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Title	**Antenna Arrays for MBWA: Overview and Field Experiments**
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Re:	MBWA ECSG Call for Contributions
Abstract	This submission presents an overview of antenna array technologies for mobile broadband wireless systems and presents recent field results from a 2x2 OFDM experimental testbed.
Purpose	For informational use only
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Antenna Arrays for MBWA: Overview and Field Experiments

IEEE 802.20

March 10-14, 2003

Motivation – Why Antenna Arrays?

- **Ultimate Goal**: Increase Capacity and Reliability

- Capabilities:
  - Coherent beamforming gain
  - Space-Diversity Exploitation
  - Interference Suppression

- Benefits:
  - Improve Link Quality
  - Improve Coverage Reliability
  - Enhance Range

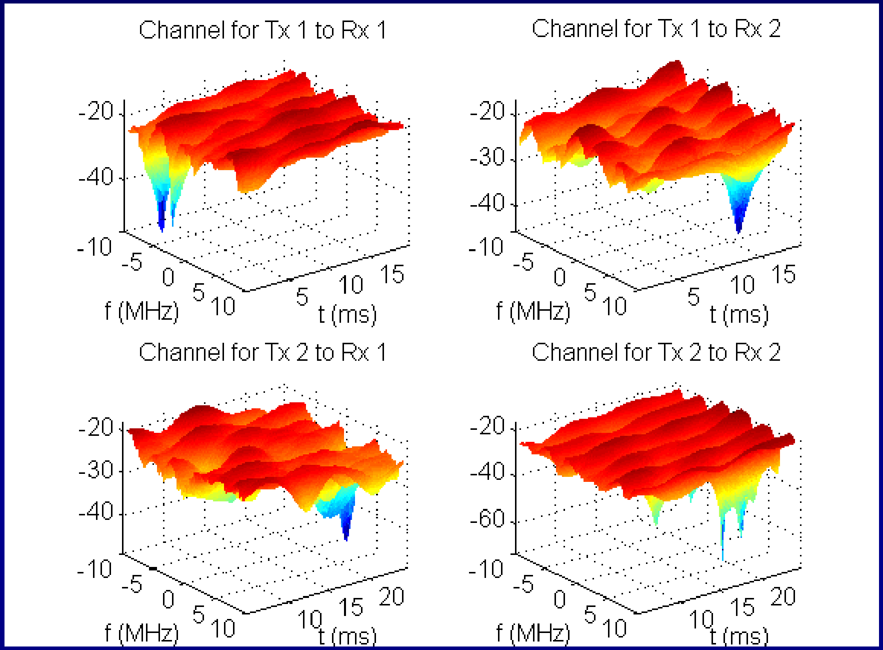
- Increase capacity via:
  - Enable higher order modulation
  - Enable smaller re-use factors

- Multiply capacity: spatial multiplexing
  - Spatial Division Multiple Access (SDMA)
  - Multiple Input Multiple Output (MIMO)

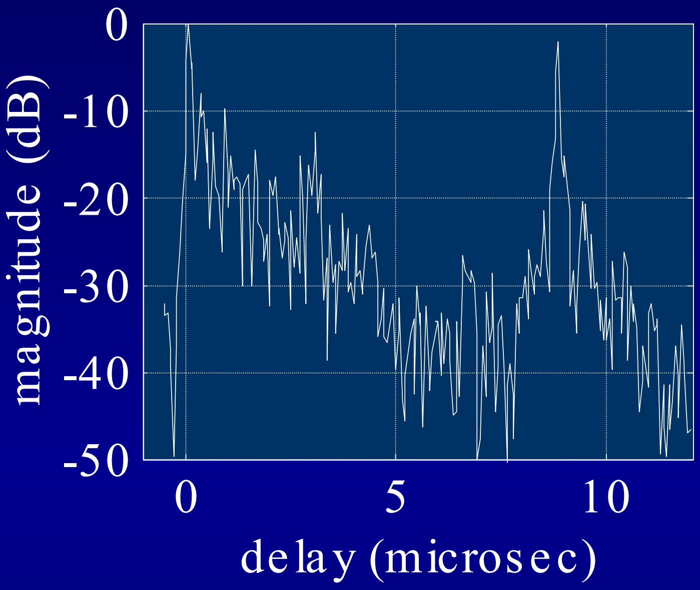
- Current standards are incorporating Antenna Array techniques
  - 3G CDMA: Space Time Transmit Diversity (STTD/Alamouti), Transmit Adaptive Arrays (TXAA), with MIMO on the horizon
- Many different techniques for exploiting multiple antennas
- For best results, AAs must be matched to the entire system
- Gains are environmentally dependent

Challenges in Broadband Mobile Systems

Example 1:



Example 2:

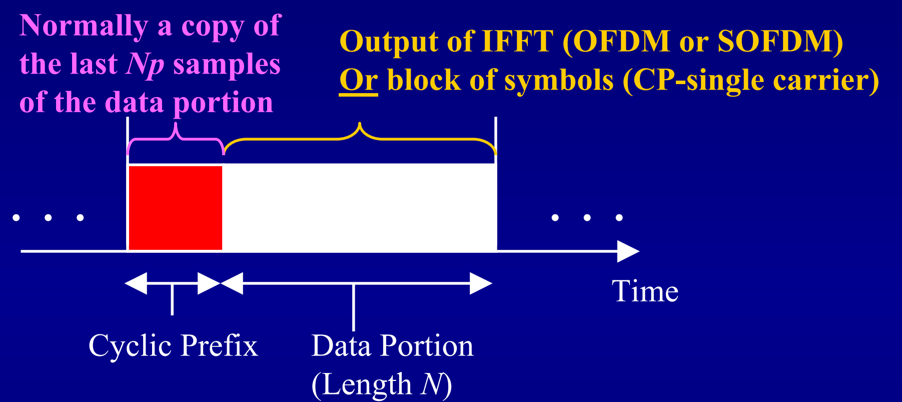


- Mobile Broadband is a <u>challenging environment</u> for Antenna Arrays
  - **High mobility:** causes rapid variations across the time-dimension
  - **Multipath delay spread:** causes severe frequency-selective fading
  - **Multipath angular spread:** causes significant variations in the spatial channel responses of the incident signals
  - For best performance, the Rx & Tx algorithms must accurately track all dimensions of the channel responses (time, frequency, and space)

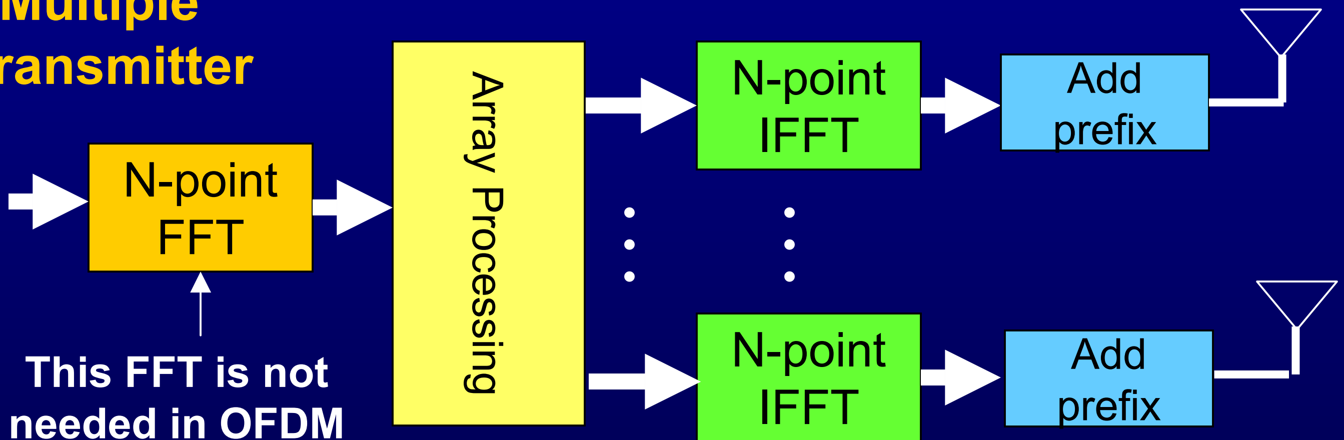
Frequency-Domain Transmit Array Processing

- Orthogonal Frequency Division Multiplexing (OFDM)
- Cyclic-Prefix Single Carrier
- Better complexity & performance vs. time-domain approaches in broadband high delay spread channels

Transmission Format:

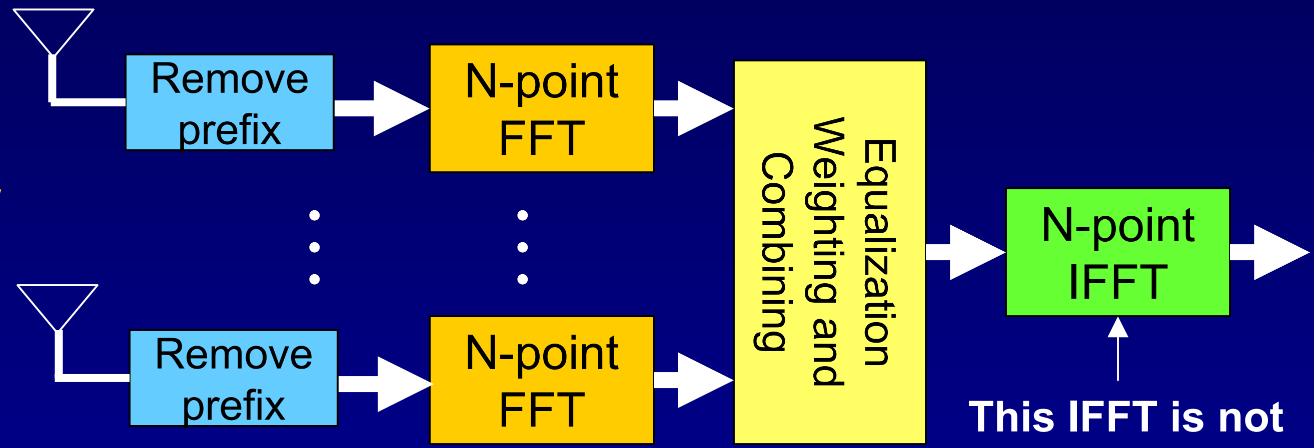


General Multiple Antenna Transmitter



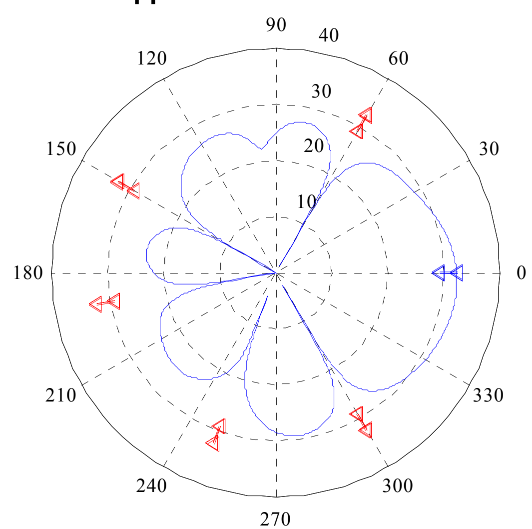
Frequency-Domain Receive Array Processing

General Multiple Antenna Receiver



- **Max Ratio Diversity Combining**
  - Optimize for <u>Maximum S/N</u>
  - Beamforming gain over noise
  - Diversity gain in faded channels
- **Optimal Combining**
  - Optimize for <u>Maximum S/(I+N)</u>
  - Tradeoff between Beamforming & Diversity Gain and Interference Suppression

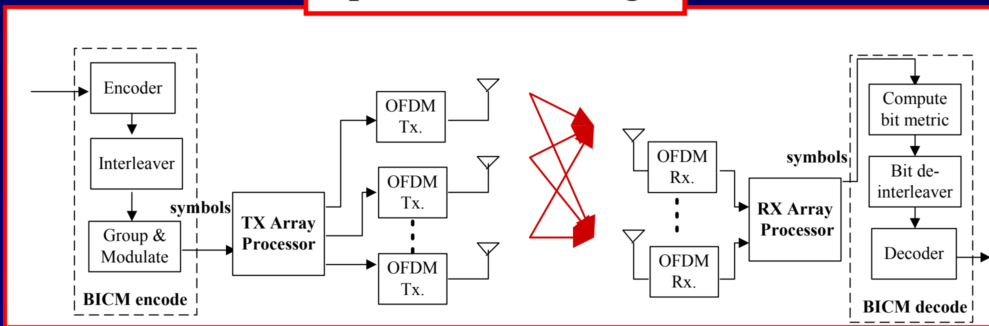
Active Interference Suppression with an 8-Element circular array



Angular Array Response on one OFDM subcarrier (simulated)

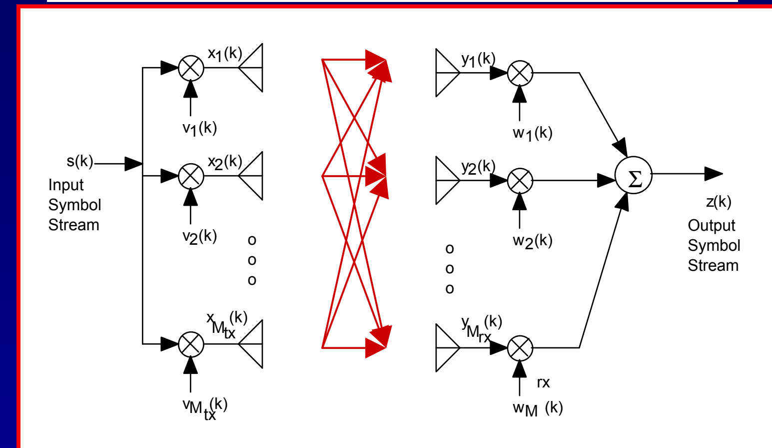
Common Transmit Array Techniques

Space-Time Coding



- **Alamouti Transmit Diversity**
  - Multiplex two QAM / PSK symbols onto two antennas over two symbol intervals.
  - TX diversity gain with no channel knowledge at transmitter
  - Incorporated in 3G-CDMA (STTD)
  - Easily applied to OFDM
    - Apply across bauds or across subcarriers
  - Easily applied to CP-Single Carrier
    - Time-Reversal & Conjugation trick

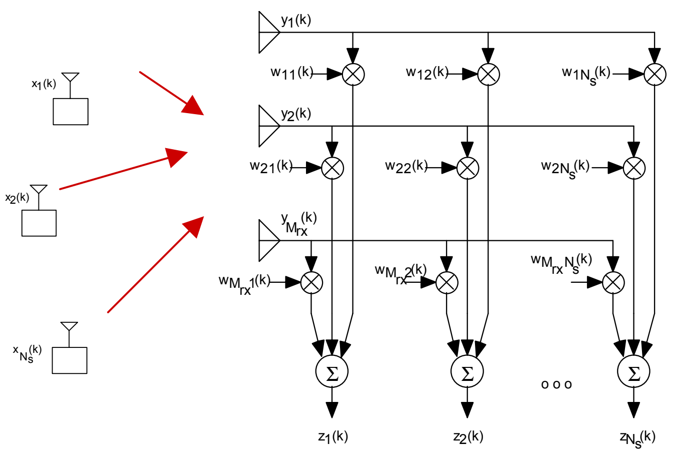
Transmit and Receive Array Processing



- **Transmit Adaptive Beamforming**
  - Direction-based tracking of subscriber
  - Focus Tx energy towards subscriber
  - Reduces interference to other cells
  - Limited Tx diversity gain in fading
- **Transmit Adaptive Array (TXAA)**
  - Incorporated into 3G-CDMA
  - A diversity-spaced array provides both beamforming & diversity gains
    - FDD: feedback
    - TDD: reuse uplink information
  - Gains diminish with inaccurate channel information in mobile channels

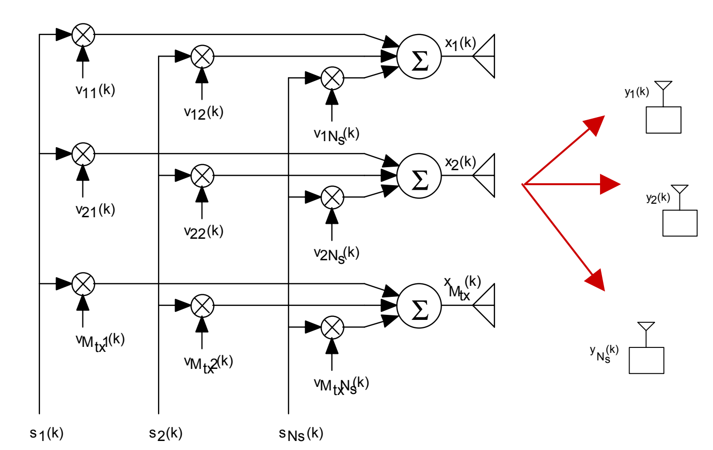
Spatial Division Multiple Access (SDMA)

RX SDMA



Multiple user signals received on same time-frequency resources

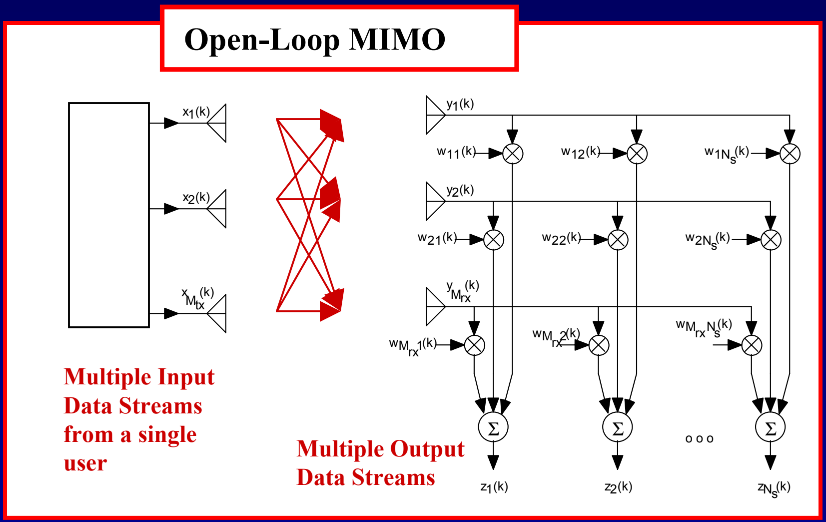
TX SDMA

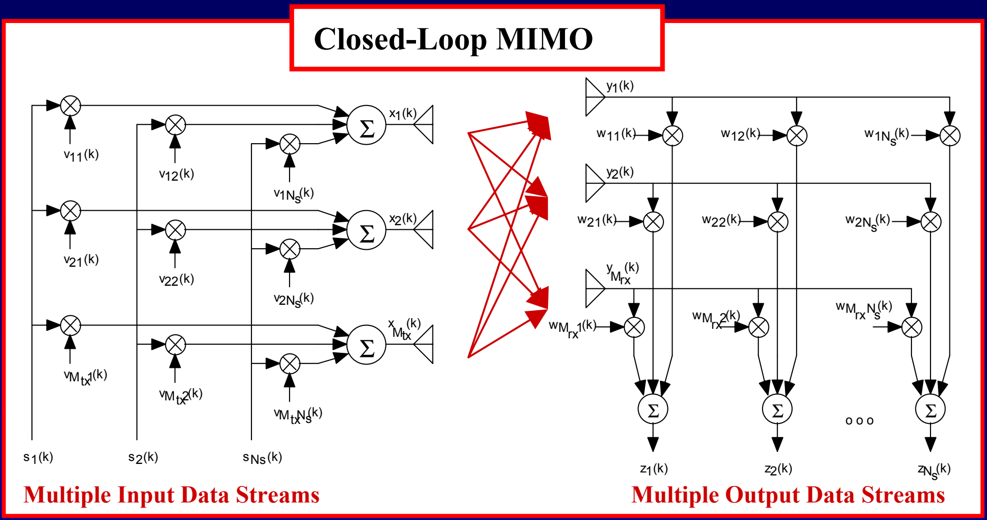


Multiple user signals transmitted on same time-frequency resources

- Base station communicates with multiple subscriber devices on the same time-frequency resources simultaneously
- Multiply capacity by serving multiple users simultaneously
- Receive SDMA relies on multi-user channel estimation and tracking along with baseband array combining algorithms
- Transmit SDMA may be difficult to implement in fast-moving broadband channels
  - Need precise channel information at the transmit array to eliminate cross-talk between the spatial channels

Multiple Input Multiple Output (MIMO)





- Transmitting one or more data streams over multiple spatial channels between a single TX and RX device
- Advantage:
  - Vastly increased theoretical capacity vs single-stream/antenna methods
  - Practical view: Form multiple spatial channels each using a small modulation & coding rate rather than using a single spatial channel having a large modulation & coding rate
- Disadvantage:
  - MIMO methods need sufficient angular multipath scattering so that the transmit antennas are "spatially separable"
  - MIMO methods fail when channel matrix has high levels of correlation

Field Data Collection Description

Base Site Antennas

Test Truck

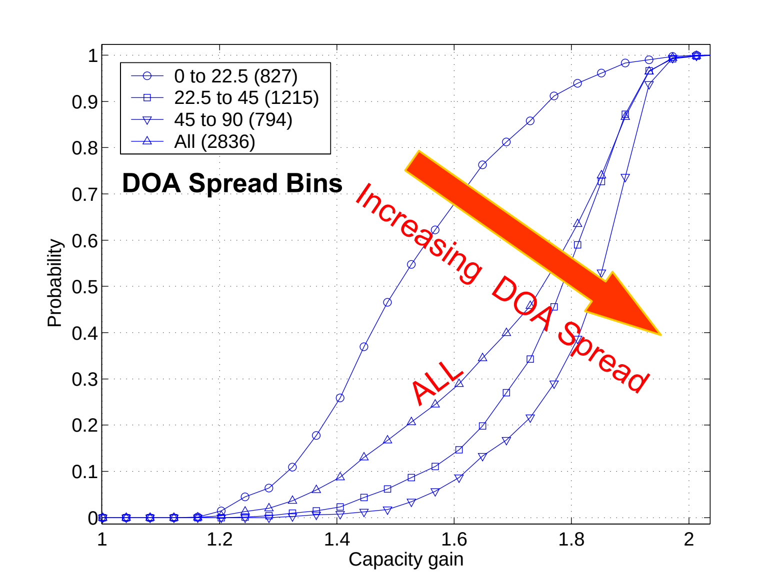
3.675 GHz carrier
20 MHz channel BW

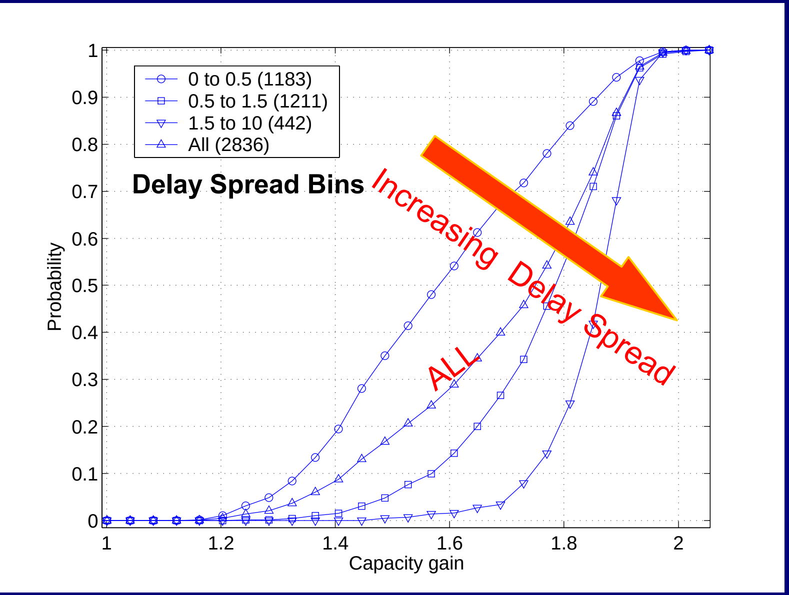
- 6 sectors, 2 antennas/sector
- Located on top of 6-story building
- 5 λ antenna spacing (~41 cm)
- 18 dBi antenna gain (80º beamwidth)

- Two identical & independent Rx
- 5 dBi omni antennas, spaced ~9.3 λ (~75cm)
- Synchronized to GPS and received signal
- Time & Frequency domain data
- 720 snapshots of 9 MBytes per hour, 6.4GB/h

Theoretical 2x2 Capacity Gain over 1x1 Based on Measured Channels

- Multi-antenna Shannon capacity formula (see Foschini, Teletar, etc.)
- Using measured frequency-domain channel matrices
- CDF of open-loop 2x2 capacity gain over 1x1



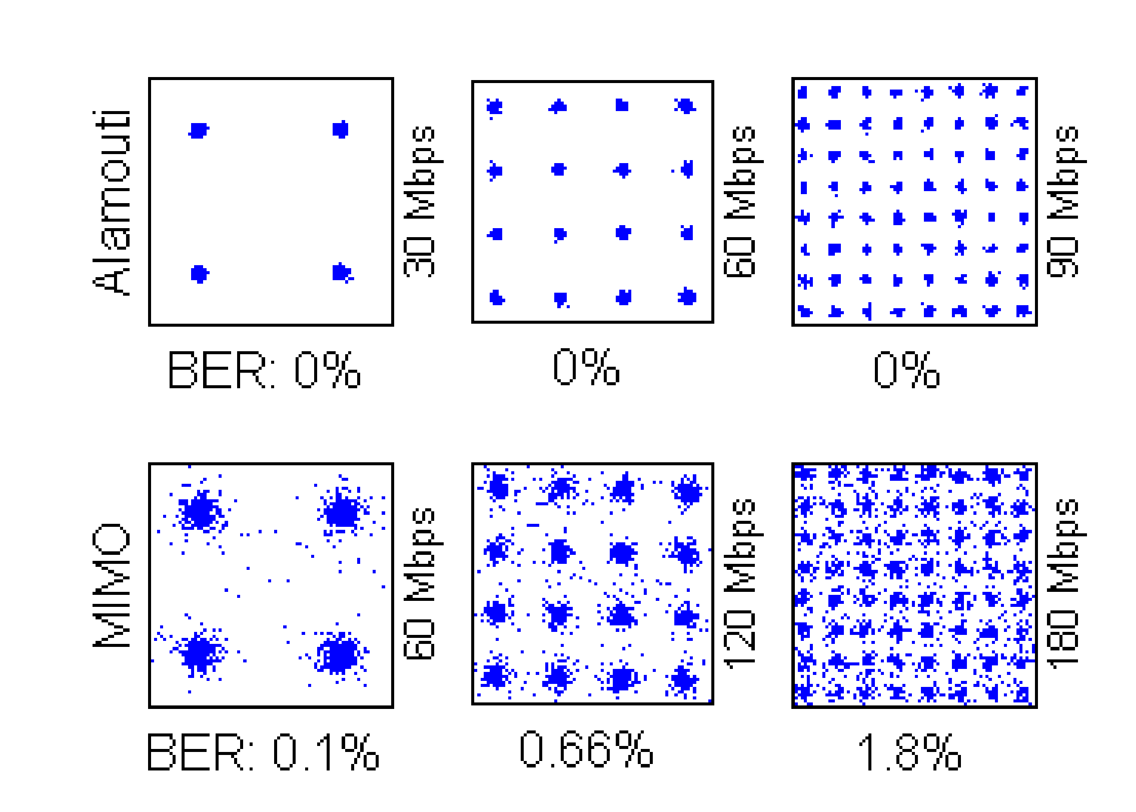


- Dependency on DOA spread
  - Directions of Arrival measured with synthetic aperture method (To appear: Krauss, et al., VTC-2003-Spring, April 2003)
  - Higher DOA spreads correspond to higher capacity gain over 1x1

- Dependency on Delay Spread
  - Higher Delay Spreads tend to correspond to rich scattering conditions

Alamouti vs MIMO

- **QAM Constellations & Uncoded BER (Off-line)**

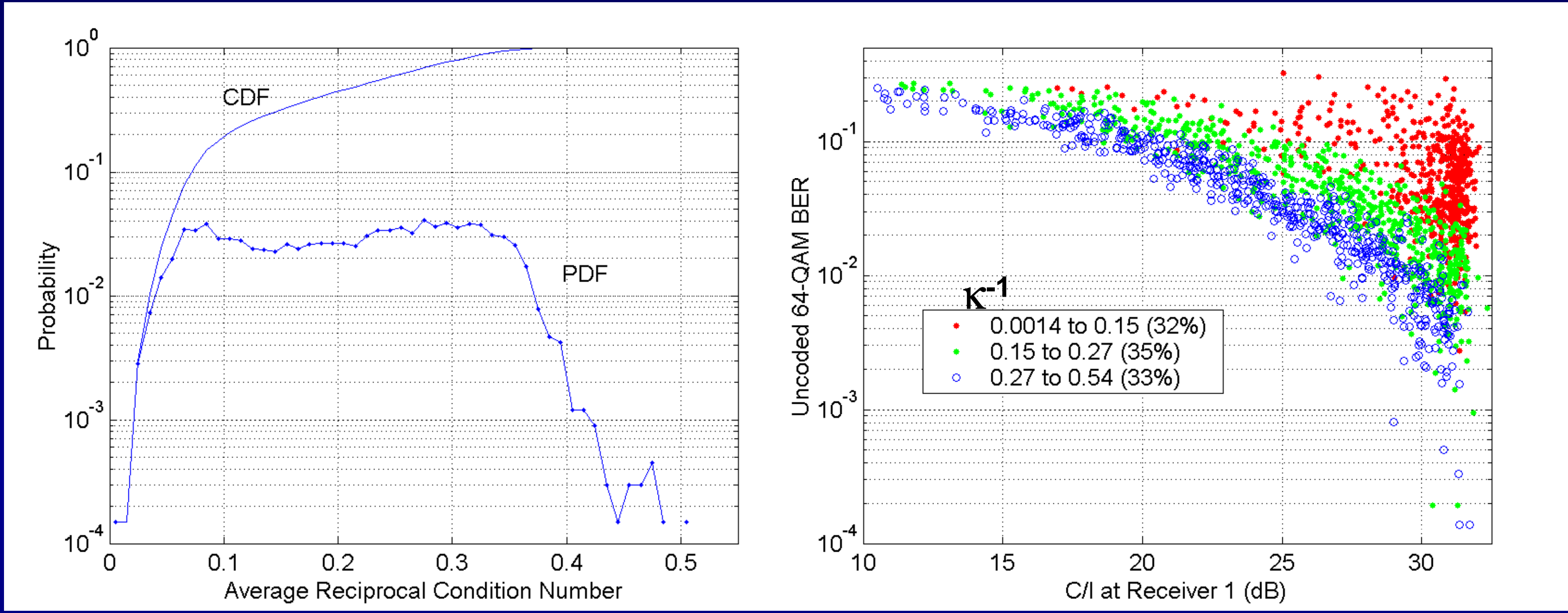


- **"Alamouti" scheme has both transmit and receive diversity (2x2)**

- **2x2 MIMO processing:**
  - **- linear MMSE equalization**
  - **- offers 2x the data rate**

- **Non-linear receiver processing and coding can help achieve the higher capacity benefits of MIMO transmission**
- **For MIMO to perform well, need good spatial conditioning**

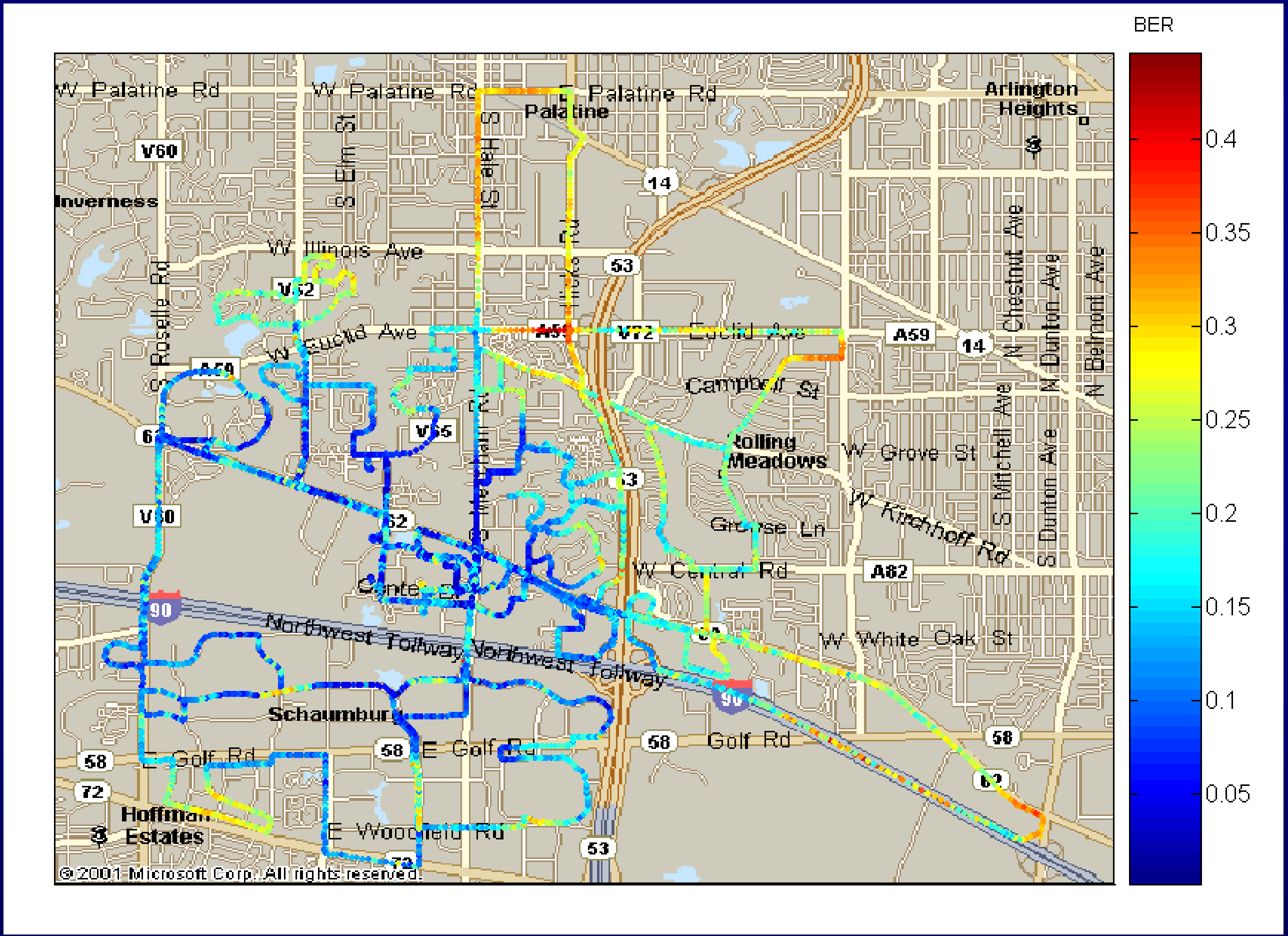
Spatial Conditioning: Open-Loop 2x2 MIMO Performance



- The average reciprocal condition number ($0< \kappa^{-1} <1$) gives a rough sense of how well 2x2 MIMO will work
  - κ^{-1} =1: The spatial Tx signatures are orthogonal and equal magnitude
  - κ^{-1} =0: Singular 2x2 channel matrix, can't separate the two Tx streams
- Although κ^{-1} never reaches unity, the 64-QAM performance indicates that there is enough spatial separation much of the time to support MIMO operation in this environment
- Field observation: κ^{-1} >.3 indicates good spatial conditioning, κ^{-1} <.2 indicates poor spatial conditioning
- In this environment: ~30% of the time the channel exhibits good spatial conditioning (i.e. the channel is suitable for MIMO operation)

Pushing the Limits of 2x2 MIMO (300 Mbps)

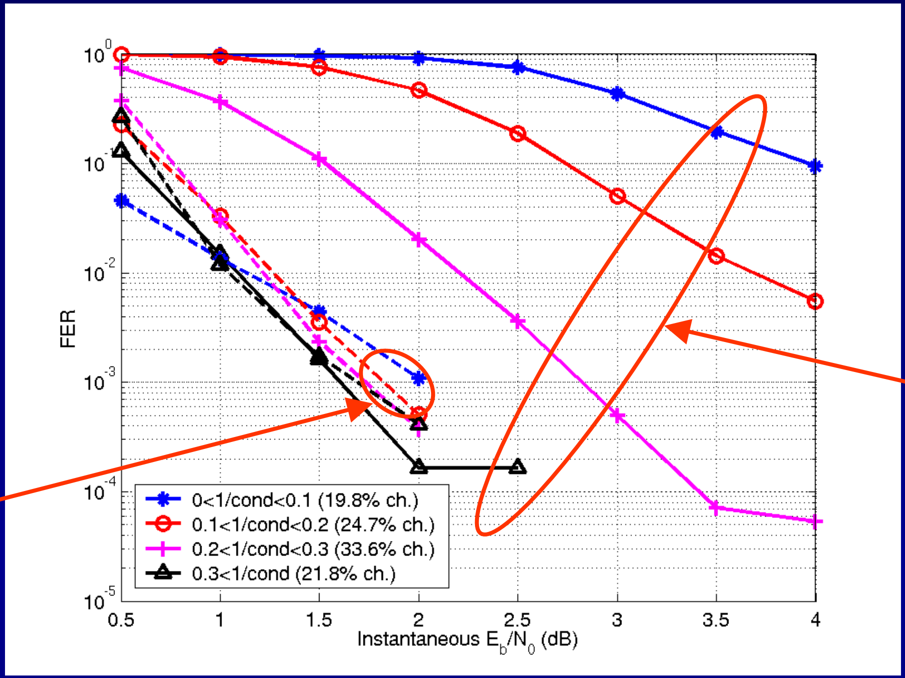
- BER vs. position for Uncoded 2-stream High Order-QAM w/ MIMO
  - Optimal channel estimation, 10dB excess Tx power, no interference
  - Receive antennas mounted on top of the test truck
  - 300 Mb/second channel data rate (18.8 MHz Bandwidth)



- Low BER locations indicate sufficient multipath scattering.
- Although this is an idealized case, it does show that MIMO detection is worth further consideration

Alamouti vs. MIMO in measured 2x2 channels

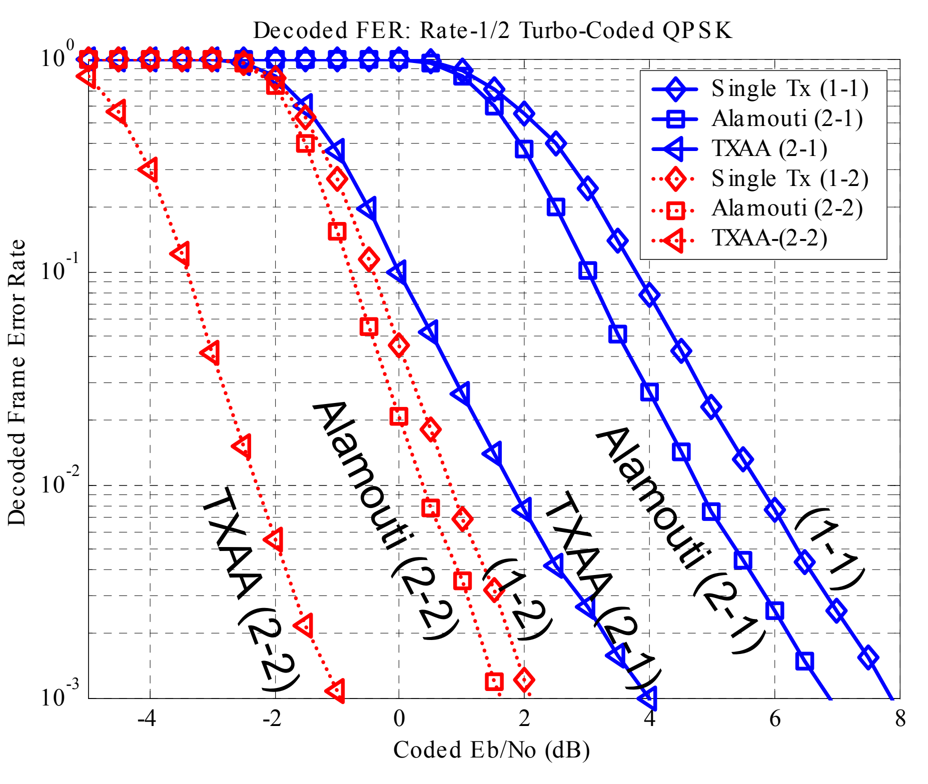
- 2 TX, 2 RX
- 2 bits/subcarrier
- MIMO = 2 streams of rate ½ QPSK
- Alamouti = 1 stream of rate ½ 16-QAM
- ML Receivers

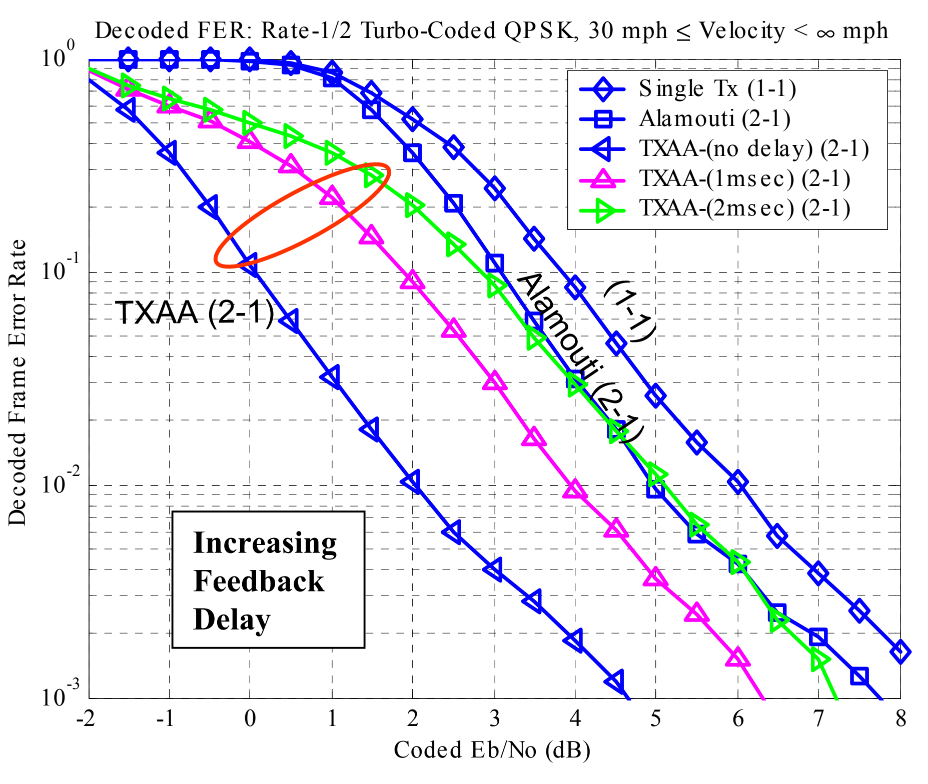


- Decoded FER performance for different ranges of the reciprocal condition number of the matrix channel response
- Alamouti (2-2) performance fairly constant with the condition number
- MIMO (2-2) performance degrades significantly in poorly conditioned channels
- In well conditioned channels: MIMO (2-2) only slightly better than Alamouti (2-2)

Evaluating Downlink TX Diversity & TX Adaptive Arrays in Measured Channels

- Simulated Turbo Coded 2x2 OFDM using measured channels





- 1-TX vs. 2-TX (Alamouti & TXAA)
- TXAA with ideal channel knowledge
- Additional Rx antenna better than additional Tx antennas
  - More Rx diversity than Tx diversity in this environment

- Effect of feedback latency on TXAA
- Feedback latency of 2msec causes TXAA to provide no gain over Alamouti for velocities > 30mph
- TXAA appropriate for stationary receivers, not appropriate for high velocity users

Conclusion

- Provided a basis for future discussion & proposals on antenna array technologies for MBWA

- Antenna Array technology widely viewed as critical for future mobile broadband communication systems
  - Many configurations to choose from, each with pros & cons

- Results from one set of suburban 2x2 field experiments:
  - Multiple receive antennas provide largest benefits
  - MIMO advantageous at high SNRs, high data rates, good spatial conditioning
  - Alamouti outperforms 2x2 MIMO at low data rates, low SNRs, low scattering
  - TXAA advantageous for low-mobility / portable subscribers

- Evaluating Antenna Array Technology:
  - Performance tends to be environmentally dependent
  - Realistic channel models are needed in evaluations
  - Evaluations should involve coded performance
  - Evaluations should examine system-level gains