Issues in Mobile Multi-User MIMO Networks

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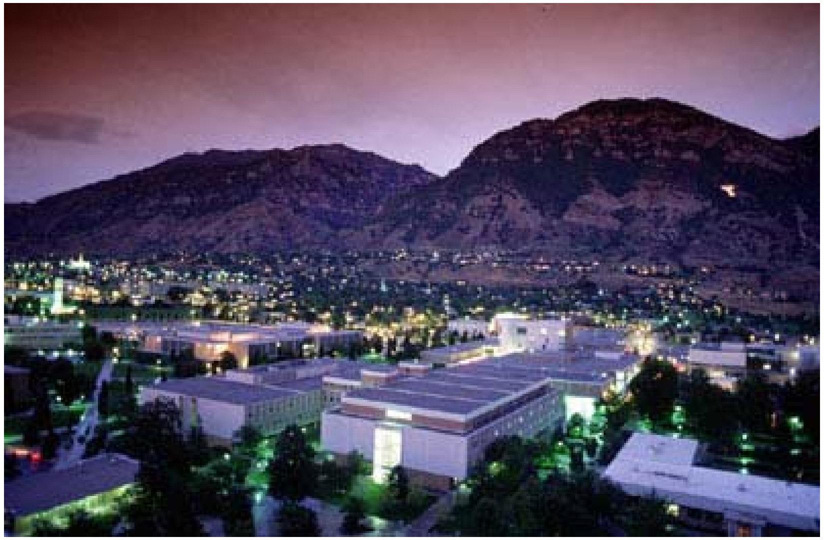
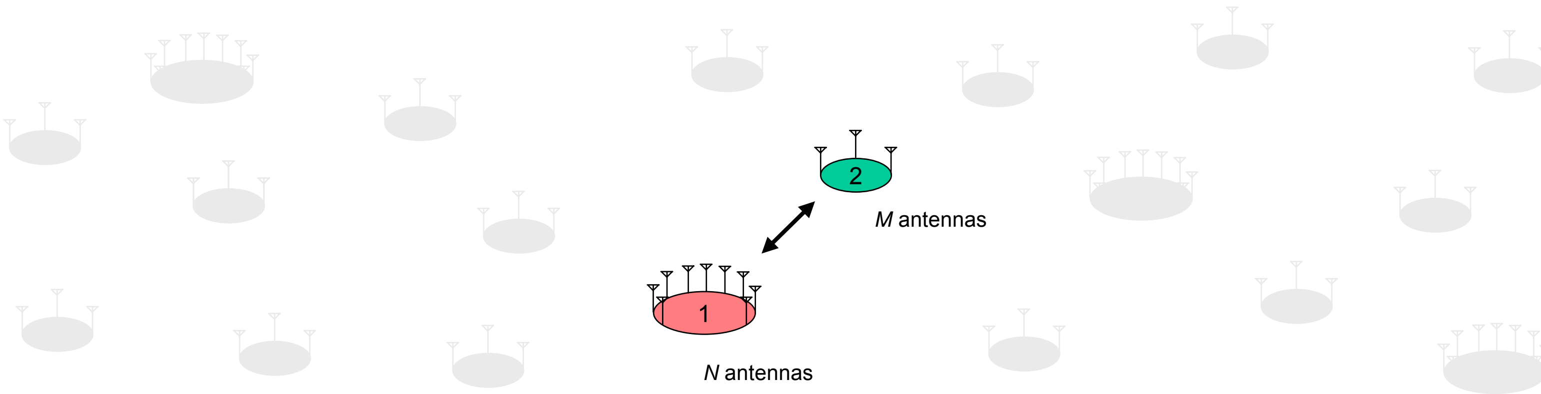


Presentation Outline

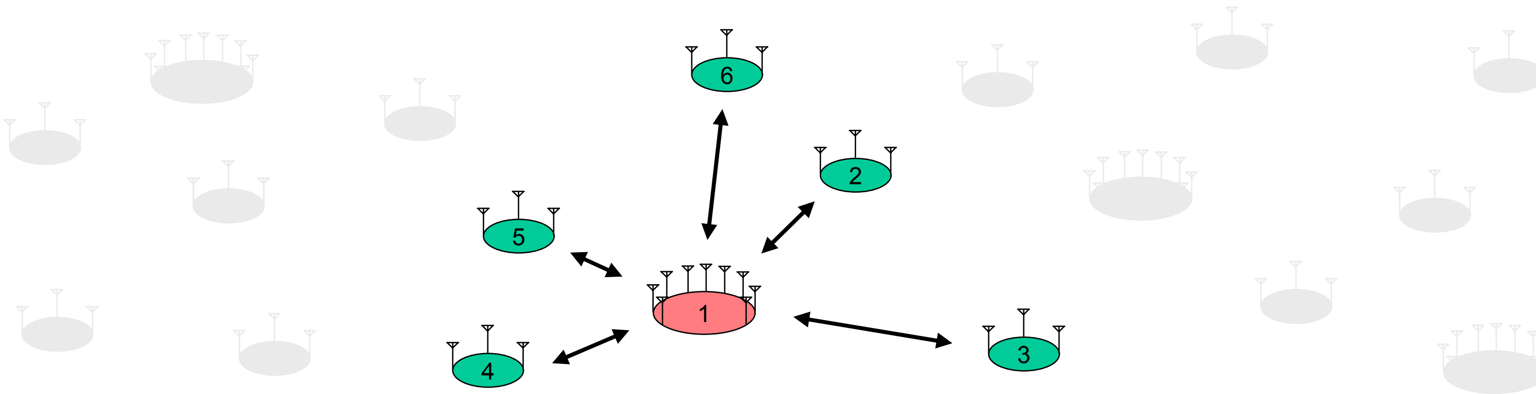
- Channel State Information
  - Single-User vs. Multi-User MIMO Scenarios
  - Multicast, Broadcast Examples
- Coordinated Tx-Rx Beamforming
  - Issues
  - Alternatives
- Interference-Dependent Coding
  - Channel Inversion
  - Modulo Pre-coding
- MIMO Channel Prediction
- Other Interesting Directions

Channel State Information: Single-User, Point-to-Point MIMO



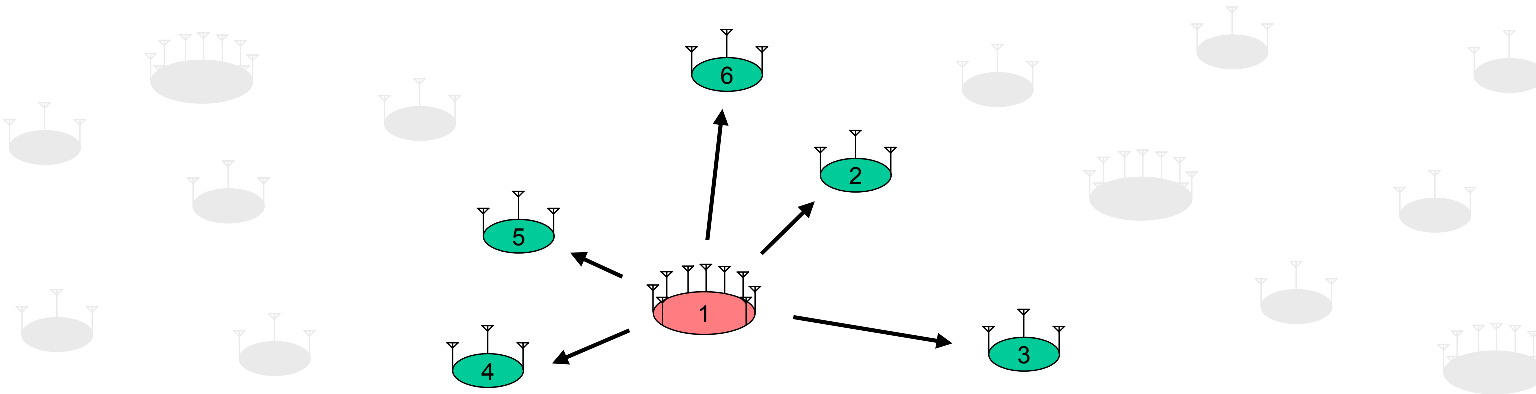
- Under ideal conditions (e.g., independent Rayleigh fading)
  - capacity grows linearly with min(N,M)
  - capacity growth is independent of CSI at the transmitter
- If channel is rank deficient or $N > M$, transmit CSI much more important
- Single-user point-to-point model appropriate if all network neighbors are time- or frequency-multiplexed.

Channel State Information: Multi-User Network MIMO



- Spatial multiplexing possible if node A is multicasting or “multi-routing”
- Transmit CSI is now critical to balance interference & throughput
  - receivers may not be able to perform MUD
  - little capacity growth with *N*, *M* or SNR
- Intelligent allocation of spatial resources also requires transmit CSI

MIMO Multicast Example



Channels: $\mathbf{H}_2, \mathbf{H}_3, \mathbf{H}_4, \mathbf{H}_5, \mathbf{H}_6$

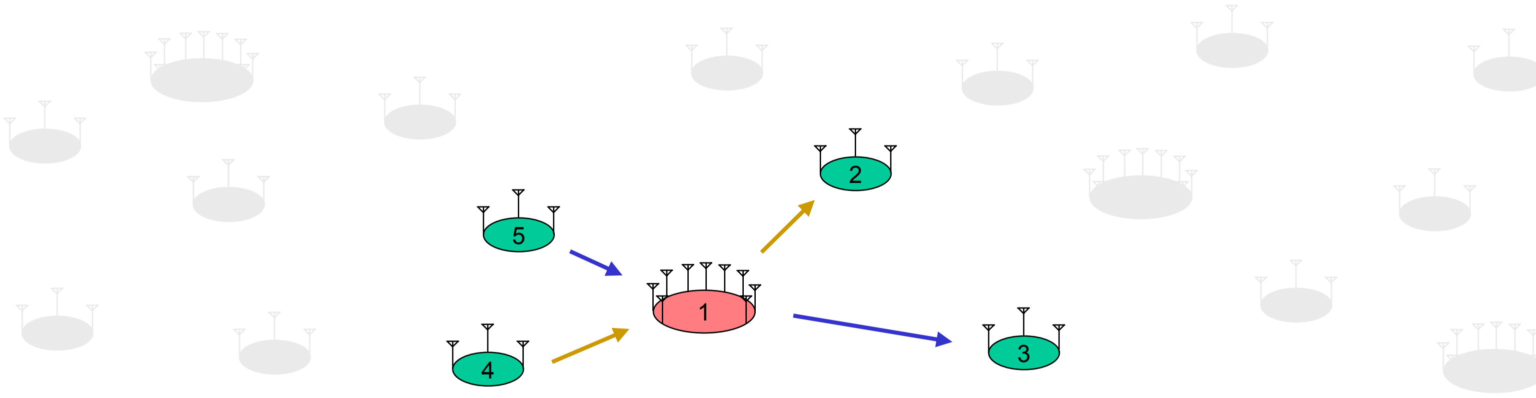
Transmit beamformer: $\mathbf{b}$

Receive data model: $x_2 = \mathbf{w}_2^* \mathbf{H}_2 \mathbf{b} d + \mathbf{n}_2 \quad x_3 = \mathbf{w}_3^* \mathbf{H}_3 \mathbf{b} d + \mathbf{n}_3 \quad \cdots$

Receive beamformers: $\mathbf{w}_2 = \mathbf{H}_2 \mathbf{b} \qquad \mathbf{w}_3 = \mathbf{H}_3 \mathbf{b} \qquad \cdots$

Problem: $\min_{\mathbf{b}} \mathbf{b}^* \mathbf{b} \quad \text{s.t.} \quad \mathbf{b}^* \mathbf{H}_i^* \mathbf{H}_i \mathbf{b} \geq \gamma_i \ , \ i = 2, \cdots, 6$

Spatially Multiplexed Routing Example (MIMO Broadcast Channel)



Channels: $\mathbf{H}_2, \mathbf{H}_3, \mathbf{H}_4, \mathbf{H}_5$

Transmit beamformer: $\mathbf{b}_2, \mathbf{b}_3$

Receive beamformers: $\mathbf{w}_3 = \left(\mathbf{H}_2\mathbf{b}_2\mathbf{b}_2^*\mathbf{H}_2^* + \sigma^2\mathbf{I}\right)^{-1}\mathbf{H}_3\mathbf{b}_3$

Problem:

$$\min_{\mathbf{b}} \mathbf{b}_2^*\mathbf{b}_2 + \mathbf{b}_3^*\mathbf{b}_3 \quad \text{s.t.} \quad \frac{\left|\mathbf{w}_i^*\mathbf{H}_i\mathbf{b}_i\right|^2}{\left|\mathbf{w}_i^*\mathbf{H}_i\mathbf{b}_j\right|^2 + \sigma^2\mathbf{w}_i^*\mathbf{w}_i} \geq \gamma_i \ , \ \{i, j\} = 2, 3$$

Coordinated Tx-Rx Beamforming

- despite non-convex constraints, multicast beamforming problem is efficiently solved via semi-definite optimization (SDO)
- unless receive nodes have 1 antenna, this is *not* true for broadcast case
- possible iterative solution:
  - (i) assume initial set of receive beamformers $\mathbf{w}_i$
  - (ii) find optimal transmit beamformer $\mathbf{b}$ using SDO
  - (iii) recalculate receive beamformers
  - (iv) go to step (ii)
- Issues:
  - when can convergence be guaranteed?
  - are there simpler alternatives to SDO for step (ii)?
  - are there alternatives to full transmit CSI?
  - optimal initialization to reduce # of iterations
  - sensitivity to CSI accuracy
- Alternative strategies:
  - downlink training, uplink "best" single-stream beamformer
  - beamformer "codebooks"
  - interference-dependent ("dirty-paper") coding
  - MIMO channel prediction

Interference-Dependent Coding

- although relatively simple, linear beamforming is not capacity optimal
- "dirty-paper" techniques are known to achieve sum capacity in certain cases
- a broadcast example:

xmit node has *M* antennas, *K* rcv nodes w/ 1 antenna each: $\underset{K \times 1}{\mathbf{x}} = \underset{K \times M}{\mathbf{H}}\mathbf{s}$

channel inversion: $\mathbf{s} = \gamma \mathbf{H}^* \left(\mathbf{H}\mathbf{H}^*\right)^{-1} \mathbf{d}$

performs poorly even in ideal i.i.d. Rayleigh fading case
ill-conditioned channel leads to signal attenuation, not noise amplification

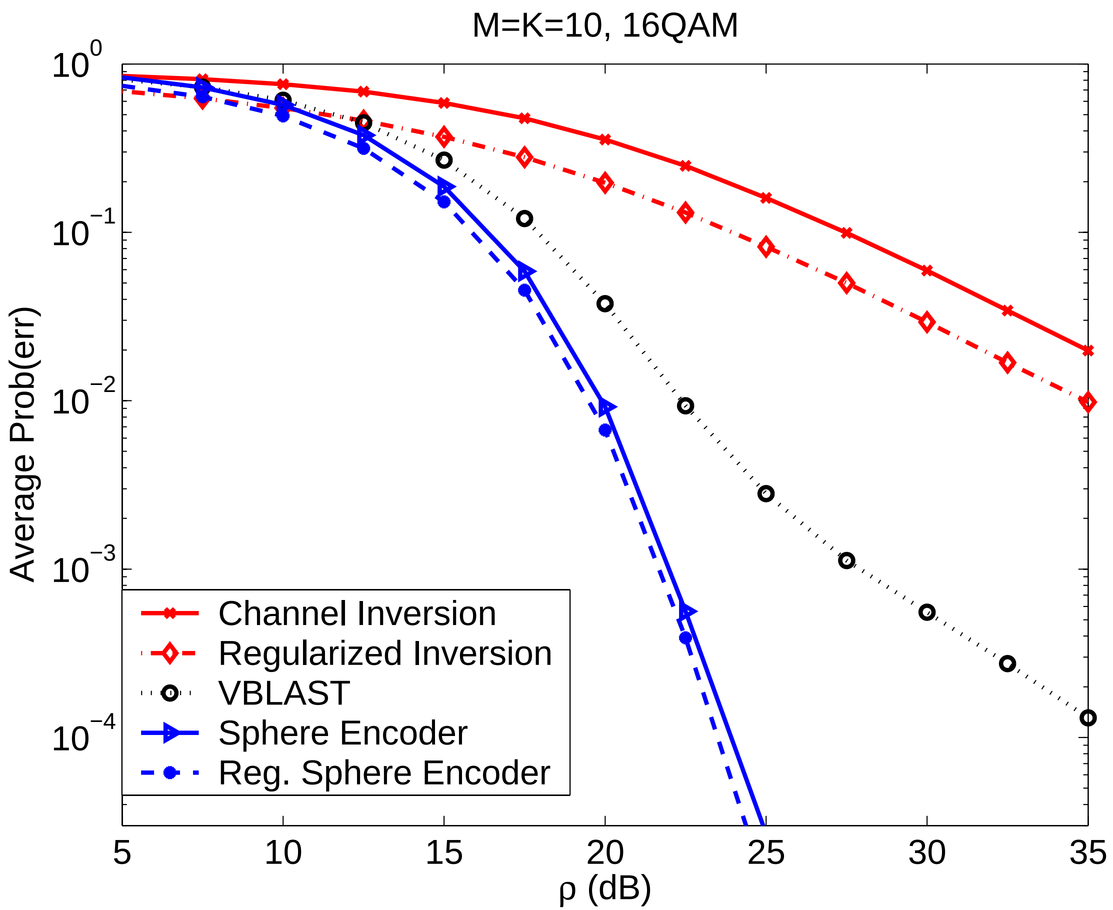
regularized channel inversion: $\mathbf{s} = \gamma \mathbf{H}^* \left(\mathbf{H}\mathbf{H}^* + \alpha \mathbf{I}\right)^{-1} \mathbf{d}$

offers some improvement, but must choose α carefully

modulo precoding: $\mathbf{s} = \gamma \mathbf{H}^* \left(\mathbf{H}\mathbf{H}^*\right)^{-1} (\mathbf{d} + \tilde{\mathbf{d}})$

code perturbation is channel (interference) dependent
perturbation is restricted to integer lattice for modulo decoding
can be thought of as "sphere encoding"

Modulo Precoding Example

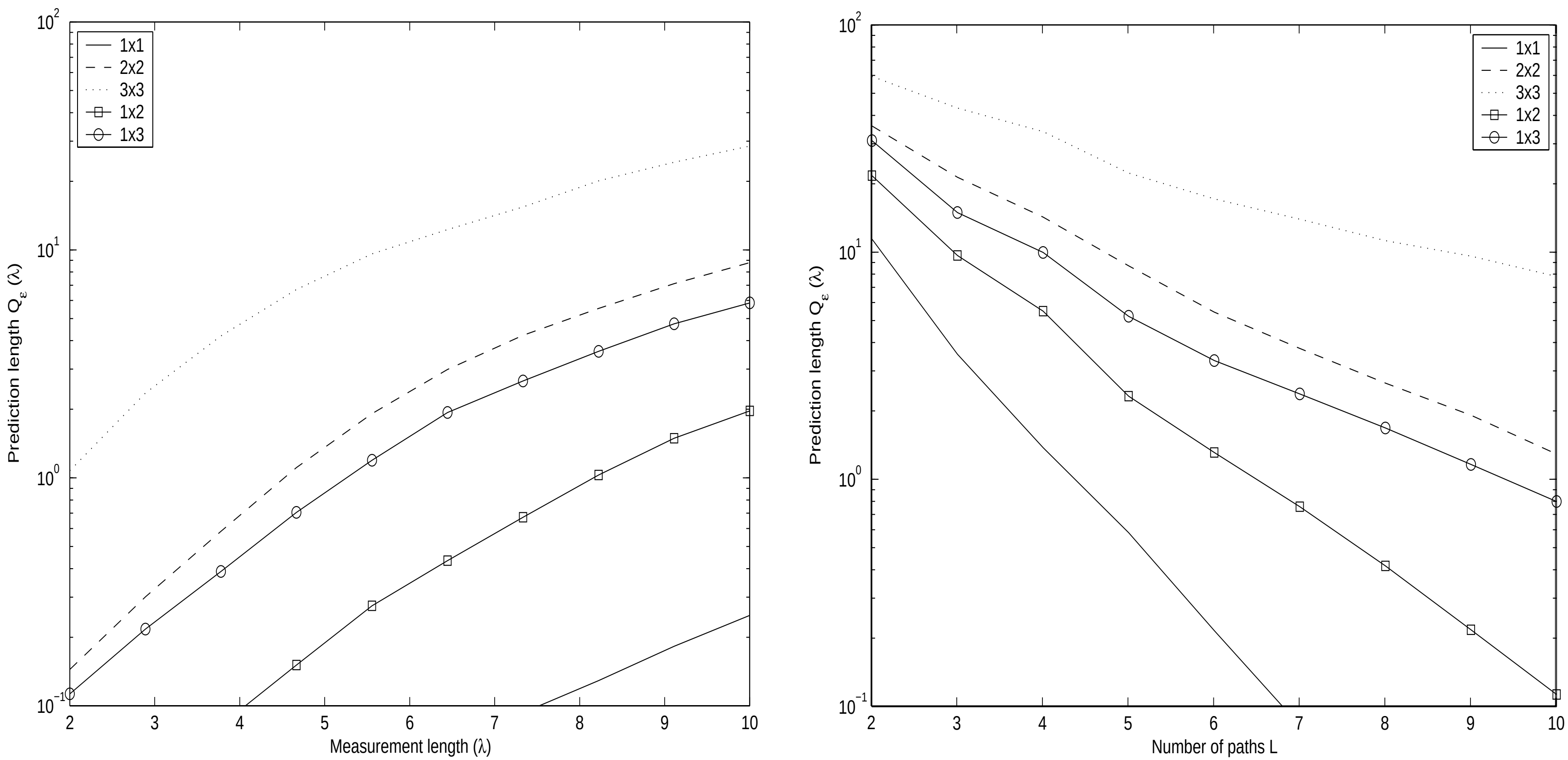


Issues:

- what if rcv nodes have more than 1 antenna?
- no analytical performance analysis now available
- better performance can be achieved with higher dim-ensional lattices
- computationally complex

MIMO Channel Prediction

CRB analysis indicates that channel prediction horizons are much longer for MIMO than SISO systems (joint work w/ T. Svantesson):



MIMO Channel Prediction Issues

- algorithms to realize the bounds (or get close)
- Kalman filters, auto-regressive models are obvious possibilities
- element-wise AR models do not capture MIMO structure

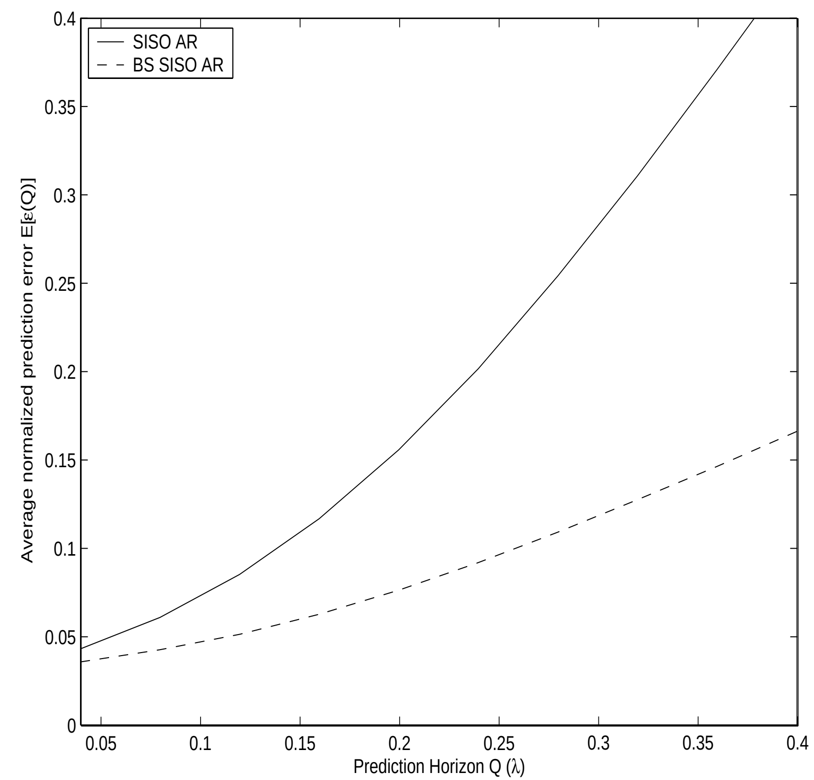
$$h_{ij}(t) = \alpha_{ij} h_{ij}(t-1) + \varepsilon(t)$$

- alternative: beamspace AR

$$\bar{h}_{ij}(t) = \alpha_{ij} \bar{h}_{ij}(t-1) + \varepsilon(t)$$

$$\bar{\mathbf{H}}(t) = \mathbf{W}^* \mathbf{H}(t) \mathbf{W}$$

- example shows results for 10x10 ULA and uniform DOA sampling
- performance still significantly short of the CRB
- improvements possible using channel-dependent beamspace transformation



Other Interesting Directions

- blind & semi-blind channel estimation
  - reduces training overhead
  - exploit structure due to space-time coding
- beamforming vs. space-time coding trade-off
  - both are special cases of affine pre-coding framework:

$$\mathbf{s}_k = \mathbf{U}_k \mathbf{d} + \mathbf{t}_k$$

T x 1 block for xmit antenna *k* ($\mathbf{s}_k$)

T x D pre-coder ($\mathbf{U}_k$)

D x 1 block of data symbols ($\mathbf{d}$)

T x 1 block of training (if present) ($\mathbf{t}_k$)

  - all rational rates possible, determined by pre-coder dimensions
  - allows for superimposed training
  - prior work exploits framework for (semi-)blind equalization
- resource allocation
  - multi-user diversity, routing decisions require single FOM for each channel
  - due to spatial dimension, there are multiple FOMs per user
  - FOMs depend on which users are spatially multiplexed
  - need “spatial compatability” metrics; e.g.,

$$\xi_{ij} = \frac{\|\mathbf{H}_i^* \mathbf{H}_j\|_F^2}{N_i N_j}$$