Multi-User MIMO Wireless System

-From Theory to Chip Design-

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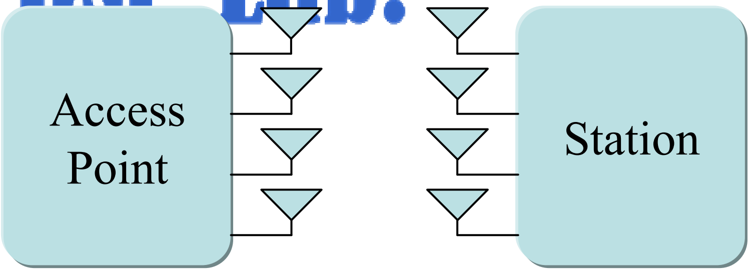
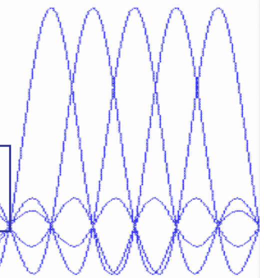
Background



MIMO System

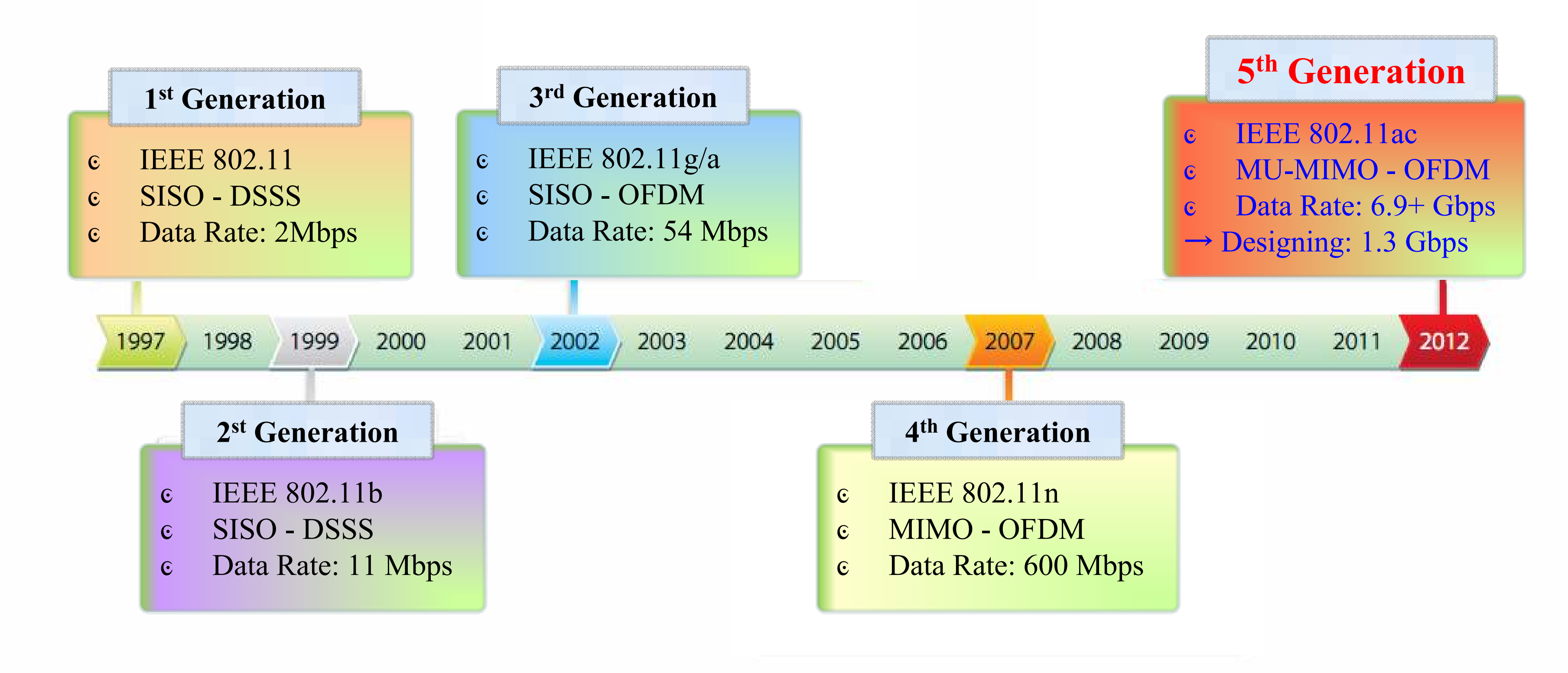
- **IEEE 802.11a** Maximum transmission rate: 54[Mbps]
  - OFDM (Orthogonal Frequency Division Multiplexing)
- **IEEE 802.11n** Maximum transmission rate: 600[Mbps]
  - MIMO (Multiple Input Multiple Output)
  - Transmission method with multi-user
    - CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance)

⇒ Overall system throughput is reduced by a higher number of users.



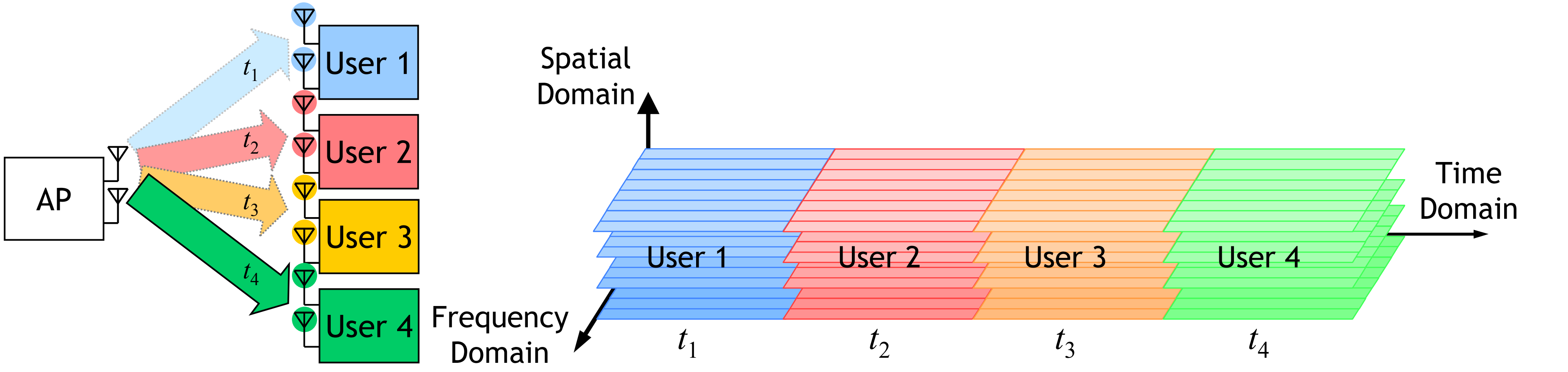
- **IEEE 802.11ac** Maximum transmission rate: more than 1[Gbps]
  - **Simultaneous communication with multiple users (MU-MIMO).**

IEEE802.11

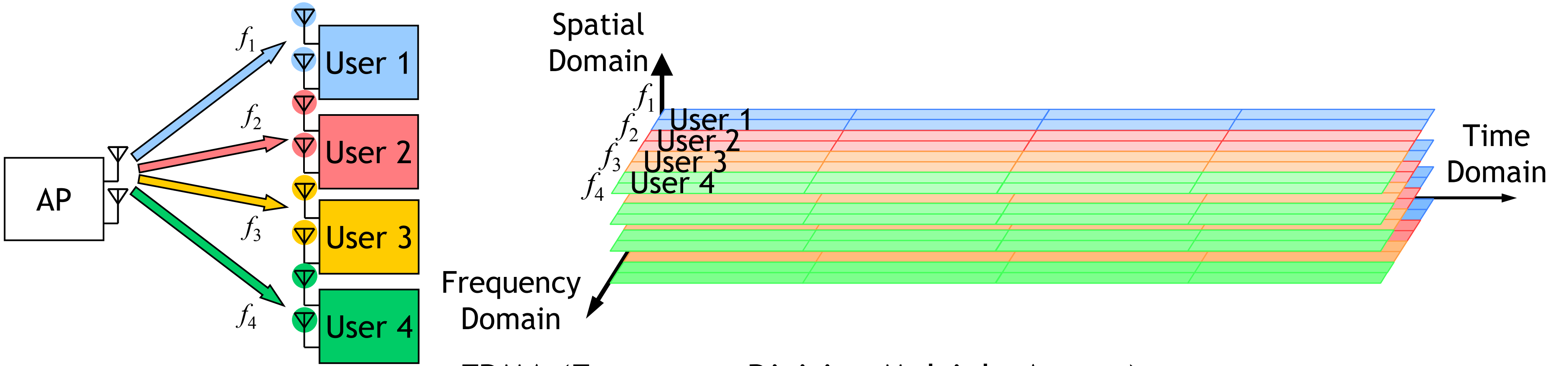


DSSS : Direct Sequence Spread Spectrum
OFDM : Orthogonal Frequency Division Multiplexing
SISO : Single Input Single Output
MIMO : Multi Input Multi Output
MU-MIMO: Multi-User MIMO

Multiple Access in Single User MIMO

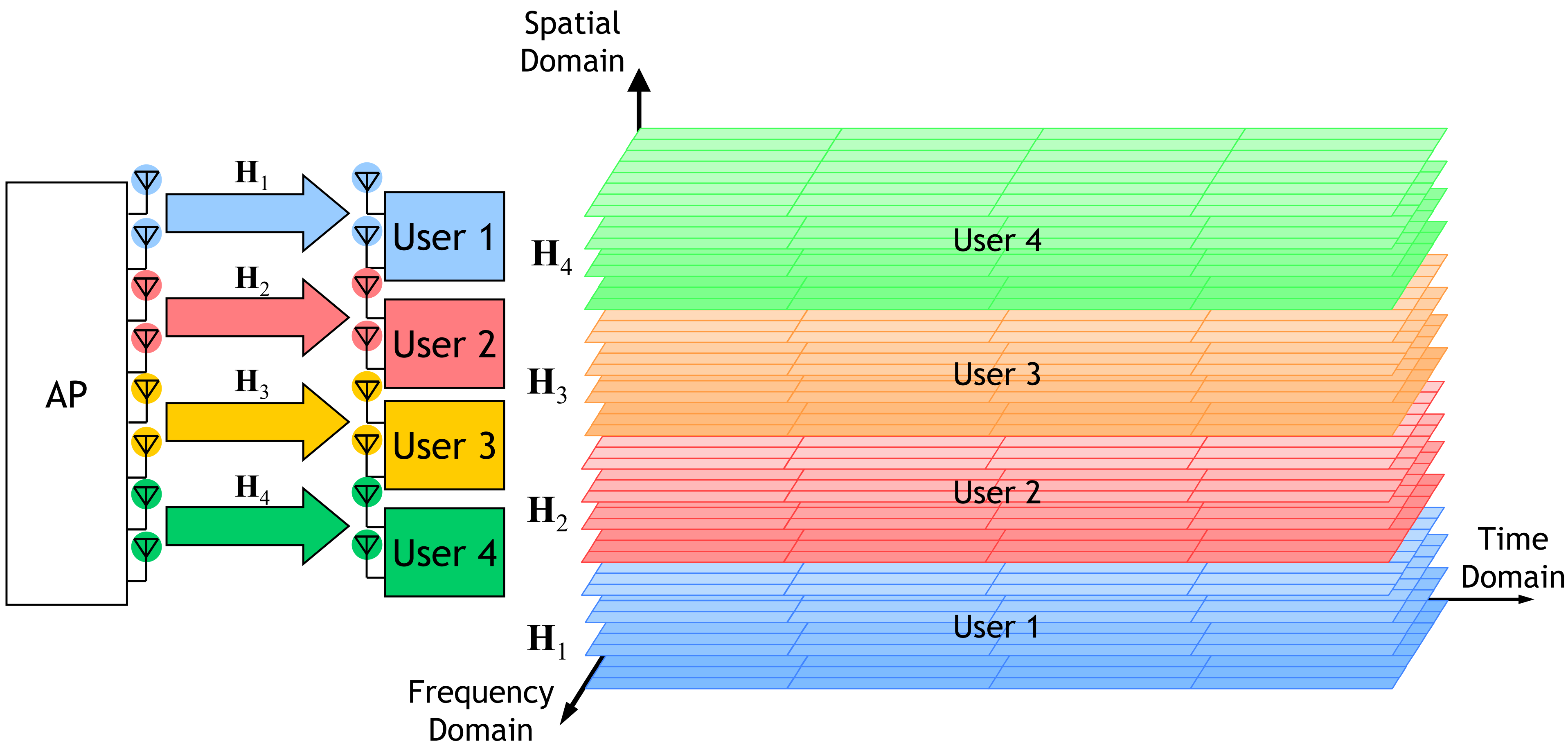


TDMA (Time Division Multiple Access)



FDMA (Frequency Division Multiple Access)

Multiple Access in Multi User MIMO



SDMA (Spatial Division Multiple Access)

MU-MIMO in LTE・LTE Advanced

		3GPP E-UTRA		
		LTE		LTE Advanced
		Release 8	Release 9	Release 10
Down Link	SU-MIMO	Up to 4 streams	Up to 4 streams	Up to 8 streams
	MU-MIMO	Up to 2 users (unitary precoding)	Up to 4 users (non-unitary precoding)*	Under Development
Up Link	SU-MIMO	1 stream	1 stream	Up to 4 streams
	MU-MIMO	Up to 8 streams	Up to 8 streams	Under Development

*Release 8 unitary precoding for up to 2 users is still supported in Release 9 and 10.

Reference
Qinghua Li et al., "MIMO Techniques in WiMAX and LTE: A Feature Overview" IEEE Communication Magazine, May 2010

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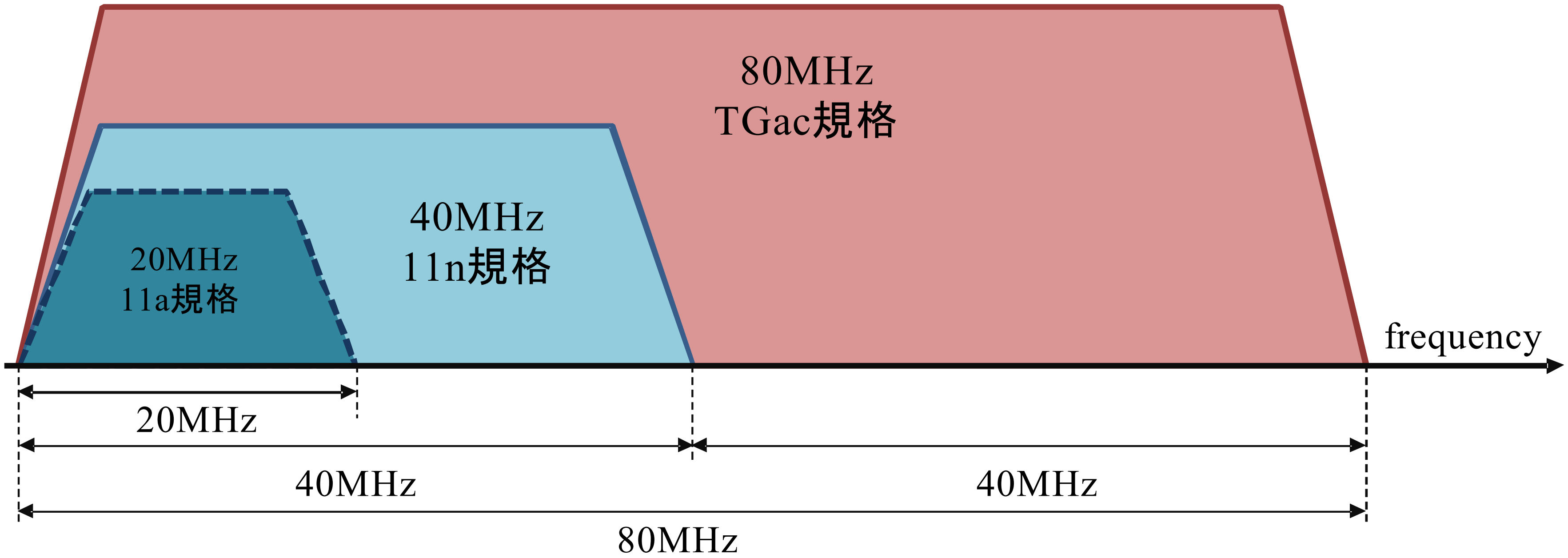
MU-MIMO in WiMax2 (IEEE802.16m)

	Mode index	SU/MU	OL/CL	MIMO mode	Encoding	Precoding	
DL	Mode 0	Single user MIMO	Open Loop	Tx diversity	SFBC, VE	non-adaptive	
	Mode 5				CDR, VE		
	Mode 1			SM	VE		
	Mode 2		Closed Loop			adaptive	Codebook based
							Sounding based
	Mode 3	Multi-user MIMO	Open Loop		ME	non-adaptive	
	Mode 4		Closed Loop			adaptive	Codebook based
							Sounding based

Sponsor LAN/MAN Standards Committee of the IEEE Computer Society and the IEEE Microwave Theory and Techniques Society, “Part16: Air Interface for Broadband Wireless Access Systems”, 6th May 2011.

IEEE 802.11ac Specification

Wide bandwidth



PHY Specification

PARAMETER	11ac draft Mandatory	11ac draft Optional
Number of Antenna	1-2 (non AP/AP)	5-8
MCS	0-7	8-9 (256-QAM)
Packet Mode	Legacy mode (V)HT Mixed mode	Legacy mode (V)HT Mixed mode
Number of subcarrier	52 /56/114/242	52 /56 /114/242/484
Bandwidth	20/40/80 [MHz]	20/40/80/160/80+80 [MHz]
Other	-	Short G.I. TX Beamforming MU-MIMO LDPC, STBC
Transmission Rate	6.0 – 292.5 [Mbps]	6.0 – 6933.3 [Mbps]

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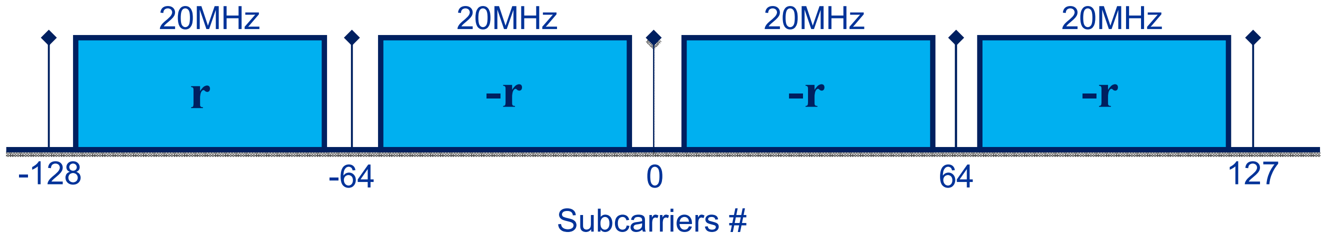
IEEE802.11TGac International Standardization

- **Sameer Vermani, Lin Yang, Richard van Nee, Thet Htun Khine, Leonardo Lanante, Yuhei Nagao, Vinko Erceg, Eldad Perahia, Youhan Kim, Hongyuan Zhang, Sudhir Srinivasa, "Phase Rotations for 80 MHz", IEEE802.11-10/1083r0, Sep., 2010.**

> - In 80MHz transmission, the phase rotations to be used in each 20 MHz sub-band.
> - Phase rotation pattern should achieve low PAPR and backward compatibility with 11a/n.

For 80 MHz PPDU transmissions,

$$\Upsilon_{k,80} = \begin{cases} 1 & , \quad k < -64 \\ -1 & , \quad k \geq -64. \end{cases} \qquad (22\text{-}6)$$



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- Jun Zheng, Vinko Erceg, Sameer Vermani, Hongyuan Zhang, Eldad Perahia, Youhan Kim, Uikun Kwon, Yongho Seok, Brian Hart, Sean Coffey, Vish Ponnampalam, George Vlantis, Thet Htun Khine, Leonardo Lanante, "Legacy CSD Table for 11ac", IEEE802.11-10/1301r0, Nov., 2010.

> CSD is a simple way to avoid unintentional beamforming that causes large variations in receive power.

Table 22-7--Cyclic shift values for L-STF, L-LTF, L-SIG and VHT-SIG-A portions of the packet

$T_{CS}^{i_{TX}}$ values for L-STF, L-LTF, L-SIG and VHT-SIG-A portions of the packet								
Total number of transmit antennas (N_{TX})	Cyclic shift for transmit antenna i_{TX} (in units of ns)							
	1	2	3	4	5	6	7	8
1	0	-	-	-	-	-	-	-
2	0	-200	-	-	-	-	-	-
3	0	-100	-200	-	-	-	-	-
4	0	-50	-100	-150	-	-	-	-
5	0	-175	-25	-50	-75	-	-	-
6	0	-200	-25	-150	-175	-125	-	-
7	0	-200	-150	-25	-175	-75	-50	-
8	0	-175	-150	-150	-25	-100	-50	-200

MU-MIMO Key Technology

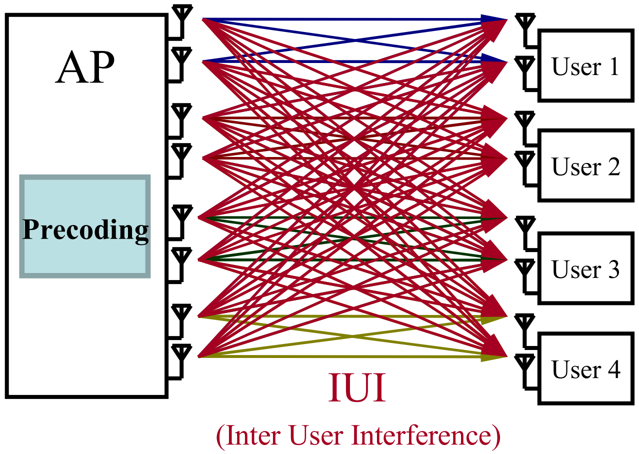
Pre-Coding

Background

Spatial Division Multiplexing Access (SDMA)

- Advantage
  - AP can transmits data simultaneously to multiple users in the same frequency band.
- Disadvantage
  - An Inter User Interference (IUI) occurs.

➡ **Precoding techniques** cancel IUI.



- Linear precoding - Low complexity, Low data rate (capacity)
  - Channel Inversion
  - Block Diagonalization]
- Non-linear precoding - High complexity, High data rate (capacity)
  - Tomlinson Harashima Precoding
  - Vector Perturbation

Research Theme

Improving transmission performance by using new precoding algorithm

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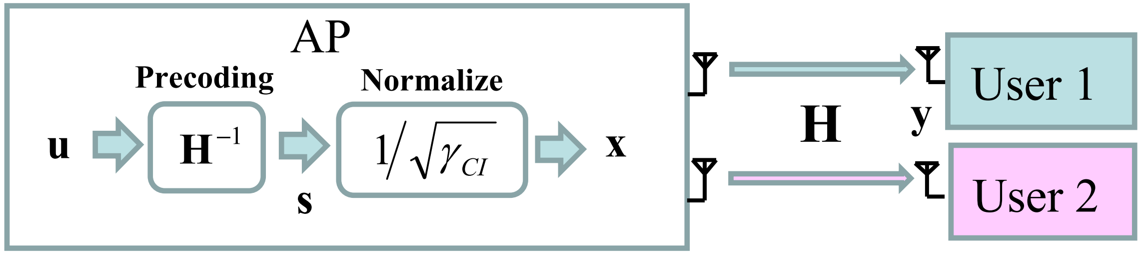
Linear Precoding

Channel Inversion



Transmitter

Transmit symbol $\mathbf{u}$

Precoded symbol $\mathbf{s} = \mathbf{H}^{-1}\mathbf{u}$

Transmit signal (Normalized precoded symbol)

$$\mathbf{x} = \frac{1}{\sqrt{\gamma_{CI}}}\mathbf{s} = \frac{1}{\sqrt{\gamma_{CI}}}\mathbf{H}^{-1}\mathbf{u}$$

Normalization Gain $\gamma_{CI} = \|\mathbf{s}\|^2$

Receiver

Receive signal

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \boxed{\mathbf{n}} = \frac{1}{\sqrt{\gamma_{CI}}}\mathbf{H}\mathbf{H}^{-1}\mathbf{u} + \mathbf{n}$$

AWGN noise

$$= \frac{1}{\sqrt{\gamma_{CI}}}\mathbf{u} + \mathbf{n}$$

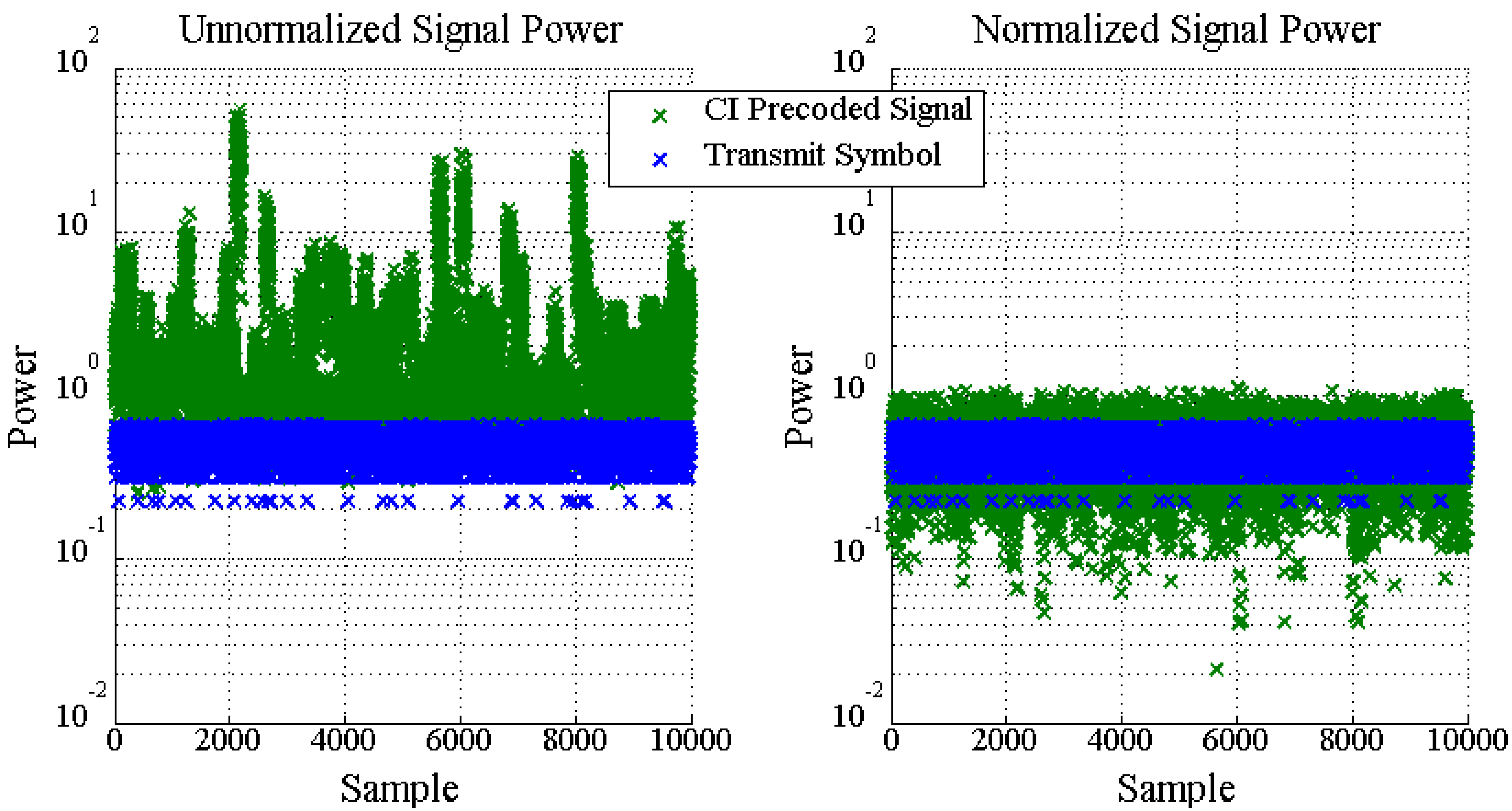
Decoding Process

Noise Enhancement Gain

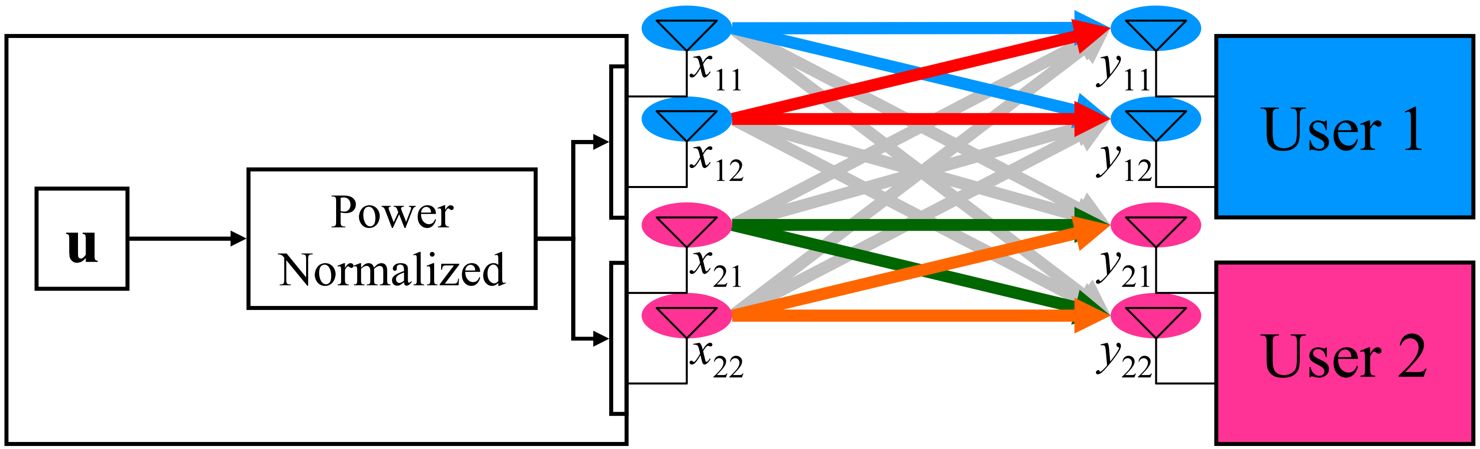
$$\hat{\mathbf{y}} = \sqrt{\gamma_{CI}}\,\mathbf{y} = \mathbf{u} + \boxed{\sqrt{\gamma_{CI}}}\,\mathbf{n}$$

Multi User MIMO model
Normalization in TX

- Why should we normalize transmit power?
  - Transmit signal power is limited by Wireless LAN standards



Block Diagonalization



u: Transmitted Signal
y : Received Signal

In multi-user communication, time and frequency are used simultaneously by some users.

Received symbol

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

IUI (Inter-User Interference)

$$\begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \end{bmatrix} = \begin{bmatrix} y_{11} \\ y_{12} \\ y_{21} \\ y_{22} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{bmatrix} \begin{bmatrix} x_{11} \\ x_{12} \\ x_{21} \\ x_{22} \end{bmatrix}$$

user 1

user 2

Without MU-MIMO Precoding, each user will receive interference from all other users

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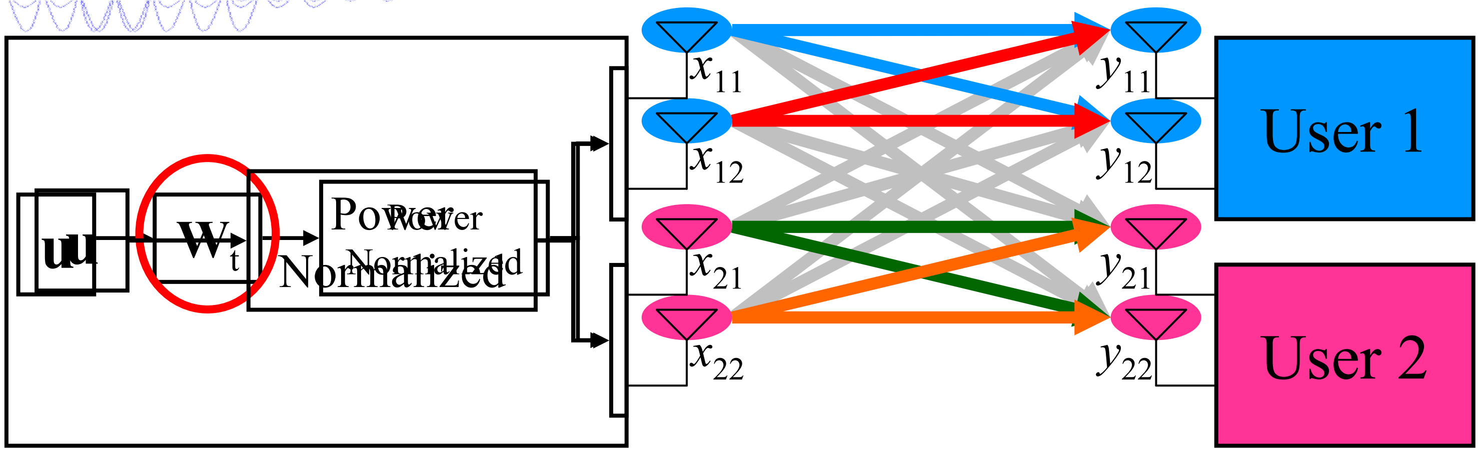
Block Diagonalization



$\mathbf{W}_t$: Precoding Matrix

In multi-user communication, time and frequency are used simultaneously by some users.

$$\mathbf{x} = \mathbf{W}_t \mathbf{u}$$

Received symbol

$$\mathbf{y} = \mathbf{H}\mathbf{x} = \left(\mathbf{H}\mathbf{W}_t\right)\mathbf{u}$$

IUI is removed

$$\begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \end{bmatrix} = \begin{bmatrix} y_{11} \\ y_{12} \\ y_{21} \\ y_{22} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & 0 & 0 \\ h_{21} & h_{22} & 0 & 0 \\ 0 & 0 & h_{33} & h_{34} \\ 0 & 0 & h_{43} & h_{44} \end{bmatrix} \begin{bmatrix} u_{11} \\ u_{12} \\ u_{21} \\ u_{22} \end{bmatrix}$$

IEEE 802.11ac System

IUI can be removed by precoding matrix

Precoding Matrix Generation Method

1. **Obtaining Channel Information**
2. **Calculating Precoding Matrix**
   - **Channel Inversion**
   - **Block Diagonalization**

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Nonlinear Precoding

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Tomlinson Harashima Precoding (THP)

QR Decomposition (QRD)

(We assume that $M = K$)

$$\mathbf{H}^H = \mathbf{Q}\mathbf{R}$$

$$\left(\mathbf{H}^{-1} = \mathbf{Q}\left(\mathbf{R}^H\right)^{-1}\right)$$

$$\mathbf{Q} = \begin{bmatrix} Q_{1,1} & \cdots & Q_{1,K} \\ \vdots & \ddots & \vdots \\ Q_{K,1} & \cdots & Q_{K,K} \end{bmatrix} \quad \mathbf{R} = \begin{bmatrix} R_{1,1} & \cdots & R_{1,K} \\ & \ddots & \vdots \\ 0 & & R_{K,K} \end{bmatrix} \quad \mathbf{D} = \begin{bmatrix} D_{1,1} & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & D_{K,K} \end{bmatrix} = \begin{bmatrix} R_{1,1} & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & R_{K,K} \end{bmatrix}$$

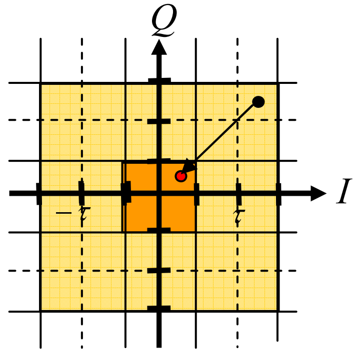
A decomposition of the matrix into an unitary matrix and an upper triangular matrix.

Modulo Operation

$$f_\tau(\mathbf{z}) = \mathbf{z} - \left\lfloor \frac{\mathbf{z} + \tau/2}{\tau} \right\rfloor \tau$$

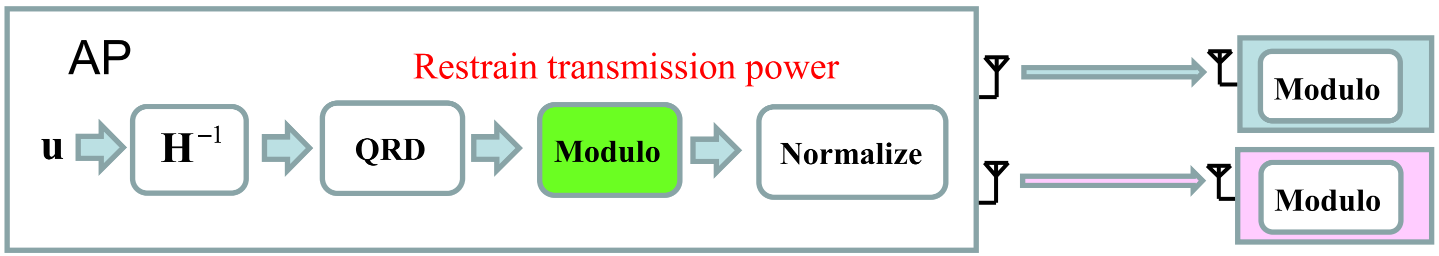
The modulo operation lets I-ch and Q-ch of signals go into the range of original symbol mapping. [- τ /2, τ /2)

(τ is a symbol mapping width)



Symbol mapping (QPSK)

Tomlinson Harashima Precoding



Vector Perturbation

Vector Perturbed symbol $\tilde{\boldsymbol{u}} = \boldsymbol{u} + \underline{\tau \boldsymbol{l}}$

Precoded symbol $\boldsymbol{s} = \boldsymbol{H}^{-1}\tilde{\boldsymbol{u}}$

Choose ***l*** such that the norm of ***s*** is minimized

Thus, vector perturbation technique minimizes the signal power and hence has higher capacity

Transmit symbol

$$\boldsymbol{x} = \frac{1}{\sqrt{\gamma}}\boldsymbol{s}$$

$$= \frac{1}{\sqrt{\gamma}}\boldsymbol{H}^{-1}\tilde{\boldsymbol{u}}$$

Vector Perturbation

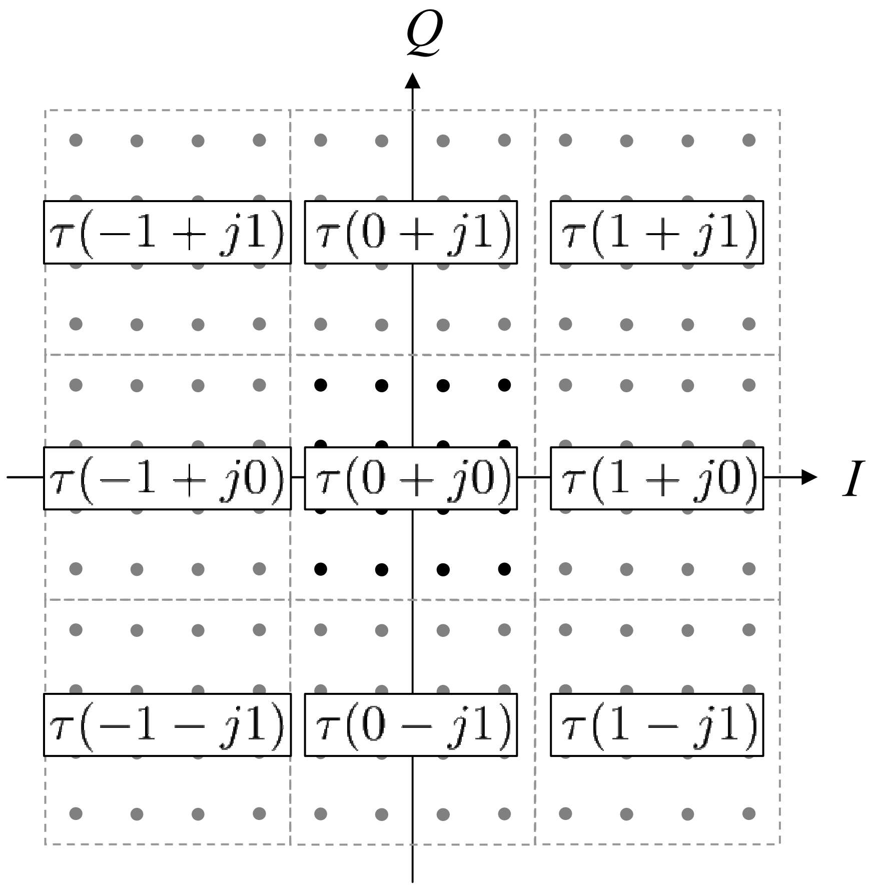
$$\mathbf{l} = \arg\min_{\mathbf{l}'} \gamma$$

$$= \arg\min_{\mathbf{l}'} \left\| \mathbf{H}^{-1} \left(\mathbf{u} + \tau \mathbf{l}' \right) \right\|^2$$

- Example
  - Number of transmit antenna : 4
  - Number of Constellation set : 9

    Needed iteration for finding optimal perturbation vector

    $9^4 = 6561$



Kyutech DSP Lab. Simulation Results

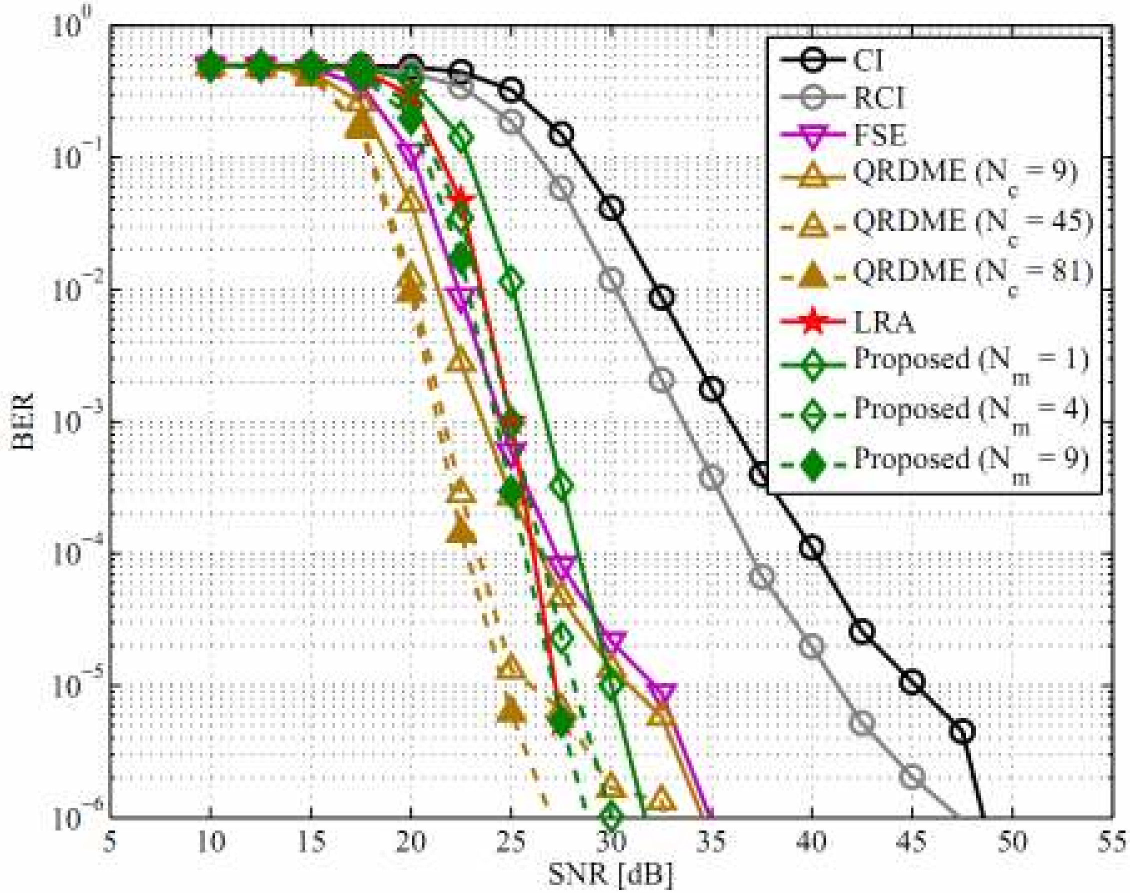


図 5.10: 8 × [2 2 2 2] MU-MIMO システムの BER-SNR 特性 (w. FEC, 符号化率：3/4)

Nm/Nc are the tradeoff parameters of the proposed algorithm and QRDME respectively

The proposed algorithm has roughly the same performance compared to QRDME

The complexity comparisons are seen on the next slide

11ac System RTL Design

4x[2 2] MU-MIMO System for 11ac

表 1 Design Specification

Parameters	Implemented	Mandatory
TX/RX antennas	$4 \times \{2, 2\}$	1×1
No. of Users	2	1
Max Throughput per user	650Mbps	325Mbps
Max Throughput total	1300Mbps	325Mbps
FEC	BCC	BCC
MU-MIMO Pre-coding	Block Diagonal-ization	NA
Channel Feedback	Compressed V Feed-back	NA
Guard Interval	Long/Short GI	Long
Bandwidth	20/40/80 MHz	20/40/80 MHz
Compatibility	802.11a/n/ac	802.11a/n/ac
Operation Frequency	240MHz	-

4x[2 2] MU-MIMO System for 11ac

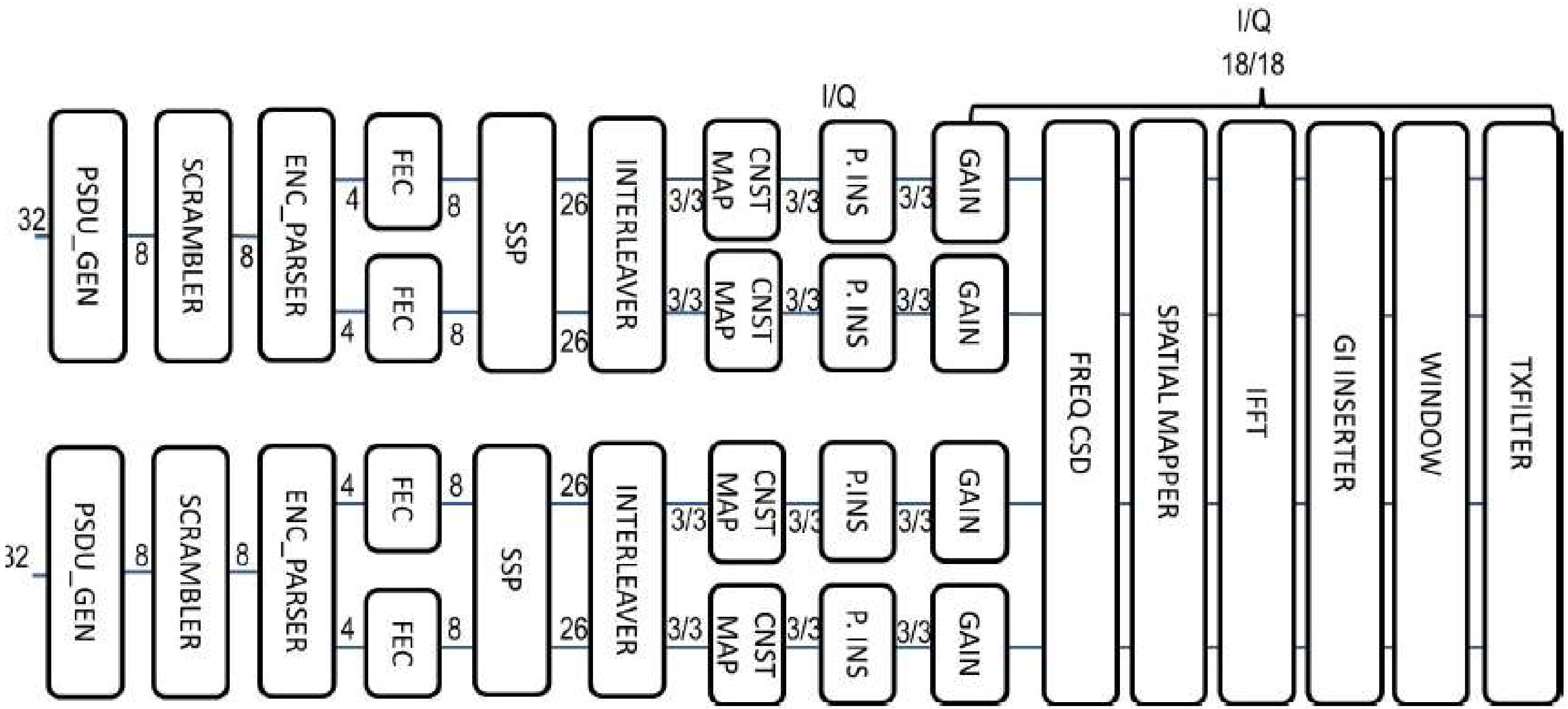


Fig. 1. MU-MIMO Capable Transmitter Block Diagram

4x[2 2] MU-MIMO System for 11ac

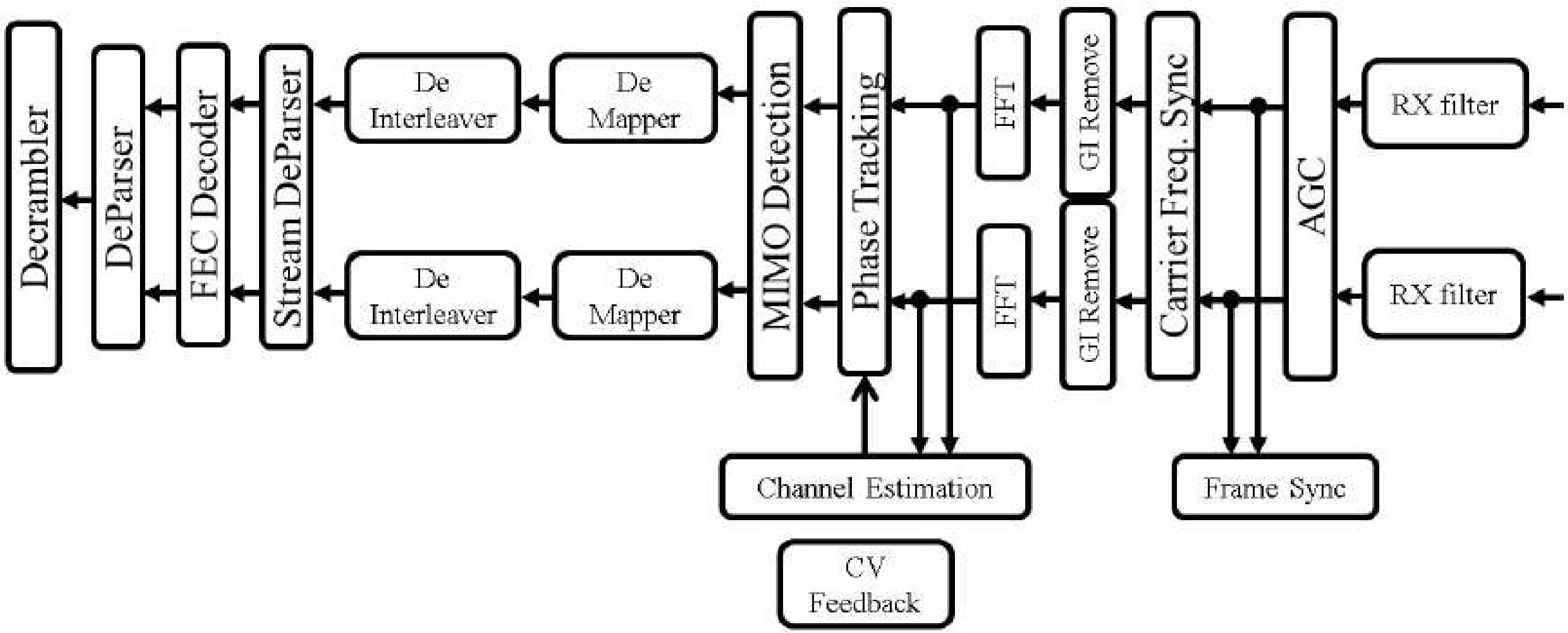


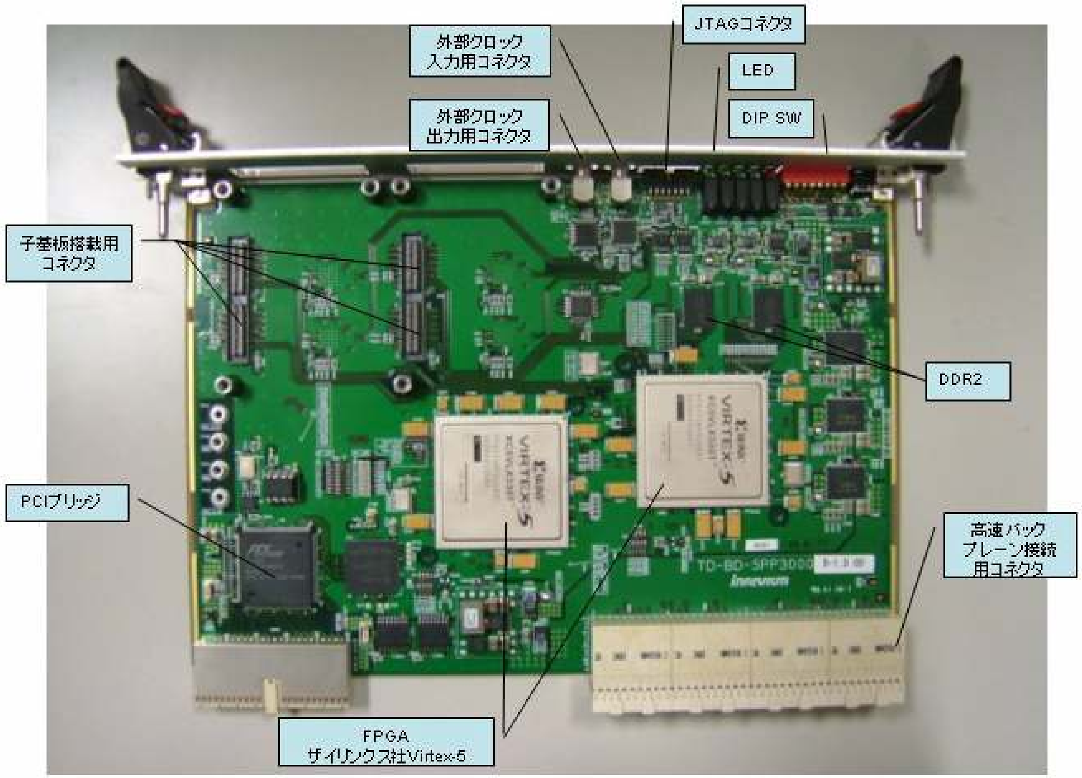
Fig. 2. MU-MIMO Capable Receiver Block Diagram

Synthesis Target

- 4x[2 2] MU-MIMO System Synthesis Target
  - FPGA
    - Virtex 5
    - XC5VSX240T

      149760 LUTs and

      registers



画像:http://www.inrevium.jp/data/board/TD-BD-SPP3000-090402.pdf

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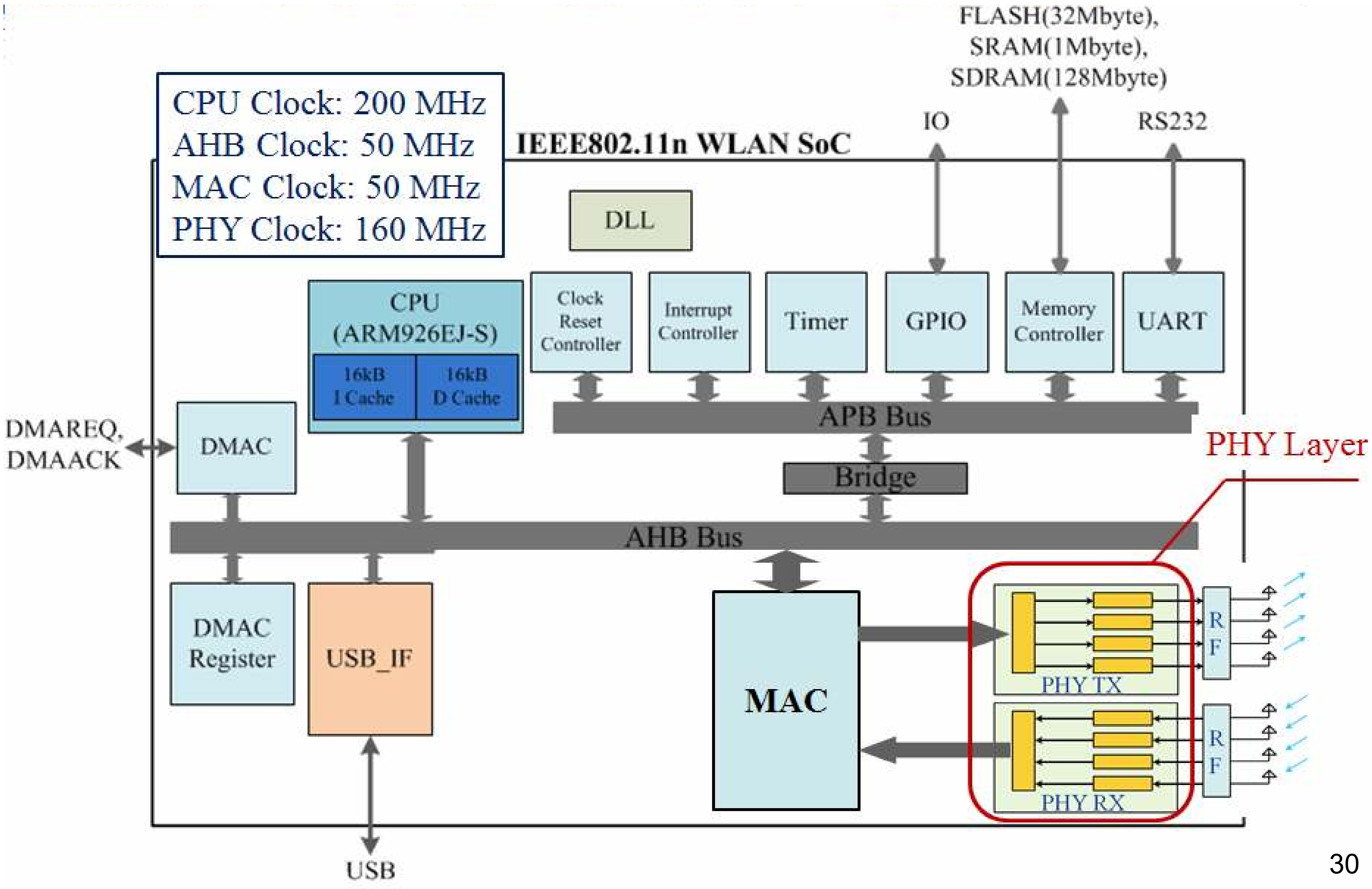
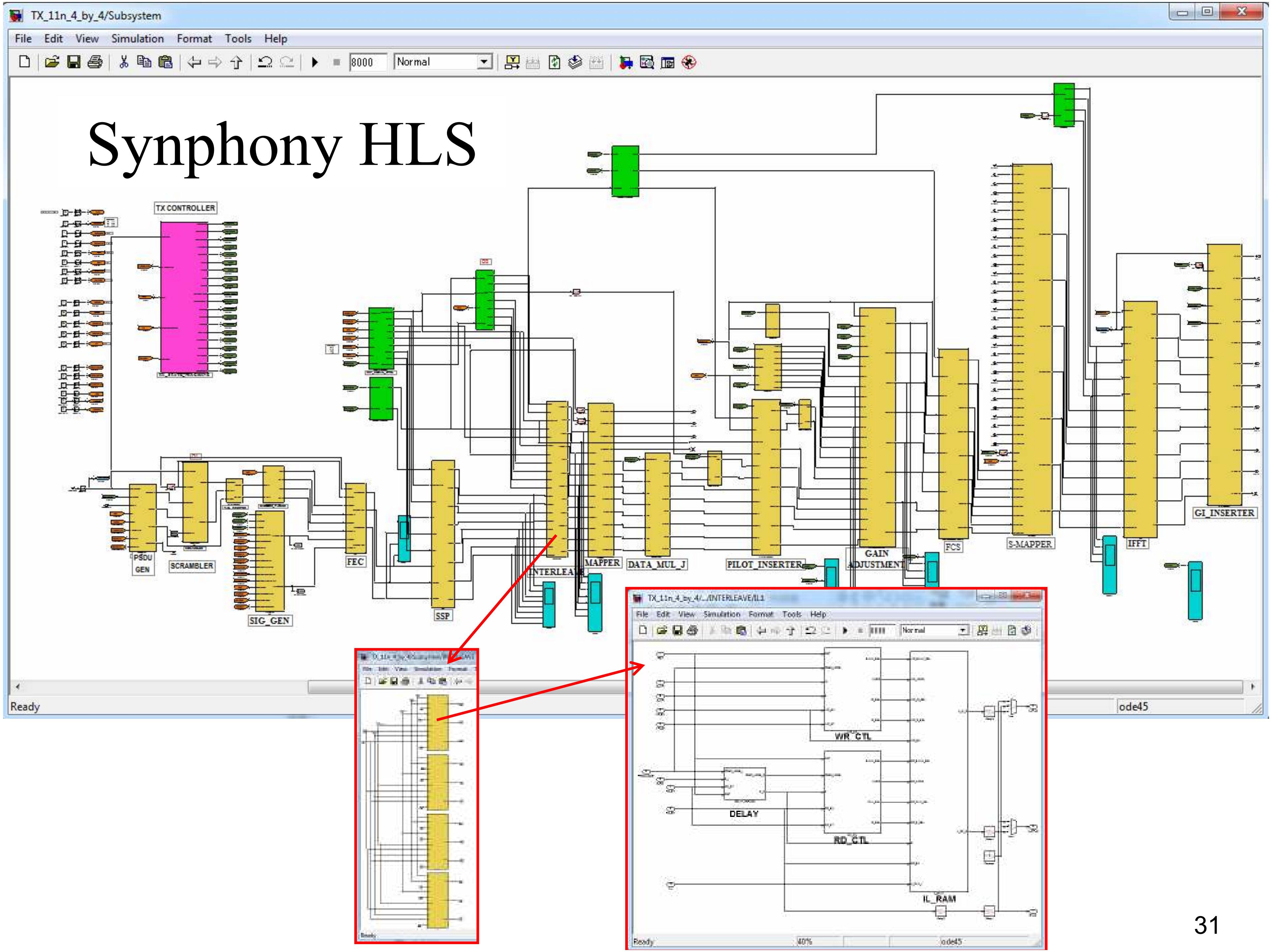
SoC Architecture for 11n



Synphony HLS



Synthesis Result

Transmitter	Register	LUTs	RAM
PSDU	248	632	0
Scrambler	32	32	0
Encoder Parser	12	30	0
Convolutional Encoder	58	70	0
Spatial Stream Parser	688	5506	0
Interleaver	2690	3532	32M=312
Constellation Mapper	152	868	0
Pilot Inserter	64	278	0
Spatial Mapper	1225	26448	1
IFFT (4 parallel)	10710	34795	36B=17
GI Inserter	50	402	36B=10
Windowing	3262	11665	0
Total	19192	84258	

Synthesis Result

Receiver	Register	LUTs	RAM
GI Remover	111	268	32X1D=16, 16B=1
FFT (2 parallel)	5362	17420	36B=9
Channel Estimator	687	2783	36B=8
MU-MIMO Decoder	2169	32131	0
Demapper	92	1518	0
DeInterleaver	1150	2290	32M=156, 36B=2
Spatial Stream Deparser	237	463	0
Encoder Deparser	15	15	0
Scrambler	28	19	0
Total	9761	56907	

Synthesis Results

Receiver	Register	LUTs	Max Frequency
SVD	2641	28552	81.7 MHz
V Compression	1035	8591	74.3 MHz
Block Diagonalization	931	18904	109 MHz

Final goal of this project is the ASIC implementation running at 240 MHz. SVD and V compression might need further modification to meet this timing.

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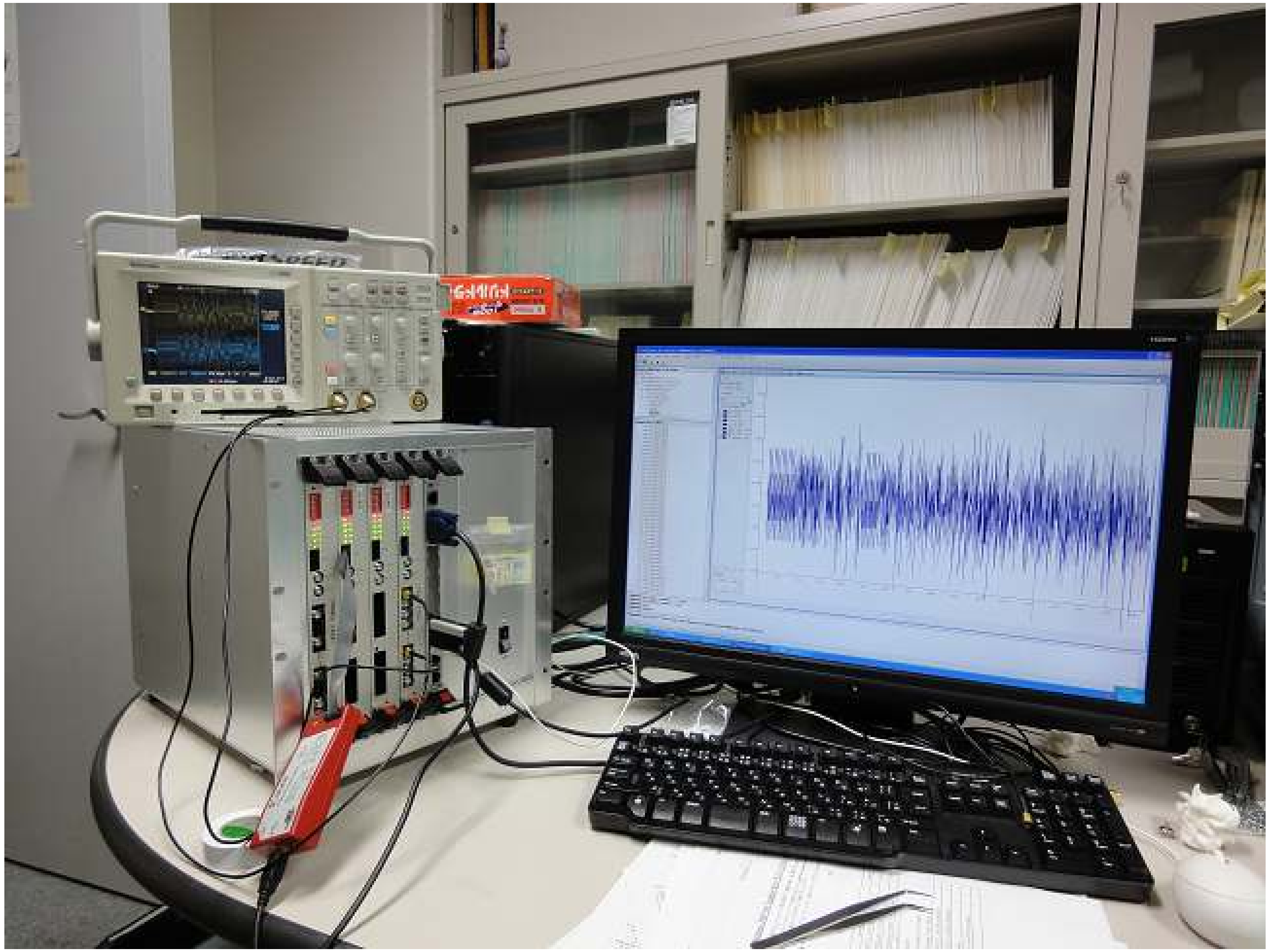
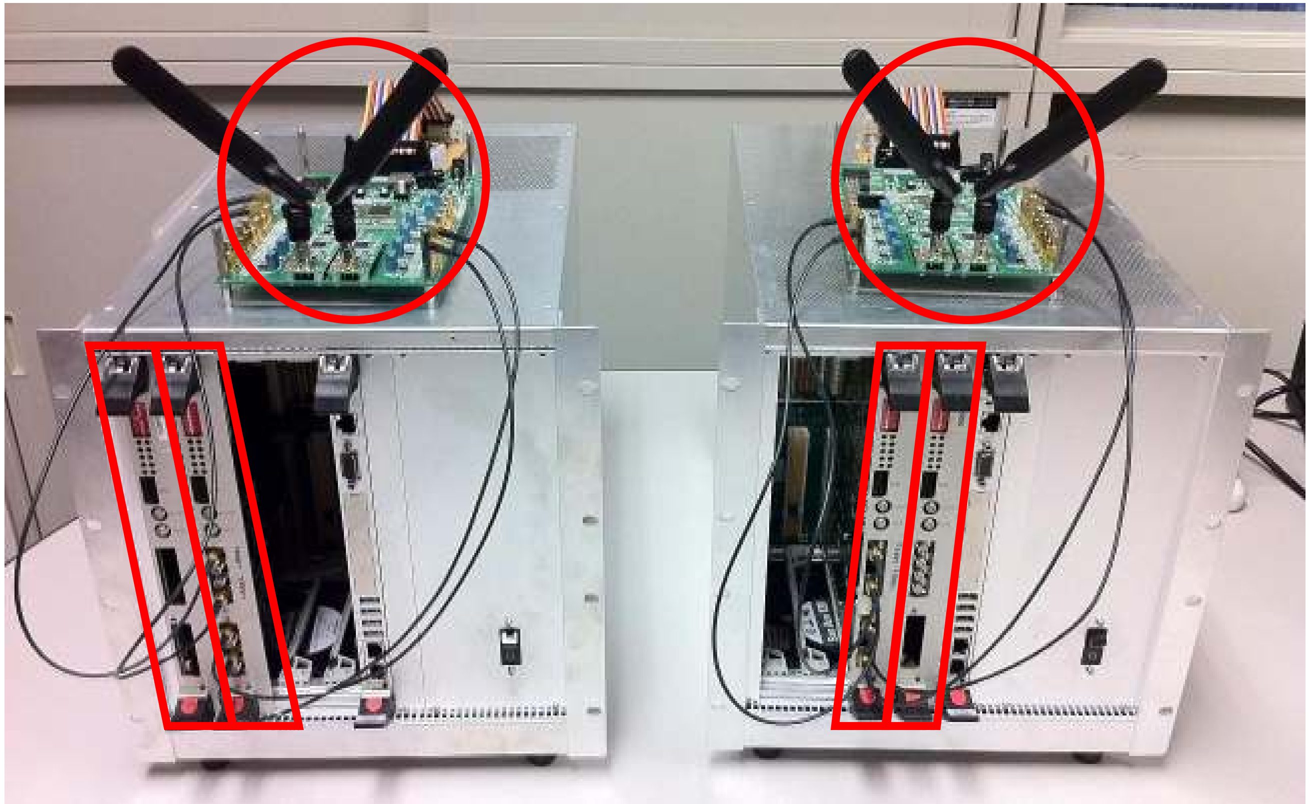
Demonstration Environment

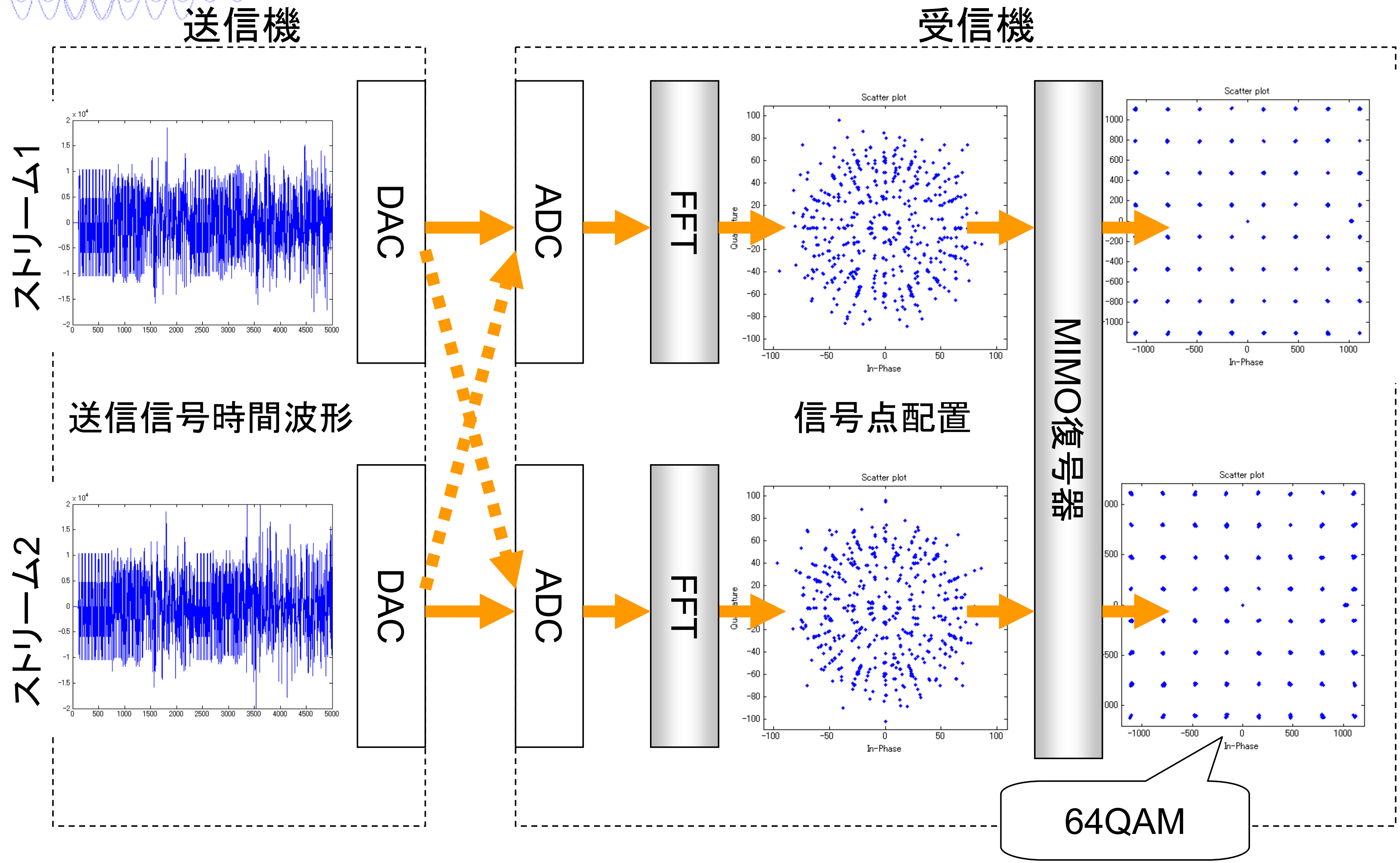
- We use the four boards for IEEE802.11n 2x2 WLAN implementation



RF Experiments

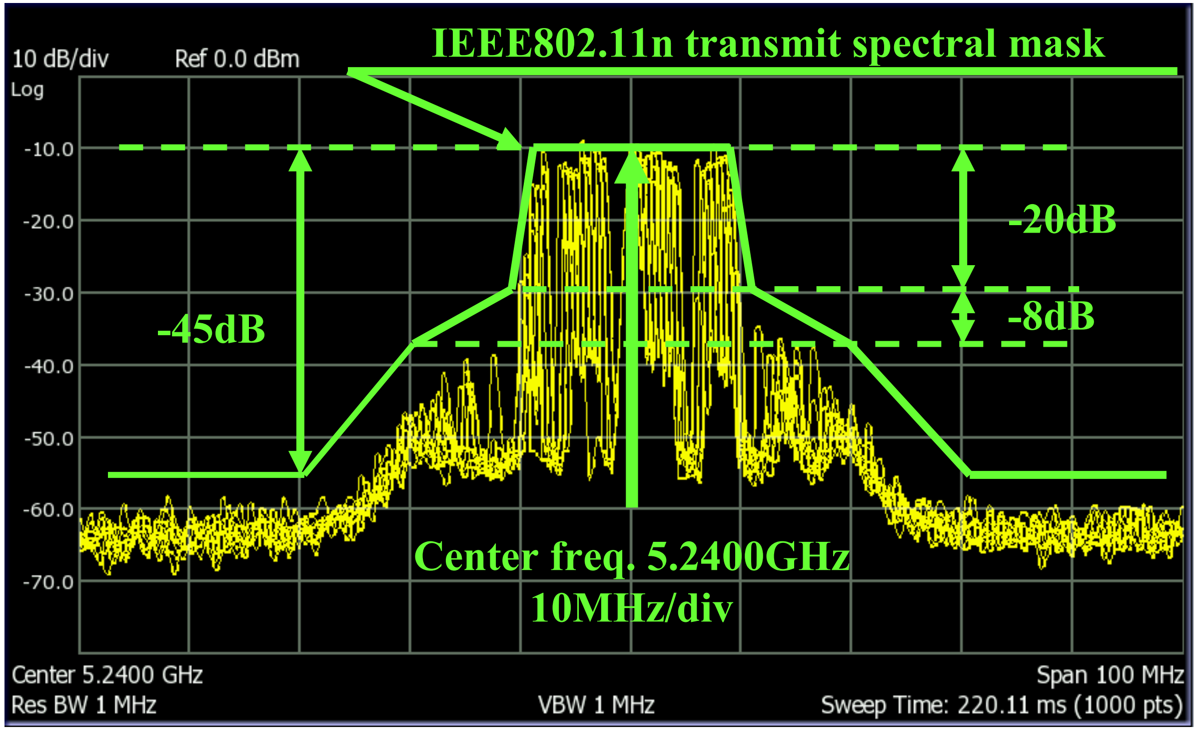


Constellation Comparisons



Spectrum Mask

- Satisfy IEEE802.11n Spectrum Mask
- fc=5.24GHz, BW=20MHz



IEEE802.11n 2x3MIMO Chip

by Radrix co.ltd

Conclusion & Future work

- Conclusion
  - We have presented our hardware design of a 1.3Gbps 802.11ac MU-MIMO system its synthesis result on FPGA.
  - Some blocks such as the viterbi decoder, and MU-MIMO related blocks are still work in progress either to reduce complexity or meet timing.
- Future work
  - FPGA prototype
  - MU-MIMO Experimental validation

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Reference

[1] T.H. Tran, A. Ardiansyah, N. Surantha, Y. Nagao, M. Kurosaki, H. Ochi,"Design and ASIC Implementation of 600Mbps IEEE 802.11n 4x4 MIMO OFDM System," IEICE Society Conference 2011, Hokkaido, Japan, Sept.2011

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[4] Q.H., Spencer, "An introduction to the multi-user MIMO downlink", IEEE Communications Magazine, Vol. 42, Issue 10, 2004

[5] E. Perahia, R.Stacey, Next Generation Wireless LANs: Throughput, Robustness, and Reliability in 802.11n, Cambridge University Press, 2008.

[6] Q. H. Spencer, A. L. Swindlehurst, and M. Haardt, "Zero-Forcing Methods for Downlink Spatial Multiplexing in Multi-User MIMO Channels", IEEE Trans. Sig. Proc., vol. 52, 2004

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Published Paper List

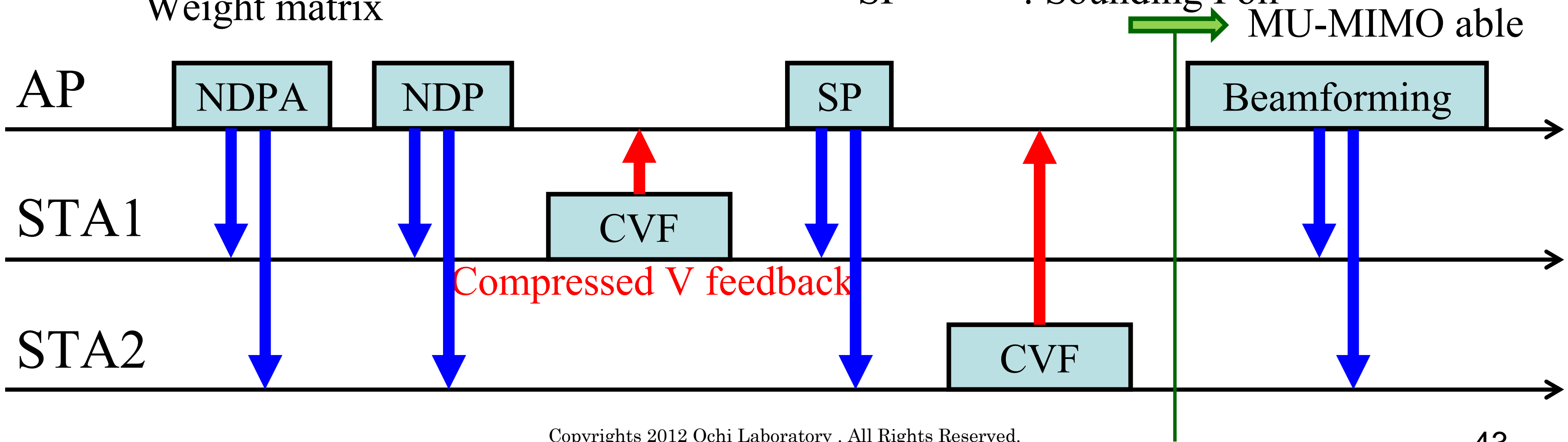
- Leonardo Lanante Jr., Arumjeni Mitayani, Yuhei Nagao, Masayuki Kurosaki, Hiroshi Ochi, "Packet Delayed Lattice Reduction Algorithm for High Performance MIMO Decoder" IEEE Wireless Communications and Networking Conference (WCNC 2012), Paris France, April 2012, pp 236-240
- Yuya Miyaoka, Yuhei Nagao, Masayuki Kurosaki, and Hiroshi Ochi, "Sorted QR Decomposition for High-Speed MMSE MIMO Detection Based Wireless Communication Systems," Proc. 2012 IEEE International Symposium on Circuits and Systems (ISCAS2012), pp. 2857--2860, Seoul, Korea, May 20-23(23), 2012
- Thi Hong Tran, Leonardo Lanante, Yuhei Nagao, Masayuki Kurosaki, Hiroshi Ochi, "Hardware Implementation of High Throughput RC4 Algorithm," 2012 IEEE International Symposium on Circuits and Systems (ISCAS-2012), Korea, May 2012 pp. 77-80.
- Muneaki Matsuo, Masayuki Kurosaki, Akio Miyazaki and Hiroshi Ochi, "JPEG 2000 Image Transmission using Encryption Domain Authentication by Paillier Cryptosystem," IEEE International Conference on Communications(ICC) 2012, Ottawa, Canada, June. 14 2012.
- Leonardo Lanante Jr., Shogo Fujita, Yuji Yokota, Yuhei Nagao, Baiko Sai, Masayuki Kurosaki, Hiroshi Ochi, "Hardware Design of 1.3Gbps Multi-User MIMO System for IEEE802.11ac" IEEE Vehicular Technology Society(VTS) Asia Pacific Wireless Communications Symposium(APWCS) 2012, Kyoto, Japan, August , 2012
- Thi Hong Tran, Yuhei Nagao, Masayuki Kurosaki, Hiroshi Ochi, Baiko Sai, "Model-based Design Method for Wireless System VLSI with Synopsys Synphony Tool," The 2nd Solid-State Systems Symposium - VLSI & Related Technologies (4S), Vietnam, Aug. 2012, pp. 283-289.
- Shogo Fujita, Leonardo Lanante Jr., Yuhei Nagao, Masayuki Kurosaki, and Hiroshi Ochi, "Modified Tomlinson Harashima Precoding Using Square Root for Multi-User MIMO Systems", IEEE Vehicular Technology Conference(VTC) 2012-Fall, Quebec, Canada, Sep. 2012.

MU Beamforming Process

- AP announce MU transmission, then send training frames
- STAs calculate their Compressed V Feedbac and send back to AP. The compressed V Feedback is computed as follows
  - Compute V component of channel matrix using SVD
  - V matrix compression using series of Givens rotation
- AP compute beamforming weight by using received CSI from each STAs.
  - Decompress Received CV matrix
  - Compute Block Diagonalization

  Weight matrix

NDPA : Null Data Packet Announcement
NDP : Null Data Packet
SP : Sounding Poll



IEEE802.16m Specifications

	IEEE 802.16e	IEEE802.16m	
		必須	目標
周波数	2.3GHz,2.5GHz,3.3-3.8GHz	(1GHz,) 2.3GHz, 2.5GHz, 3.3-3.8GHz	
帯域幅	3.5, 5, 7, 8.75, 10MHz	5, 10, 20, 40MHz	
変調方式	OFDM(256), OFDM(2048), QPSK, 16QAM, 64QAM		
最大伝送速度 (DL)	64Mbps（2×2、チャネル帯域が10MHzの時）	160Mbps以上（2×2、チャネル帯域が20MHzの時）	300Mbps以上（4×4、チャネル帯域が20MHzの時）
最大伝送速度 (UL)	28Mbps（2×2、MIMO使用時、チャネル帯域が10MHzの時）	56Mbps（1×2、チャネル帯域が20MHzの時）	112Mbps（2×4、チャネル帯域が20MHzの時）
MIMO設定(DL)	2×2 MIMO	2×2 MIMO	2×4, 4×2, 4×4, 8×8 MIMO
MIMO設定(UL)	1×2 MIMO	1×2 MIMO	1×4, 2×2, 2×4 MIMO

[1]