbf{h}_{n,*}=\left[b_1(\mathbf{x}(n,k)),\ \ldots\ ,\ b_K(\mathbf{x}(n,k))\right]G_{nk}(\mathbf{x}(n,k))a(\mathbf{x}(n,k))$$

Statistics along time and space
Correlated Area concept

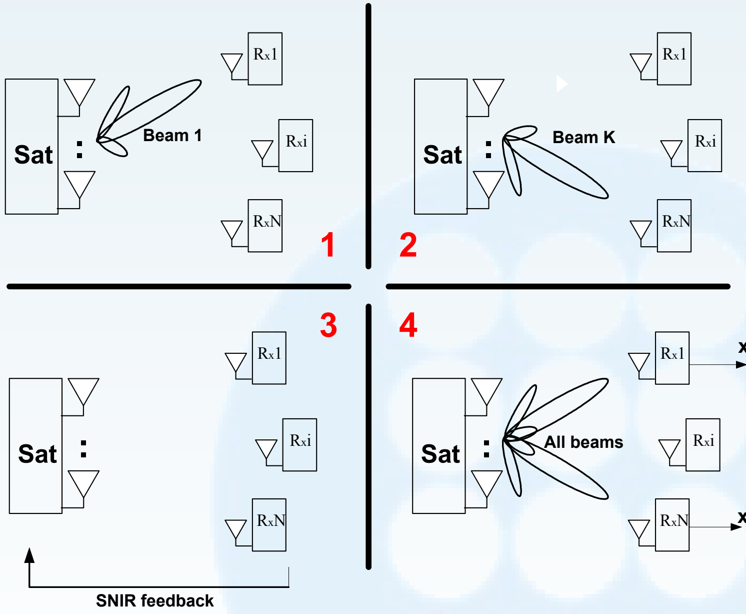


MIMO Precoding: Scheme

- *Multibeam Opportunistic Beamforming (MOB)*
  - **The precoding matrix** B **is a random matrix following an orthonormal generation such that** BB^H**=**I . Also user selection

Procedure

I. Random generation of K beams
II. User selection
   1) Beam 1 transmits
      a pilot signal
   2) All beams transmit
      a pilot signal successively
   3) Users report de SNIR
   4) The best user per beam
      is selected



MIMO Precoding: Results

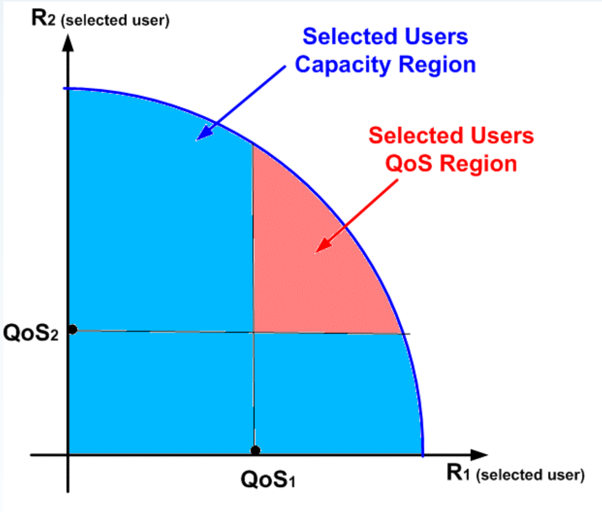
		Uniform power loading		
		Rate (bps/Hz)	Availability	Rate variance
Reference	Beam 1	2.55	96.3%	1.347
	Beam 4	1.45	92.7%	0.16
	Aggregate	16.80	95%	1.19
MMSE	Beam 1	3.16	84.9%	4.24
	Beam 4	1.89	74.8%	1.63
	Aggregate	20.9	83.7%	3.89
MOB	Beam 1	0.86	43%	0.11
	Beam4	0.86	42.5%	0.11
	Aggregate	6.04	42.7%	0.11
Improved MOB	Beam 1	8.09	100%	3.74
	Beam 7	2.19	87.6%	0.74
	Aggregate	24.39	95.5%	1.12

The outage concept is present

Improvement of MOB

Further improvements can be done for sparse networks:

- Power allocation for robust schemes
- Number of beams or selected users
- Enhance beam design by incorporating more feedback
- Interaction with upper layers (System issues and cross-layer design)
  - Admission control: design of N (controls the MUD)
  - TDMA vs SDMA



Further improvements can be done on fairness

- Incorporate QoS constraints (fairness)

Key point: good managemente of SNIRk

MOB: improvement of # beams

For some applications, the transmitter can allow for some outage in the QoS requirements, so that the QoS can be unsatisfied for some users, with a probability of ξ

$$\max \ \mathrm{W}$$
$$\text{s.t.} \ \ \mathrm{Prob}\left\{\mathrm{SNIR}_i - \mathrm{snir}^{th} \le 0\right\} \le \xi$$

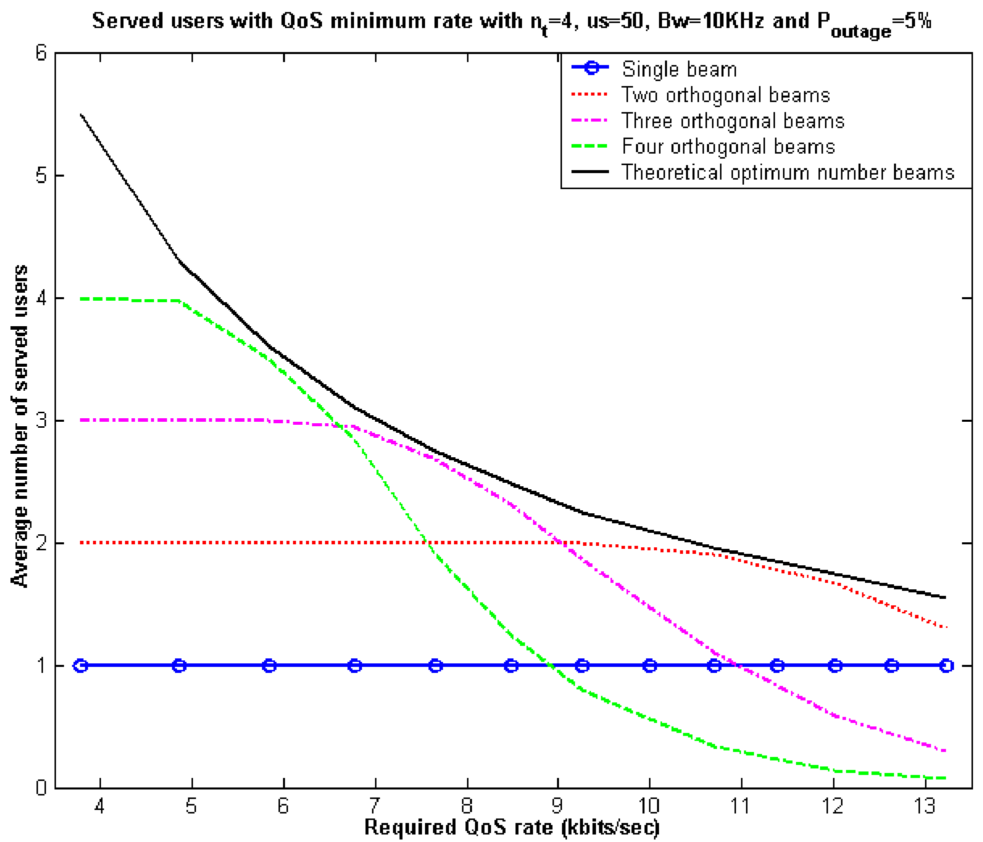
Using the SNIR distribution, the CDF of the serving SNIR can be formulated to provide a closed form expression of W as

$$\mathrm{W} \le \frac{\ln\left(1+\mathrm{snir}^{th}\right) - \ln\left(1-\sqrt[N]{\xi}\right)}{\ln\left(1+\mathrm{snir}^{th}\right) + \dfrac{\mathrm{snir}^{th}}{\beta}}$$

β = received SN

MOB: improvement of # beams

Comparing the performance of the available schemes in literature, to the obtained expression for the optimum number of beams under QoS constraints, we get



N=50

nt=4

Bw=1 MHz

ξ =5%

An example: Improvement of MOB by incorporating CSIT

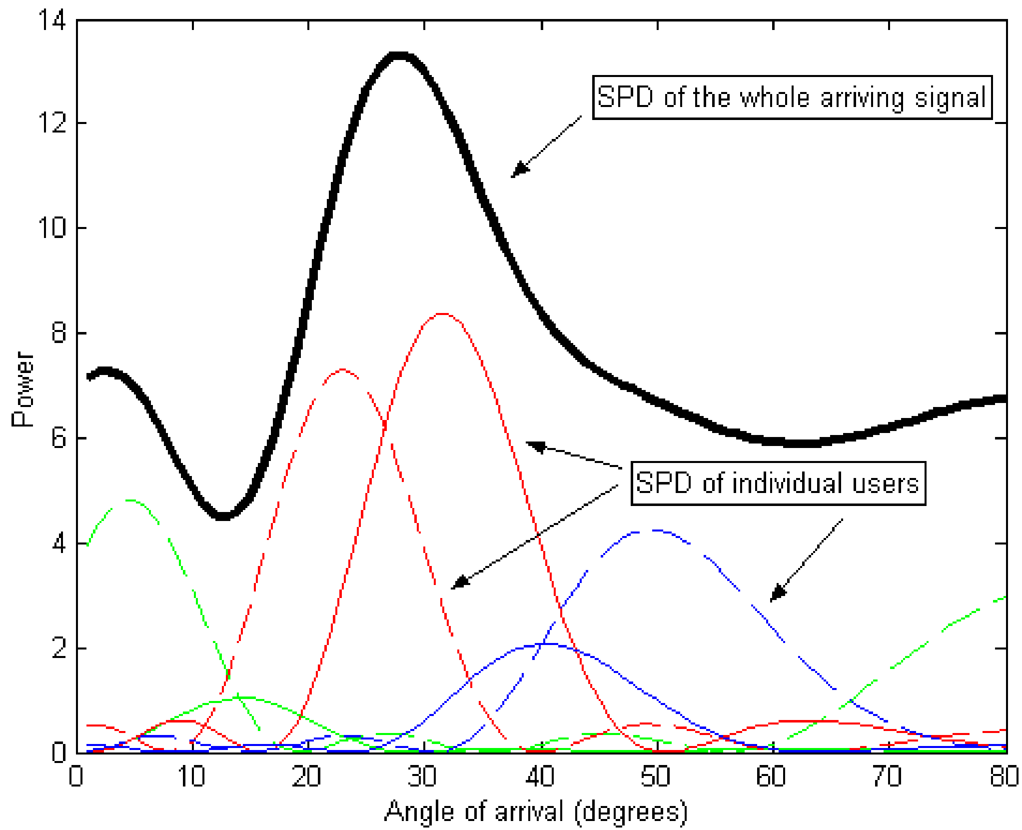
Smart Beam Generation

A smarter approach to obtain the beams is by making each beam to look towards the best direction upon the arriving channel power distribution

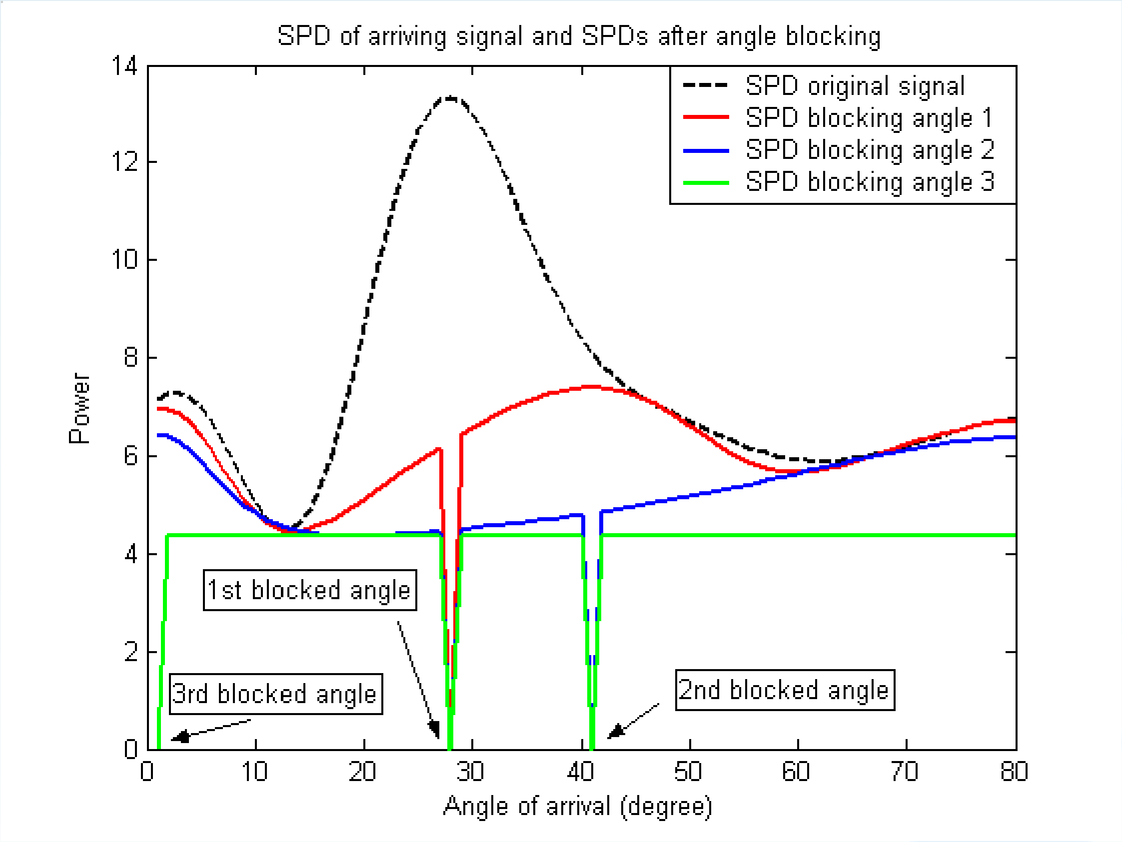
Sequentially generated beams are constrained to a zero cross product so that the originated beams are orthogonal.

The Spatial Power Density is easily obtained from the Covariance channel information. The Covariance is obtained through uplink-downlink 2^{nd} order reciprocity even they operate at slightly different frequencies.

Smart Beam Generation



Smart Beam Generation



Smart Beam Generation

The beam generation pursues the following procedure:

•A scanning vector is set up for the different arriving angles

1st Tx beam design

$$\mathbf{a}_1(\theta) = [1, e^{2\pi(1)\sin(\theta)}, \ldots, e^{2\pi(nt-1)\sin(\theta)}]^T$$

•The angle with maximum spatial power density (SPD) is calculated as follows

$$\theta_{sel}^1 = \arg\max_{\theta} \frac{\mathbf{a}_1(\theta)^H \mathbf{R}\, \mathbf{a}_1(\theta)}{\mathbf{a}_1(\theta)^H \mathbf{a}_1(\theta)}$$

•Design the 1st beam for transmission as $\mathbf{b}_1 = \mathbf{a}_1(\theta_{sel}^1)$

•A selection of the best user for this transmitting beam is accomplished by the opportunistic scheme: the user that feeds the largest SNR value is selected.

Smart Beam Generation

•Subsequent mth beams (m=2..nt) are sequentially carried out following an interference mitigation scheme:

a.- A blocking matrix *C* is set up to guarantee an orthogonal beam generation $\mathbf{C}_m(\theta) = [\mathbf{a}_1(\theta) \;\; \mathbf{a}(\theta_{sel}^{(1:(m-1))})]$

b.- Set up a selection vector $\mathbf{1}_m$ with zeros in all positions but the

c.- Calculate the scanning beam m^{th}

$$\mathbf{s}_m(\theta) = \mathbf{C}_m(\theta)[\mathbf{C}_m(\theta)^H \; \mathbf{C}_m(\theta)]^{-1}\mathbf{1}_m$$

d.- The calculations of the SPD,

$$\theta_{sel}^m = \arg\max_{\theta} \frac{s_m(\theta)^H \mathbf{R} \, s_m(\theta)}{s_m(\theta)^H s_m(\theta)}$$

Smart Beam Generation

e.- The calculations of the m^{th} transmitting beam and selected user are carried as previously mentioned.

$$\mathbf{b}_m = s_m(\theta_{sel}^m)$$

•Once all the beams are generated, the BS scheduler enters the transmission step and forwards each user with its corresponding information.

Higher performance of this strategy as compared to the presented random generated beams MOB is expected, as the BS scheme projects its beams in the direction of maximum power density while the standard MOB does not.

Smart Beam generation

EXAMPLE

- Note that in case that for the 2 user case in a LOS

$$\mathbf{H} = \begin{bmatrix} \mathbf{a}^H(\theta_1) \\ \mathbf{a}^H(\theta_2) \end{bmatrix}$$

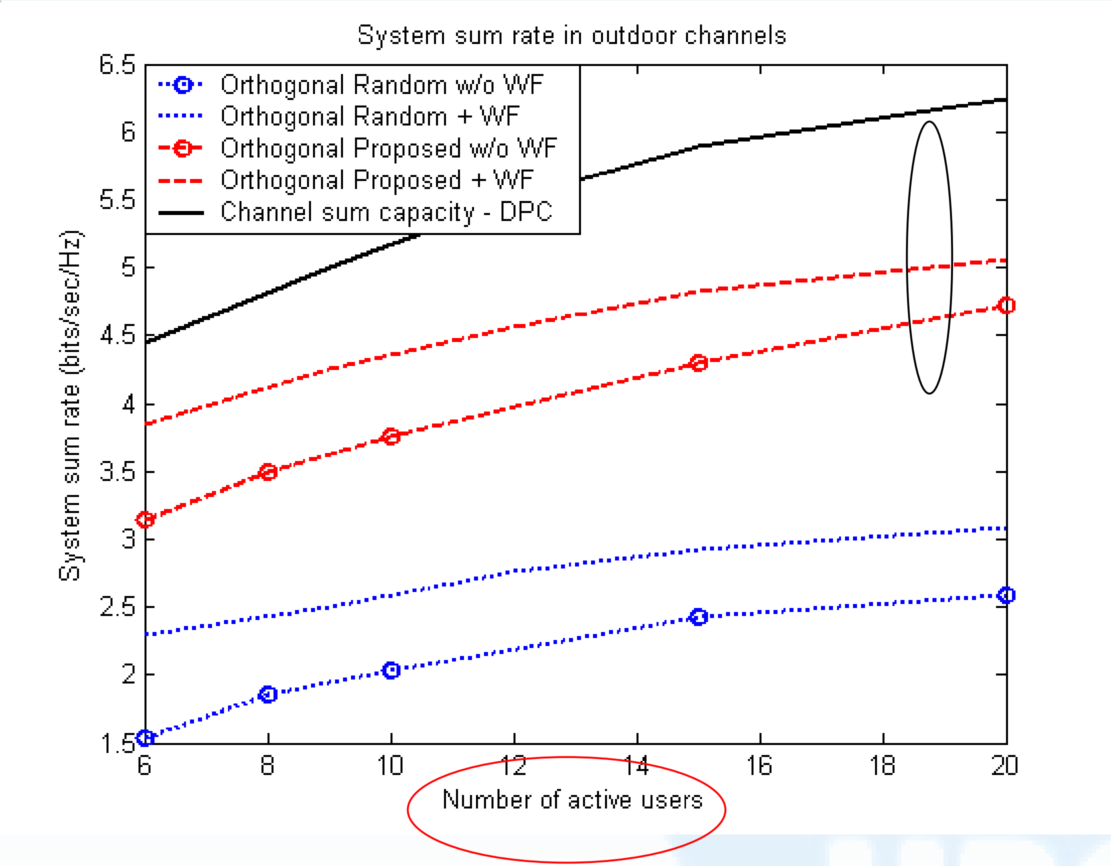
$$\mathbf{y} = \mathbf{HBx} = \begin{bmatrix} \mathbf{a}^H(\theta_1) \\ \mathbf{a}^H(\theta_2) \end{bmatrix} \begin{bmatrix} \mathbf{b}_1 & \mathbf{b}_2 \end{bmatrix} \mathbf{x} = \begin{bmatrix} 1 & 0 \\ \rho & 1 \end{bmatrix} \mathbf{x}$$

DPC-like interference: note that the DPC performs a triangular interference cancellation so that each user i only receives interference from the i-1 users encoded with DPC

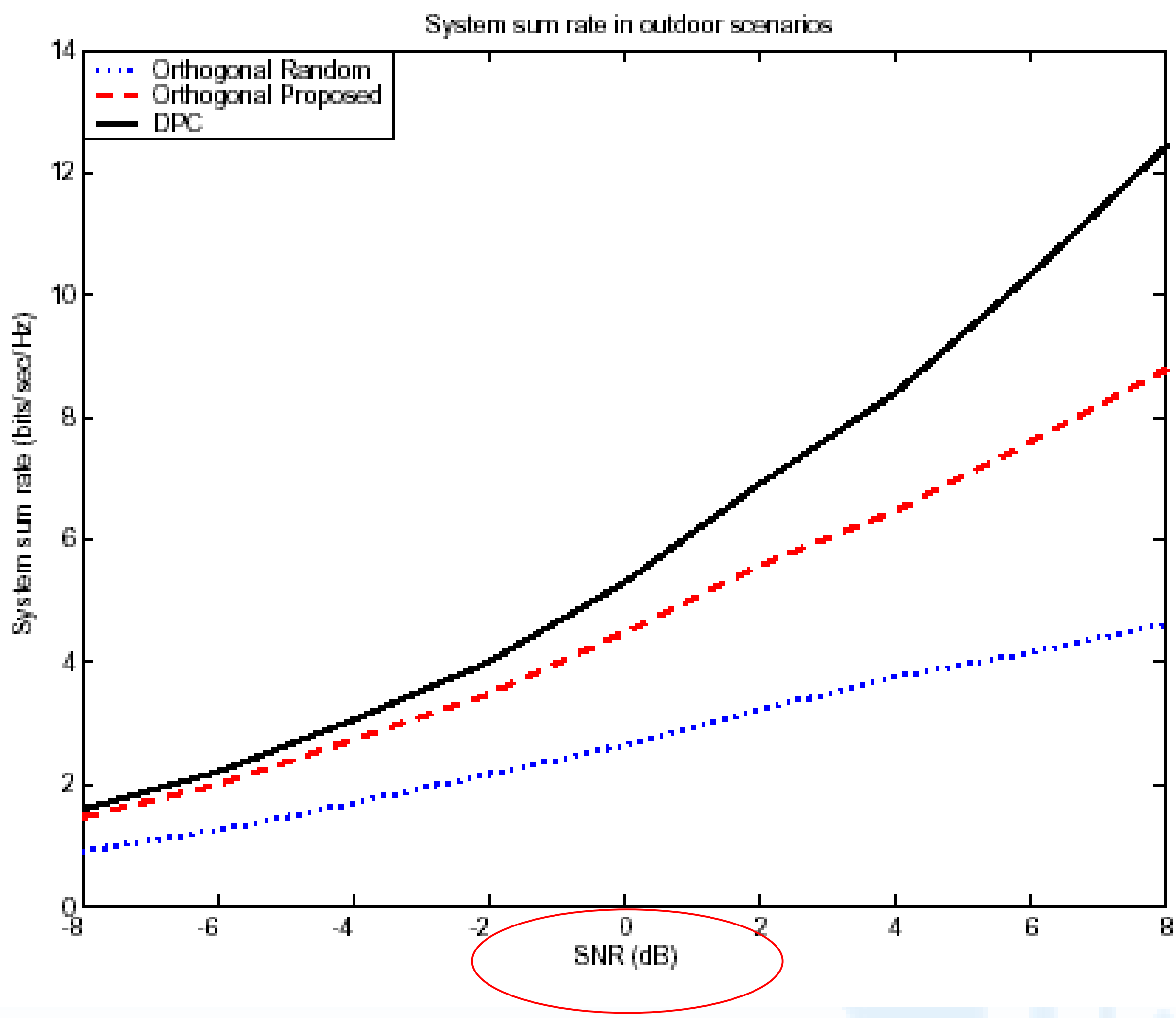
Smart Beam Generation

To further improve the performance of the OpBF, an iterative Waterfilling is also done over the transmitted beams.

- An Outdoor channel in Urban scenario IEEE-SCM model, AS=20º.
- 4 transmitting antennas and single receiving antenna per user.
- SNR= 0 dB



Smart Beam Generation



On Demand CSIT scenario

To further enhance the performance of the MOB, an interference cancellation is required. Notice that the previous scheme generates orthogonal beams so that it only allows for an interference mitigation.

The only way to make an interference cancellation is with the presence of full CSI at the transmitter side.

On-demand full CSI: In the strategy already presented, if the BS asks for full CSIT to the progressively scheduled users, then the Blocking matrix C can account for the channel realization of the previous users to avoid the interference terms. This will boost the system performance while it only represents a small extra load on the feedback link.

On Demand CSIT scenario

The algorithm for the On-demand CSI system is identical to the previous transmission one, but while in the previous scheme the blocking matrix was computed as

$$\mathbf{C}_m(\theta) = [\mathbf{a}_1(\theta) \;\; \mathbf{a}(\theta_{sel}^{(1:(m-1))})]$$

the *C* blocking matrix for the on-demand CSI scenario is formulated as

$$\mathbf{C}_m(\theta) = [\mathbf{a}_m(\theta) \;\; \mathbf{h}_{(1:(m-1))}]$$

where the interference to the previously selected users is blocked, and triangular interference matrix is obtained (similar to DPC one !).

On Demand CSIT scenario

The system performance of the presented scheme is compared to other realizable transmission schemes in the presence of full CSI:

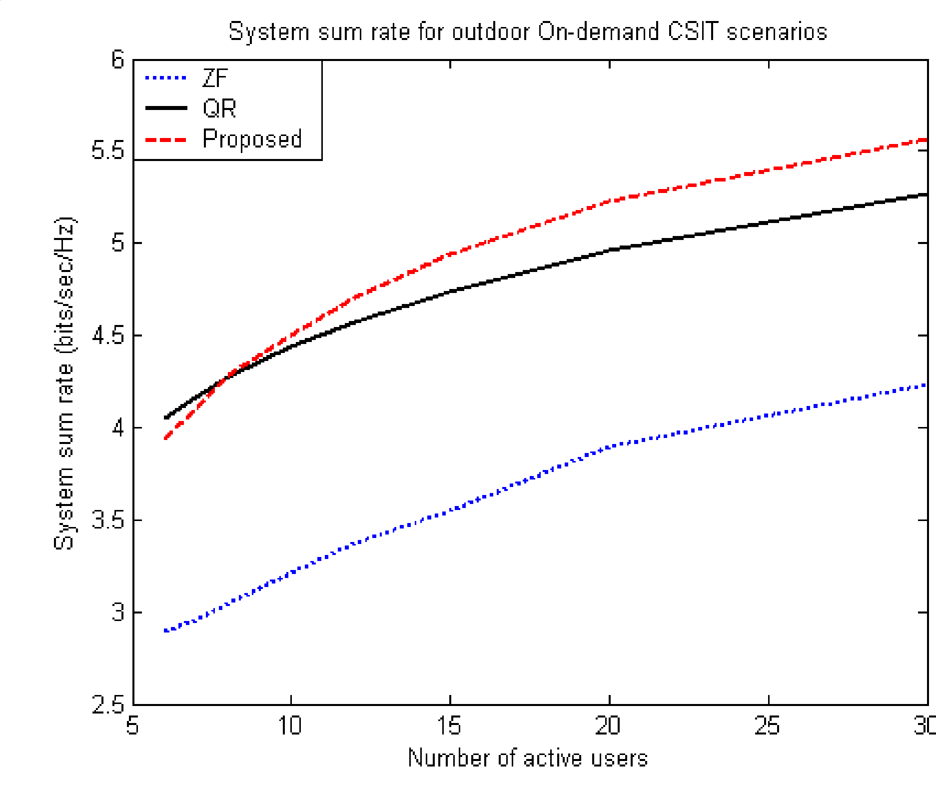
1.-Zero Forcing (ZF).

$$\mathbf{B} = \mathbf{H}^H \left(\mathbf{H}\mathbf{H}^H \right)^{-1}$$

2.-Channel QR Decomposition.

$$\mathbf{B} = \mathbf{Q}^H \qquad \mathbf{H} = \mathbf{R}\mathbf{Q}$$

QR decomposition also achieves a triangular interference matrix.



Conclusions

•A smart beam generation policy can improve the performance of the opportunistic schemes in outdoor scenarios with limited number of users.

•A power allocation over the transmitted beams also enhances the performance of MOB.

•To further boost the efficiency of MOB, a progressively full CSIT from the scheduled users can be used to obtain a triangular interference cancellation.

Other alternatives for CSIT and precoding ?

IT IS AN UNSOLVED PROBLEM

In SU- MIMO: feedback of B

BUT in MU-MIMO: Bi (i=1…N) precoders that depend on Hj

Partial CSIT

- IN PRACTICE IT IS A TWO STAGE PROBLEM
  - 1. User selection: Decision making process
    - Signal Processing for opportunistic identification
    - System issues for opportunistic exploitation
  - 2. Precoder design
- DIMENSION REDUCTION & PROJECTION TECHNIQUES

Projecting the matrix channel onto one or more basis vectors known to the tx and rx

Ex.: For densily populated areas

$$\varphi_k = \max_{i=1..nt} \frac{\left| h_k^H b_i \right|^2}{\sigma^2 + \sum_{i \neq j} \left| h_k^H b_j \right|^2}$$

- TEMPORAL STATISTICAL FEEDBACK: for low mobility
- SPATIAL STATISTICAL FEEDBACK: for outdoor

Partial CSIT

- SPATIAL STATISTICAL FEEDBACK: for outdoor

Channel statistics (macroscopic information of the channel): $h_k \sim CN\left(\bar{h}_k, R_k\right)$

Instantaneous information: Example

1st. Estimation of hk for user selection

$$\gamma_k = \left|h_k^H B_k\right|^2 \quad If \quad B_k = I \rightarrow \left|h_k^H\right|^2$$

$$\hat{h}_k = E\left\{h_k / \gamma_k\right\}$$

$$\hat{R}_k = E\left\{h_k^H h_k / \gamma_k\right\}$$

$$or$$

$$\max_{h_k} h_k^H R_k h_k$$

$$s.t. \quad \left|h_k^H B_k\right|^2 = \gamma_k \Rightarrow \hat{h}_k = \max eig\left(R_k, B_k B_k^H\right)$$

2nd. CSIT request

Partial CSIT

- QUANTIZATION-BASED FEEDBACK

It is the first idea that comes into mind when thinking about source compression