Is OFDMA, MIMO and OS the Right Stuff for Mobile Broadband ?

A Paulraj
With help from K. Oteri, E. Stauffer, F. Lee

Stanford University
Beceem Communications Inc.

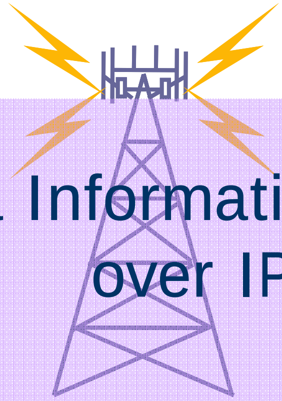
September 27, 2005
VTC Fall 2005
Dallas

Outline

- **Introduction**
- Single Sector - MIMO, OFDMA, OS
- Multi Sector - IM
- Imperfect side information
- Some results and summary

OS Opportunistic Scheduling
IM Interference Mitigation

Mobile Internet Delivery



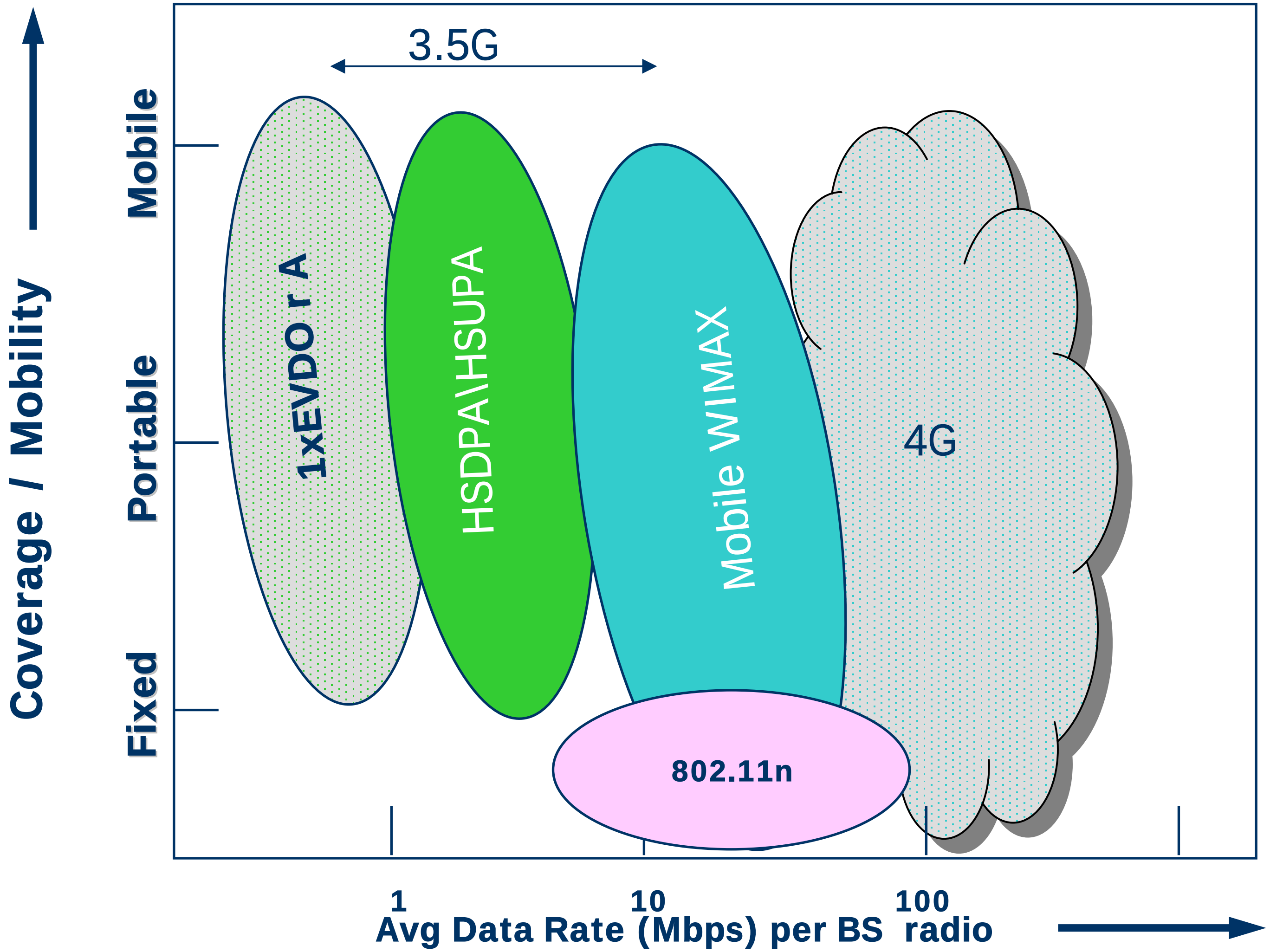
Broadband Multimedia Information / Entertainment over IP

Portable terminal

Mobile terminals

Consumer Devices

Wireless Internet Standards



Carrier Requirements

- Aggregate Avg. throughput per BS > 10 Mbps
- Sustained throughput per SS > 1 Mbps
- High Spectrum Eff. > 7.5 bps/Hz/Cell
- Delay < 50 ms
- Flexible channelization & band plans to suit regional needs
- Multimedia services delivered over IP v4, v6
- Mobility (capacity may degrade > 60 Kmph)
- All IP core network architecture
- Low power terminals - Joules / Mbyte
- Low cost - $ / Mbps / Sq. Km

Baseline Features for 3.5G

- Cellular 1x1 (full) frequency reuse
- Closed loop transmit channel state information (Tx-CSI)
- Fast HARQ, fast link adaptation, fast BS switching
- High order QAM, Soft handoff on UL
- Interference averaging

Evolutionary Features 3.5G

- Multiple access - OFDMA
- Wideband 10/20 MHz
- MIMO: single user and cooperative MIMO
- Opportunistic scheduling in time, frequency and space
- Interference avoidance/ cancellation

3.5G Technologies

	DO Rel A	HSDPA	WiMax (802.16(e))
DL peak data rate Bandwidth	3.07 Mbps 1.25 MHz	14.4 Mbps 5 MHz	70 Mbps 20 MHz
UL peak data rate	1.8 Mbps	2 Mbps	20 Mbps
IP termination	RNC/PDSN	RNC/PDSN	BTS
Bandwidth efficiency features	- CDMA + Low latency - IP at RNC**	- CDMA + PHY HARQ - IP at RNC**	+ OFDM - MAC HARQ* + IP at BTS
Standards compatibility	Yes	Yes	Yes
Deployment	2005	2005	2005
Duplexing	FDD	FDD	TDD / FDD
BB complexity (incl. memory)	~1.2 million gates	~ 1 million gates	~ 2.5 million gates

Problem

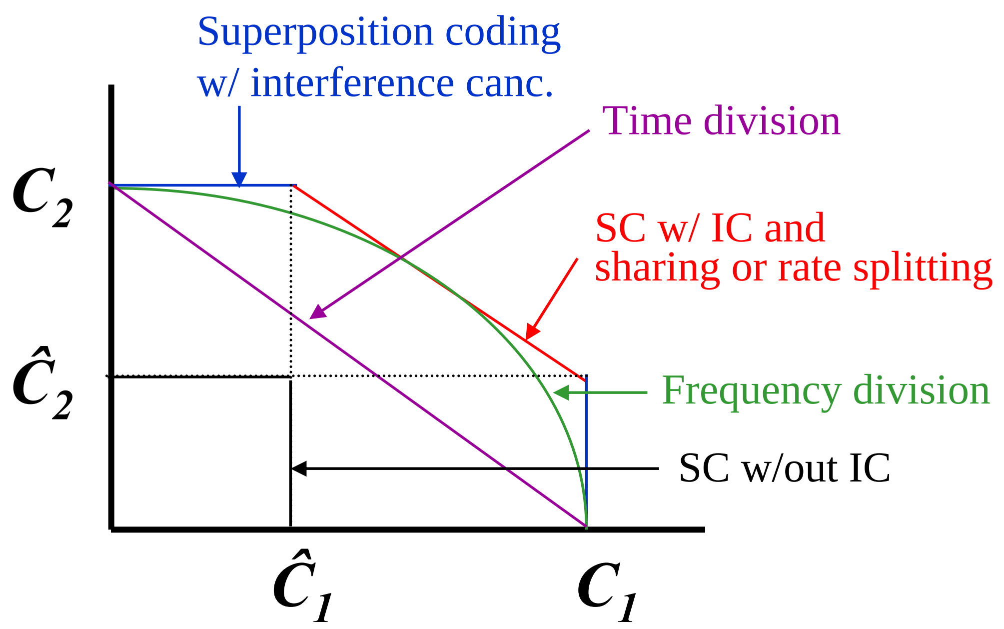
- How do we allocate radio resources (power, freq. time and space) to maximize DL network capacity
- Keeping in mind
  - Fairness
  - Latency
  - Power/EIRP
  - Robustness
  - Terminal power

Outline

- Introduction
- **Single Sector - MIMO, OFDMA, OS**
- Multi Sector - IM
- Imperfect side information
- Some results and summary

OS Opportunistic Scheduling
IM Interference Mitigation

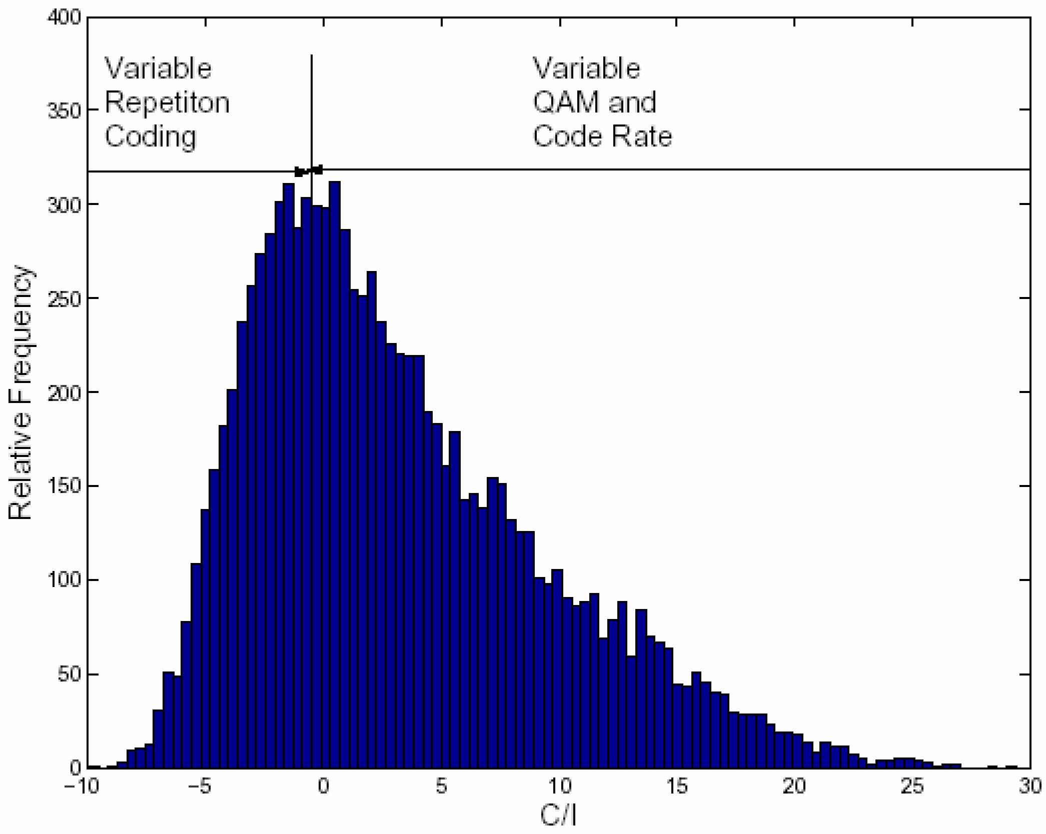
Theory – Two-User MAC Region



Keeping everything orthogonal* with appropriate resource allocation is near optimum and keeps things simple

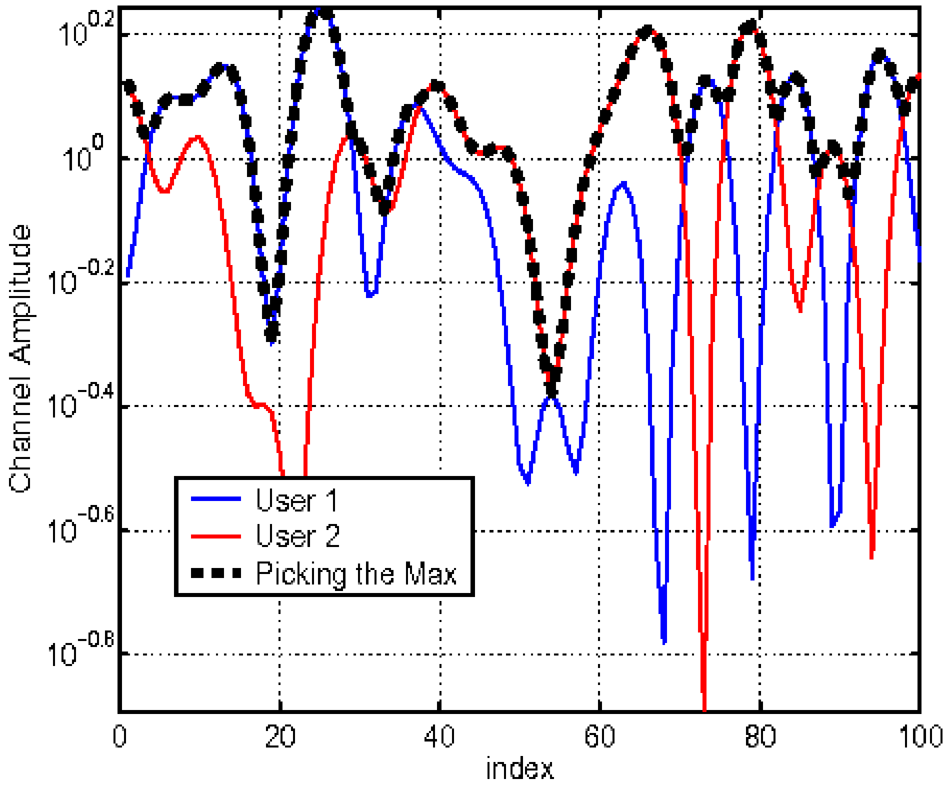
* OFDMA, OS, B/forming

Downlink C/I Statistics



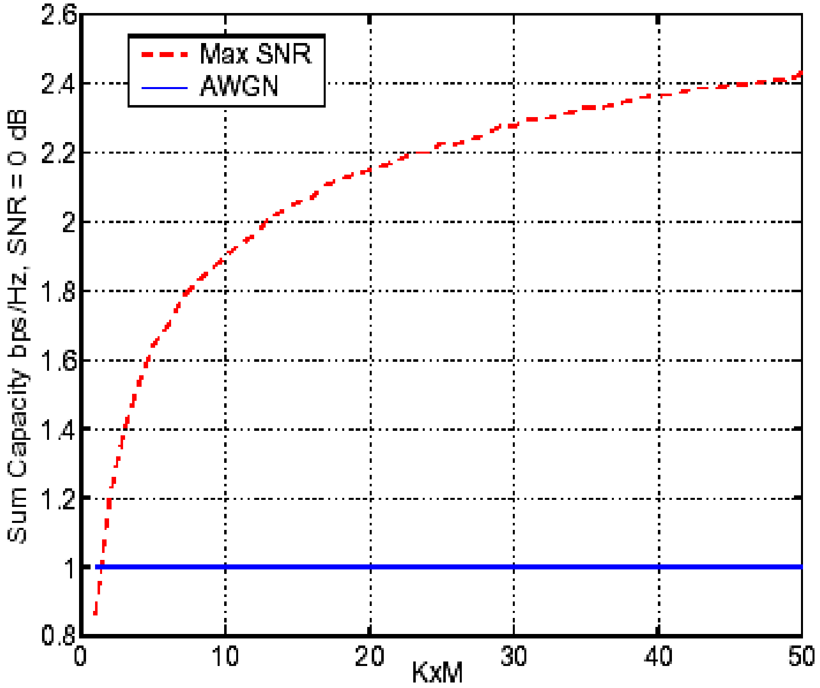
60% of users are below 3 dB C/I

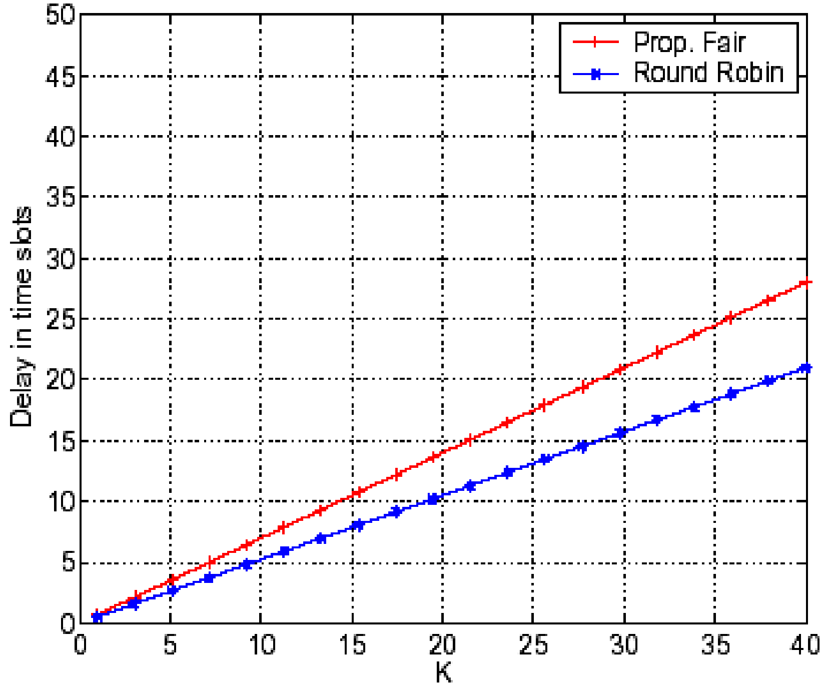
Opportunistic Scheduling (OS)



Scheduling users with maximum rate (channel gain), improves sum capacity

Capacity and Delay in OS

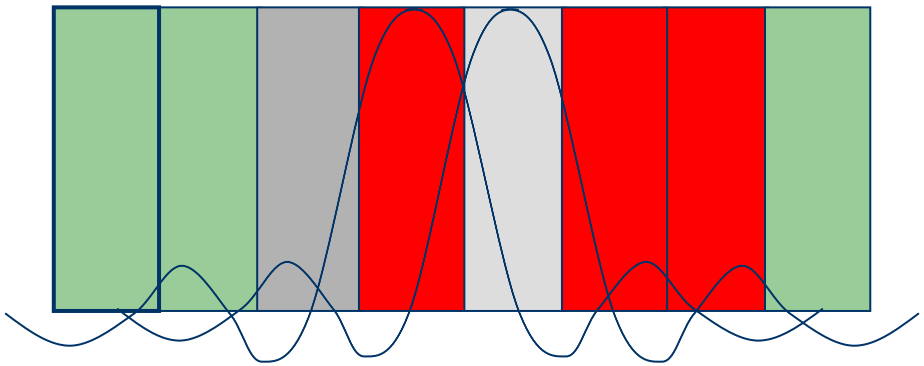




C ~ O (log log K) K users

Delay ~ O (K log K) for Prop. Fair Scheduling

OFDMA



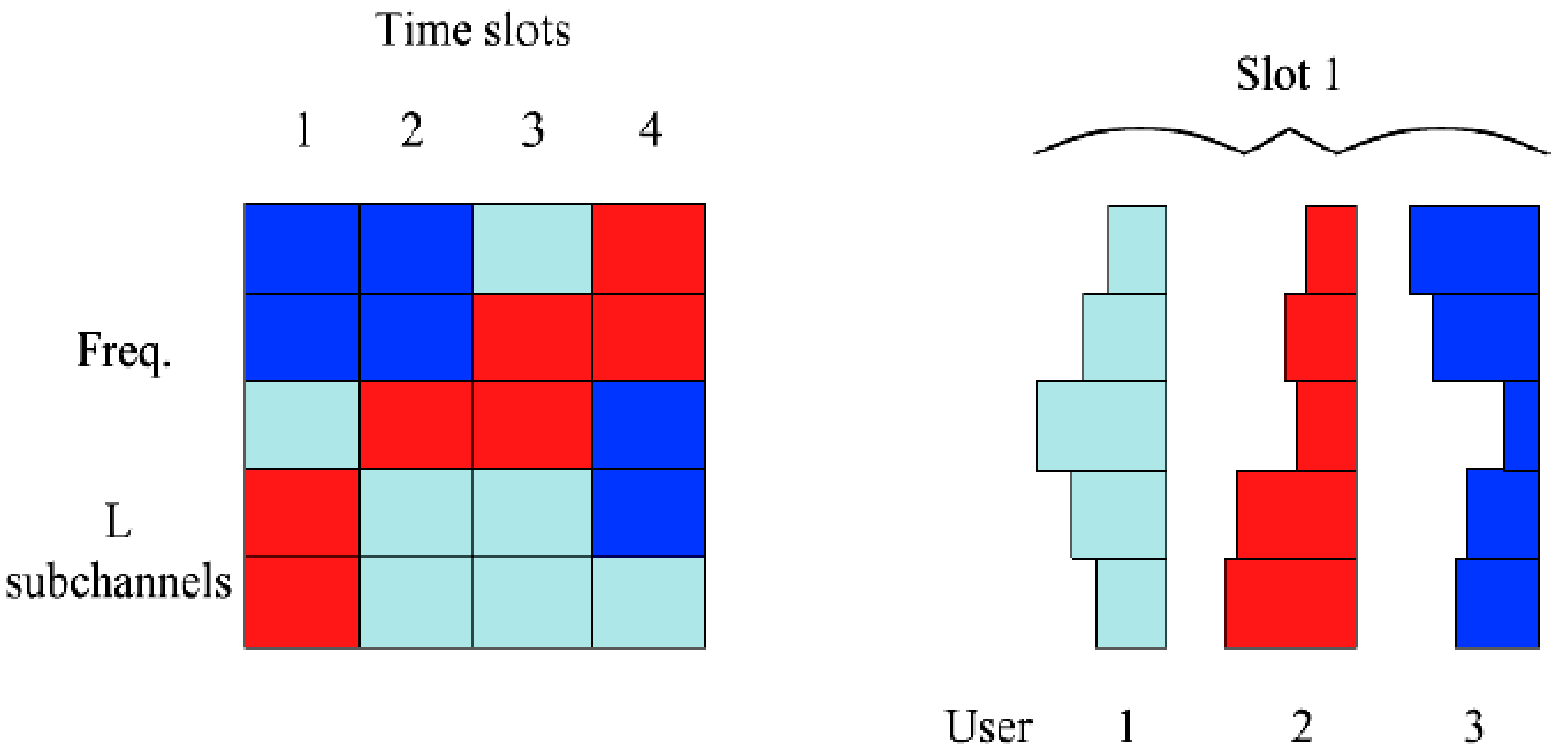
- Users allocated to sub channels
- No multi-path and multi-user interference
- Permits frequency specific user power, bandwidth allocation, pre-coding, beam forming,...

OFDMA vs CDMA Single Sector

	OFDMA	CDMA
Multi-path Interference	Avoids*	Needs equalization, noise enhancing
Frequency selective waterfilling	Yes	No
Freq. selective beamforming / pre-coding	Yes	Difficult
Multi-user interference on DL	Avoids*	Needs equalizer

*OFDMA advantage 20% or bigger in wideband
Multi-path rich urban channels. OFDMA advantage stronger at high SNRs

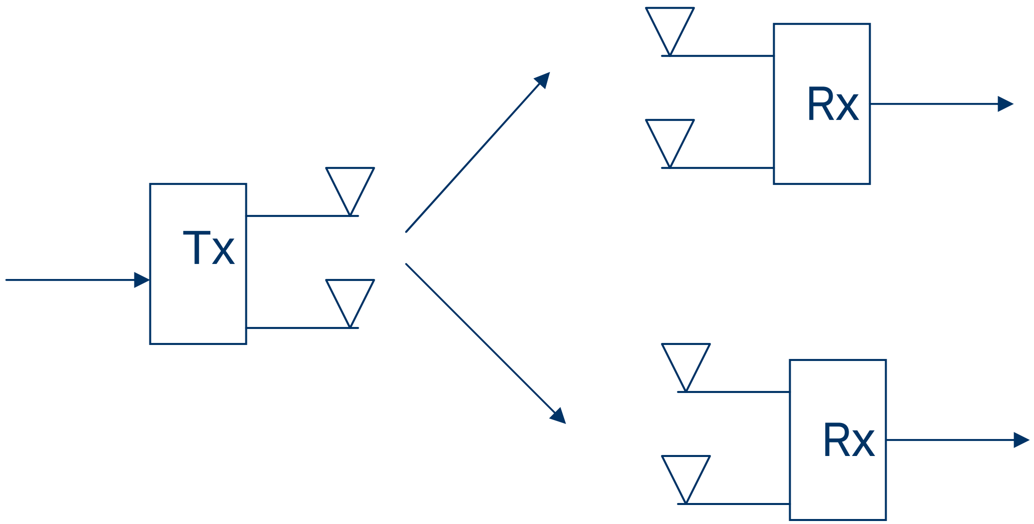
Opportunistic OFDMA



Every subchannel is scheduled based on max C/I

$C \sim O(\log \log K)$

MIMO

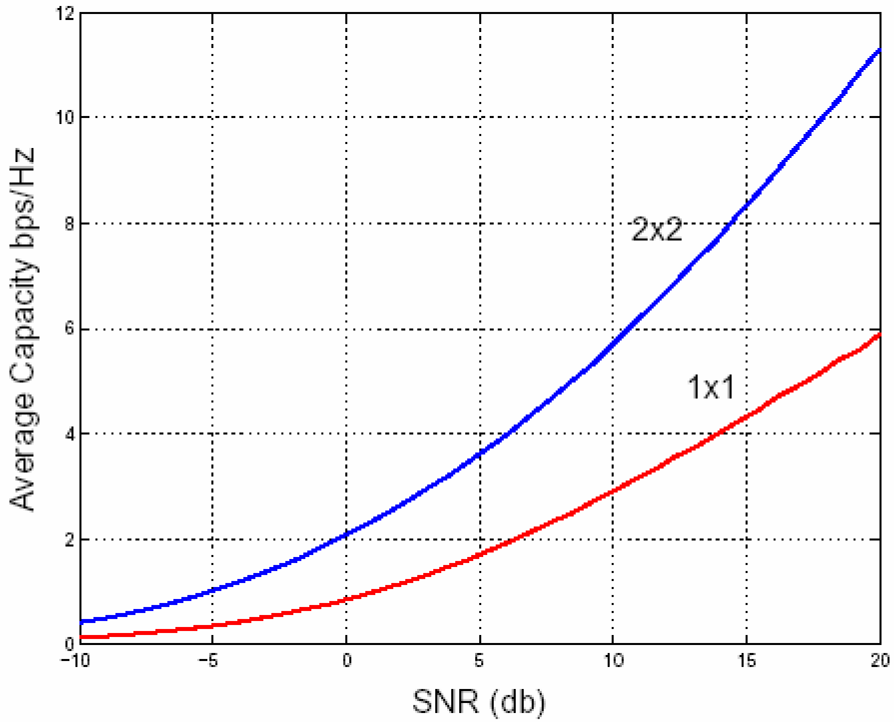


Use spatially diverse channels to support increased sum rates

MIMO Capacity with Tx-CSI

Perfect Tx-CSI

Single User

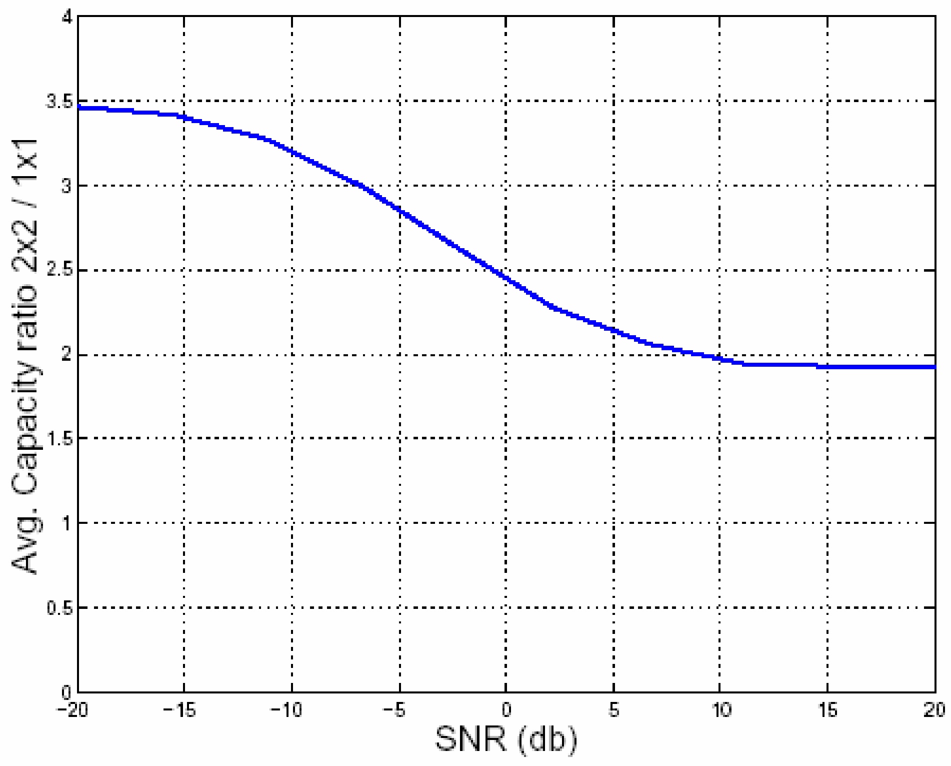


Average Capacity ≈ O (M log $_2$(SNR))

Low SNR Capacity Ratio

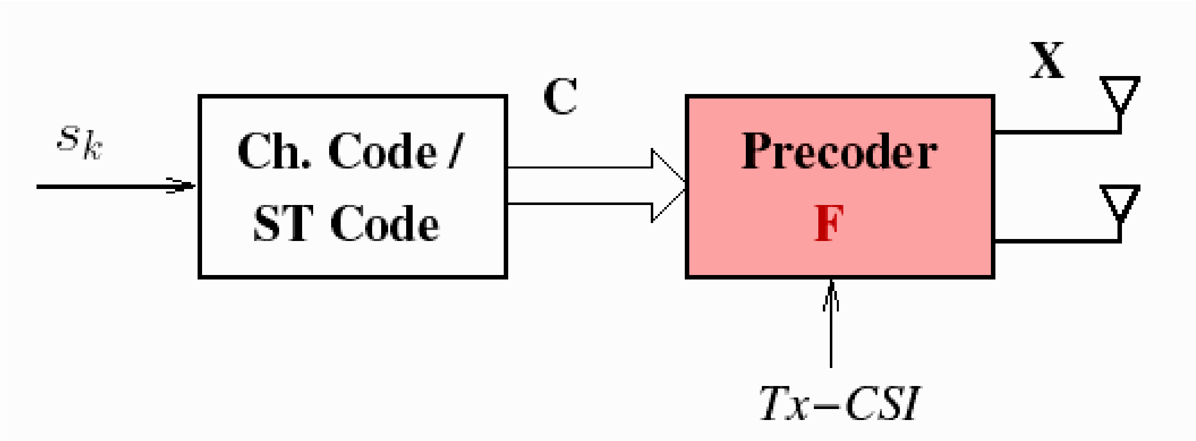
Perfect Tx-CSI

Single User



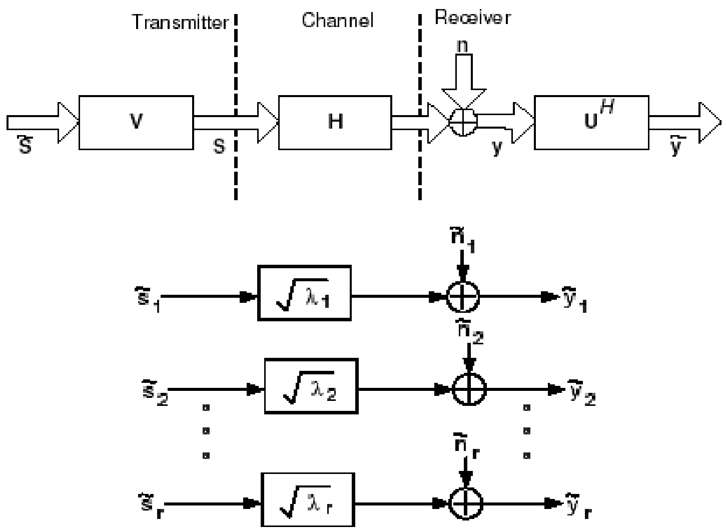
Capacity advantage higher at low SNR

Pre-coding in MIMO



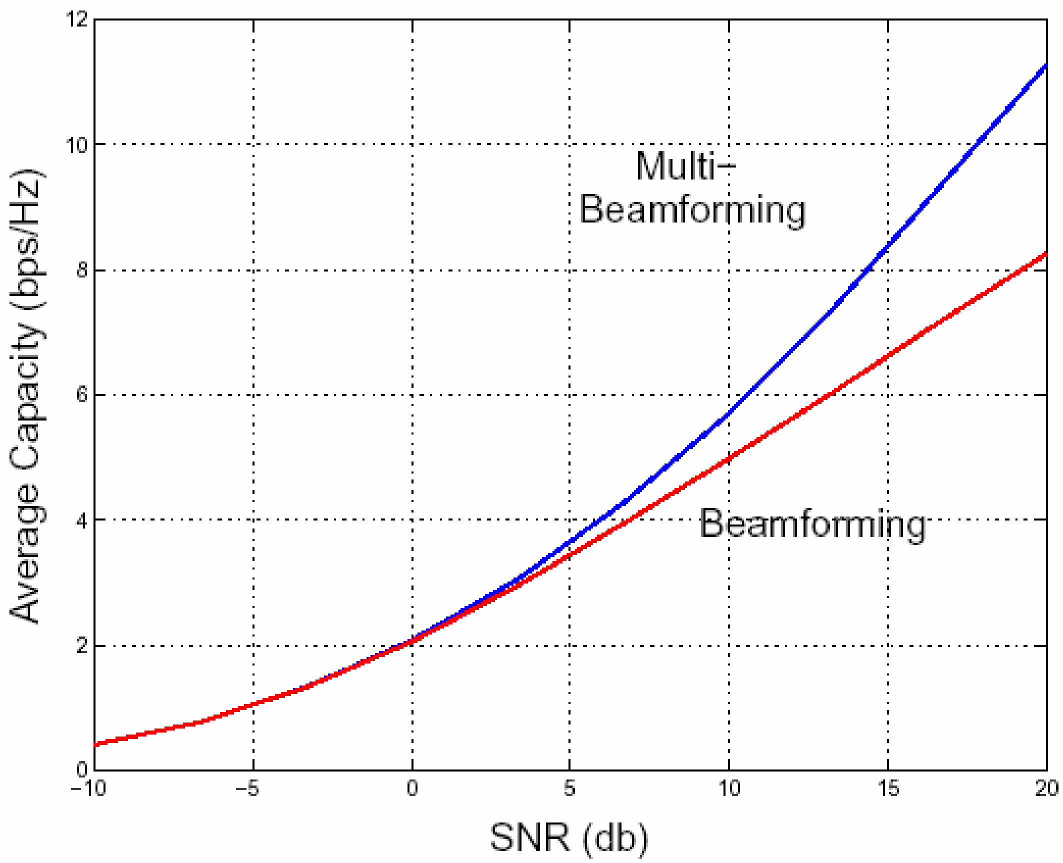
- General Principle:
  - Design ST Coding assuming zero Tx-CSI
  - Use a linear pre-coder (beam former) based on Tx-CSI

ST- Coding with Tx-CSI



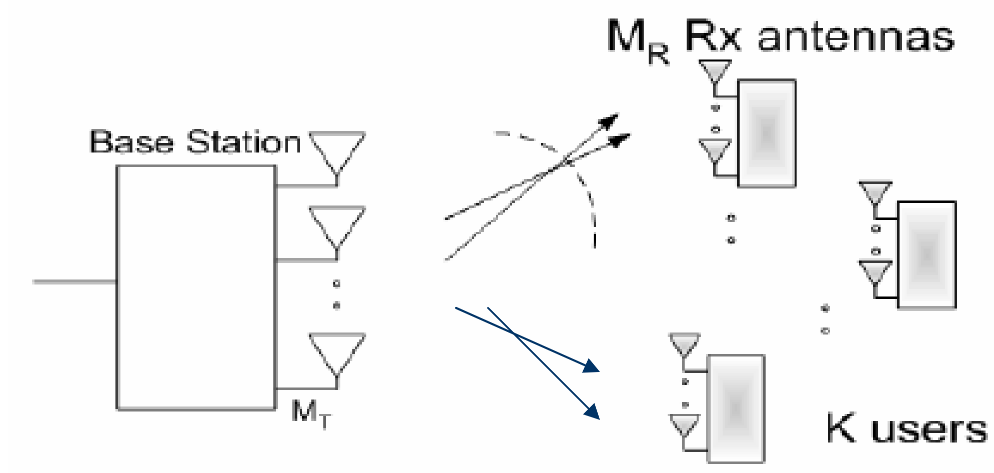
- Decomposes into parallel SISO modes
- SISO Coding
- Per mode rate Control
- Low Rx Complexity

ST Coding with Tx-CSI



Single beam for SNRs below 3 dB is optimal and multiple beam needed above that

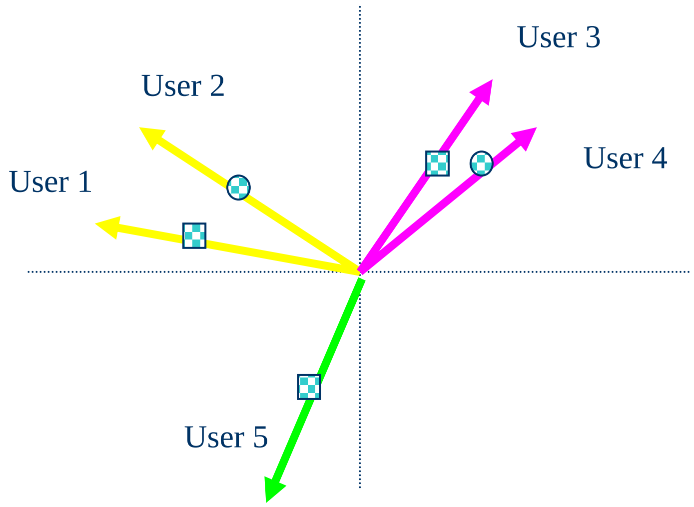
Opportunistic MIMO



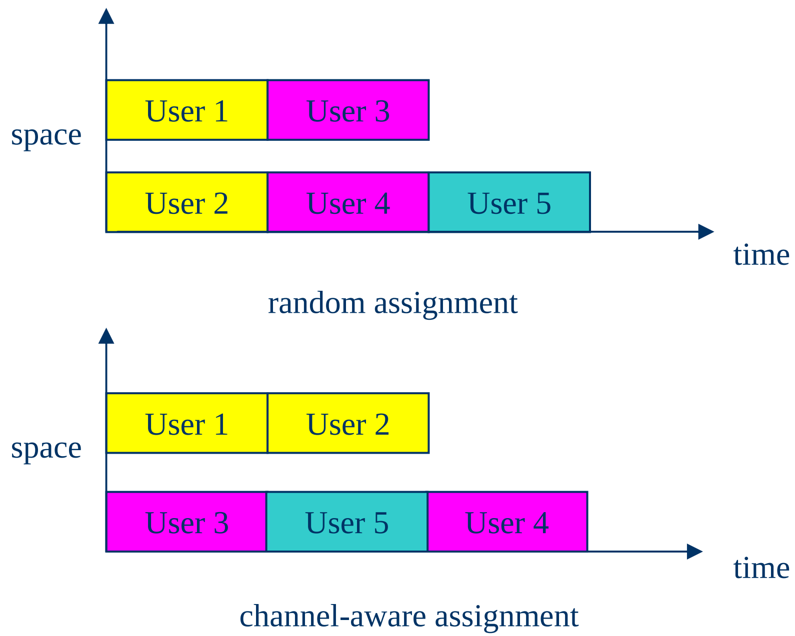
Choose users who such that orthogonal Tx modes couple to the best available modes to maximize sum capacity.

Users use linear processing only which is optimal

Opportunistic MIMO



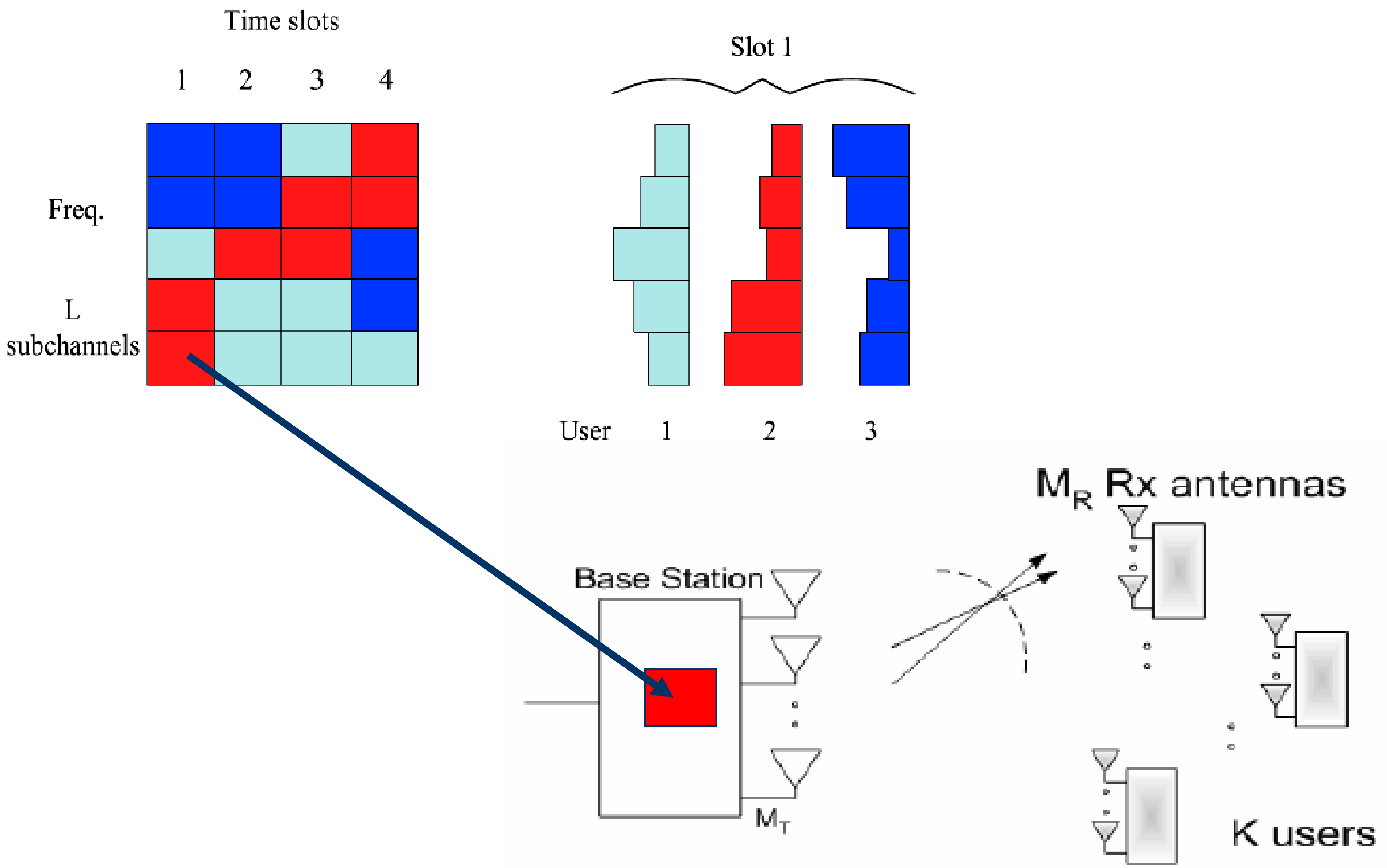
Spatial signatures



$C_{sum} \sim O\left(M \log \left((1/M) \log K \right) \right)$; needs $M \sim \log K$

For single Rx antenna

Opportunistic OFMDA+MIMO



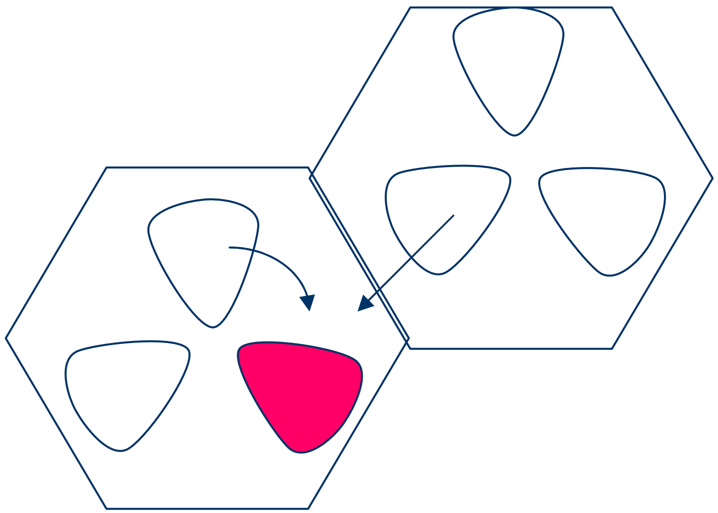
Outline

- Introduction
- Single Sector - MIMO, OFDMA, OS
- **Multi Sector - IM**
- Imperfect side information
- Some results and summary

OS Opportunistic Scheduling
IM Interference Mitigation

Interference Sources – Per OFDMA MIMO Tile

- Multiple sectors in cell use same tile (sector reuse - antenna pattern separation)
- Multiple cells use same tile (cell reuse - cell-to-cell geographic separation)



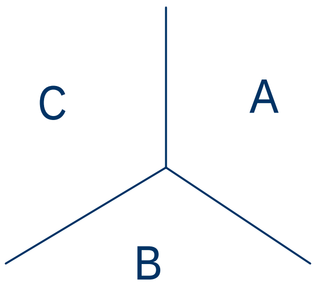
OFDMA vs CDMA Multi-Sector

	OFDMA	CDMA
Multi-sector/cell interference	Variable reuse Interference avoidance Interference cancellation Variable spreading Interference averaging	Variable spreading, Interference cancellation Interference averaging

Both OFDMA and CDMA have interference variability issues

Opportunistic Interference Avoidance

- Pick reuse group per tile across sectors / cells to ensure good SNR for own user (s) in sector and no cross interference to users within group in other sectors



OFDMA Tile

Interference Matrix

	A	B	C
A	X	0	0
B	0	X	0
C	0	0	x

Interference Management, Cont'd

- Interference avoidance (variable reuse)
  - Drop reuse for selected tiles
- Power control
  - Power control across sectors / cells to increase sum capacity
- Variable spreading, interference averaging and link adaptation

Outline

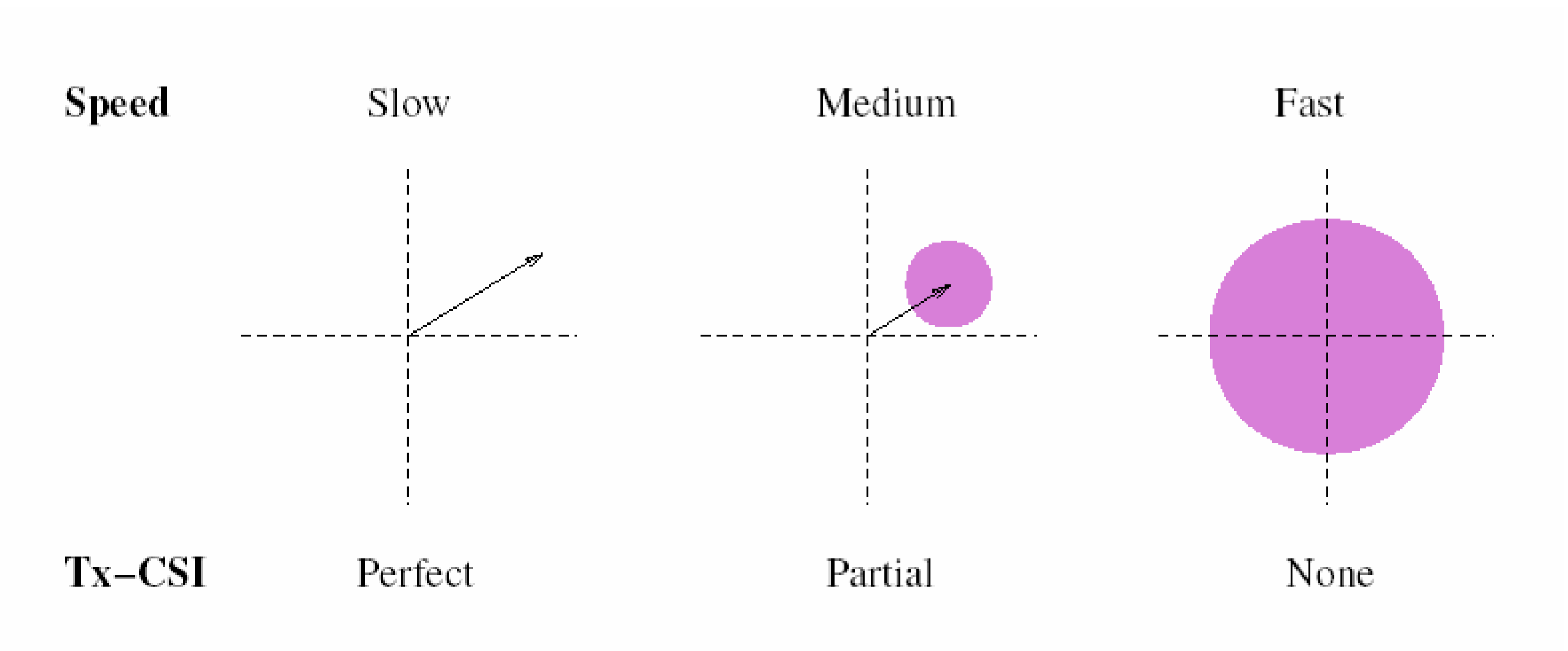
- Introduction
- Single Sector - MIMO, OFDMA, OS
- Multi Sector - IM
- **Imperfect side information**
- Some results and summary

OS Opportunistic Scheduling
IM Interference Mitigation

Side Information at Tx

- Channel side information
  - Needs open / closed loop techniques
  - Degraded by system lags, mobility, limited feedback channel
- Interference side information
  - Needs closed loop methods
  - Degraded by lag, mobility, interference persistence, spatial processing

Channel Side Information at Tx



Channel Side Information – Tx is degraded due several factors – primarily lag

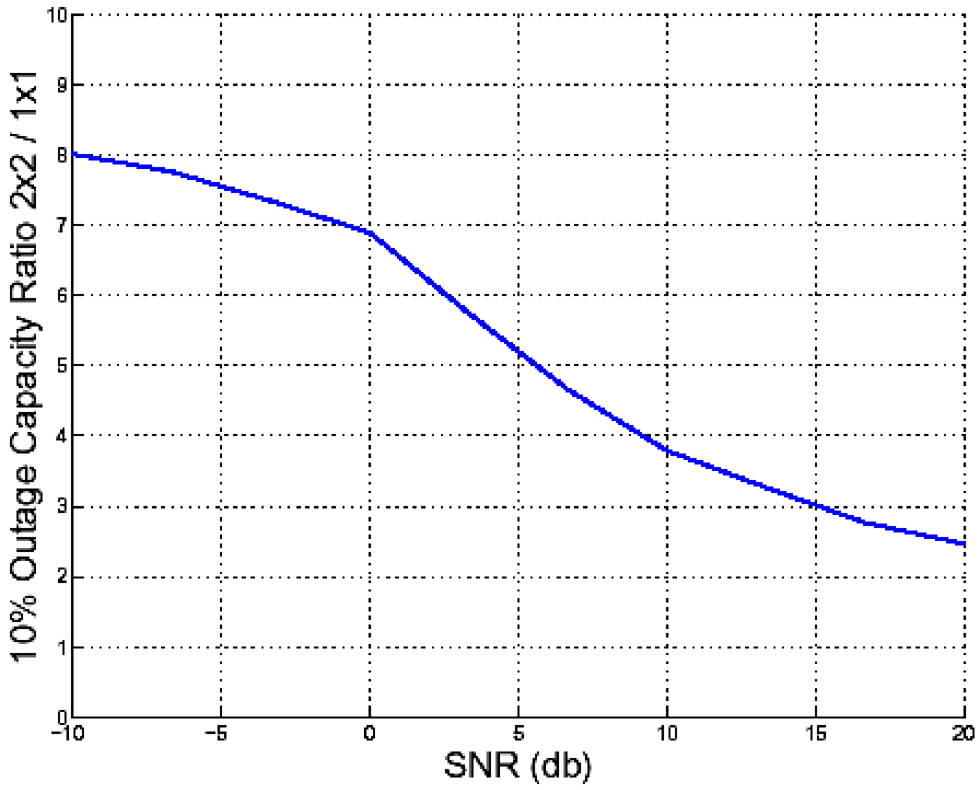
DL Tx-CSI

	Latency	Pilot Overhead	Tx-Rx antenna reuse	Feedback Overhead	Tx-Rx calibration
Closed loop FDD and TDD	Lower for FDD	Dependent on Tx antennas Independent of Rx antennas	Not required	Yes Product of Tx and Rx antennas	Not required
Open loop TDD only	Lower for channel sounding	Independent of Tx antennas Dependent on Rx antennas	Required	No	Required

Low SNR Capacity Ratio

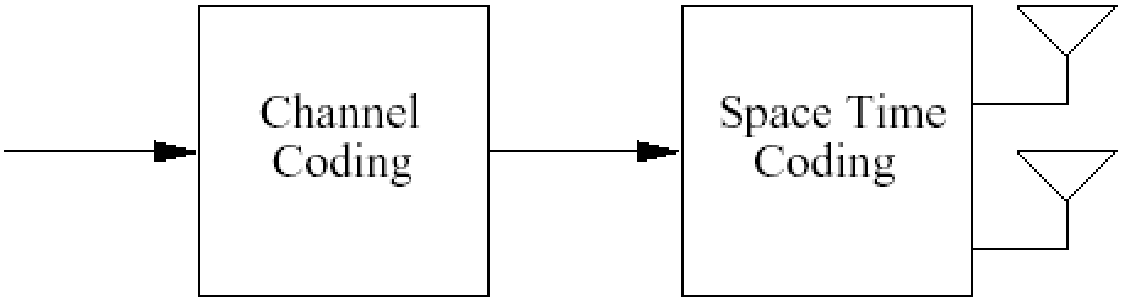
Without Tx-CSI

Single User



Capacity advantage even higher at low SNR

ST Coding without Tx-CSI



- Diversity is important

    Improves Outage Capacity

- Receive Diversity

    Available, unless we use linear receivers

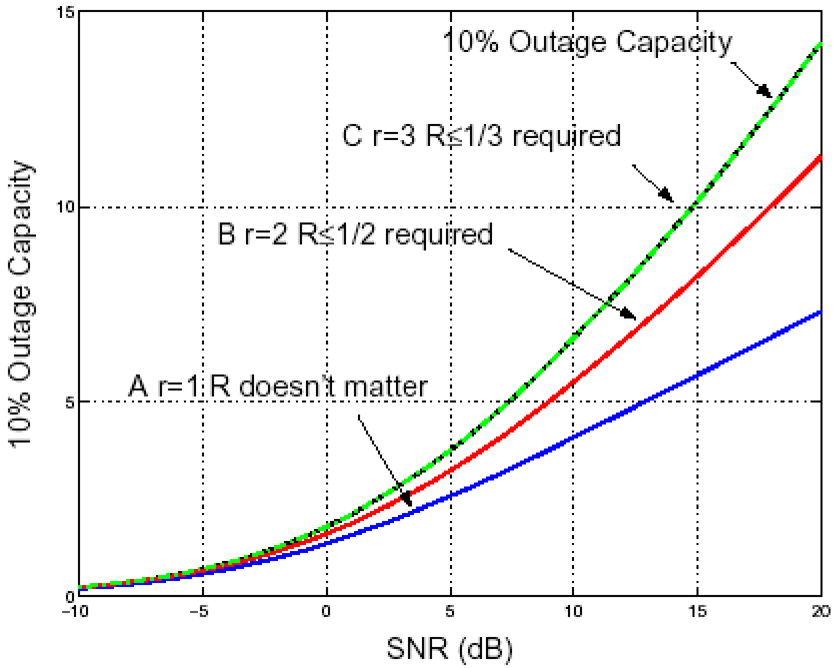
- Transmit Diversity M_t

    Requires coding

    Code rate R ≤ 1 / Mt to capture full Tx diversity

ST Coding Design

3x3 MIMO



$$A:\begin{bmatrix} s_1 & s_2^* \\ s_2 & -s_1^* \\ 0 & 0 \end{bmatrix}$$

$$B:\begin{bmatrix} s_1 & s_2^* \\ s_2 & -s_1^* \\ s_3 & s_4 \end{bmatrix}$$

$$C:\begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix}$$

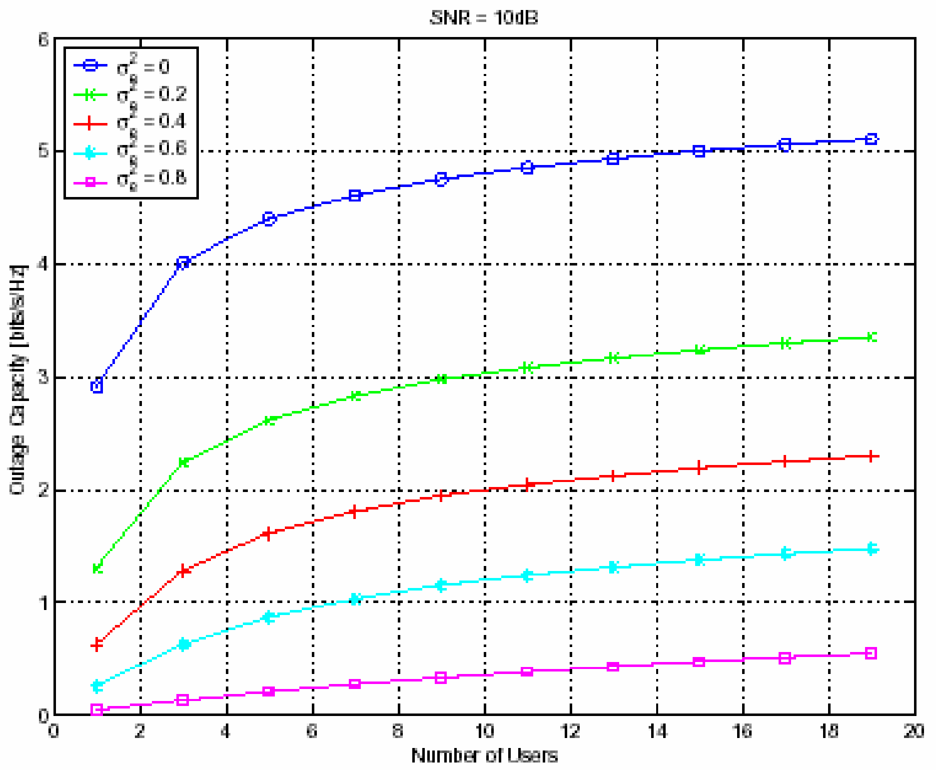
For each SNR band, choose ST code with multiplexing gain and coding gain to hug outage capacity curve at the lowest complexity

Diversity available both from the ST code and channel code

Partial Tx-CSI and Loss in OS Gain

SISO with channel gain reported with error

σ^2 is the normalized error in Tx-CSI



For K=15, OS gain .

Imperfect Side Information

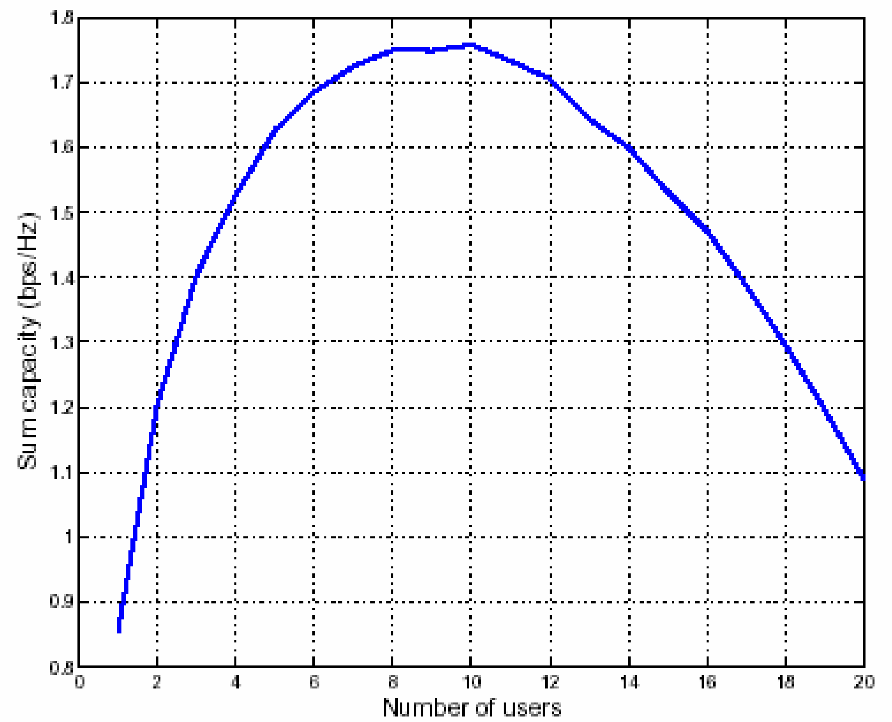
- OFDMA+OS
  - Move to diversity allocation (equiv. to FH)
- MIMO+OS
  - Move to single user space-time diversity coding
- Interference mitigation
  - Move to interference averaging (eq. random freq hopping)

Outline

- **Introduction**
- Single Sector - MIMO, OFDMA, OS
- Multi Sector - IM
- Imperfect side information
- Some results and summary

OS Opportunistic Scheduling
IM Interference Mitigation

Delay Constraint and OS Gain

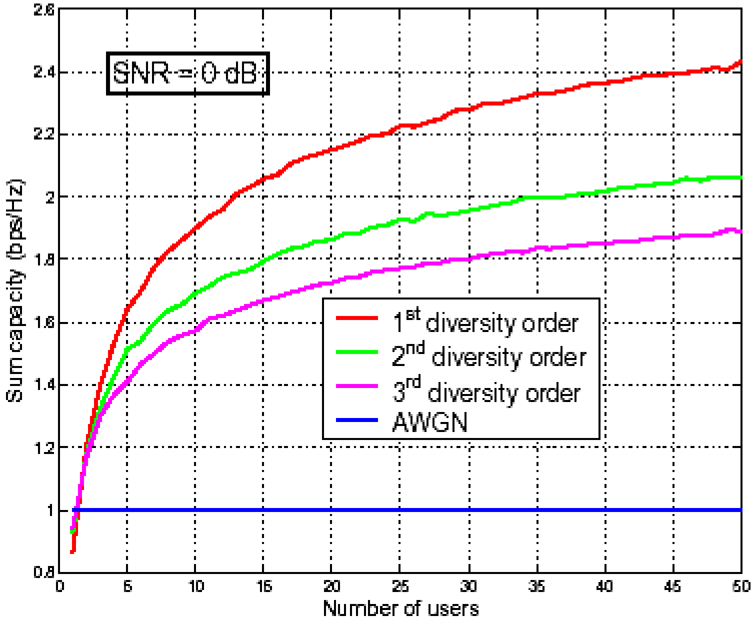


Delay constraint = 20 time slots

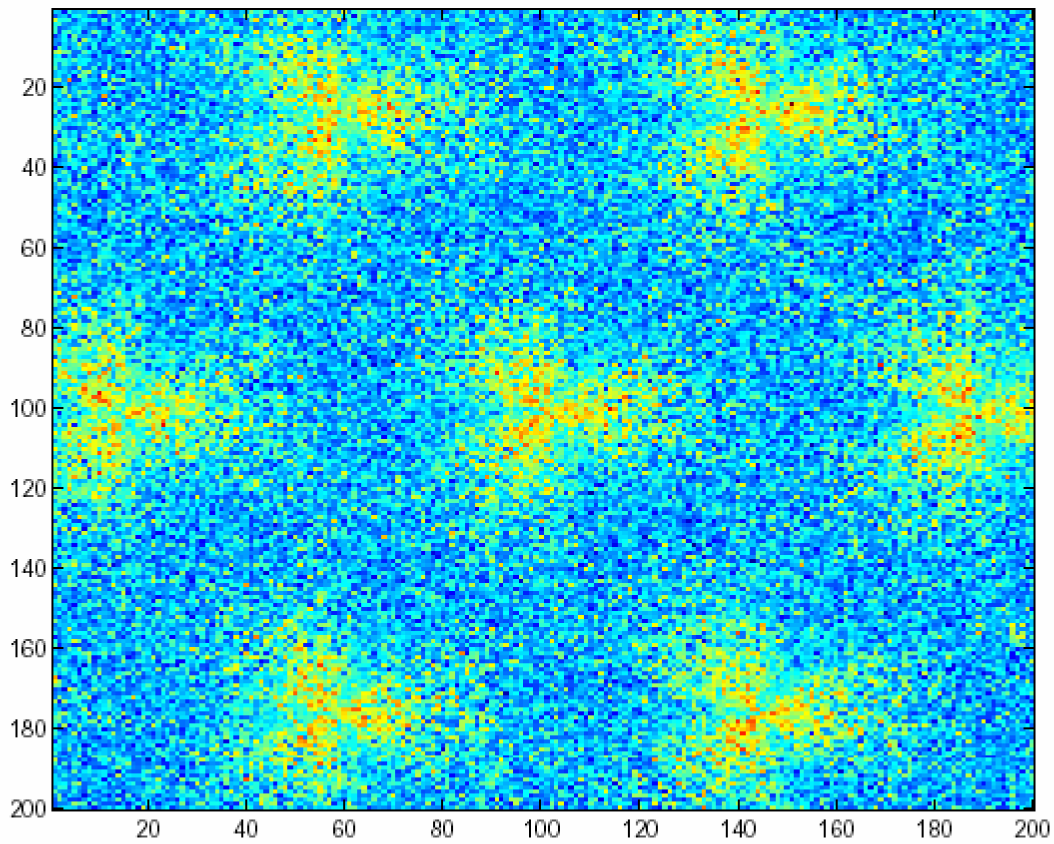
Delay constraint dramatically reduces OS gain.

Diversity and Loss in OS Gain

SISO channel with diversity



Raw C/I in Toroidal Universe



Spatial distribution of downlink C/I

Network Simulation Results

- Downlink
- Techniques: OFDMA, MIMO and OS
- Three sectors, full reuse (1x1)
- Modeling: Toroidal universe, standard path loss and shadow fading modeling
- Parameters

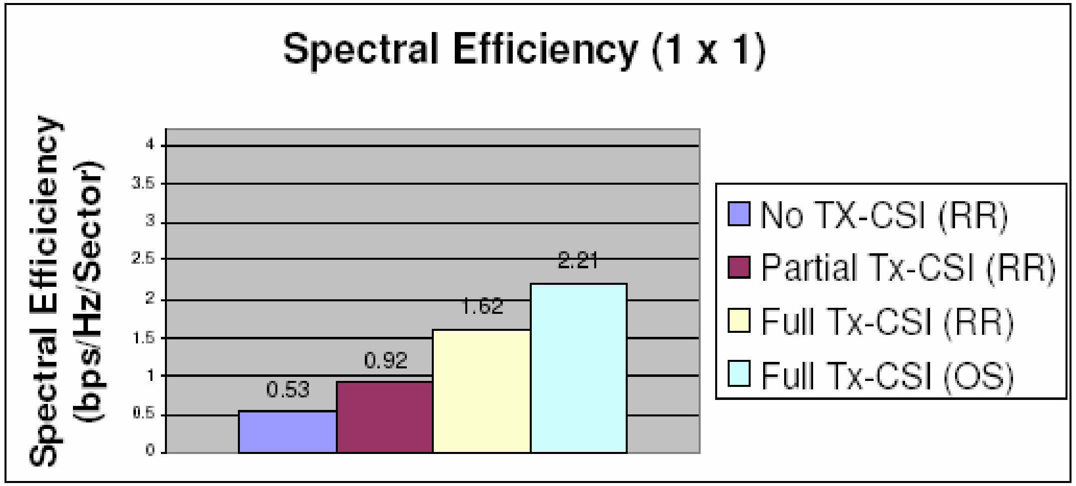
  - No. of users K = 15 or 1

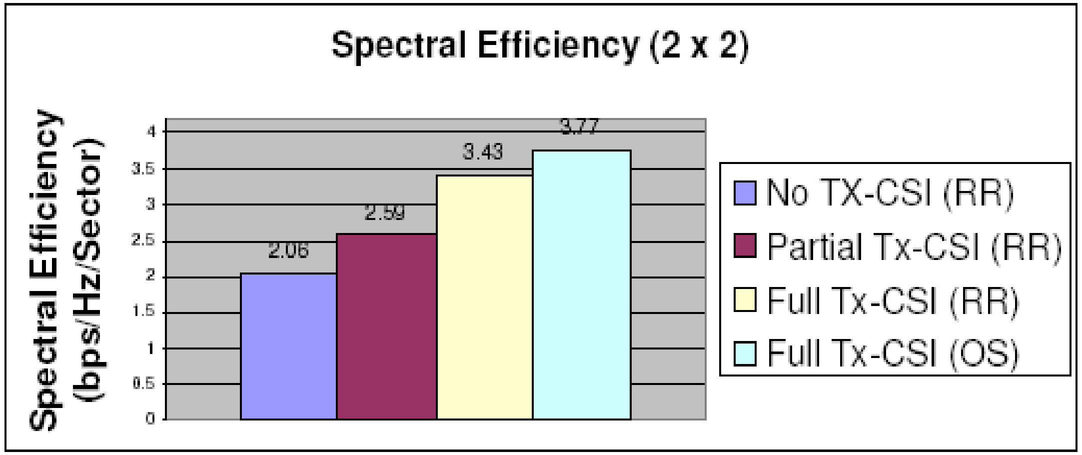
  - Antennas $M_t = M_r$ 2x2 or 1x1

  - No. of sub channels L=5 or 1

  - i.i.d. MIMO channels (Ricean factor = 0)

Spectral Efficiency: BPS/Hz/Sector



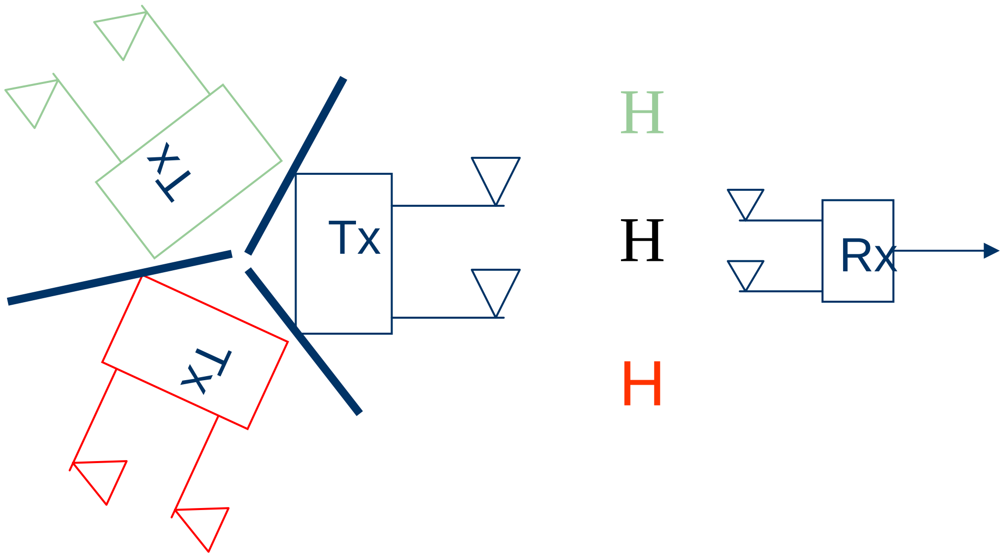


Does not include system overheads and modem inefficiencies

Summary

- A combination of OS+OFMDA+MIMO+IM offers a reasonable path to 3.5G
- Wideband channels, large number of users is advantageous
- Tx side information is critical but expensive. We need to balance performance with overhead

Interference Side Information at Transmit



Interference side information is degraded both due to lag, feedback bandwidth and scheduling persistence

Does MIMO work?

- Low SNRs – needs only beam forming, CDMA self noise is not a problem. OFDMA and CDMA performance is comparable
- High SNRS – needs complex receivers to handle SM, and CDMA self noise floors performance. OFDMA wins strongly.

ST Coding Design Challenges

Decode complexity:

$$O\left(2^{M_t \frac{1}{R_c} \frac{b}{2}}\right)$$

Complexity due to joint detection (M_t)

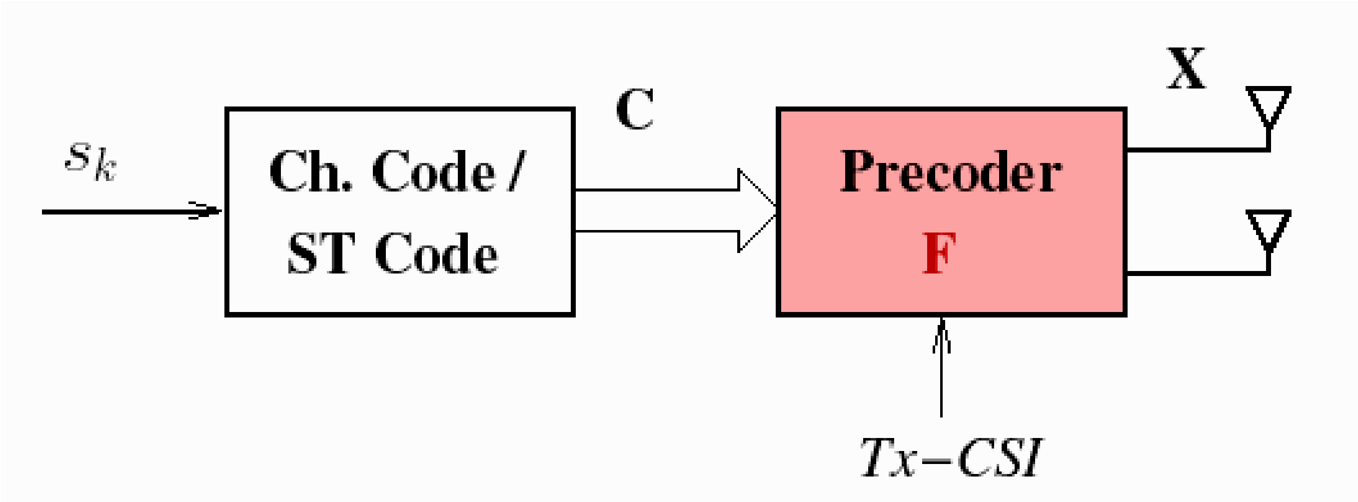
Complexity due to joint detection ($\frac{1}{R_c}$)

bits per dimension ($\frac{b}{2}$)

- Demapping large QAMs is a problem
- Repetition based codes escape this trend due to linear processing

  - But are multiplexing gain suboptimal

Utilizing Partial Tx–CSI



- General Principle:
  - Design ST Coding assuming zero Tx-CSI
  - Use a linear pre coder as a function of the Tx-CSI
- The Linear Pre coder matches
  - ST code on one side
  - Channel on the other side.

$$\mathbf{Y} = \mathbf{HFC} + \mathbf{N}$$

Outline

- Introduction
- Single-user MIMO
- **OFDMA and MIMO**
- Opportunistic Scheduling and MIMO
- Summary

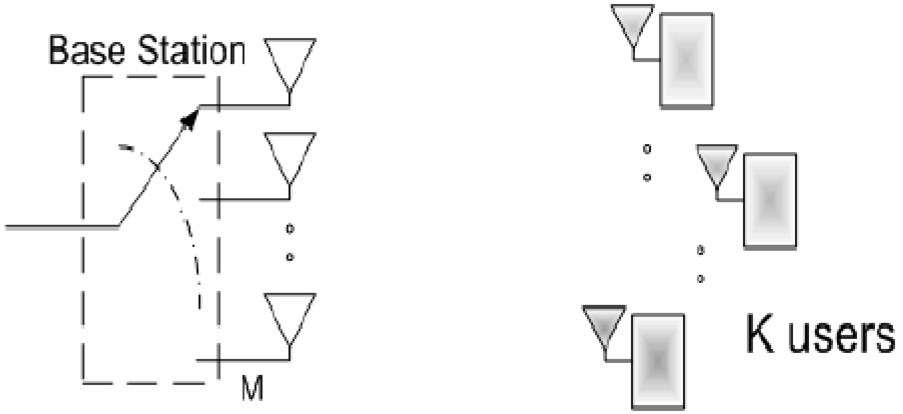
OFDMA and MIMO

- MIMO receiver complexity is lower - no multipath or multiuser interference to be dealt with
- Supports space-frequency-time coding – better Doppler tolerance
- Spatial interference cancellation more effective (few dominant interferers)

Outline

- Introduction
- Single-user MIMO
- OFDMA and MIMO
- **Opportunistic Scheduling and MIMO**
- Summary

OS and Multiple Antennas



- TDMA, tr
- Independent fading channels across antennas & users
- BS antenna branch “l”, user “i” are selected as:

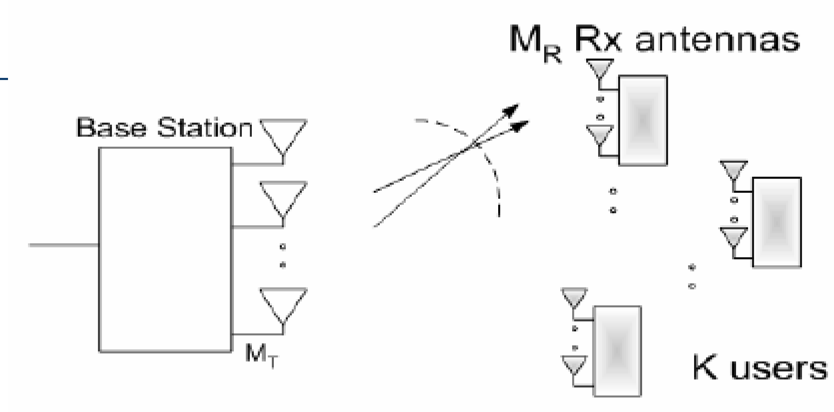
$$(l, i) = \arg\left(\max_{m=1,\cdots,M \;\; k=1,\cdots,K} \gamma_{m,k}\right)$$

- Sum capacity ~ O ($\log_2 \log_e$ MK)
- For single packet transmission, Delay ~ O (K log K)

Fairness and Delay

- Resource fairness – each user gets on average equal *time x bandwidth* resource
- If channel fades are independent from slot to slot (duration T_s), then average delay experienced by sending 1 packet is
  - $O(K)$ slots for Round Robin (RR)
  - $O(K \log K)$ slots for Proportional Fair (PF)
- Fairness window is average time window over which fairness is achieved. For slot-to-slot independent fading, fairness window is $O(K)$ for RR
- If channel fades slowly, then fairness window expands to $O(KT_c / T_s)$ slots. We can convert space or frequency selectivity to reduce fairness window.

MIMO and OS: TDMA



- TDMA, transmit to a single user "i" at a time, based on max MIMO capacity

$$i = \arg\left(\max_{k=1,\cdots,K} C_{MIMO,k}\right)$$

- Therefore

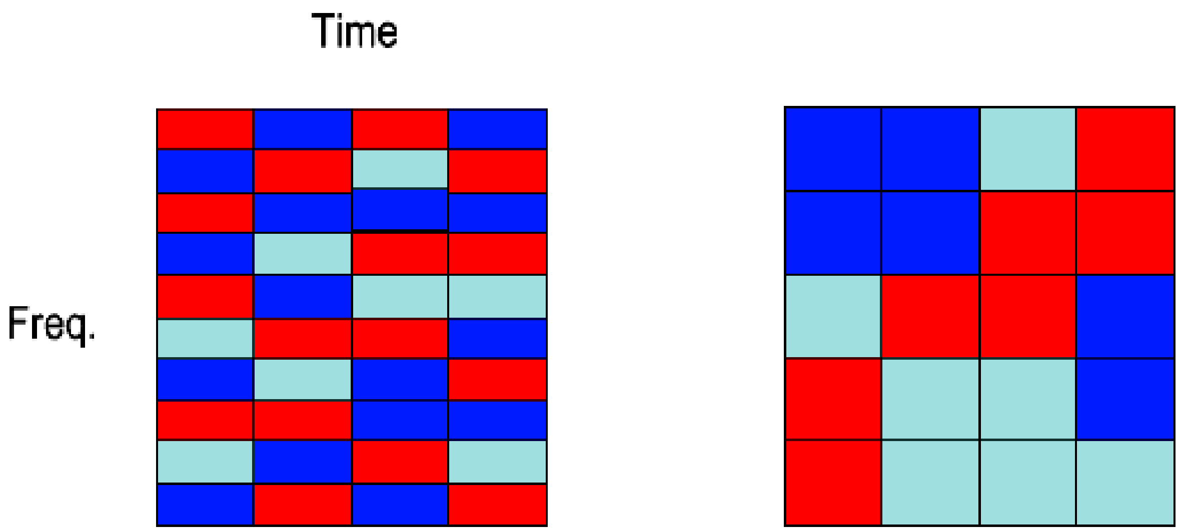
  $C_{sum} \sim O(\min(M_T, M_R) \log_e \log_2 K)$ for $M \times M$

  $C_{sum} \sim O(\log_e(M \log_2 K))$ for $M \times 1$

  Delay $\sim O(K \log K)$

  Links now have a spatial diversity reducing OS gain

OFDMA



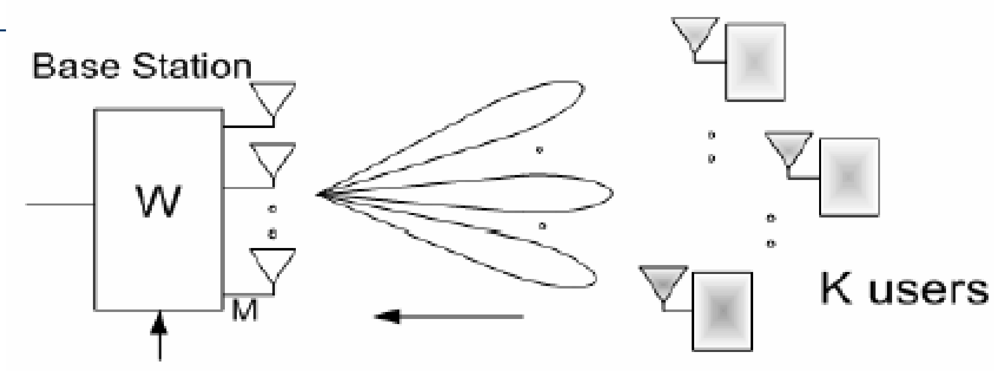
Freq. diversity mode - no Tx-CSI

OS mode - with Tx-CSI

OFDMA outperforms CDMA in broadband

- Avoids multipath and multiuser interference
- Better spectral efficiency
- Allows frequency domain power control
- Opportunistic scheduling in frequency domain

MIMO and OS: SDMA



- Transmit to M users per time slot (SDMA)
- No DPC, only simple beamforming with M users scheduled simultaneously
- Pick best M users based on orthogonality of user channels and channel gain
- Therefore, for unit transmit power

$$C_{sum} \sim O\left(M \log_2 \left((1/M) \log_e K \right) \right); \text{ needs } M \sim \log K$$

[Yoo, Goldsmith '05], [Sharif, Hassibi '05]

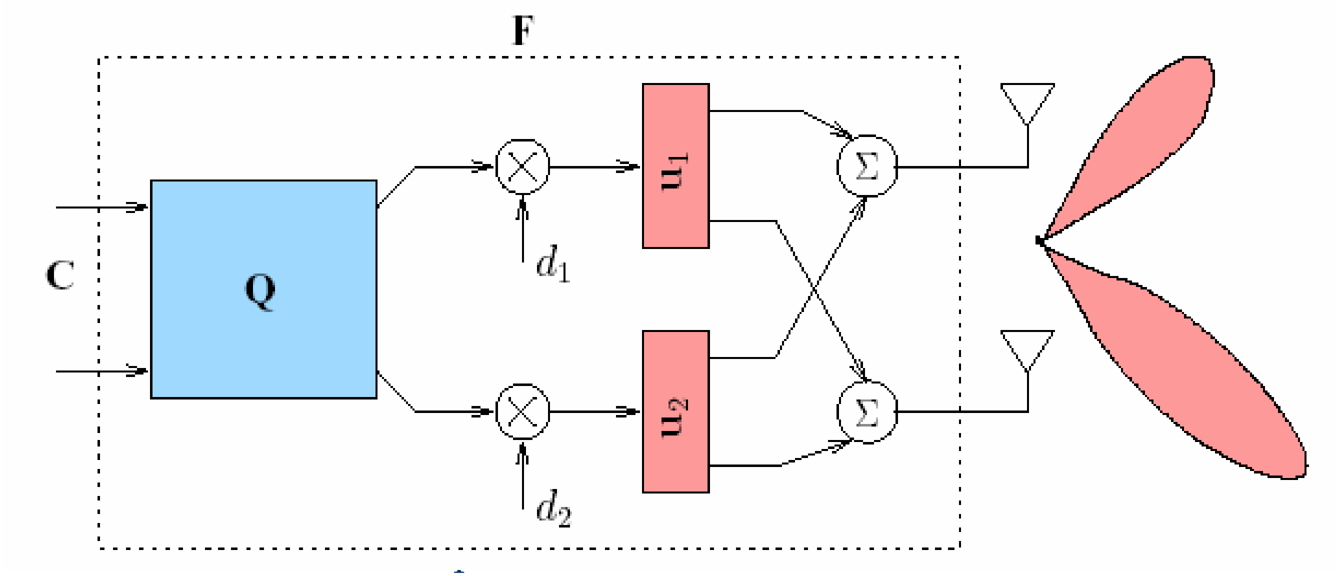
Summary

- OFDMA has significant advantages over CDMA in rich multipath (high bandwidth x delay spread) channels. OFDMA eliminates multipath and multiuser interference, and the OS gain loss associated with CDMA.
- MIMO increases system capacity to its full promise in OFDMA.
- OS works well with OFDMA with no delay penalty.

OS Summary

- C_{sum}
  - O (M log log K) for MIMO-TDMA
  - O (log M log K) for MISO-TDMA
  - O (log log KM) for SISO-TDMA
- Delay O (K log K) in TDMA
- Delay reduces ~ O (L) in OFDMA or ~ O (M) in SDMA

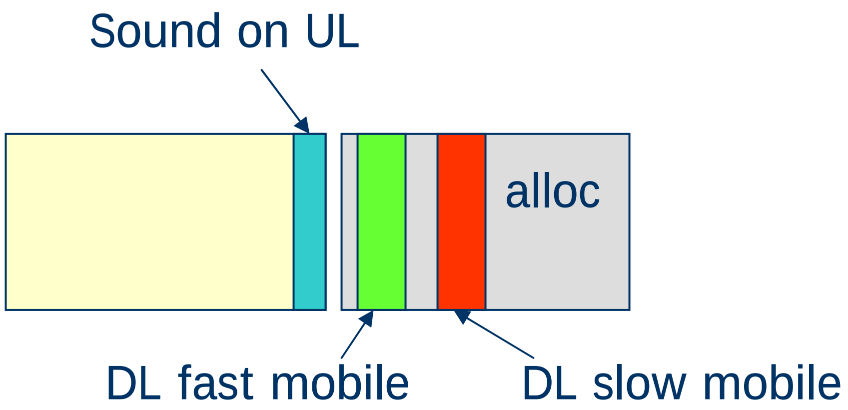
MIMO Precoding



- Output beam directions **u1, u2** depend on eigenvectors of
  E [**H** **H***]
- Beam powers d determined by water filling
- Input shaping **Q** depends on the codeword covariance

H

Fast Tx–CSI



- Fast turn around by open loop sounding gives good Tx-CSI which has no mul. antenna penalty
- Gives good performance for antenna rich deployments and supports fast mobiles