2012 2nd semester
MIMO Communication Systems

#1: Introduction

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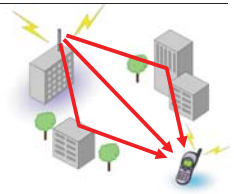
1. Outline of Lecture

Warm up



- Question

Given a communication system below,
double the peak transmission rate by some means

Commun. system with transmission power of 10W and bandwidth of 10MHz that realizes 100Mbps throughput.

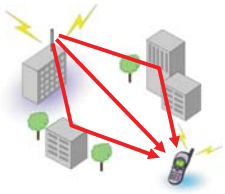
- Channel Capacity Theorem

Maximum information transmission rate

$$C = B\log_2\left(1+\frac{P_s g_h}{P_n}\right) \quad \text{[bits/s]}$$

B : Frequency bandwidth
P_s : Transmission power
P_n : Noise power
g_h : Gain of channel

Warm up



- Question

Given a communication system below,
double the peak transmission rate by some means

Commun. system with transmission power of 10W and bandwidth of 10MHz that realizes 100Mbps throughput.

Answer: Square the power, Double the bandwidth,
Double the number of antennas

- Channel Capacity Theorem

Maximum information transmission rate

$$C = B\log_2\left(1+\frac{P_s g_h}{P_n}\right) \quad \text{[bits/s]}$$

B : Frequency bandwidth
P_s : Transmission power
P_n : Noise power

Summary of Class

- Aim of class

To provide various aspects of MIMO communication systems. The class supports information theory, signal processing, transceiver system, and access schemes. Basics on wireless communication and array signal processing are provided ahead. Future perspective on wireless LAN and mobile phone with MIMO schemes is also provided.

- Prerequisite
  - Commun. Engineering (undergraduate 6th semester)
  - Wireless Commn. System (undergraduate 7th semester)
  - Wireless Commun. Engineering I (graduate 1st semester)
- How to Grade

Reports (45 points): At least 3 times in the course
Final exam. (55 points): will be held on July 12, 2011 (Tue)

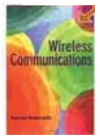
Text Book

- Lecture notes
  - **Lecture notes are made by Prof. Kei Sakaguchi**
  - **Some parts are added by Prof. Sawahashi**
  - **Lecture notes are provided by OCW-i.**
- Related text book

A) MIMO communications

E.Biglieri, R.Calderbank, A.Constantinides, A.Goldsmith, A.Paulraj, and H.V.Poor, "*MIMO Wireless Communications*," Cambridge Univ. Press, 2007.

B) Fundamentals of wireless communications



A.Goldsmith, "*Wireless Communications*," Cambridge Univ. Press, 2005.

Contents of Textbook A

A) *MIMO Wireless Communications*

Chap.	Titile	Relation with the class
1	Introduction	Main topic
2	Capacity limits of MIMO systems	Main topic
3	Precoding design	Main topic (including higher level study)
4	Space-time coding for wireless communications: principles and applications	Main topic
5	Fundamentals of receiver design	Main topic (including higher level study)
6	Multi-user receiver design (multiple access)	Main topic (broadcast is not included)

Contents of Textbook B

B) *Wireless Communications*

Chap.	Title	Relation with the class
1	Overview of wireless commun.	Main topic
2	Path loss and shadowing	Main topic
3	Statistical multipath channel models	Main topic
4	Capacity of wireless channels	Main topic
5	Digital modulation and detection	Main topic
6	Performance of digital modulation over wireless channels	Main topic
7	Diversity	Main topic

Contents of Textbook B

B) *Wireless Communications*

Chap.	Title	Relation with the class
8	Coding for wireless channels	Out of scope
9	Adaptive modulation and coding	Main topic
10	Multiple antennas and space-time commun.	Main topic
11	Equalization	Out of scope
12	Multicarrier modulation	Main topic
13	Spread spectrum	Out of scope
14	Multiuser systems	Main topic
15	Cellular systems and infrastructure-based wireless networks	Main topic
16	Ad hoc wireless networks	Partially related

Schedule (1st half)

	Date	Text	Contents
#1	Oct. 02	A-1, B-1	Introduction
#2	Oct. 16	B-5, B-6	Multi-access schemes for mobile communications
#3	Oct. 23	B-12	Orthogonal Frequency Division Multiple Access (OFDMA)
#4	Oct. 30	A-1, B-7	Outline of MIMO channel techniques
#5	Nov. 06	A-1, B-2, 3	MIMO channel models
	Nov. 13		No class
	Nov. 20		No class
#6	Nov. 27	A-2, B-10	MIMO channel capacity: single-user MIMO
#7	Dec. 04	A-2, B-10	MIMO channel capacity: multiuser MIMO
#8	Dec. 11	A-3, B-10	Precoding design

Schedule (2nd half)

	Date	Text	Contents
#9	Dec. 18	A-4, B-10	Space-time coding
#10	Jan. 08	A-4, B-10	Transmit diversity
#11	Jan. 15	A-5, B-10	Fundamentals of MIMO receiver design
#12	Jan. 22	A-6, B-14	Multiuser MIMO
#13	Jan. 29	B-15, 16	Distributed MIMO networks
#14	Feb. 05		MIMO channel techniques for HSPA, LTE, and LTE-Advanced
#15	Feb. 12		Final Examination

2. Outline of Mobile Communication (Cellular) Systems

(Why are MIMO channel techniques necessary?)

Features of Wireless Communications

Features of wireless communications

■ Advantage

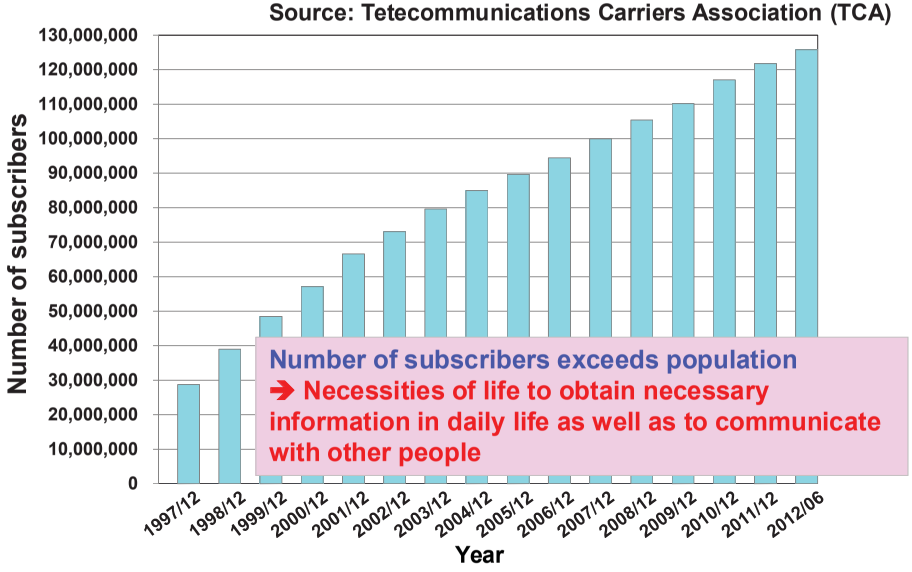
- Support of Mobility: maintaining communication link when a user moves with high speed
- Usability in wide range of areas: communicate any where
- No need of wired line: wired line (cable) is unnecessary in office or meeting rooms etc.

■ Disadvantage

- "Fading" occurs when a user moves from a base station relatively ➔ brings about "decoding error"
- "Interference" from other users using the same frequency band impairs received quality, i.e., bit error rate or block error rate.

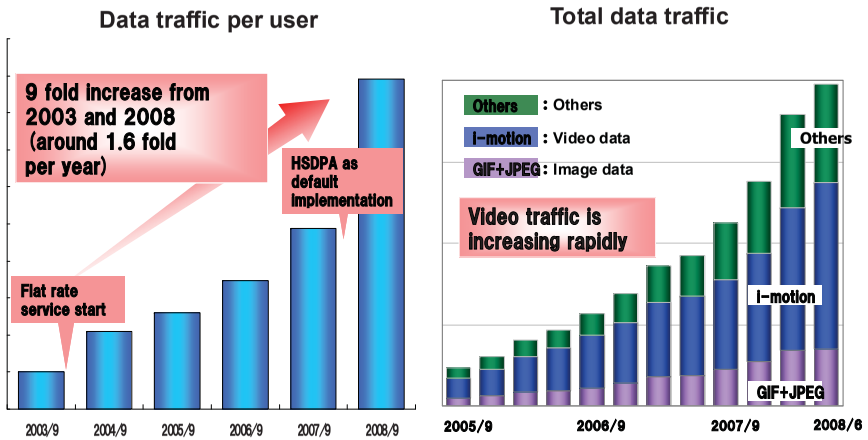
Increase in Number of Subscribers in Japan

Source: Tetecommunications Carriers Association (TCA)



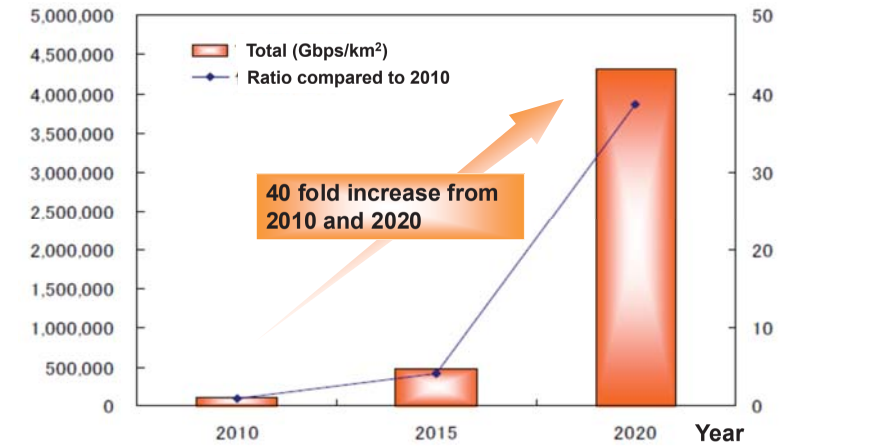
Number of subscribers exceeds population
➔ Necessities of life to obtain necessary information in daily life as well as to communicate with other people

Increase in Data Traffic in DOCOMO Network



Data Traffic Forecast

Source: ITU-R Report M.2078



Developments of networks and equipment are necessary to support of significantly increasing traffic, i.e., near 100 times compared to the current traffic within 10 years.

Evolution of Cellular Systems (1)

- 1st Generation ➔ commercial service ended
  - Analog cellular systems
- 2nd Generation ➔ commercial service ended
  - Digital cellular systems
  - Focus on voice communication
  - TDMA (Time Division Multiple Access)
  - Three-cell frequency reuse
  - Modulation schemes
    - GMSK (Gaussian-filtered Minimum Shift Keying)
    - $\pi/4$-shift QPSK (Quadri Phase Shift Keying)
  - Commercial systems
    - Japan:
      PDC (Personal Digital Cellular) ➔ $\pi/4$-shift QPSK
    - Europe (de facto standard):
      GSM (Global System for Mobile Communications) ➔ GMSK
    - US:
      IS-54 ➔ $\pi/4$-shift QPSK

Evolution of Cellular Systems (2)

- 3rd Generation
  - IMT (International Mobile Teleommunications)-2000
  - Global systems using common frequency spectrum in the world
  - Original purpose to develop 3G systems is to increase voice capacity, but it has been changed to support increasing traffic for mobile Internet and multimedia including video traffic.
  - CDMA (Code Division Multiple Access)
  - One-cell frequency reuse
  - Commercial systems
    - ✓ 3.0 G ➔ for supporting of increasing voice traffic
      - W-CDMA: Europe and Japan
      - CDMA2000: US
    - ✓ 3.5 G ➔ for supporting of increasing data traffic
      - HSDPA / HSUPA: Europe, Japan, and Korea
      - 1x EV-DO (1x EV-DV): US

Evolution of Cellular Systems (3)

- 3rd Generation
  - ✓ 3.9 G
    - LTE (3GPP)
    - Mobile WiMAX (IEEE)
- 4th Generation
  - Referred to as IMT-Advanced
    - LTE-Advanced (3GPP)
    - WirelessMAN-Advanced (IEEE)

- HSDPA: High-Speed Downlink Packet Access
- HSUPA: High-Speed Uplink Packet Access
- LTE: Long-Term Evolution
- WiMAX: Worldwide Interoperability for Microwave Access
- MAN: Metropolitan Access Network

3G Enhancement and 4G

- 3.0 G W-CDMA / 3.5 G HSDPA & HSUPA
- 3GPP standardization: from 1998
- Commercial service launch: W-CDMA 2001, HSDPA 2006
- Peak data rate wide area: 1 Mbps, local area: 10 Mbps
- Mobility focus

- 3.9 G Long-Term Evolution (LTE)
- 3GPP standardization: from 2004
- Commercial service launch: aiming at 2010
- Peak data rate wide area: 10 Mbps, local area: 100 Mbps
- Support of only packet domain
- Further improving throughput compared to that for HSDPA/HSUPS particularly at cell edge

- 4G: LTE-Advanced
- Peak data rate wide area: 100 Mbps, local area: 1 Gbps
- Extend capability and performance of LTE
- Enhancement of radio interface for LTE with some new techniques including enhanced MIMO, CoMP (network MIMO), relays etc.

System Requirements and Targets

- In standardization meetings for air interface including 3GPP and IEEE, we first decide system requirement and targets.
- Major requirements and targets on radio access
  - Peak data rate: achievable maximum data rate based on frequency bandwidth, modulation scheme, channel coding rate, and numbers of transmitter and receiver antennas (MIMO)
  - Peak spectrum efficiency (bps/Hz): achievable spectrum efficiency considering interference from other cells
  - Cell throughout: average user throughput within a cell considering interference from other cells
  - Cell-edge user throughput: user throughput at the 5 % in CDF within a cell considering interference from other cells
  - Voice capacity: number of simultaneously accommodated voice channels
  - Transmission delay in radio access networks

➔ MIMO channel techniques are essential to achieve these system requirements and targets

HSDPA / HSUPA Enhancements

- HSDPA enhancement ➔ increase in peak data rate
- Release 5 (original specification): 14 Mbps ➔ 16QAM, 1-antenna transmission & 2-antenna received (1x2), 5-MHz 1 carrier (5 MHz)
- Release 7: 28 Mbps ➔ 16QAM, 2 x 2 MIMO, 5-MHz 1 carrier (5 MHz)
- Release 8: 42.2 Mbps ➔ 64QAM, 2 x 2 MIMO, 5-MHz 1 carrier (5 MHz) OR 64QAM, 1x2 SIMO, 5-MHz 2 carriers (10 MHz)
- Release 9: 84.4 Mbps ➔ 64QAM, 2 x 2 MIMO, 2 carriers (10MHz)
- Release 10 : 168.8 Mbps ➔ 64QAM, 2 x 2 MIMO, 4 carriers (20 MHz)
- HSUPA enhancement ➔ increase in peak data rate
- Release 6 (original specification): 5.76 Mbps ➔ QPSK, 5-MHz 1 carrier
- Release 7: 11.5 Mbps ➔ 16QAM, 5-MHz 1 carrier
- Release 9: 23 Mbps ➔ 16QAM, 5-MHz 2 carriers

LTE: System Targets and Achieved Performance

- Spectrum efficiency (bps/Hz/cell)

Downlink:
(Requirement: 3 - 4 fold from Rel. 6 HSDPA)

Cell Distance	500 m		1732 m	
HSPA 1x2	0.53	-	0.52	-
LTE 2x2 MIMO	1.69	x 3.2	1.56	x 3.0
LTE 4x2 MIMO	1.87	x 3.5	1.85	x 3.6
LTE 4x4 MIMO	2.67	x 5.0	2.41	x 4.6

Uplink:
(Requirement: 2 - 3 fold from Rel. 6 HSUPA)

Cell Distance	500 m		1732 m	
HSPA 2 Rx div	0.33	-	0.32	-
LTE 2 Rx div	0.74	x 2.2	0.68	x 2.2
LTE 4 Rx div	1.10	x 3.3	1.04	x 3.3

- Voice capacity (users/5 MHz)

Cell Distance	Downlink	Uplink
500 m	317	241
1732 m	289	123

➔ Introduction of maximum 4 x 4 MIMO channel techniques

- U-plane latency (one-way transmission delay in RAN)

(Requirement: 5-msec one-way delay in RAN)

Function	Value (0% HARQ)	Value (30% HARQ)
Total one-way delay	3.5 ms	5 ms

LTE-Advanced: System Requirements (1)

- Peak data rate and peak spectrum efficiency

		Rel. 8 LTE	LTE-Advanced	IMT-Advanced
Peak data rate	DL	300 Mbps	1 Gbps	1 Gbps(*)
	UL	75 Mbps	500 Mbps	
Peak spectrum efficiency [bps/Hz]	DL	15	30	15
	UL	3.75	15	6.75

*"100 Mbps for high and 1 Gbps for low mobility" is one of the key features as written in Circular Letter (CL)

- Peak data rate
- 1 Gbps data rate will be achieved by 4-by-4 MIMO and transmission bandwidth wider than approximately 70 MHz
- Peak frequency efficiency
- DL: Rel. 8 LTE satisfies IMT-Advanced requirement
- UL: IMT-Advanced requirement is double the requirement for LTE

LTE-Advanced: System Requirements (2)

■ Capacity and cell-edge user throughput

		Ant. Config.	Rel. 8 LTE	LTE-Advanced*	IMT-Advanced**
Capacity [bps/Hz/cell]	DL	2-by-2	1.69	2.4	–
		4-by-2	1.87	2.6	2.2
		4-by-4	2.67	3.7	–
	UL	1-by-2	0.74	1.2	–
		2-by-4	–	2.0	1.4
Cell-edge user throughput [bps/Hz/cell/user]	DL	2-by-2	0.05	0.07	–
		4-by-2	0.06	0.09	0.06
		4-by-4	0.08	0.12	–
	UL	1-by-2	0.024	0.04	–
		2-by-4	–	0.07	0.03

x1.4-1.6

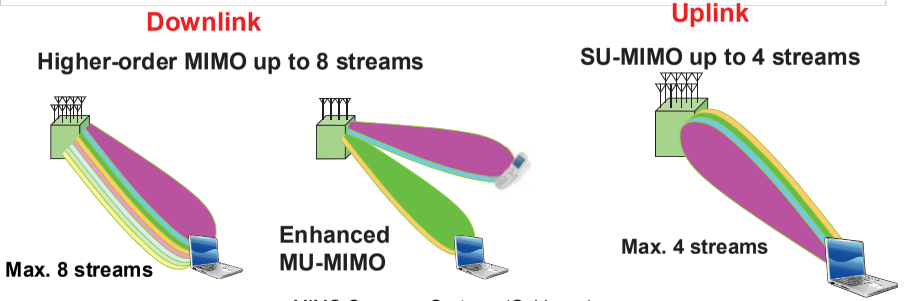
* For Case 1 scenario in 3GPP ** For Base Coverage Urban scenario in IMT.EVAL

■ DL/UL: IMT-Advanced improves requirements on capacity and cell-edge user throughput compared to those for LTE

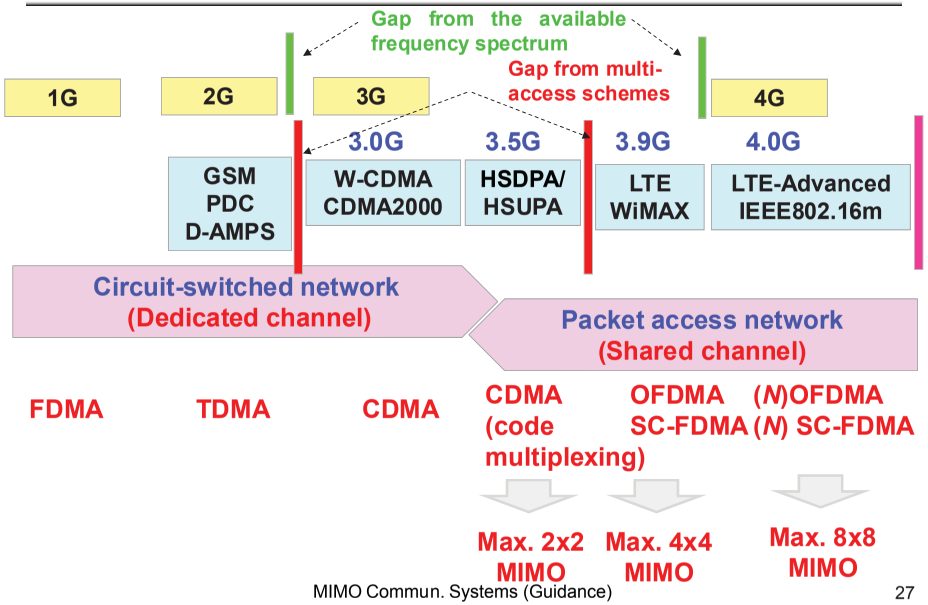
LTE-Advanced: Enhancements in MIMO

■ Downlink: Extension up to 8-stream transmission
- Rel. 8 LTE supports up to 4-stream transmission, LTE-Advanced supports up to 8-stream transmission
  ➔ Satisfy requirement for peak spectrum efficiency, i.e., 30 bps/Hz

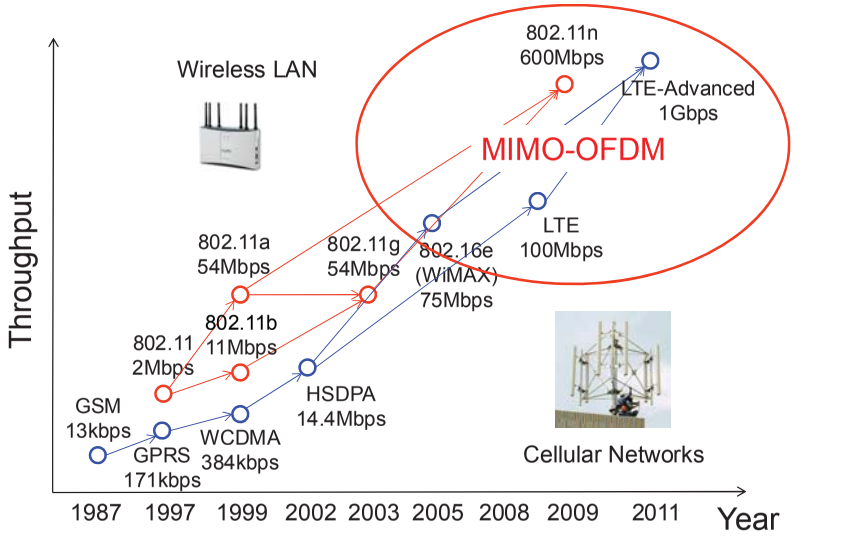
■ Uplink: Introduction of single user (SU)-MIMO up to 4-stream transmission
- Whereas Rel. 8 LTE does not support SU-MIMO, LTE-Advanced supports up to 4-stream transmission
  ➔ Satisfy requirement for peak spectrum efficiency, i.e., 15 bps/Hz



Summary for Multi-Access and MIMO



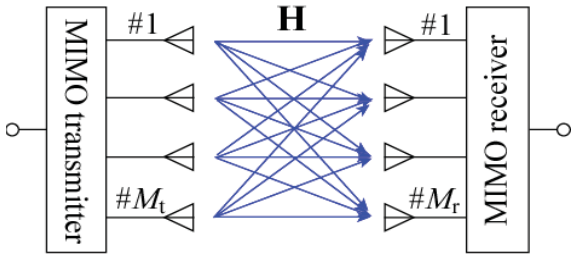
Innovation of Wireless Systems



3. History and Reference for MIMO

What is MIMO

- **Multiple antennas both at transmitter & receiver (MIMO)**
- **Different information streams are spatially multiplexed at the same time and same frequency**
- **Channel capacity of MIMO system increases linearly with respect to the number of antennas**
- **Benefits of MIMO are throughput & area coverage enhancement**



History of MIMO

1995 Information theoretic study on MIMO commun. system [Telater]

1996 MIMO spatial multiplexing (BLAST) [Foschini]

1998 Alamouti Space Time Block Code (STBC) [Alamouti]

1998 Development on MIMO channel model [COST 273]

2003 Information theoretic study on Multi-user MIMO [Goldsmith]

2005 IEEE802.16e WMAN standard ratified

2006 IEEE802.11n WLAN draft standard approved

Pre-N WLAN was released in market

WiBro WMAN was released in market

2008 3GPP-LTE (E-UTRA) standard ratified

2009 IEEE802.11n WLAN standard ratified

MIMO in IEEE802.11n

- Standardization
  - High throughput WLAN backward compatible with 802.11a/b/g
  - Standardization started in 2004 and was ratified in 2009
  - TGnSync & WWiSE Pre-N unofficial standard in 2005
- Feature
  - Upto 4x4 MIMO spatial multiplexing with 20/40MHz bandwidth OFDM
  - Transmit beamforming with implicit/explicit feedback
  - 600Mbps maximum data rate is available
- Product examples

Buffalo WZR-APMG300NH 300Mbps I-O Data WN-GDN/R3 300Mbps Atheros AP9002AP-4XHG 600Mbps

MIMO in WiMAX (IEEE802.16e)

- Standardization
  - Mobility enhanced IEEE802.16 fixed wireless access
  - Standardization started in 2002 and was ratified in 2005
  - WiMAX forum certifies the interoperability of products
- Feature
  - Upto 2x4 MIMO spatial multiplexing with scalable OFDMA
  - Transmit precoding based on matrix codebook
  - 75Mbps maximum data rate is available (40Mbps in WiMAX wave 2)
- Product examples

UQ-WiMAX UD03SS 40Mbps

Intel WiMAX/WiFi Link 5150 40Mbps

MIMO in LTE (3GPP Release 8)

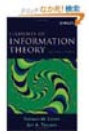
- Standardization
  - Long term evolution of 3GPP-HSPA (Release 5/6)
  - Standardization started in 2004 and was ratified in 2008
  - NTT docomo launched the service of LTE on Dec. 24, 2010
- Feature
  - Up to 2 layers MIMO spatial multiplexing with scalable OFDMA
  - Various MIMO schemes (SM, STBC, Precoding, MU-MIMO)
  - 100Mbps maximum data rate is available (37.5Mbps in Xi)
- Product examples

NTT docomo Xi L-02C 37.5Mbps

Verizon & Samsung Smartphone 37.5Mbps

NTT docomo LTE-MIMO 100Mbps

Required Knowledge



Information theory

Array signal processing

Wireless commun. → MIMO commun. system ← EM wave theory

Linear algebra

Convex optimization

Probability and Stochastic Process

Recommended References

Other text books

1. **Da-shan Shiu, "Wireless Communication using Dual Antenna Arrays," Kluwer Academic, 2000.**
2. **Branka Vucentic, Jinhong Yuan, "Space-Time Coding," John Wiley & Sons, 2003.**
3. **Gregory D. Durgin, "Space-Time Wireless Channels," Prentice Hall PTR, 2003.**
4. **Arogyaswami Paulraj, Rohit Nabar, Dhananjay Core, Introduction to Space-Time Wireless Communications, Cambridge, 2003.**
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MIMO channel capacity

1. I.E.Telater, "Capacity of Multi-Antenna Gaussian Channels," AT&T Bell Labs Technical Memo, June 1995.
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MIMO propagation

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2. J.W.Wallace, M.A.Jensen, "Modeling the Indoor MIMO Wireless Channel," IEEE Trans. Antennas and Propagation, vol.50, no.5, pp.591-599, May 2002.
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4. A.F.Molisch, "A Generic Model for MIMO Wireless Propagation Channels in Macro- and Microcells," IEEE Trans. Signal Processing, vol.52, no.1, pp.61-71, Jan. 2004.
5. H.Xu, D.Chizhik, H.Huang, R.Valenzuela, "A Generalized Space-Time Multiple-Input Multiple-Output (MIMO) Channel Model," IEEE Trans. Wireless Communications, vol.3, no.3, pp.966-975, May 2004.

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MIMO communications

1. G.J.Foschini, "Layered Space-Time Architecture for Wireless Communication in a Fading Environment When Using Multi-Element Antennas," Bell Lab Techn. J., Autumn, pp.41-59, 1996.
2. S.M.Alamounti, "A Simple Transmit Diversity Technique for Wireless Communications," IEEE J. Selected Areas in Communications, Vol.16, pp.151-1458, 1998.
3. V.Tarokh, H.Jafarkhani, A.R.Calderbank, "Space-Time Block Codes from Orthogonal Designs," IEEE Trans. Information Theory, vol.45, no.5, pp.1456-1467, July. 1999.
4. S.Zhou, G.B.Giannakis, "Optimal Transmitter Eigen-Beamforming and Space-Time Block Coding Based on Channel Mean Feedback," IEEE Trans. Communications, vol.49, no.12, pp.2599-2631, Oct. 2002.
5. H.Sampath, P.Stoica, A.Paulraj, "Generalized Linear Precoder and Decoder Design for MIMO Channels using the Weighted MMSE Criterion," IEEE Trans. Communications, vol.49, no.12, pp.2198-2206, Dec. 2002.
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Multi-user MIMO & others

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2. R.S.Blum, "MIMO Capacity with Interference," IEEE J. Selected Areas in Communications, vol.21, no.5, pp.793-801, June 2003.
3. S.Vishwanath, N.Jindal, A.J.Goldsmith, "Duality, achievable rates, and sum-rate capaity of Gaussian MIMO Broadcast Channels," IEEE Trans. Information Theory, vol.49, no.10, pp.2658-2668, Oct. 2003.
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