MIMO Techniques in the IEEE 802.11n Standard

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Overview

1. Overview 802.11 Standard
2. Wireless Channel
3. OFDM
4. BICM
5. Diversity
6. MIMO
7. Antenna Selection
8. Beamforming
9. Space-Time Block Coding
10. Spatial Multiplexing

IEEE 802.11a/b/g

In brief

The 802.11a/b/g family of standards addresses packet-based point-to-point communications in a wireless local area network with maximum PHY data rate of 54Mbps. They provide connectivity in the range of 10-50m on 20MHz channels.

- 802.11
  - Spread-spectrum
  - DBPSK (1Mbps) and DQPSK (2Mbps)
  - 2.4 GHz ISM band
- 802.11a
  - OFDM
  - BPSK, QPSK, 16QAM, 64QAM
  - Convolutional coding (CR 1/2,2/3,3/4)
  - 6/9/12/18/24/36/48/52Mbps
  - 52 sub-carriers (48 data, 4 pilot)
  - Symbol length 4us (3.2us + 0.8us GI)
  - 2.4 GHz ISM band

IEEE 802.11a/b/g (ctd')

- 802.11b
  - Spread-spectrum
  - CCK
  - 5.5Mbps and 11Mbps
  - 2.4 GHz ISM band
- 802.11g
  - Extension to 5GHz band
  - Comprises 11&a&b

IEEE 802.11n

In brief

The 802.11n standard is an amendement addressing enhancements for high-throughput transmissions up to 600Mbps. It provides connectivity in an increased range of up to 100m over 20MHz and 40MHz channels.

- Key features
  - Backwards compatibility to 802.11a/g
  - OFDM
  - BPSK, QPSK, 16QAM, 64QAM
  - Convolutional coding (CR 1/2,2/3,3/4,5/6)
  - Up to 4 independent streams
  - 77 MCS values (combinations of modulation and coding)
  - 20MHz: 54 sub-carriers (52 data, 4 pilot) - 64 point FFT
  - 40MHz: 114 sub-carriers (108 data, 6 pilot) - 128 point FFT
  - Symbol length 4us (3.2us + 0.8us GI) or 3.6us (3.2us + 0.4us GI)

IEEE 802.11n (ctd')

- PHY high-throughput enabling features
  - Higher bandwidth 40MHz
  - Improved spectral exploitation (factor 2.25 over 20MHz in 11a)
  - Additional coding rate 5/6
  - Short GI of only 0.4us (11% increase)
  - Support of fast link adaptation by protocol (+HTC field)
  - Greenfield mode
- PHY range increasing features
  - Space-time block codes (STBC)
  - Beamforming
  - Fast link adaptation
- Further PHY features
  - Antenna selection
  - Low Density Parity Check (LDPC) codes

IEEE 802.11n (ctd')

- MAC efficiency increasing features
  - Aggregation of packets (header is sent only ones for several consecutive packets)
  - Short inter-frame spacing (IFS)
- MAC efficiency
  - 70-80%
- Most "fancy" features that allow for HT are optional and not mandatory to be compliant to 802.11n!

Minimal mandatory requirement

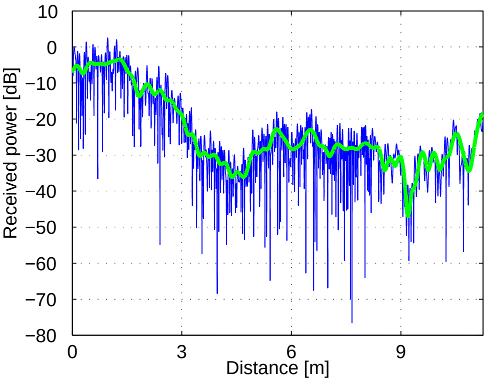
- 20MHz
- Convolutional coding supporting all rates
- MCS 0-7 (1 spatial stream)
- GI 0.8us

Wireless Channel

Example

Instanteanous reception power at 2GHz.

- Large scale fading
  - Path loss
  - Shadowing
  - Under control
- Small scale fading
  - Scattering



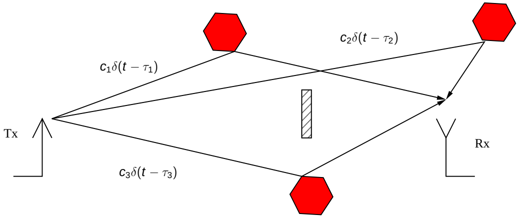
Wireless Channel (ctd')

- Scatterers have complex amplitude c_i and delay τ_i

$$h(t) = \sum_{\ell}^{L'-1} c_\ell \delta(t - \tau_\ell).$$

- Contributions with $\tau_i \approx \tau_j$ add up and are perceived as one single contribution. This can be viewed as scatterers lying on the same ellipsoid. Reduction to L effective taps.
- The envelope of the superposed individual scatterers at an effective tap is Rayleigh-distributed (central limit theorem)

$$f_{\text{Rayleigh}}(p) = \frac{p}{\sigma_p^2} \exp\left(-\frac{p^2}{2\sigma_p^2}\right) \quad \text{for} \quad p \geq 0.$$



Orthogonal Freq. Division Multiplexing (OFDM)

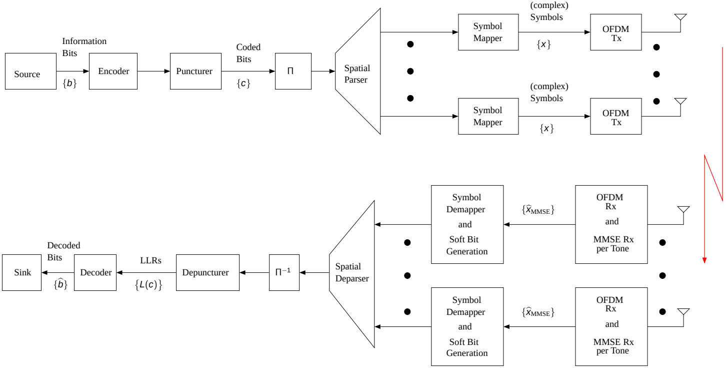
- Information is modulated onto non-interfering sub-carriers in the frequency domain and then transformed into the time-domain via an N-IFFT

$$\tilde{\boldsymbol{x}} = \boldsymbol{F}^{\mathrm{H}} \boldsymbol{x}$$

  To the beginning of the time signal $\tilde{\boldsymbol{x}}$ a cyclic prefix (CP) is added, i.e., a repetition of the last part of the signal. This CP must be longer than the expected maximum delay spread. In that case, during FFT in the receiver, the integration periods cover integer periods of the sinusoidal signals and hence remains interference-free.
- Each sub-carrier is flat-fading for itself.
- The whole transceiver processing is done sub-carrier wise. This is allows for “simpler” processing than in the time-domain.
- Frequency diversity is attained by coding over independently faded subcarriers. The coding problem is identical to that for temporal diversity.

Bit Interleaved Coded Modulation (BICM)

- [Zehavi 1992] and [Caire et al. 1998]
- Separate coding and modulation. Apply interleaving on bit level and use Gray mapping.
- In fading channels this scheme provides gains over coded modulation schemes! Does not hold in AWGN.



Multiple Input Multiple Output (MIMO)

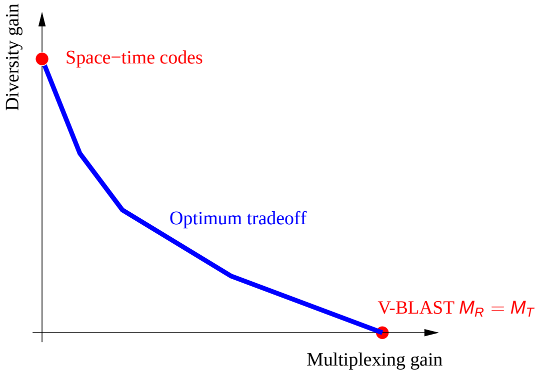
Problem

MIMO means different things to different people!

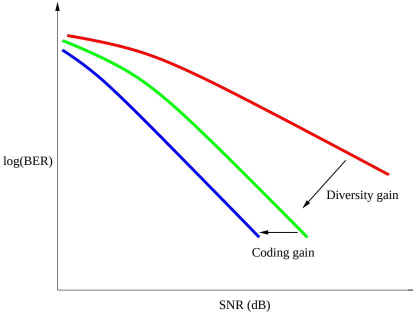
- So, what MIMO can mean:
  - SIMO – Rx diversity
  - MISO – Beamforming, Tx diversity
  - MIMO – Comprises both above and spatial multiplexing
- Improvements associated to MIMO
  - Array gain – more antennas increase receive power
  - Multiplexing gain – several parallel spatial channels allow for higher spectral efficiency
  - Diversity gain – more antennas improve diversity
  - Interference mitigation – spatial suppression

Tradeoff

The MIMO gains can not all be exploited at the same time. There is a fundamental multiplexing-diversity trade-off. [Zheng & Tse 2003]



Diversity



- Definition

$$D \triangleq -\lim_{\mathrm{SNR}\to\infty} \frac{\log P_e(\mathrm{SNR})}{\log \mathrm{SNR}}$$

$$P_e(\mathrm{SNR}) = \mathrm{c} \times \mathrm{SNR}^{-\mathrm{D}}$$

- c is determined by the coding gain
- D is determined by the diversity
- The practically important region is the low SNR regime. It can happen that coding is more important there.

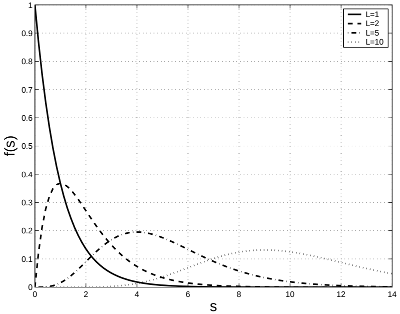
Maximum Ratio Combining (MRC)

Combination of L independent sources at a reception point

$$x = \sum_{l=1}^{L} |h_l|^2 x_l \Big/ \sum_{k=1}^{L} |h_k|^2$$

The variable $|x|^2$ is Chi-square distributed with 2L degrees of freedom

$$f_\chi(s) = \frac{s^{L-1}}{(\sigma_{h,l}^2)^L (L-1)!} \exp\left(-\frac{s}{\sigma_{h,l}^2}\right) \quad \text{for} \quad s \geq 0$$

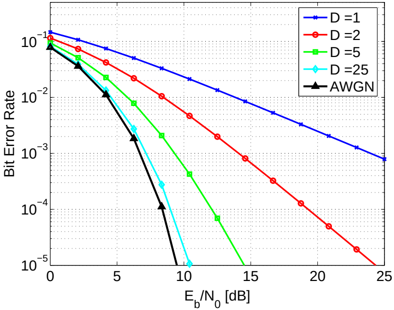


Maximum Ratio Combining (ctd')

- BER for BPSK over L i.i.d. Rayleigh channels

$$\mathrm{BER} = \left(\frac{1-\mu}{2}\right)^L \sum_{i=0}^{L-1} \binom{L-1+i}{i} \left(\frac{1+\mu}{2}\right)^i$$

with $\mu = \sqrt{\gamma/(1+\gamma)}$ and SNR $\gamma = \sigma_h^2/\sigma_v^2$



- $L = 1$: worst performance
- $L \to \infty$: best performance (AWGN)

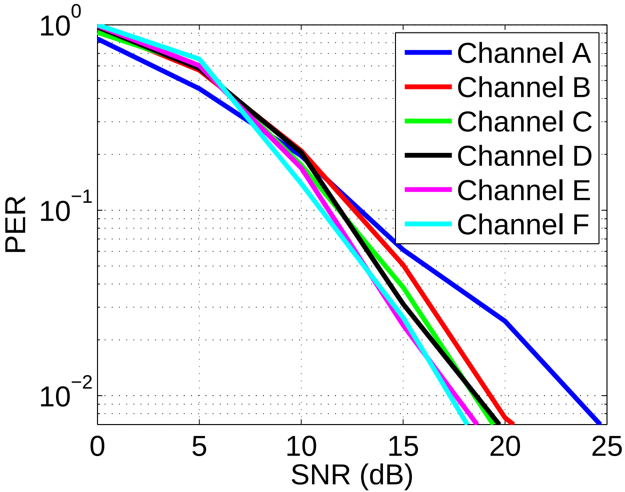
IEEE Channel Models

- The WLAN MIMO channel models are defined in [Erceg et al. 2004].
- Features
  - Cluster based
  - 10ns temporal tap spacing
  - Include antenna spacing – correlation considered
  - Scatterers move at 1.2kmph
  - Power-delay-profile (PDP) modelled as exponentially decaying function

Model	rms delay spread	No. of clusters	No. of taps	Scenario
A	0ns	N/A	1	Flat fading
B	15ns	2	9	Residential
C	30ns	2	14	Small office
D	50ns	3	18	Typical office
E	100ns	4	18	Large office
F	150ns	6	18	Large space

IEEE Channel Models (ctd')

- BPSK modulation
- Packetlength=100Bytes



Diversity Combining

Channel provides N independent paths with SNR γ_n

- Maximum Ratio Combining (MRC) - choose N of N paths

$$\gamma_{\mathrm{MRC}} = \sum_{\ell=0}^{N-1} \gamma_\ell$$

- Selection Combining (SC) - choose the strongest of N paths

$$\gamma_{\mathrm{SC}} = \operatorname*{argmax}_i \gamma_i$$

- Hybrid selection/maximum ratio combining (H-S/MRC) - choose L strongest of N. Assume $\gamma_0 > \ldots > \gamma_{N-1} > 0$

$$\gamma_{\mathrm{H-S/MRC}} = \sum_{\ell=0}^{L-1} \gamma_\ell$$

Antenna Selection

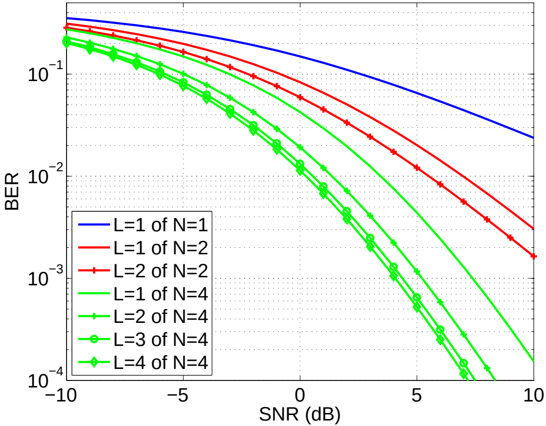
- Aims at using only L out of N available Tx or Rx antennas in a station.
- This considerably reduces power consumption since RF paths can be switched off.
- Further, the complexity of algorithms is lowered to the reduced dimension.
- 802.11n supports selection by protocol of up to 8 antennas.
- A good overview is given in [Molisch & Win 2004].

The resulting SEP with MPSK modulation in case of L out of N receive antennas is given as [Win & Winters 2001]

$$\mathrm{SEP} = \frac{1}{\pi} \int_0^{\theta} \left[\frac{\sin^2(\theta)}{c\Gamma + \sin^2(\theta)} \right] \prod_{n=L+1}^{N} \left[\frac{\sin^2(\theta)}{c\Gamma \frac{L}{n} + \sin^2(\theta)} \right] d\theta$$

with $\Theta = \pi(M-1)/M$, $c = \sin^2(\pi/M)$, and Γ denoting the SNR.

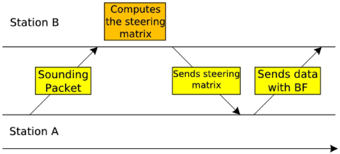
Antenna Selection (ctd')



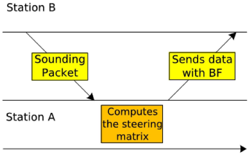
- BPSK modulation
- H-S/MRC – chose L strongest of N_{Rx} i.i.d. paths
- Antenna selection preserves diversity!

Beamforming

- Explicit Beamforming
  - No calibration required
  - Degrades throughput
  - Receiver must be able to feedback steering matrix or CSI
  - Channel should not change too much



- Implicit Beamforming
  - Exploits channel reciprocity
  - Does not degrade throughput
  - Calibration required
  - Receiver must be able to send sounding packet



Beamforming (ctd')

- Direct transmission model

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{s} + \boldsymbol{n}$$

  - $\boldsymbol{y} \in \mathbb{C}^{N_{Rx} \times 1}$ ... received vector
  - $\boldsymbol{H} \in \mathbb{C}^{N_{Rx} \times N_{Tx}}$ ... MIMO channel with Rayleigh distributed entries
  - $\boldsymbol{s} \in \mathbb{C}^{N_{Tx} \times 1}$ ... signal vector with BPSK, QPSK, 16QAM, 64QAM values
  - $\boldsymbol{n} \in \mathbb{C}^{N_{Rx} \times 1}$ ... noise vector $\mathcal{CN}(0, \sigma_n^2 \boldsymbol{I})$

- Computation of steering matrix is based on singular value decomposition (SVD) of the MIMO channel

$$\boldsymbol{H} = \boldsymbol{U}\boldsymbol{\Sigma}\boldsymbol{V}^{\mathrm{H}}$$

  - $\boldsymbol{U} \in \mathbb{C}^{N_{Rx} \times N_{Rx}}$ ... unitary matrix, i.e., $\boldsymbol{U}\boldsymbol{U}^{\mathrm{H}} = \boldsymbol{U}^{\mathrm{H}}\boldsymbol{U} = \boldsymbol{I}$
  - $\boldsymbol{V} \in \mathbb{C}^{N_{Tx} \times N_{Tx}}$ ... unitary matrix
  - $\boldsymbol{\Sigma} \in \mathbb{C}^{N_{Rx} \times N_{Tx}}$ ... diagonal, with real entries in descending order, representing the singular values.

Beamforming (ctd')

- Apply beamforming matrix $\boldsymbol{V}$ prior to transmission

$$\boldsymbol{y}_{BF} = \boldsymbol{H}\underbrace{\boldsymbol{V}\boldsymbol{s}}_{\boldsymbol{s}_{BF}} + \boldsymbol{n}$$

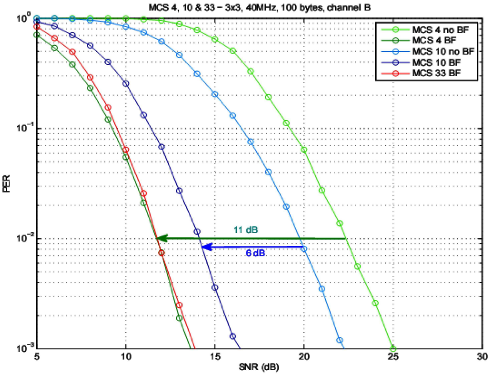
$$\boldsymbol{y}_{BF} = \underbrace{\boldsymbol{U}\boldsymbol{\Sigma}}_{\boldsymbol{H}_{BF}}\underbrace{\boldsymbol{V}^{\mathrm{H}}\boldsymbol{V}}_{\boldsymbol{I}}\boldsymbol{s} + \boldsymbol{n}$$

The receiver estimates $\boldsymbol{H}_{BF}$. If it is applied in a simple zero-forcing manner to the received vector we obain

$$\begin{aligned}\left(\boldsymbol{H}_{BF}^{\mathrm{H}}\boldsymbol{H}_{BF}\right)^{-1}\boldsymbol{H}_{BF}^{\mathrm{H}}\boldsymbol{y}_{BF} &= \left(\boldsymbol{\Sigma}^{\mathrm{T}}\underbrace{\boldsymbol{U}^{\mathrm{H}}\boldsymbol{U}}_{\boldsymbol{I}}\boldsymbol{\Sigma}\right)^{-1}\boldsymbol{\Sigma}^{\mathrm{T}}\boldsymbol{U}^{\mathrm{H}}\boldsymbol{y}_{BF} \\ &= \left(\boldsymbol{\Sigma}^{\mathrm{T}}\boldsymbol{\Sigma}\right)^{-1}\boldsymbol{\Sigma}^{\mathrm{T}}\underbrace{\boldsymbol{U}^{\mathrm{H}}\boldsymbol{U}}_{\boldsymbol{I}}\boldsymbol{\Sigma}\boldsymbol{s} + \boldsymbol{n}'.\end{aligned}$$

- Hence, for $N_{Tx} = N_{Rx} = N$, the beamforming transforms the MIMO channel into N separate streams. The SNR of each stream is proportional to its squared singular value.
- Applying unequal modulation formats on the different streams can improve PER performance!

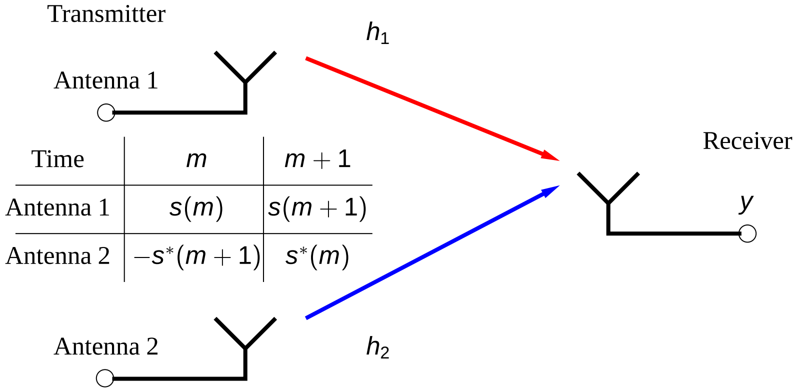
Beamforming (ctd')



- MCS 4: 16QAM, 81Mbps
- MCS 10: QPSK, QPSK, 81Mbps
- MCS 33: 16QAM, QPSK, 81Mbps

Space-Time Block Codes (STBC)

- Transmit diversity
- “Alamouti” scheme [Alamouti 98]



Time	m	$m+1$
Antenna 1	$s(m)$	$s(m+1)$
Antenna 2	$-s^*(m+1)$	$s^*(m)$

Space-Time Block Codes (ctd')

Observation

$$\begin{pmatrix} y(m) \\ y(m+1) \end{pmatrix} = \begin{pmatrix} s(m) & -s^*(m+1) \\ s(m+1) & s^*(m) \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} + \begin{pmatrix} n(m) \\ n(m+1) \end{pmatrix}$$

Taking the conjugate of the first line results in

$$\begin{pmatrix} y^*(m) \\ y(m+1) \end{pmatrix} = \begin{pmatrix} h_1^* & -h_2^* \\ h_2 & h_1 \end{pmatrix} \begin{pmatrix} s_1^*(m) \\ s(m+1) \end{pmatrix} + \begin{pmatrix} n^*(m) \\ n(m+1) \end{pmatrix}$$

Equivalenty, in matrix formulation

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{s} + \boldsymbol{n}.$$

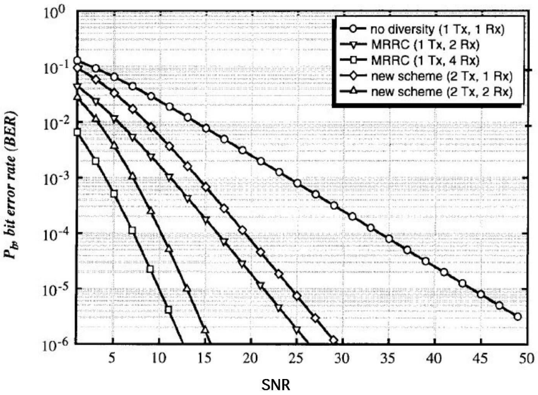
Further, we observe

$$\boldsymbol{H}^{\mathrm{H}}\boldsymbol{H} = \gamma \boldsymbol{I}$$

with $\gamma = |h_1|^2 + |h_2|^2$. Due to the orthogonal structure of the effective channel $\boldsymbol{H}$ the symbols can be obtained by zero-forcing as

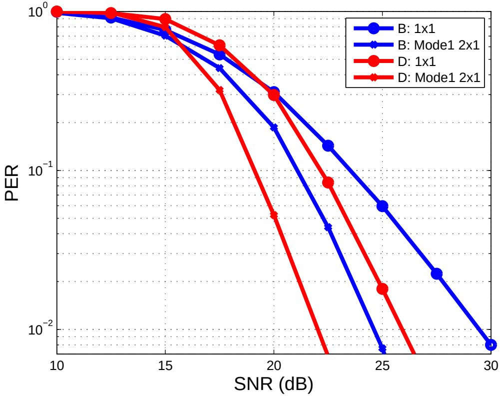
$$\hat{\boldsymbol{s}} = \frac{1}{\gamma}\boldsymbol{H}^{\mathrm{H}}\boldsymbol{y}.$$

Space-Time Block Codes (ctd')



- Gain is in the order of 10 dB BER=10^{-3}!
- Increase in range.
- Rate 1. Rate is not increased!

Space-Time Block Codes (ctd')



- IEEE channel B (rms delay spread 15ns, 9 taps)
- IEEE channel D (rms delay spread 50ns, 18 taps)
- Packetlength=1046bytes, MCS=4 (16QAM, CR=3/4), 40MHz

Space-Time Block Codes (ctd')

- STBC useful for
  - Channels with low diversity
  - Good for client devices that are limited in size and power
  - Increased range
- STBC modes in 11n
  - Mode 1: 2 STS streams, 1 ind. stream (Alamouti)
  - Mode 2: 3 STS streams, 2 ind. streams
  - Mode 3: 4 STS streams, 2 ind. streams
  - Mode 4: 4 STS streams, 3 ind. streams
- Modes 2–4 are hybrid VBLAST-Almouti schemes.
- Modes 2&4 have non-orthongal effective channels and hence, can only be fully recovered by non-linear schemes, e.g., layer decoding by successive cancellation.

Multiplexing

Objective

Maximize throughput by transmitting independent data streams over all N_{Tx} transmit antennas.

- Model

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{s} + \boldsymbol{n}$$

- Linear receivers

$$\hat{\boldsymbol{s}} = \boldsymbol{f}\boldsymbol{y}$$

  - Zero-forcer

$$\boldsymbol{f} = \left(\boldsymbol{H}^{\mathrm{H}}\boldsymbol{H}\right)^{-1}\boldsymbol{H}^{\mathrm{H}}$$

  - MMSE

$$\boldsymbol{f} = \left(\boldsymbol{H}^{\mathrm{H}}\boldsymbol{H} + \sigma_n^2\boldsymbol{I}\right)^{-1}\boldsymbol{H}^{\mathrm{H}}$$

  - Number of receive antennas must be at least the number of transmit antennas.
  - Increased robustness through additional receive antennas.
  - Suffer from ill-conditioned channel matrices $\boldsymbol{H}$.
  - Performance can degrade severly.

Multiplexing (ctd')

- Non-linear receivers
  - Maximum likelihood detector (ML) – hard output

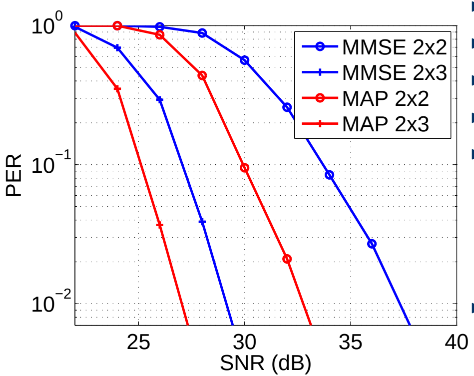
$$\hat{\mathbf{s}} = \underset{\mathbf{b}}{\operatorname{argmin}} ||\mathbf{y} - \mathbf{Hb}||^2$$

    Example – Let us consider $N_{Tx} = 2$. The number of candidate vectors grows exponentially to the cardinality of the modulation symbol set.

    - BPSK: $2^2 = 4$
    - QPSK: $4^2 = 2^4 = 16$
    - 16QAM: $16^2 = 2^8 = 256$
    - 64QAM: $64^2 = 2^{12} = 4096$

    Decoding for $N_{Tx} = 3, 4$ becomes prohibitive.
  - Sphere decoder
    - Proposes an efficient way to restrict search only to a subset of candidate vectors.
  - MAP detector – soft output
    - Leads to improved performance by 2dB since information to convolutional channel decoder is “soft”.
  - Successive cancellation
    - Decode first stream with highest SNR.
    - Substract decided stream from observation.
    - Decode second strongest stream . . .

Multiplexing (ctd')



- IEEE channel D
- 40MHz
- MCS 15
- Packetsize=1000Bytes
- In order to achieve a PER of 1%, the 2x2 system with linear MMSE requires an SNR that is higher than the typical limit of 35dB.
- An additional receive antenna improves diversity.

Summary

- IEEE 802.11n incorporates many advanced communication concepts like
  - Spatial multiplexing
  - STBC
  - Beamforming
  - Antenna selection
  - LDPC coding
- Only a small set of all defined features is mandatory.
- Whether a feature is implemented is a question of gain vs. implementation complexity!
- Efficient implementations, small in gate-count size with small power dissipation are the challenge!
- The market will be interesting!

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