Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: Adaptive MIMO OFDM PHY Proposal for IEEE 802.15.7r1

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Abstract: This contribution presents a partial PHY proposal for IEEE 802.15.7r1 based on adaptive MIMO OFDM architecture.

Purpose: This is a partial PHY proposal based on adaptive MIMO OFDM architecture. Such advanced features are essential to achieve the ambitious targets of 10 Gbit/s envisioned in TCD Document.

Adaptive MIMO OFDM VLC PHY Proposal for IEEE802.15.7r1

Outline

- Introduction
- Description of adaptive MIMO OFDM VLC System
- Simulation Settings and Results
- Conclusions

Introduction

- This contribution presents a partial PHY proposal based on **adaptive MIMO OFDM** architecture. Such advanced features are essential to achieve the ambitious targets of 10 Gbit/s envisioned in IEEE 802.15.7r1 TCD Document

Related excerpts from the TCD Document

4.5.3
The standard must support at least one PHY mode that supports peak data rates of 10 Gbps at the PHY SAP.

4.5.5
The standard must provide MAC/PHY mechanisms to support adaptive transmission as well as the support of multiple users communicating different data streams from the same light source (multiple access).

4.5.9
The standard must support at least one optional PHY mode that supports multiple coordinated/uncoordinated transmitters, which is referred to as multiple-input multiple-output (MIMO) communications.

Background (1): MIMO Communications

- MIMO schemes can provide either improvement in spectral efficiency (through multiplexing gain) or link reliability (through diversity gain).

- **Spatial Multiplexing (SMUX)**
  - Independent data streams are transmitted through each LED.
  - Multiplexing gain is min (M,N) where M and N respectively denote the number of LEDs and PDs.

- **Space-Time Coding**
  - Coded data streams are transmitted through each LED.
  - Diversity gain is M x N where M and N respectively denote the number of LEDs and PDs.
  - Unlike RF communications with coherent detection, VLC systems can use simple versions of space-time coding (repetition coding, RC) to extract diversity gains [1, 2].

[1] M. Safari and M. Uysal, “Do We Really Need OSTBCs for Free-Space Optical Communication with Direct Detection?”, *IEEE Transactions on Wireless Communications*, vol. 7, no. 11, p. 4445-4448, November 2008.
[2] T. Fath and H. Haas, "Performance Comparison of MIMO Techniques for Optical Wireless Communications in Indoor Environments," in *Communications, IEEE Transactions on* , vol.61, no.2, pp.733-742, February 2013.

Background (2): Link Adaptation

- In adaptive communication systems, transmission parameters such as modulation type/size, transmit power etc. can be selected according to channel conditions.

- **Example:** In low SNR conditions, to ensure link reliability, a modulation with small constellation size (e.g., BPSK) can be used. In high SNR conditions, high order modulation (e.g., 8-PSK) can be used to increase the data link.

- In MIMO systems, spatial dimension can be further included as an additional adaptive parameter, i.e., MIMO type, configuration etc.

- Link adaptation is commonly deployed in RF wireless standards, i.e., cellular, WiFi etc.

Background (3): O-OFDM

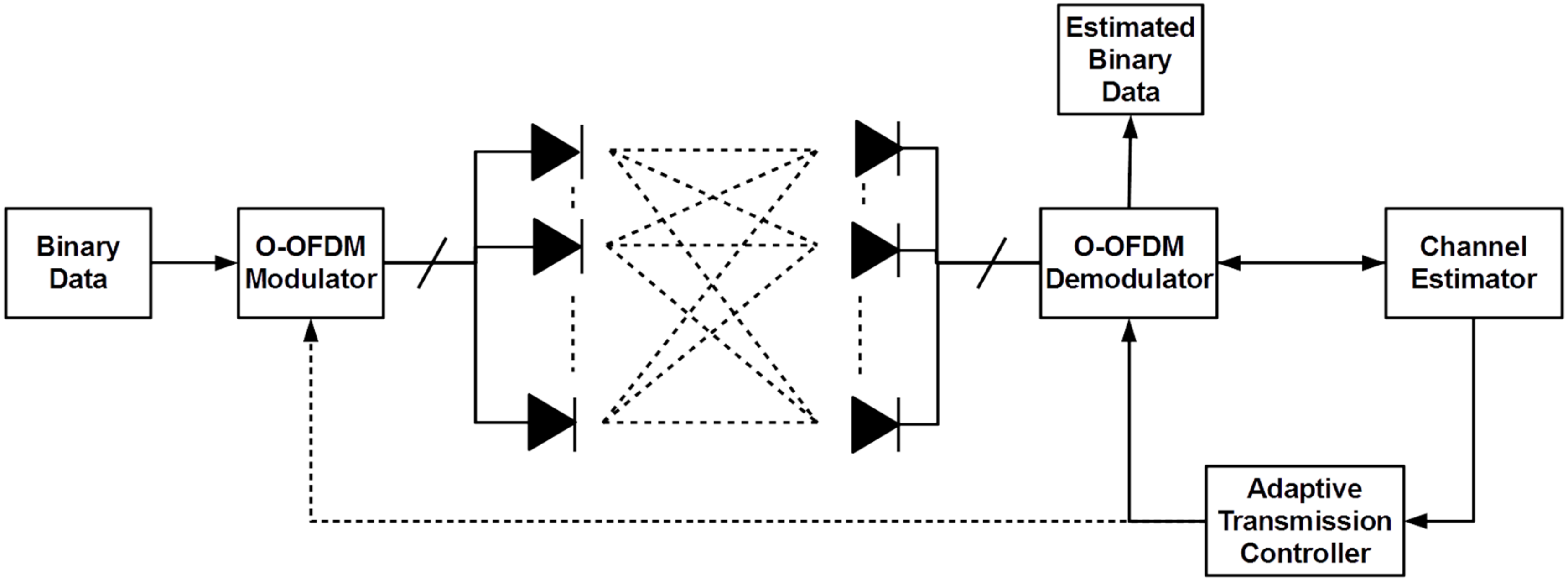
- As observed from reference channels, the VLC channel is of multipath nature and results in frequency-selectivity when high data speeds are targeted. An efficient approach to mitigate intersymbol interference (ISI) resulting from high frequency-selectivity is orthogonal frequency division multiplexing (OFDM).

- OFDM is a multi-carrier transmission system where the high-rate data stream is demultiplexed and transmitted over a number of frequency subcarriers. In general, OFDM output is complex and bipolar; however, a real and non-negative signal should be used in optical communication with intensity modulation.

- To solve this problem, modified OFDM schemes are proposed in the literature
  - DC biased optical OFDM (DCO-OFDM) [3]
  - Asymmetrically clipped optical OFDM (ACO-OFDM) [4]
  - Unipolar OFDM [5] or Flip OFDM [6]

[3] J. Armstrong, "OFDM for optical communications," Journal of Lightwave Technology, vol. 27, no. 3, pp. 189–204, February 2009.
[4] J. Armstrong and A. Lowery, "Power efficient optical OFDM, " Electronics Letters, vol. 42, no. 6, pp. 370–372, March 2006.
[5] N. Fernando, Y. Hong, and E. Viterbo, "Flip-OFDM for unipolar communication systems," IEEE Transactions on Communications, vol. 60, no. 12, pp. 3726–3733, December 2012.
[6] D. Tsonev, S. Sinanovic, and H. Haas, "Novel unipolar orthogonal frequency division multiplexing U-OFDM for optical wireless communication," IEEE Vehicular Technology Conference, 2012, pp. 1–6.

Block Diagram of Adaptive MIMO OFDM



Overall Summary of Proposed System

- Channel state information (CSI) is estimated. This may include the estimation of path loss, channel correlations, signal-to-noise-ratio, etc.

- According to the CSI, adaptive transmission controller at the receiver selects the optimal transmission parameters (i.e., modulation type, modulation order, MIMO configuration and MIMO type) that yield the highest performance metric under a given constraint metric and feeds back to the transmitter.

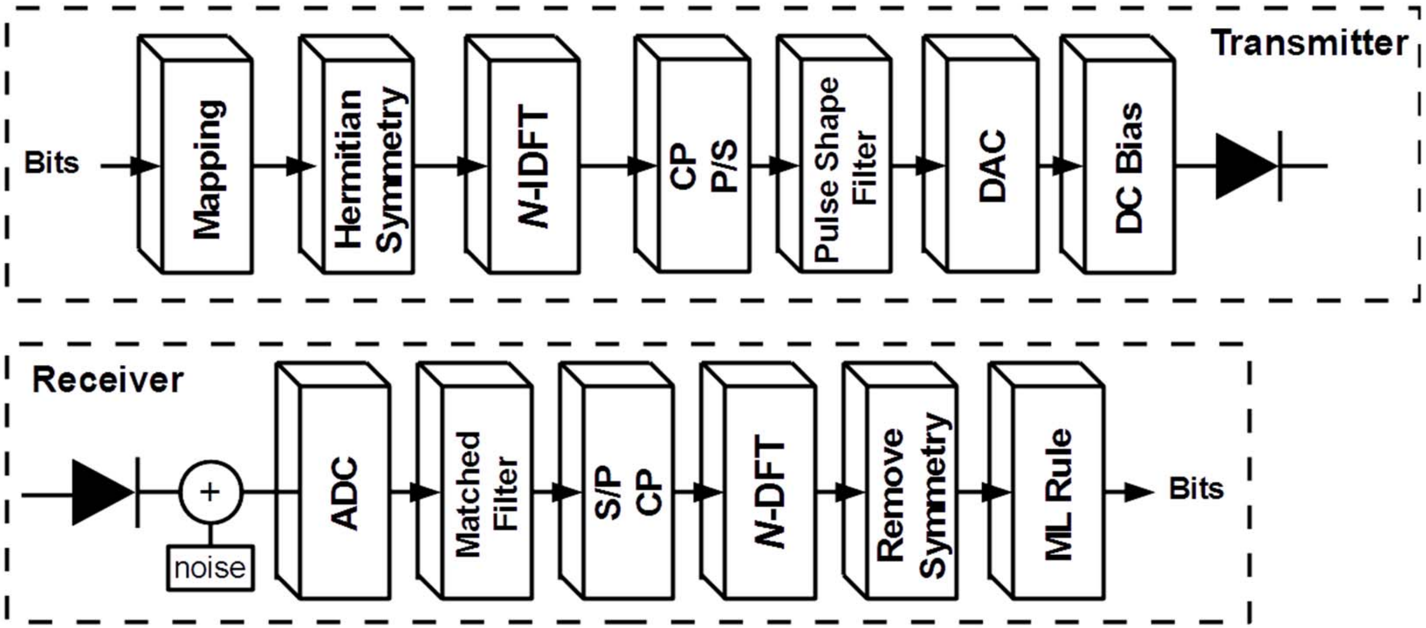
- To further improve the system performance, bit loading can be further performed.

Look-Up Table

Adaptive Transmission Mode	MIMO Configuration	MIMO Type	Modulation Type	Modulation Order	Performance Metric	Constraint Metric
1 2 . . .	1x1 1x2 ... *M*x*N*	RC SMUX	PSK QAM	2 4 8 16 32 64 128 256 512 1024 2048 4096	Pre-determined values for performance metric according to QoS requirements for targeted applications	Pre-determined values for constraint metric according to QoS requirements for targeted applications

OFDM Modulator/Demodulator

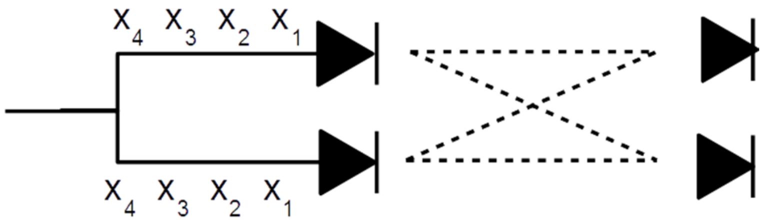
- The proposed adaptive structure is independent of OFDM type. In our proposal, we use DCO-OFDM with its better spectral efficiency in comparison to ACO-OFDM and U-OFDM (or Flip OFDM) counterpart.



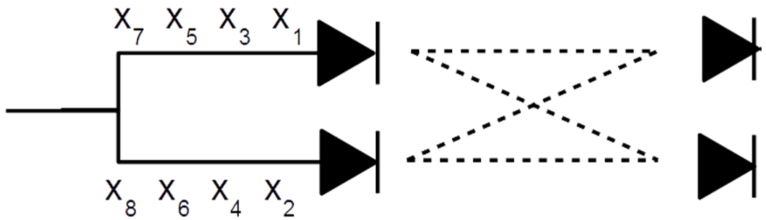
MIMO Schemes

- In our proposal, we use repetition code or spatial multiplexing to provide diversity or multiplexing gain.

- **Repetition coding (RC)**



- **Spatial Multiplexing**



PHY Rates (20 MHz, Diversity Mode)

PHY transmission rate, Mbit/s										
	x1 mode (NOT MIMO)		x2 mode		x4 mode		x6 mode		x8 mode	
Modulation	without CP	with CP	without CP	with CP	without CP	with CP	without CP	with CP	without CP	with CP
BPSK	15,00	14,33	15,00	14,33	15,00	14,33	15,00	14,33	15,00	14,33
4-QAM	30,00	28,66	30,00	28,66	30,00	28,66	30,00	28,66	30,00	28,66
8-QAM	45,00	42,99	45,00	42,99	45,00	42,99	45,00	42,99	45,00	42,99
16-QAM	60,00	57,31	60,00	57,31	60,00	57,31	60,00	57,31	60,00	57,31
32-QAM	75,00	71,64	75,00	71,64	75,00	71,64	75,00	71,64	75,00	71,64
64-QAM	90,00	85,97	90,00	85,97	90,00	85,97	90,00	85,97	90,00	85,97
128-QAM	105,00	100,30	105,00	100,30	105,00	100,30	105,00	100,30	105,00	100,30
256-QAM	120,00	114,63	120,00	114,63	120,00	114,63	120,00	114,63	120,00	114,63
512-QAM	135,00	128,96	135,00	128,96	135,00	128,96	135,00	128,96	135,00	128,96
1024-QAM	150,00	143,28	150,00	143,28	150,00	143,28	150,00	143,28	150,00	143,28
2048-QAM	165,00	157,61	165,00	157,61	165,00	157,61	165,00	157,61	165,00	157,61
4096-QAM	180,00	171,94	180,00	171,94	180,00	171,94	180,00	171,94	180,00	171,94

PHY Rates (20 MHz, Multiplexing Mode)

PHY transmission rate, Mbit/s										
	x1 mode (NOT MIMO)		x2 mode		x4 mode		x6 mode		x8 mode	
Modulation	without CP	with CP	without CP	with CP	without CP	with CP	without CP	with CP	without CP	with CP
BPSK	15,00	14,33	30,00	28,66	60,00	57,31	90,00	85,97	120,00	114,63
4-QAM	30,00	28,66	60,00	57,31	120,00	114,63	180,00	171,94	240,00	229,25
8-QAM	45,00	42,99	90,00	85,97	180,00	171,94	270,00	257,91	360,00	343,88
16-QAM	60,00	57,31	120,00	114,63	240,00	229,25	360,00	343,88	480,00	458,51
32-QAM	75,00	71,64	150,00	143,28	300,00	286,57	450,00	429,85	600,00	573,13
64-QAM	90,00	85,97	180,00	171,94	360,00	343,88	540,00	515,82	720,00	687,76
128-QAM	105,00	100,30	210,00	200,60	420,00	401,19	630,00	601,79	840,00	802,39
256-QAM	120,00	114,63	240,00	229,25	480,00	458,51	720,00	687,76	960,00	917,01
512-QAM	135,00	128,96	270,00	257,91	540,00	515,82	810,00	773,73	1080,00	1031,64
1024-QAM	150,00	143,28	300,00	286,57	600,00	573,13	900,00	859,70	1200,00	1146,27
2048-QAM	165,00	157,61	330,00	315,22	660,00	630,45	990,00	945,67	1320,00	1260,90
4096-QAM	180,00	171,94	360,00	343,88	720,00	687,76	1080,00	1031,64	1440,00	1375,52

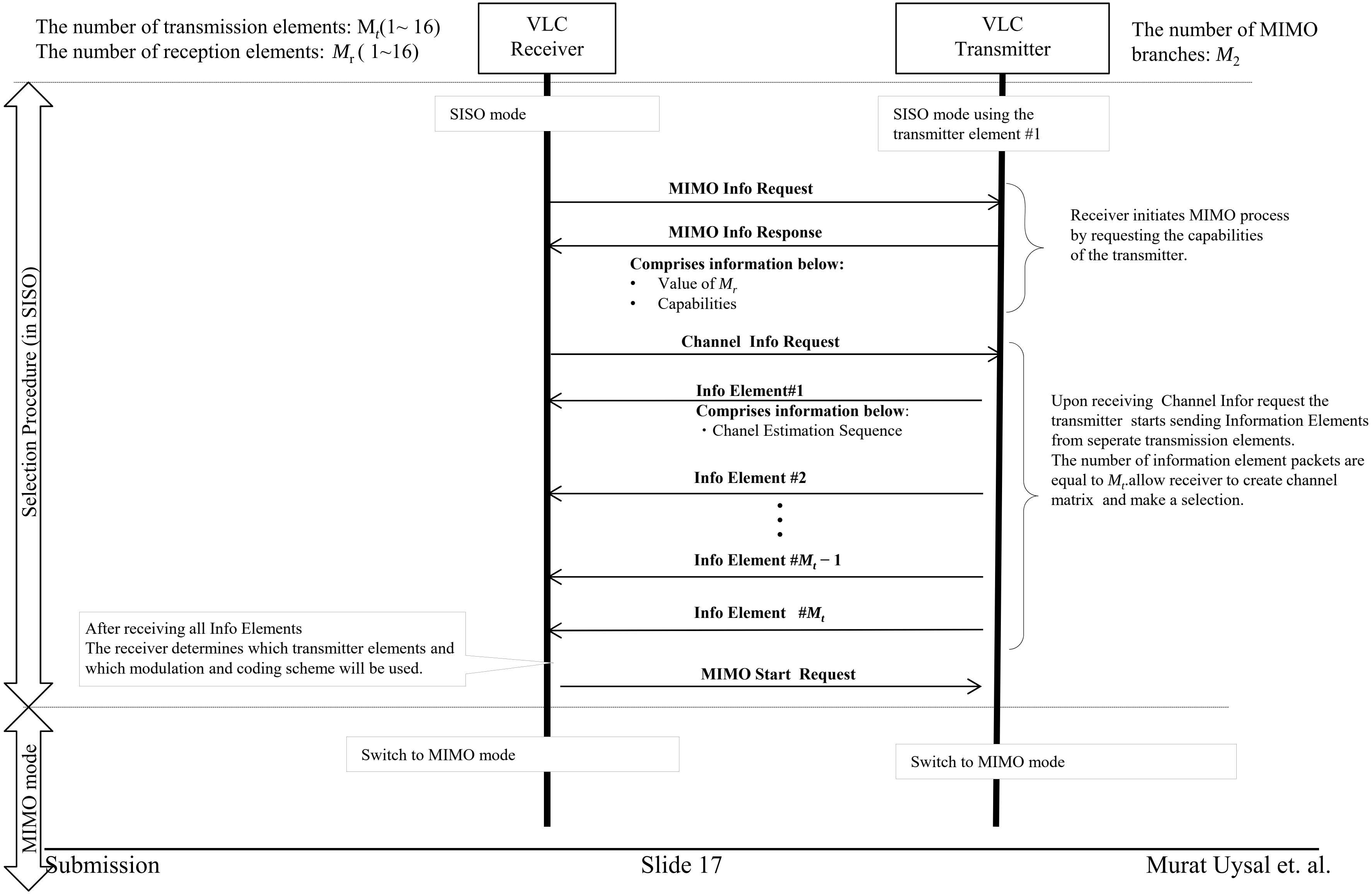
PHY Rates (200 MHz, Diversity Mode)

PHY transmission rate, Gbit/s										
	x1 mode (NOT MIMO)		x2 mode		x4 mode		x6 mode		x8 mode	
Modulation	without CP	with CP	without CP	with CP	without CP	with CP	without CP	with CP	without CP	with CP
BPSK	0,19	0,18	0,19	0,18	0,19	0,18	0,19	0,18	0,19	0,18
4-QAM	0,38	0,36	0,38	0,36	0,38	0,36	0,38	0,36	0,38	0,36
8-QAM	0,56	0,54	0,56	0,54	0,56	0,54	0,56	0,54	0,56	0,54
16-QAM	0,75	0,72	0,75	0,72	0,75	0,72	0,75	0,72	0,75	0,72
32-QAM	0,94	0,90	0,94	0,90	0,94	0,90	0,94	0,90	0,94	0,90
64-QAM	1,13	1,07	1,13	1,07	1,13	1,07	1,13	1,07	1,13	1,07
128-QAM	1,31	1,25	1,31	1,25	1,31	1,25	1,31	1,25	1,31	1,25
256-QAM	1,50	1,43	1,50	1,43	1,50	1,43	1,50	1,43	1,50	1,43
512-QAM	1,69	1,61	1,69	1,61	1,69	1,61	1,69	1,61	1,69	1,61
1024-QAM	1,88	1,79	1,88	1,79	1,88	1,79	1,88	1,79	1,88	1,79
2048-QAM	2,06	1,97	2,06	1,97	2,06	1,97	2,06	1,97	2,06	1,97
4096-QAM	2,25	2,15	2,25	2,15	2,25	2,15	2,25	2,15	2,25	2,15

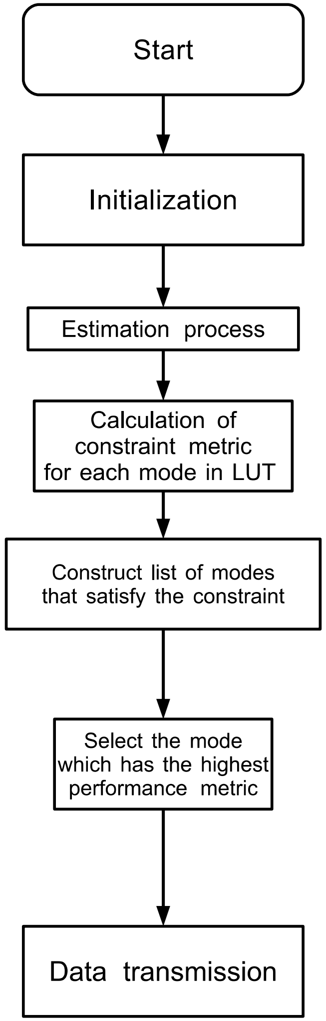
PHY Rates (200 MHz, Multiplexing Mode)

PHY transmission rate, Gbit/s										
	x1 mode (NOT MIMO)		x2 mode		x4 mode		x6 mode		x8 mode	
Modulation	without CP	with CP	without CP	with CP	without CP	with CP	without CP	with CP	without CP	with CP
BPSK	0,19	0,18	0,38	0,36	0,75	0,72	1,13	1,07	1,50	1,43
4-QAM	0,38	0,36	0,75	0,72	1,50	1,43	2,25	2,15	3,00	2,87
8-QAM	0,56	0,54	1,13	1,07	2,25	2,15	3,38	3,22	4,50	4,30
16-QAM	0,75	0,72	1,50	1,43	3,00	2,87	4,50	4,30	6,00	5,73
32-QAM	0,94	0,90	1,88	1,79	3,75	3,58	5,63	5,37	7,50	7,16
64-QAM	1,13	1,07	2,25	2,15	4,50	4,30	6,75	6,45	9,00	8,60
128-QAM	1,31	1,25	2,63	2,51	5,25	5,01	7,88	7,52	10,50	10,03
256-QAM	1,50	1,43	3,00	2,87	6,00	5,73	9,00	8,60	12,00	11,46
512-QAM	1,69	1,61	3,38	3,22	6,75	6,45	10,13	9,67	13,50	12,90
1024-QAM	1,88	1,79	3,75	3,58	7,50	7,16	11,25	10,75	15,00	14,33
2048-QAM	2,06	1,97	4,13	3,94	8,25	7,88	12,38	11,82	16,50	15,76
4096-QAM	2,25	2,15	4,50	4,30	9,00	8,60	13,50	12,90	18,00	17,19

Setup Sequence for MIMO Transmission



Determination of MIMO Type

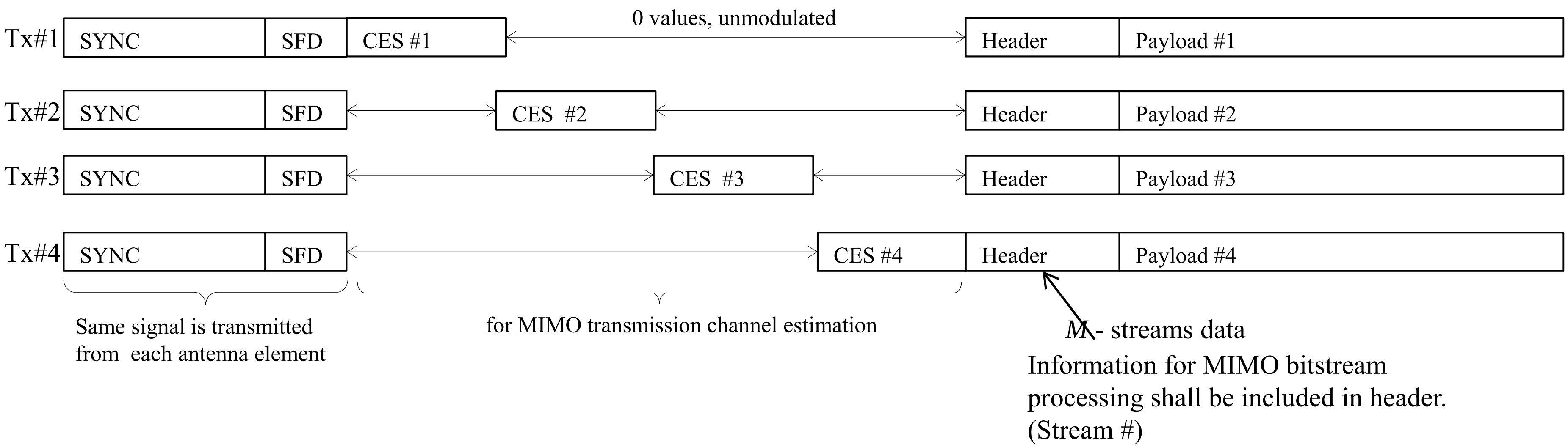


Receiver sends MIMO request

Estimation process starts with ChannelInfo.request Request Receiver obtains channel state information.

Receiver informs MIMO type to transmitter

PHY Frame Structure



- Synchronization (SYNC) part is used for frame detection, frame synchronization, frequency recovery and timing acquisition. Start Frame Delimiter (SFD) is to show that SYNC part finished.
- Channel Estimation Sequence (CES) should provide channel estimation of each transmitter.
- In all those parts, known sequences with good autocorrelation should be used, such as m sequences or Golay sequence.
- The Header contains essential information such as payload size, modulation, and coding used in the payload.

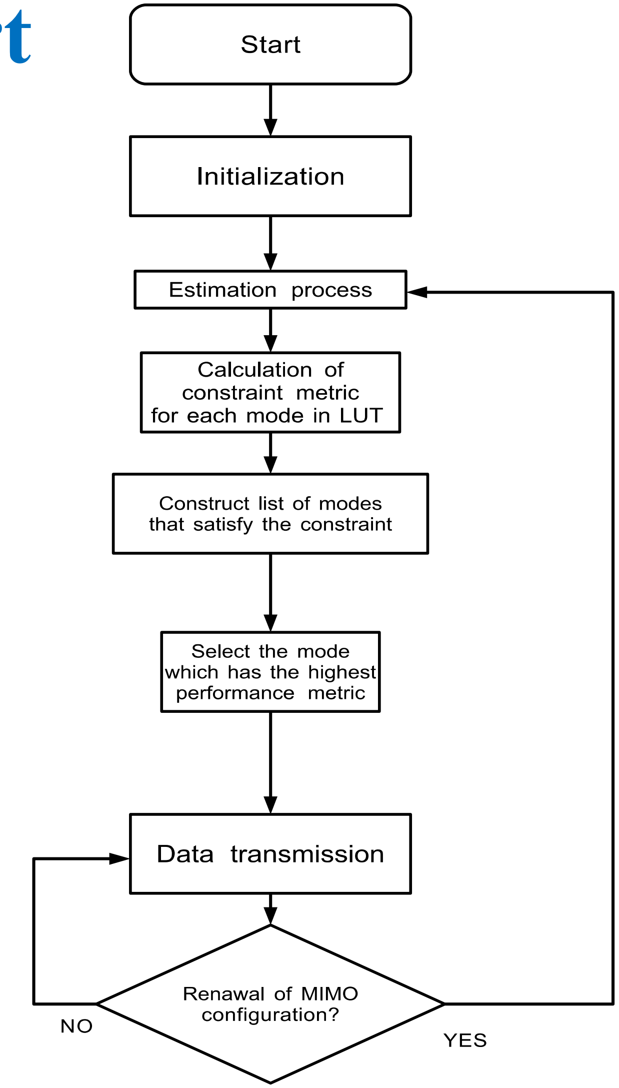
Transmitter Setup

- During data transmission the receiver uses the CES sequences to obtain CSI, adaptive transmission controller at the receiver selects the optimal transmission parameters (i.e., modulation type, modulation order, MIMO configuration and MIMO type) and feeds back to the transmitter in the ACK frame sent after each data frame.

- During data transmission, the adaptive transmission controller checks if renewal of the MIMO setup is necessary. Reasons for the setup renewal can be due to
  - The duration after the initial setup (i.e., a timer)
  - Low received signal strength from one or more transmitters
  - Low throughput or high frame error rate from the current configuration

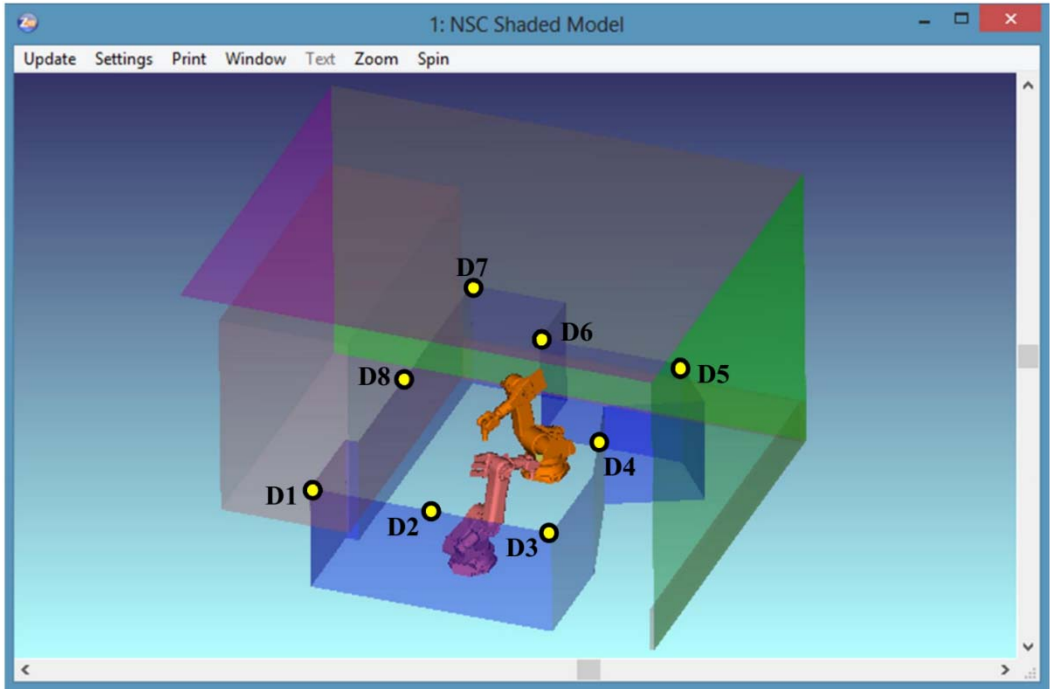
Transmitter Setup Flowchart

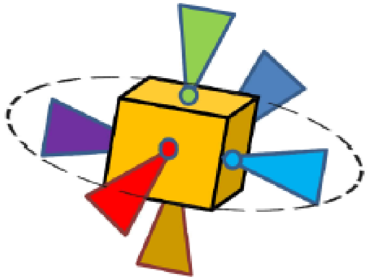
- If renewal of the MIMO setup is necessary, The receiver sends ChannelInfo.request to transmitter and the MIMO Setup process shown in slide 15.

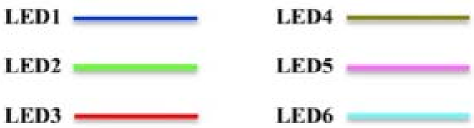


Simulation Settings (1/2)

- Scenario 4 (IEEE P802.15-15-0746-01-007a) with multiple transmitters is used for simulations





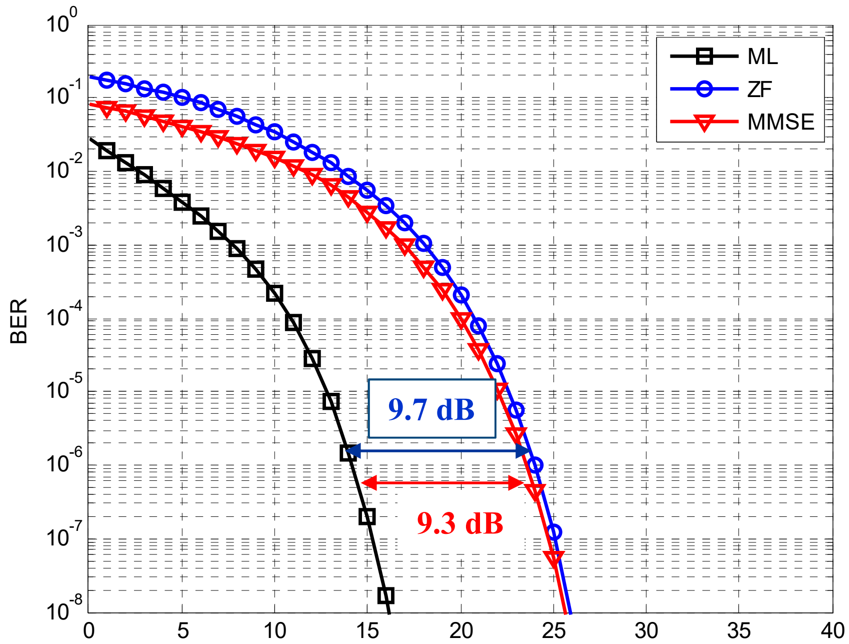


Simulation Settings (2/2)

System Bandwidth	20 MHz	200 MHz
Number of Subcarriers	256	2048
Number of Carriers for Data	96	960
Cyclic Prefix Length	12	96

Simulation Results (1/5)

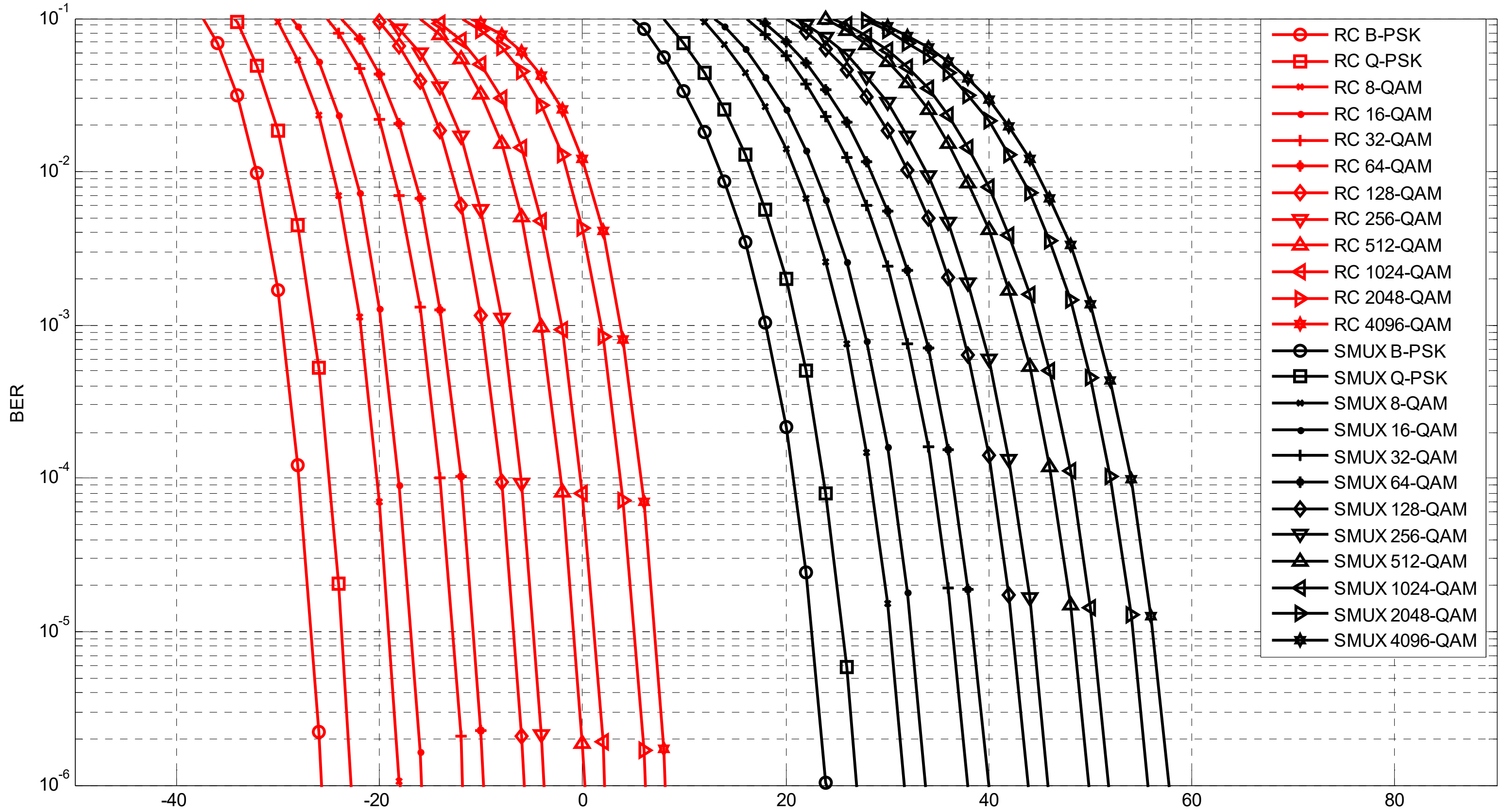
- *Maximum likelihood* (ML) decision rule is the optimal decoder. Its complexity can be prohibitively large for SMUX. Alternative receiver types are zero-forcing (ZF) and minimum mean square error (MMSE) receiver structures.



- 6x6 MIMO with B-PSK modulation in 20 MHz bandwidth is considered.
- In 6x6 MIMO structure, ML outperforms MMSE and ZF with the gains of 9.3 dB and 9.7 dB at the 10^{-6} BER.

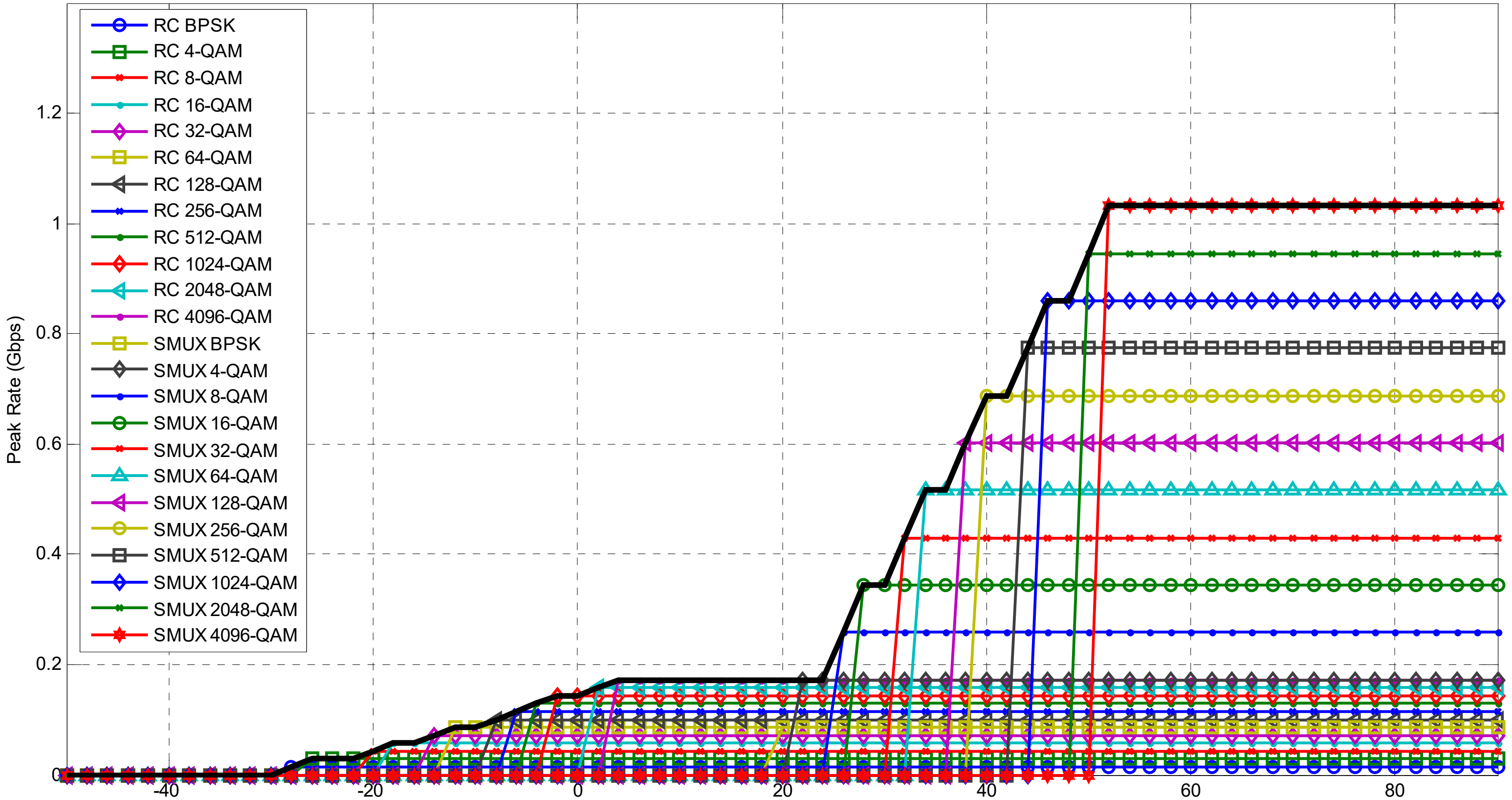
Simulation Results (2/5)

- BER performance of 6x6 MIMO systems (*B*=20 MHz)



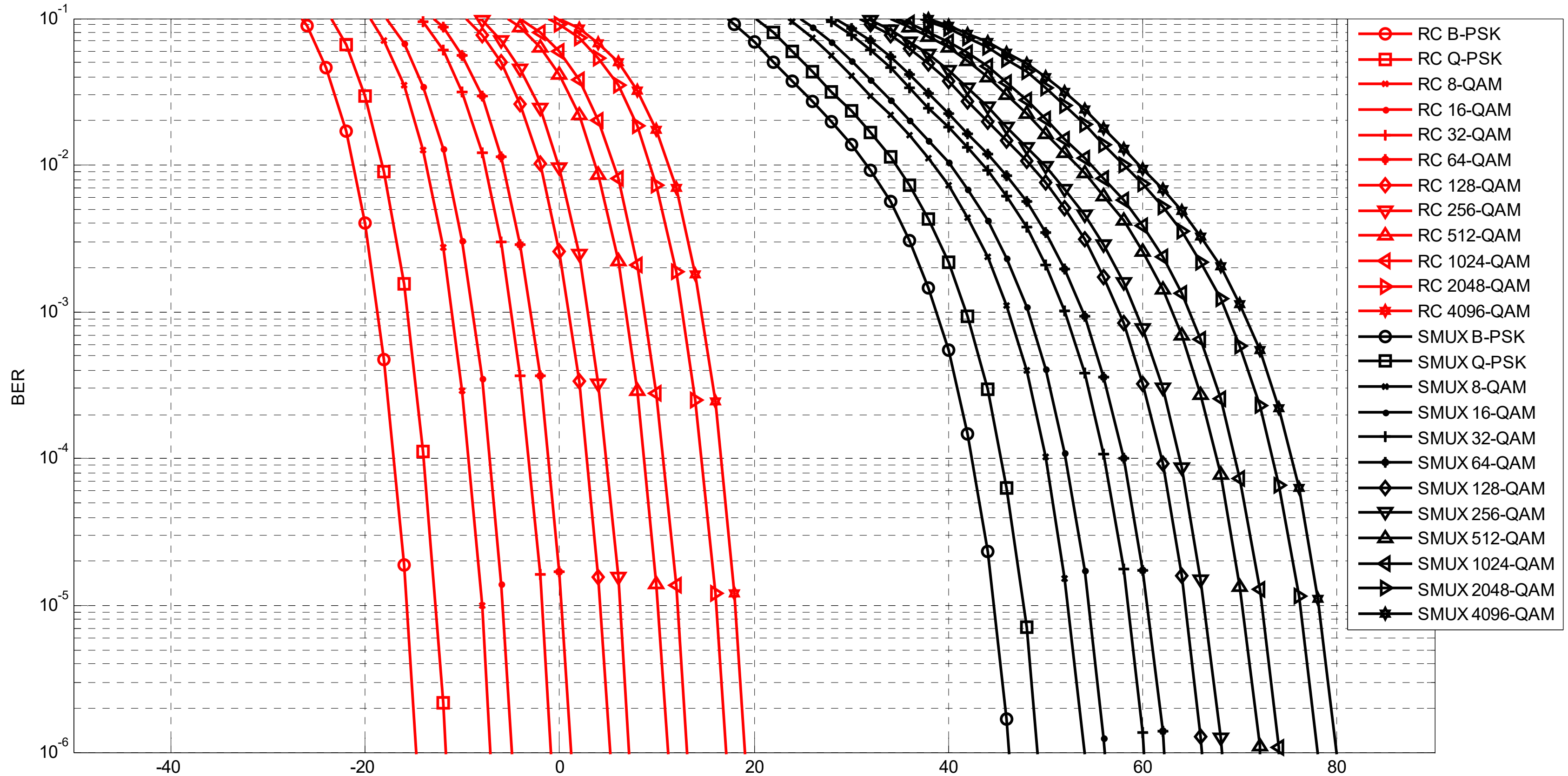
Simulation Results (3/5)

- Peak data rate of 6x6 MIMO systems (*B*=20 MHz)
- Target BER is set to 10^{-6}.



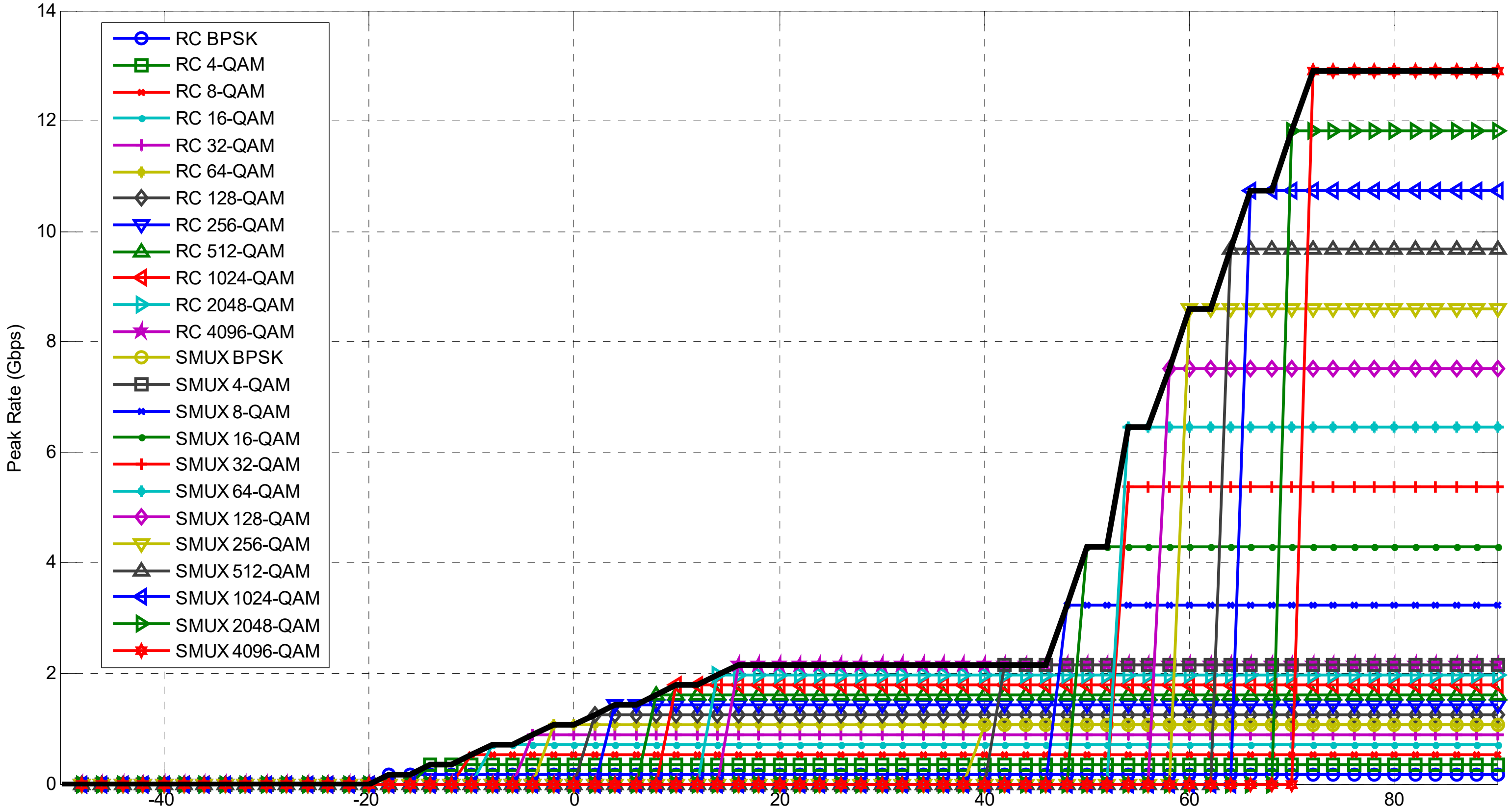
Simulation Results (4/5)

- BER performance of 6x6 MIMO systems (*B*=200 MHz)



Simulation Results (5/5)

- Peak data rate of 6x6 MIMO systems (*B*=200 MHz)
- Target BER is set to 10^{-6}.



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