2011 1st semester
MIMO Communication Systems

#9: Adaptive MIMO Communications

Kei Sakaguchi
<sakaguchi@mobile.ee.titech.ac.jp>

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Schedule (2^{nd} half)

	Date	Text	Contents
#7	May 31	A-5	MIMO receiver
#8	June 7	A-3, 4	MIMO transmitter
#9	June 14	B-9	Adaptive commun. system
#10	June 21	A-6, B-14	Multi-user MIMO
#11	June 28	B-15, 16	Distributed MIMO networks
#12	July 5		Standardization of MIMO
	July 12		Final Examination

Agenda

- **Aim of today**

  Derive throughput performances
  of adaptive MIMO communication systems

- **Contents**

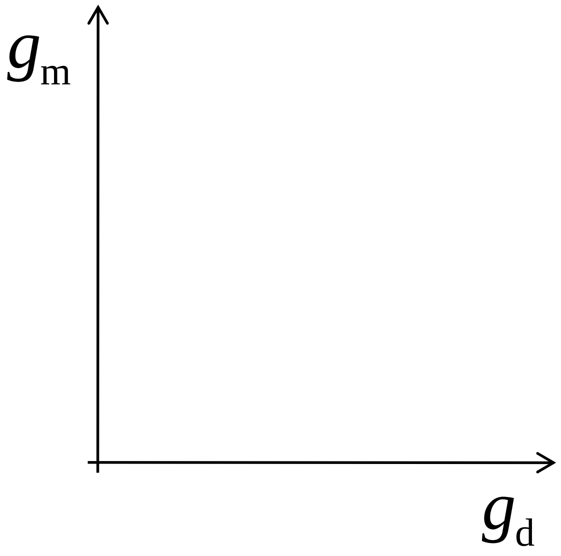
  - Architecture of adaptive MIMO communication
  - Adaptive Modulation Coding (AMC)
  - MIMO Equal Adaptation (EA)
  - MIMO Per Antenna Adaptation (PAA)
  - MIMO EigenMode Adaptation (EMA)
  - Measurement experiment

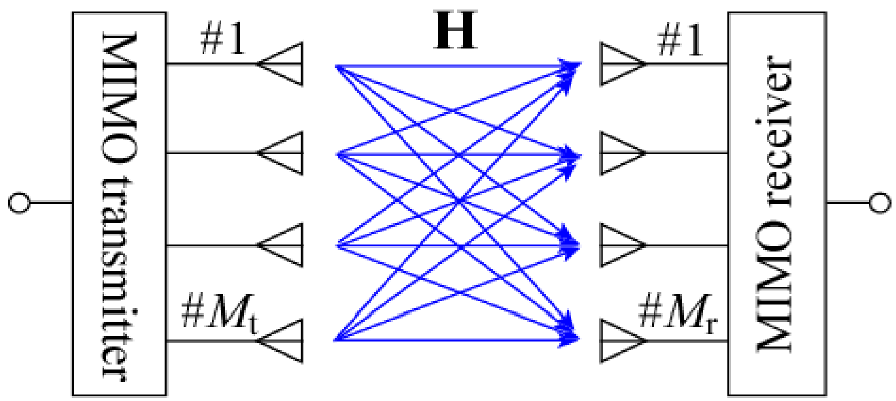
Warming Up

■ Question

Given a 4x4 MIMO system, draw multiplexing gain g_m vs. diversity gain g_d by changing the number of streams m.

(In the case when the diversity gain of the system is not unique, pick up minimal diversity gain as representative value.)



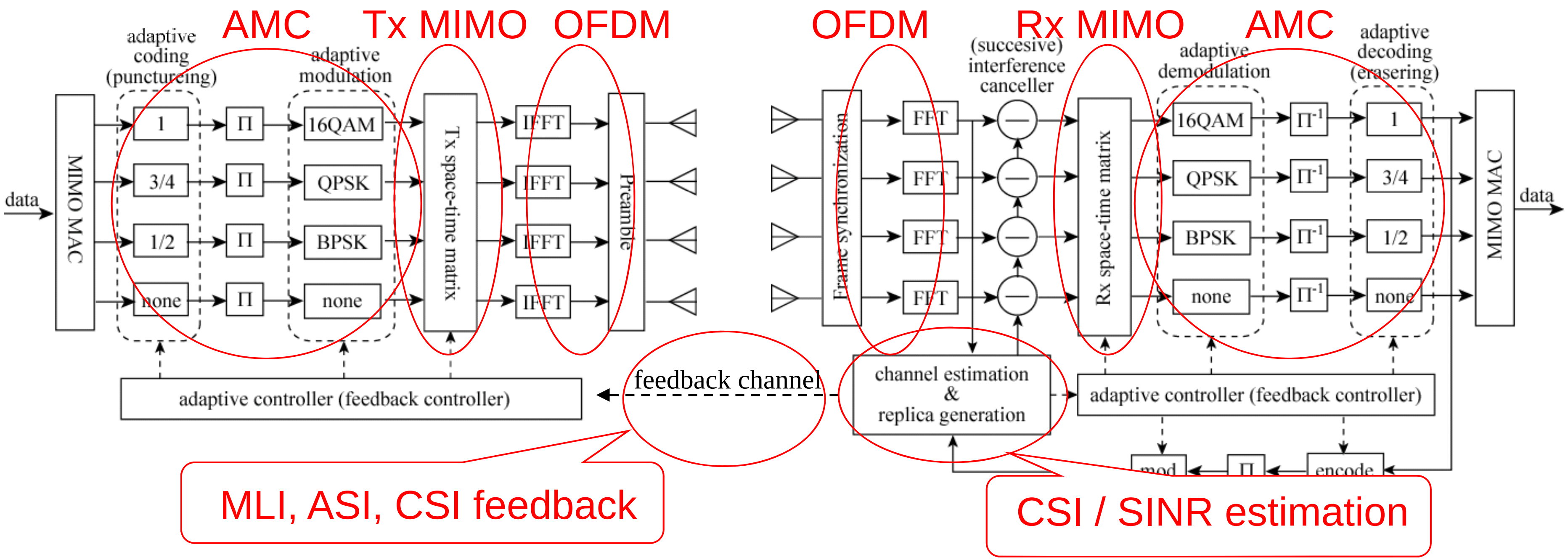


Adaptive MIMO Commun. Architecture

- MIMO combined with OFDM and Adaptive Modulation Coding (AMC)
- Different adaptive algorithms for different Tx and Rx MIMO schemes
- Tradeoff between feedback complexity and system performance

→ Modulation level (MLI), antenna selection (ASI), channel state information (CSI) feedback

MIMO-OFDM transmitter MIMO-OFDM receiver



Classification of Adaptive MIMO

	Multiplexing	Diversity	Complexity
MIMO EA	Full	Receive	Low
MIMO PAA	Adaptive	Full (Selective Tx)	Moderate
MIMO EMA	Adaptive	Full	High

Adaptive Modulation

Instantaneous SNR

$$\gamma(t) = \frac{P|h(t)|^2}{\sigma^2}$$

Throughput of different modulation

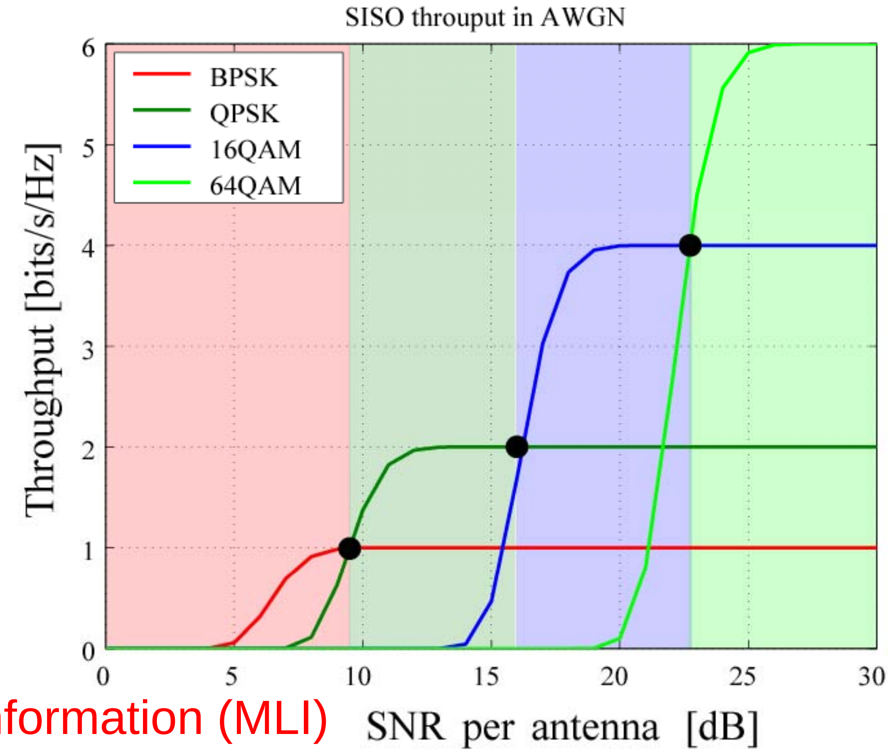
$$TP(\gamma, M^{\text{ary}}) = \log_2 M^{\text{ary}} (1 - P_{\text{eb}}(\gamma))^L$$

BPSK $$P_{\text{eb}}(\gamma) = \frac{1}{2}\text{erfc}\left(\sqrt{\gamma}\right)$$

QAM $$P_{\text{eb}}(\gamma) = \frac{2}{\log_2 M^{\text{ary}}}\left(1 - \frac{1}{\sqrt{M^{\text{ary}}}}\right)$$

$$\text{erfc}\left(\sqrt{\frac{3\gamma}{2(M^{\text{ary}} - 1)}}\right)$$

Throughput of different modulation



Adaptive algorithm

Modulation level information (MLI)

$$\hat{M}^{\text{ary}} = \arg\max_{M_{\text{ary}}} TP(\gamma, M^{\text{ary}})$$

Adaptive Modulation in Fading

Average throughput

$$\overline{TP}(\bar{\gamma}, M^{\text{ary}}) = \int f(\gamma) TP(\gamma, M^{\text{ary}}) \mathrm{d}\gamma$$

PDF of SNR in Rayleigh fading

$$f(\gamma) = \frac{1}{\bar{\gamma}} \exp\left(-\frac{\gamma}{\bar{\gamma}}\right) \qquad \bar{\gamma} = \mathrm{E}\left[\frac{P|h(t)|^2}{\sigma^2}\right]$$

Adaptive modulation

$$\overline{TP}(\bar{\gamma}) = \int_0^{\gamma_1} f(\gamma) TP(\gamma, 2) \mathrm{d}\gamma + \cdots$$

$$+ \int_{\gamma_3}^{\infty} f(\gamma) TP(\gamma, 64) \mathrm{d}\gamma$$

$$\gamma_1 = 10^{9.5/10} \qquad \gamma_2 = 10^{16/10} \qquad \gamma_3 = 10^{22.5/10}$$

Throughput of different modulation

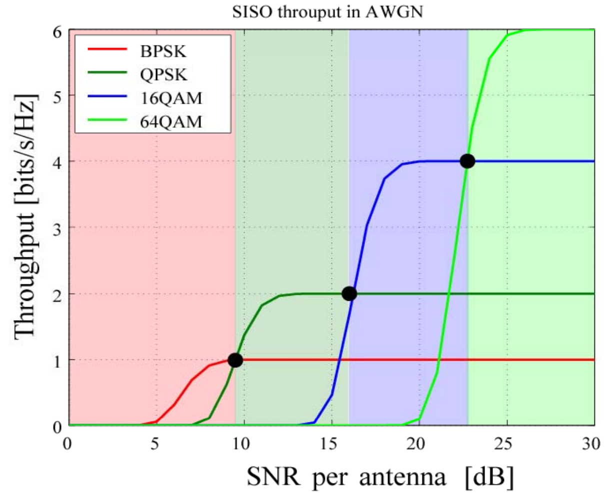
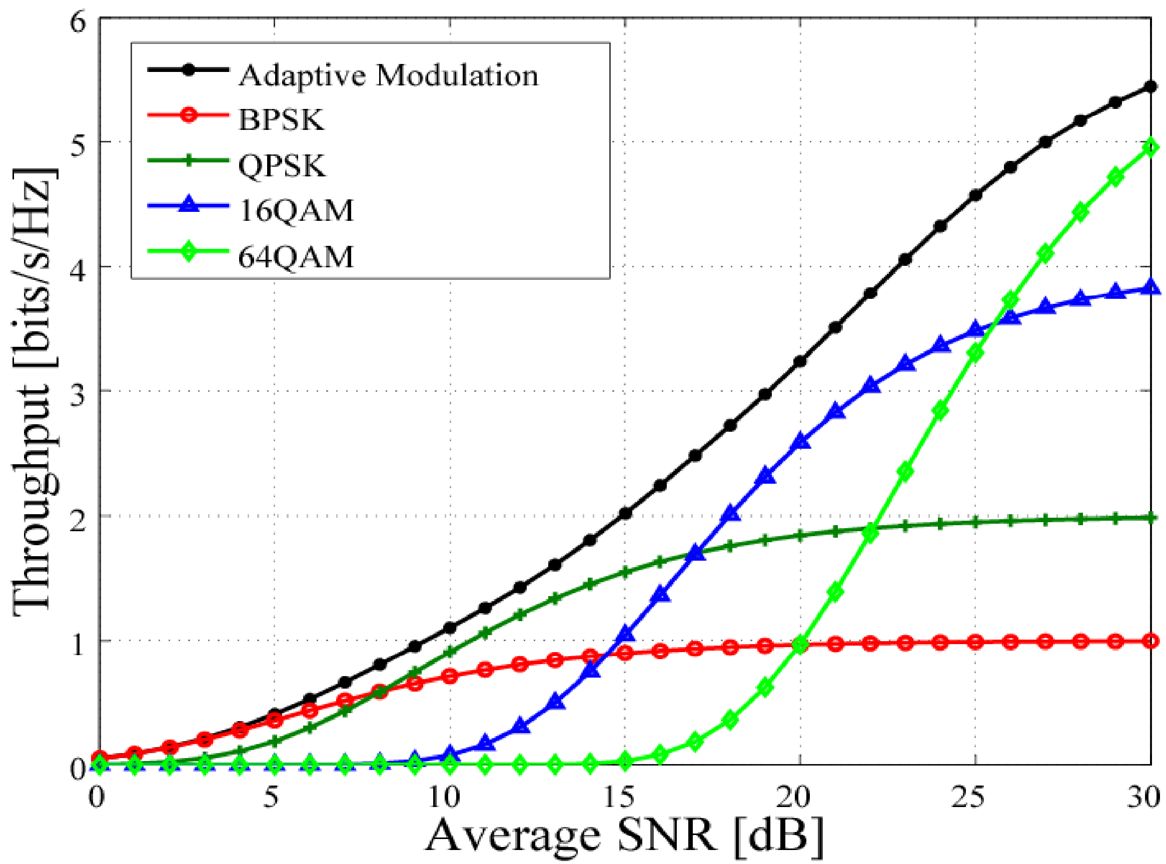


Table for adaptive modulation

Inst. SNR	Modulation
- 9.5dB	BSPK
9.5dB – 16dB	QPSK
16dB – 22.5dB	16QAM
22.5dB	64QAM

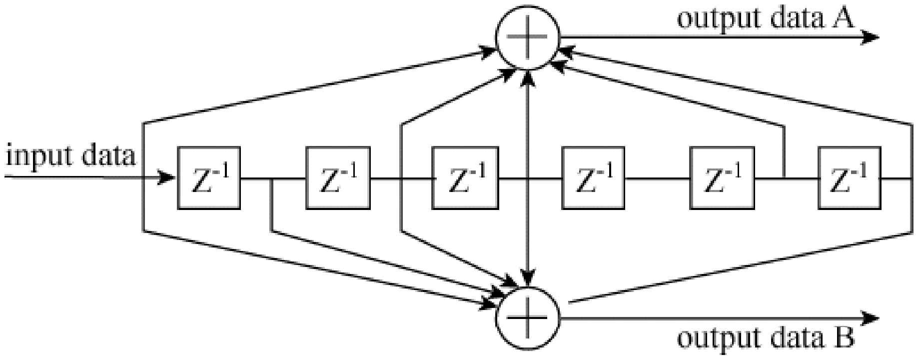
Adaptive Modulation in Rayleigh Fading

- Adaptive modulation achieves better performance than fixed modulation



Convolutional Coding & Puncture

Convolutional coding



Input data

0	1	2	3	4	5	6	7	8	9

Encoded data with puncture 2/3 3/4

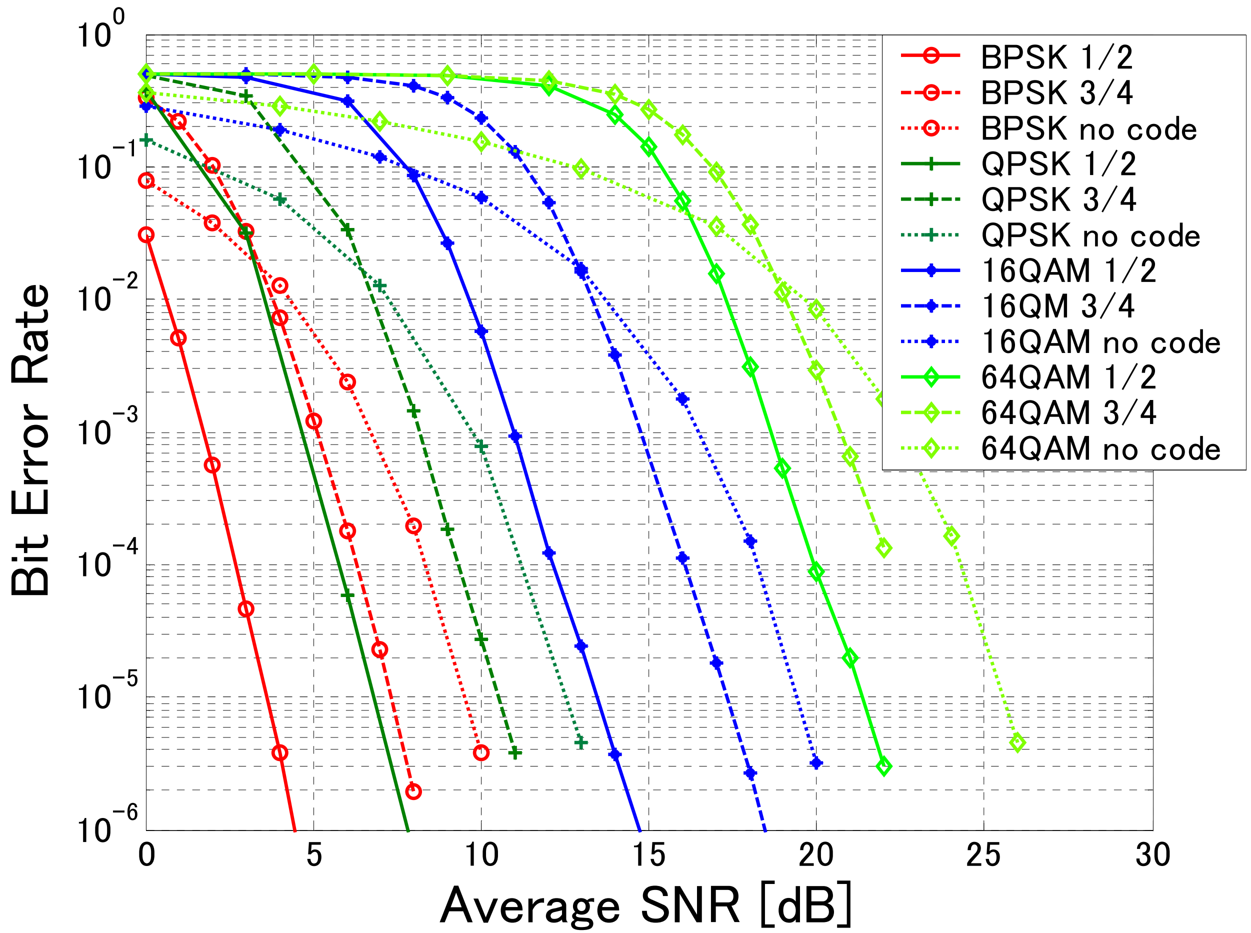
A	0	1	2	3	4	5	6	7	8	9
B	0	1	2	3	4	5	6	7	8	9

Puncture pattern

R=2/3		R=3/4		R=4/5		R=5/6	
P	d_{free}	P	d_{free}	P	d_{free}	P	d_{free}
10 11	6	110 101	5	1111 1000	4	11010 10101	4

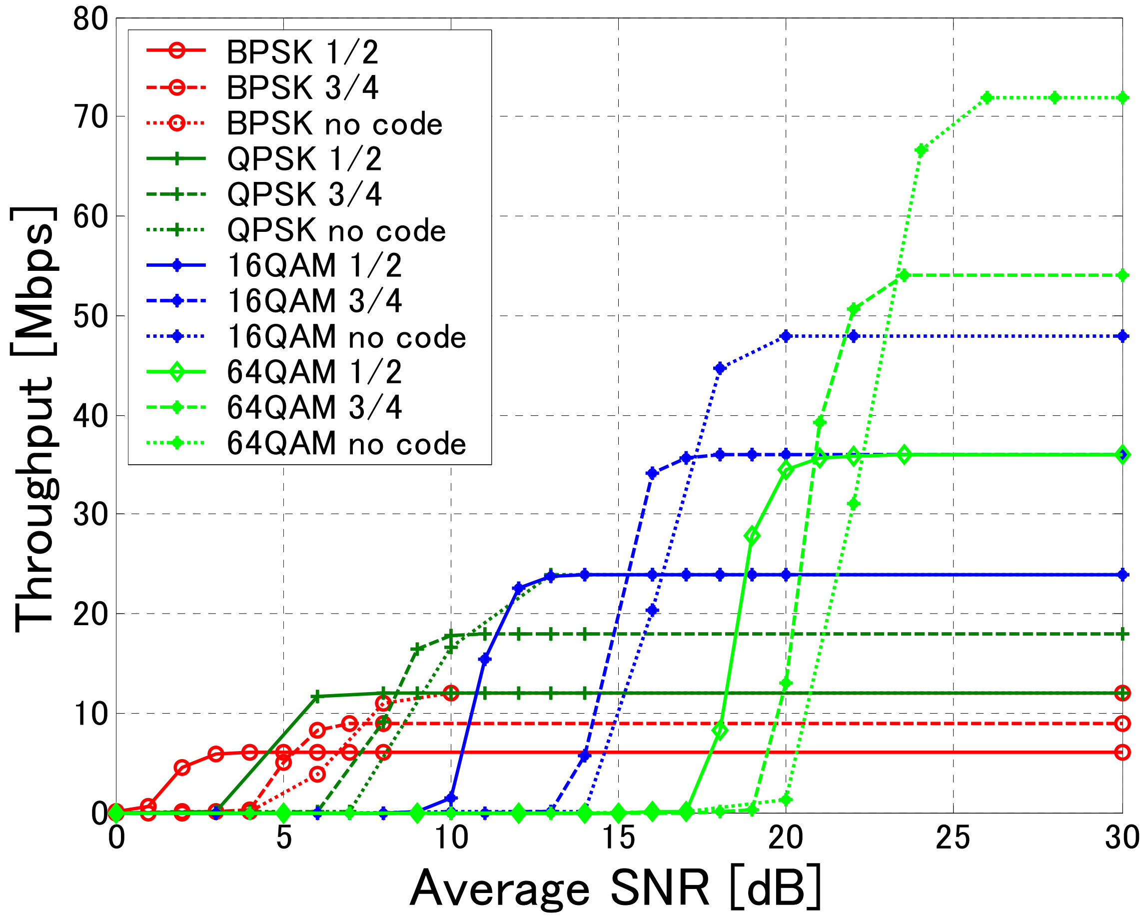
Performance of Coding

- Error correction property when the number of error is less than $\frac{d_{\text{free}}}{2} - 1$



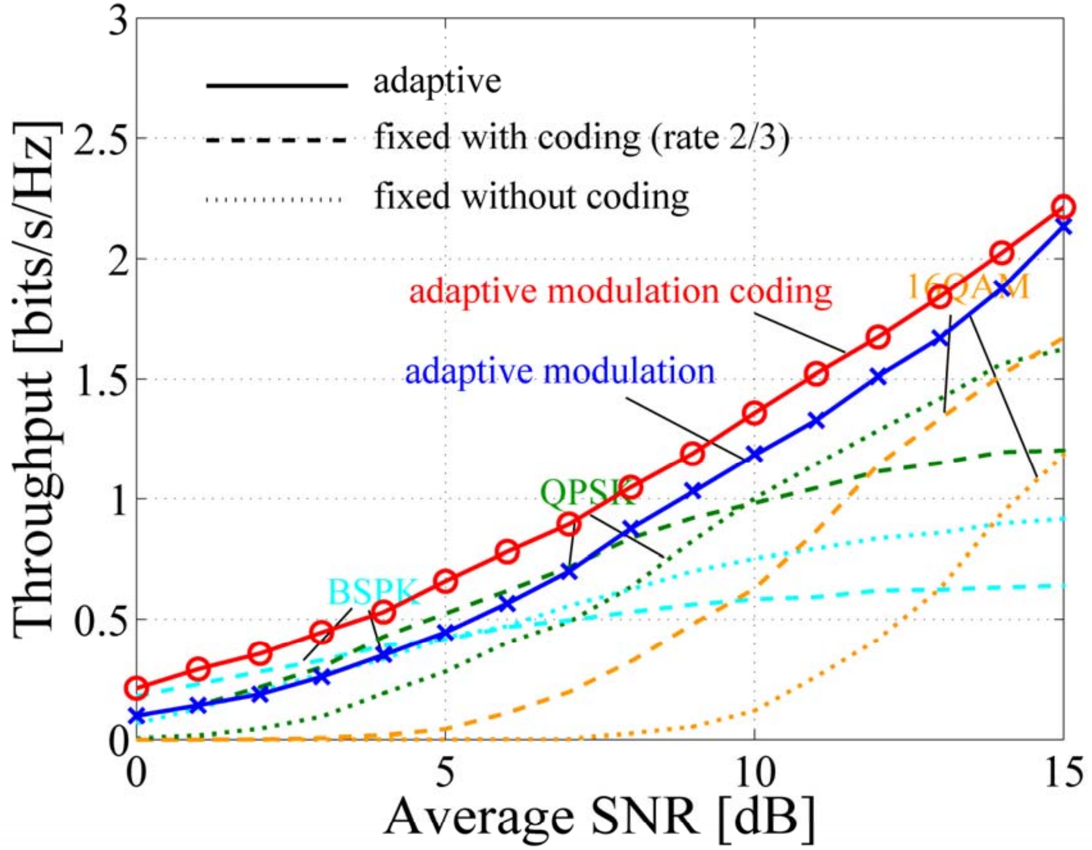
Performance of Coding

- Coding improves the variety of adaptive control



AMC in Rayleigh Fading

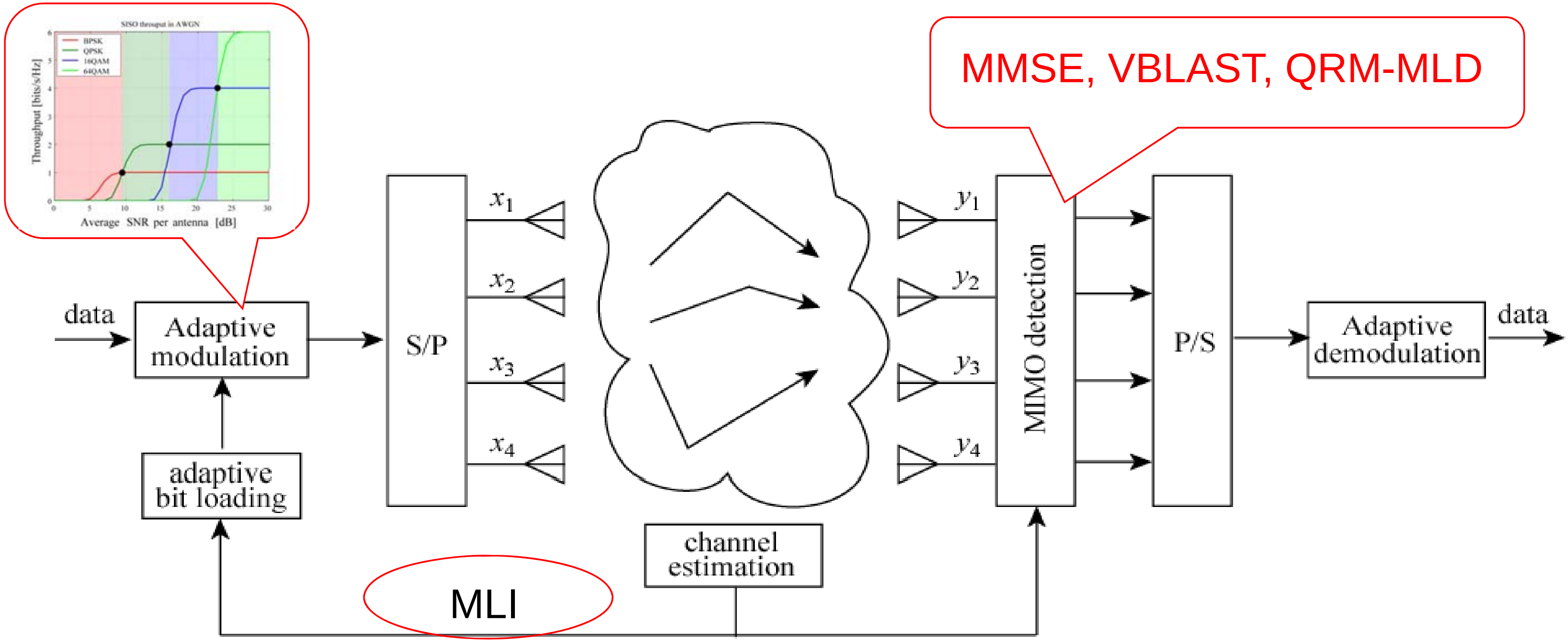
- Coding improves the performance of adaptive modulation



MIMO Equal Adaptation (EA)

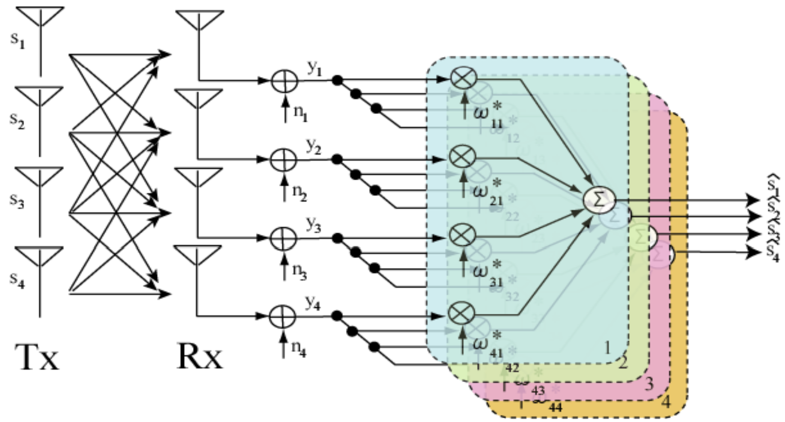
- Simple adaptive modulation based on estimated BER of combined signal
- Simple feedback of modulation level information (MLI)
- Different diversity gains for different MIMO detection schemes

MMSE: $M_r - M_t - 1$ VBLAST: $M_r - M_t - stage$ QRM-MLD: $\leq M_r$



Simple feedback

Adaptive Algorithm for MIMO-EA



Received signal

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

In the case of MMSE detection

$$\mathbf{W} = \left(\mathbf{H}^H \mathbf{H} + \frac{M_\mathrm{t} \sigma^2}{P} \mathbf{I}_{M_\mathrm{t}} \right)^{-1} \mathbf{H}^H$$

$$\gamma_i^{\mathrm{MMSE}} = \frac{1}{\left(\frac{P}{M_\mathrm{t} \sigma^2} \mathbf{H}^H \mathbf{H} + \mathbf{I}_{M_\mathrm{t}} \right)^{-1}_{ii}} - 1$$

Different diversity gain
for different detection schemes

Adaptive algorithm

$$\hat{M}^{\mathrm{ary}} = \arg\max_{M_{\mathrm{ary}}} \sum_{i=1}^{M_\mathrm{t}} TP\left(\gamma_i^{\mathrm{MMSE}}, M^{\mathrm{ary}}\right)$$

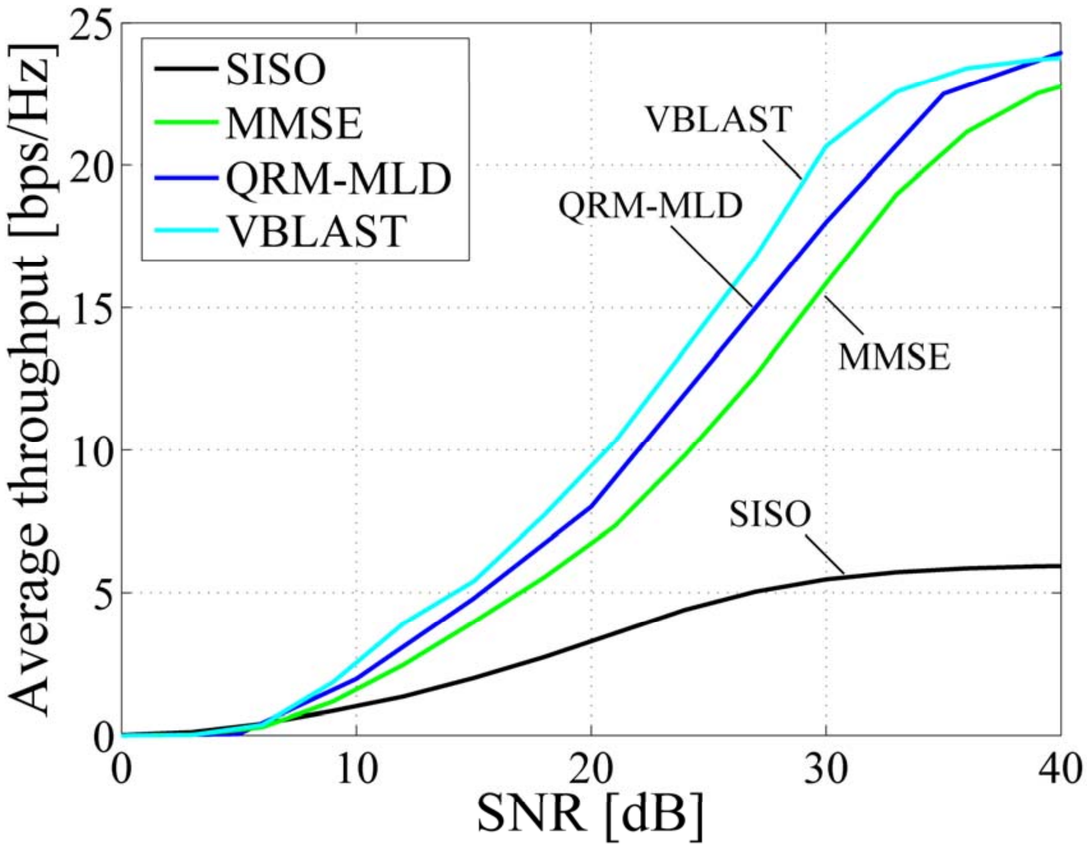
MLI

Diversity gain of MMSE

$$g_\mathrm{d} = M_\mathrm{r} - M_\mathrm{t} + 1$$

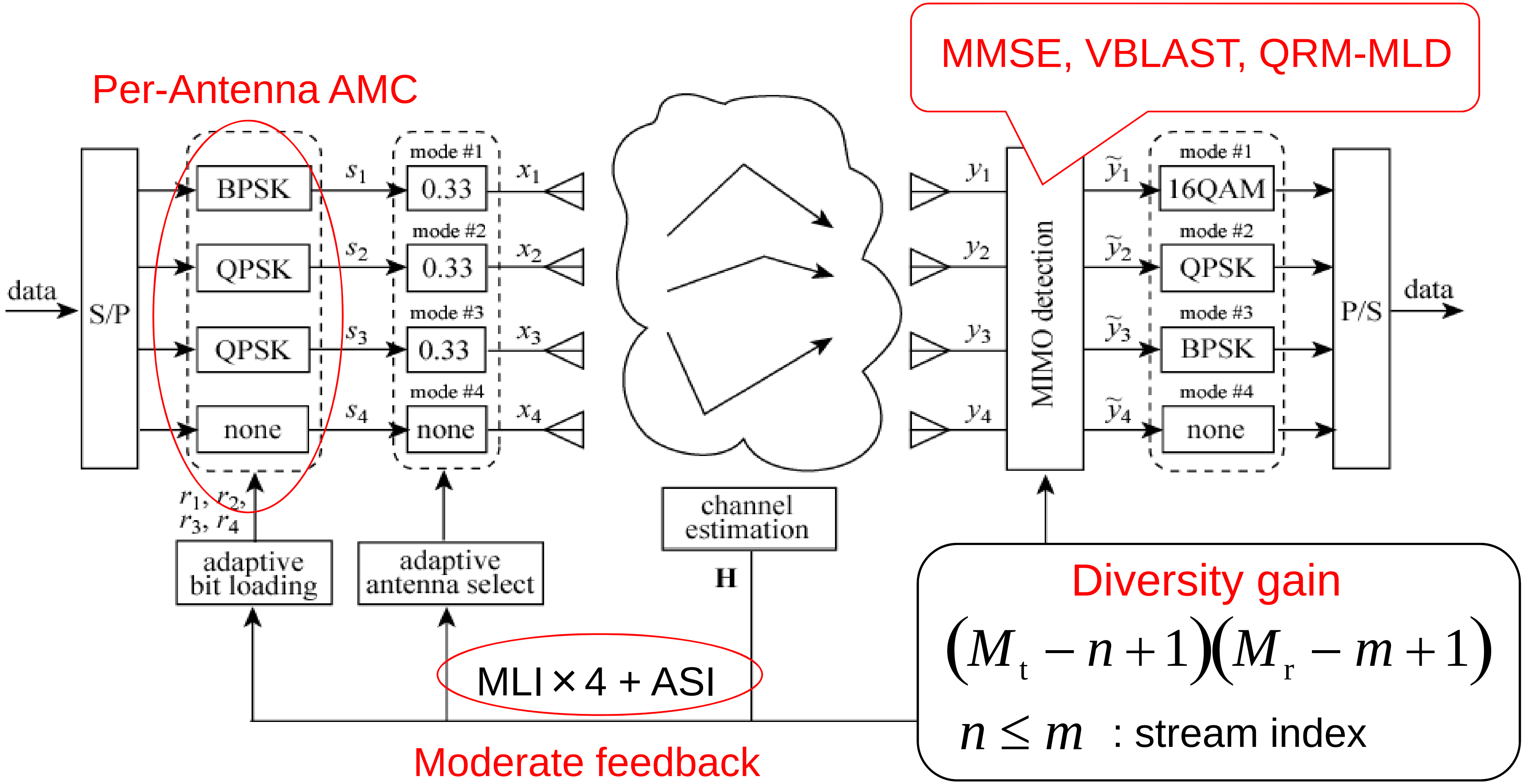
Throughput Performance of MIMO-EA

- Full multiplexing gain is achieved at extremely high SNR region
- VBLAST & QRM-MLD improve the performance owing to the diversity gain

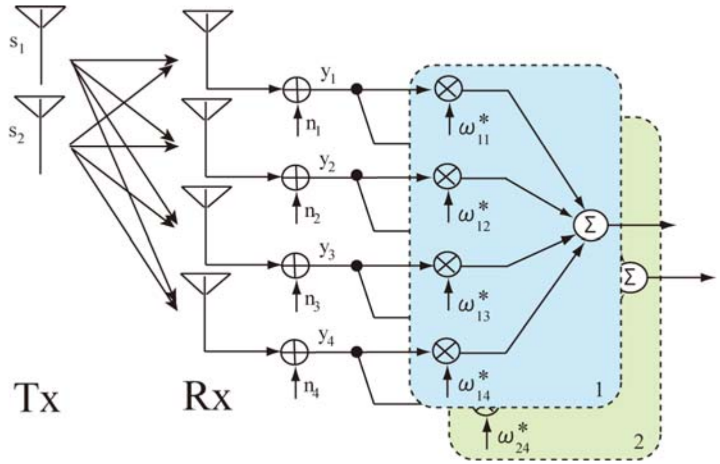


MIMO Per Antenna Adaptation (PAA)

- Per-antenna adaptive modulation based on estimated SINR of each stream
- Moderate feedback of MLI and antenna selection information (ASI)
- Transmit diversity due to m active antenna selection from M_t antennas



Adaptive Algorithm for MIMO-PAA



Antenna selection at Tx

$$\mathbf{W}_{\mathrm{t}} = \mathrm{diag}[1,1,0,0]$$

when selecting antenna #1 & #2

out of ${}_{M_{\mathrm{t}}}\mathrm{C}_m$ combinations

Transmit diversity

MMSE detection at Rx

$$\mathbf{W} = \left(\tilde{\mathbf{H}}^H \tilde{\mathbf{H}} + \frac{m\sigma^2}{P} \mathbf{I}_m \right)^{-1} \tilde{\mathbf{H}}^H$$

$$\tilde{\mathbf{H}} = \mathbf{H}\mathbf{W}_{\mathrm{t}} \in C^{M_{\mathrm{r}} \times m}$$

Receive diversity

SNR for each stream

$$\gamma_i^{\mathrm{MMSE}} = \frac{1}{\left(\frac{P}{m\sigma^2} \tilde{\mathbf{H}}^H \tilde{\mathbf{H}} + \mathbf{I}_m \right)^{-1}_{ii}} - 1$$

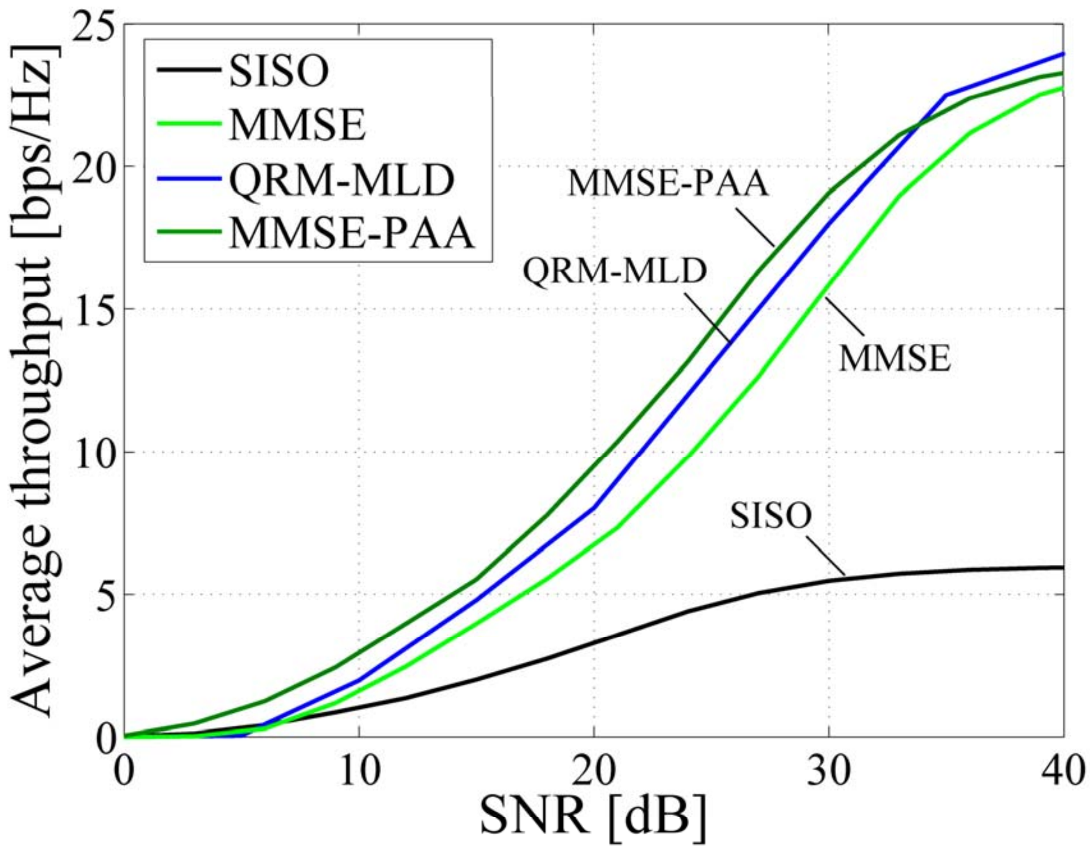
Adaptive algorithm

MLIs

$$\hat{M}_i^{\mathrm{ary}} = \arg\max_{M_{\mathrm{ary}}} TP\left(\gamma_i^{\mathrm{MMSE}}, M^{\mathrm{ary}}\right) \longrightarrow TP = \sum_{i=1}^{m} TP\left(\gamma_i^{\mathrm{MMSE}}, \hat{M}_i^{\mathrm{ary}}\right)$$

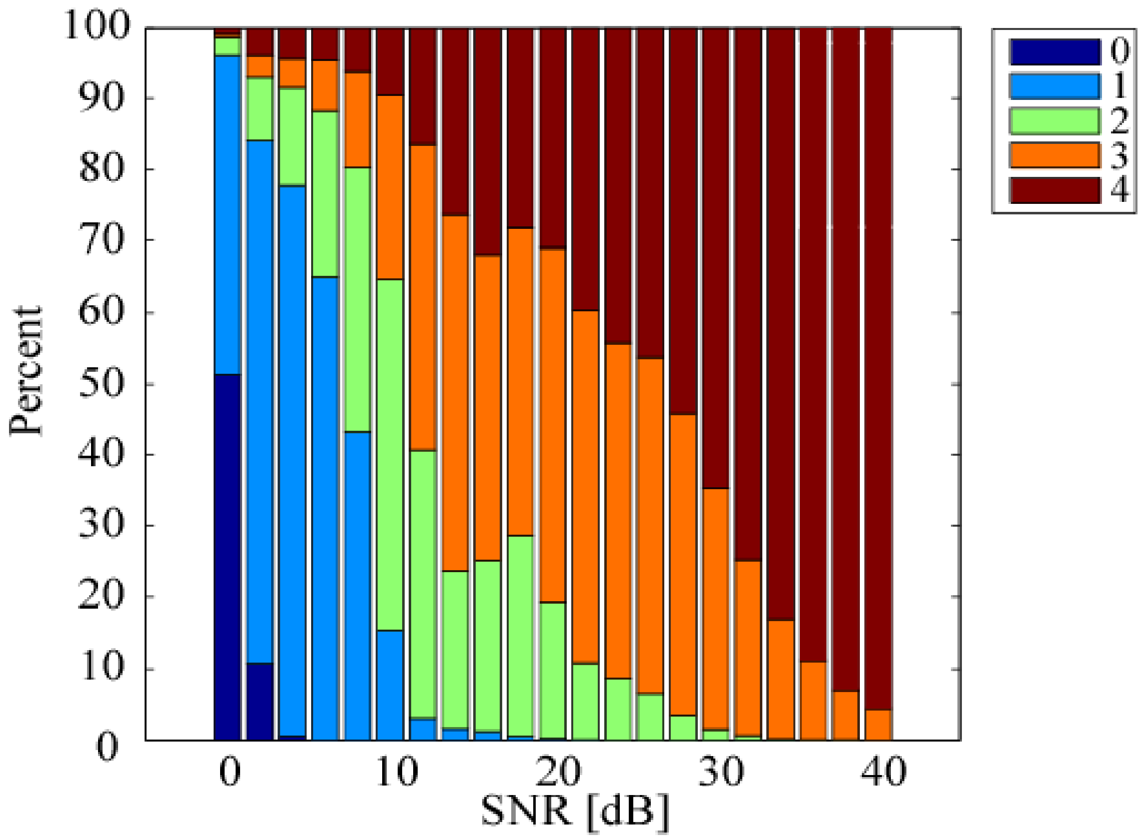
Throughput Performance of MIMO-PAA

- MIMO-PAA achieves better performance at low SNR region even with MMSE detection



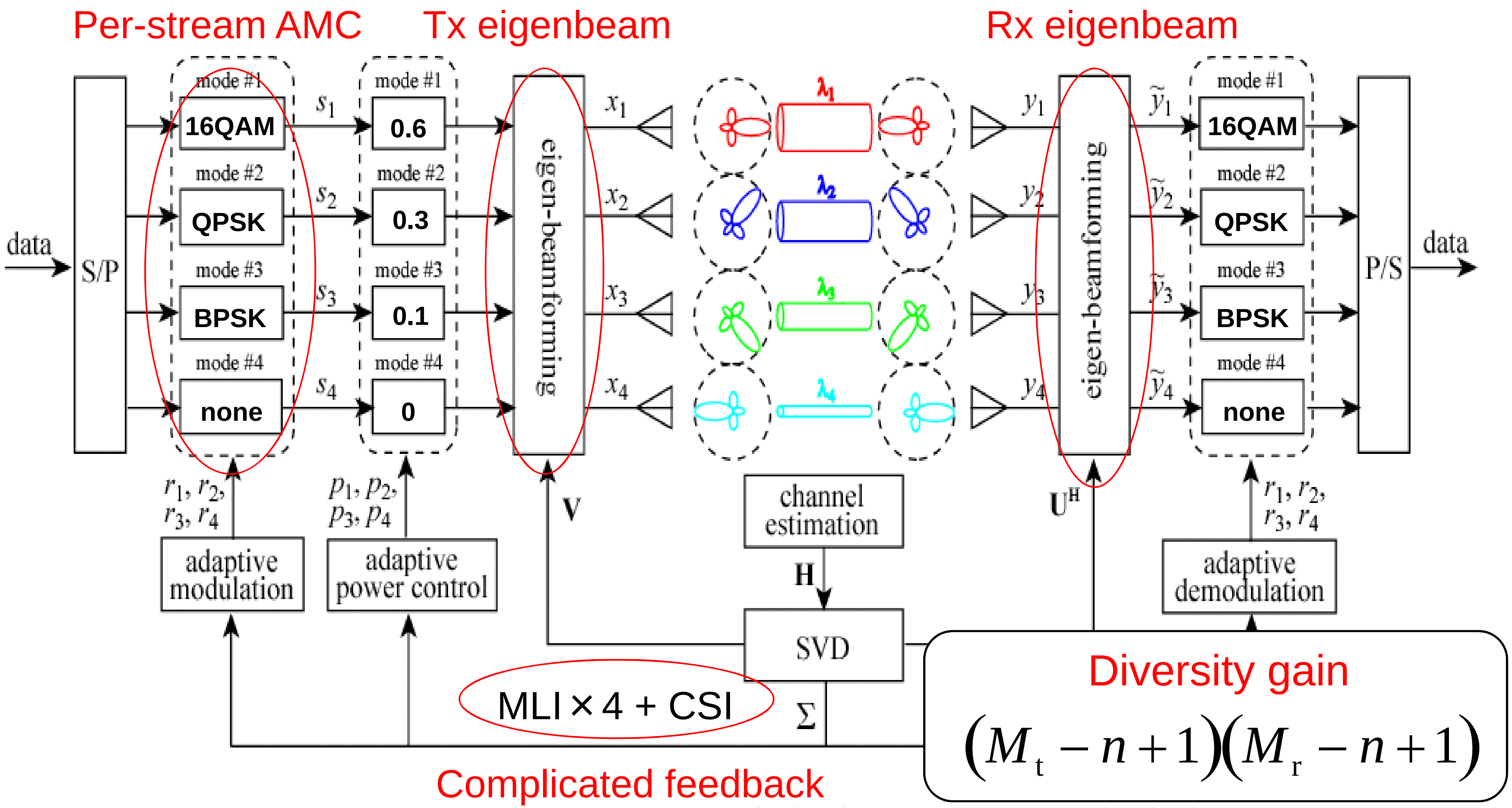
Antenna Selection Probability

- Full diversity gain at low SNR region
- Full multiplexing at high SNR region

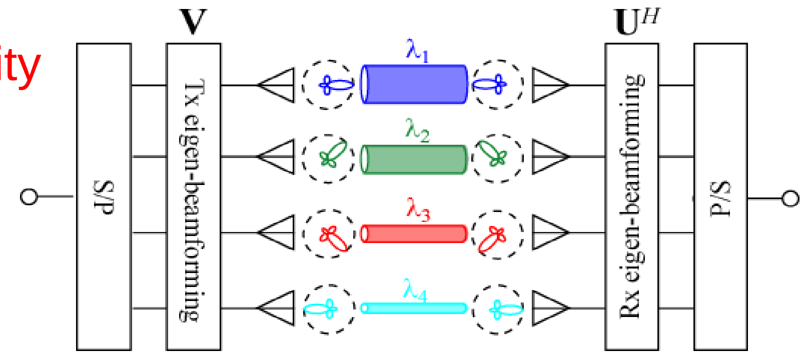


MIMO EigenMode Adaptation (EMA)

- Per-stream adaptive modulation based on estimated SNR of each eigenmode
- Complicated feedback of MLI + channel state information (CSI) for SVD-MIMO



Adaptive Algorithm for MIMO-EMA



SVD-MIMO

SVD of estimated channel

Full diversity

$$\mathbf{H} = \mathbf{U}\Sigma\mathbf{V}^H \qquad \Sigma = \mathrm{diag}\left[\sqrt{\lambda_1}, \cdots, \sqrt{\lambda_m}\right]$$

Transmit & receive eigen-beamforming

$$\mathbf{y}(t) = \mathbf{W}_{\mathrm{r}}^H \mathbf{H}\mathbf{W}_{\mathrm{t}}\mathbf{s}(t) + \mathbf{W}_{\mathrm{r}}^H \mathbf{n}(t)$$

$$= \Sigma\mathbf{s}(t) + \tilde{\mathbf{n}}(t) \quad \text{if} \quad \mathbf{W}_{\mathrm{r}} = \mathbf{U} \quad \mathbf{W}_{\mathrm{t}} = \mathbf{V}$$

Channel feedback

SNR for each eigenmode

For equal power allocation

$$\gamma_i = \frac{P\lambda_i}{\sigma^2 m}$$

For adaptive power allocation

$$\gamma_i = \frac{P_i\lambda_i}{\sigma^2} \qquad P_i = \left[\mu - \frac{\sigma^2}{\lambda_i}\right]^+$$

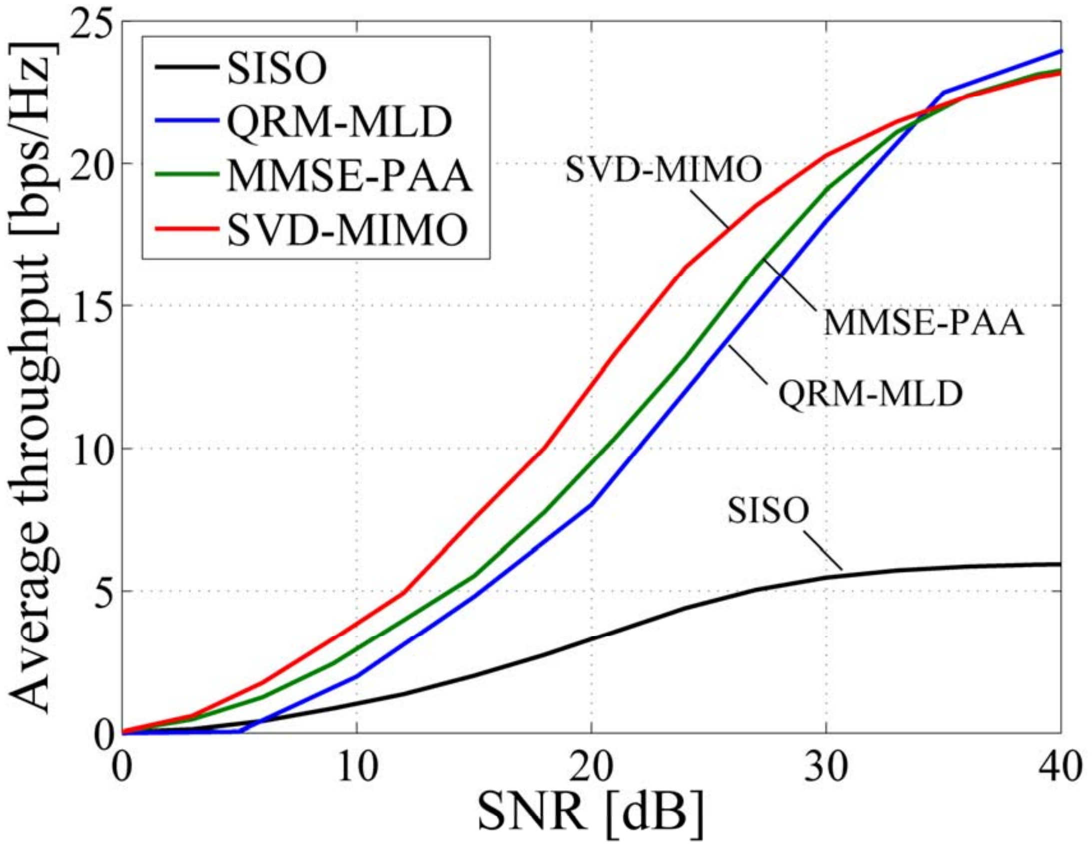
Adaptive algorithm

MLIs

$$\hat{M}_i^{\mathrm{ary}} = \arg\max_{M_{\mathrm{ary}}} TP\left(\gamma_i, M^{\mathrm{ary}}\right) \longrightarrow TP = \sum_{i=1}^{m} TP\left(\gamma_i, \hat{M}_i^{\mathrm{ary}}\right)$$

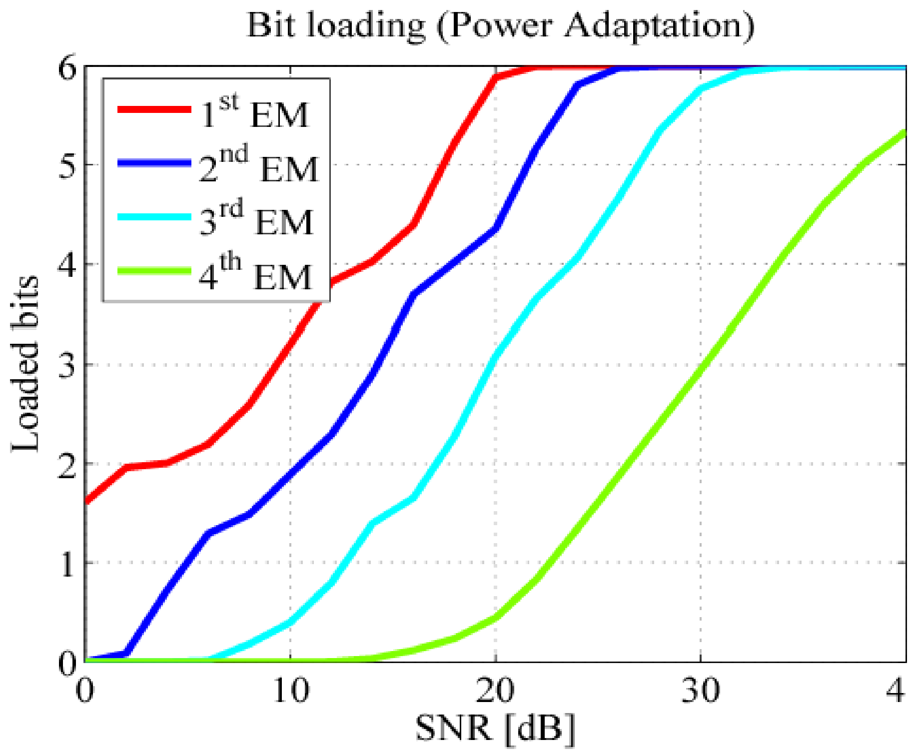
Throughput Performance of MIMO-EMA

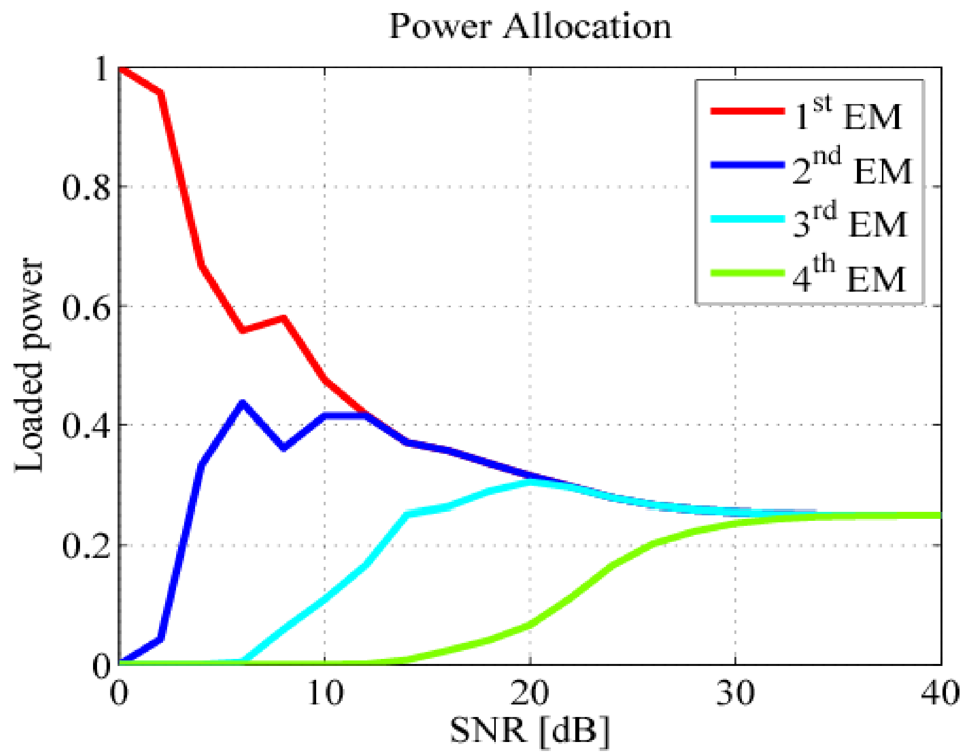
- SVD-MIMO (EMA) achieves best performance at reasonable SNR region



Bit & Power Allocation Probability

- Full diversity gain at low SNR region by using 1st eigenmode only
- Full multiplexing gain at high SNR region by using all eigenmodes
- The performance at high SNR region will be improved by employing higher modulation order





Comparison of Adaptive MIMO Algorithm

	Diversity	Multiplexing	Feedback	Performance
MMSE-EA	$(M_{r}-M_{t}+1)$	M_{t}	MLI	$>$ZF-EA
QRMLD-EA	M_{r}	M_{t}	MLI	$>$MMSE-EA
MMSE-PAA	$(M_{t}-n+1)\times(M_{r}-m+1)$	m	ASI, MLI $\times M_{t}$	$>$QRMLD-EA
SVD-MIMO	$(M_{t}-n+1)\times(M_{r}-n+1)$	m	CSI, MLI $\times M_{t}$	$>$MMSE-PAA

MLI： Modulation Level Information

ASI： Antenna Selection Information

CSI： Channel State Information

Measurement Experiment

MIMO configuration	4 (Tx) x 4 (Rx)
MIMO channel	Measured data (IID for simulation)
MIMO transmitter	Spatial multiplexing, SVD-MIMO
MIMO receiver	MMSE, VBLAST, QRM-MLD
MIMO adaptation	EA, PAA, EMA
Modulation order	BPSK, QPSK, 16QAM, 64QAM
Frame configuration	IEEE802.11a based w/o coding
Packet length	480 bits
Channel estimation	Perfect
Transmit power	0 dBm

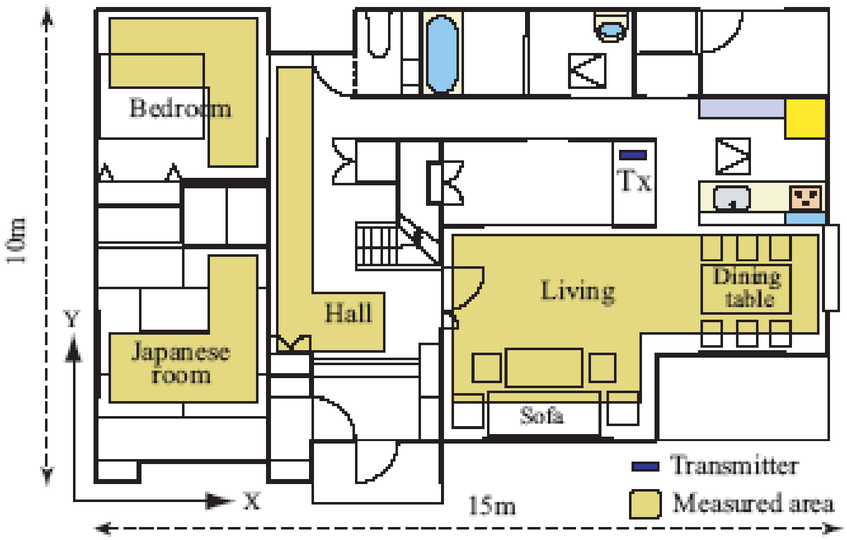
Channel Measurement

Measurement condition

MIMO configuration	4(Tx) x 4(Rx)
Array configuration	Half a wavelength spacing ULA
Center frequency	5.06 GHz
# of measurement points	55,738 (2cm step)

Pana home

Measurement area

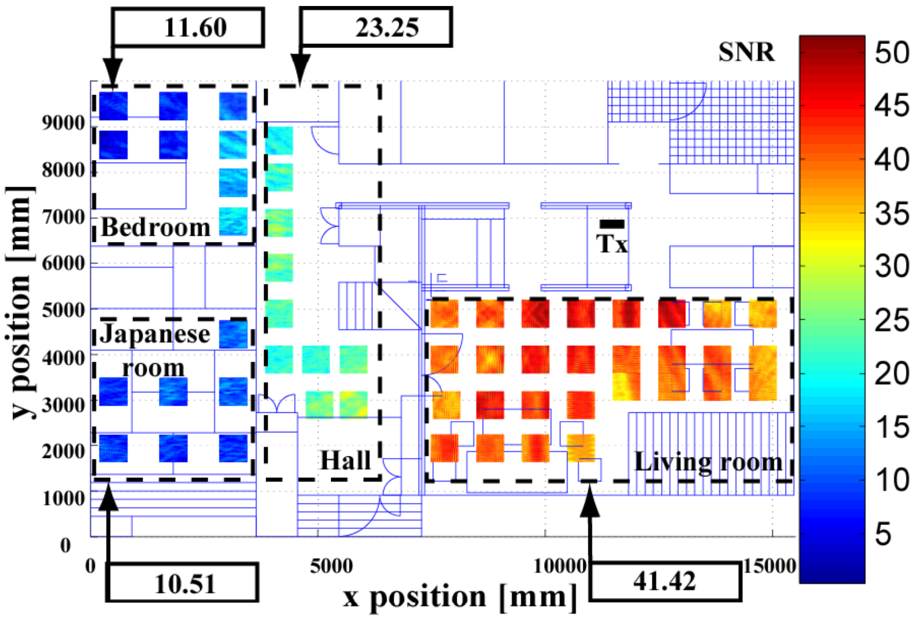


SNR / Spatial Correlation Distribution

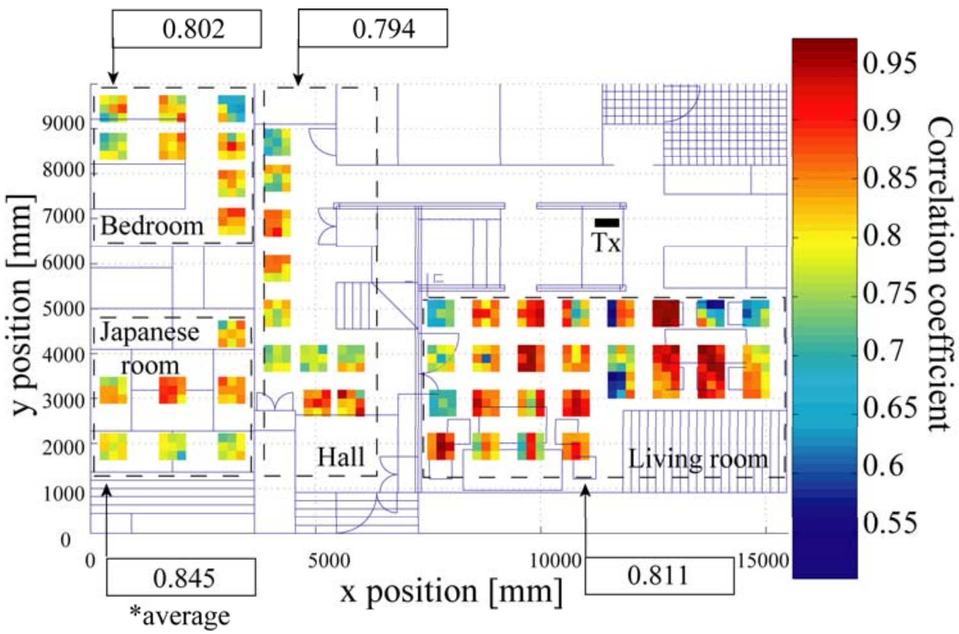
- High SNR in living room due to strong LOS component
- High spatial correlation even in NLOS environment

  ⟶ Wooden house is not a rich scattering environment

SNR distribution



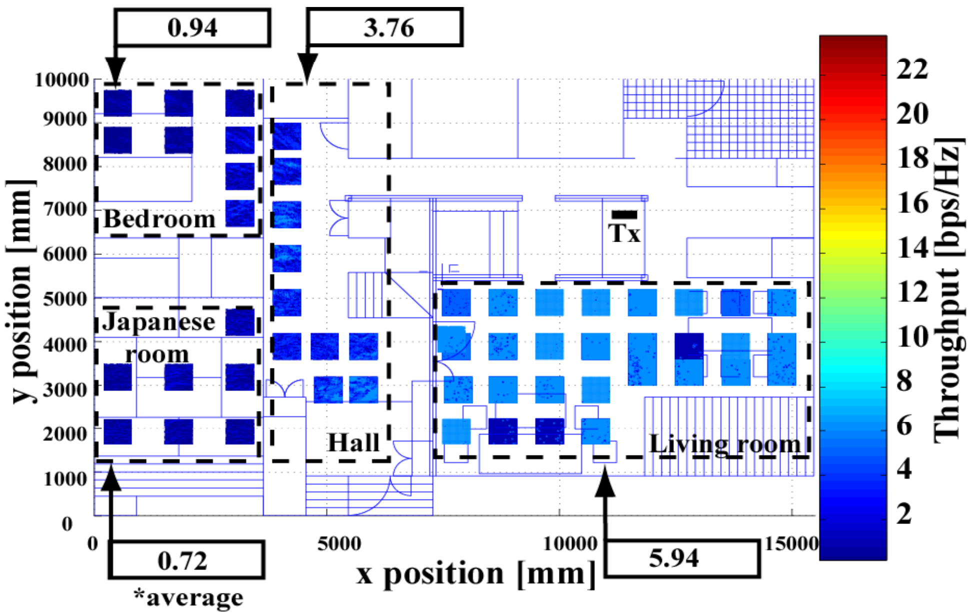
Spatial correlation distribution



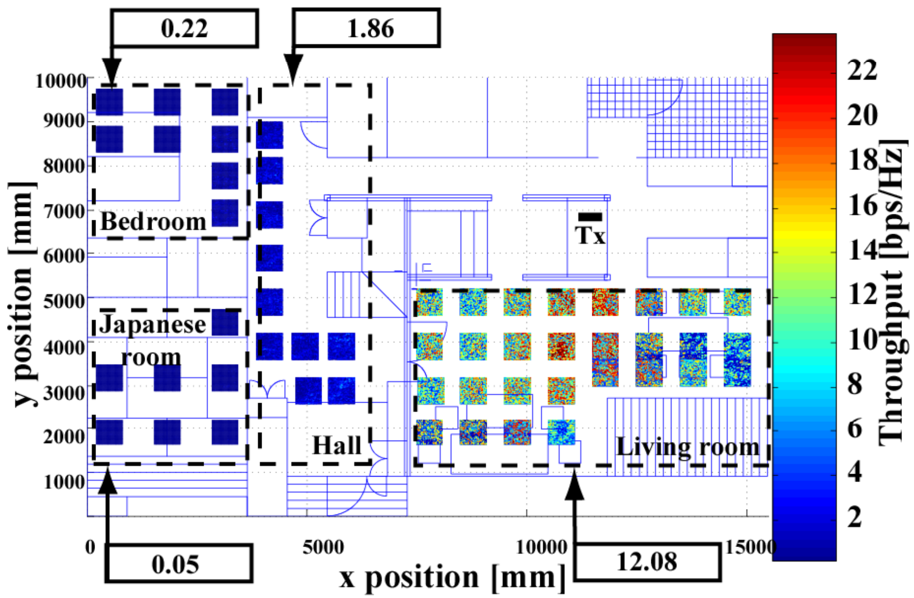
SISO vs. MIMO-EA (MMSE)

- Higher throughput of MMSE (MIMO-EA) in living room with high SNR
- Throughput degrades in low SNR region due to bit over loading

SISO



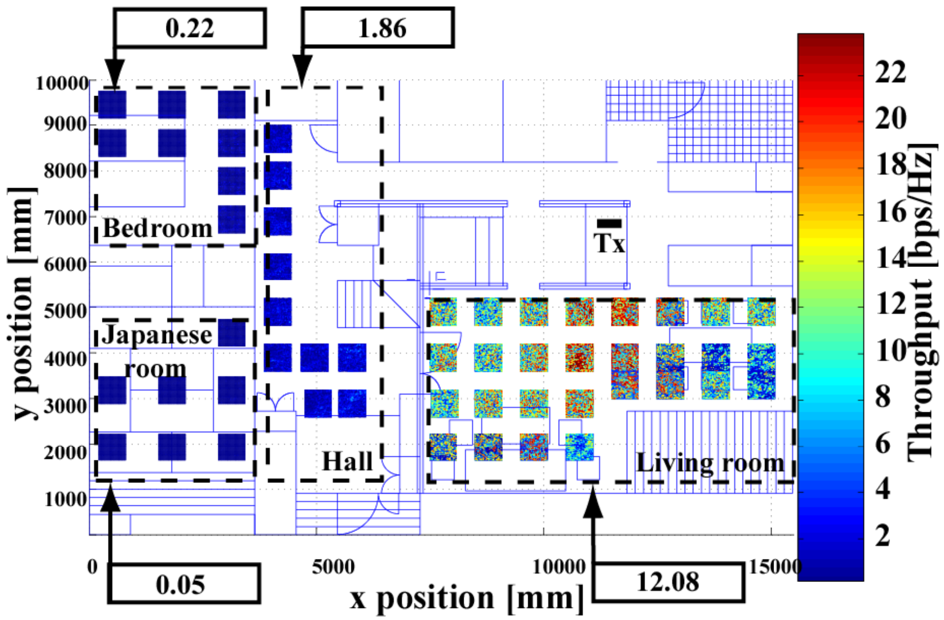
MMSE



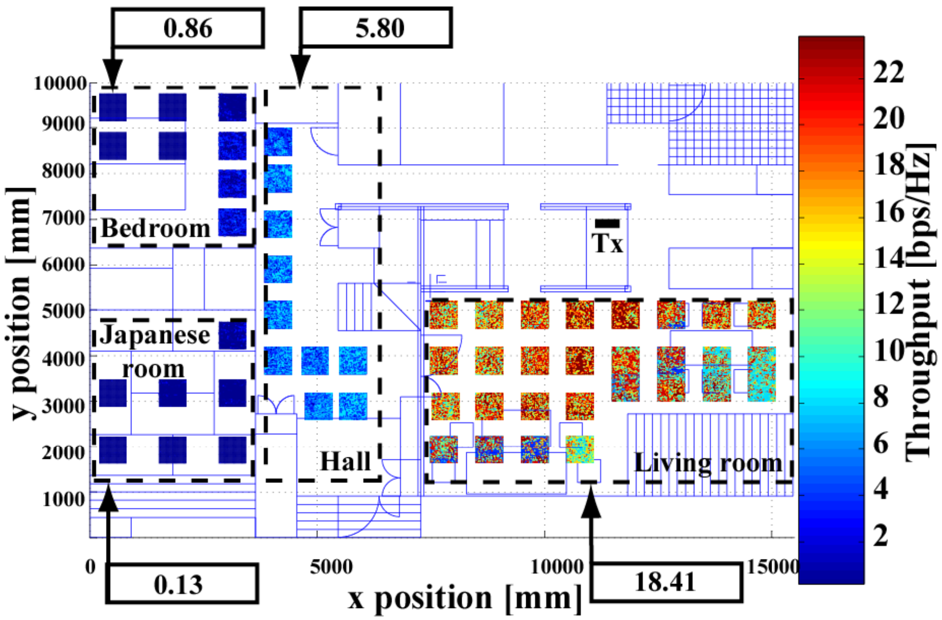
MMSE vs. VBLAST

- Performance improvement by VBLAST due to diversity gain
- Diversity function improves robustness against spatial correlation

MMSE



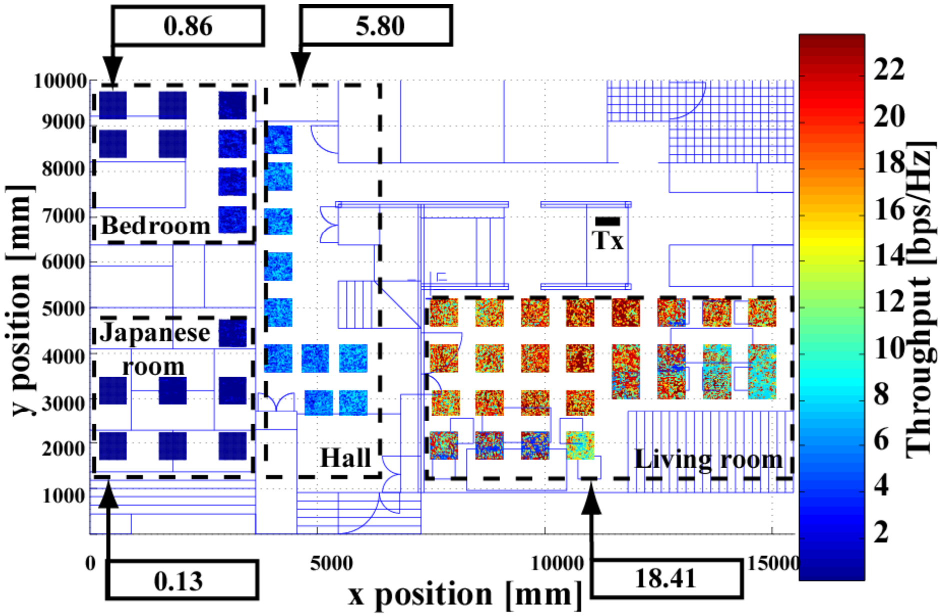
MMSE-VBLAST



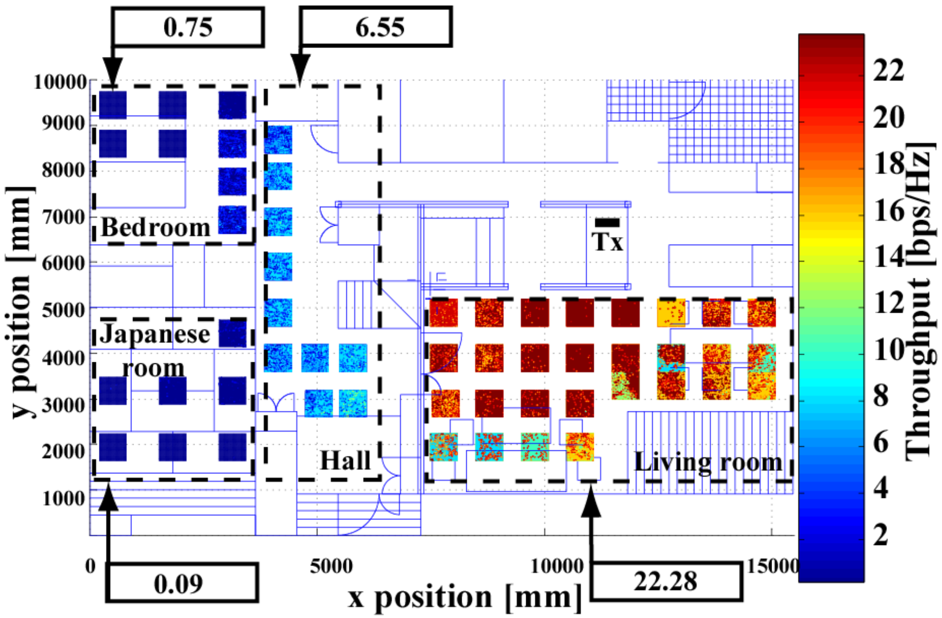
VBLAST vs. QRM-MLD

- Further performance improvement due to full receive diversity gain
- Slight performance degradation due to SNR penalty at low SNR

MMSE-VBLAST

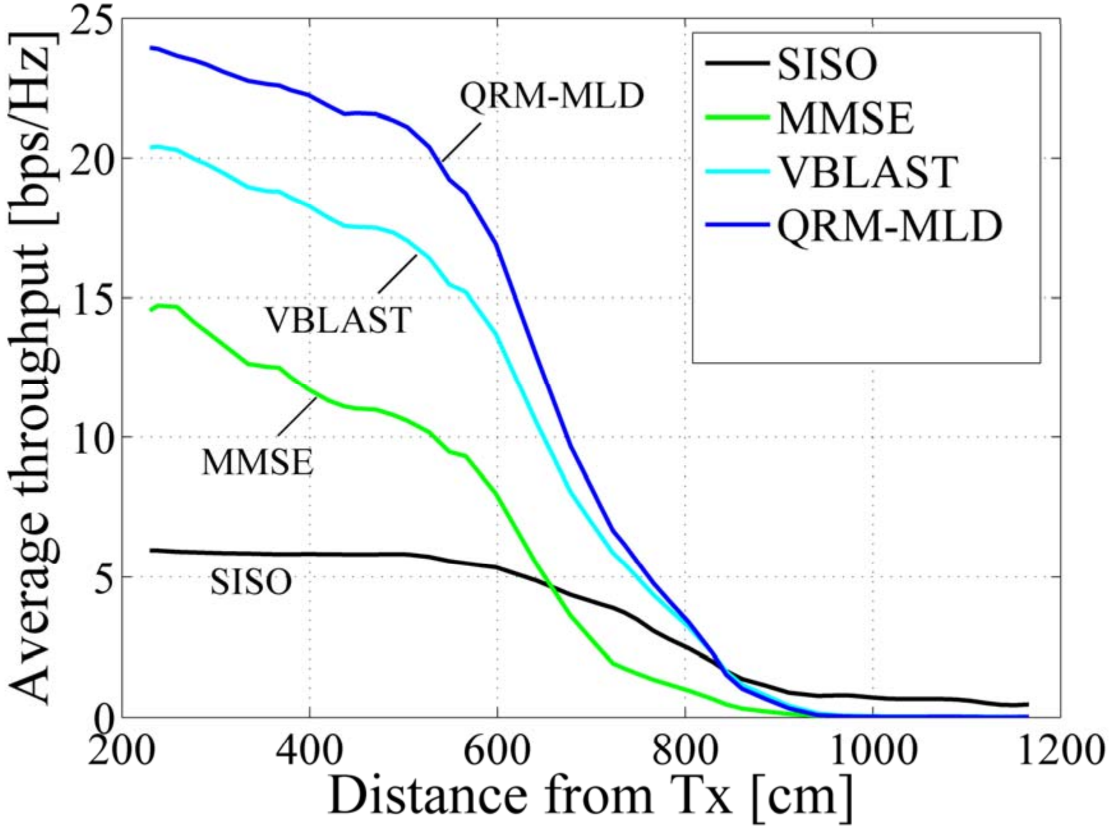


QRM-MLD



Distance vs. Throughput on MIMO-EA

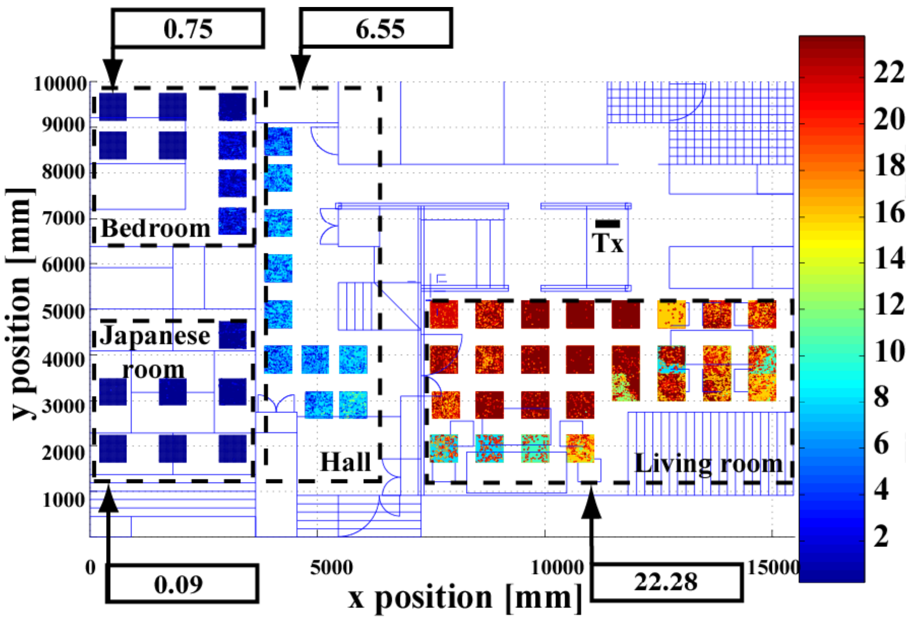
- Performance of MMSE is not worth employing in real environment
- VBLAST and QRM-MLD improve performance by receive diversity gain
- QRM-MLD achieves full multiplexing gain at high SNR region



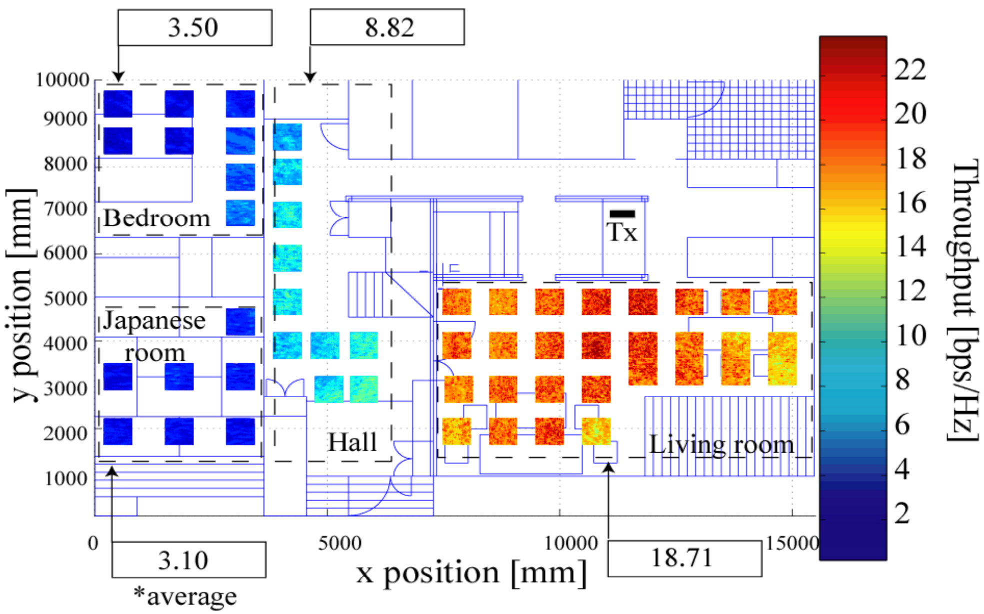
QRM-MLD vs. MIMO-PAA (MMSE)

- MMSE-PAA improves performance at low SNR region drastically
- Transmit diversity is effective to improve area coverage

QRM-MLD



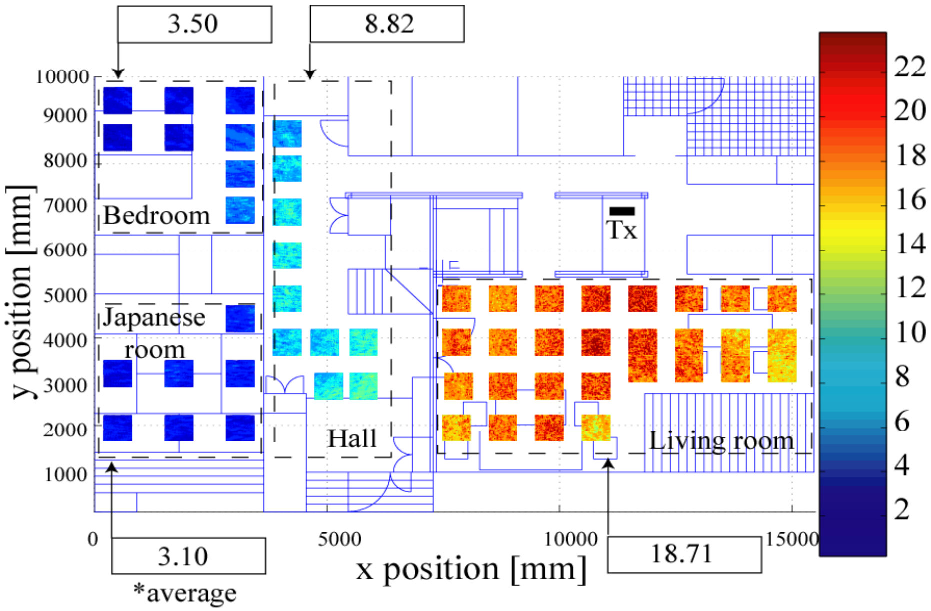
MMSE-PAA



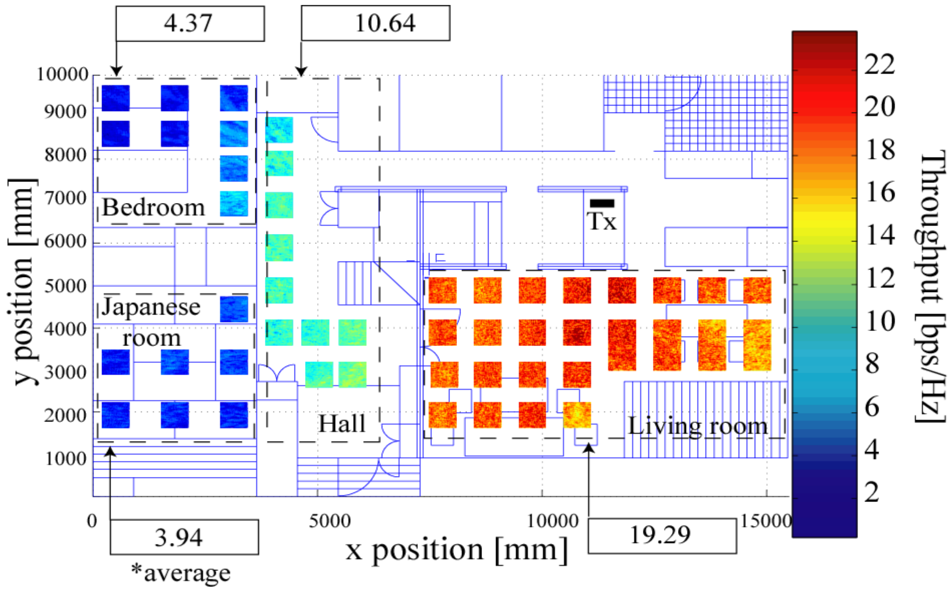
MMSE-PAA vs. MIMO-EMA (SVD-MIMO)

- Further performance improvement due to full diversity gain of SVD-MIMO
- Performance at high SNR region will be improved by employing higher modulation order

MMSE-PAA

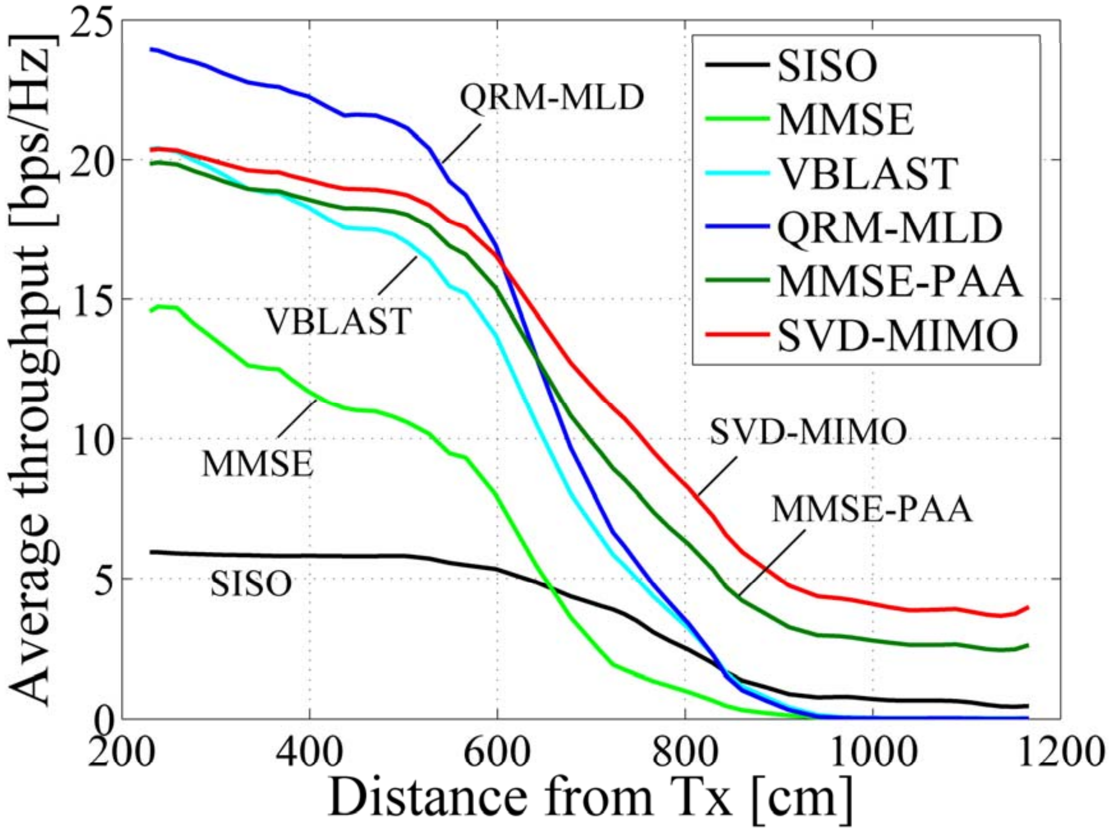


SVD-MIMO



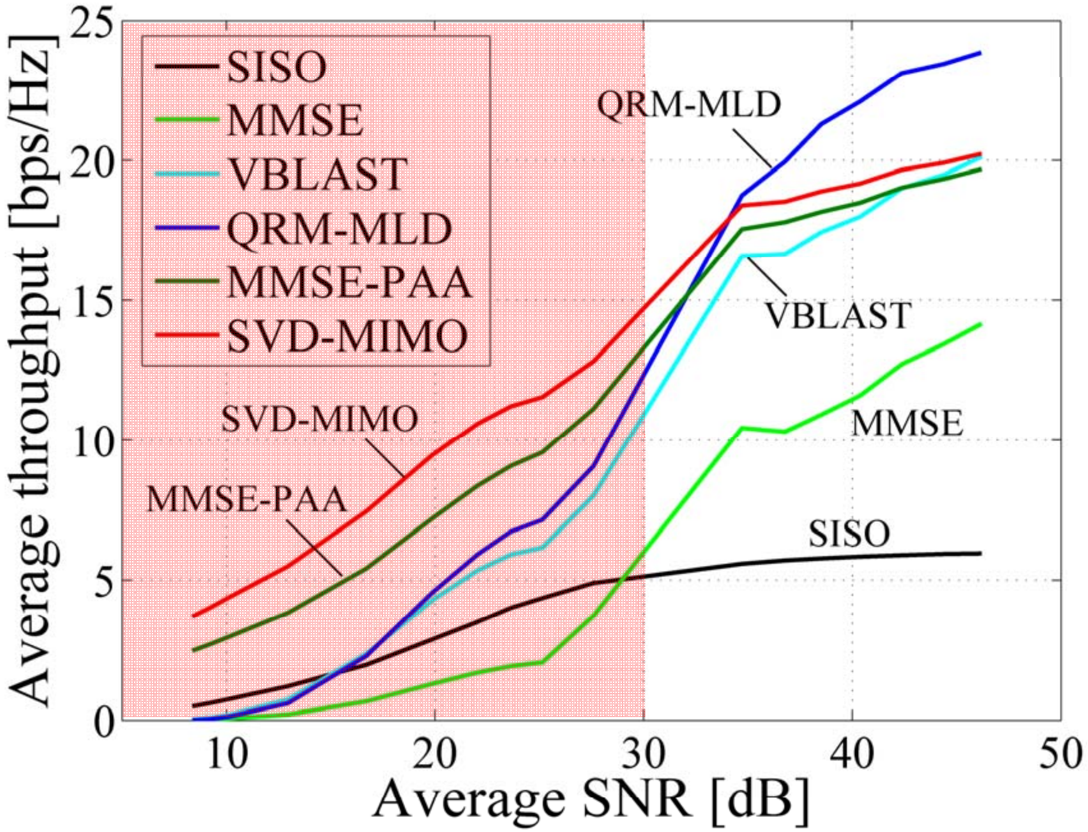
Distance vs. Throughput

- Full multiplexing gain of QRM-MLD is effective at high SNR region
- Full diversity gain of SVD-MIMO is effective at low SNR region



SNR vs. Throughput

- Performance of SVD-MIMO is best at reasonable SNR up to 30dB
- MMSE-PAA works effectively with reasonable feedback information



Summary

- Adaptive MIMO communication
  - Adaptive modulation coding based on instantaneous SINR
  - Active channel control based on feedback information
  - Tradeoff between feedback complexity and system performance

Complexity: MIMO-EA < MIMO-PAA < MIMO-EMA
Performance: MIMO-EA < MIMO-PAA < MIMO-EMA

Application of adaptive MIMO communication system to general scenario

Multi-User MIMO Communication