Utilizing channel information at the CDMA transmitter

Balaji Raghothaman,

Nokia Research Center,

Irving, TX.

Balaji.raghothaman@nokia.com

Outline

Introduction

Channel knowledge: Why?

Channel information: How?

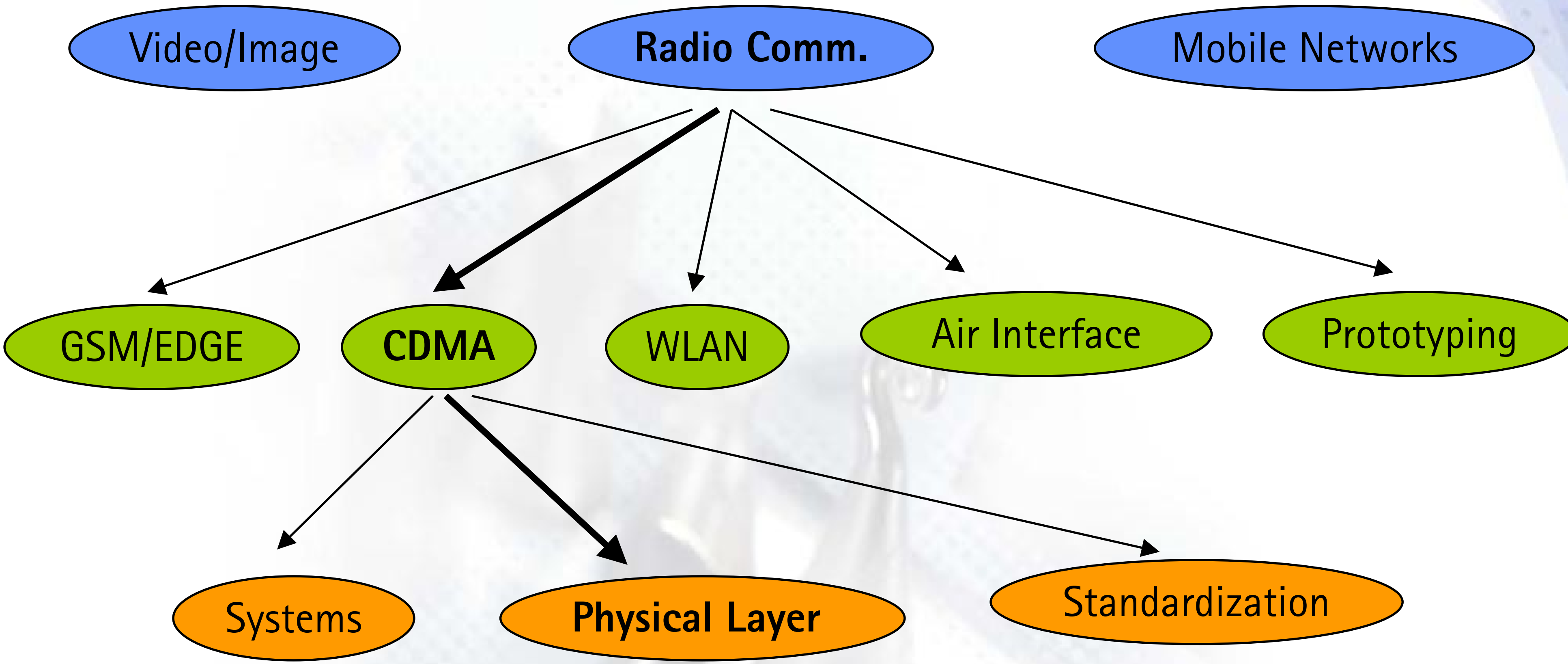
Reciprocal beamforming

Feedback methods

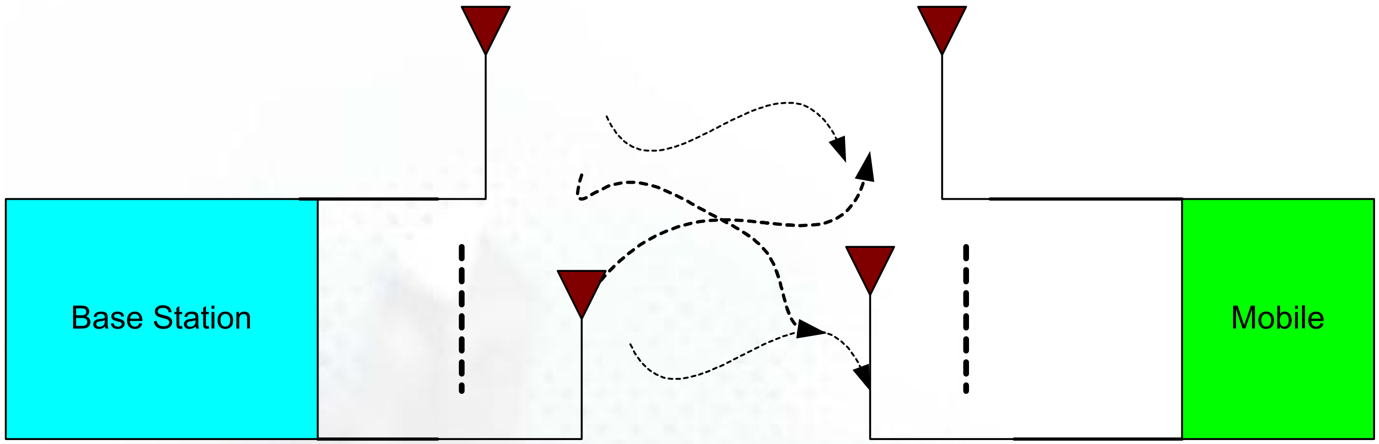
Adaptive methods

Standards Proposals

Nokia Research Center, Dallas



Introduction

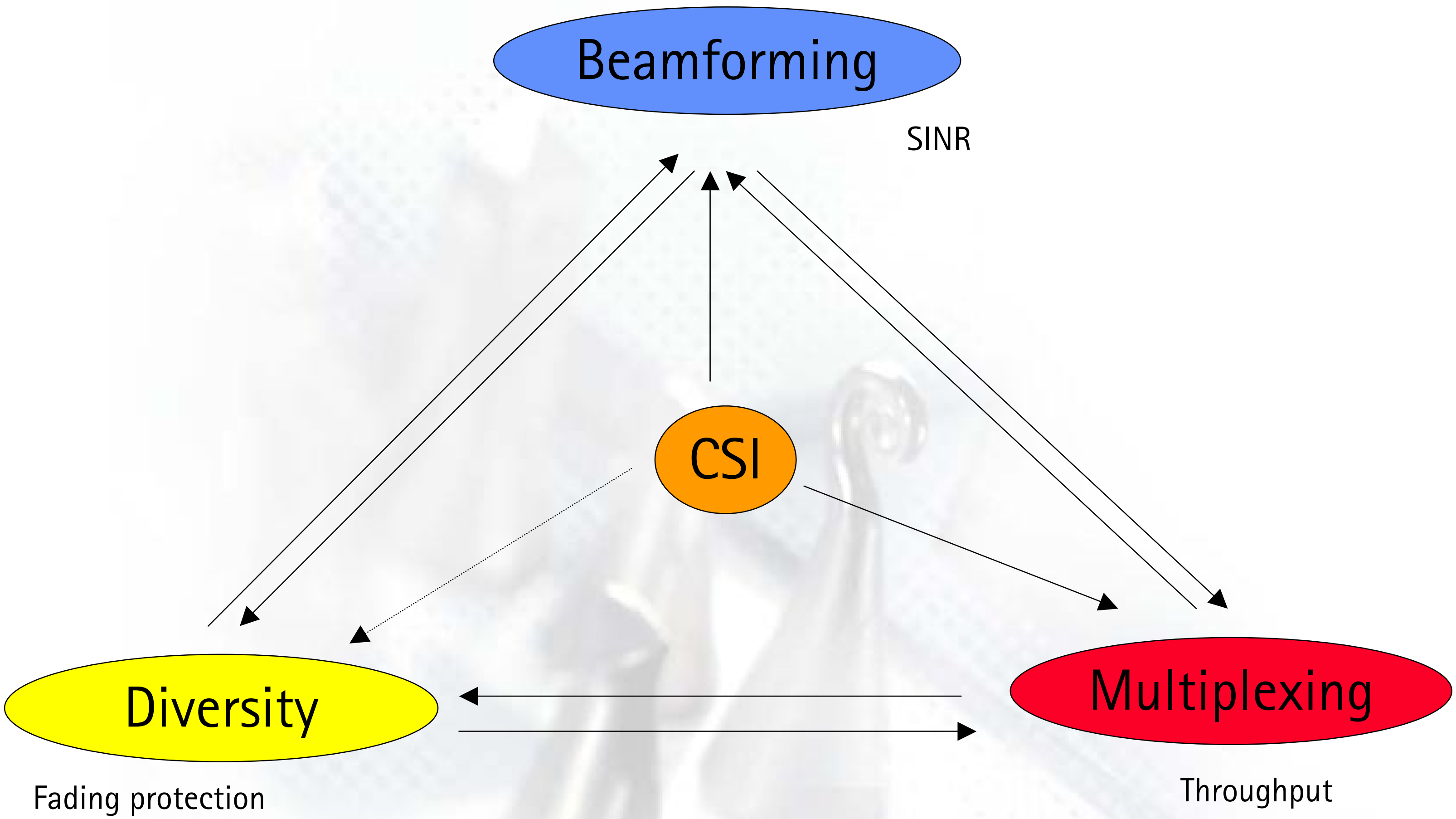


- Capacity of cellular systems can be increased by employing multiple antennas, either at the receiver or the transmitter or both.
- Multiple antennas can be placed in order to provide either diversity or directivity or both.
- Larger antenna spacing -> independent channels -> diversity.
- Smaller antenna spacing -> correlated channels -> directivity.

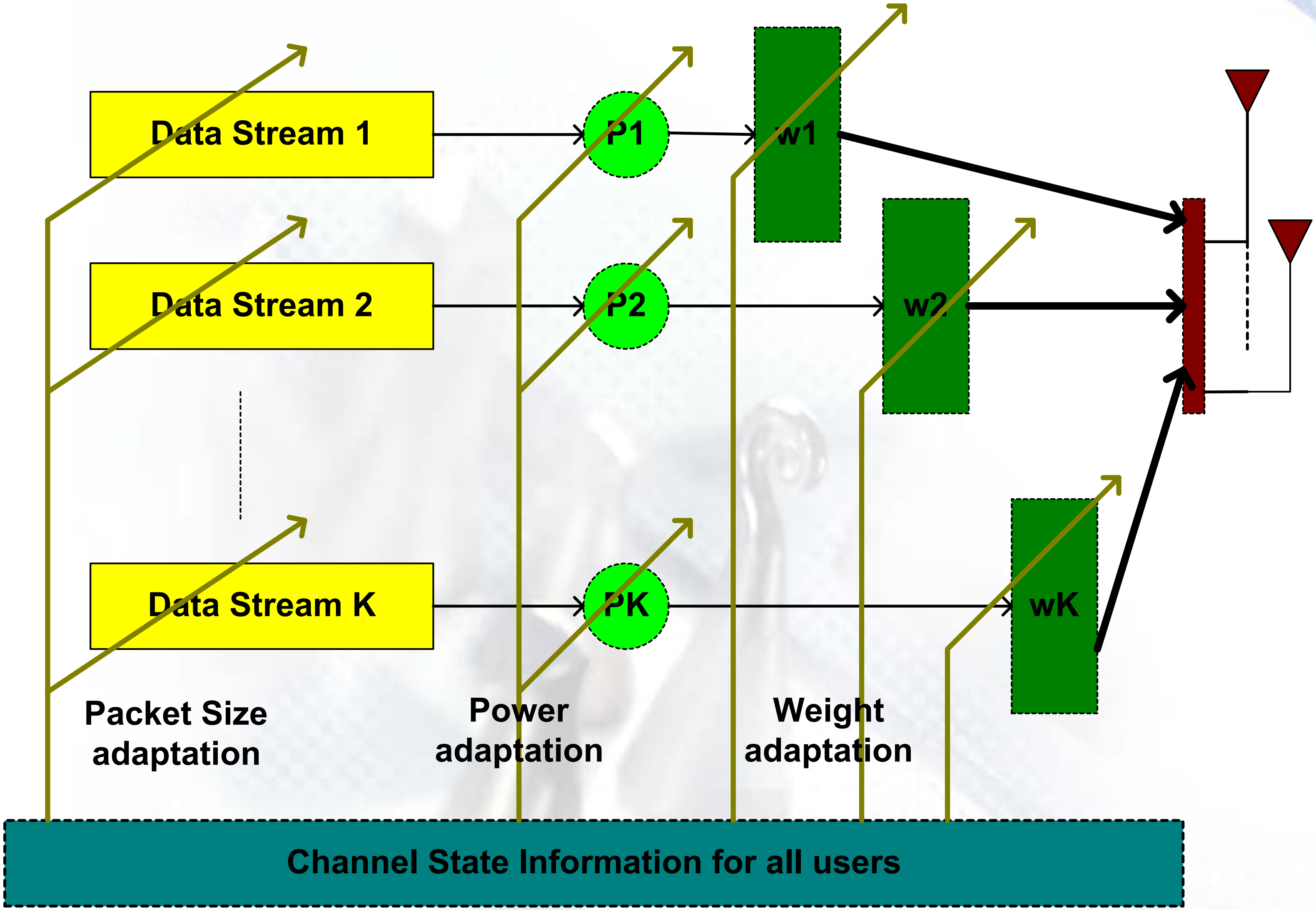
Introduction (2)

- Space-time code designs like the Alamouti scheme provide diversity gains by making it possible to achieve separable diversity paths from the composite signal at the receiver antenna.
- The availability of channel information makes it possible to increase these gains so that they are comparable to receiver diversity gains.
- The addition of *antenna gain* to the *diversity gain* makes this possible.
- Some of the ways in which channel information can be used are:
    - Power control
    - Link adaptation
    - Scheduling
    - Antenna switching
    - Beamforming / weighted diversity
    - MIMO transmission

Multiantenna transmission



Using Channel State Information



NOKIA

Channel Information: Why ?

- Alamouti Scheme:

$$\begin{bmatrix} r_e \\ r_o \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} h_1 x_o W + h_2 x_e^{\ast} W \\ h_1 x_e W - h_2 x_o^{\ast} W \end{bmatrix} + \begin{bmatrix} \gamma_e \\ \gamma_o \end{bmatrix}$$

$$SNR \le \frac{|h_1|^2 + |h_2|^2}{2} \frac{Es}{No}.$$

- Weighted diversity transmission:

$$y = \begin{bmatrix} h_1 & h_2 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} x + \gamma$$

$$SNR \le \left(\frac{|h_1|^2 + |h_2|^2}{\sqrt{|h_1|^2 + |h_2|^2}} \right)^2 \frac{Es}{No} = \left(|h_1|^2 + |h_2|^2 \right) \frac{Es}{No}$$

Joint beamforming and power allocation

- Naguib *et.al.* showed the capacity gains due to the usage of multiple antennas for beamforming on the downlink.
- The problem of estimating the beamforming weights at the base station can be cast as an optimization problem which maximizes the SINR at the mobile in question.
- Beamforming can be combined with power control as a joint optimization problem over all mobiles and base-stations in a network vicinity. (Farrokhi *et.al.)*

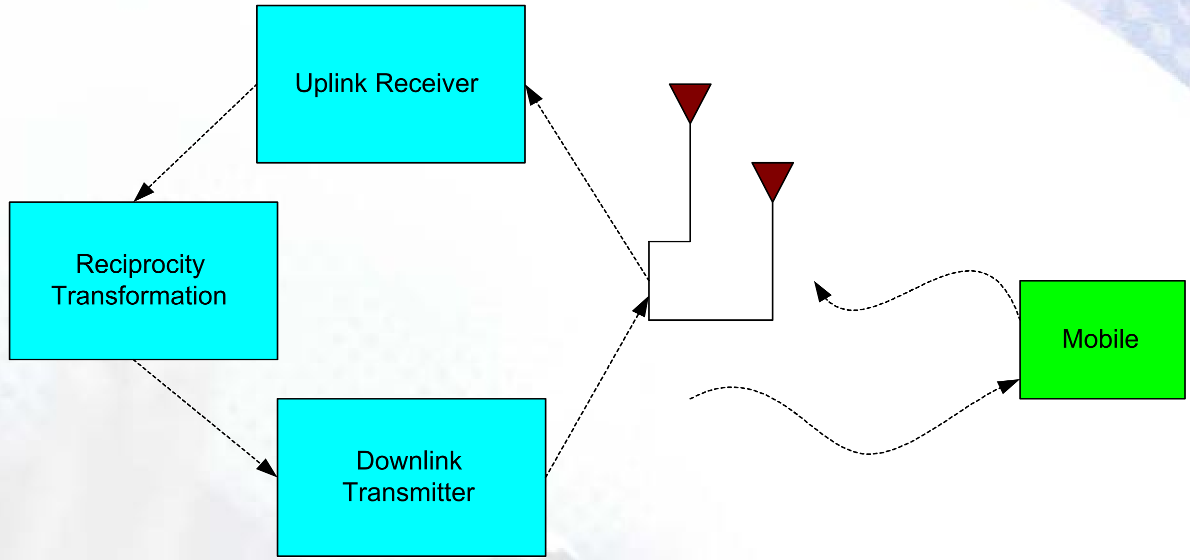
$$\Gamma_i = \frac{\tilde{P}_i \mathbf{w}_i^H G_{ii}^S \mathbf{w}_i}{\sum_b \tilde{P}_b \mathbf{w}_b^I G_{ib}^S \mathbf{w}_b + \tilde{N}_i},$$

$$\min_{\tilde{\mathbf{P}},\mathbf{A}} \sum_i \tilde{P}_i \left\|\mathbf{w}_i\right\|^2, \text{ subject to } \Gamma_i \geq \gamma_i$$

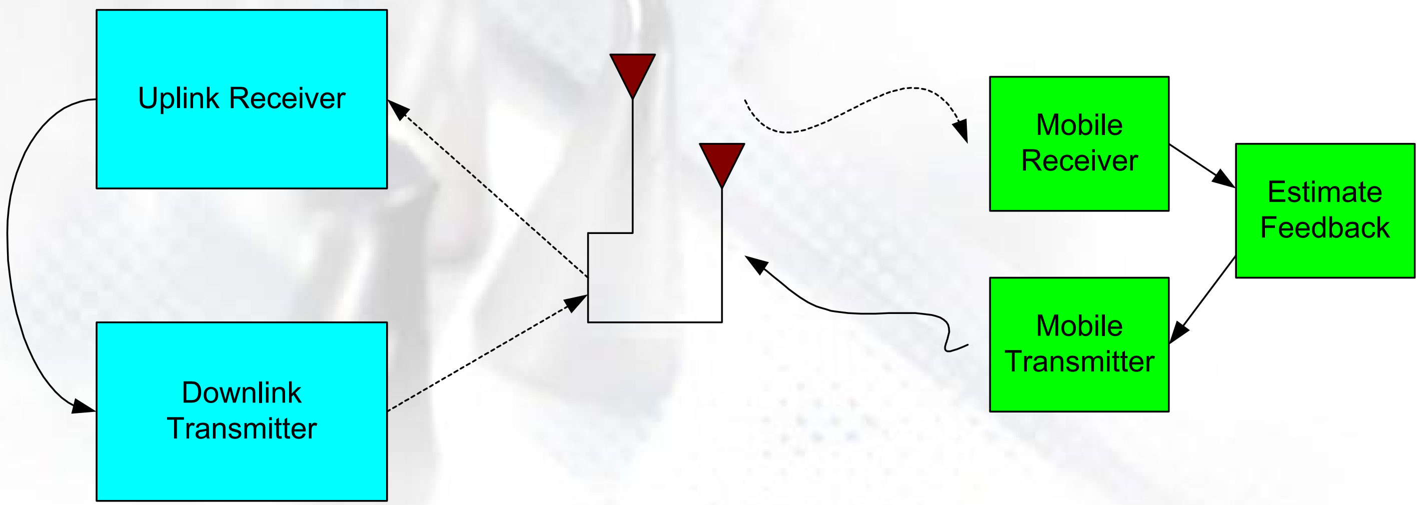
NOKIA

Channel Information: How?

- Reciprocity



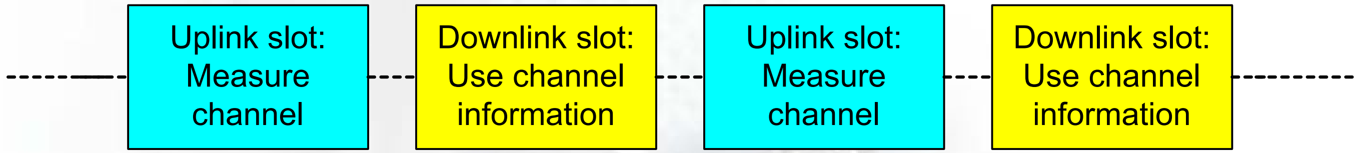
- Feedback



Reciprocity

- Reciprocity applicable only to duplex systems.
- In Time Division Duplex systems (TDD), the channel is assumed to be identical in both directions. Hence transformation is not needed – except for a possible temporal interpolation.

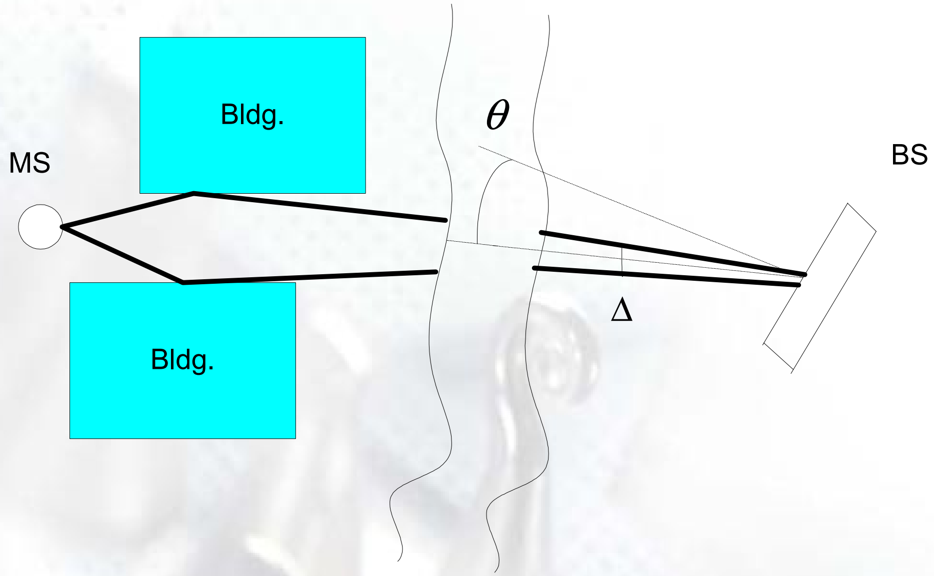
Reciprocity in TDD systems



- In Frequency Division Duplex systems (FDD), the channel on the uplink is different from the downlink channel due to the difference in carrier frequency.
- Instantaneous channel cannot be tracked using reciprocity in FDD.
- However there is a relation between the average channel covariance of the uplink and the downlink.

Spatial Channel Model

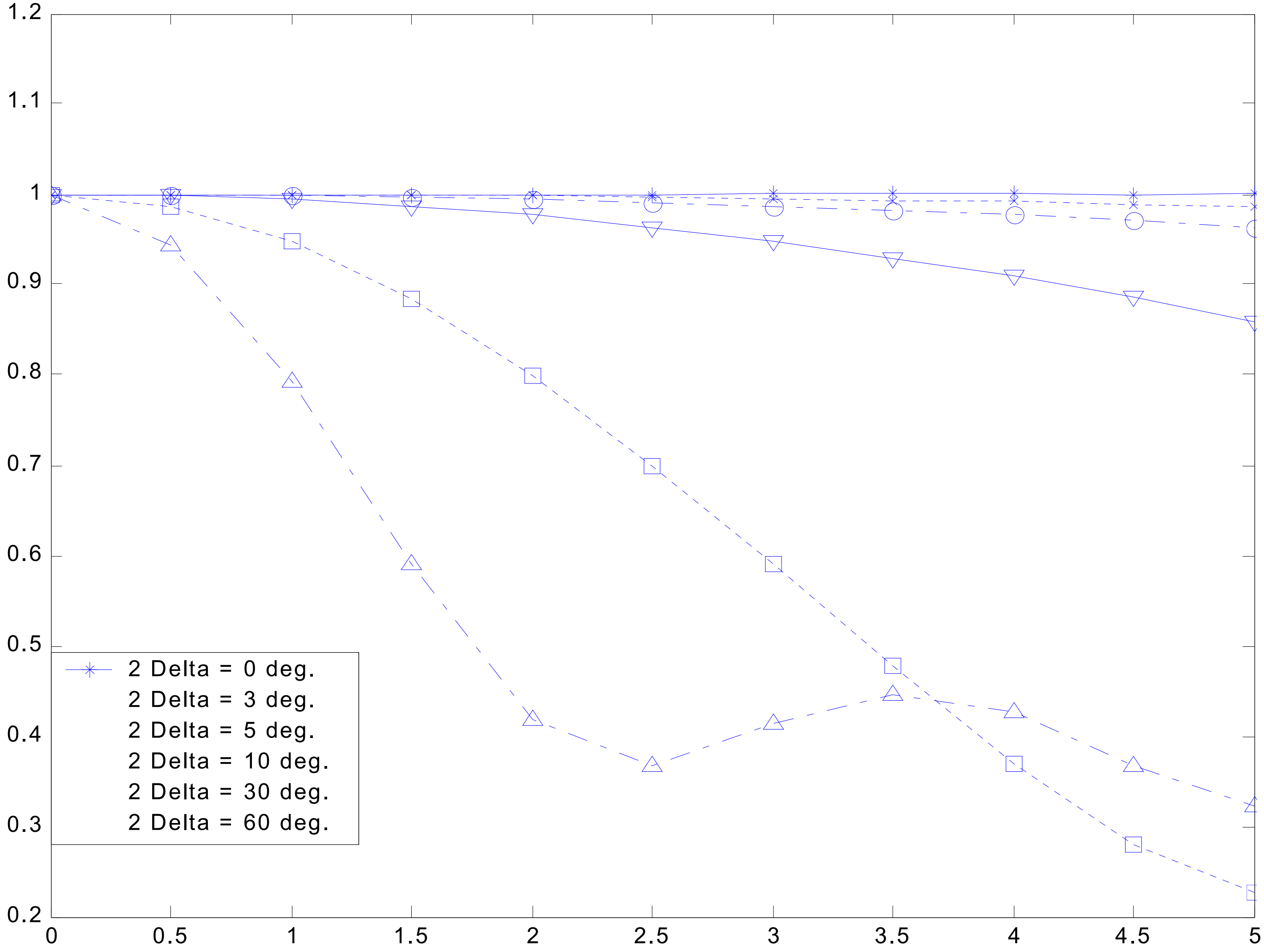
- The multipath channel is modeled as having angles of arrival and angular spread associated with them.



- The correlation between antenna elements is given by:

$$r(D) = J_0\left(2\pi \frac{D}{\lambda_c}\right) + 2\sum_{k=1}^{\infty} (j)^k J_k\left(2\pi \frac{D}{\lambda_c}\right) \cos(k\theta)\,\mathrm{sinc}(k\Delta/\pi)$$

Spatial Correlation



NOKIA

Reciprocity in FDD

- First approach is to estimate θ and Δ for each path on the uplink, and then use it to estimate the downlink channel covariance matrix.
  - Δ is extremely difficult to estimate.
    (Olivier Besson and Petre Stoica, 2000)
  - Errors in estimation of θ and Δ lead to significant degradation.

- Second approach is to find a transformation that directly maps the uplink channel covariance matrix to the downlink equivalent.
- Two methods to estimate this transformation will be discussed:
  1. Fourier series expansion.
  2. Discrete Fourier Transform interpolation.

Reciprocity in FDD: Fourier series expansion

- The channel covariance matrix can be expressed as a Fourier series:

$$\boldsymbol{R}^{s}_{u(d),k} = E_{\beta,\alpha}[\boldsymbol{a}_{u(d),k}\boldsymbol{a}_{u(d),k}{}^{H}] \approx \sum_{l=-L+1}^{L-1} c_{kl}\boldsymbol{\Psi}^{l}_{u(d),k},$$

$$\boldsymbol{\Psi}^{l}_{uk} = \int_{-\pi/Q}^{\pi/Q} \boldsymbol{v}(\theta \mid f_{uk})\ \ \boldsymbol{v}^{\boldsymbol{H}}(\theta \mid f_{uk})\ \ e^{jlQ\,\theta} d\theta$$

- Only the terms c_{kl} have to be estimated online. Least squares approaches can be used:

$$\hat{\boldsymbol{c}} = \arg\ \min \left\| \hat{\boldsymbol{R}}_{u_k} - \sum_{l=-L+1}^{L-1} c_{kl}\ \ \boldsymbol{\Psi}^{l}_{u,k} \right\|_F^2$$

- Once estimated, the terms c_{kl} can be used to arrive at the downlink channel covariance matrix.

(Fonollosa *et. al, 2000*)

NOKIA

Reciprocity in FDD: DFT redistribution

- Applicable to uniformly spaced linear arrays.
- The up(down)link spatial signature for each angle is given by

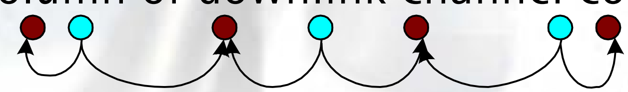
$$\mathbf{v}(\theta \mid f_{u(d)}) = [1,\ e^{j2\pi\ f_{u(d)} \frac{z}{c}\cos\theta},\ .\ .\ .\ ,\ e^{j(M-1)\ 2\pi\ f_{u(d)} \frac{z}{c}\cos\theta}]^T$$

- The DFT of the first column of the uplink **R** gives the frequency response, sampled at radial frequencies [0 2π/N , … , 2π(N-1)/N].
- From uplink to downlink, the angular frequencies have shifted, hence the mapping of the DFT indices is given by

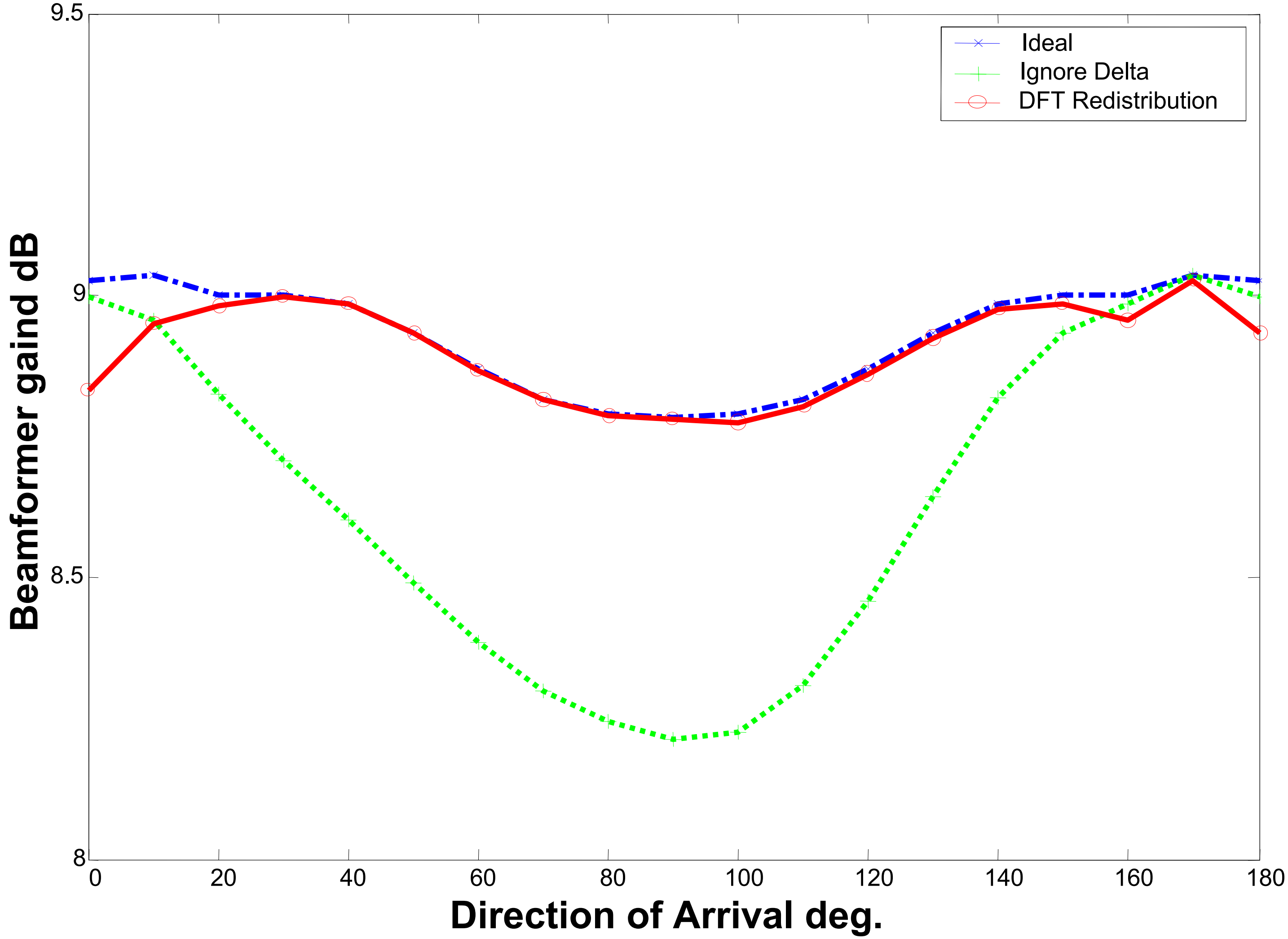
$$\left[0,1,2,\ldots,(\frac{N}{2}-1)\right] \rightarrow \alpha\left[0,1,2,\ldots,(\frac{N}{2}-1)\right],$$

$$\left[\frac{N}{2},(\frac{N}{2}+1),\ldots,(N-1)\right] \rightarrow (N-1)-\alpha\left[(\frac{N}{2}-1),\ldots,1,0\right],\ \text{where } \alpha = \frac{f_d}{f_u}$$

- We can shift back to equally spaced DFT by using a nearest neighbor interpolation.
- Finally IDFT gives first column of downlink channel correlation matrix.



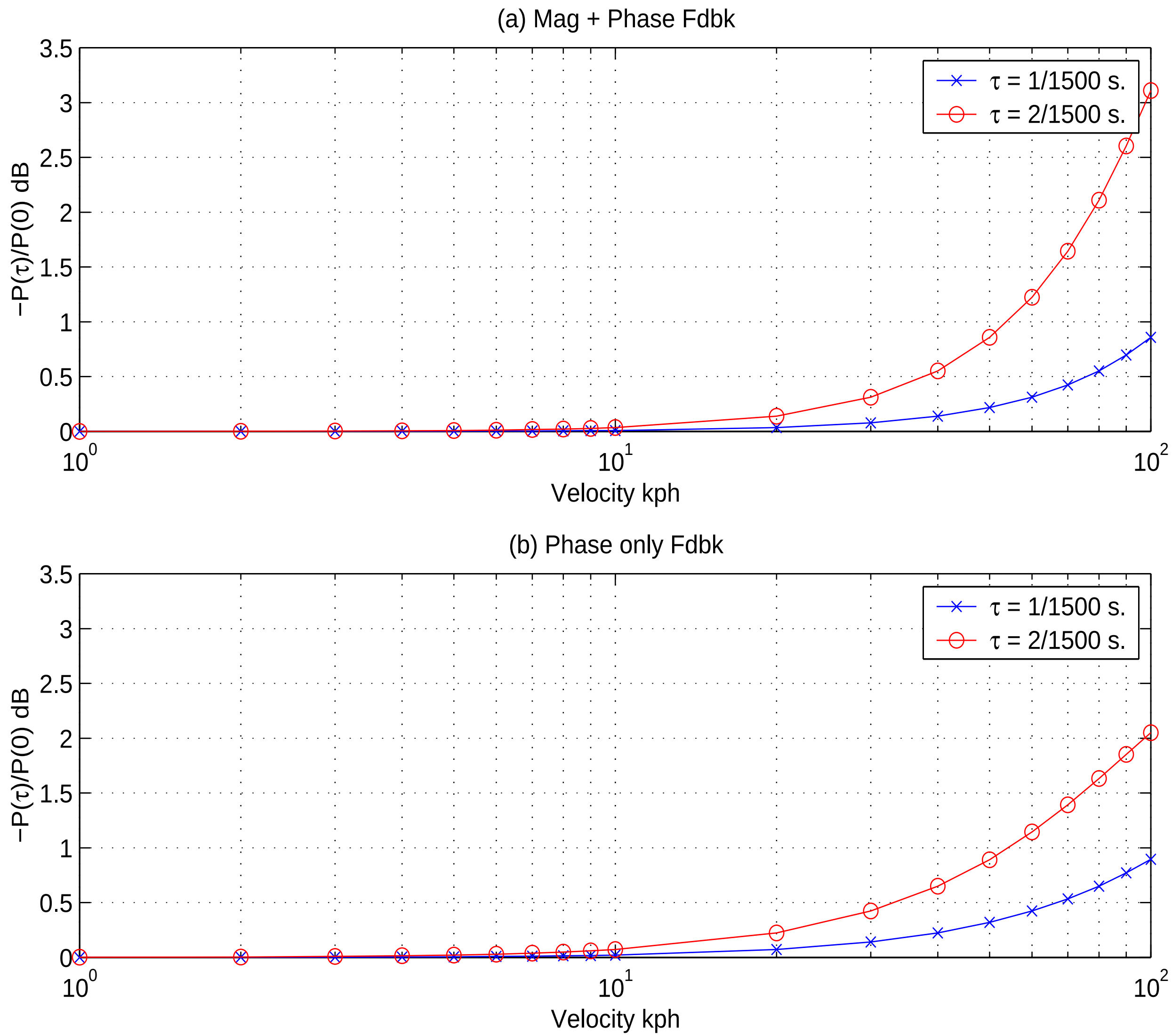
Reciprocity in FDD: DFT redistribution



Feedback Methods for Tx. Diversity : Issues

- There is very limited feedback bandwidth.
  Hence these methods suffer from severe *quantization* effects.
- They try to keep up with instantaneous channel –
  hence they *fail in fast fading* conditions.
- The *delay* involved in receiving feedback also causes degradation in fast fading.
- There is currently no *error* protection for the feedback channel (in WCDMA). Any errors due to feedback result in incorrectly weighted transmission.
- There is no simple *soft handoff* solution.

Effect of Feedback Delay



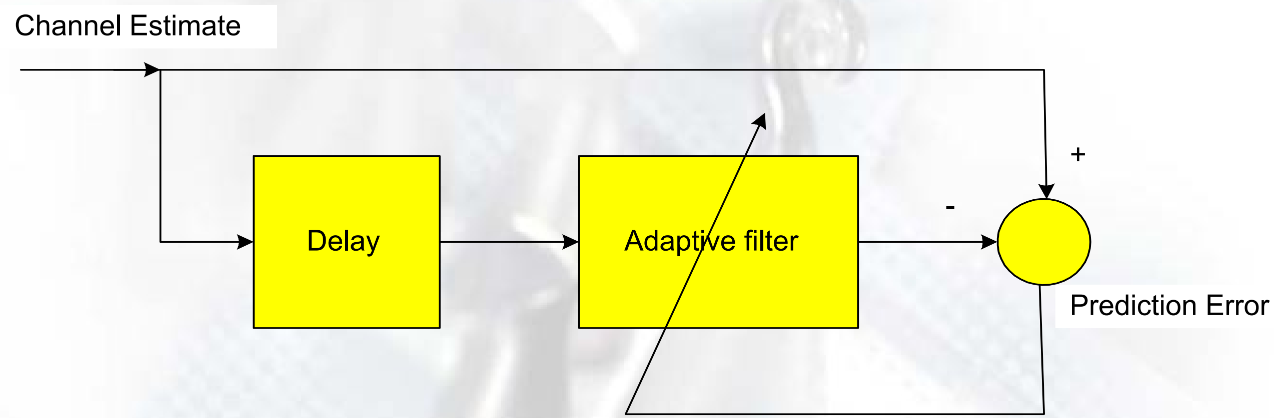
Channel prediction to combat delay

- The fading channel can be modeled as an autoregressive (AR) model:

$$H(z) = \frac{1}{1 - \sum_{j=1}^{p} a_j z^{-j}},$$

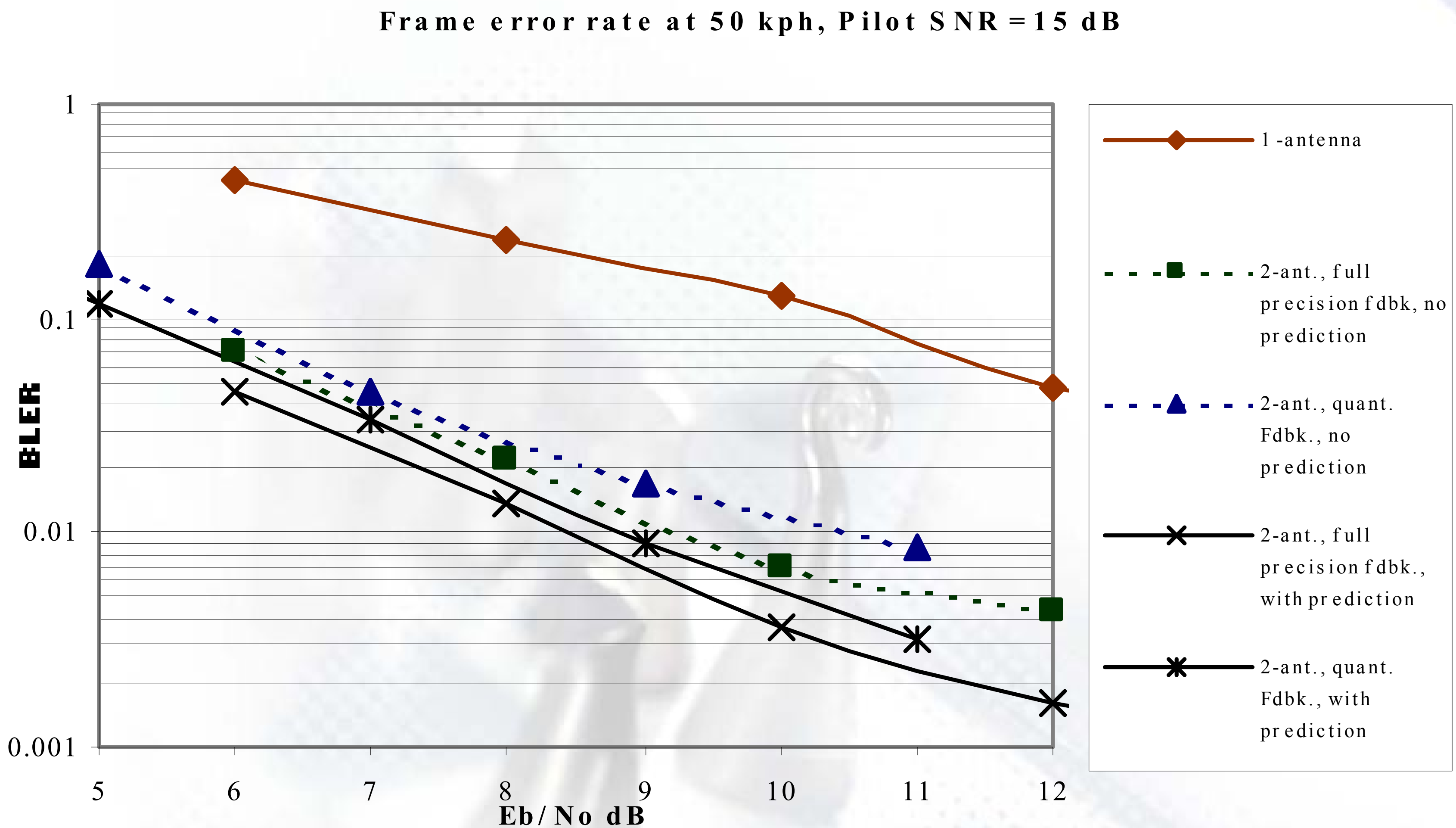
$$h(t) = \sum_{j=1}^{p} a_j h\left(t - jT_p\right) + \gamma$$

- The parameters a_j can be estimated using a prediction model.



- The feedback is calculated based on the predicted channel conditions instead of the currently measured conditions.

Channel Prediction (2)



Combating feedback error

- Incorrectly received feedback leads to erroneous weighted transmisison.
- The process of correcting feedback errors at the mobile receiver is called *verification*.
- Dedicated pilots are used to aid this process of verification.
- The hypothesis being tested is given as:

$$H_0 : w_{l,k}^c = \Im\left(\theta_{l,k-1,} \hat{\theta}_{l,k-2}, \ldots, \hat{\theta}_{l,k-N}\right),$$

$$H_1 : w_{l,k}^e = \Im\left(\overline{\theta}_{l,k-1}, \hat{\theta}_{l,k-1}, \ldots, \hat{\theta}_{l,k-N}\right)$$

- We assume that the error probability associated with the feedback is known: $p\left(\hat{\theta}_{l,k} = \theta_{l,k}\right) = p_c$ and $p\left(\hat{\theta}_{l,k} = \overline{\theta}_{l,k}\right) = p_e = 1 - p_c$
- The Bayesian rule gives: $\dfrac{p(z / H_1)}{p(z / H_0)} > \dfrac{p(H_0)}{p(H_1)} \Rightarrow H_1, \text{ else } H_0$
- Assuming that the noise is AWGN, $\dfrac{2\gamma}{\sigma^2} \mathrm{Re}\left[h_d h_c^* \left(w_{l,k}^e - w_{l,k}^c\right)^*\right] > \ln\left(\dfrac{p_c}{p_e}\right) \Rightarrow H_1$

NOKIA

Transmission subspace tracking

- Feedback methods discussed so far have related to some kind of instantaneous quantized feedback.
- Adaptive subspace tracking is a possibility, but is limited by feedback bandwidth.
- A perturbation based gradient approach was recently proposed.
- The concept originated in stochastic control theory and neural network learning.
- This class of methods works for correlated environments. It also gives good performance in uncorrelated low mobility conditions.
- The feedback bandwidth required is independent of the number of antennas.

NOKIA

Transmission subspace tracking (2)

- The cost function to be maximized is given by $$J_k = \frac{\mathbf{w}_k{}^H \hat{\mathbf{R}}_k \mathbf{w}_k}{\mathbf{w}_k{}^H \mathbf{w}_k}$$
- The gradient of the cost function is then $\mathbf{g}_k = \frac{\partial J_k}{\partial \mathbf{w}_k} = \frac{2\hat{\mathbf{R}}_k \mathbf{w}_k}{\mathbf{w}_k^H \mathbf{w}_k}$ and the adaptation is given as $$\mathbf{w}_{k+1} = \mathbf{w}_k + \mu \mathbf{g}_k$$
- Feedback of entire gradient vector is not feasible.
- Perturbation approach: If we perturb the weight vector by a random complex vector in either direction as $\mathbf{w}_{e(o)} = \mathbf{w}_k \pm \beta \Delta \mathbf{w}_k$, and estimate the received power in each case, then,
$$E_{\Delta \mathbf{w}}\left[c \Delta \mathbf{w}\right] \propto \mathbf{g}_k, \text{ where } c = \frac{\mathbf{w}_e{}^H \hat{\mathbf{R}}_k \mathbf{w}_e}{\mathbf{w}_e{}^H \mathbf{w}_e} - \frac{\mathbf{w}_o{}^H \hat{\mathbf{R}}_k \mathbf{w}_o}{\mathbf{w}_o{}^H \mathbf{w}_o}$$
- Now the scalar quantity c can be fed back with any precision.

NOKIA

Deterministic perturbation

- Consider $\tilde{\mathbf{Q}}_M = [\mathbf{Q}_M \quad j\mathbf{Q}_M]$ where $\mathbf{Q}_M = [\mathbf{q}_0, \mathbf{q}_1, \ldots, \mathbf{q}_{M-1}]$ form an orthonormal set of *M*-length vectors. The perturbation vector is selected from this set.
- Using an approximation from the gradient:

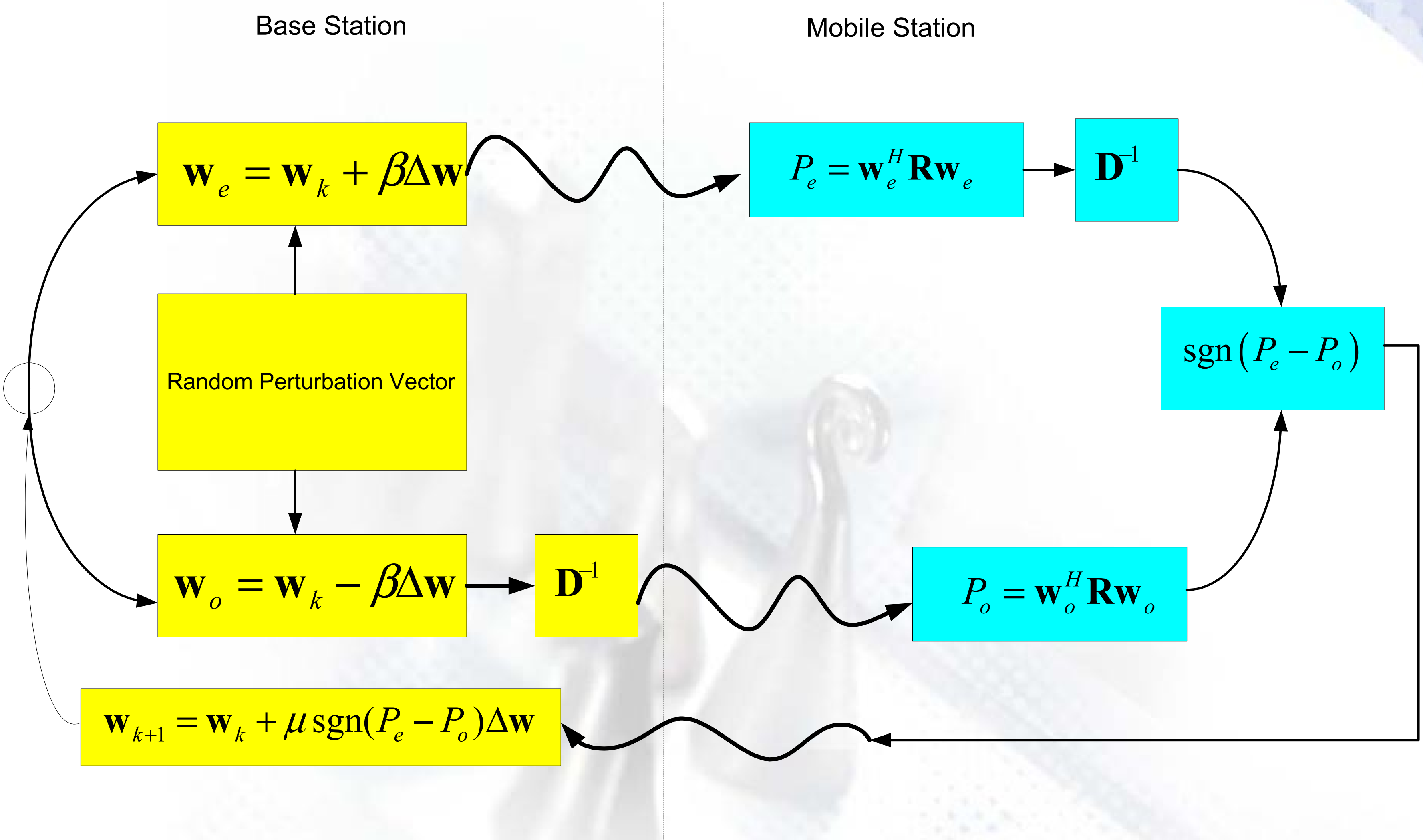
$$c\Delta\mathbf{w} = 2\beta\left(\mathbf{g}_k^H \Delta\mathbf{w} + \Delta\mathbf{w}^H \mathbf{g}_k\right)\Delta\mathbf{w}$$

- The expected value is given as:

$$\begin{aligned} E[c\Delta\mathbf{w}] &= \frac{\beta}{2M}\left[\sum_i \left(\mathbf{g}_k^H \mathbf{q}_i + \mathbf{q}_i^H \mathbf{g}_k\right)\mathbf{q}_i\right] + \frac{\beta}{M}\left[\sum_i \left(\mathbf{g}_k^H (j\mathbf{q}_i) + (j\mathbf{q}_i)^H \mathbf{g}_k\right)(j\mathbf{q}_i)\right] \\ &= \frac{\beta}{M}\left[\sum_i \left(\mathbf{q}_i^H \mathbf{g}_k\right)\mathbf{q}_i\right] \\ &= \frac{\beta}{M}\mathbf{Q}_M \mathbf{Q}_M^H \mathbf{g}_k \\ &= \frac{\beta}{M}\mathbf{g}_k, \ \text{since } \mathbf{Q}_M \mathbf{Q}_M^H = \mathbf{I} \end{aligned}$$

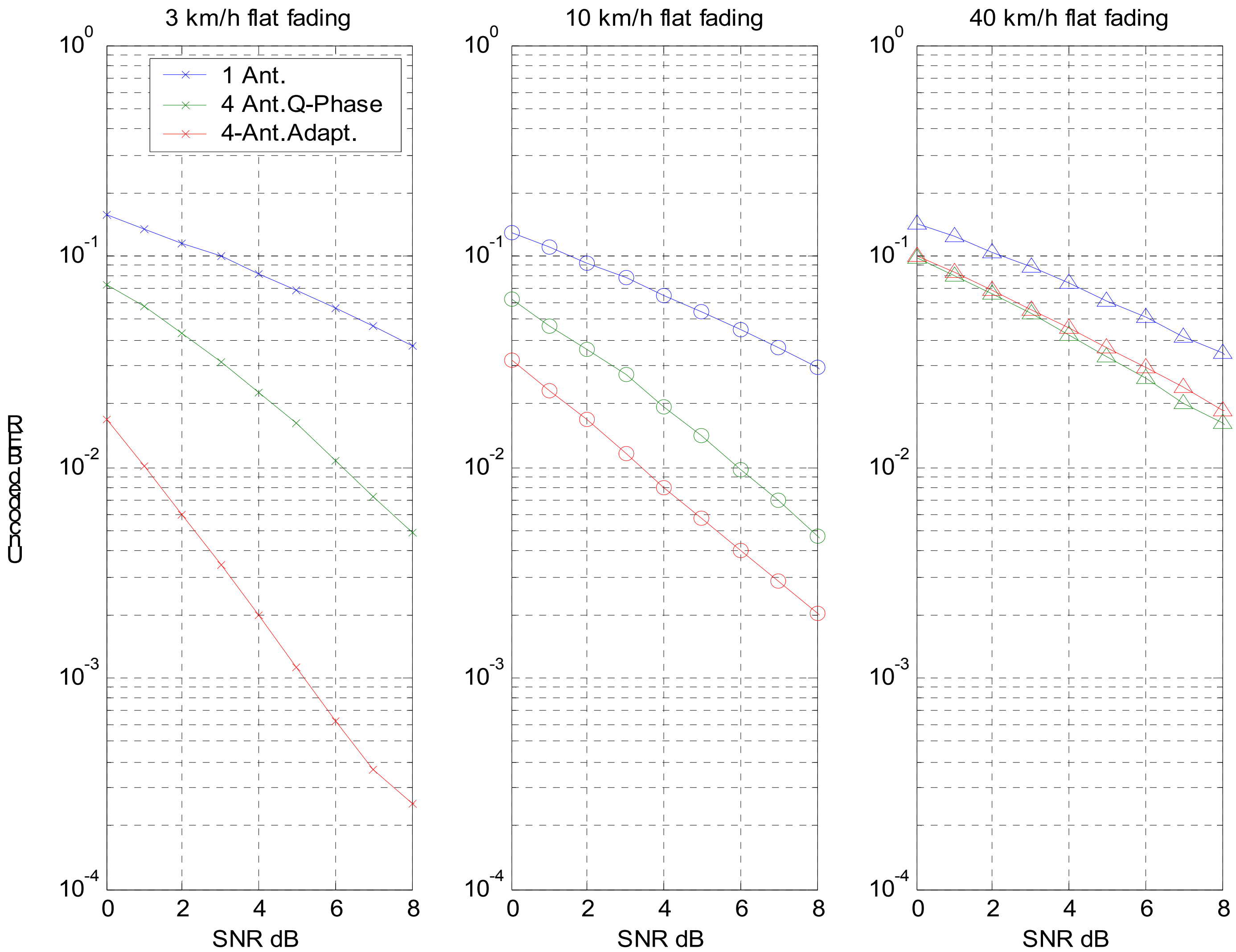
NOKIA

Transmission subspace tracking (3)



NOKIA

Transmission subspace tracking (4)



WCDMA/HSDPA

1. Mode 1: Involves phase feedback only. Feedback rate is 1500 bps.
   - Phase quantized to 1-bit according to set partitioning in table:

Bit	Even Slot	Odd Slot
0	0	$\pi/2$
1	π	$-\pi/2$

   - Weight is obtained by filtering over multiple phase feedbacks.

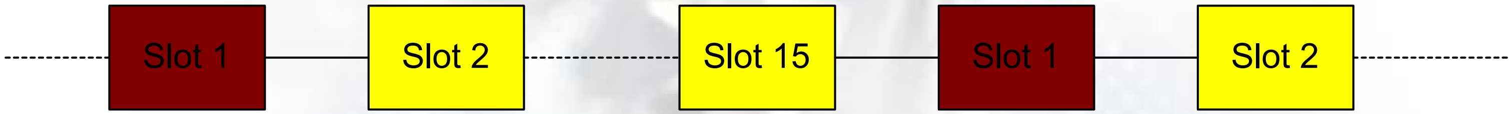
$$w_{m,k} = \left(\sum_{l=1}^{N} e^{j\theta_{k-l}} \right) \Big/ \left| \sum_{l=1}^{N} e^{j\theta_{k-l}} \right|$$

2. Mode 2: Magnitude and phase feedback.
   - Two bits magnitude and three bits phase.
   - Successive updating using 1-bit feedback each time.

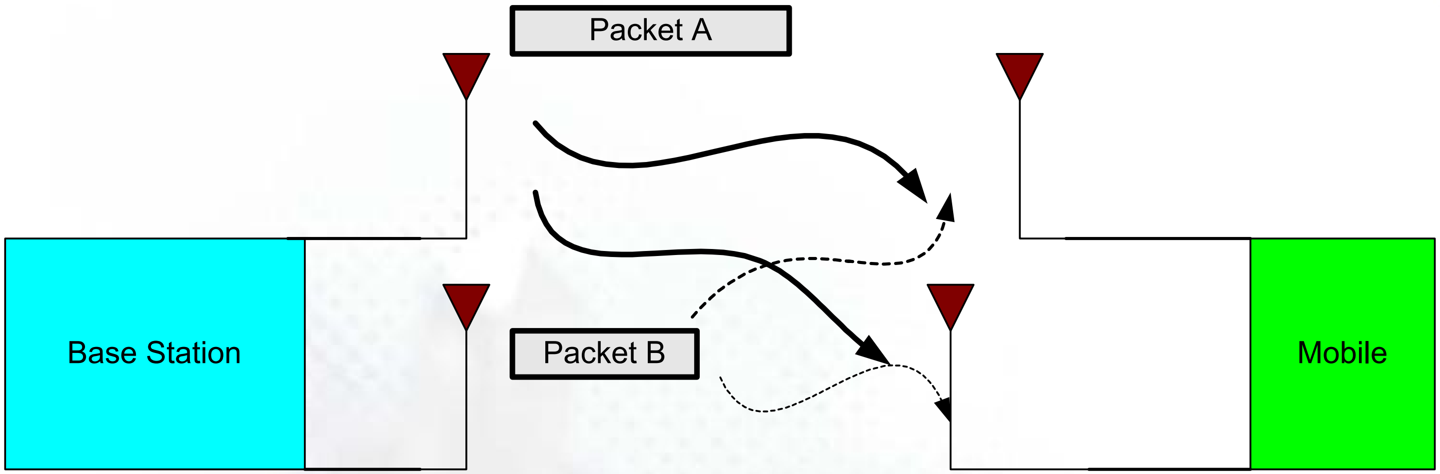
NOKIA

Proposals for Release 6: Eigenbeamformer

- Tracks long term covariance matrix at the mobile, and estimates the eigenvectors corresponding to 2 largest eigenvalues.
- Feeds back the 2 quantized eigenvectors at rate of 1 bit per frame.
- The short term feedback consists of selecting between the 2 eigenvectors.
- Has shown good performance with correlated antennas.



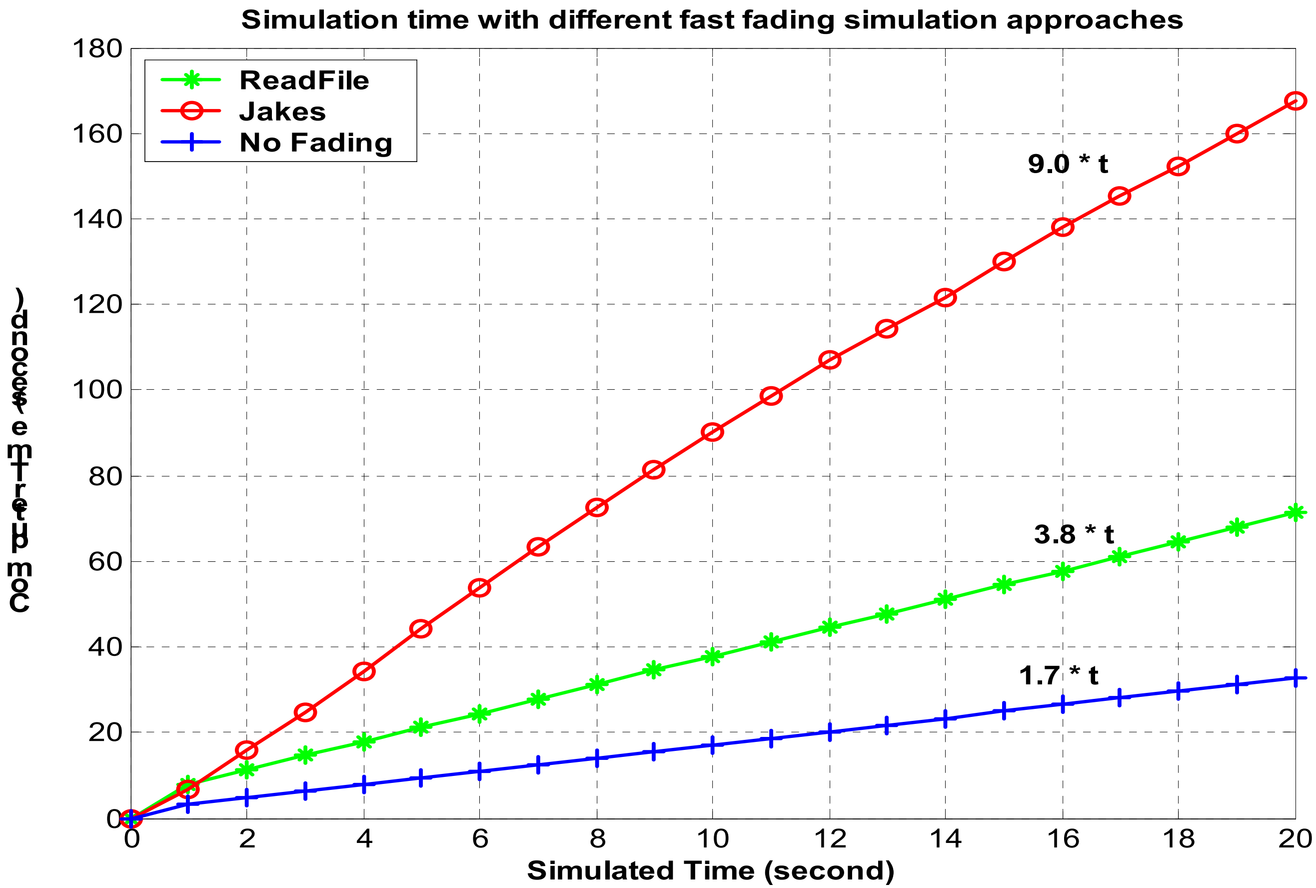
Per Antenna Rate Control (PARC)



- 2x2 MIMO scheme.
- Takes "water filling" approach.
- Control the modulation and coding schemes, as well as packet size of data stream emanating from each antenna, using strength of channel as criteria.
- Decoder complexity and design is an issue

Challenges : System evaluation

System simulation : 19 cells, 57 sectors, 120 mobiles, 2Tx-1Rx antenna



(Ack: Zhouyue Pi, NRC Dallas)

NOKIA

Further study areas

- Packet data is moving towards shorter bursts of high density transmissions.
  - In this paradigm, is most of the gain in better scheduling rather than in space-time code design or MIMO design ? (Pramod Vishwanath, IT, 2002)
- Better (more) feedback on the reverse link leads to better downlink design -> For higher capacity on one link, we sacrifice some capacity on the other link. What is the trade-off ?