IWSDA'09, Fukuoka International Congress Center, Fukuoka, Japan, 22 October, 2009.

Wireless Challenge

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OUTLINE

- Wireless Evolution
- Technical Issues for 4G
- Frequency-domain Signal Processing
- Distributed Antenna Network

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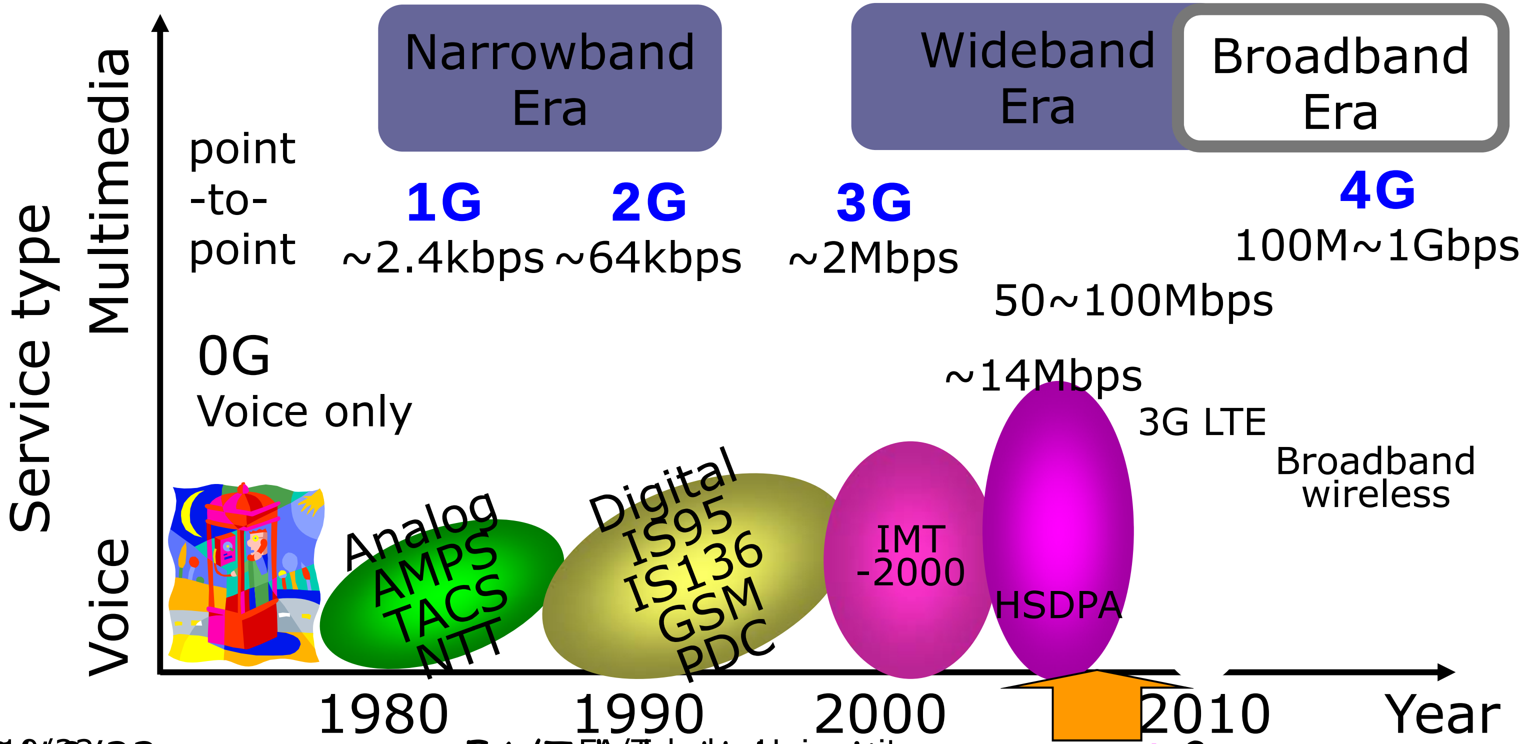
Wireless Evolution

Wireless Evolution

- In early 1980's, communications systems changed from fixed "point-to-point" to wireless "anytime, anywhere" communication.
- Cellular systems have evolved from narrowband network of around 10kbps to wideband networks of around 10Mbps.
- Now on the way to broadband networks of 1Gps.



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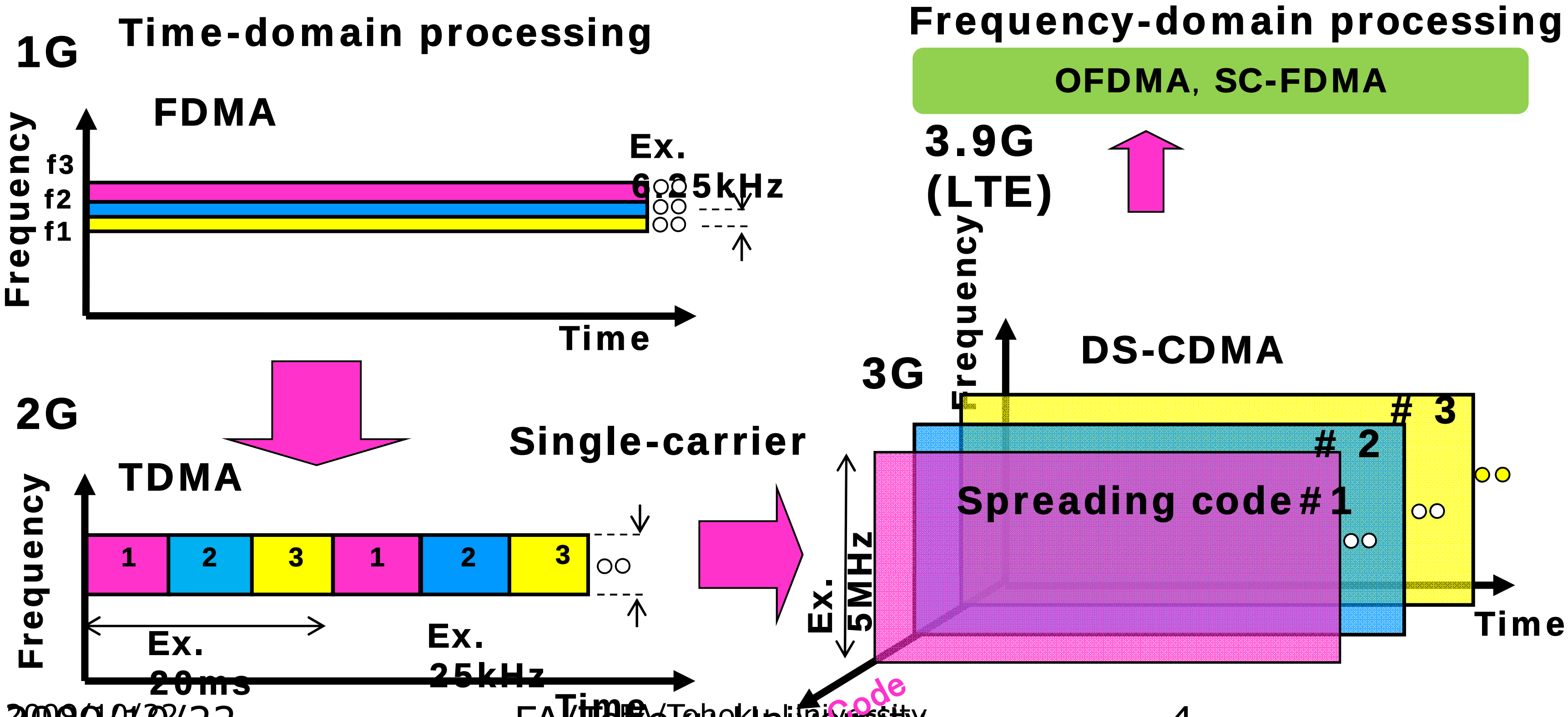
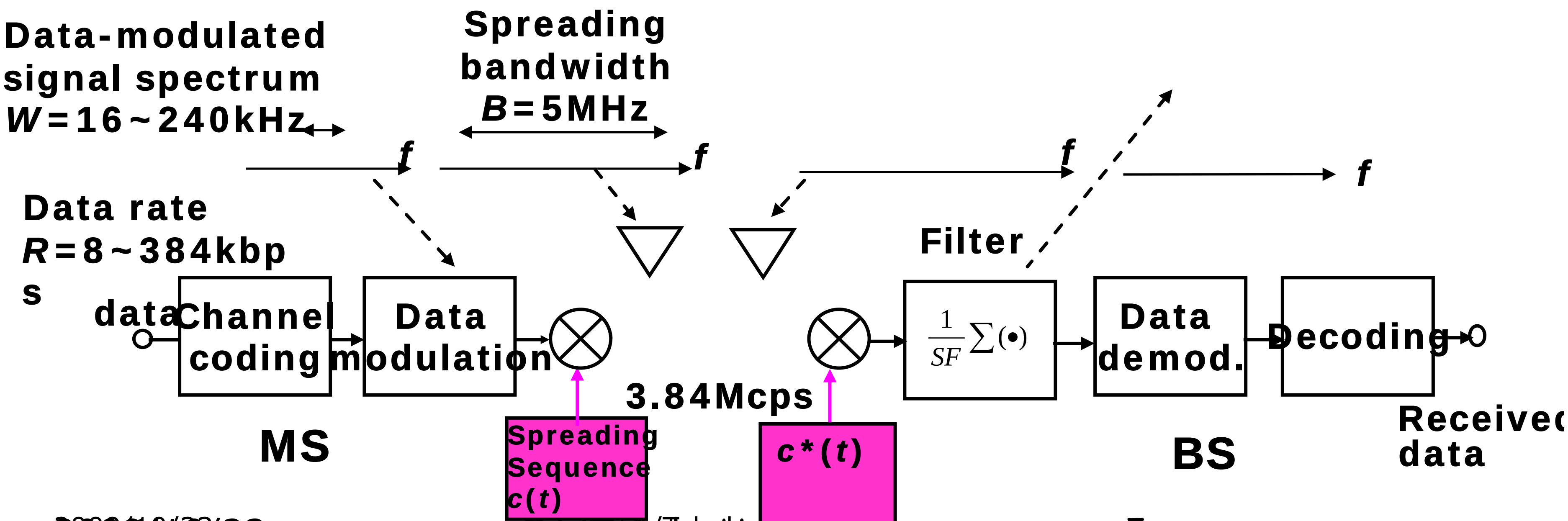
- Multiple access technique used in cellular systems has been changed from FDMA to DS-CDMA.
  - FDMA was used in 1G, TDMA in 2G, DS-CDMA in 3G
  - OFDMA and SC-FDMA are used for downlink and uplink , respectively, in 3.9G(LTE)



3G Uses DS-CDMA

- In 3G systems, DS-CDMA with rake combiner is adopted.
  - The user data of rate *W* is spread over *B* (=5MHz) by multiplying a user specific spreading sequence.
  - Various rate data can be transmitted just by changing the spreading factor and channel coding rate.
  - Chip rate: 3.84Mcps



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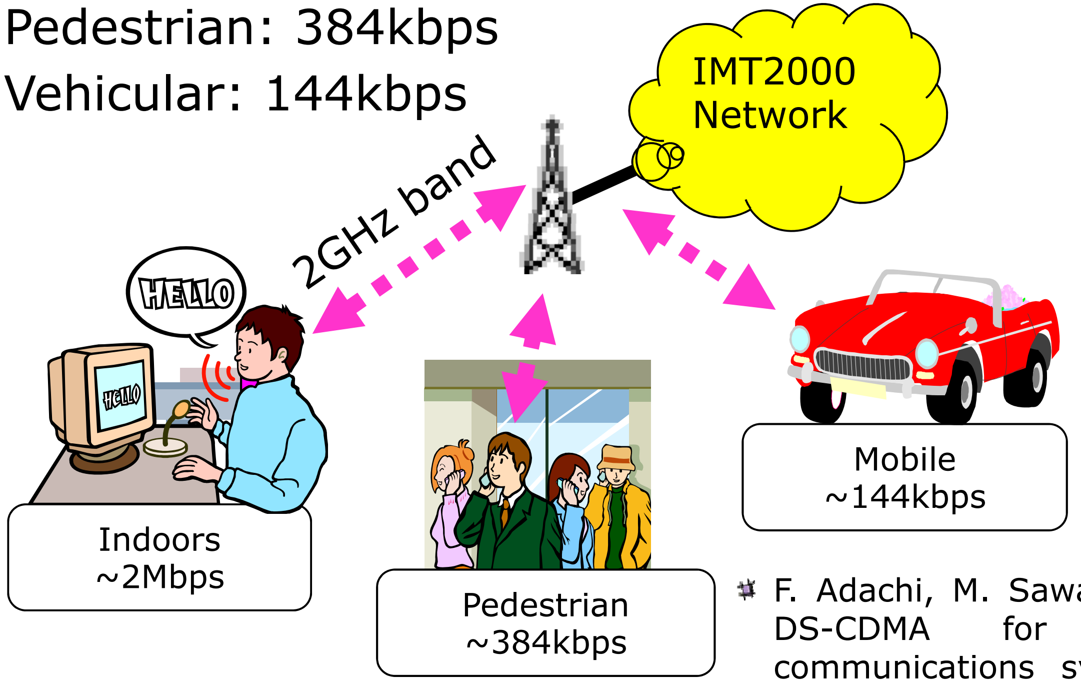
3G Systems Using W-CDMA

- Data transfer rates in 2G systems are too slow for retrieving rich information distributed in the Internet.
- 3G cellular systems are designed to offer cellular users a significantly higher data-rate services using wideband DS-CDMA technology (5MHz bandwidth).
  - Indoor: 2Mbps
  - Pedestrian: 384kbps
  - Vehicular: 144kbps



F. Adachi, M. Sawahashi and H. Suda, "Wideband DS-CDMA for next generation mobile communications systems," IEEE Commun. Mag., vol. 36, pp. 56-69, Sept. 1998.

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On-going Shift To 3G Systems (Japan)

- 3G services (~384kbps) started in 2001 in Japan.
- Growth rate of 3G systems were very slow in the first few years, but now it is really taking off.
- Total no. of cellular subscribers @end of Dec. 2008
  - 105,825,200 (penetration: 90.8 %)
- 2G (9,758,700)
  - PDC: 9,411,900
  - cdmaOne: 346,800
- 3G (96,066,500)
  - 81.4 % of total
  - W-CDMA: 65,863,100
  - CDMA2000 1x: 30,203,400

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Growing Wireless Internet

- Broadband multimedia services
  - In line with the increasing popularity of Internet in fixed networks, cellular systems are evolving from simply providing traditional voice communication services to providing broadband multimedia services through Internet access.
- Internet cell phones @end of Dec. 2008 (source: TCA)
  - Total cellular users: 105,825,200 (penetration 90.8%*)
  - Users connected to Internet: 90,173,100 (85.2%)
    - i-mode (DoCoMo): 48,149,500
    - Ezweb (au): 25,913,300
    - Yahoo Ke-tai (SoftBank): 16,061,000
    - Emnet: 49,300

* Japan population estimate:127.69m @Oct. 2005

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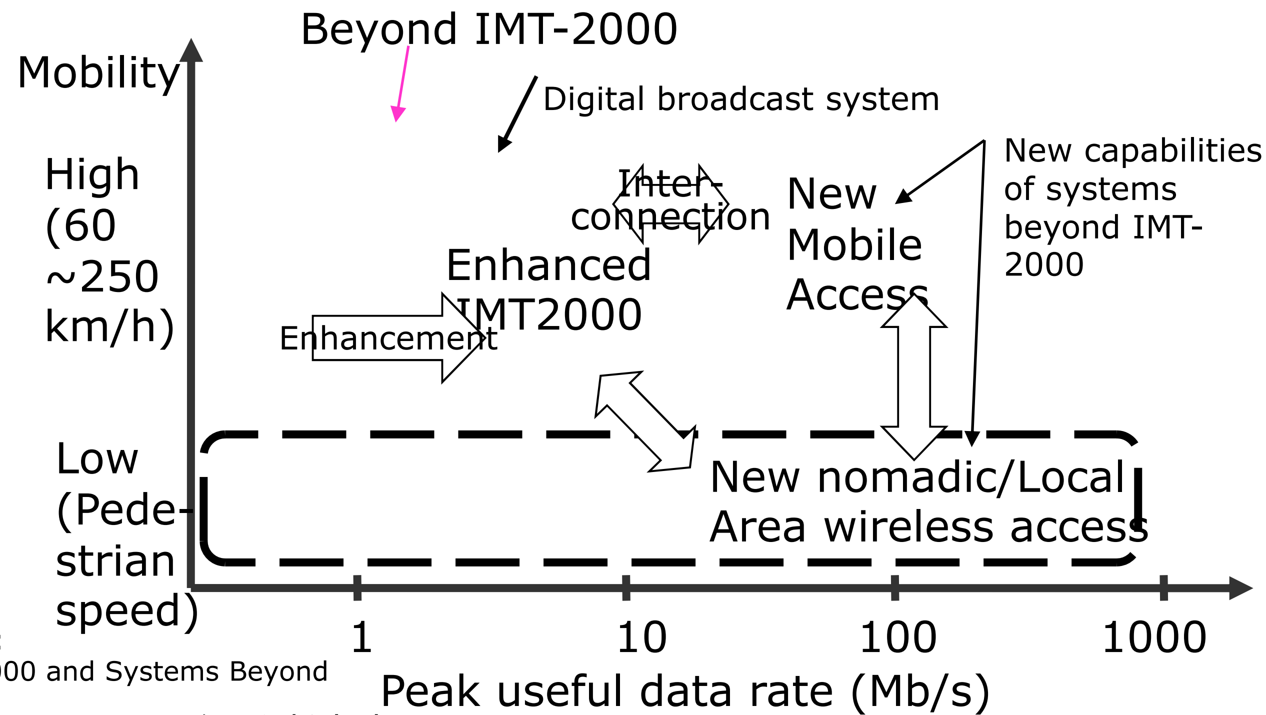
4G Vision

- Broadband services: data rates for mobile services may be up to 100 Mbps and those for nomadic services may be up to 1Gbps.
- Gigabit wireless: an important technology for the realization of 4G systems.



ITU-R WP8F (Ottawa, June 2002) : illustration of Capabilities of IMT2000 and Systems Beyond

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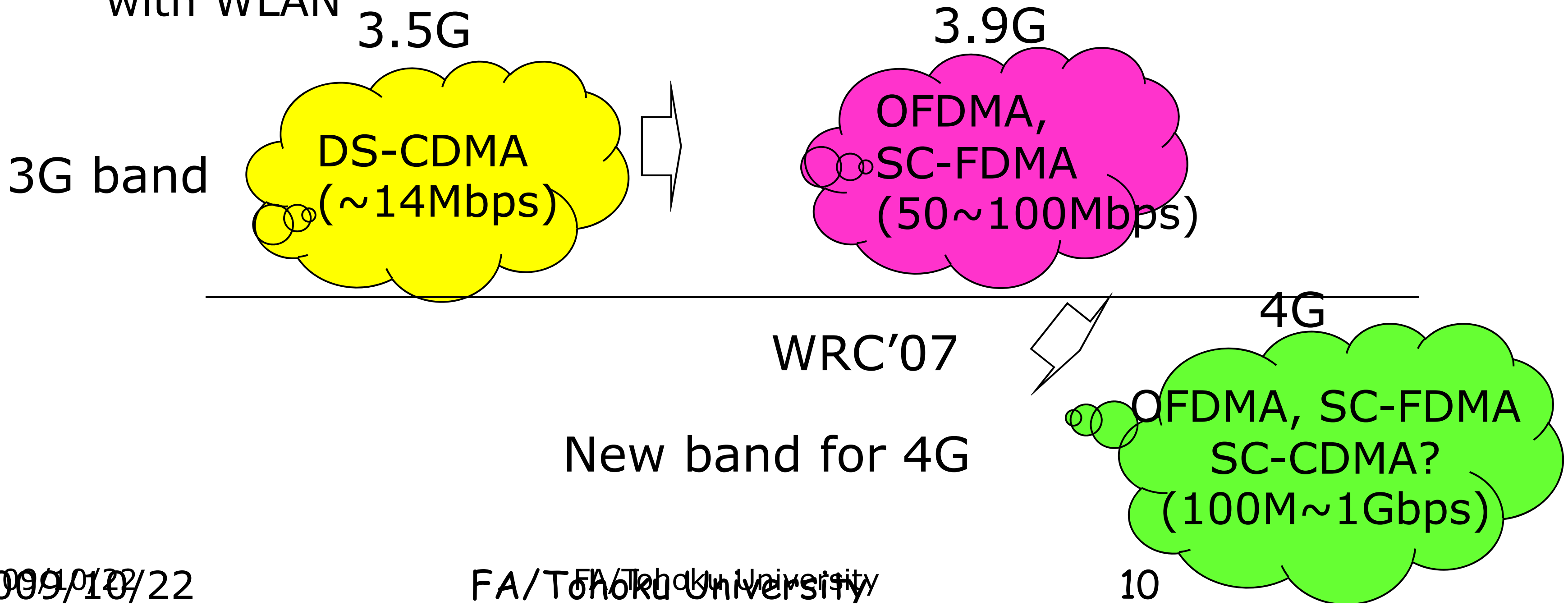
Before 4G, There Will Be 3.9G

- 3G band will be used
  - No available bandwidth of 100MHz (a hot matter of WRC-07)
  - Present 3G bandwidth (1.25~20MHz) will be used to provide much faster rate data services
  - Target: 100Mbps for downlink, 50Mbps for uplink
- Difference from 3G wireless technology
  - 3~3.5G：DS-CDMA□3.9G OFDMA?
  - Promising transmission performance and good commonality with WLAN



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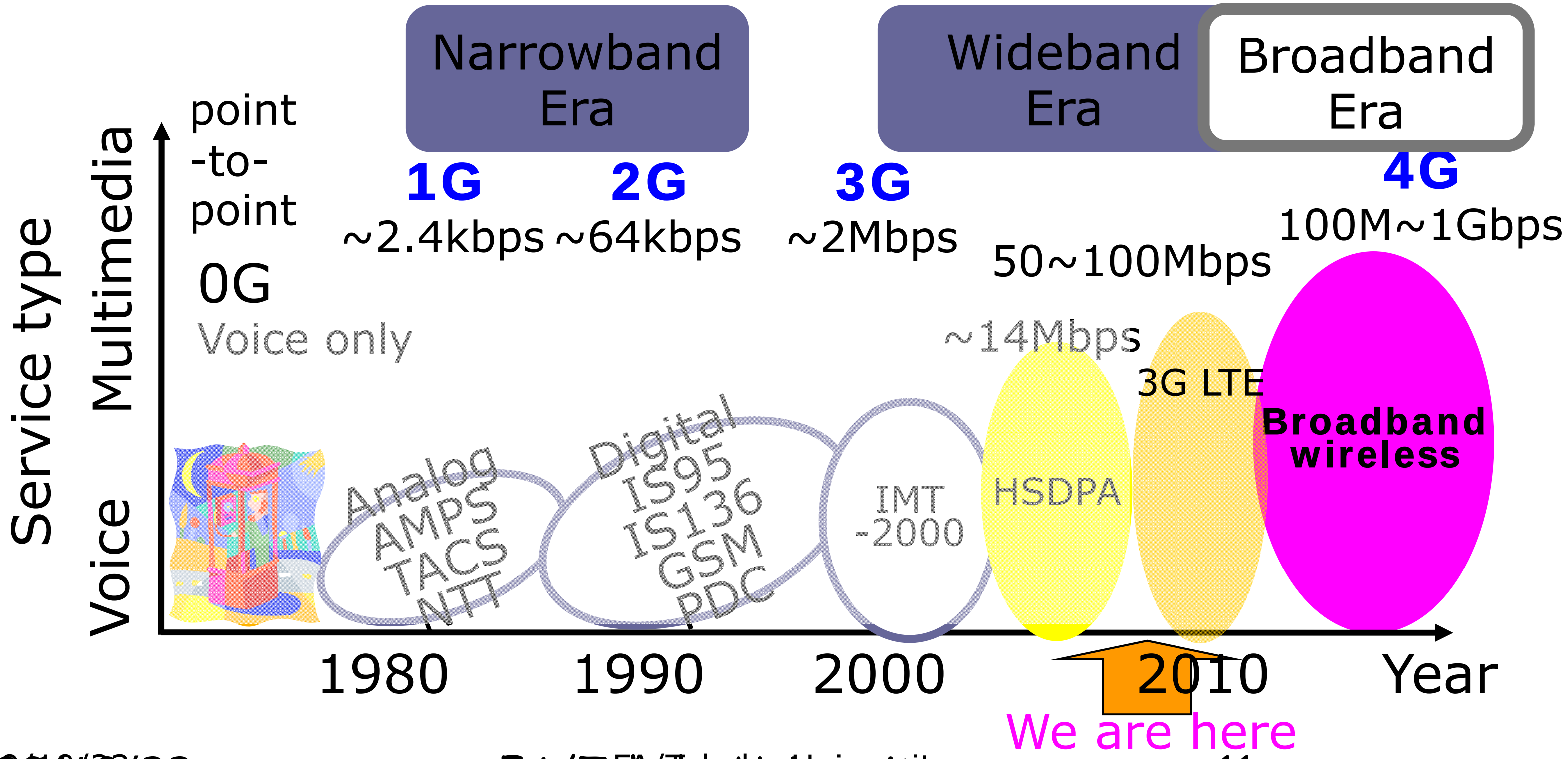
Evolution Into 4G

- 4G systems are required to provide much faster packet data services of a peak rate of 100M~1Gbps.
- ITU allocated the spectrum for 4G systems in Dec. 2007.
  - 450~470MHz (20MHz), 790~806MHz (16MHz), 2.3~2.4GMHz (100MHz), 3.4G~3.6GHz Global use (200MHz)



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Technical Issues of 4G

Limited bandwidth Problem

- ITU allocated the spectrum for 4G systems in Dec. 2007.
  - 450~470MHz (20MHz)
  - 790~806MHz (16MHz)
  - 2.3~2.4GMHz (100MHz)
  - 3.4G~3.6GHz Global use (200MHz)
- 200MHz bandwidth in the global frequency band must be shared by several operators (at least 2) and reused everywhere.
- Probably, frequency reuse factor can be around 25% ☐ an effective bandwidth/BS is only around 12.5MHz/link.
- 1Gbps/12.5MHz is equivalent to 80bps/Hz/BS!!

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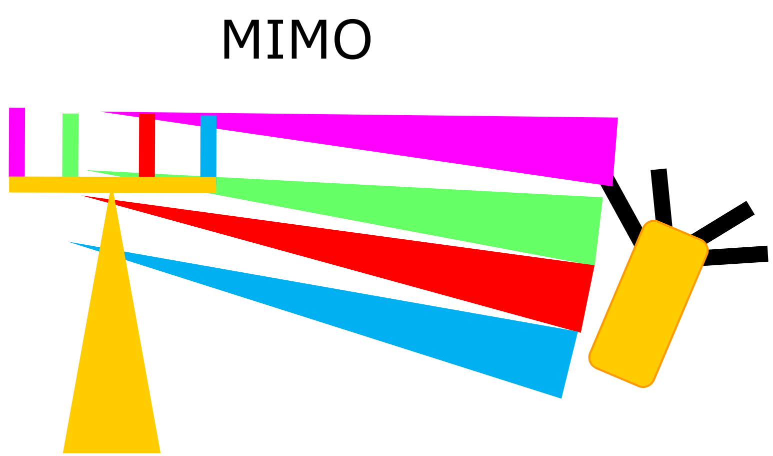
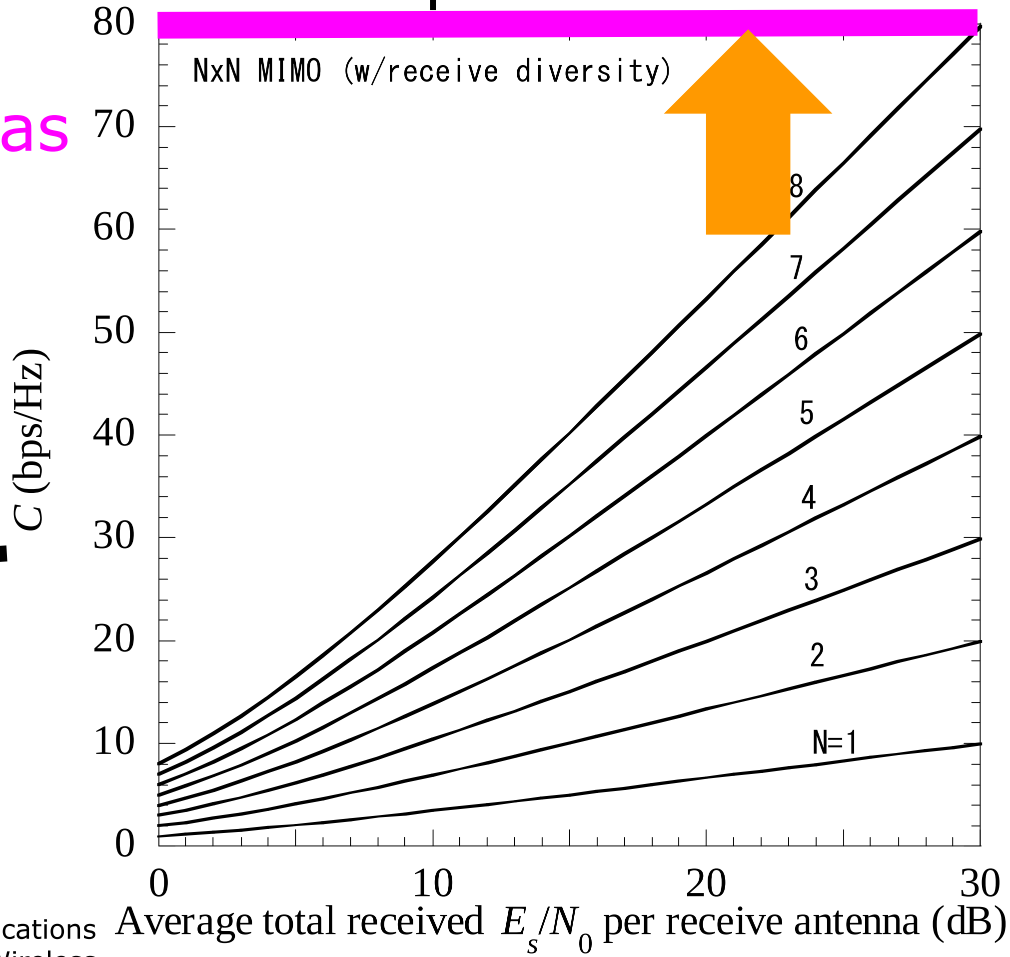
- MIMO multiplexing can improve the spectrum efficiency or can decrease the required transmit power.
- But, too many antennas are necessary.





G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," Wireless Personal Commun., Vol.6, No. 3, pp.311-335, Mar. 1998.

Transmit Power Problem

- Peak power is in proportion to “transmission rate” x “*fc*2.6 [Hata-formula]” where *fc* is the carrier frequency.
- The required transmit power for 8kbps@2GHz is 1Watt for a communication range of 1,000m.
- The required peak transmission power for 1Gbps@3.5GHz needs to be increased by 1Gbps/8kbps x (3.5GHz/2GHz)2.6 =535,561 times, that is, 536kWatt.
- Obviously, this cannot be allowed !

M. Hata, “Empirical formula for propagation loss in land mobile radio services”, IEEE Trans. Veh. Technol., VT-29, pp. 317-325, 1980.

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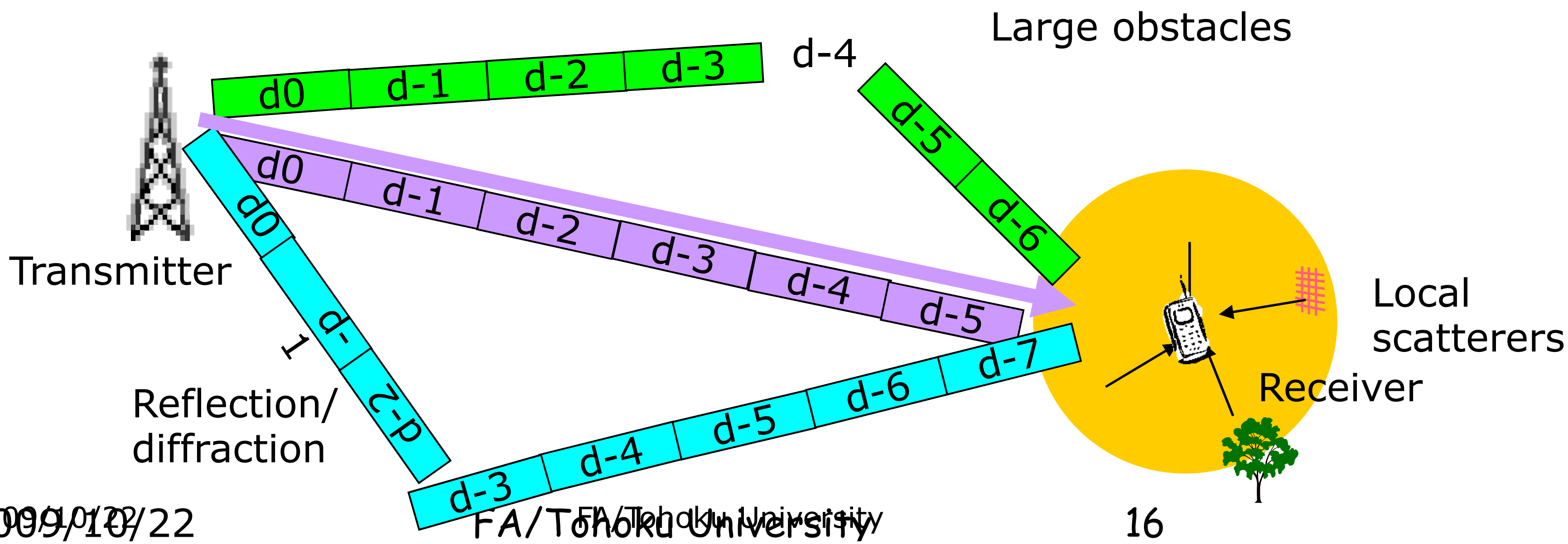
Severe Channel Problem

- In terrestrial wireless communications, the transmitted signal is reflected or diffracted by large buildings between transmitter and receiver, creating propagation paths having different time delays.
- For signal transmissions using 25MHz bandwidth, 1 symbol length in time is equivalent to the distance of 12 m. So, many distinct multipaths exist, thereby extremely enhancing the channel frequency-selectivity.



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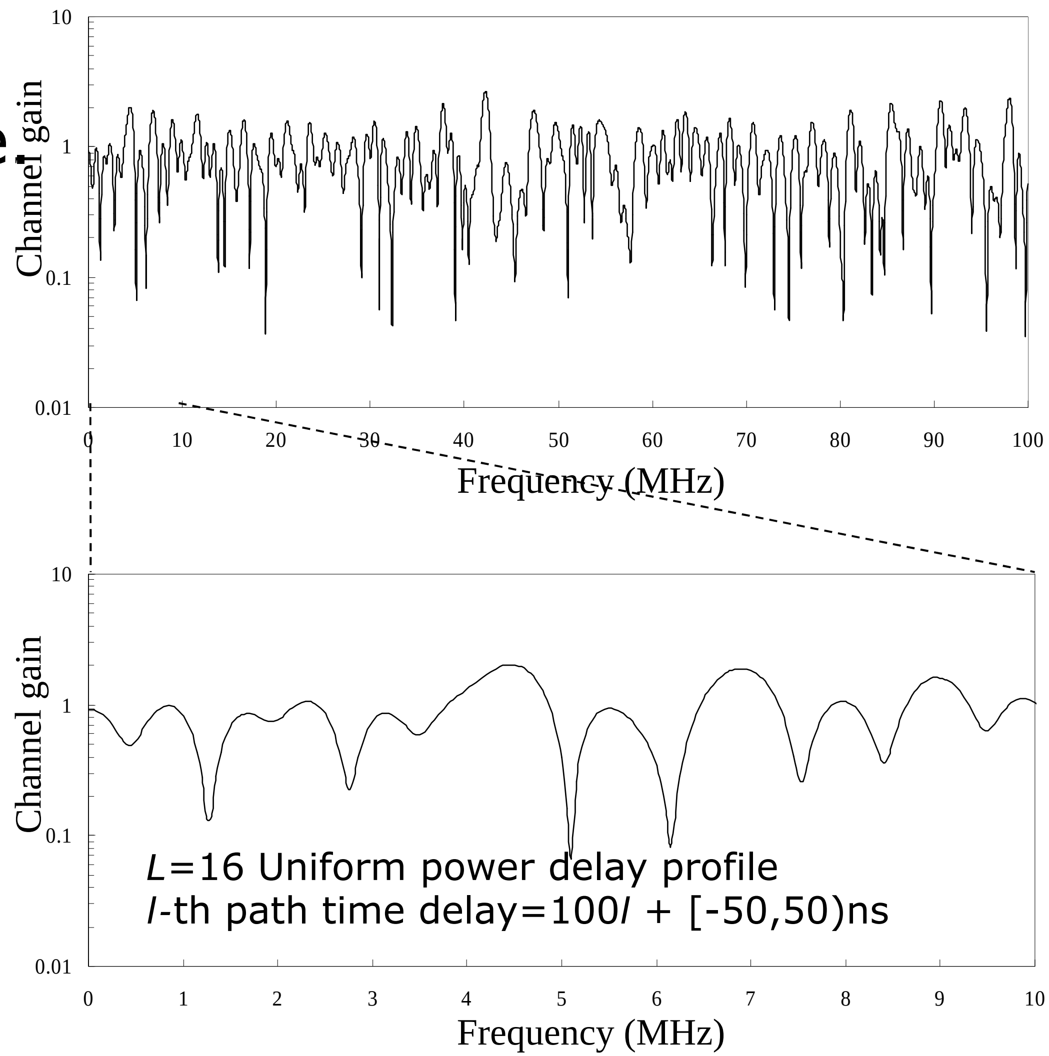
- Wireless channel is extremely frequency-selective.
- Some advanced equalization technique is necessary.



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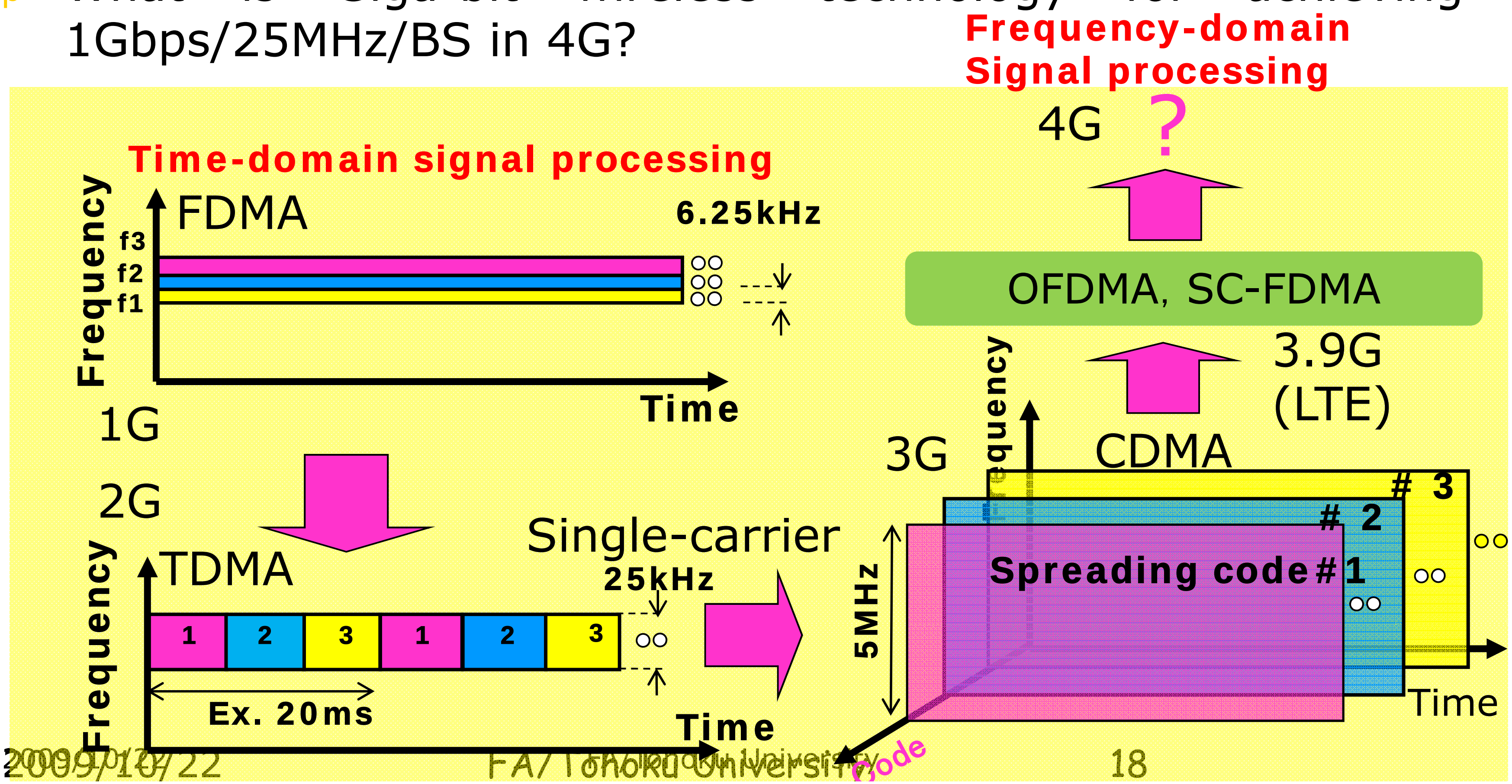
Evolution of Wireless Access

- FDMA was used in 1G, TDMA in 2G, DS-CDMA in 3G
- OFDMA and SC-FDMA are used for downlink and uplink , respectively, in 3.9G(LTE)
- What is Giga-bit wireless technology for achieving 1Gbps/25MHz/BS in 4G?

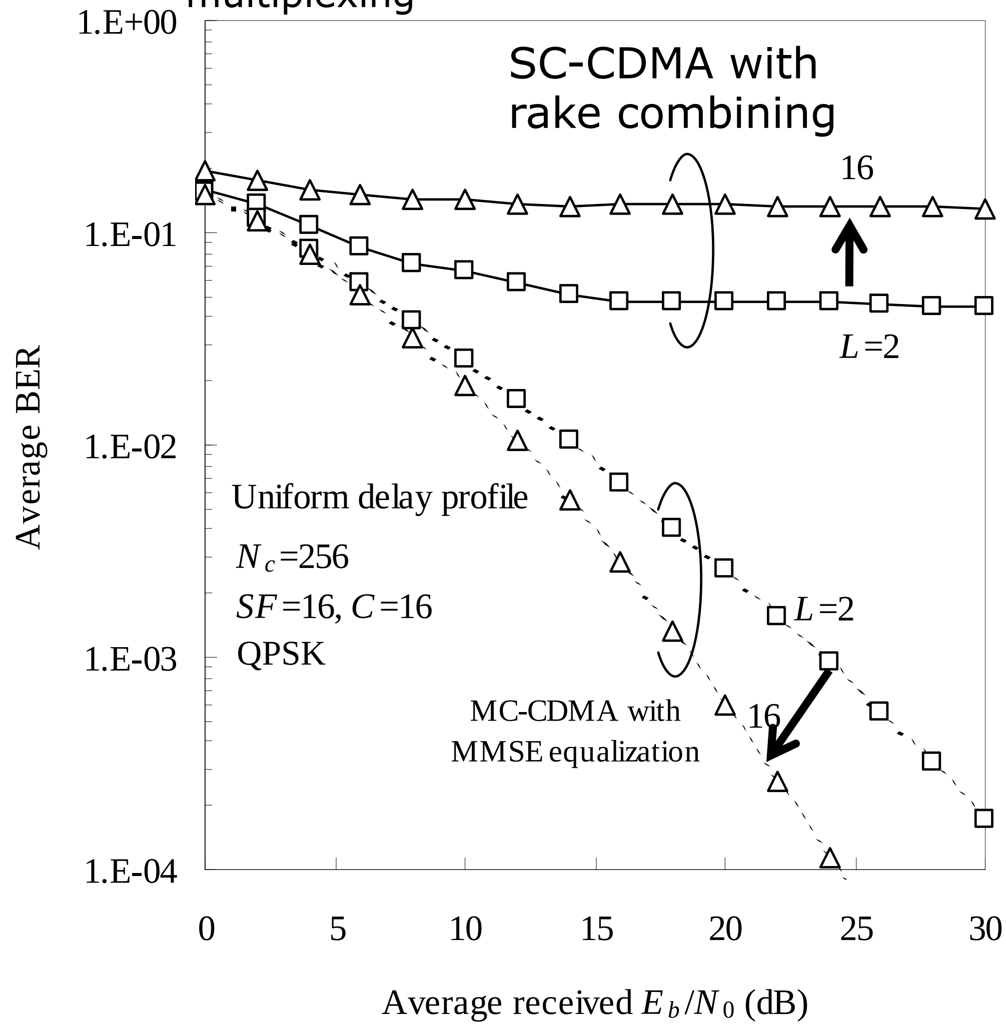


Frequency-domain Signal Processing

DS with Rake vs. MC with FDE

- As the number of resolvable paths increases, the channel frequency-selectivity gets stronger.
- The achievable BER performance of 3G SC(DS)-CDMA with rake combining degrades significantly due to strong IPI.
  - For a heavily loaded channel, even with *L*=2, a high BER floor appears if the code-multiplexing order is high.
- On the other hand, MC-CDMA with MMSE-FDE provides much better performance.
  - Performance improves as *L* increases.

SC-CDMA for downlink w/full code-multiplexing



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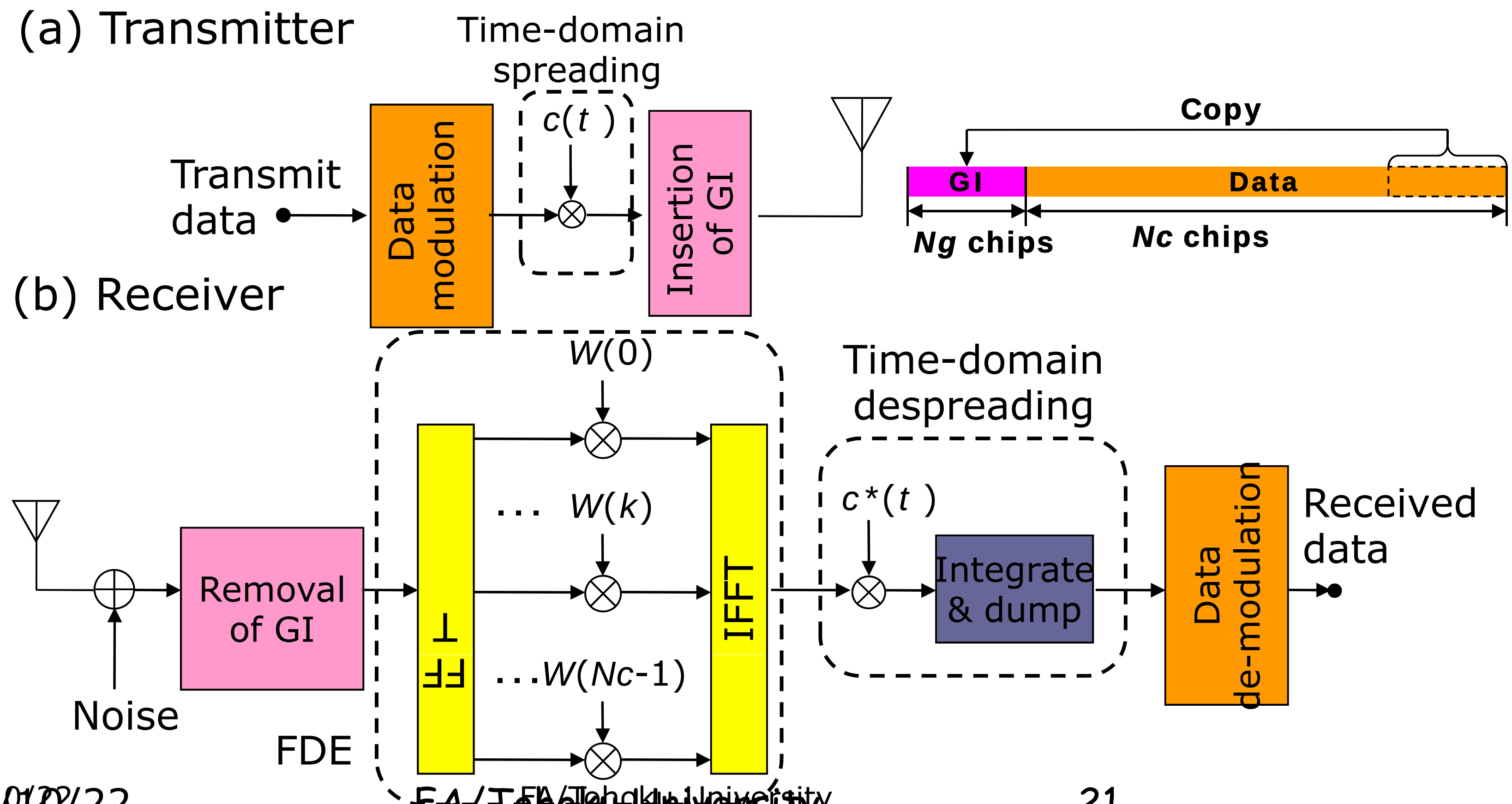
FDE Improves SC-CDMA Performance

- Coherent Rake combining can be replaced by one-tap FDE
  - Block transmission of *Nc* chips
  - Insertion of guard interval (GI) at the transmitter
  - FFT/IFFT at the receiver



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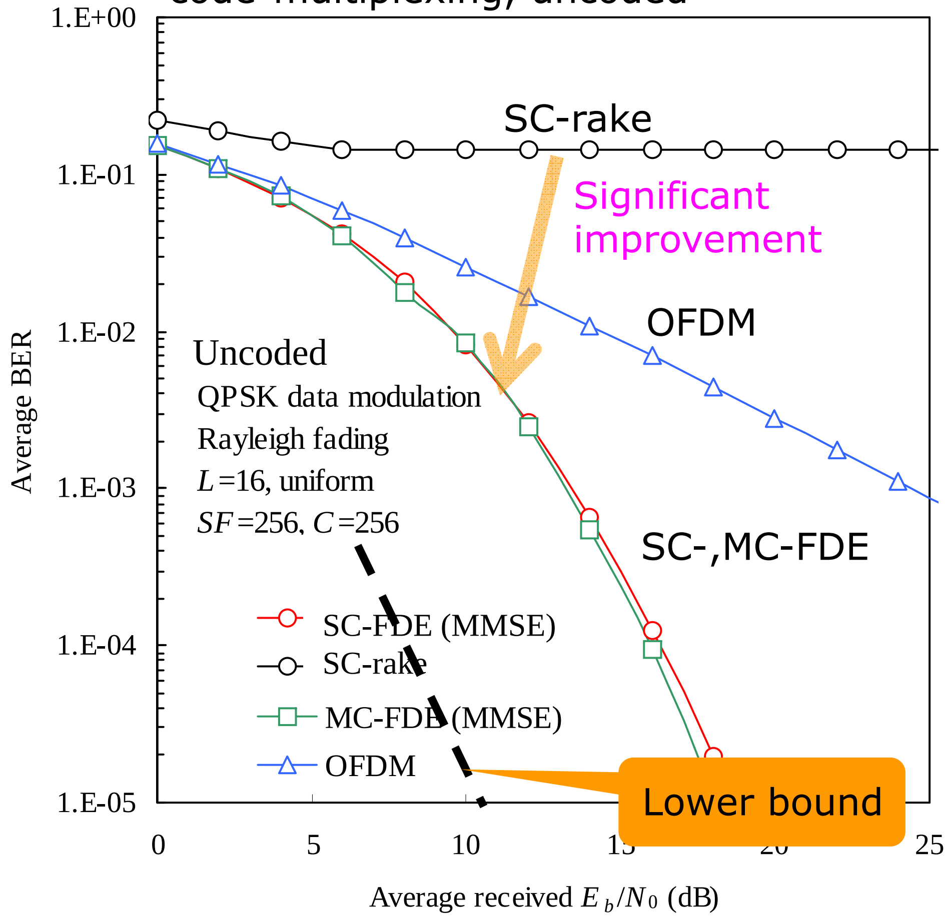
- Downlink BER performance can be significantly improved compared to the coherent rake receiver.
- However, there is still a big performance gap from the theoretical lower bound.
  - This is due to residual ISI after MMSE-FDE.
  - Introduction of ISI cancellation technique can reduce the performance gap.

Multicode DS-CDMA for downlink w/full code-multiplexing, uncoded



F. Adachi, D. Garg, S. Takaoka, and K. Takeda, "Broadband CDMA techniques," IEEE Wireless Commun. Mag., Vol. 12, No. 2, pp. 8-18, April 2005

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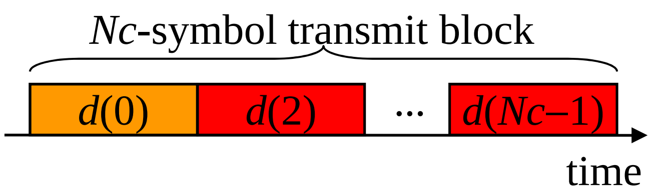
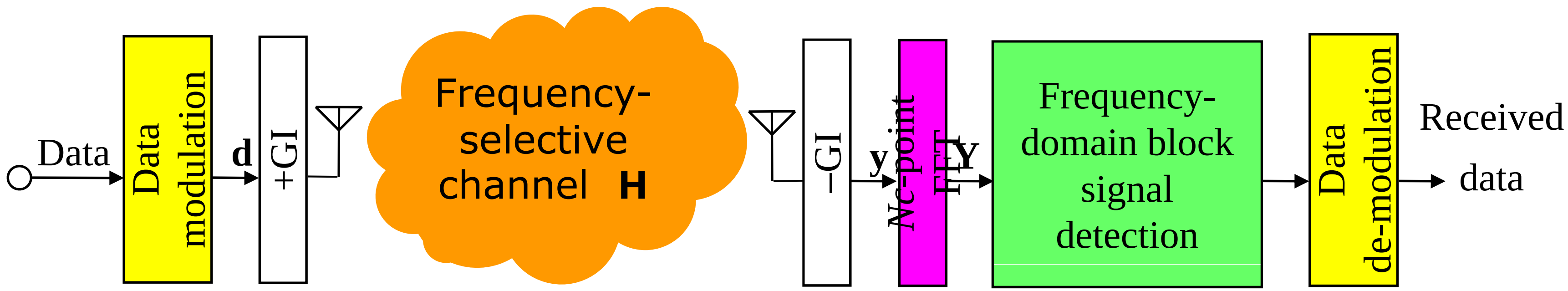
Frequency-domain Block Signal Detection

- For the broadband single-carrier signal transmissions, the BER performance significantly degrades due to the strong inter-symbol interference (ISI).
- Frequency-domain block signal detection is very promising that combines frequency-domain equalization (FDE) and block signal detection.



$$\mathbf{Y} = \sqrt{\frac{2E_s}{T_s}}(\mathbf{HF})\mathbf{d} + \mathbf{N}$$



T. Yamamoto, et. al., to be presented at The VTC-fall, Anchorage, Alaska, USA, 21~23 Sept. 2009.

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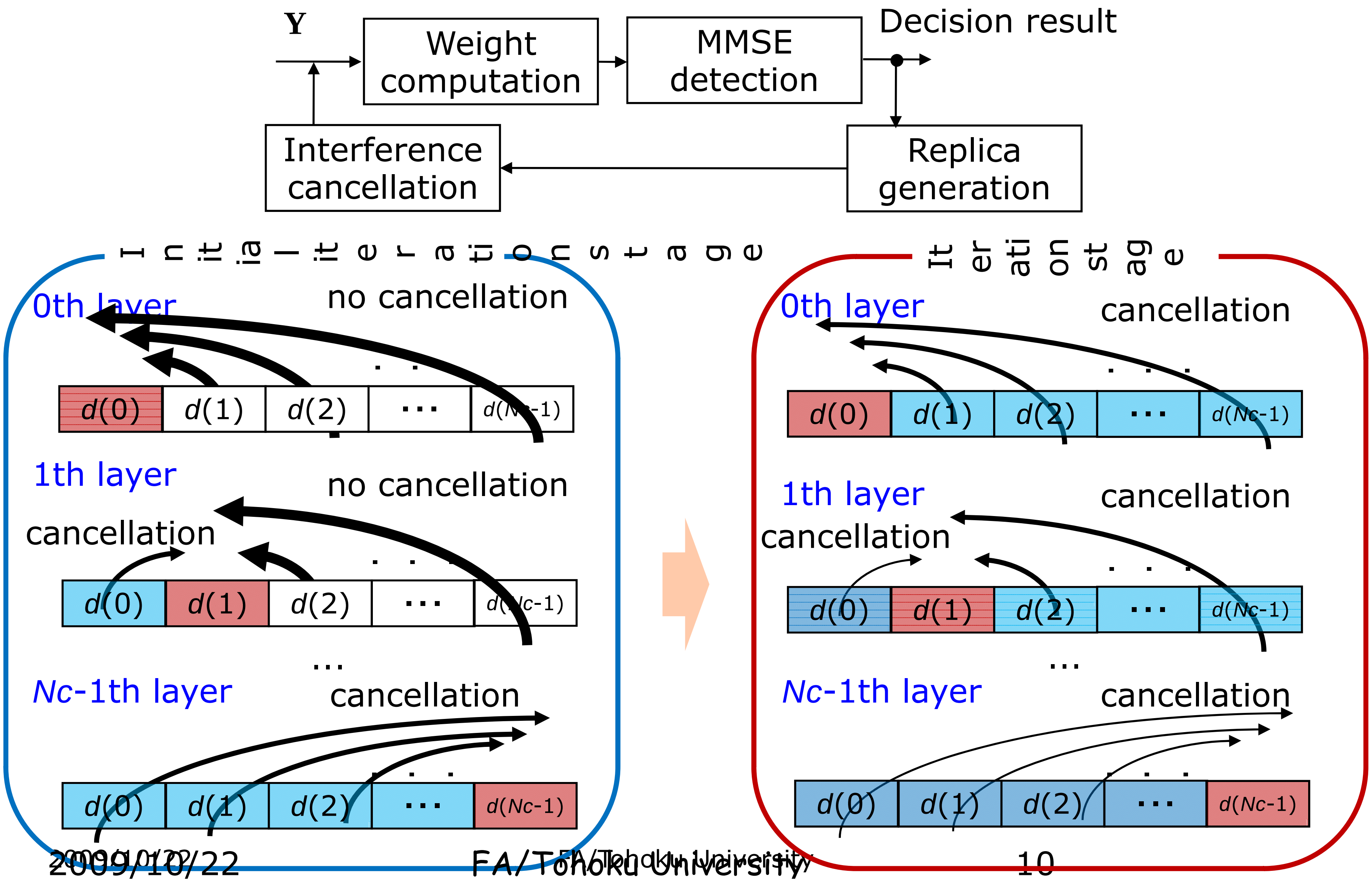
SIC & MMSED



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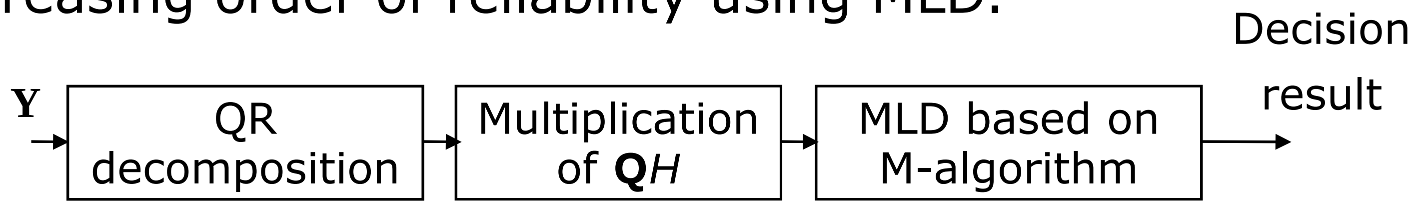
QRM-MLD

- QR decomposition is applied to **Y** to detect the symbols in decreasing order of reliability using MLD.



$$\mathbf{HF} = \mathbf{QR}$$

- MLD based on the M-algorithm
  - Reliability based on the squared Euclidian distance is calculated.
  - *M* symbol candidates having the highest reliability are selected as surviving symbol candidates.

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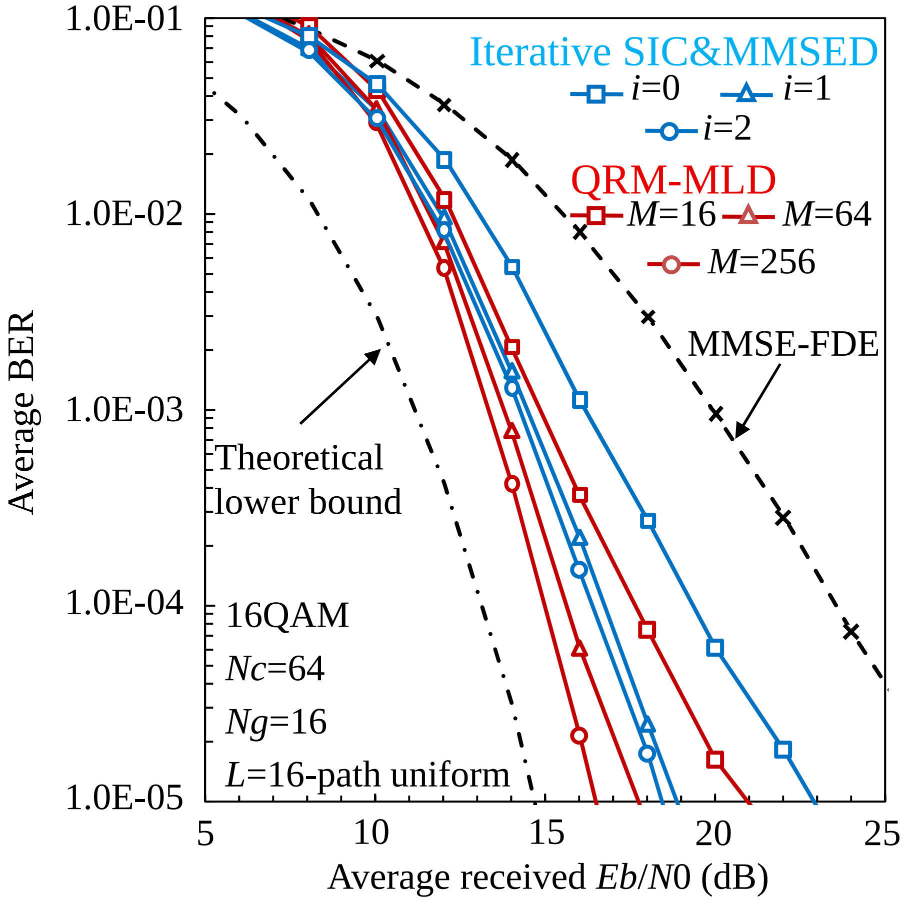
- As the number of iterations increases, the BER performance improves and approaches that of the lower bound.
- The *Eb*/*N*0 gap from the lower bound for the average BER=10-4 reduces by 3.2 dB when using two iterations (*i*=2).
- Much better performance can be achieved by using QRM-MLD (the number *M* of surviving symbol replica candidates equals to 64 and 256) than iterative SIC&MMSED.



T. Yamamoto, K. Takeda, and F. Adachi, "A Study of Frequency-Domain Signal Detection for Single-Carrier Transmission," Proc. IEEE VTC 2009 Fall, 20-23 Sept, 2009, Araska, US.

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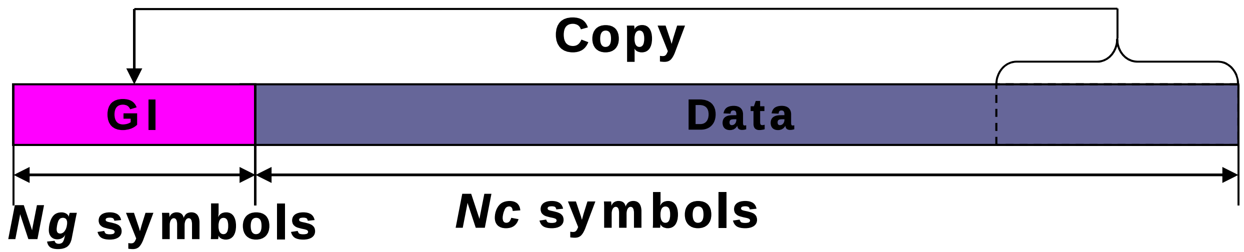
Overlap FDE

- The insertion of GI (CP) for FDE reduces the throughput by a factor of 1/(1+*Ng*/*Nc*).



- Without GI insertion, the inter-block interference (IBI) is produced.
  - FDE output without GI insertion

$$\hat{s}(t)=\sqrt{\frac{2E_s}{T_c}}\left(\frac{1}{N_c}\sum_{k=0}^{N_c-1}W(k)H(k)\right)s(t)+\text{residual ISI}+\text{residual IBI}+\text{Noise}$$

Average equivalent channel gain

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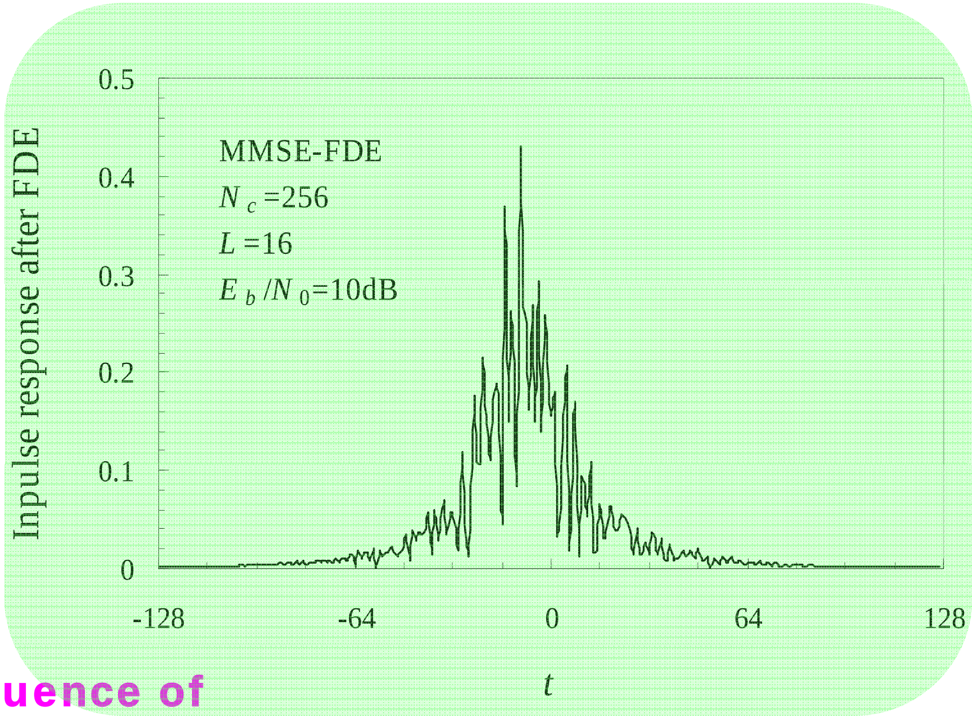
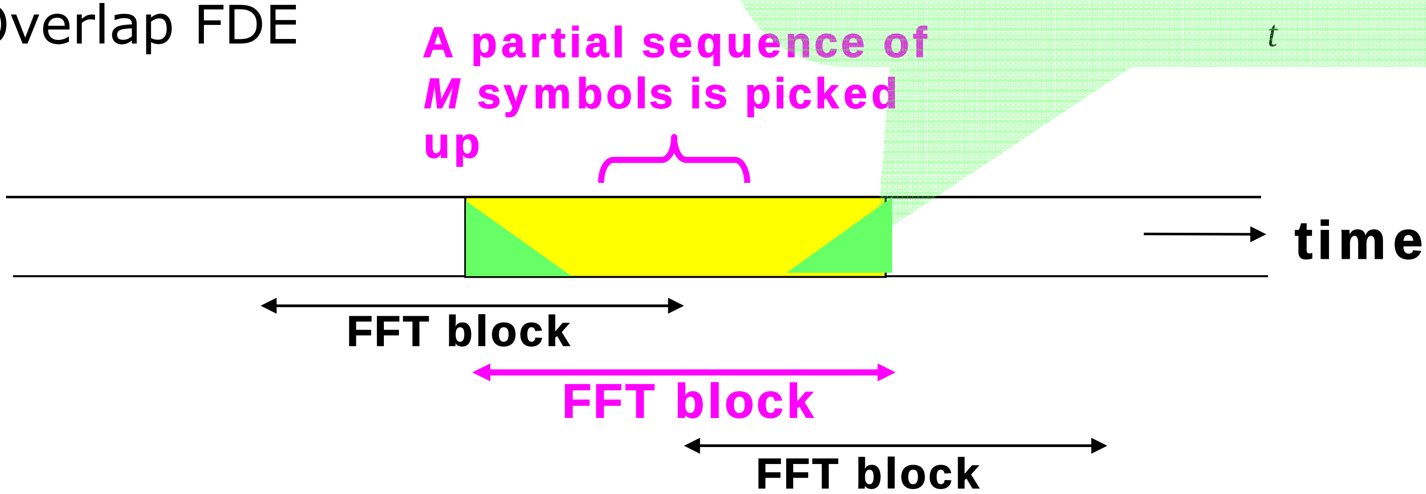
- Impulse response of circular FDE filter concentrates at the vicinity of t=0.
- This property can be exploited to mitigate the IBI after FDE.



- Overlap FDE



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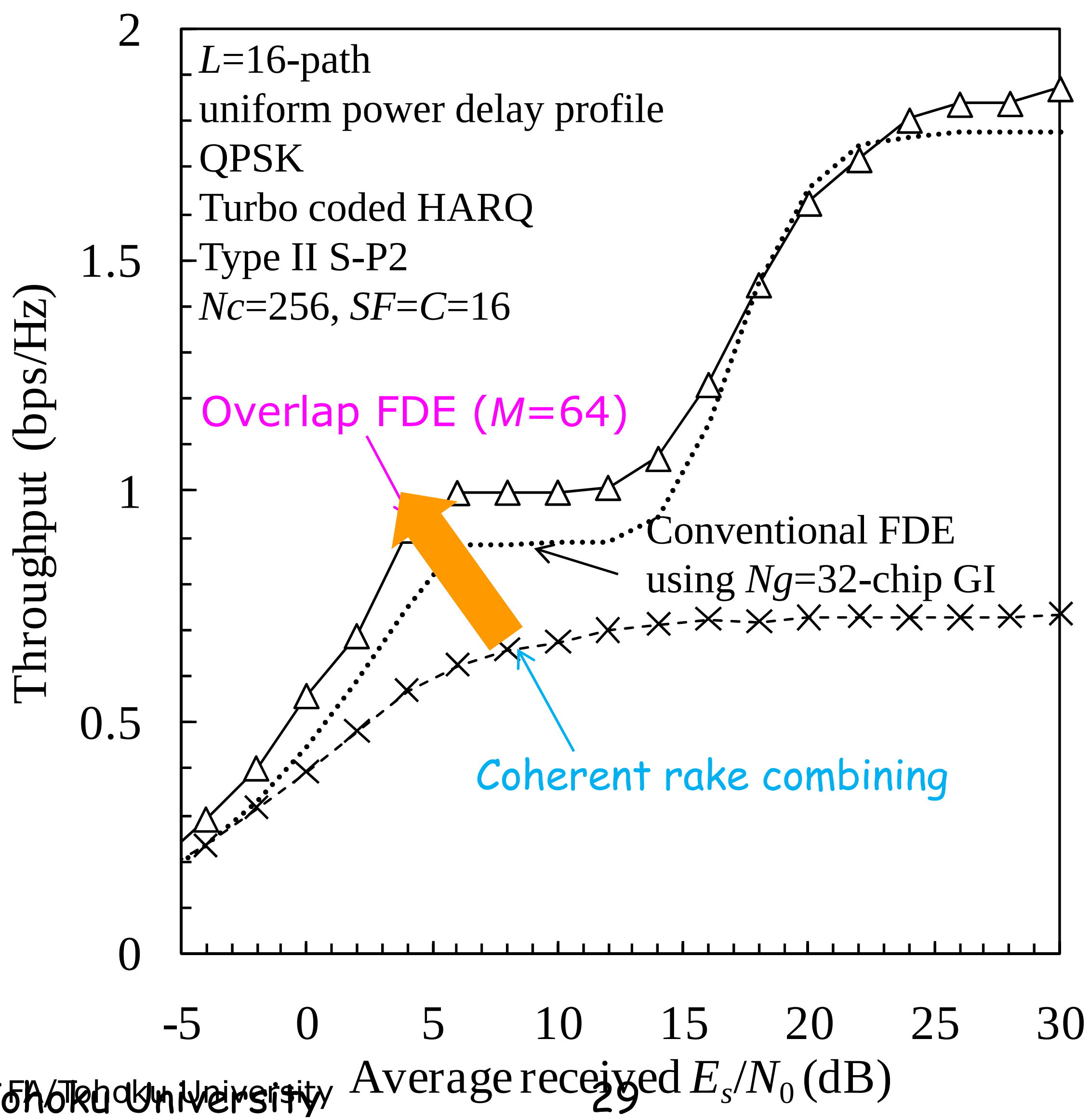
Application of Overlap FDE to DS-CDMA

- Overlap FDE improves the throughput of SC HARQ.
- Since GI (CP) insertion is not required, overlap FDE can be applied to the present HSDPA using SC-CDMA technology.
  - Much higher throughput can be achieved.
  - The 3G air interface does not need to be changed at all.



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- Only 200MHz bandwidth is available for the global use of 4G spectrum. This bandwidth must be shared by the up/down links. Even though the single frequency reuse is used, an effective bandwidth may be around 25MHz/BS.
- Therefore, achievable peak data rate is, when using 25MHz, 1.8bps/Hz × 25MHz=45Mbps
- Single use of HARQ technique cannot achieve 1Gbps!
- Multiple-input/multiple-output (MIMO) antenna technique will play an important role to realize 4G systems.

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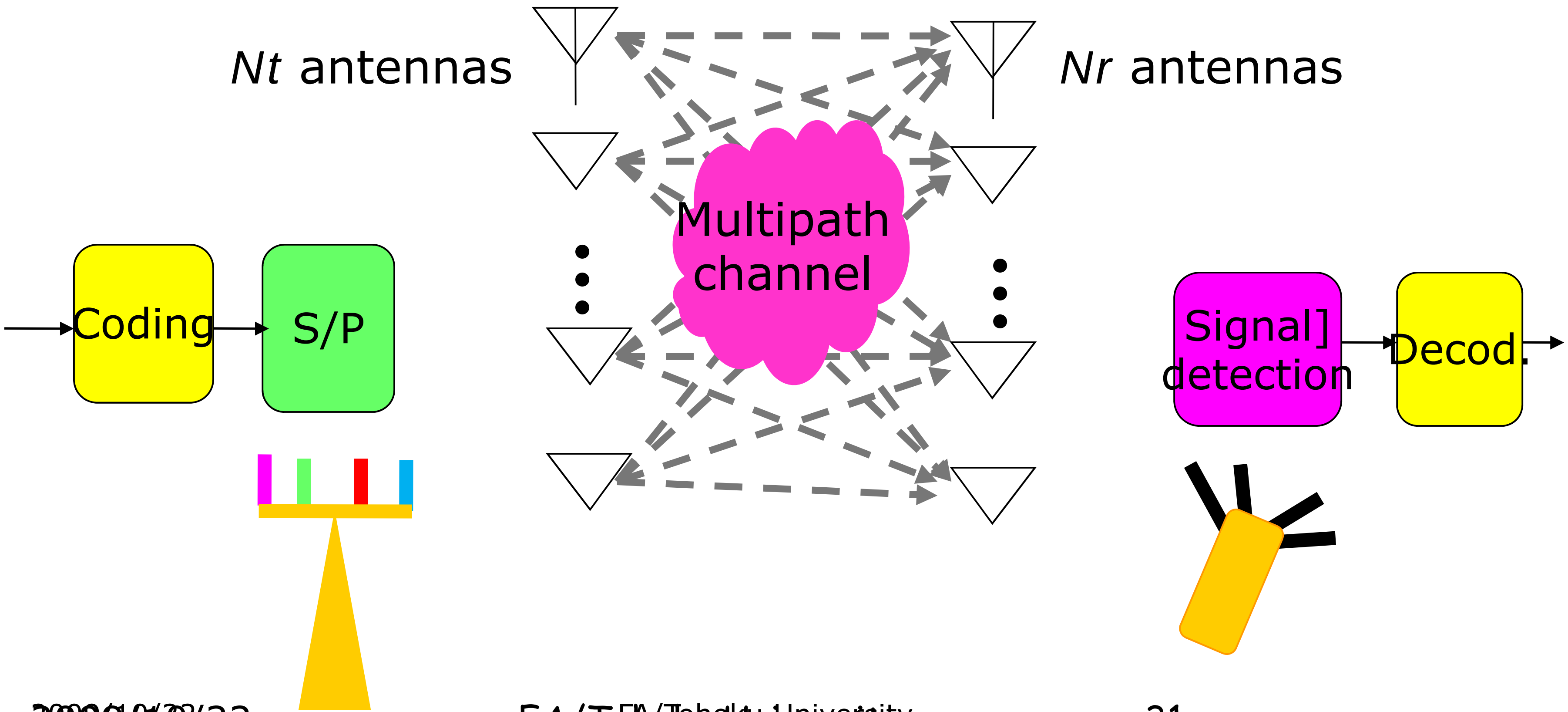
MIMO Multiplexing May Be A Savior

- Independent data streams are transmitted simultaneously from transmit antennas using the same carrier frequency.
- SDM is to increase achievable data rate within the limited bandwidth, i.e., the channel capacity in bps/Hz.



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SDM

- Next generation (4G) wireless systems are expected to provide broadband packet data services of up to 1Gbps. However, available bandwidth is limited.
  - In December 2007, ITU allocated 3.4~3.6GHz band for 4G services. Only 200MHz is available for global use.
  - This must be shared by the up/down links. Although one-cell reuse of 100MHz is possible, but, effective bandwidth which can be used at each BS is only around 25MHz/link. 1Gbps/25MHz is equivalent to 40bps/Hz/BS!!
- Thus, the development of a highly spectrum efficient wireless transmission technology of >40bps/Hz/BS is demanded

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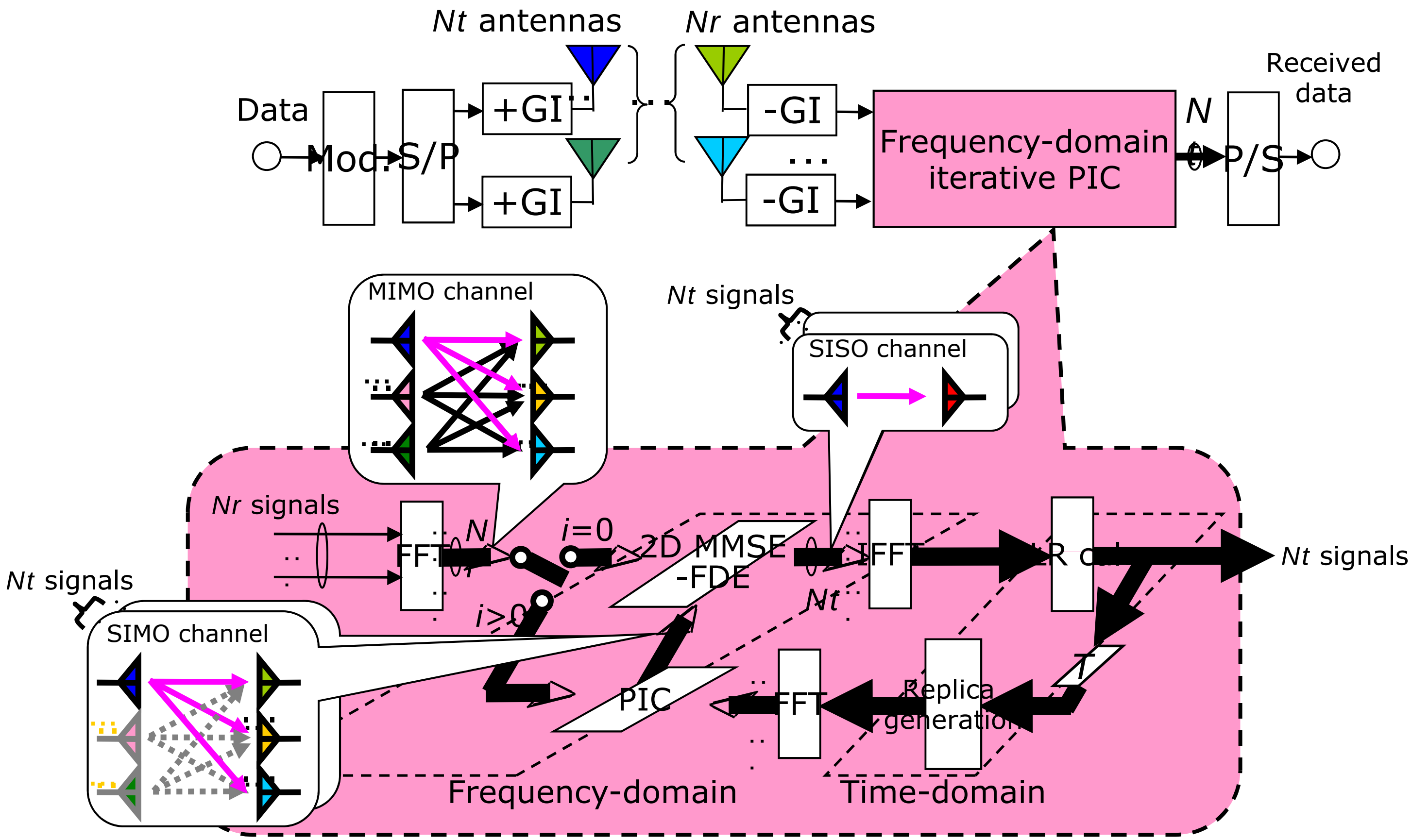
Single-carrier MIMO SDM

- Joint MMSE frequency-domain equalization (FDE) and parallel interference cancellation (PIC) is repeated for de-multiplexing while achieving frequency-diversity gain.



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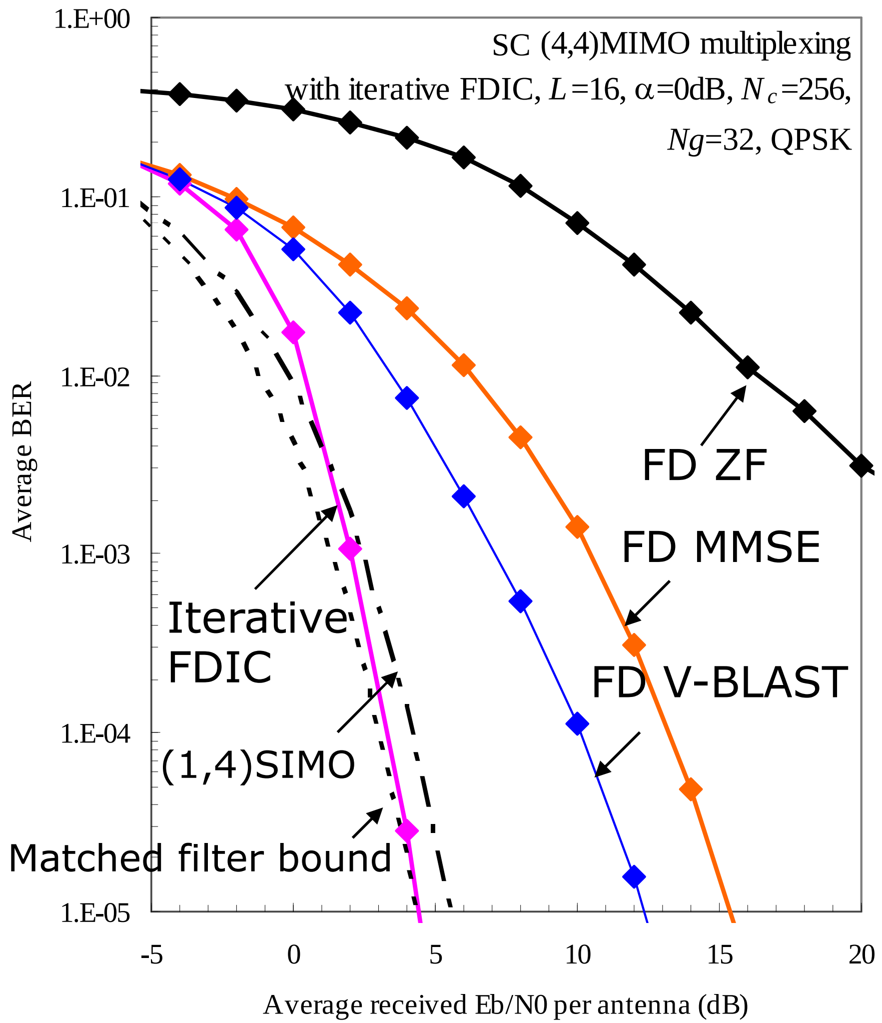

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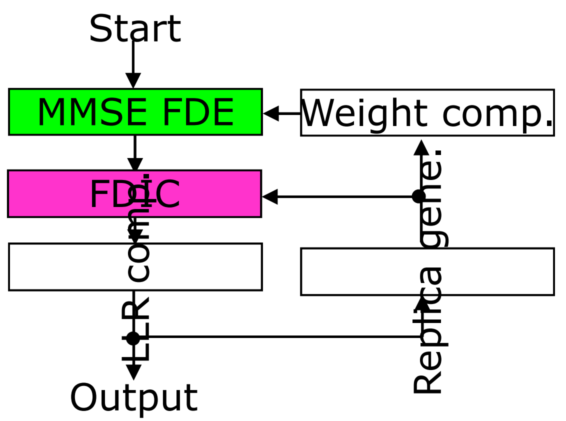
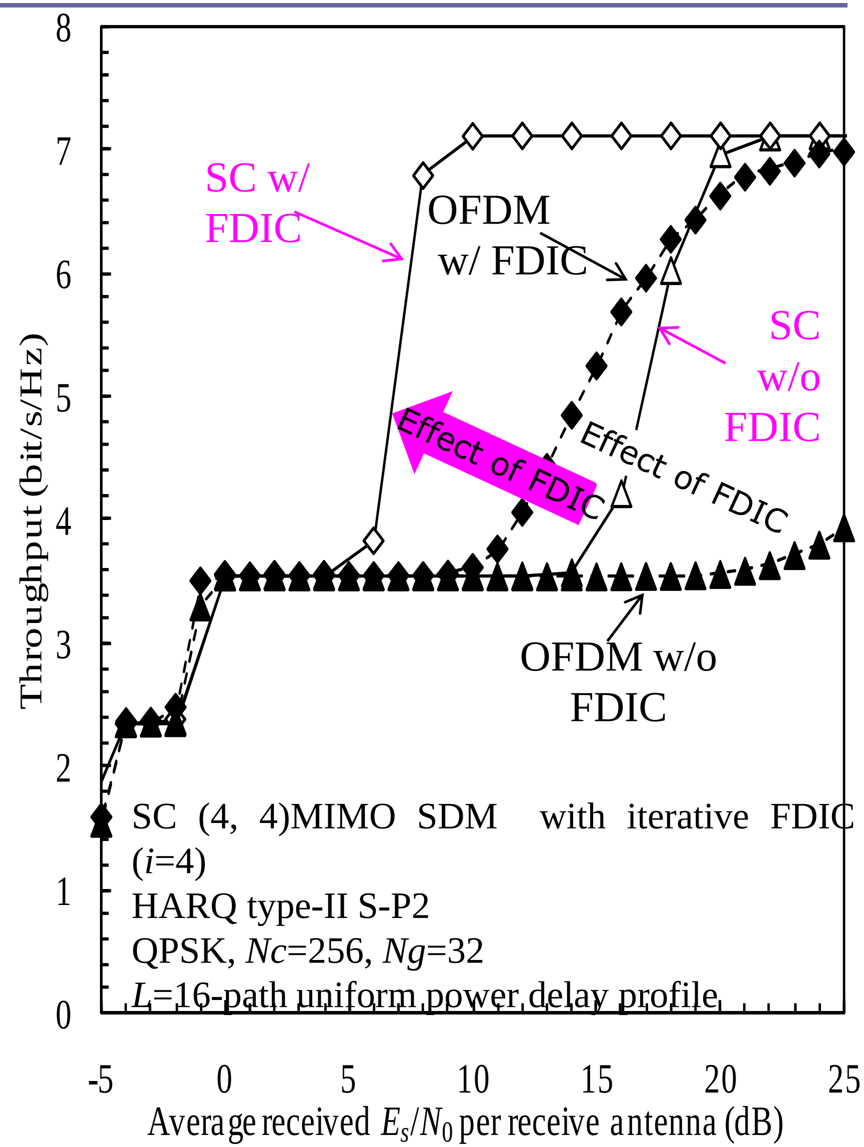
4x4 MIMO SDM Throughput

- MIMO signal detection using FDE and FD IC provides higher throughput than OFDM.



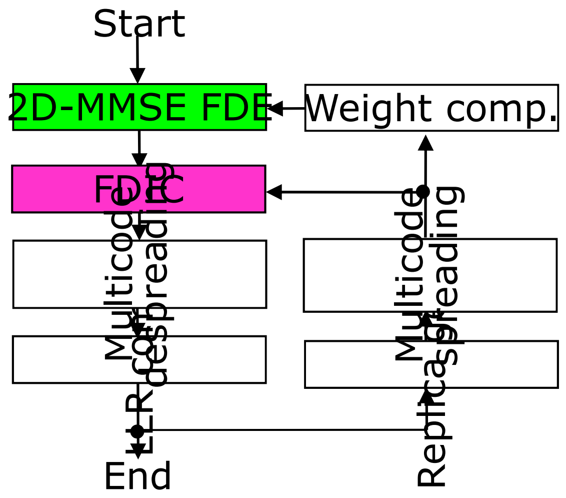


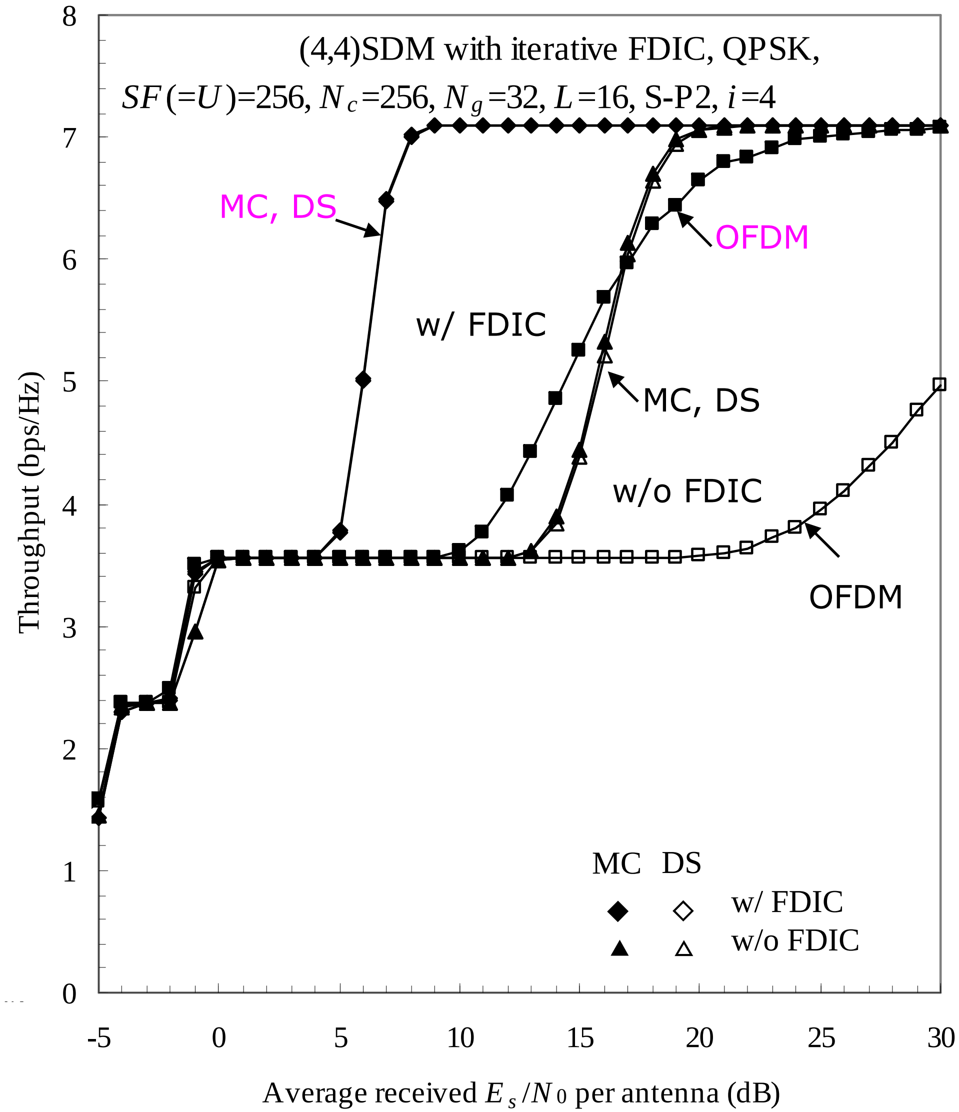
A. Nakajima, D. Garg and F. Adachi, "Frequency-domain iterative parallel interference cancellation for multicode DS-CDMA-MIMO multiplexing," Proc. IEEE VTC'05 Fall, Vol.1, pp. 73-77, Dallas, U.S.A., 26-28 Sept. 2005.

A. Nakajima and F. Adachi, "Iterative FDIC using 2D-MMSE FDE for turbo-coded HARQ in SC-MIMO multiplexing," IEICE Trans. Commun. Vol. E90-B, No.3, pp.693-695, Mar. 2007.

Spread 4x4 MIMO/SDM Throughput

- Spread MIMO SDM w/FDIC provides the throughput similar to non-spread SC.
  - Much better throughput than OFDM in a high *Es/N0* region.
  - Almost the same throughput as OFDM in a low *Es/N0* region.





- A. Nakajima, D. Garg and F. Adachi, "Frequency-dor iterative parallel interference cancellation for multicode CDMA-MIMO multiplexing," Proc. IEEE VTC'05 Fall, Vol.1, pp. 77, Dallas, U.S.A., 26-28 Sept. 2005.
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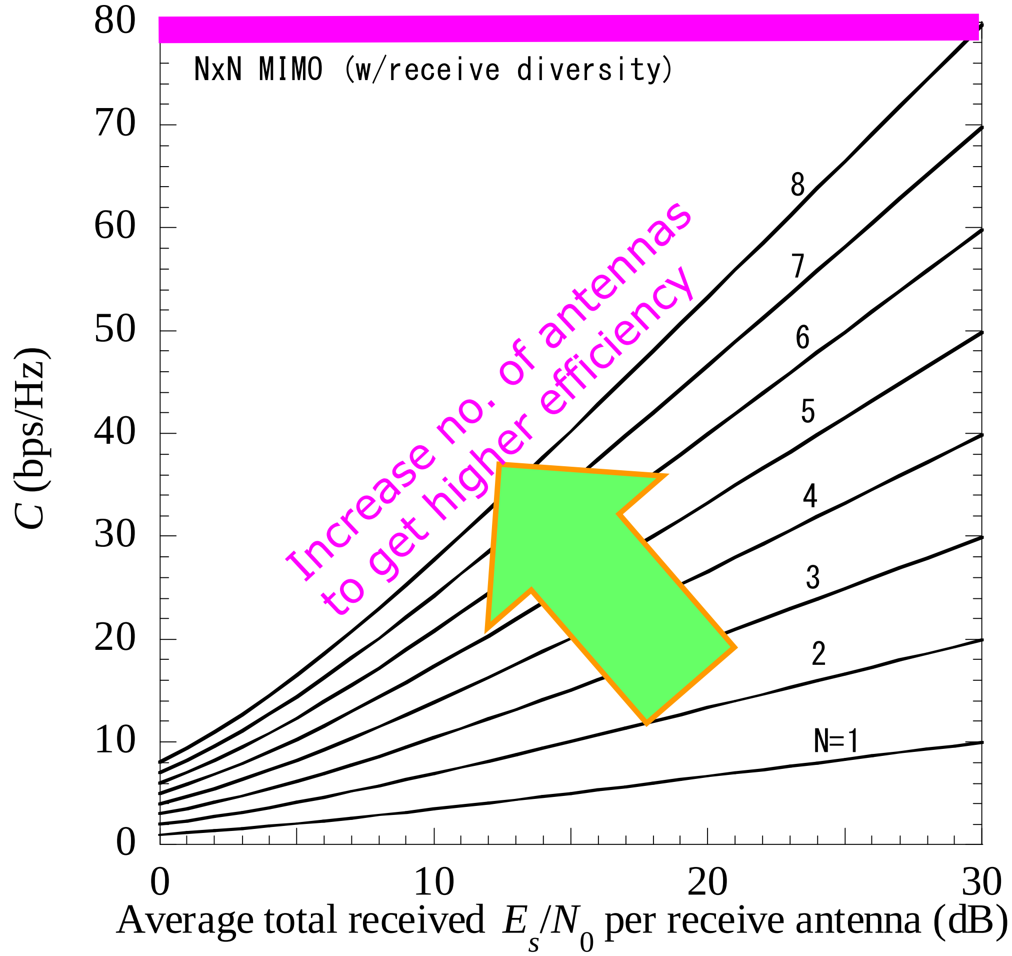
- Increasing the no. of antennas can improve the spectrum efficiency or can decrease the required transmit power.



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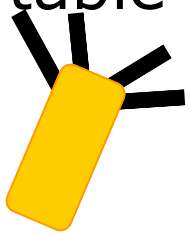
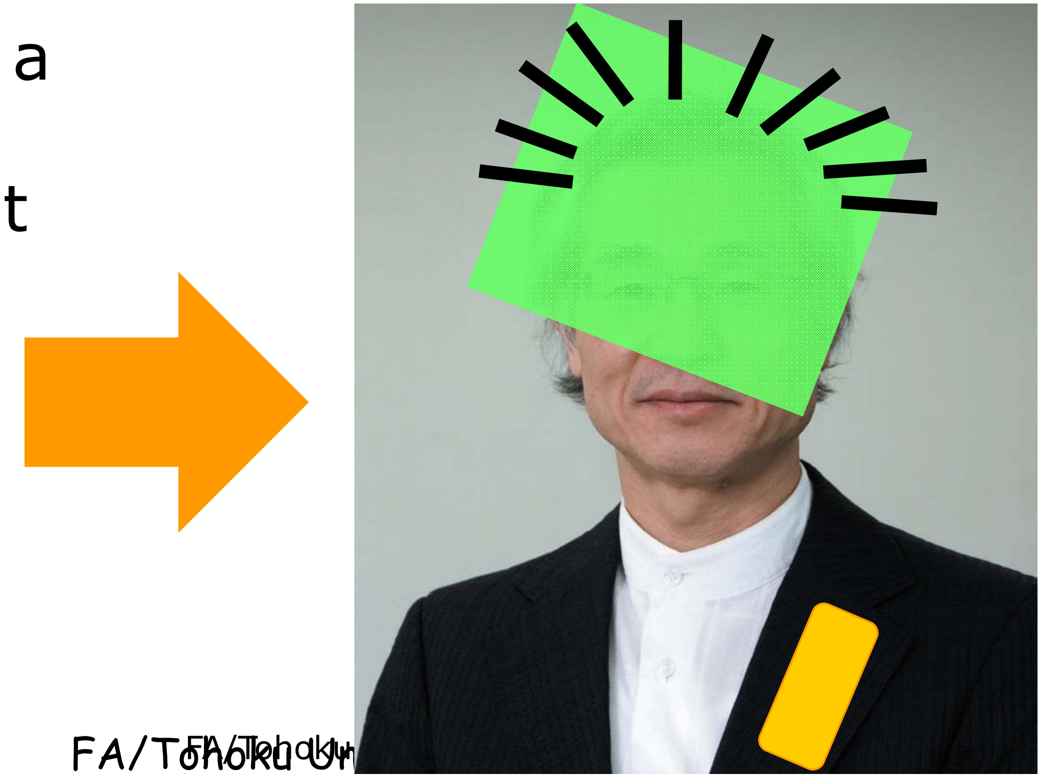
However, Space for MIMO Antennas Is Limited !

- How to implement many antennas in a hand portable unit?
- Wearable antenna on your head?

Head antenna

No space in a small hand portable unit





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MIMO Cannot Solve Power Problem

- Peak power is in proportion to "transmission rate" x "*fc*2.6 [Hata-formula]" where *fc* is the carrier frequency.
- Links for broadband data services will be severely power-limited.
- Let's consider the peak transmit power for 1Gbps@3.5GHz at a communication range of 1,000m. We assume the required transmit power for 8kbps@2GHz is 1Watt.
- The required peak transmission power increases by

  1Gbps/8kbps x (3.5GHz/2GHz)2.6 = 535,561 times, that is 536kWatt. Obviously, this cannot be allowed.

M. Hata, "Empirical formula for propagation loss in land mobile radio services", IEEE Trans. Veh. Technol., VT-29, pp. 317-325, 1980.

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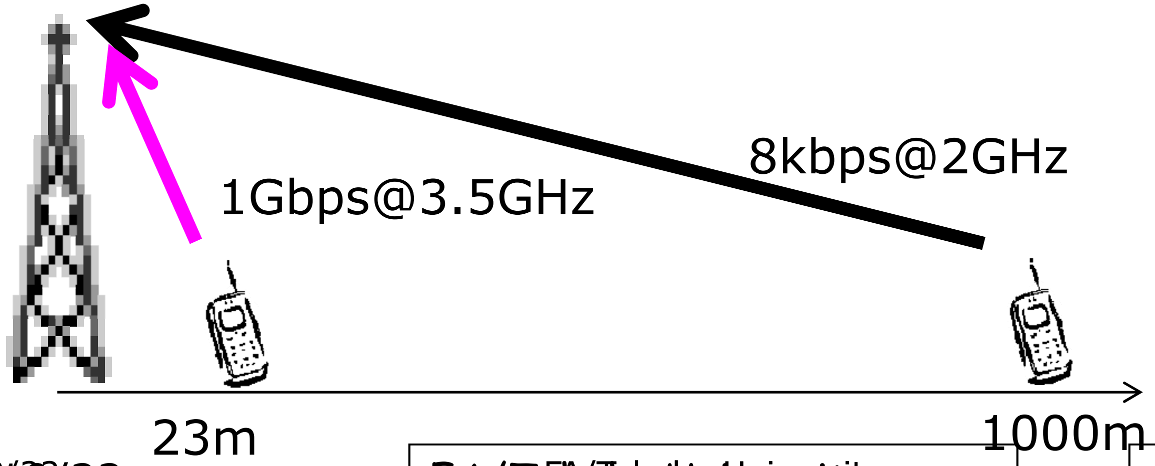
Distributed Antenna Network (or Distributed MIMO)

Transmit Power Problem

- Peak power is in proportion to “transmission rate” x “*fc*2.6 [Hata-formula]” where *fc* is the carrier frequency.
  - Assume that the required transmit power for 8kbps@2GHz is 1Watt for a communication range of 1,000m. The required peak transmission power for 1Gbps@3.5GHz needs to be increased by 1Gbps/8kbps x (3.5GHz/2GHz)2.6 = 535,561 times, that is, 536kWatt. Obviously, this cannot be allowed.
- To keep the 1W power, the communication range should be reduced by 43 times(i.e., 1,000m □23m). □Femto cellular network.



M. Hata, “Empirical formula for propagation loss in land mobile radio services”, IEEE Trans. Veh. Technol., VT-29, pp. 317-325, 1980.

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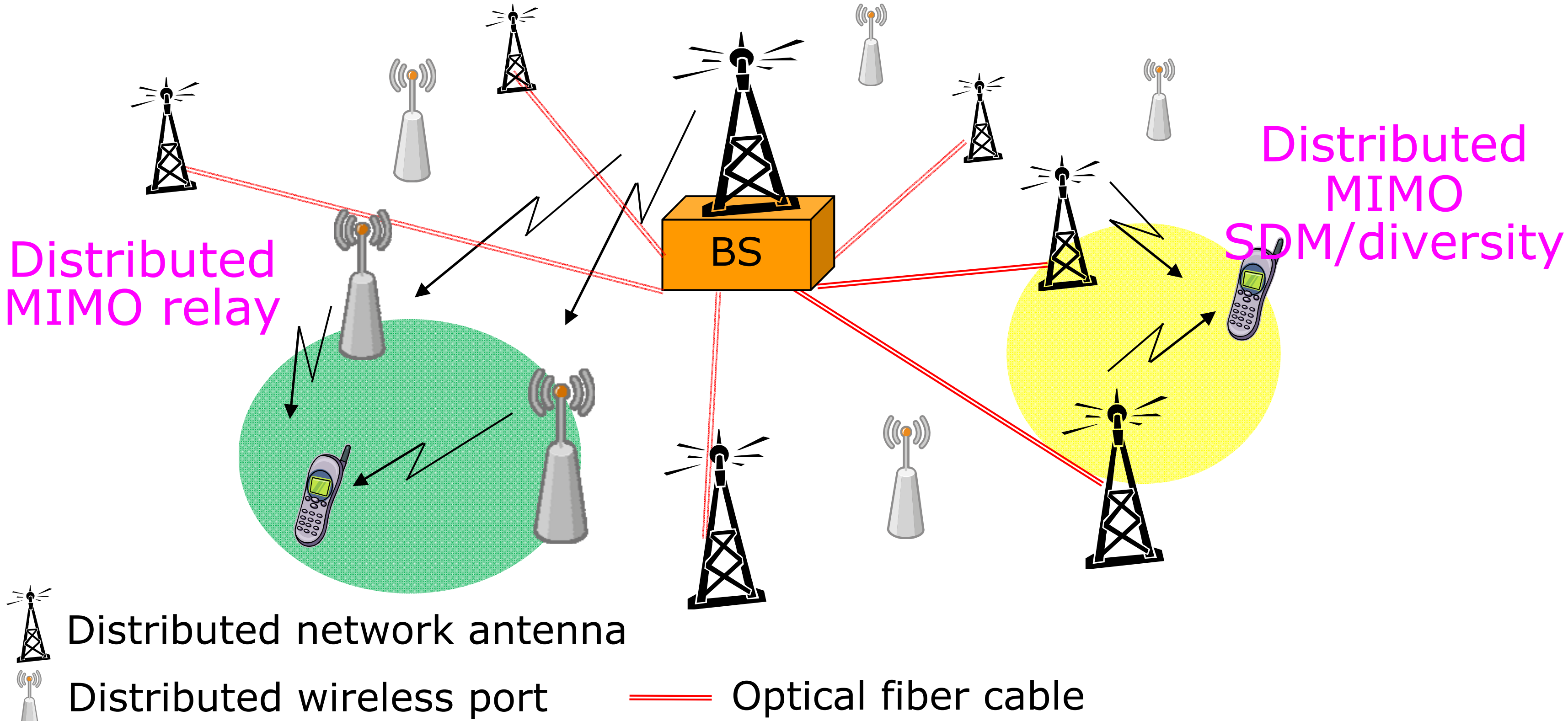
Distributed Antenna Network

- A group of distributed antennas serves a user in a cooperative manner to mitigate the power.
- The distributed MIMO diversity transmission can mitigate the problems resulting from path loss, shadowing loss, and multi-path fading.



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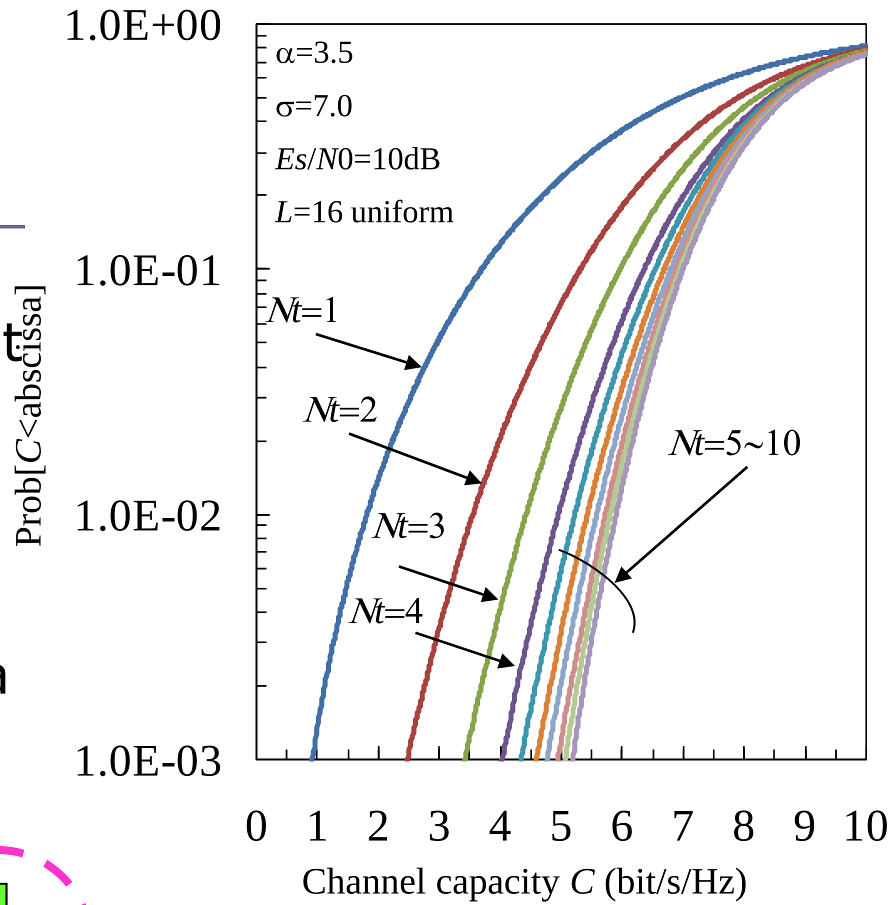
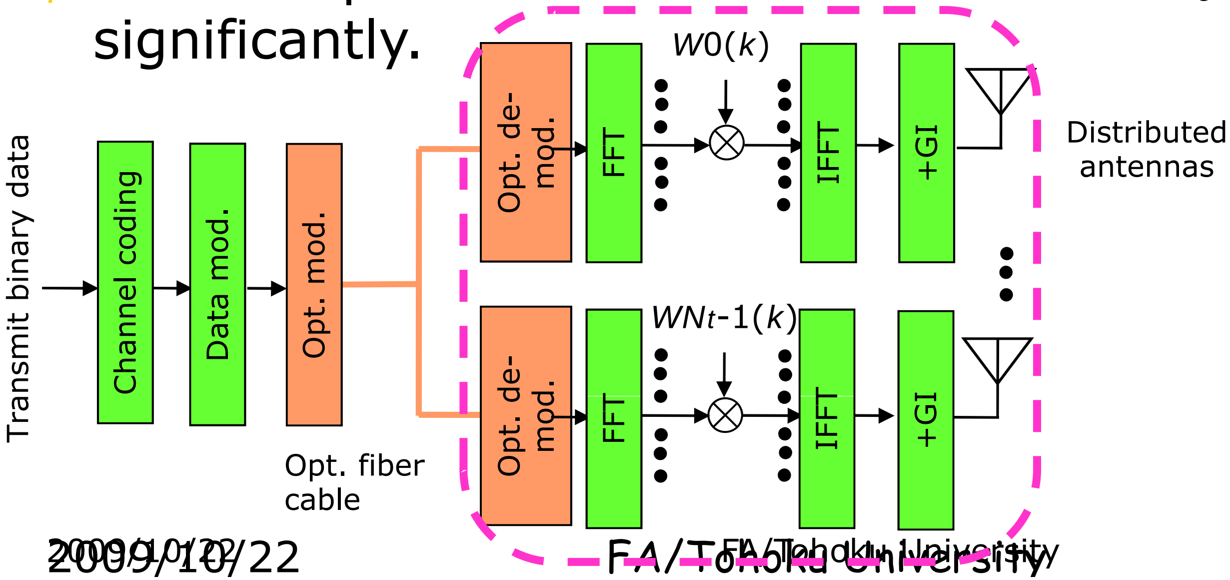
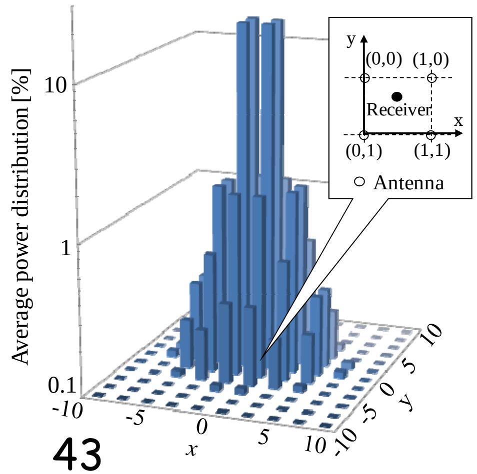
- The distributed MIMO diversity using the maximal ratio transmit (MRT) diversity increases significantly the channel capacity.
- The use of only around 5 antennas near a user provides a sufficient improvement.
- Transmit power can reduce significantly.







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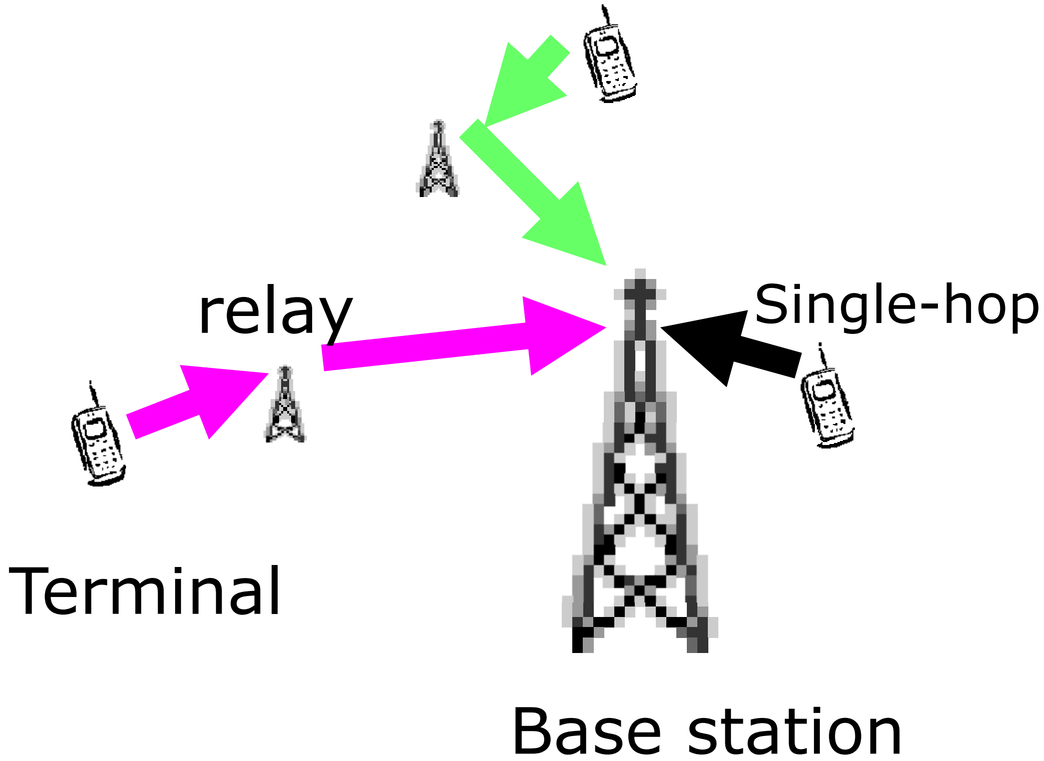
OFDMA 2-hop VCN

- An introduction of 2-hop relay may be a good solution at the beginning.



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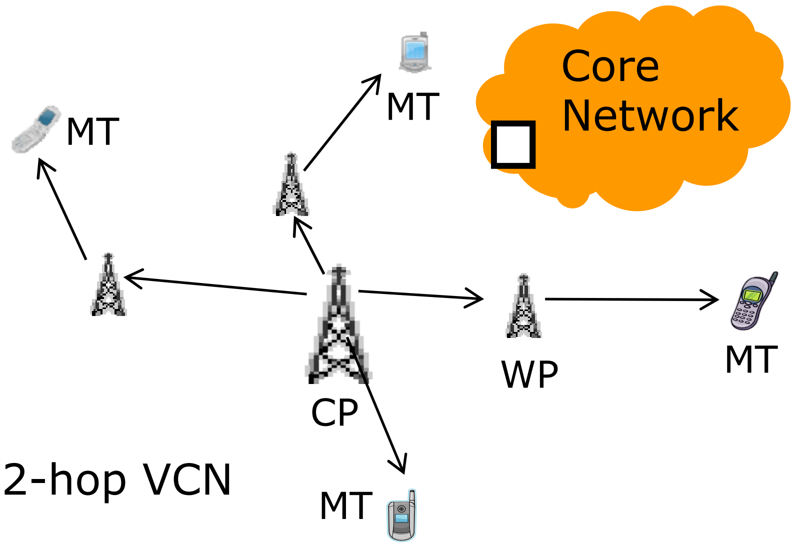
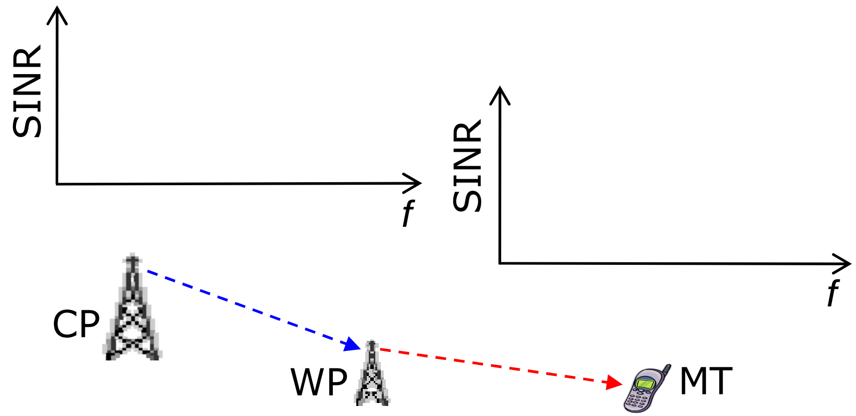
- OFDMA is suitable for multi-hop relaying.
- The same subcarriers can be reused at different links. Different groups of subcarriers are allocated to neighbor links, but the same subcarriers can be reused by links which are far away each other.
- Adaptive subcarrier allocation based on the SINR maximization is promising*.



2-hop VCN



Adaptive channel allocation

H. Ishida, E. Kudoh and F. Adachi, "A study on subcarrier allocation for a 2-Hop OFDMA virtual cellular network", Proc. 4th International Workshop of Tohoku University and Yeungnam University, pp.7-8, 11-13 Nov. 2007. FA/Tohoku University

Some Concluding Remarks

- Next generation wireless networks will require Giga-bit wireless technology of ~1Gbps and 40bps/Hz/BS under severe co-channel interference.
- Frequency-domain signal processing plays an important role in the signal transmissions in a severe frequency-selective channel.
- To meet the spectrum efficiency and transmit power requirement, distributed antenna network is attractive.
- Lots of interesting and important research topics remain before the born of next generation wireless systems.

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