Fast Link Adaptation for IEEE 802.11n

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Agenda

1 IEEE 802.11n WLAN Overview and Background

2 IEEE Channel Models

3 Link Adaptation for IEEE 802.11n

4 Accuracy, Search and Bounds

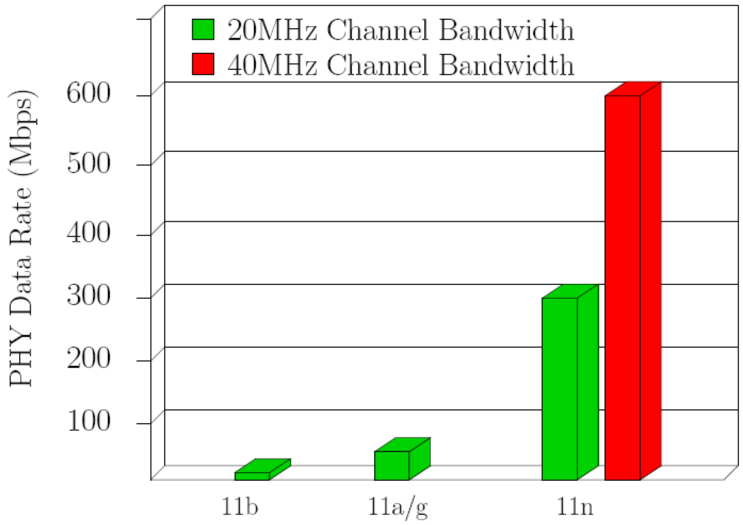
5 Results

6 Conclusions

Overview IEEE 802.11n

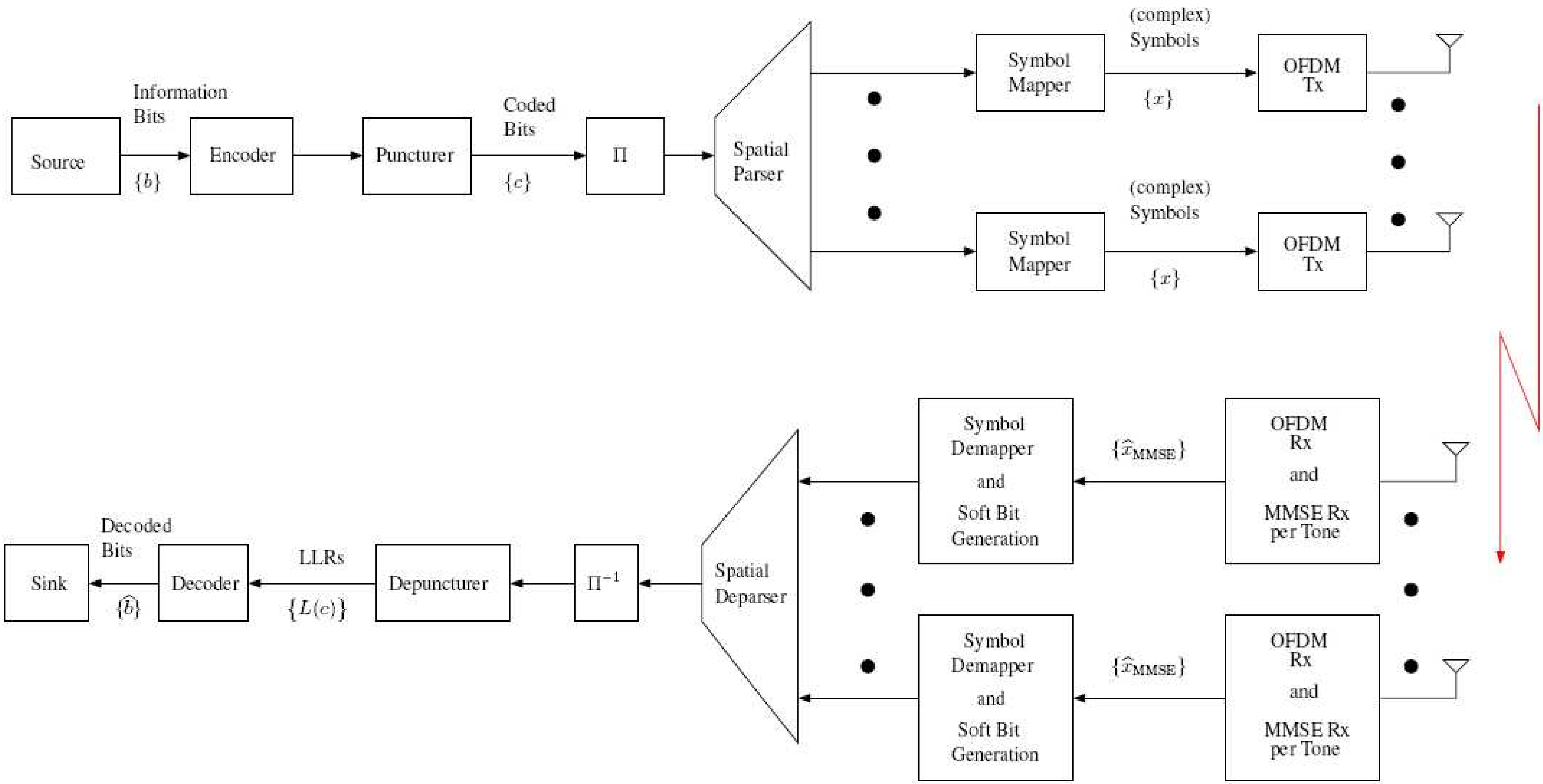
- **IEEE 802.11n**
  - **Multiple input multiple output (MIMO)**
  - **Orthogonal frequency division multiplexing (OFDM)**
  - **Bit interleaved coded modulation (BICM)**
- **Objectives**
  - **Support applications requiring high data rates like multiple high definition TV channels streaming**
  - **Enhance the range**
  - **Keep backward compatibility with IEEE 802.11a/b/g (legacy devices)**
- **MAC features**
  - **Frame aggregation**
  - **SIFS**
- **PHY features**
  - **6 - 600 Mbps in 2.4 & 5 GHz bands**
  - **Channel BW**
    - **20 MHz (mandatory): 52 Data SCs & 4 Pilot SCs**
    - **40 MHz (optional): 108 Data SCs & 6 Pilot SCs**
  - **Modulation: BPSK, QPSK, 16QAM & 64QAM**
  - **Code Rates: 1/2, 2/3, 3/4 & 5/6**
  - **Spatial streams: 1 - 4**
  - **Convolutional code: generator $(133,171)_8$**
  - **Optional link adaptation, beamforming, LDPC, antenna selection, etc**

MCS



Block Diagram of the System Model

- **System model of IEEE 802.11n standard based on MIMO BICM-OFDM**



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IEEE Channel Models [TGn Channel 2004]

Channel Models	K-factor for LOS/NLOS	RMS Delay Spread (ns)	Number of Clusters	Number of Taps	Modelled Environment
A	0 / -∞	0	N/A	1	Flat fading (no multipath)
B	0 / -∞	15	2	9	Residential
C	0 / -∞	30	2	14	Residential / Small Office
D	3 / -∞	50	3	18	Typical Office
E	6 / -∞	100	4	18	Large Office
F	6 / -∞	150	6	18	Large Space (indoors / outdoors)

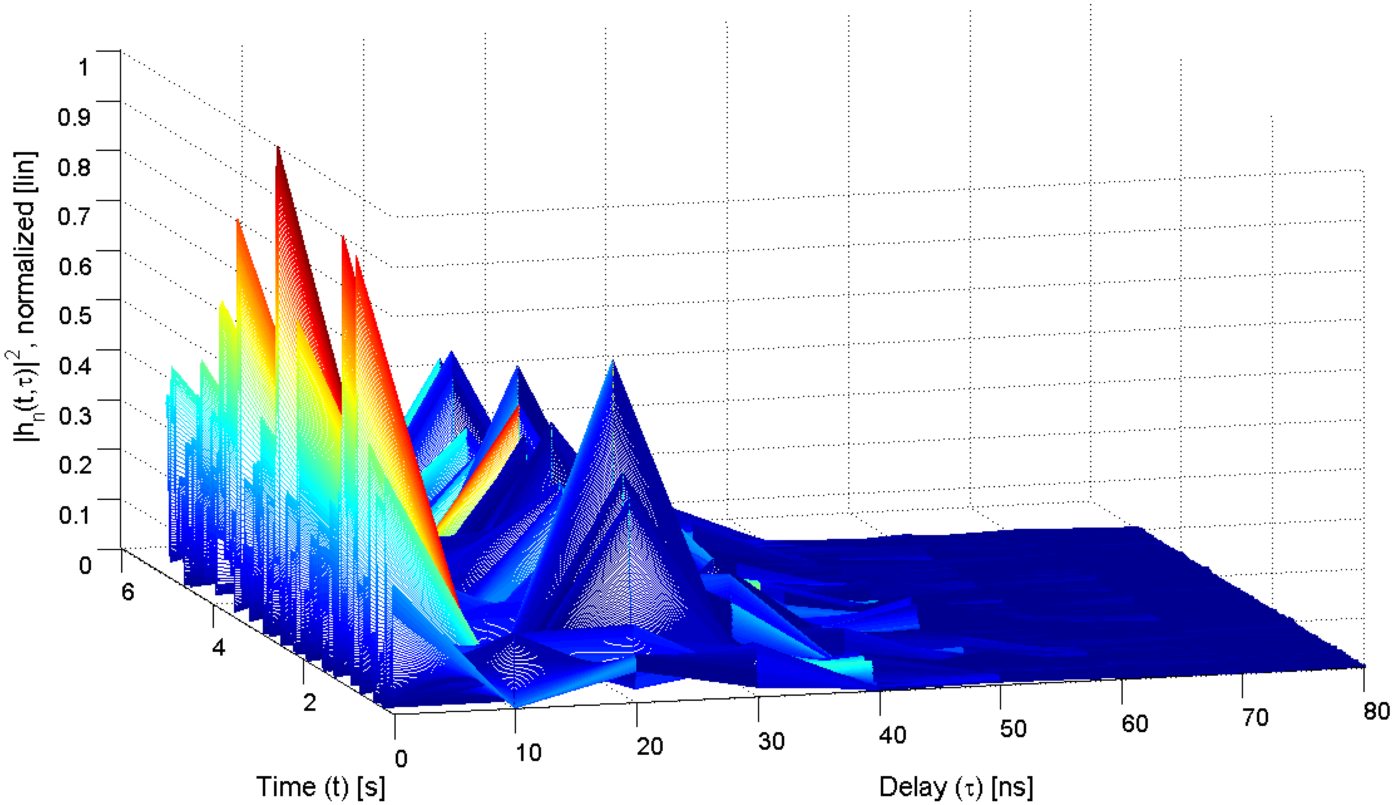
- **IEEE channel models are slow time varying channels.**
- **Only scatterers are moving with velocity of 1.2 km/h.**
- **No explicit relative velocity between Tx and Rx.**
- **IEEE channels are modelled by cluster modelling approach.**

Channel Model B: Power Delay Profile

	Tap index	1	2	3	4	5	6	7	8	9
	Excess delay [ns]	0	10	20	30	40	50	60	70	80
Cluster 1	Power [dB]	0	-5.4	-10.8	-16.2	-21.7				
AoA	AoA [°]	4.3	4.3	4.3	4.3	4.3				
AS (receiver)	AS [°]	14.4	14.4	14.4	14.4	14.4				
AoD	AoD [°]	225.1	225.1	225.1	225.1	225.1				
AS (transmitter)	AS [°]	14.4	14.4	14.4	14.4	14.4				
Cluster 2	Power [dB]			-3.2	-6.3	-9.4	-12.5	-15.6	-18.7	-21.8
AoA	AoA [°]			118.4	118.4	118.4	118.4	118.4	118.4	118.4
AS	AS [°]			25.2	25.2	25.2	25.2	25.2	25.2	25.2
AoD	AoD [°]			106.5	106.5	106.5	106.5	106.5	106.5	106.5
AS	AS [°]			25.4	25.4	25.4	25.4	25.4	25.4	25.4

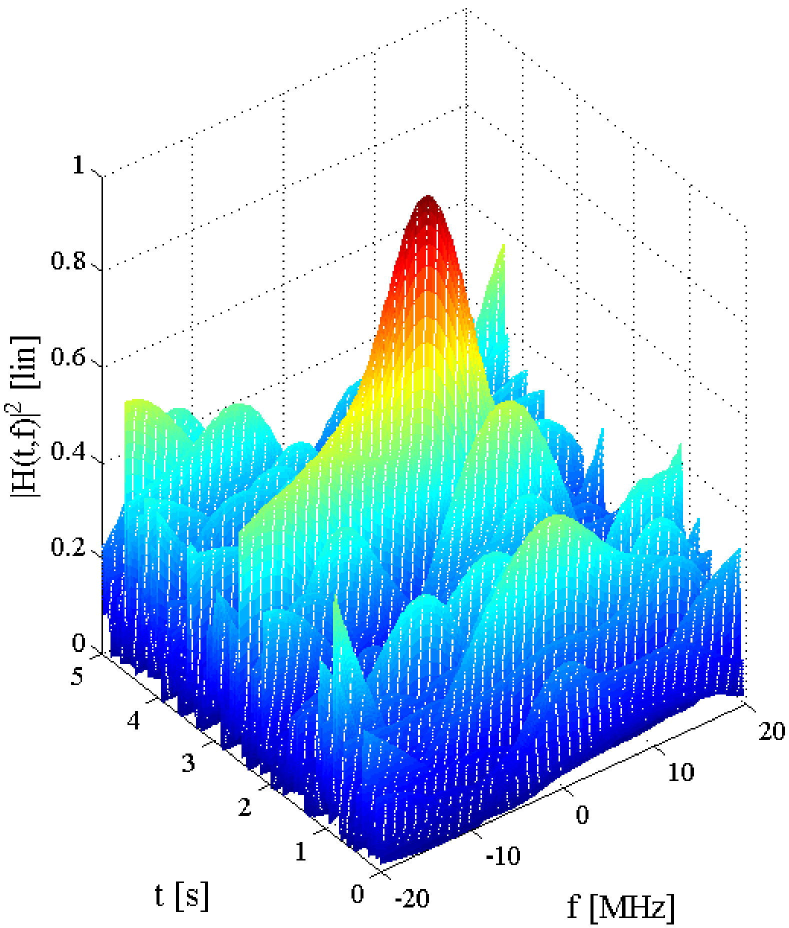
- **PDP can be modeled as an exponential decaying function.**
- **Each cluster is caused by a specific group of scatterers and denotes modeling of independent propagation paths.**
- **Multipath in a cluster arrive at the Rx from the same general direction.**

Channel Model B: Time-Variant Response

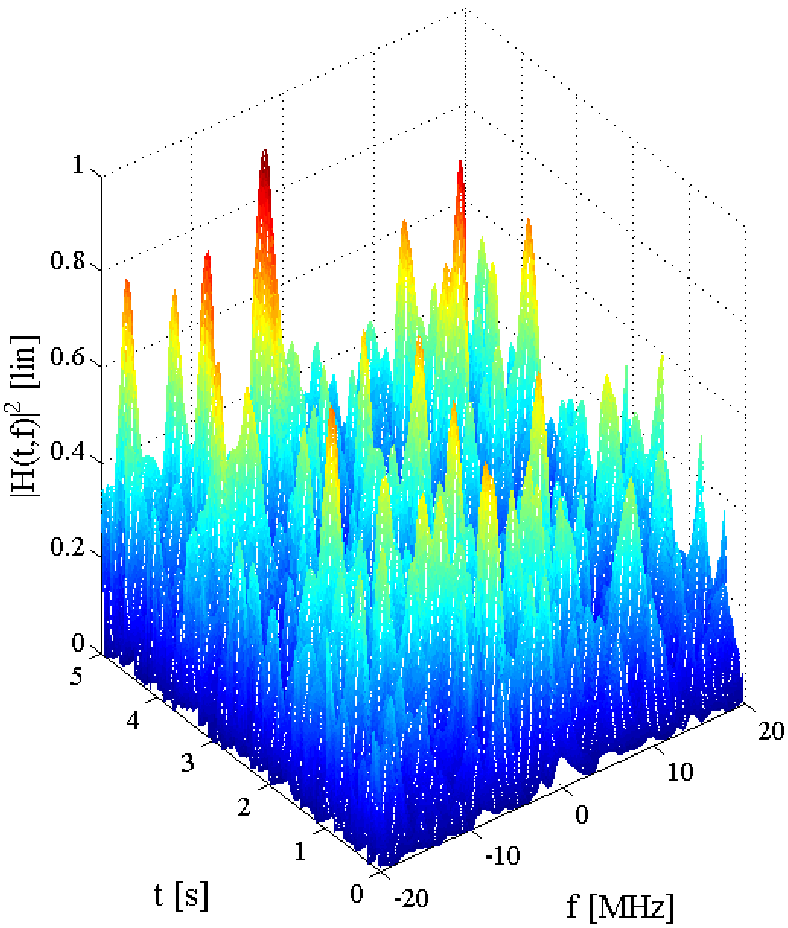


- **We can see two clusters**
  - **First cluster starts from 1st tap (delay 0 ns)**
  - **Second cluster starts from 3rd tap (delay 20 ns)**

Time Variant Transfer Function

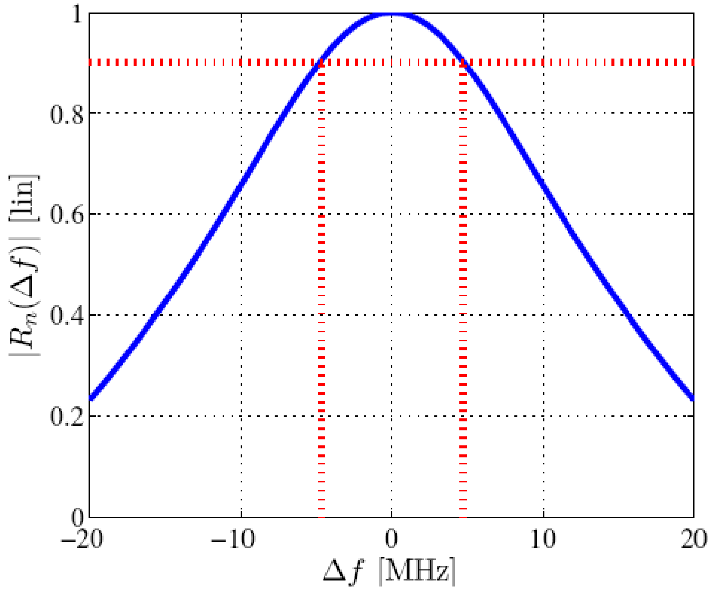


Channel Model B

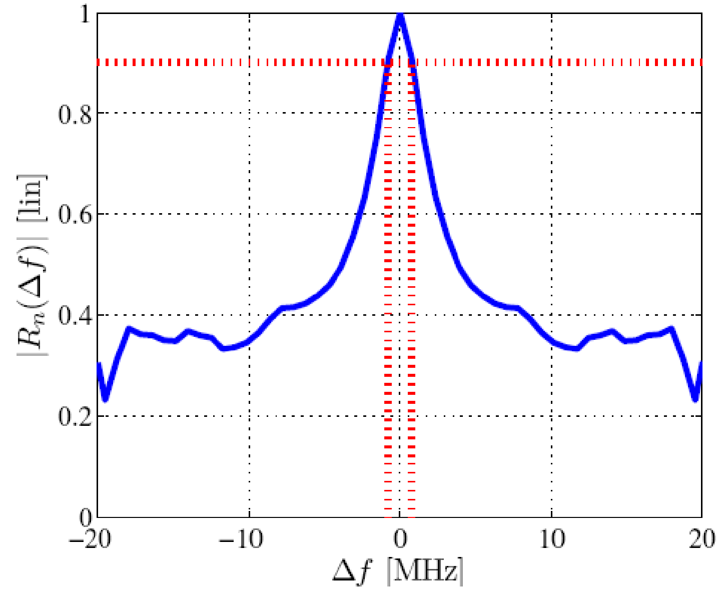


Channel Model E

Coherence Bandwidth



Channel Model B

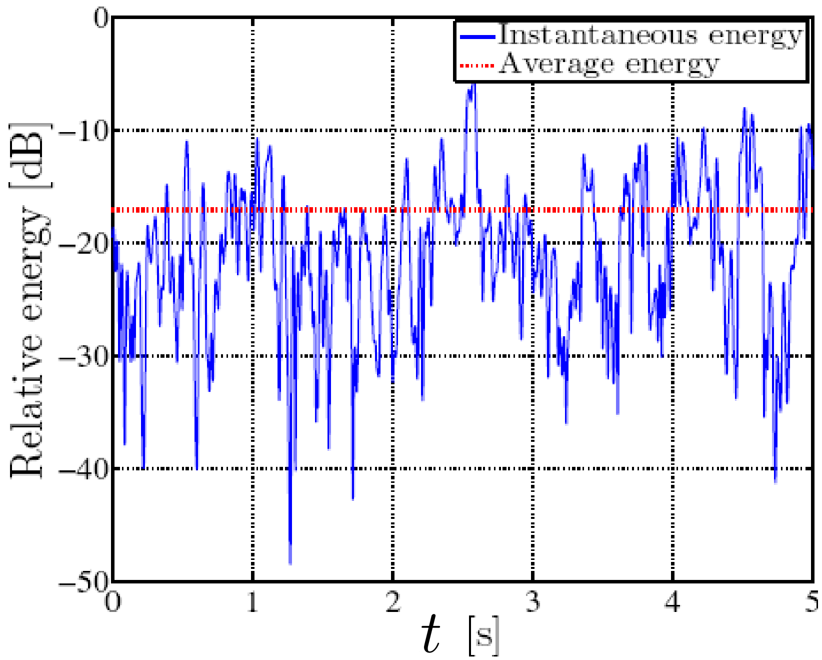


Channel Model E

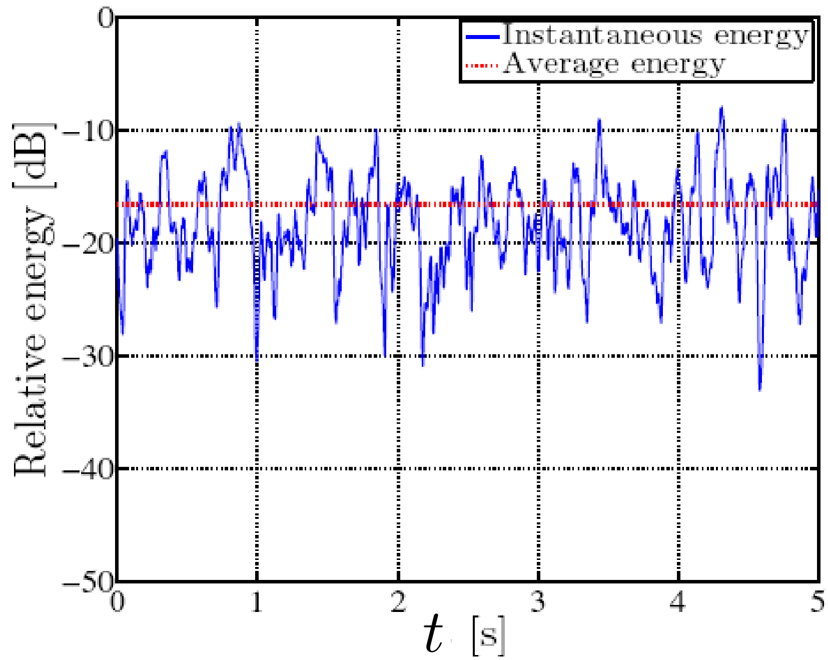
$$|R_n(t,\Delta f)| = E\{H'(t,f)H(t,f+\Delta f)\}$$

- **Coherence bandwidth for channel B (4.9 MHz) > channel E (0.9 MHz).**

Channel Quality Over Time

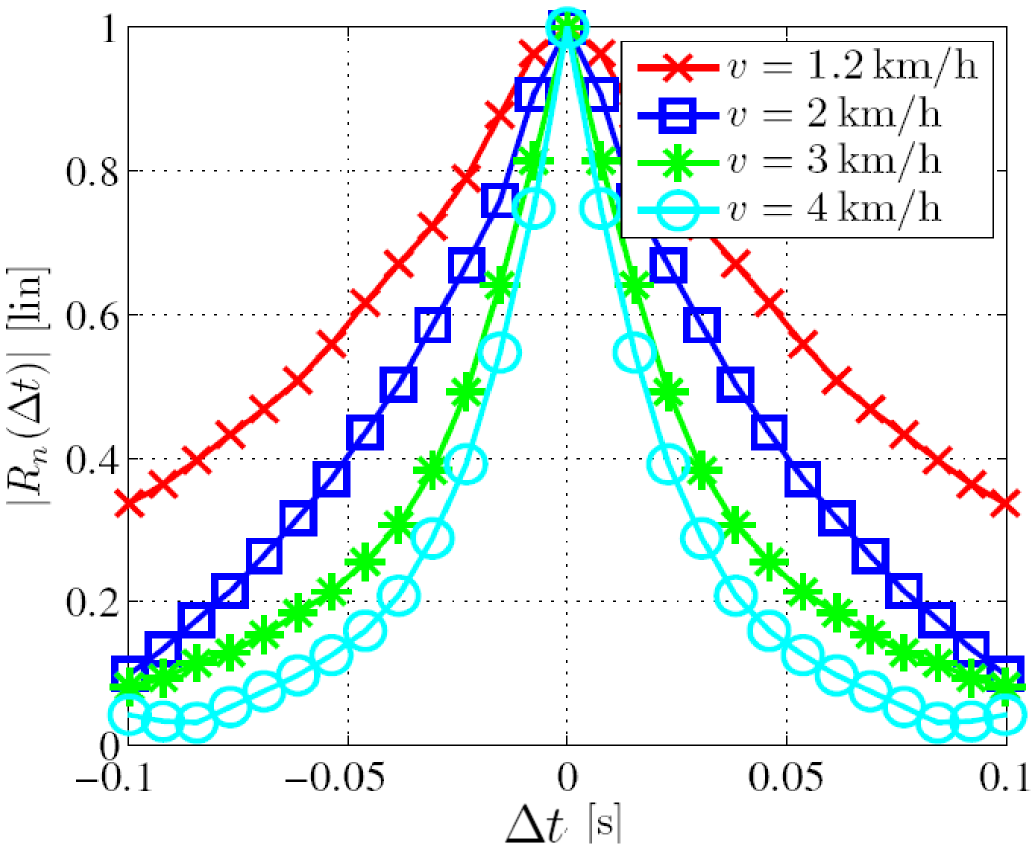


Channel Model B



Channel Model E

Channel Model B: Correlation Time Function



Speed [km/h]	Coherence Time [ms]
1.2	13.8
2.0	8.0
3.0	5.3
4.0	4.2

$$|R_n(\Delta t, f)| = E\{H'(t, f)H(t+\Delta t, f)\}$$

- **Coherence time is decreasing with the increase of speed of scatterers.**

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Link Adaptation for IEEE 802.11n

- LA can be segregated in two major types
  - **Slow link adaptation (SLA)**
  - **Fast link adaptation (FLA)**

- Channel state information (CSI) not available at Rx
  - **SLA will be an easiest choice.**
  - **SLA depends on long term packet error rate (PER) statistics at MAC, i.e., on averaging over NACK/ACK.**
  - **Averaging over many channel realizations.**

- CSI available at Rx
  - **FLA can be deployed.**
  - **FLA can adapt MCS according to time varying channel conditions to increase throughput of a system.**

Link Adaptation Protocol in IEEE 802.11n

- **Modes**
  - **Immediate response**
  - **Unsolicited (delayed) response, delay is unconstrained.**
- **MFB requester (Tx) can request MCS from Rx by setting MCS request field**
  - **It sends a sounding packet (to identify all spatial dimensions).**
- **MFB responder (Rx) sends estimated MCS**
  - **By setting the recommended value in MCS feedback field (0-77).**
  - **By conveying the MCS sequence index (MSI) along with the MCS value.**

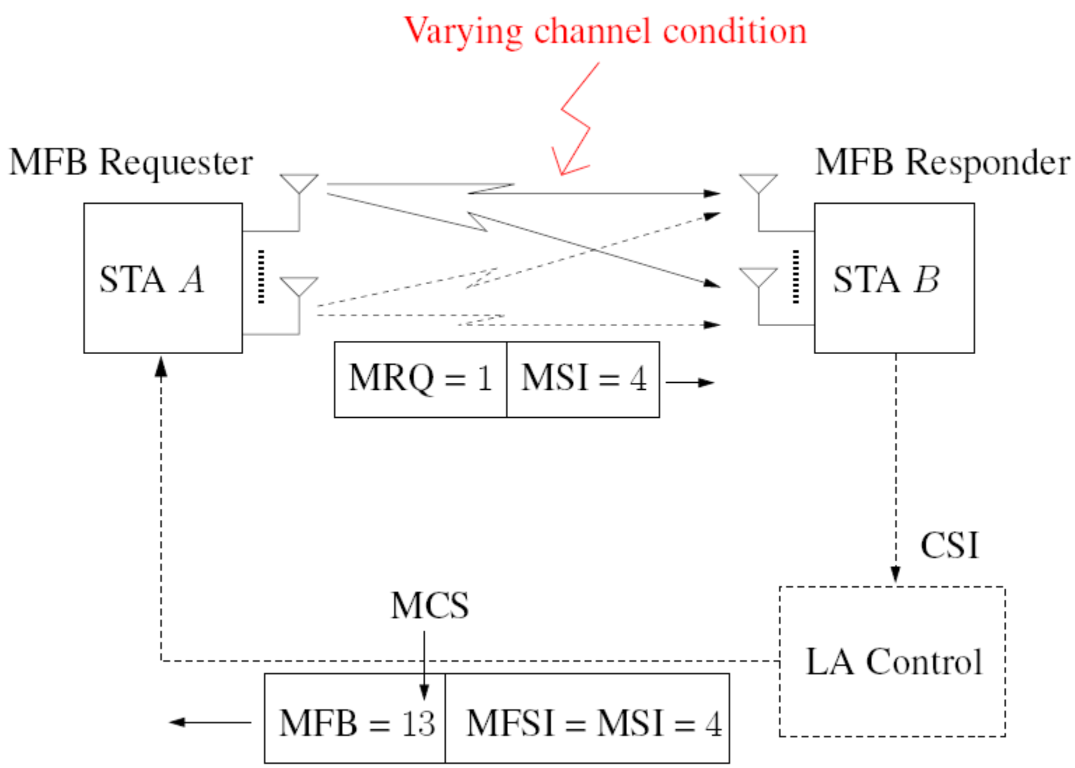


Table of Some Selected MCS Values

- MCS 0 – 7 mandatory
- MCS 8-77 optional
- MCS value determines modulation format, code rate and number of spatial streams.
- 40 MHz BW provides higher throughput (TP) by a factor of approximately 2.1 compared to 20 MHz BW.
- 400 ns GI provides higher TP approximately by a factor of 1.11 compared to 800 ns GI.

MCS Index	Modulation		Code Rate	PHY Rate (Mb/s)			
				800 ns GI		400 ns GI	
	SS 1	SS 2		20 MHz	40 MHz	20 MHz	40 MHz
0	BPSK	-	1/2	6.5	13.5	7.2	15.0
1	QPSK	-	1/2	13.0	27.0	14.4	30.0
2	QPSK	-	3/4	19.5	40.5	21.7	45.0
3	16QAM	-	1/2	26.0	54.0	28.9	60.0
4	16QAM	-	3/4	39.0	81.0	43.3	90.0
5	64QAM	-	2/3	52.0	108.0	57.8	120.0
6	64QAM	-	3/4	58.5	121.5	65.0	135.0
7	64QAM	-	5/6	65.0	135.0	72.2	150.0
8	BPSK	BPSK	1/2	13.0	27.0	14.4	30.0
11	16QAM	16QAM	1/2	52.0	108.0	57.8	120.0
15	64QAM	64QAM	5/6	130.0	270.0	144.4	300.0
33	16QAM	QPSK	1/2	39.0	81.0	43.3	90.0
35	64QAM	16QAM	1/2	65.0	135.0	72.2	150.0
38	64QAM	16QAM	3/4	97.5	202.5	108.3	225.0

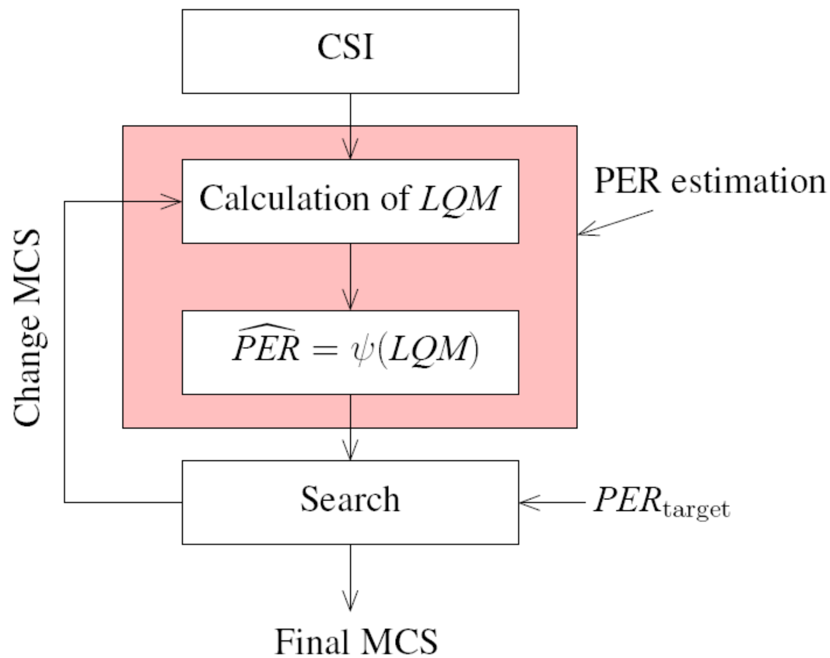
General Concept of FLA

- **Post-processing SINRs are computed from CSI (*H, N_{Rx} x N_{SS}*)**

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$$

$$SINR_j(k) = \frac{1}{\left[\left(\frac{1}{\sigma^2}\mathbf{H}^H(k)\mathbf{H}(k) + \mathbf{I}_{N_T}\right)^{-1}\right]_{j,j}} - 1$$

- **FLA comprises**
  - **PER estimation block which contains link quality metric (LQM) computation**
  - **Search mechanism finds a suitable MCS fulfilling PER target, e.g., PER_{target} = 1%**



- **Concept of LQM mathematically,**

$$PER_{\text{FadingChannel}}(\{\text{CSI}\}) \approx \underbrace{PER_{\text{AWGN}}(LQM)}_{\psi_{MCS,PL}(LQM)}$$

Link Quality Metrics (LQMs)

- **Potential LQMs**
  - **Average SINR**
  - **Raw bit error rate (rawBER)**
  - **Exponential Effective SINR Mapping (EESM)**
  - **Mean Mutual Information Bit Mapping (MMIBM)**
  - **Mean Mutual Information Effective SNR Mapping (MIESM)**

- **General form of the LQMs**

$$\mathcal{G}_{\mathrm{mean}} = \frac{1}{N_{\mathrm{ss}}\,N_{\mathrm{sd}}} \sum_{j=1}^{N_{\mathrm{ss}}} \sum_{k=1}^{N_{\mathrm{sd}}} \mathcal{G}\Big(SINR_j[k], \ldots\Big)$$

  - N_{SS} **… no. of spatial streams**
  - N_{SD} **… no. of subcarriers**

- **Same problem as link-layer abstraction in system-level simulations**

Link Quality Metrics (ctd')

- **EESM (Exponential Effective SNR Mapping) [Simoens 2004]**

$$SINR_{eff} = -\beta \log\left(\frac{1}{N_{ss} N_{sd}} \sum_{j=1}^{N_{ss}} \sum_{k=1}^{N_{sd}} \exp\left(-\frac{SINR_j(k)}{\beta} \right) \right)$$

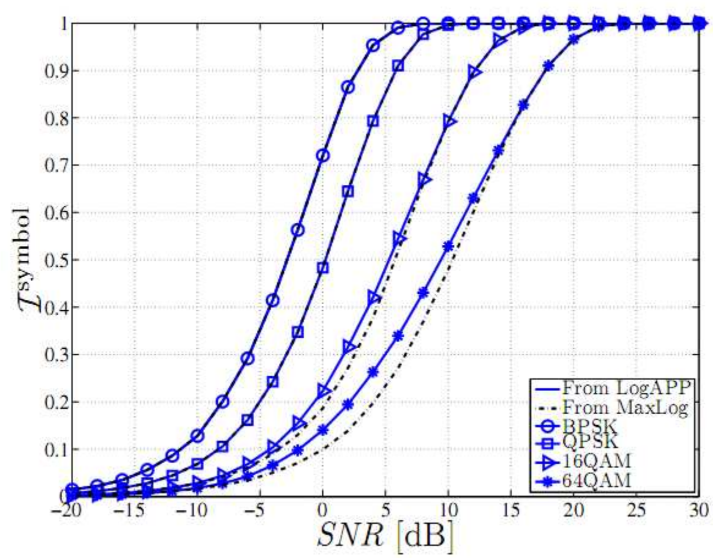
- **MIESM (Mutual Information Effective SNR Mapping) [Tsai 2003]**

$$SINR_{eff} = \gamma \left[J^{-1}\left(\frac{1}{N_{ss} N_{sd}} \sum_{j=1}^{N_{ss}} \sum_{k=1}^{N_{sd}} J\left(\sqrt{\frac{SINR_j(k)}{\gamma}} \right) \right) \right]^2$$

- **MIBM (Mutual Information Based Mapping)**

$$I_{mean}^{symbol} = \frac{1}{N_{ss} N_{sd}} \sum_{j=1}^{N_{ss}} \sum_{k=1}^{N_{sd}} I_j^{symbol}\left(SINR_j(k) \right)$$

- **J() and I() compute mutual information for different modulation schemes as a function of SINR**

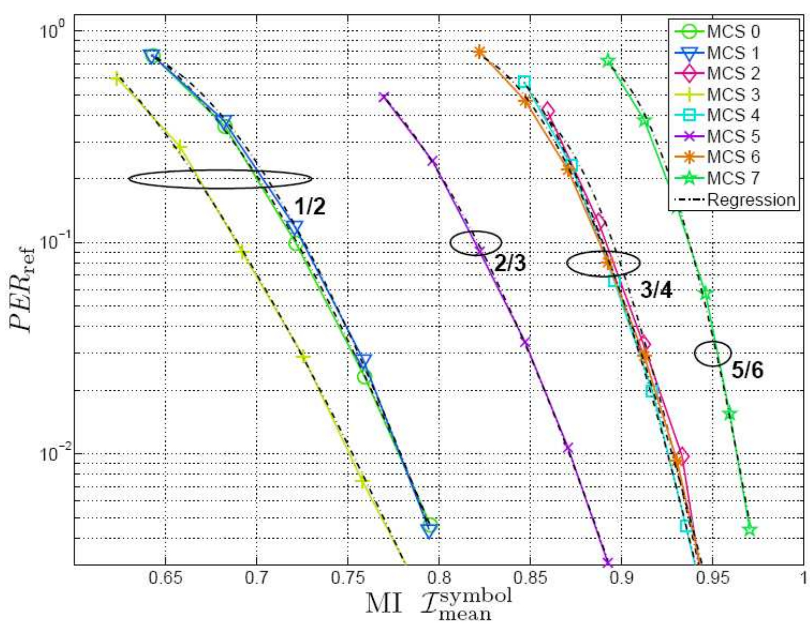


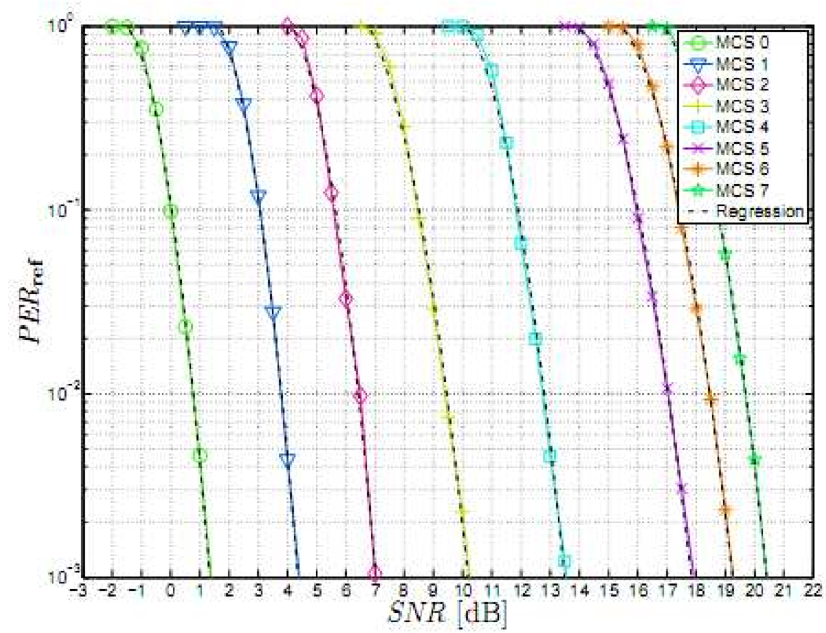
Mapping Function

- **Simulations in the AWGN channel gives the relation of the mapping from LQM to PER_{ref}.**

- **Reference packet length 1024 Bytes**

$$PER_{PL} = 1 - (1 - PER_{ref})^{\frac{PL}{PL_{ref}}}.$$





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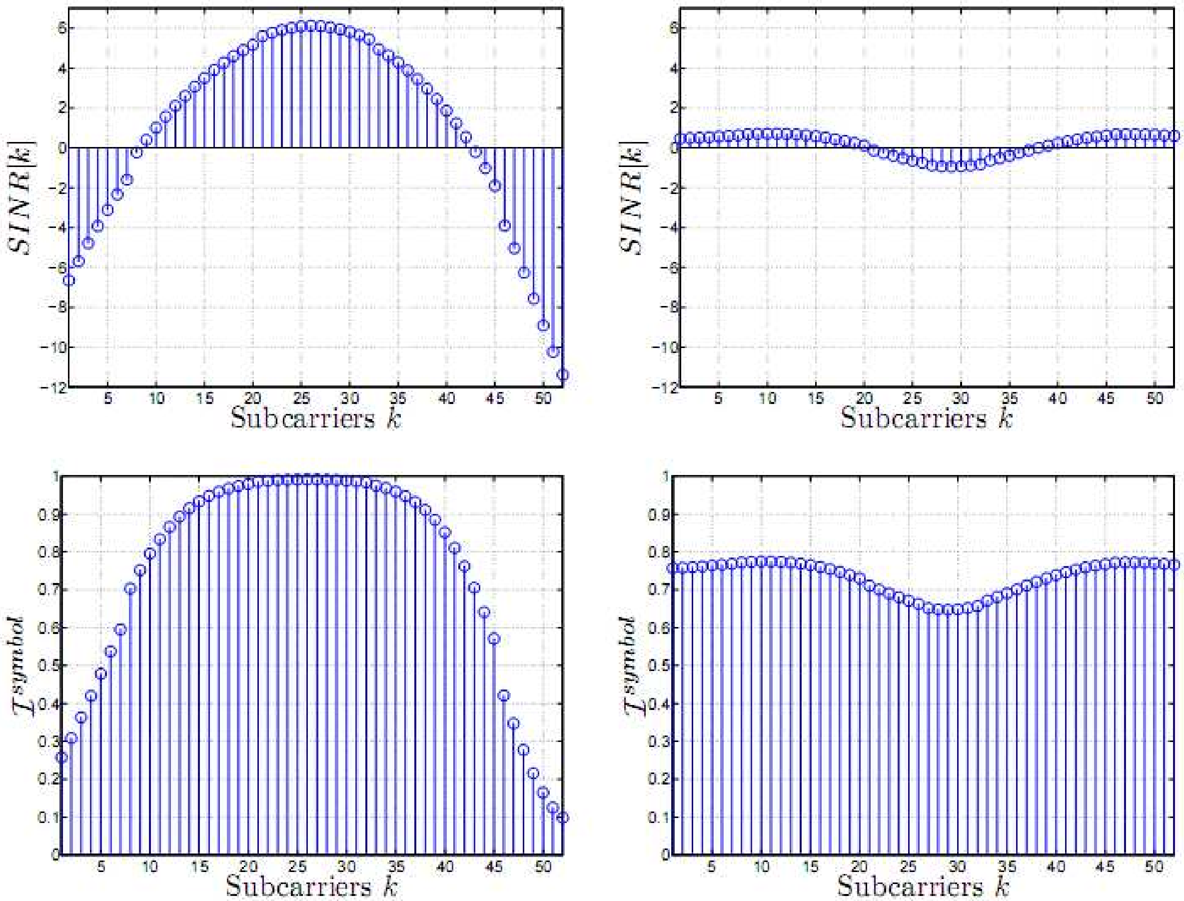
Subcarrier Variation

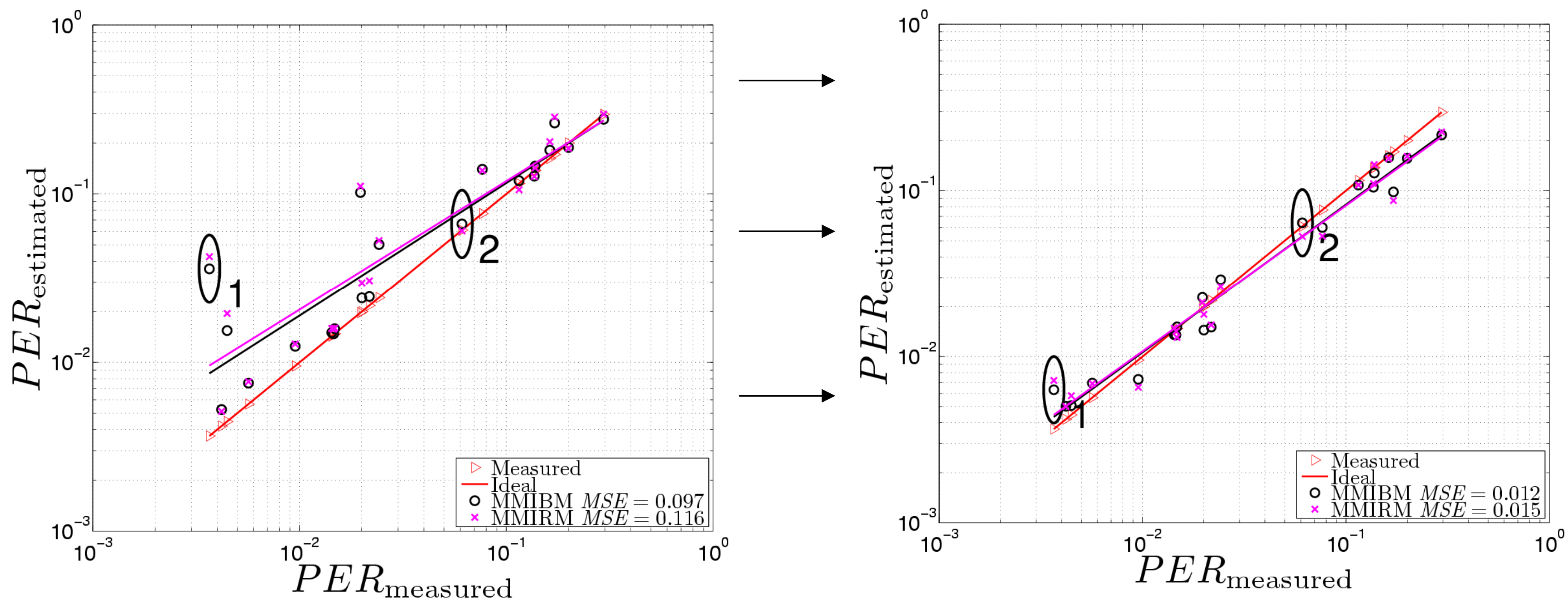


(Channel realization 1) **(Channel realization 2)**

PER Estimation Accuracy – MI Correction

- **LQMs based on MI without correction factors give inaccurate results.**
- **Correction factors improve PER estimation accuracy.**
  - **High SINR dynamics over the subcarriers for a single channel realization makes it necessary to introduce a correction factor.**

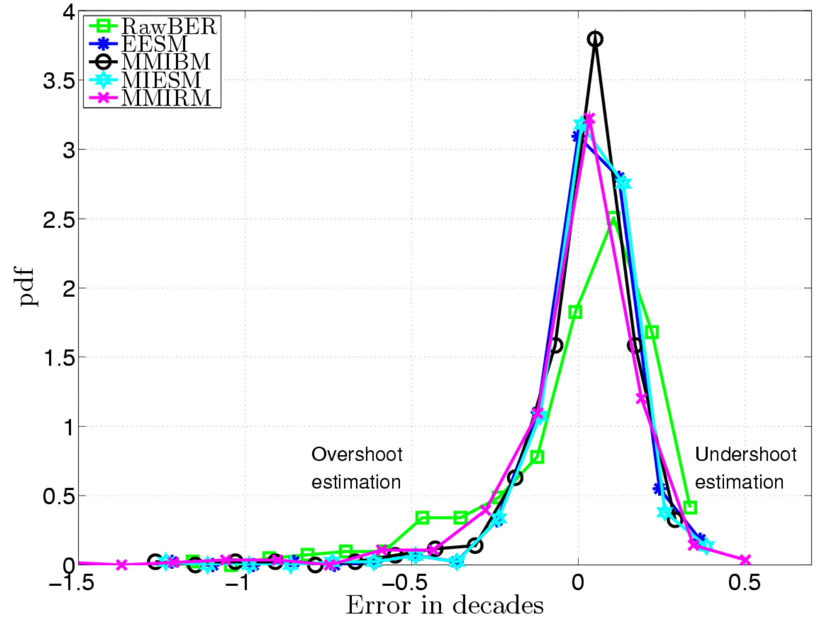
$$I_{mean}^{symbol} = \frac{1}{N_{ss} N_{sd}} \sum_{j=1}^{N_{ss}} \sum_{k=1}^{N_{sd}} I_j^{symbol}\left(SINR_j(k)\right) + \frac{1}{N_{ss}} \sum_{j=1}^{N_{ss}} \lambda_j \operatorname{var}\left\{ I_j^{symbol}(k) \right\}$$



No correction **MCS 0** **With Correction**

PER Estimation Accuracy

- Example of pdf (from histogram) of estimation errors for channel model B.



258 measurements (MCS 0-15).

- Optimization and evaluation are done on the same set of measurements.
- EESM, MIESM and MMIBM are the most accurate LQMs; MMIRM is less accurate and RawBER is the least accurate.

MCS Search

- **Optimization problem**

$$\max_{MCS \in \Omega(N_\mathrm{T})} \quad TP(MCS)$$
$$\text{s.t.} \quad PER(MCS) \le PER_{\mathrm{Threshold}}$$

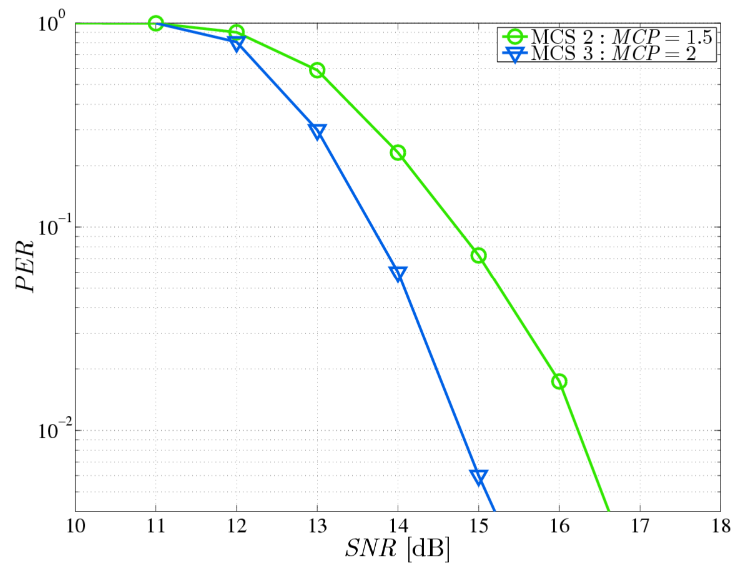
- **Search set**

$$\Omega(N_\mathrm{T}) = \text{set of allowed MCS} \quad |\Omega(1)| = 8, |\Omega(2)| = 16, |\Omega(2 + \text{unequal})| = 22$$

- **If some subcarriers are in deep fade, it is more important to have a large Hamming distance than a large Euclidean distance [van Nee 2000].**

$$PER(MCSx) \le PER(MCSy)$$
$$\not\Leftrightarrow TP(MCSx) \le TP(MCSy)$$

- **Search**
  - **Exhaustive**
  - **From top**
  - **From bottom**
  - **From last value**

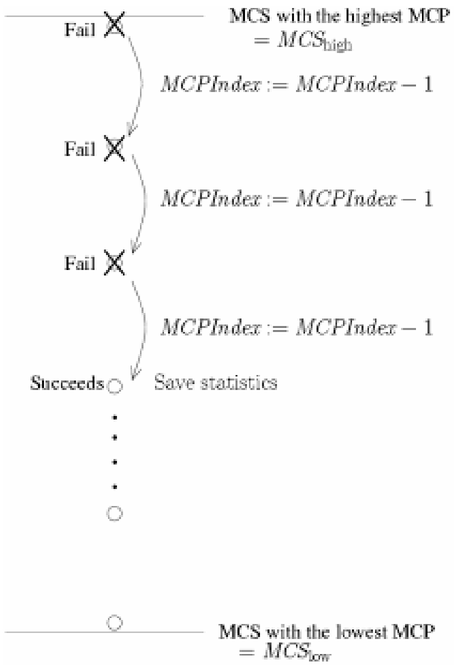


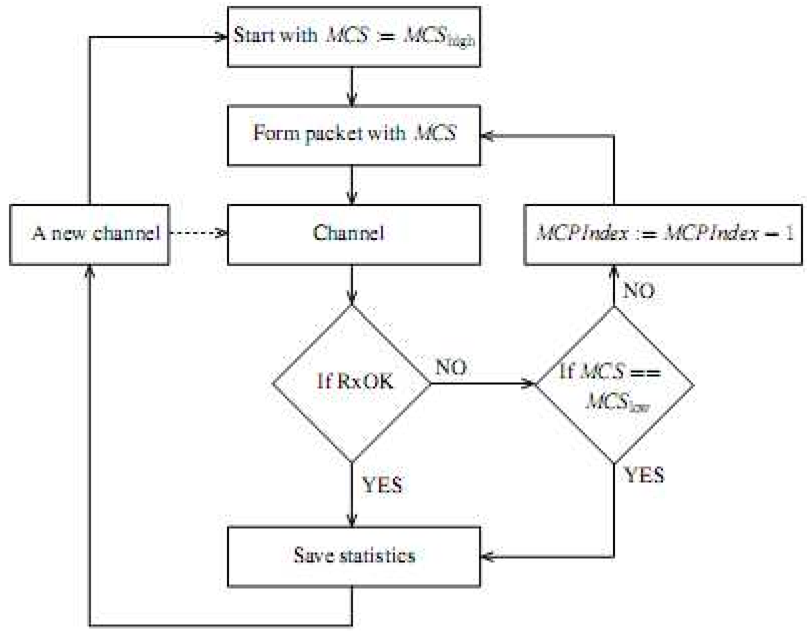
MCS 2, QPSK, Rc ¾

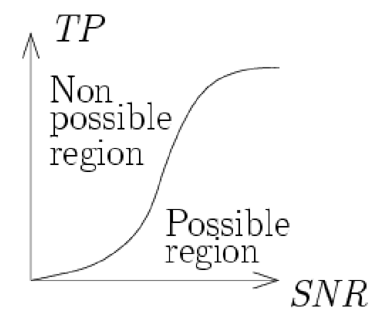
MCS 3, 16QAM, Rc ½

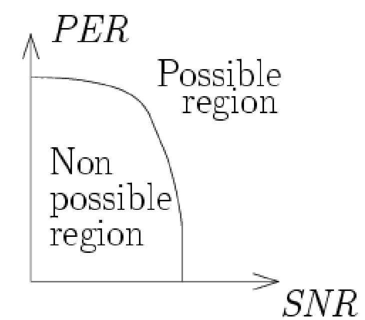
Upper Bound of any LA Algorithm

- Upper bound of TP (and lower bound on PER)









- $PER_{UB} \leq PER(MCSx)$ This is the lower bound on PER.
  - The bound is introduced because all MCS are under trial.
- Let $MCSx$ be the MCS selected with genie knowledge of the PER
  - The $MCSx$ succeeds with the same probability for genie as for upper bound.
  - For TP_{UB}, MCSs prior to $MCSx$ can succeed.
  - If any failure, MCS with lower MCP can succeed.

$\left.\begin{array}{l} \\ \end{array}\right\}$ Trials

$$TP_{\text{UB}} \geq TP_{\text{Genie}} \geq TP_{\text{LA algorithm}}$$

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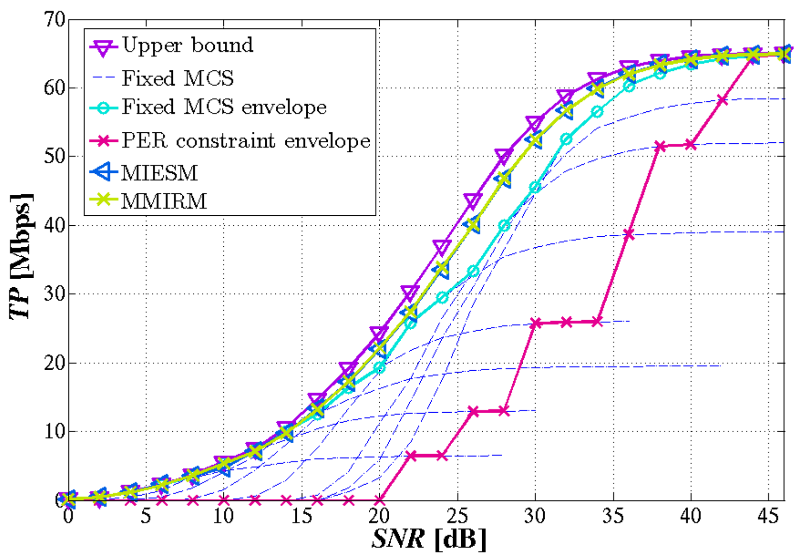
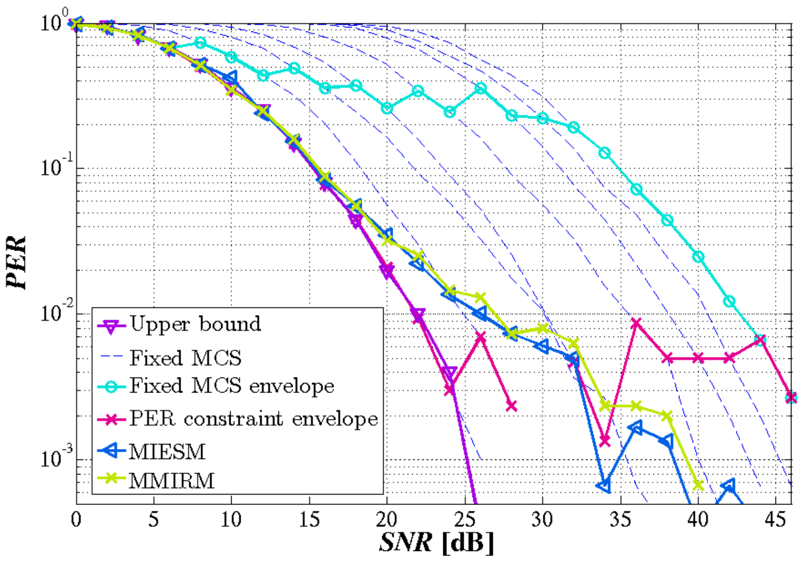
Numerical Results

- **Show**
  - **TP vs. SNR**
  - **PER vs. SNR**
- **Simulation Assumptions**
  - **Channel B or E**
  - **20 MHz BW**
  - **Packetlength = 1024 Bytes**
  - **1x1, 2x2 MIMO configurations**
  - **Mutual information based metrics only**
  - **Perfect channel knowledge at Rx**

1x1, Channel Model B

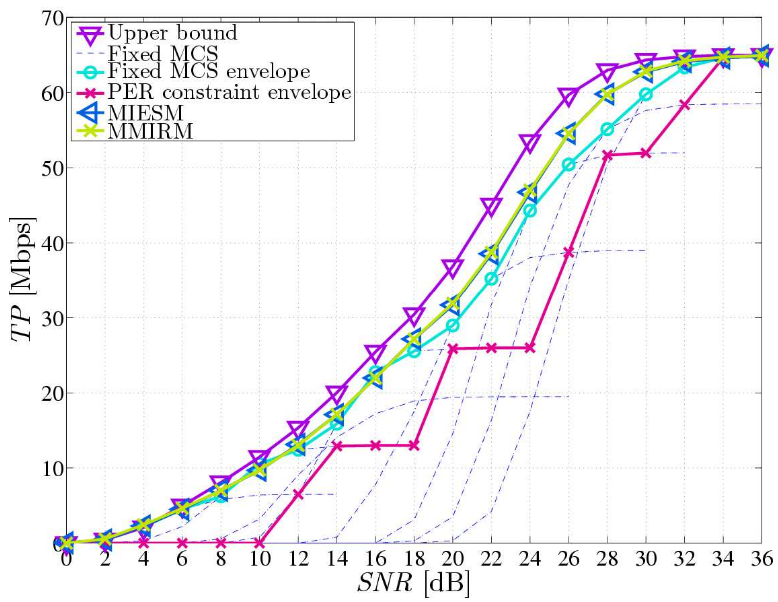
- **Consider MIESM and MMIRM**

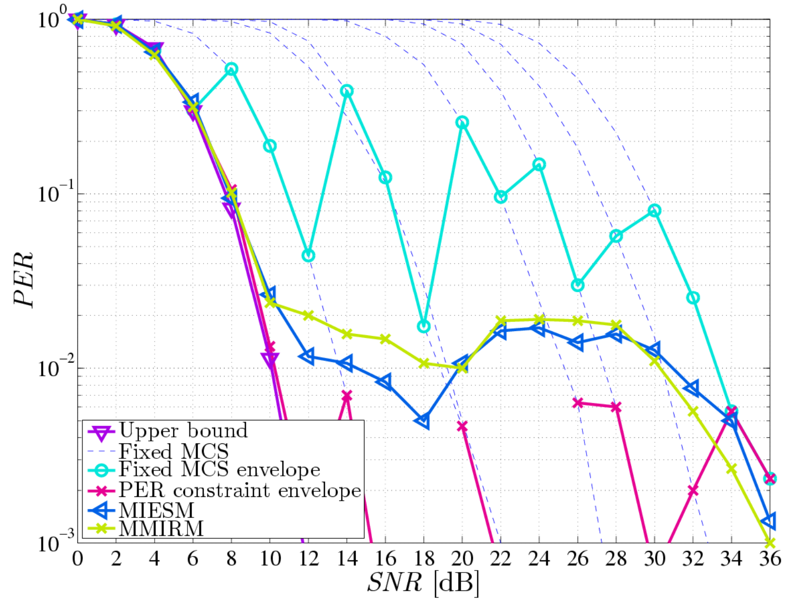




- **Larger gain compared to PER constraint envelope (320% at SNR = 22 dB).**
- **Largest gain in the mid SNR regime. Bounded by the available MCSs.**

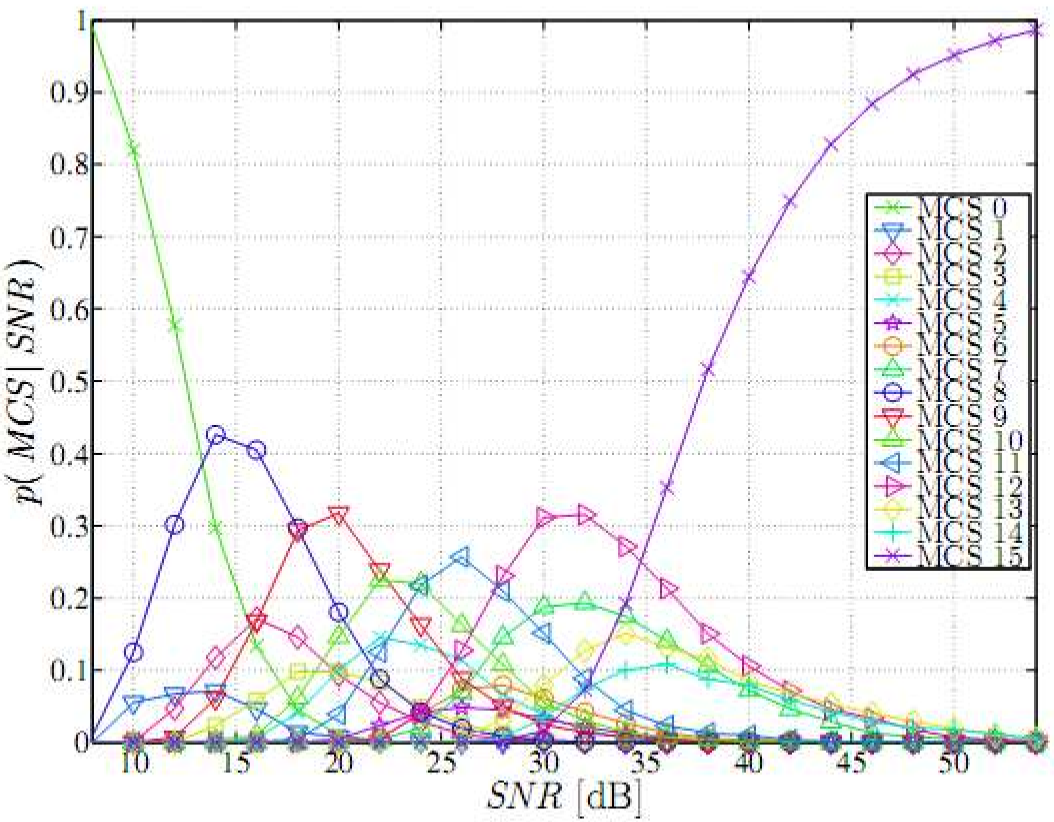
1x1, Channel Model E





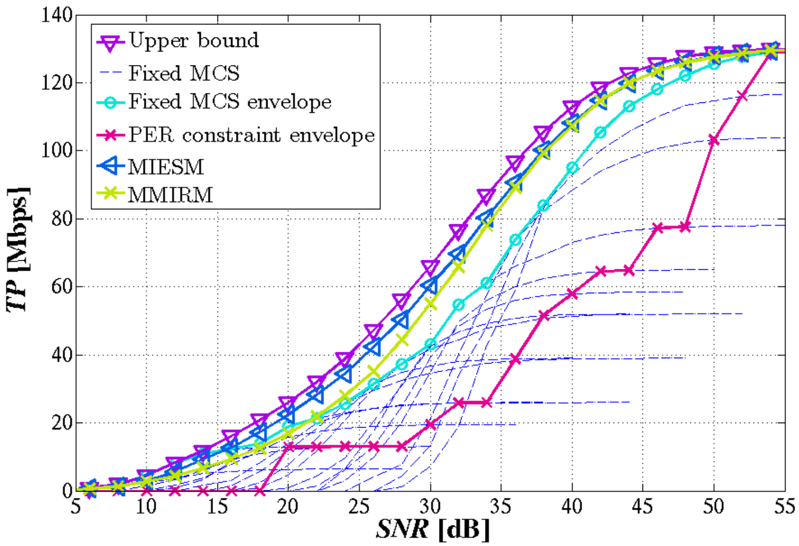
- Distance to PER constraint envelope is smaller and gap to upper bound is larger compared to the example for channel model B.
- Benefit of FLA is largest in settings with the lowest diversity.
  - FLA exploits varying channel quality.

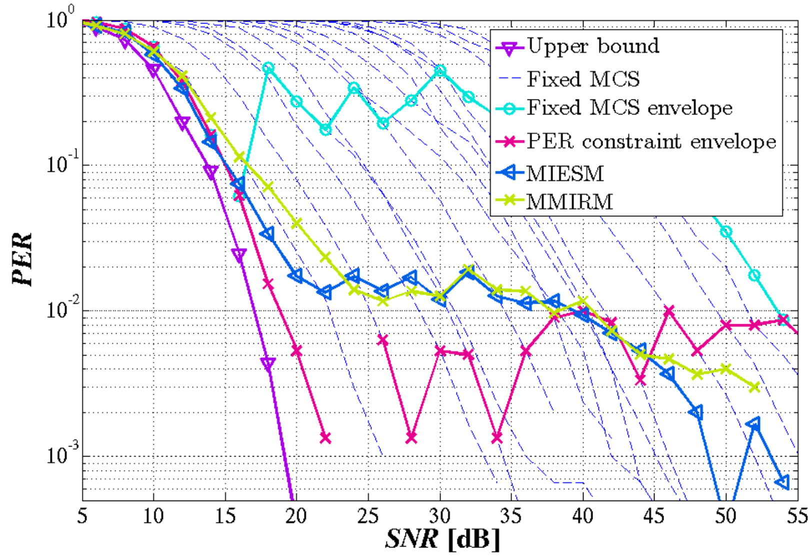
2x2, Channel B, MCS Distribution



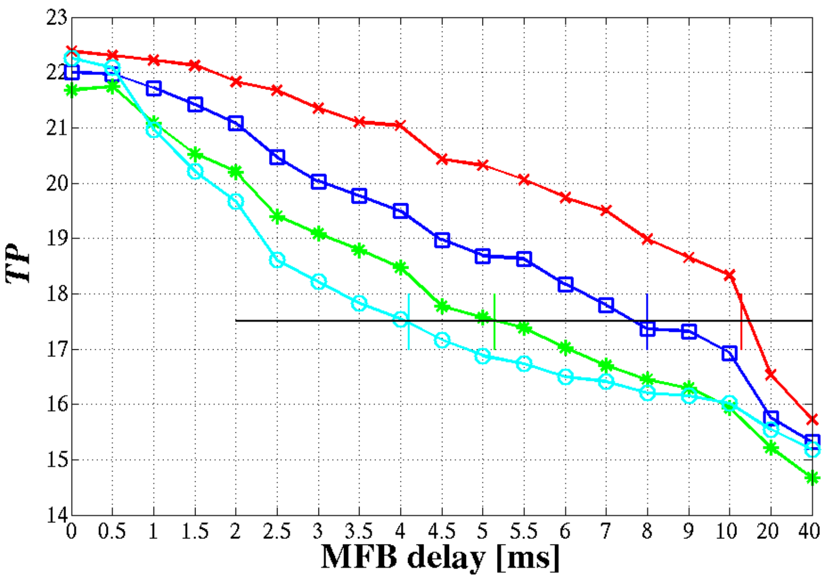
2x2, Channel Model B

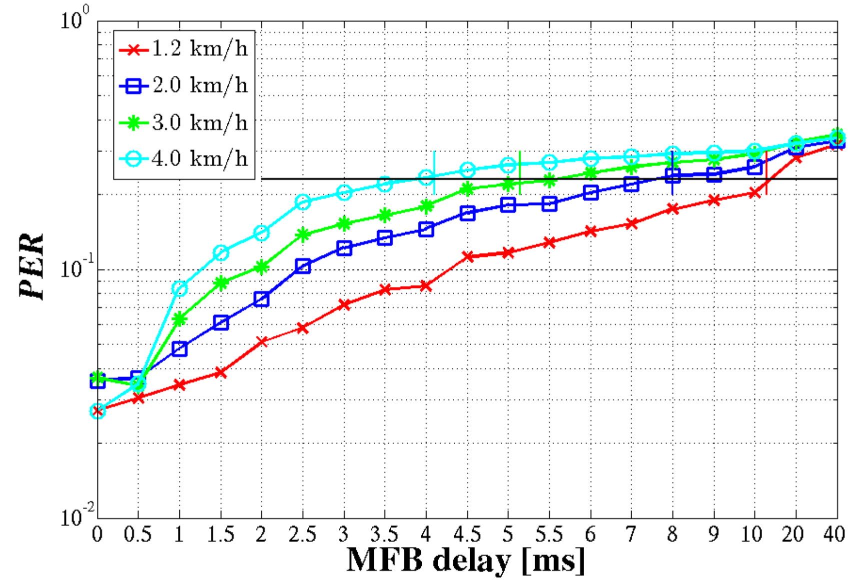
- **No. of spatial streams ≤ no. of transmit antennas**
  - **LQMs utilizing post-processing SINRs can calculate the required SINRs for the cases of a lower number of spatial streams. Only constraint is that all spatial dimensions are sounded.**





Feedback Delay and Speed





- SNR = 20dB
- At coherence time (4.2, 5.3, 8, 13.8 ms) ~20% loss in TP and ~23% PER
- PER increases fast to a non acceptable level
- The speed of the scatterers, Tx or Rx are unconstrained in some practical conditions.
  - Outer loop adjusting selection threshold such that the desired PER can be met.

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Conclusions

- **Link Adaptation**
  - **FLA has advantages compared to SLA**
  - **Protocol for LA**

- **FLA comprises**
  - **PER estimation using LQM**
    - **Mapping fading channel into an equivalent AWGN channel.**
    - **Methods considered: SNR effective and mutual information.**
    - **Evaluated the accuracy.**
    - **Search Criteria and Optimality.**

- **Bounds**
  - **FLA algorithm under investigation and bound for any link adaptation algorithm for the settings applied.**

- **Unconstrained delay and speed of scatterers**
  - **Requires outer loop to maintain target PER because the FLA algorithm can not adjust it by itself.**

- **FLA exploits lack of diversity**
  - **Most pronounced gain in the mid SNR regime.**

References

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