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Reality Constrained Capacity –
The Curious Case of Mobile Broadband Access

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Motivation

- Mobile broadband systems will be reuse-1 MIMO-OFDM
  - Highly interference limited behaviour
  - Interference power, profile, and statistics, could vary frame-to-frame
- Interference aware Tx, Rx techniques to maximize
  - Cell avg. spectral efficiency (SE) in bits/sec/Hz/cell while ensuring a minimum guaranteed SE to cell-edge users is required
- Capacity of interference channels is an open problem
  - Constellation constrained capacity is well understood
  - Focus here is on constraints put by (a) standards, (b) practical implementations, and (c) insufficient or mis-specified statistics
- Therefore, rather than trying to study the capacity of such VBR systems, it is more practical to focus on:
  - Average SE
  - Throughput (per user, cell average)
    - **While ensuring "fairness" and/or latency specs**

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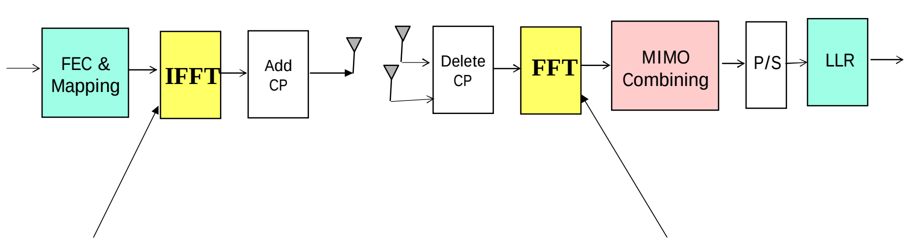
Coded OFDM -- Downlink

- Nearly all new and emerging wireless standards use OFDM
  - Flexibility in resource allocation
  - Ability to scale with bandwidth easily



If $x_0(k)$ modulates the k^{th} subcarrier

measurement on the k^{th} subcarrier is $y(k) = H(k)x_0(k)+v(k)$

Channel Model

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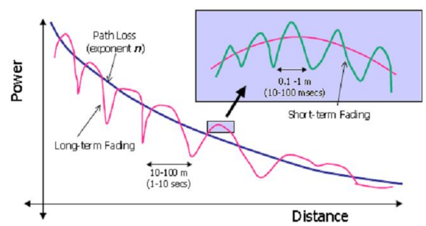
- Assuming (nearly) perfect timing and freq. synchronisation in OFDM# downlink

$y(n,k) = H(n,k)x_0(n,k) + v(n,k)$, where $x_0(n,k)$ is a QAM symbol and $v(n,k)$ is $N(0,\sigma_v^2)$

Question : How to model $H(n,k)$? (We drop time index n)

- In link level studies, $H(k)$ is taken as Rayleigh, Rician, Nakagami etc.
- For system level studies, a better model is $H(k) = \left(\frac{P_T}{r_0^n}\right) L_0 \tilde{H}(k)$
- Here, r_0^n is the pathloss, and L_0 is log - normal shadowing



SIMO Measurement Model with CCI

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- Considering SIMO OFDM downlink (any virtual antenna Tx mode)

For 2 Rx antennas, $y(k) = H(k)x_0(k) + v(k)$ is modified to

$$\begin{bmatrix} y_1(k) \\ y_2(k) \end{bmatrix} = \begin{bmatrix} H_1(k) \\ H_2(k) \end{bmatrix} x_0(k) + \begin{bmatrix} v_1(k) \\ v_2(k) \end{bmatrix}, \text{ or simply, } \mathbf{y}(k) = \mathbf{H}(k)x_0(k) + \mathbf{v}(k)$$

- In the presence of cochannel interference signals, the measuremen ts are

$$\mathbf{y}(k) = \mathbf{H}(k)x_0(k) + \underbrace{\sum_{i=1}^{L} \mathbf{G}_i(k)x_i(k) + \mathbf{v}(k)}_{\mathbf{z}(k)}$$

- The raw (or pre - processing) SINR is given by

$$\text{r - SINR} = \frac{\mathbf{H}^H(k)\mathbf{H}(k)\sigma_0^2}{\mathbf{z}^H(k)\mathbf{z}(k)}$$

Linear MMSE Receiver

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- Recall the CCI measurement model

$$\mathbf{y}(k) = \mathbf{H}(k)x_0(k) + \underbrace{\sum_{i=1}^{L}\mathbf{G}_i(k)x_i(k) + \mathbf{v}(k)}_{\mathbf{z}(k)}$$

- The <u>true</u> interference + noise covariance is given by

$$\mathbf{R} = E[\mathbf{z}(k)\mathbf{z}^H(k)] = \sum_{i=1}^{L} E[\mathbf{G}_i(k)\mathbf{G}_i^H(k)]\sigma_i^2 + \sigma_v^2\mathbf{I}_{2\times 2}$$

LMSE Receiver – contd.

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Factorizing $\mathbf{R}^{-1} = \mathbf{R}^{-1/2}\mathbf{R}^{-1/2}$, coloured noise $\mathbf{z}(k)$ is whitened by

$$\mathbf{R}^{-1/2}\mathbf{y}(k) = \mathbf{R}^{-1/2}\mathbf{H}(k)x_0(k) + \tilde{\mathbf{z}}(k)$$

- Next, by projecting this in the direction of $\mathbf{R}^{-1/2}\mathbf{H}(k)$, we get the scalar output

$$u(k) = (\mathbf{R}^{-1/2}\mathbf{H}(k))^H\mathbf{R}^{-1/2}\mathbf{y}(k) = (\mathbf{R}^{-1/2}\mathbf{H}(k))^H\left\{\mathbf{R}^{-1/2}\mathbf{H}(k)x_0(k) + \tilde{\mathbf{z}}(k)\right\}$$

- i.e., using the LMSE receiver $\mathbf{w} = \mathbf{R}^{-1}\mathbf{H}$, we have obtained

$$u(k) = \mathbf{w}^H\mathbf{y}(k) = \mathbf{w}^H\mathbf{H}(k)x_0(k) + \mathbf{w}^H\mathbf{z}(k)$$

- The post-processing SINR after the LMSE receiver is therefore

$$\text{pp-SINR} = \{\mathbf{H}^H(k)\mathbf{R}^{-1}\mathbf{H}(k)\}\sigma_0^2$$

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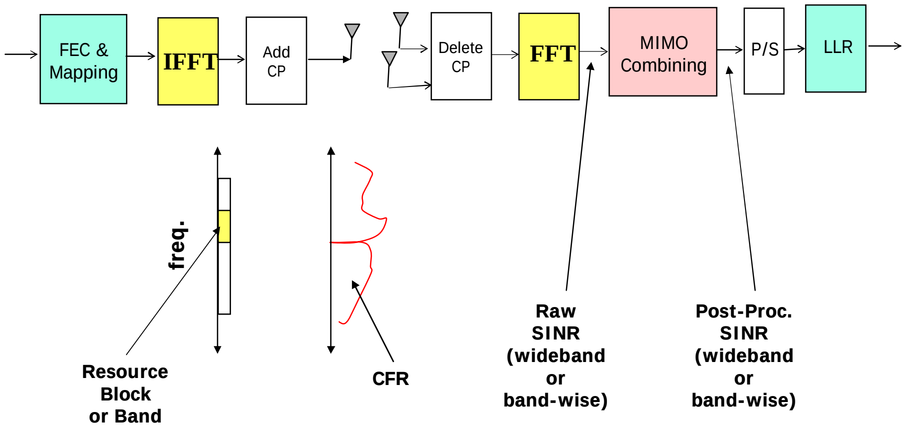
Coded OFDM -- Downlink



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Problem Statement

- In frame #n :
  - pp-SINR → avg. mutual info. → modulation and coding rate that can be supported for frame #n
- Question : In frame #n+Δ, if the user is scheduled
  - What should be the rate that the user be assigned?
  - What will be the actual rate delivered or seen by the user (after accounting for HARQ)?
- Part Answer : Depends on how “stable” is the interference profile

Recall the CCI measurement model

$$\mathbf{y}(k) = \mathbf{H}(k)x_0(k) + \underbrace{\sum_{i=1}^{L} \mathbf{G}_i(k)x_i(k) + \mathbf{v}(k)}_{\mathbf{z}(k)}$$

Freq. Reuse and SINR Distribution

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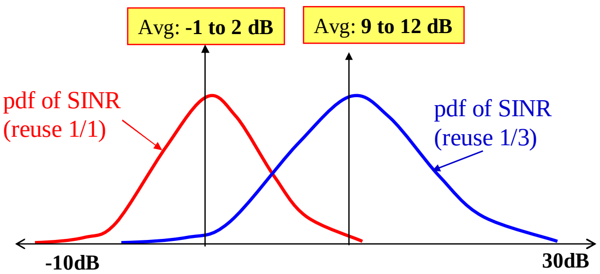
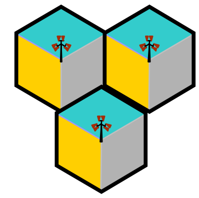
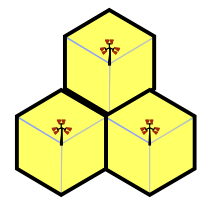




Reuse 1/3



Reuse 1/1

Q: How does the SINR cdf look like?

SINR CDF in Different Models in Het-net

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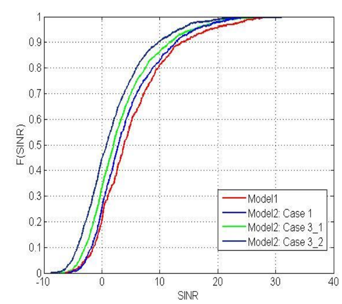
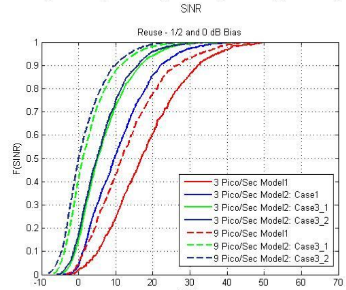
- 4 models for pathloss in the macro-pico scenario
- 3 picos per macro sector
  - Plot1 – Reuse-1/1
  - Plot2 – Reuse-1/2





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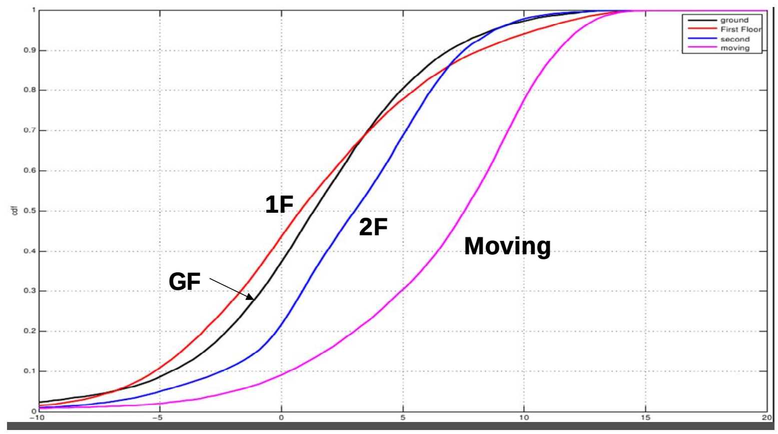
SINR Distribution Measured at the Geographical Cell-Edge



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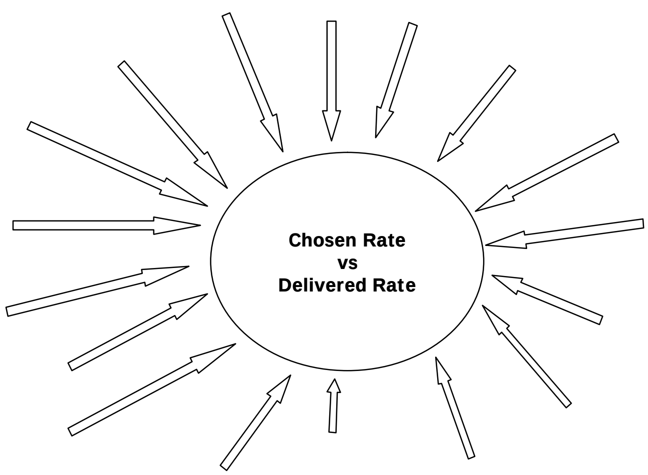
Performance : Expected vs Delivered

1. Unicast or Groupcast?



Performance : Expected vs Delivered

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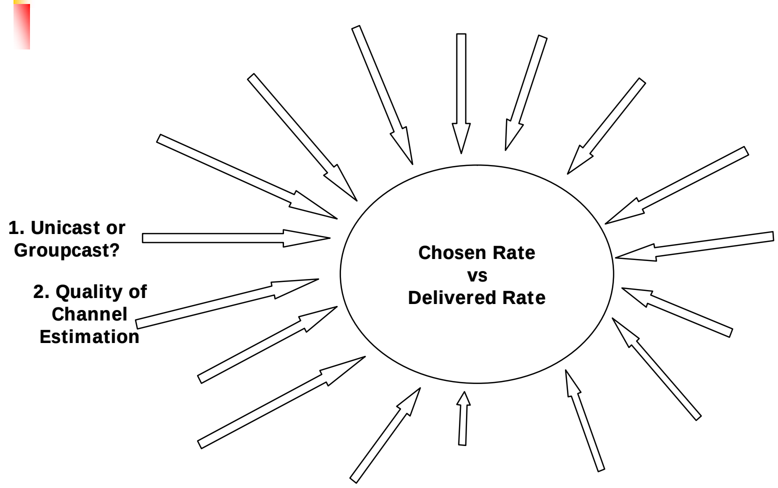

Performance : Expected vs Delivered

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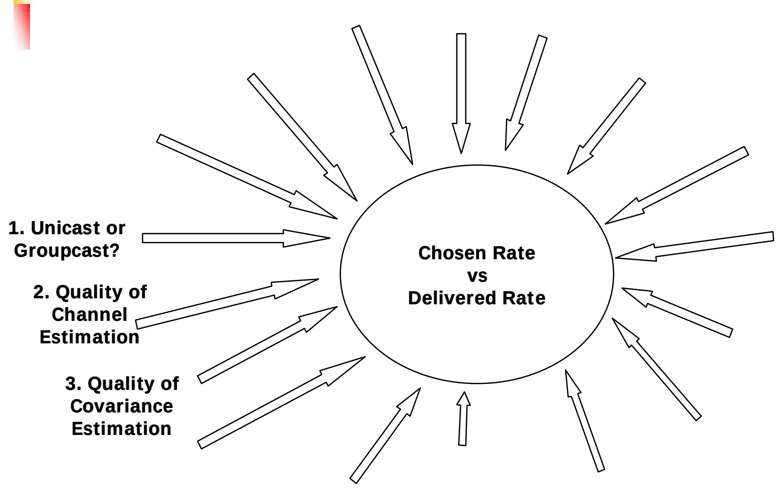

Enhanced Channel Estimation

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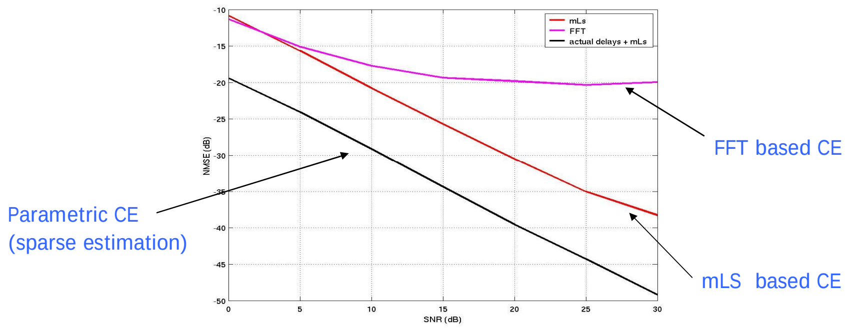

Better CE → Better LMSE Covariance → Lower BER

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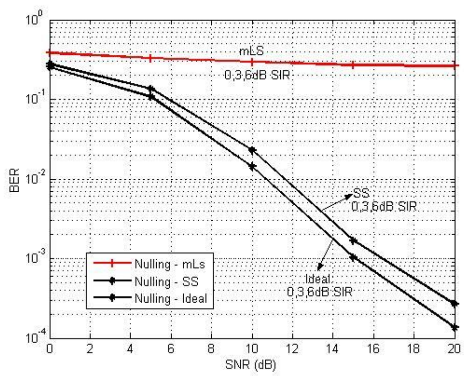

Performance comparison of different CE methods with “nulling”

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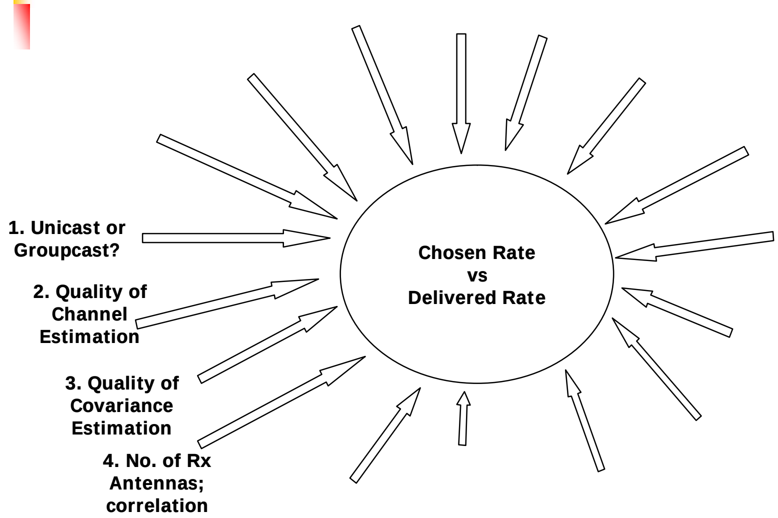
Performance : Expected vs Delivered



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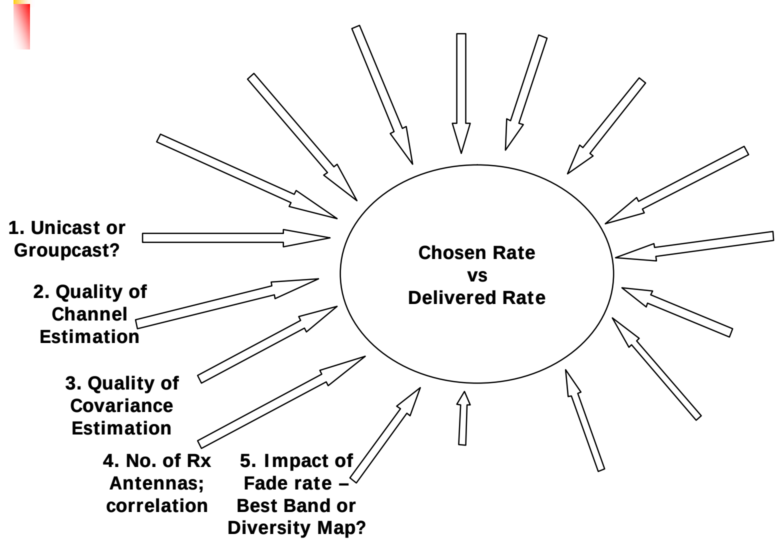
Performance : Expected vs Delivered



Performance : Expected vs Delivered

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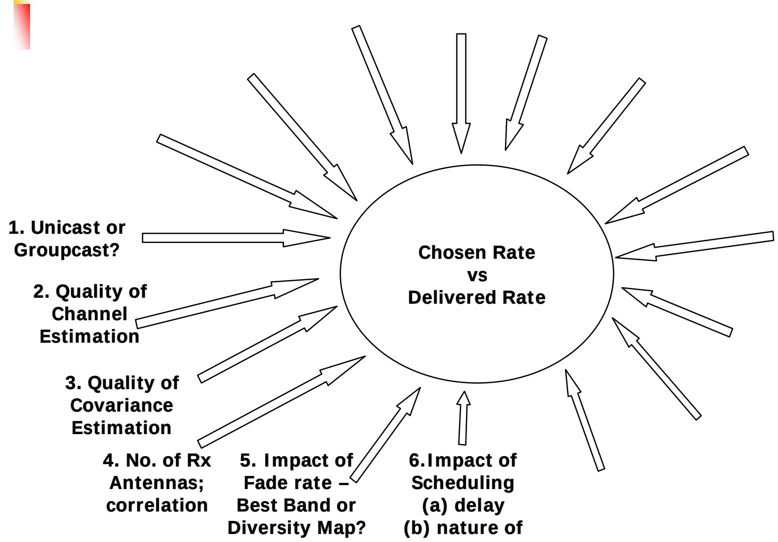

Performance of Proportional Scheduler (Homogeneous Network)

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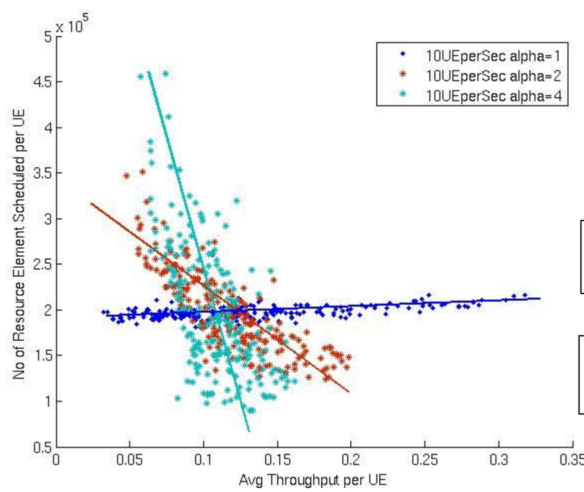

$$PF_{metric} = \frac{R}{(E[R])^{\text{alpha}}}$$

As alpha increases, more resources are given to Users with low throughput

***Simulation with Urban Macro Scenario**

Average Cell Spectral Efficiency (Het-Net)

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3 picos/Sector

	alpha = 0 (Max Rate)	alpha = 1 (PF)	alpha = 2	alpha = 4
Average Cell Spectral Efficiency (b/s/Hz/Sector)	5.23	3.25	2.82	2.58

Avg Thruput reduces

*** Model 2 Case 3_1: Pico Tx power – 37dBm Bias – 6dB**

Performance : Expected vs Delivered

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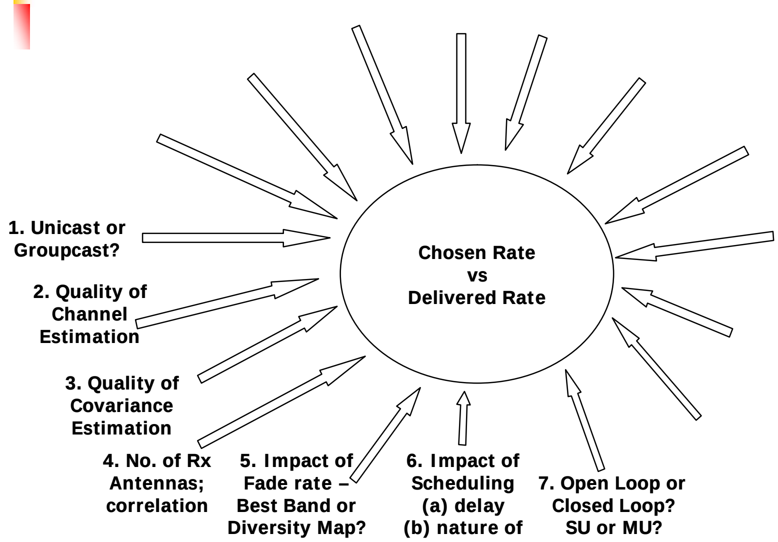

Performance : Expected vs Delivered

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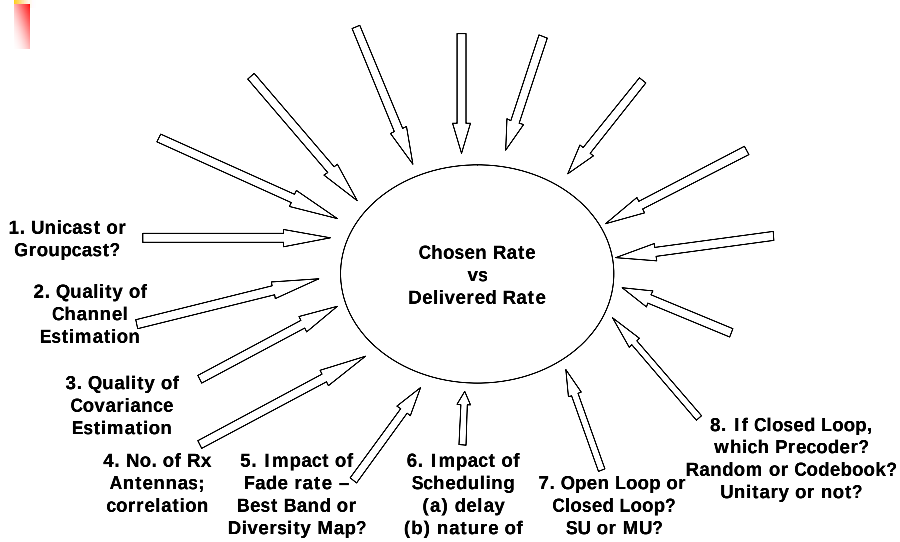

Avg. SE : OL vs CL ; SU vs MU

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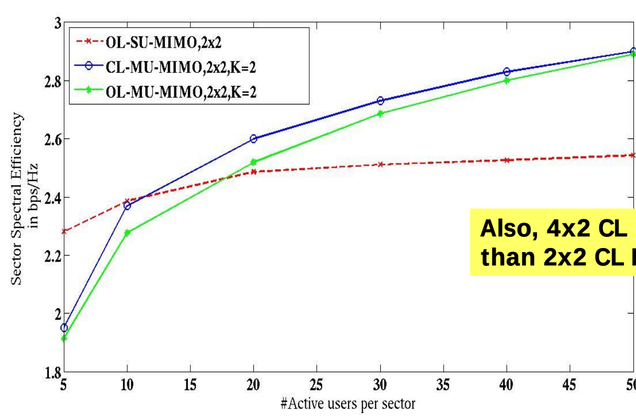
In Precoded CL MIMO (2 Tx or more)

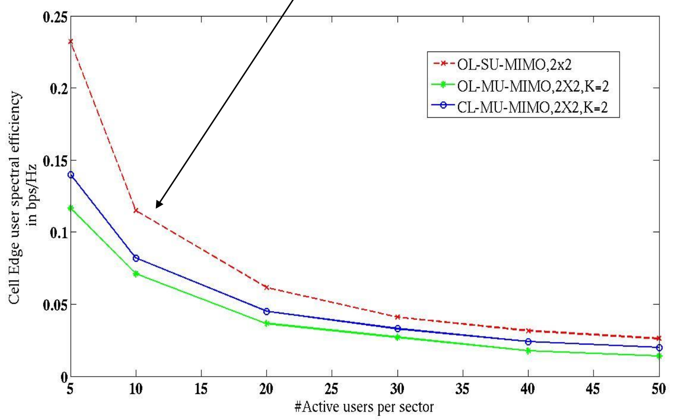
$$\mathbf{y}(k) = \mathbf{H}(k)\mathbf{P}_0(k)\mathbf{x}_0(k) + \sum_{i=1}^{L}\mathbf{G}_i(k)\mathbf{P}_i(k)\mathbf{x}_i(k) + \mathbf{v}(k)$$



Also, 4x2 CL is poorer than 2x2 CL Precoding !

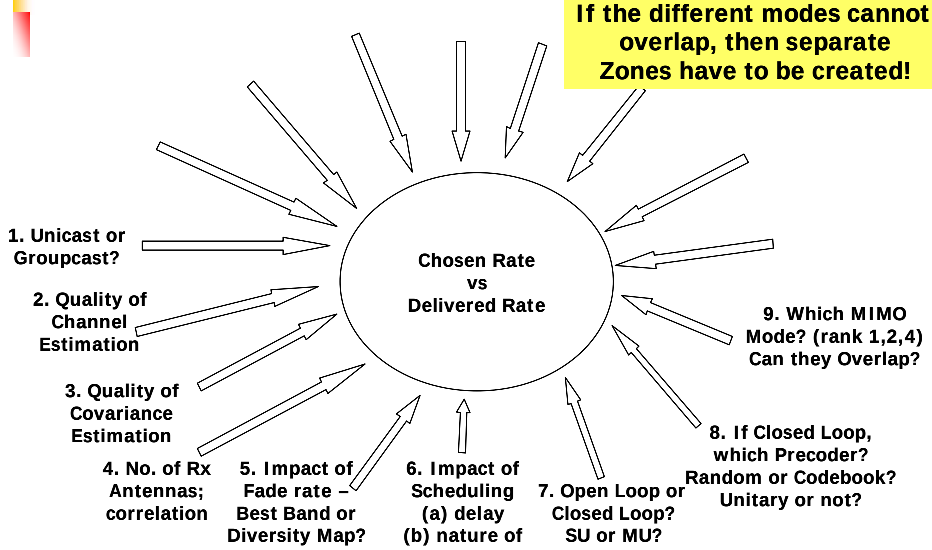
Cell Edge Spectral Efficiency

Clearly, SU is better than MU at cell-edge !



Performance : Expected vs Delivered

If the different modes cannot overlap, then separate Zones have to be created!



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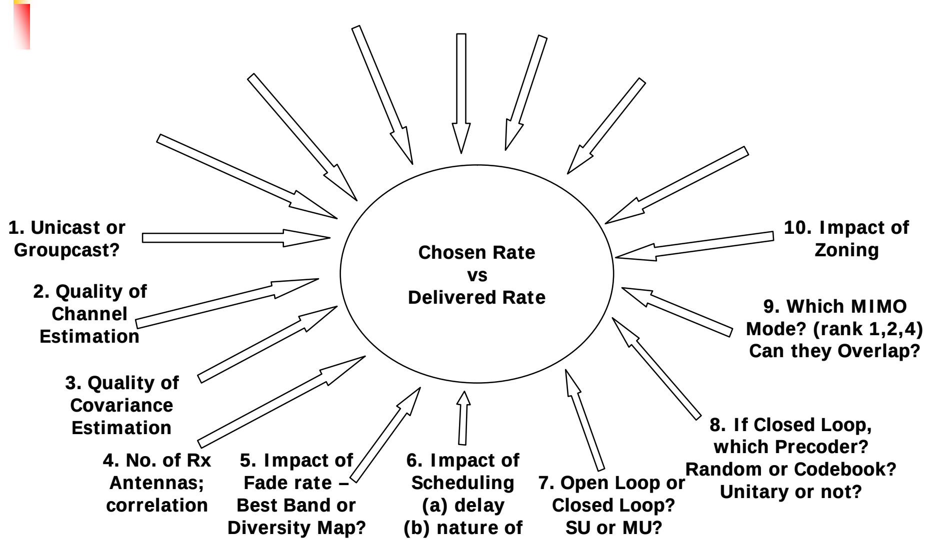
Performance : Expected vs Delivered



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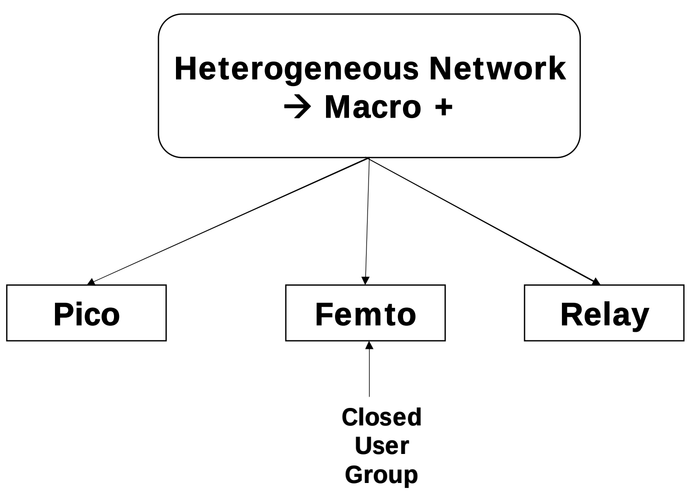

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Reuse – 1 vs Reuse – ½ (Model 2: Case 3_1)

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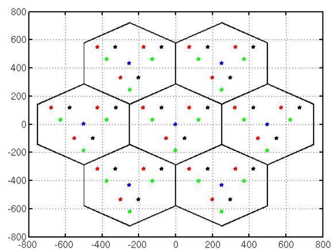
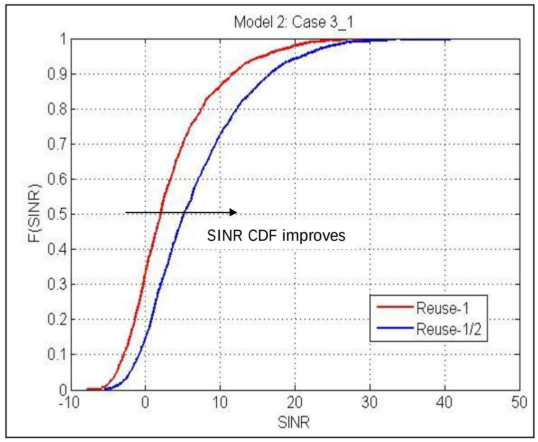
- When Macro and pico eNodeBs do not operate simultaneously in the same resource
- There are 3 to 10 picos per sector





Resource Sharing in Het-Nets

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Resources will be divided between macro and pico, based on the average load seen by a pico

Macro	**Pico**
β	1-β

If M is the avg. thruput of macro/sector, P is the avg. thruput per pico and N is the number of picos/sector, then the thruput/sector will be,

$$T = \beta M + N(1-\beta)P$$

Since β is a system wide parameter, some picos may not be able to serve all their users while some picos may have surplus resources

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Average Cell Spectral Efficiency

	Urban Macro (No Pico)	Het-Net Model 2 Case 3_1 (3 Pico/cell)
Average Cell Spectral Efficiency (b/s/Hz/cell)	1.423	3.25

*** Model 2 Case 3_1: Pico Tx power – 37dBm Bias – 6dB**

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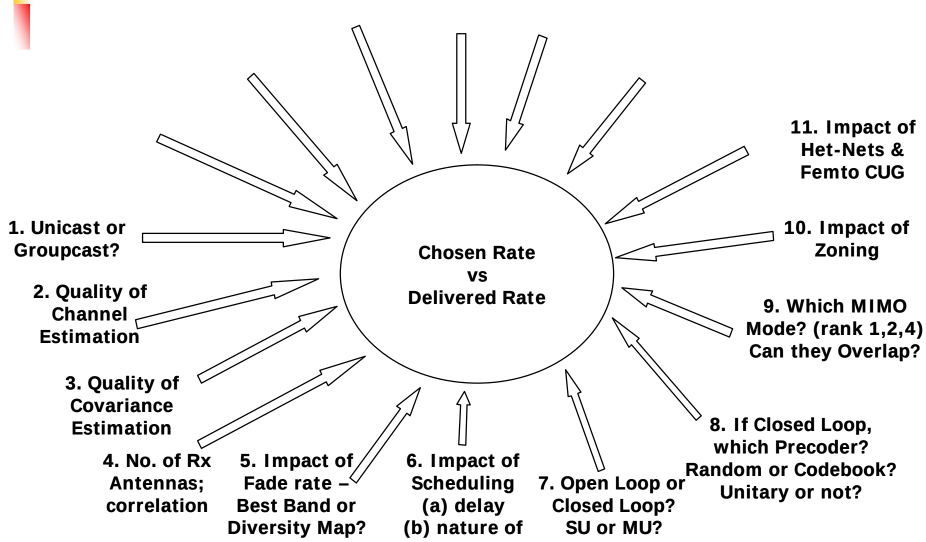
Performance : Expected vs Delivered



Performance : Expected vs Delivered

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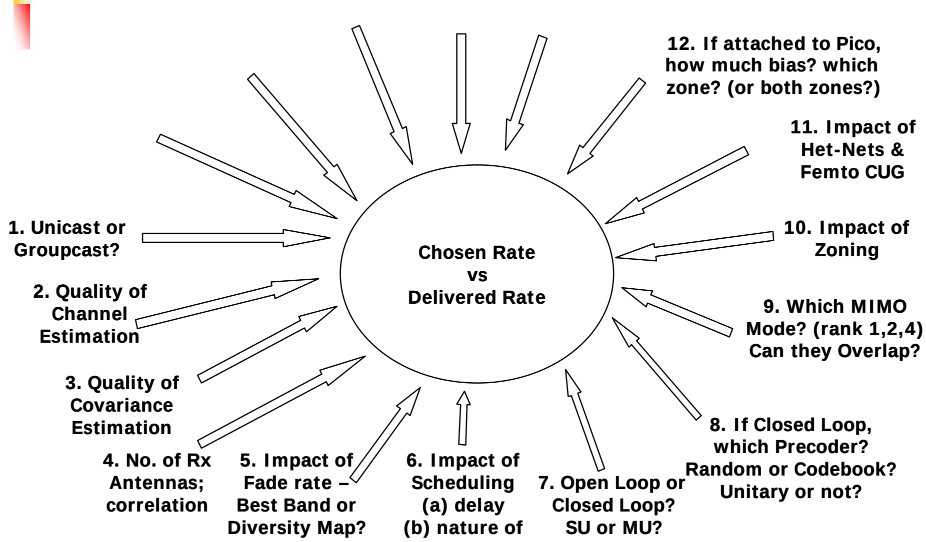

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Range Extension

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- Problem
  - Loss in capacity due to partition of resources
- Solution → Range Extension (or bias)
  - UE attaches to a pico as long as pico rec power + x > Macro rec power . 'x' (in dB) is called the bias .

Het-net Model	Pico Tx Power (dBm)	No of UE Attached to Pico(%)		
		0dB	3dB	18dB
Model 2 Case 3_1	37	49.39	58.41	92.12

Number of UEs attached to a pico increases as bias increases

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Effect of Bias → on SINR cdf

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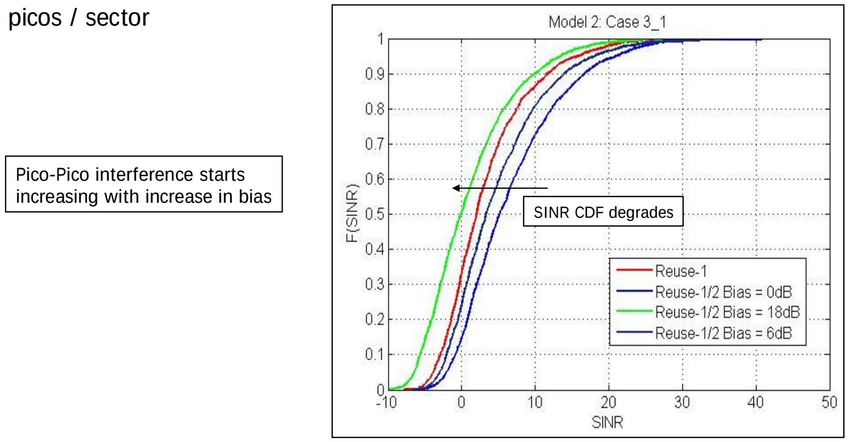
- 3 picos / sector



Effect of Bias → on loading of Picos

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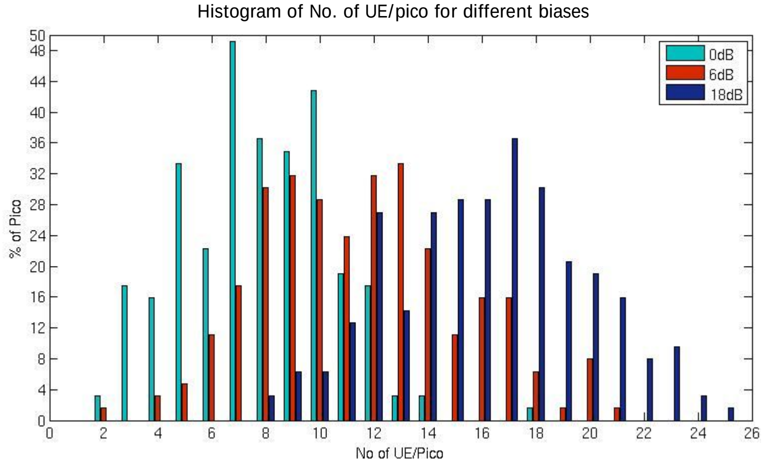
Histogram of No. of UE/pico for different biases



There is a large variation in the number of UEs/pico

Performance : Expected vs Delivered

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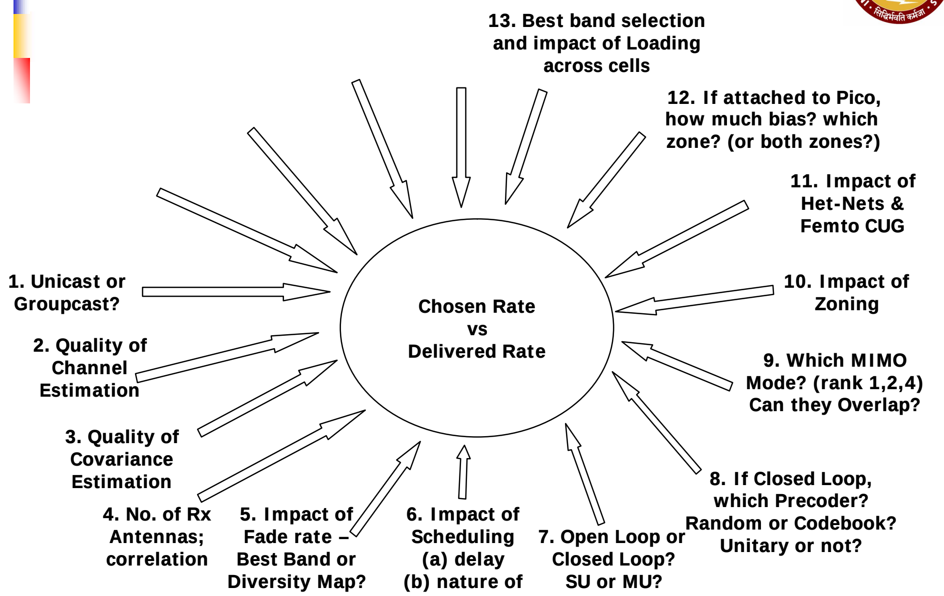

Unequal Loading, and effect of Best-band (only) feedback

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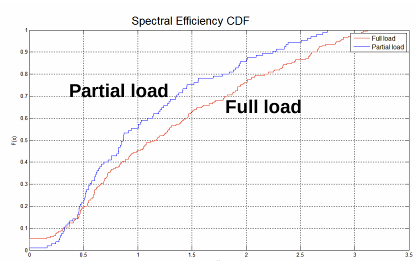

Fig 1.) **Avg. 10** users per sector is taken to be full load and 50% of it is partial load.

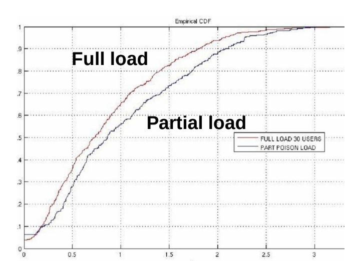

Fig 2.) **Avg. 30** users per sector is taken to be full load and 50% of it is partial load

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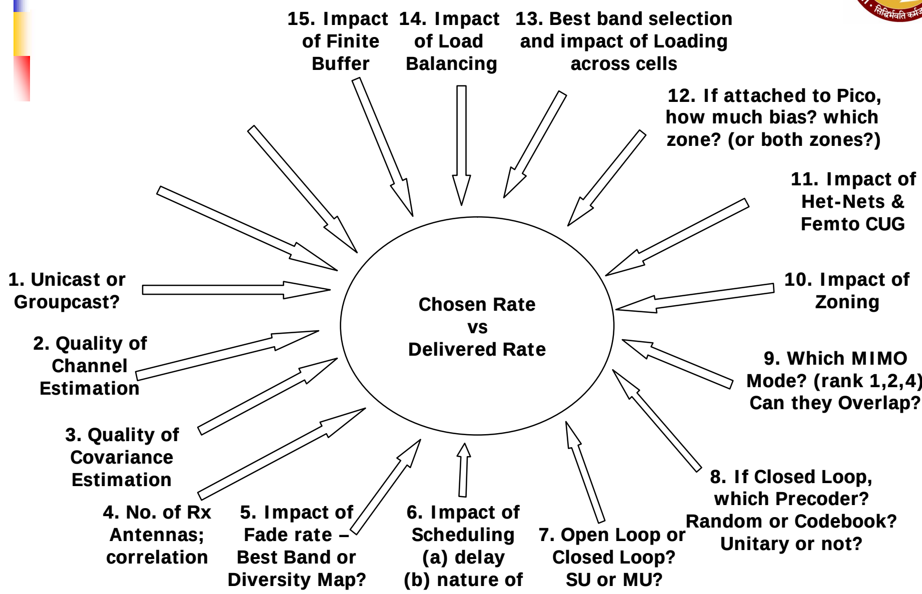
Performance : Expected vs Delivered



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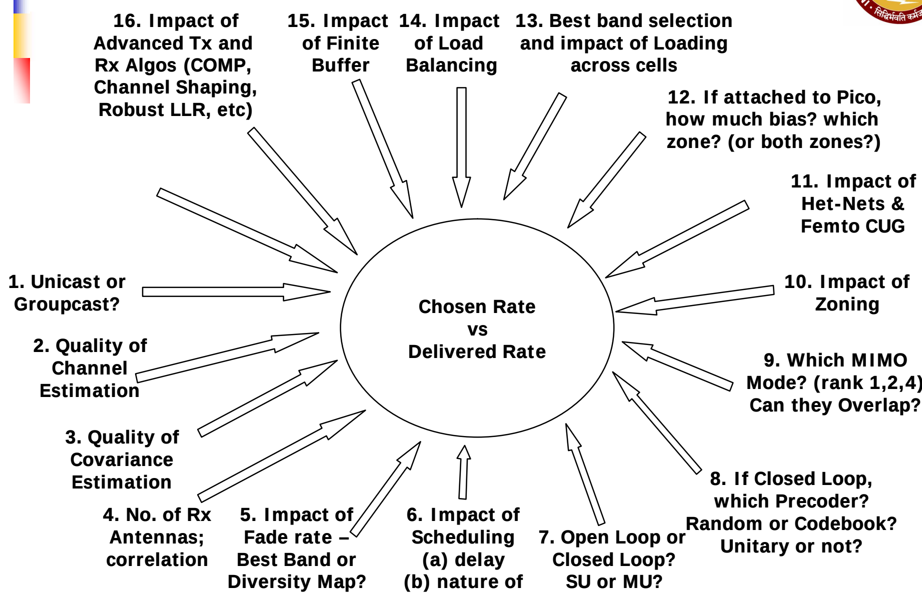
Performance : Expected vs Delivered



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Co-op Scheduling and COMP

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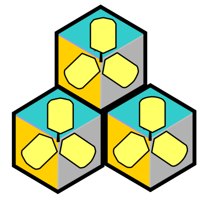
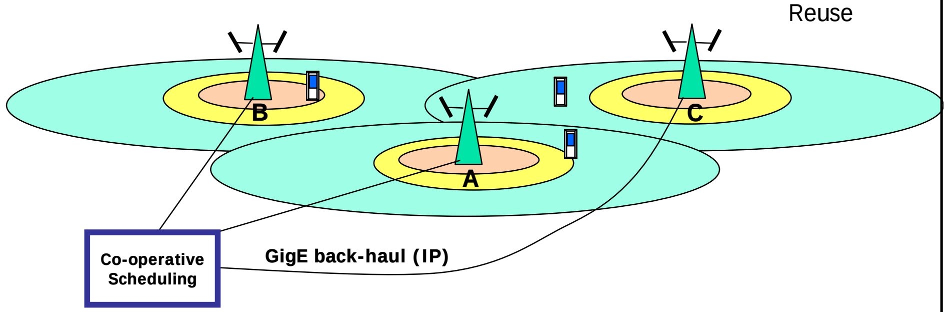
- **Pragmatic Co-operation**
  - **At (slow) signalling level between schedulers**
    - eg. FFR size, or Zone size
  - **Sharing Complexity: PMI < CQI < CSI < Data**



Fractional
Reuse



OFDM Channel Shortening

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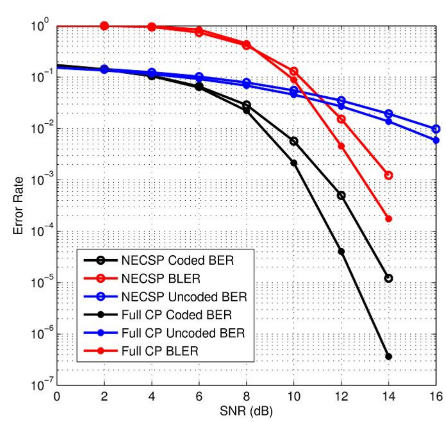
- **OFDM channel shortening can**
  - Allow large cells to be covered with high SE
  - Enable COMP over macro cells

Parameter	Value
BW	5 MHz
# Tx Antenna	1
# Rx Antenna	2
Over Sampling Rate	2
Channel Model	Modified VB
Channel Taps	**154**
Cyclic prefix Length	**20**
CSP Order	160
Energy Out side Cyclic Prefix	23%



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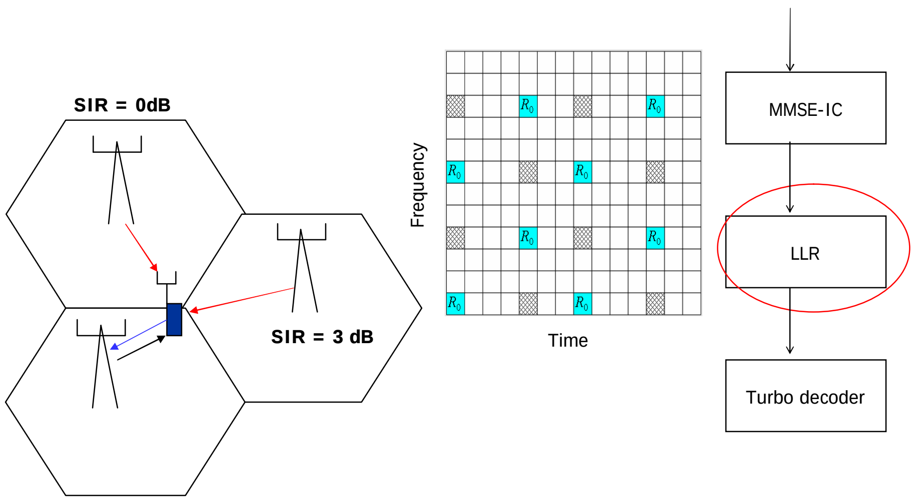
LTE Example → Intf. Alignment + Robust LLR



MMSE-IC cannot null out the pilots since they are not precoded

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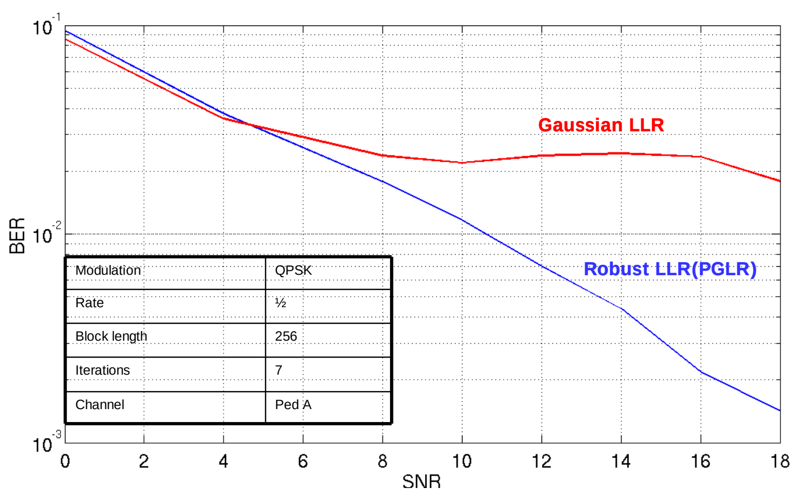
Robust LLR → Impact on BER Performance



Modulation	QPSK
Rate	½
Block length	256
Iterations	7
Channel	Ped A

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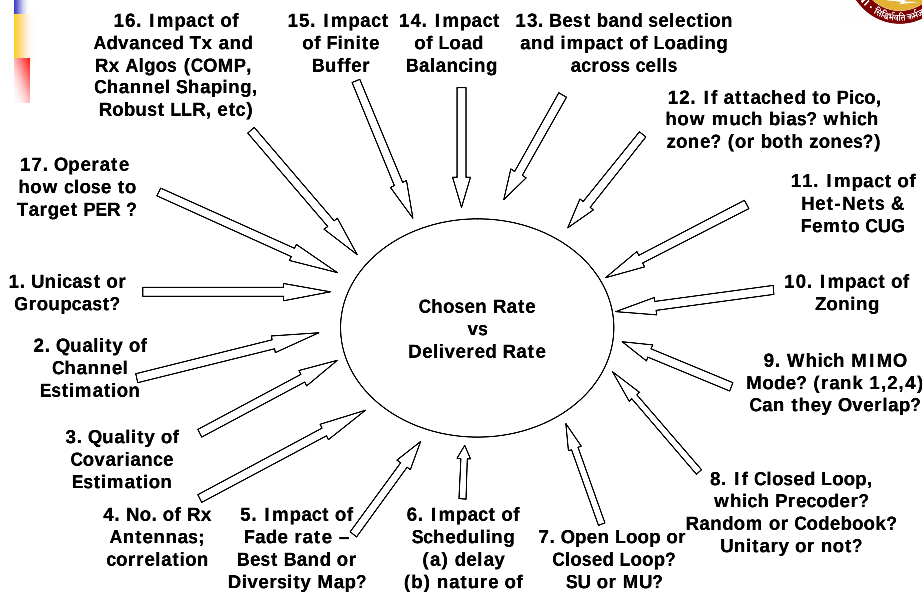
Performance : Expected vs Delivered



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Summary

- Mobile broadband systems will be reuse-1 MIMO-OFDM
  - Highly interference limited behaviour
- Stable measurement of interference statistics is key !
  - Open-loop schemes, fixed precoders help
- However, finite buffer effects, unpredictable scheduling delay, load variations, etc, make interference power (and profile) fluctuate
- Welcome to new (old?) world of working with mis-specified statistics!