PHY Design for Spatial Multiplexing MIMO WLAN

John Ketchum, Steve Howard, Mark Wallace, Rod Walton, Bjorn Bjerke, Irina Medvedev

Qualcomm, Incorporated

johnk@qualcomm.com

Presentation Outline

- Overview
- PHY design overview
- Principles of MIMO eigenvector steering operation
- PHY design details
- Summary

PHY Design Overview

Qualcomm 802.11n PHY Design

- Fully backward compatible with 802.11a/b/g
  - 20 MHz bandwidth with 802.11a/b/g spectral mask
  - OFDM based on 802.11a waveform with additional long OFDM symbols (256 sub-carriers)
- Modulation, coding, interleaving based on 802.11a
  - Expanded rate set
- Scalable MIMO architecture
  - Supports a maximum of 4 wideband spatial streams
- Two forms of spatial processing
  - Eigenvector Steering (ES): via wideband spatial modes/SVD per sub-carrier
    - Tx and Rx steering
    - Over the air calibration procedure required
  - Spatial Spreading (SS): modulation and coding per wideband spatial channel
    - No calibration required
    - SNR per wideband spatial stream known at Tx
- Sustained high rate operation possible via adaptive rate control

Observation

- *Detailed, up-to-date feedback on channel state is fundamental to achieving high throughput in a TDD MIMO WLAN*
- The challenge is to achieve this reliably with low overhead
- We believe that the design described here achieves this goal

OFDM Waveform

- Baseline OFDM structure identical to 802.11a/g
  - 64 sub-carriers/20 MHz sampling rate
  - Same sub-carrier structure
    - 48 sub-carriers for data, 4 sub-carriers for pilot
    - "DC" sub-carrier empty, 11 sub-carriers for guard band
  - 3.2 μs symbol, 800 ns cyclic prefix
  - 20% Physical-layer overhead
- Also introduce a new long OFDM symbol with 256 sub-carriers
  - Similar sub-carrier structure
    - 192 sub-carriers for data, 16 sub-carriers for pilot
    - "DC" sub-carrier empty, 47 sub-carriers for guard band
  - 12.8 μs symbol, 800 ns cyclic prefix
  - Physical-layer overhead <6%
  - Use in conjunction with legacy (short) OFDM symbols for maximum efficiency

Modulation and Coding

- Use existing 802.11 constraint length 7, rate ½ convolutional code and punctured rates.
- Retain PSK/QAM modulation from 802.11
- Additional rates adopted to provide increased spectral efficiency
  - 256 QAM modulation gives increased rates and spectral efficiency
- Code rates range from ½ bit per modulation symbol to 7 bits per sub-carrier.
- Up to four wideband spatial channels supported with separate coding/interleaving for each channel.
- Enhanced interleaving over single OFDM symbol for MIMO OFDM
  - Based on 802.11a/g interleaver
  - Simple backward compatible mode
- Turbo or LDPC may provide future performance enhancements

Code Rates and Modulation

Bits/tone	Bit/s/spatial chan[1]	Bit/s/spatial chan[2]	Code Rate	Modulation
0.50	**6 Mbit/s**	**7 Mbit/s**	**r=1/2**	**BPSK**
0.75	**9**	**10.6**	**r=3/4**	**BPSK**
1.00	**12**	**14.1**	**r=1/2**	**QPSK**
1.50	**18**	**21.2**	**r=3/4**	**QPSK**
2.00	**24**	**28.2**	**r=1/2**	**16 QAM**
2.50	**30**	**35.3**	**r=5/8**	**16 QAM**
3.00	**36**	**42.3**	**r=3/4**	**16 QAM**
3.50	**42**	**49.4**	**r=7/12**	**64QAM**
4.00	**48**	**56.5**	**r=2/3**	**64QAM**
4.50	**54**	**63.5**	**r=3/4**	**64QAM**
5.00	**60**	**70.6**	**r=5/6**	**64QAM**
5.00	**60**	**70.6**	**r=5/8**	**256 QAM**
6.00	**72**	**84.7**	**r=3/4**	**256 QAM**
7.00	**84**	**98.8**	**r=7/8**	**256 QAM**

Notes: 1) short OFDM symbols; 2) long OFDM symbols

Spatial Processing

- Two forms of Spatial Processing for data transmission
  - *Eigenvector Steering (ES)*: Tx attempts to steer optimally to intended Rx
  - *Spatial Spreading (SS)*: Tx does not attempt to steer optimally to specific Rx
- ES operating modes take advantage of channel reciprocity inherent in TDD systems
  - Full channel state information (CSI) required at Tx
  - Calibration procedure required
  - Tx steering using per-bin channel eigenvectors from SVD
  - Rx steering renders multiple Tx streams orthogonal at receiver, allowing transmission of multiple independent spatial streams
  - This approach maximizes data rate and range

Spatial Processing Tools

- Basic spatial processing techniques used in different combinations to maximize throughput, range, and reliability under a wide range of conditions
  - Cyclic transmit diversity per Tx antenna
  - Orthogonal cover across symbols and spatial channels
  - Spatial spreading with simple orthogonal matrices
  - Eigenvector steering to synthesize wideband eigenmodes
- Eigenvector Steering simplifies processing burden of AP support of many STAs
- Spatial Spreading allows STAs without full channel characterization to achieve high throughput without Tx steering
  - ~80% of the throughput of calibrated modes with simple Rx processing

Over-the-Air Calibration

- ES approach requires over-the-air calibration procedure
  - Compensates for amplitude and phase differences in Tx and Rx chains
  - Calibration required infrequently– typically on association only
  - Simple exchange of calibration symbols and measurement information requires little overhead and background processing
    - Total of ~1000 bytes of calibration data exchanged for 2x2 link
    - ~2800 bytes for 4x4 link

Feedback for ES and SS Modes

- Adaptive rate control
  - Receiving STA determines preferred rates on each of up to four wideband spatial channels
    - One rate per wideband spatial channel – NO adaptive bit loading
  - Sends one 4-bit value per spatial channel, differentially encoded, (13 bits total) to inform corresponding STA/AP of rate selections
    - Corresponding STA/AP uses this info to select Tx rates
    - Piggy-backed on out-going PPDUs
  - SS Mode can use single rate across all spatial channels
- Channel state information
  - For ES operation, Tx must have full channel state information
  - This is obtained through exchange of transmitted training sequences that are part of PLCP header
    - Very low overhead.
  - Distributed computation of steering vectors (SVD calculation)
    - STAs do SVD, send resulting training sequence to AP
  - For SS operation, unsteered training sequences transmitted in PLCP header to support channel estimate at receiver

Feedback Operates with Asynchronous MAC Transmissions

- TXOPs obtained through EDCA, HCCA, or enhanced HCCA
- Transmitting STA sends steered or unsteered training sequences in each TXOP
  - If operating in ES mode, receiving STA uses received training sequences to calculate transmit and receive steering vectors
  - If operating in SS mode, receiving STA uses received training sequences to determine Rx processing
- Receiving STA estimates rates per wideband spatial stream and includes in feedback
- Transmitting STA determines age of Tx steering vectors and falls back to SS mode if vectors are too old
- Transmitting STA determines age of rate feedback and backs off Tx rates if feedback is too old

Supported Antenna Configurations

- Scalable deployments 2x2 > 4x4
- Support for up 4 wideband spatial channels
  - Typical max antenna configuration is four antennas per STA
  - Can support more than four antennas on a STA, but without adding spatial channels
    - May provide increase range or throughput through diversity/steering gains
- STAs may have any number of antennas
  - STAs in network may have fewer antennas
  - Maximum spatial channels available on a link between two nodes is limited by STA with fewest antennas

Principles of MIMO Eigenmode Operation

Capacity-achieving Approaches to MIMO

- Transmit steering (channel eigenmode decomposition)
  - Allows straightforward power allocation among channel modes (water filling)
  - Requires detailed channel knowledge at transmitter
- Successive cancellation
  - Can be shown to result in same mutual information as eigenmode approach
    - No straightforward way to water fill
  - Significant complexity hit at receiver
  - Sub-optimal receivers (MMSE, ….) result in performance hit (~20%)

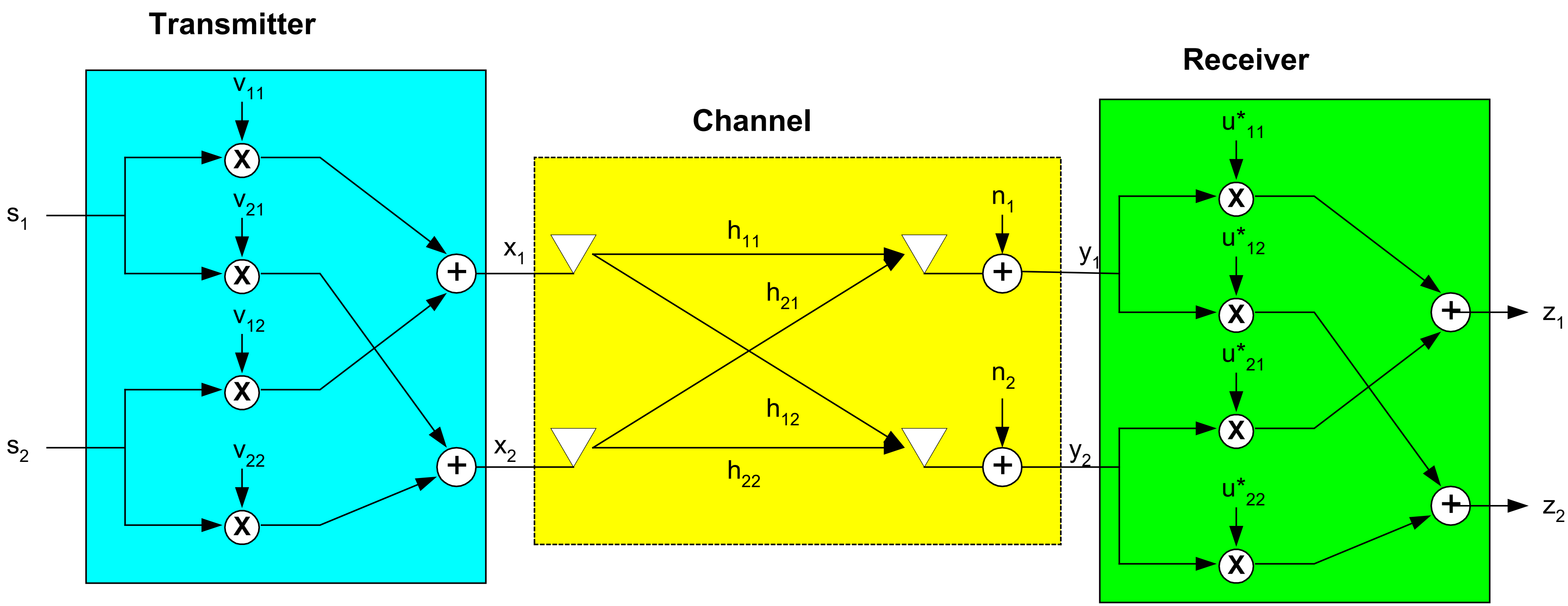
Channel Eigenmode Decomposition

- Determine Eigenmodes of channel matrix **H**
  - Singular Value Decomposition:
    - $\mathbf{H} = \mathbf{U}\mathbf{D}\mathbf{V}^{H}$
    - **U** and **V** are unitary matrices containing left and right singular vectors of **H**
    - **U** are also eigenvectors of $\mathbf{H}\mathbf{H}^{H}$, and **V** are eigenvectors of $\mathbf{H}^{H}\mathbf{H}$
    - **D** is a diagonal matrix of singular values of **H** (square roots of eigenvalues of $\mathbf{R}=\mathbf{H}\mathbf{H}^{H}$)
- Channel Capacity (no water filling)

$$C = \sum_{i=1}^{N} \log_2\left(1 + \frac{\lambda_i P_{Tx}}{\sigma^2}\right)$$

– sum of capacities of N parallel AWGN channels

Example: 2x2 Transmit-Receive Structure



$$\mathbf{x} = \mathbf{V}\mathbf{s}$$

$$\mathbf{y} = \mathbf{H}\mathbf{V}\mathbf{s} + \mathbf{n}$$

$$\mathbf{z} = \mathbf{U}^H\mathbf{H}\mathbf{V}\mathbf{s} + \mathbf{U}^H\mathbf{n} = \mathbf{D}\mathbf{s} + \hat{\mathbf{n}}$$

Spatial Matched Filter Receiver

- Received signal: $\mathbf{y} = \mathbf{HVs} + \mathbf{n}$
- Spatial matched filter: $\mathbf{M} = \mathbf{V}^H \mathbf{H}^H = \mathbf{DU}^H$
- Estimated transmit vector:

$$\hat{\mathbf{s}} = \mathbf{D}^{-2}\mathbf{My} = \mathbf{s} + \mathbf{D}^{-1}\mathbf{U}^H \mathbf{n}$$

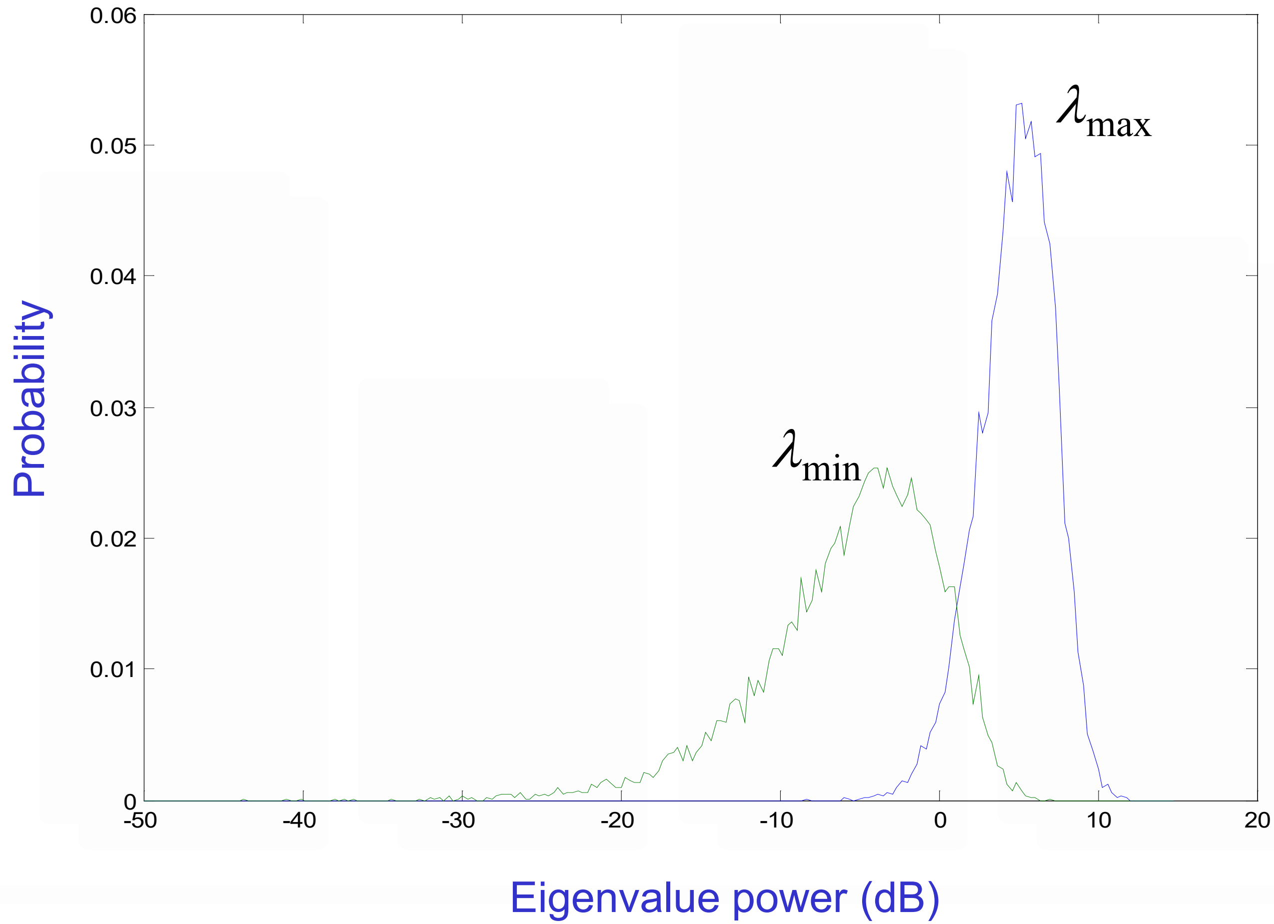
Eigenvalue statistics

- Sum of the eigenvalues of $\mathbf{HH}^H$ is equal to the squared Frobenius norm of **H:**

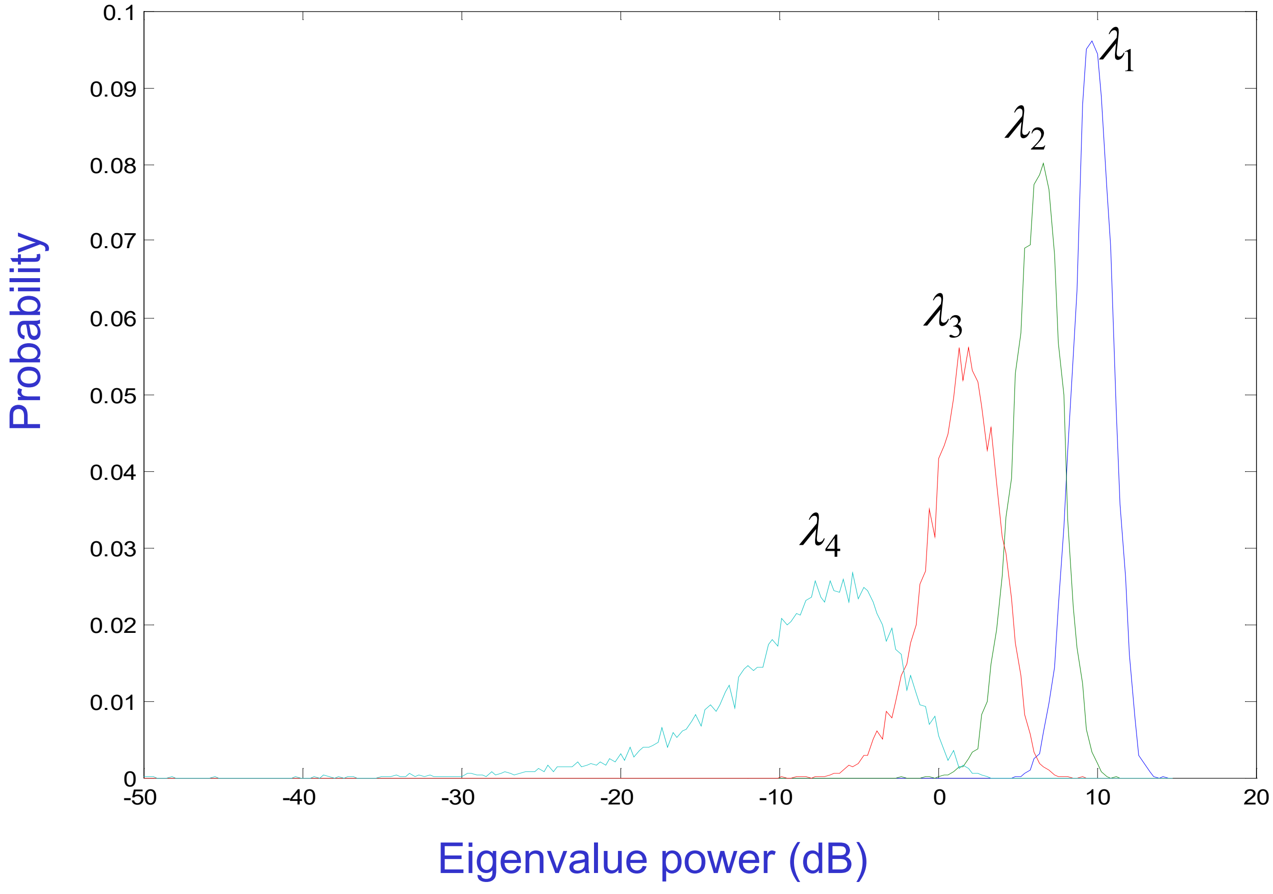
$$\sum_i \lambda_i = \|\mathbf{H}\|_F^2 = \sum_{i,j} \left| h_{ij} \right|^2$$

- For a narrowband, uncorrelated $N \times N$ Raleigh channel (elements of **H** are i.i.d. complex Gaussian random variables)
  - Sum of eigenvalues is chi-square with $2N^2$ degrees of freedom (N^2–order diversity)
  - Smallest eigenvalue is Raleigh
  - Larger eigenvalues in ranked set have successively narrower distributions (higher orders of diversity)

Ranked Eigenvalue distributions (2x2)



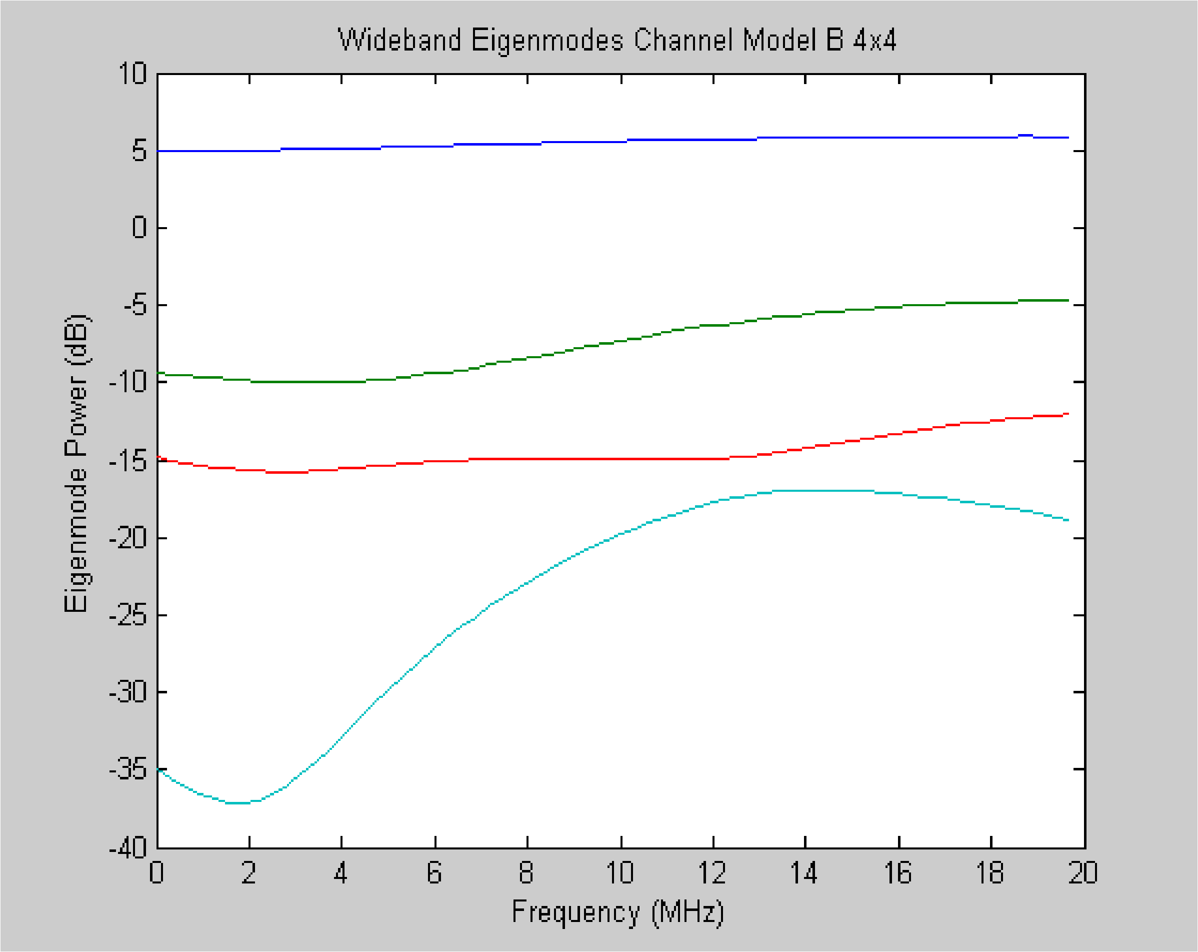
Ranked Eigenvalue distributions (4x4)



Wideband Eigenmodes and OFDM

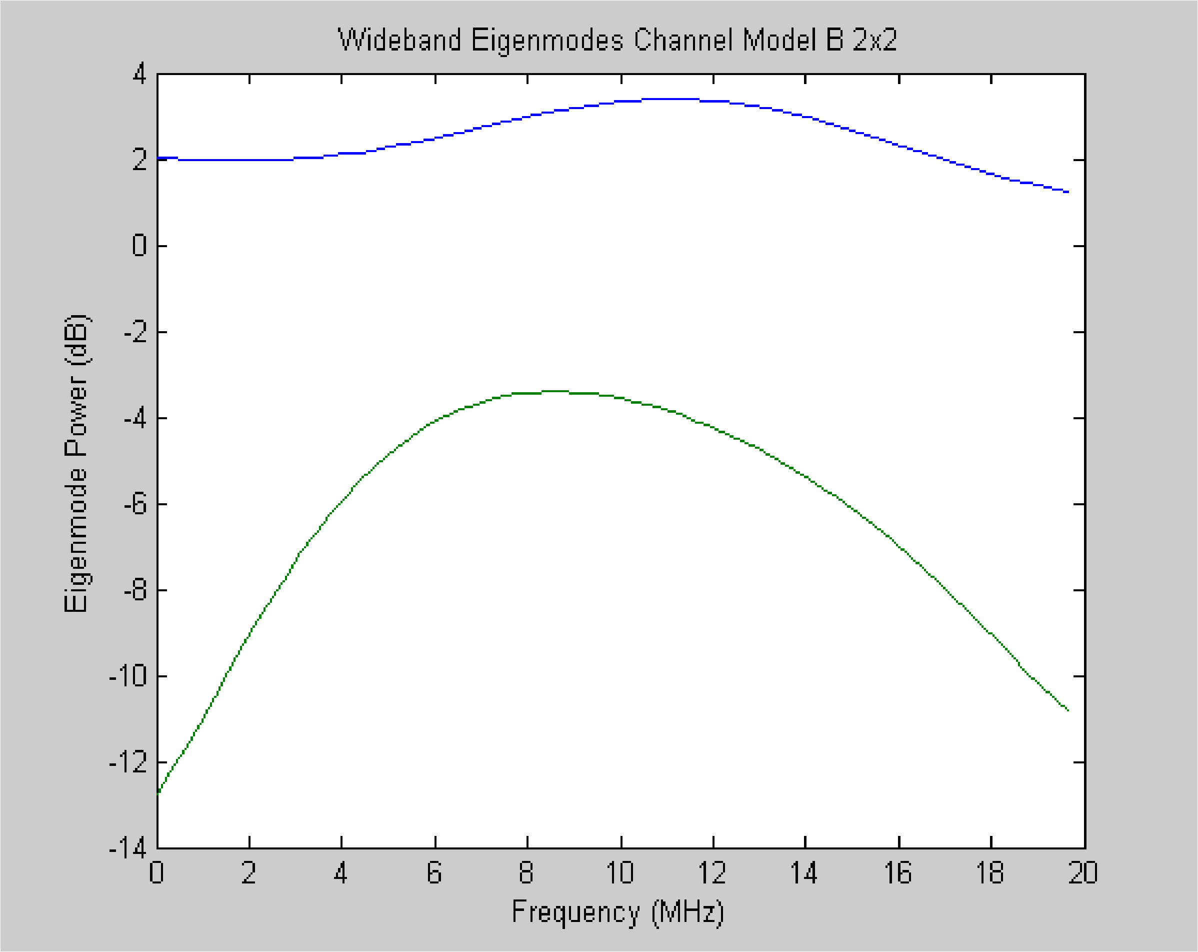
- OFDM chosen so that tone spacing << coherence bandwidth
- Find ranked eigenmodes/eigenvalues in each OFDM sub-carrier: $\lambda_1(k) > \lambda_2(k) > \cdots > \lambda_N(k)$
- Ensemble of eigenmodes of a given rank across OFDM symbol comprise a wideband eigenmode
- Highest ranked wideband eigenmodes exhibit very little frequency selectivity
- Smallest ranked wideband eigenmode exhibits frequency selectivity of underlying channel

Wideband Eigenmodes TGn Channel B



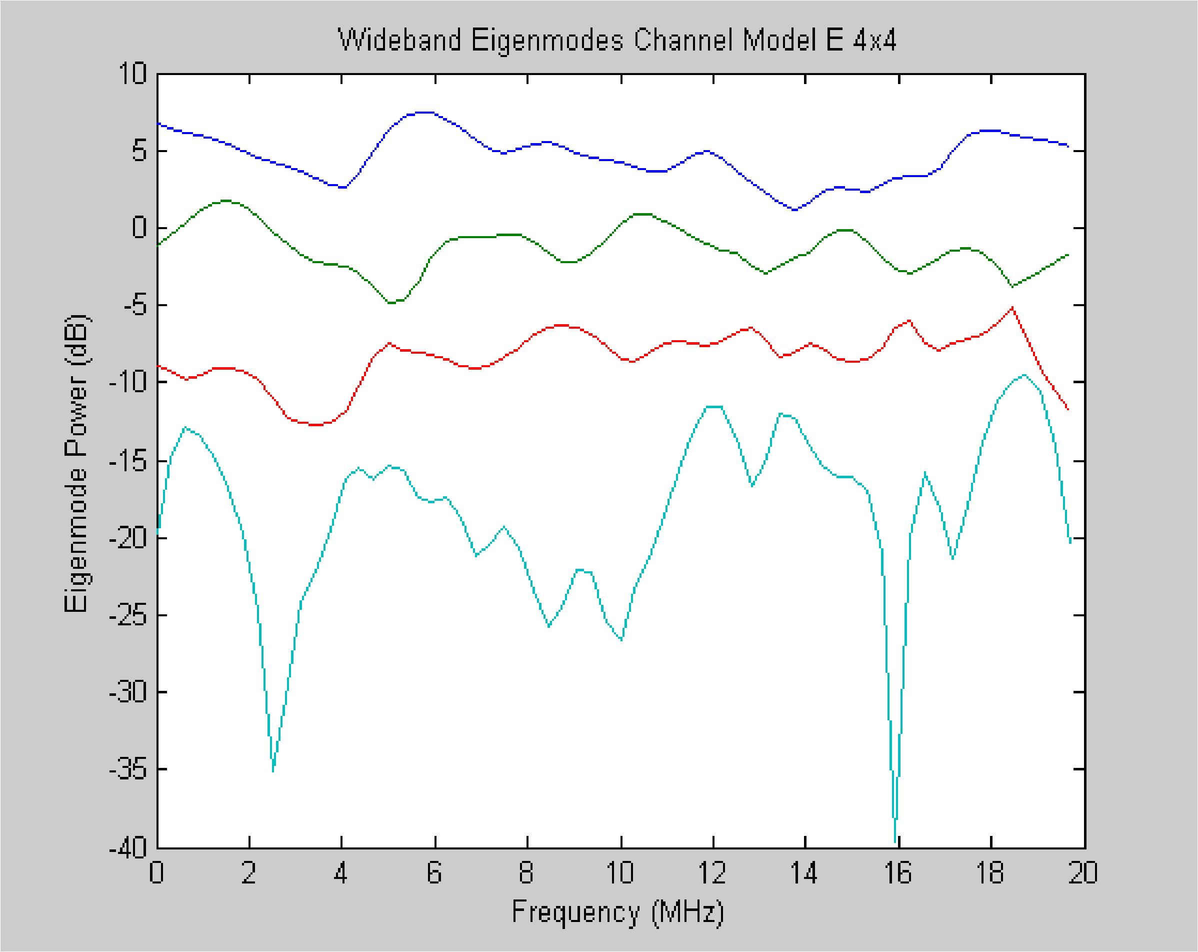
Power is relative to average total receive power at a single antenna

Wideband Eigenmodes TGn Channel B



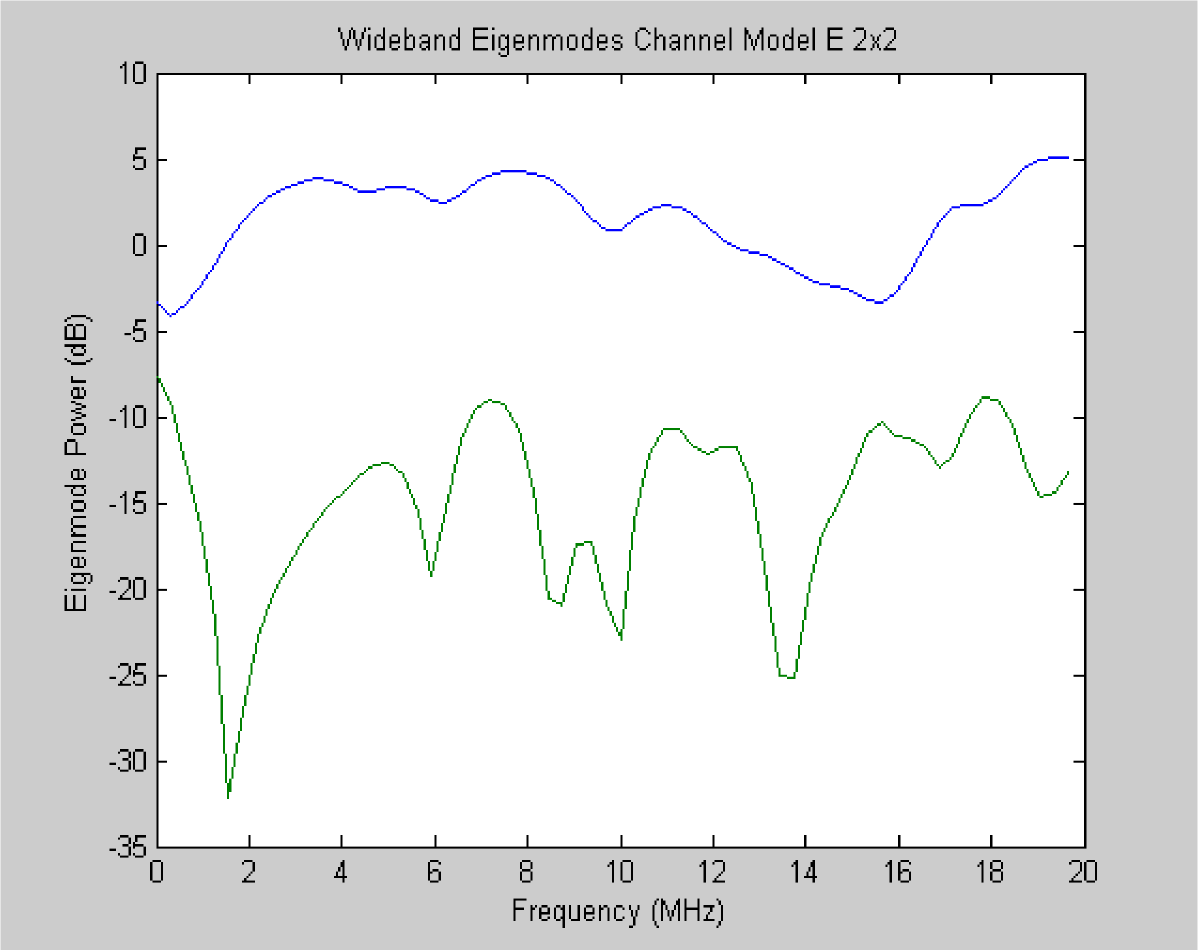
Power is relative to average total receive power at a single antenna

Wideband Eigenmodes TGn Channel E



Power is relative to average total receive power at a single antenna

Wideband Eigenmodes TGn Channel E



Power is relative to average total receive power at a single antenna

PHY Design Details

Spatial Spreading: Partial CSI Spatial Multiplexing

- Transmitter is partially informed
  - No explicit knowledge of channel or channel eigenvectors at Tx
  - Tx has only data rate per wideband spatial channel
- Primary objectives
  - Transmit full power regardless of the number of streams Tx'd
    - Requirement for robust CSMA operation
  - Maximize diversity per transmitted data stream
    - Minimize outage probability → maximize throughput
  - Backwards compatible operation
- Basic Concept
  - Spatial spreading of data with simple unitary matrices
  - Cyclic delay transmission per Tx antenna to introduce additional diversity

Steering for Spatial Spreading

- Tx data vector in OFDM sub-carrier k, $\mathbf{s}(k)$, preconditioned with orthogonal "spreading" matrix, $\mathbf{W}$
  - For Nt = 2 or 4 → $\mathbf{W}$ is Hadamard matrix (real Walsh functions)
  - For Nt = 3 → $\mathbf{W}$ is Fourier matrix (complex-valued Fourier functions)
- Transmit vector is $\mathbf{x}(k) = \mathbf{W}\mathbf{s}(k)$
- Random steering introduces full Tx diversity per stream
  - Each stream is transmitted out all Nt antennas
  - Full Tx power is used, regardless of the number of streams, Ns, transmitted
    - If Ns < Nt, spreading matrix is reduced to Ns columns

Cyclic Delay Transmission

- Each Tx antenna introduces a different cyclic delay shift
  - Creates linear phase shift across OFDM sub-carriers per antenna
  - Each "stream" is subjected to frequency selective fading across the sub-carriers
    - maximizes spatial diversity per Tx stream
  - No phase discontinuities introduced from sub-carrier to sub-carrier
    - minimizes degradation in legacy STAs channel estimation

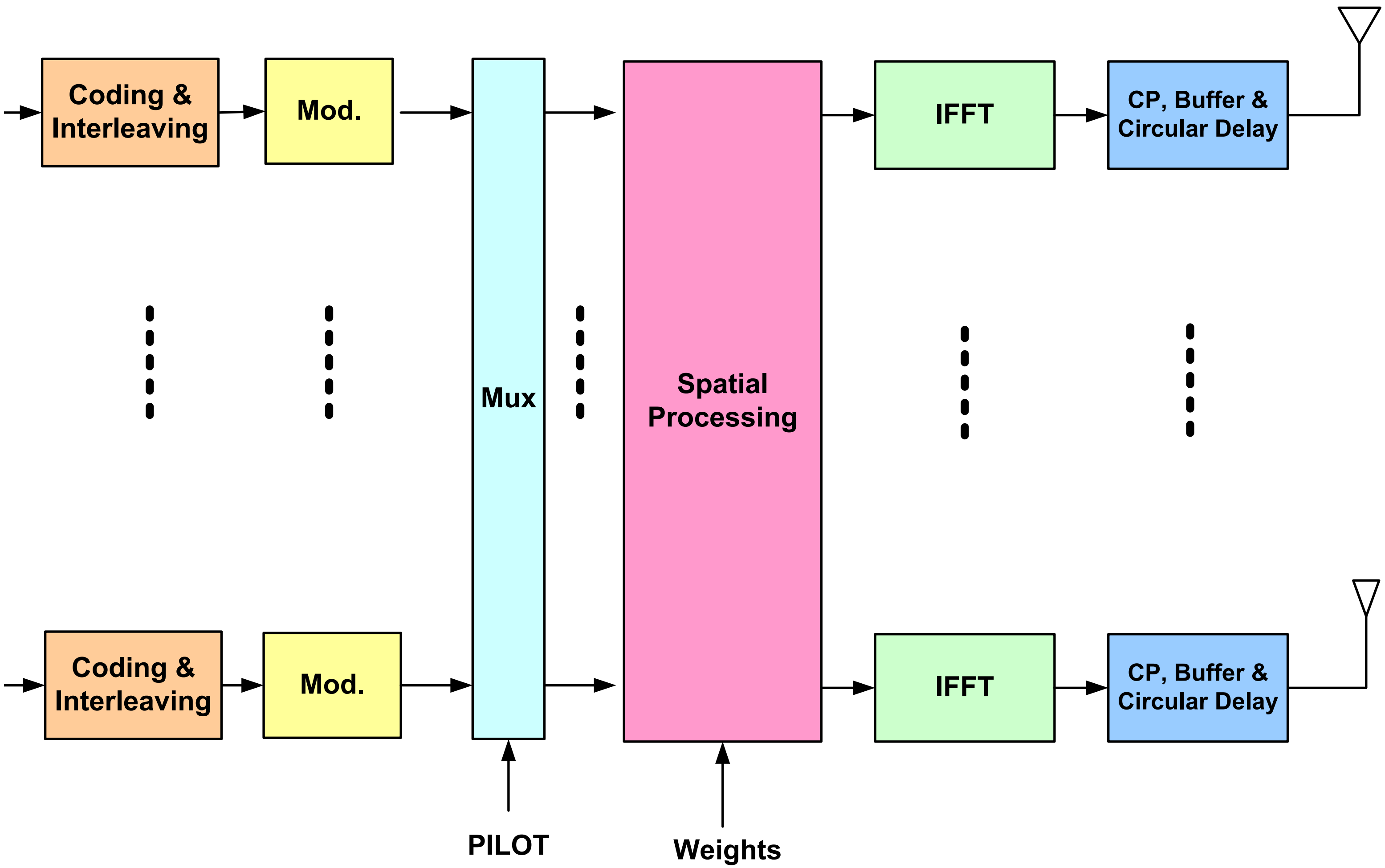
Spatial Spreading + Cyclic Delay

- Random steering matrix, W, is transformed by phase shift matrix

$$\mathbf{C}(k)=\begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & e^{-j2\pi kI/N} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & e^{-j2\pi kI(N-1)/N} \end{bmatrix}$$

  - I is the cyclic shift increment
- Transmit vector is $\mathbf{x}(k)=\mathbf{C}(k)\mathbf{W}\mathbf{s}(k)$
  - Equivalent to cyclic shift of $\mathbf{W}\mathbf{s}(k)$ in time domain

Tx Functional Block Diagram



TDD Reciprocal Channel

- In a TDD MIMO system, the over-the-air portion of the channel is reciprocal
  - The up-link channel, $\mathbf{H}_{A\to B}(\ell)$, (entity A to entity B) is the transpose of the down-link channel, $\mathbf{H}_{B\to A}(\ell)$**,** ($\ell$ is the OFDM sub-carrier index):

$$\mathbf{H}_{A\to B}(\ell) = \mathbf{H}^{t}_{B\to A}(\ell)$$

- Due to gain differences in Tx and Rx chains at both ends of the link, the baseband-to-baseband channel is not reciprocal.
  - The observed channel is weighted by two diagonal matrices with the complex gains of the transmit and receive chains:

$$\tilde{\mathbf{H}}_{B\to A}(k) = \mathbf{C}_{A,Rx}(k)\mathbf{H}_{B\to A}(k)\mathbf{C}_{B,Tx}(k)$$

$$\tilde{\mathbf{H}}_{A\to B}(k) = \mathbf{C}_{B,Rx}(k)\mathbf{H}_{A\to B}(k)\mathbf{C}_{A,Tx}(k)$$

  - These gain differences can be removed with a simple over-the-air calibration procedure that learns the gain matrices $\mathbf{C}_x(k)$
  - Result is a very stable calibrated reciprocal channel

Calibration Procedure

- Find diagonal calibration matrices that can be applied to transmit vectors to compensate for amplitude/phase variations between Rx and Tx chains in device
- Calibration required once per session; i.e., upon association
- Procedure as follows:
- Entity A (typically a STA) observes MIMO pilot from entity B (typically an AP)
  - Entity A forms an estimate of channel, $\hat{\mathbf{H}}_{B\to A}(\ell), -26 \le \ell \le 26$
- Entity A transmits MIMO pilot, which entity B observes
  - Entity B forms channel estimate, $\hat{\mathbf{H}}_{A\to B}(\ell), -26 \le \ell \le 26$
- Entity B transmits $\hat{\mathbf{H}}_{A\to B}(\ell), -26 \le \ell \le 26$ to A
  - Requires transmitting $104 N_A N_B$ 12-bit values
    - 624 B for 2x2; 2496 B for 4x4

Calibration Procedure

- Entity A now has both $\hat{\mathbf{H}}_{A\to B}(\ell)$ and $\hat{\mathbf{H}}_{B\to A}(\ell), -26 \le \ell \le 26$
- Entity A now solves for diagonal calibration matrices $\mathbf{K}_A(\ell)$ and $\mathbf{K}_B(\ell), -26 \le \ell \le 26$ such that $\hat{\mathbf{H}}_{A\to B}(\ell)\mathbf{K}_A(\ell) = \left(\hat{\mathbf{H}}_{B\to A}(\ell)\mathbf{K}_B(\ell)\right)^T$

$$\mathbf{K}_A(\ell) = \mathbf{C}_{A,Tx}(\ell)\left(\mathbf{C}_{A,Rx}^T(\ell)\right)^{-1}$$

- Entity A sends $\mathbf{K}_B(\ell)$ to entity B, then both ends of link have calibration matrix
- Requires transmitting $104N_B$ 12-bit values
  - 624 B for 4 antennas; 312 B for 2 antennas
- Calibration matrices are incorporated into Tx steering vectors.

Wideband Eigenmodes on TDD Reciprocal Channel

- Uplink channel SVD: $\mathbf{H}_u(k) = \mathbf{U}_u(k)\mathbf{D}(k)\mathbf{V}_u^H(k)$
  - Tx steering matrix: $\mathbf{V}_u(k)$
  - Rx matched filter: $\mathbf{M}_u(k) = \mathbf{V}_u^H(k)\mathbf{H}_u^H(k) = \mathbf{D}(k)\mathbf{U}^H(k)$
- Downlink SVD:

  $$\mathbf{H}_d(k) = \mathbf{U}_d(k)\mathbf{D}^t(k)\mathbf{V}_d^H(k) = \mathbf{H}_u^t(k) = \mathbf{V}_u^*(k)\mathbf{D}^t(k)\mathbf{U}_u^t(k)$$

  - $\mathbf{U}_d(k) = \mathbf{V}_u^*(k)$
  - $\mathbf{V}_d(k) = \mathbf{U}_u^*(k)$: downlink Tx steering matrix
- Transmit steering vectors at one end of the link can be computed directly from the receive matched filter at the same end of the link
  - Normalize and conjugate
- Since Tx steering vectors can be obtained directly from Rx matched filter, eigenvectors only need to be computed at one end of the link

Channel estimation for Wideband Eigenmodes

- Two kinds of training sequences:
  - MIMO Training Sequence: orthogonal pilot is transmitted on each antenna allowing the receiver to directly form an estimate of the channel matrix, $\mathbf{H}(k)$, in each OFDM sub-carrier.
    - MIMO OFDM Training Sequence
  - Steered MIMO Training Sequence: orthogonal pilot is transmitted on each eigenmode, allowing the receiver to directly form an estimate of the received matched filter, $\mathbf{M}(k)$ in each OFDM sub-carrier.
    - Steered MIMO OFDM Training Sequence
- Some definitions:
  - $p(k)$: pseudo-random sequence across OFDM tones (unique word)
  - $\mathbf{w}(n)$; $n \in [0, N_{tx}-1]$: vector of length N_{tx} orthogonal sequences (n is index over time)
    - $\mathbf{w}(n)$, $0 \le n \le N_{tx}-1$ are columns of Hadamard matrix for $N_{tx} = 2,4$; or Fourier matrix for $N_{tx} = 3$

Pilot Structure

- Common Pilot:
  - MIMO OFDM Training Sequence sent by AP as part of a control message containing scheduling information
  - Contains 0,2,3,4 MIMO OFDM training symbols
  - Number of training symbols equals number of antennas
  - For single-antenna AP (if allowed), long PLCP preamble serves as training sequence, no MIMO OFDM training sequence required
  - Occurs immediately after PLCP Preamble and Signal field
- Dedicated Pilot:
  - STA sends steered MIMO OFDM Training Sequence as part of header of every PPDU
  - Number of steered MIMO OFDM training symbols = number of antennas
  - For single-antenna station (if allowed), long training sequence serves as dedicated training sequence.

PLCP Preamble	SIGNAL	MIMO Training Sequence	DATA
16 µs	2 short OFDM symbols	0,2,3,or 4 short OFDM symbols	Variable Number of short OFDM Symbols

Channel estimation: MIMO Training Sequence

- MIMO OFDM Training Sequence
- Transmitted waveform is N_{tx} vector OFDM symbols w/orthogonal cover, transformed by cyclic shift matrix:
  - $\mathbf{s}(n,k) = p(k)\mathbf{C}(k)\mathbf{w}(n);\ 0 \le n \le N_{tx};\ 0 \le k \le 51$
- Received waveform is
  - $\mathbf{r}(n,k) = \mathbf{H}(k)\mathbf{s}(n,k) + \mathbf{n}(k) = p(k)\mathbf{H}(k)\mathbf{C}(k)\mathbf{w}(n) + \mathbf{n}(k)$
- Calculate the channel estimate by correlating with orthogonal sequence:
  - $\hat{\mathbf{H}}(k) = \frac{1}{N_{tx}} p(k) \sum_{n=0}^{N_{tx}-1} \mathbf{r}(n,k)\mathbf{w}^H(n)\mathbf{C}^*(k) = \mathbf{H}(k) + \mathbf{N}(k)$

Channel estimation: Steered Training Sequence

- Steered MIMO OFDM Training Sequence
- Transmitted waveform is N_{tx} vector OFDM symbols on eigenmodes w/orthogonal cover and cyclic shift:
  - $\mathbf{s}(n,k) = p(k)\mathbf{C}(k)\mathbf{V}(k)\mathbf{w}(n);\ 0 \le n \le N_{tx};\ 0 \le k \le 51$
- Received waveform is
  - $\mathbf{r}(n,k) = \mathbf{H}(k)\mathbf{s}(n,k) + \mathbf{n}(k) = p(k)\mathbf{H}(k)\mathbf{C}(k)\mathbf{V}(k)\mathbf{w}(n) + \mathbf{n}(k)$
- Calculate the channel estimate by correlating with orthogonal cover and integrating:

$$\mathbf{A}(k) = \frac{1}{N_{tx}} p(k) \sum_{n=0}^{N_{tx}-1} \mathbf{r}(n,k)\mathbf{w}^H(n)\mathbf{C}^*(k) = \mathbf{H}(k)\mathbf{V}(k) + \mathbf{N}(k)$$

- Then the estimated spatial matched filter is

$$\mathbf{M}(k) = \mathbf{A}^H(k)$$

Use of Training Sequences in AP-centric System

- AP transmits MIMO training sequence at the beginning of each SCAP
  - This is in addition to legacy training sequences
- STAs receive MIMO training sequence and compute channel estimate
  - STA computes transmit steering vectors via eigen-analysis or SVD on an as-needed basis, but not more frequently than every 2 msec
  - Up-to-date channel estimate and SVD always available at STA
- When an STA transmits a PPDU, steered MIMO training sequence (aka dedicated Pilot) is included in the preamble
- AP estimates Rx steering from steered MIMO training sequence
  - AP also derives Tx steering vectors from received steered MIMO training sequence
  - SVD calculation at AP not necessary
  - No need for AP to perform SVD for all associated STAs
- When AP transmits a PPDU, includes steered MIMO training sequence
- If AP does not have recent steered MIMO training sequence from STA, reverts to non-eigensteered mode.

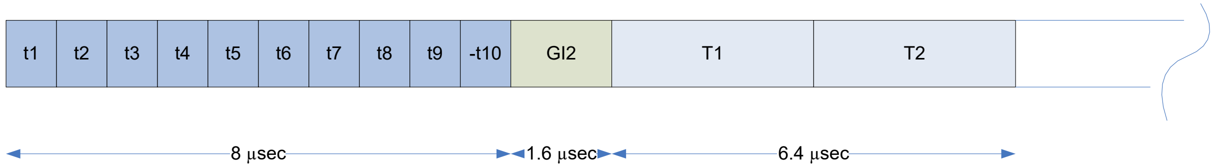
Use of Training Sequences in Peer-to-Peer Mode

- One end of link plays role of AP
  - Sends MIMO training sequence and possibly steered MIMO training sequence
- Other end plays role of STA
  - Sends steered MIMO training sequence only
- Training sequences are included as part of PLCP headers
- Low duty-cycle exchanges revert to non-eigensteered mode

Rate Control

- Rate selection performed based on post-detection SNR per stream
  - Post-detection SNR per stream is unique per sub-carrier
  - Ensemble of SNRs per stream across sub-carriers used to drive rate selection
- Independent coding for each of up to N_{tx} wideband spatial modes
- Code rate (modulation + coding) assigned based on observed SNRs, etc., across wideband spatial mode
  - Single rate across all wideband spatial channels in SS mode.
- Rate decisions communicated via short rate control words
  - (13 bits—differential encoding of rates for each for up to four modes)
  - Transmitted rates indicated via Data Rate Vector (DRV) in SIGNAL field
  - Receiver makes rate selection based on observation of received signal, and communicates result to transmitter at other end of link via DRVF (DRV feedback) in feedback field in data segment

PLCP Preamble



- Standard 802.11a preamble with enhancements
  - Last short preamble symbol is inverted to provide improved timing reference
  - Cyclic delay is applied across Tx antennas
    - Cyclic delay applied to entire 8 μs short preamble
    - Cyclic delay applied to entire 8 μs long preamble
    - Delay increment $T_{cd}=50$ ns

Summary

- MIMO PHY design builds on existing 802.11a,g PHY design
- Two operating modes provide highly robust operation under a wide range of conditions
  - Eigenvector Steering provides best rate/range performance
  - Spatial
- Adaptive rate control through low-overhead rate feedback supports sustained high throughput operation
- Low-overhead training sequence exchange supports high-capacity Eigenvector Steered operation for best rate/range performance
- Spatial Spreading operation provides robust high throughput operation when Tx does not have sufficiently accurate channel state information