Next Generation Wireless Technology

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OUTLINE

- Wireless Evolution
- Multi-carrier vs Single-carrier
- New Approach In Mobile Networks

Wireless Evolution

- From 2G to 3G
- Then into 4G

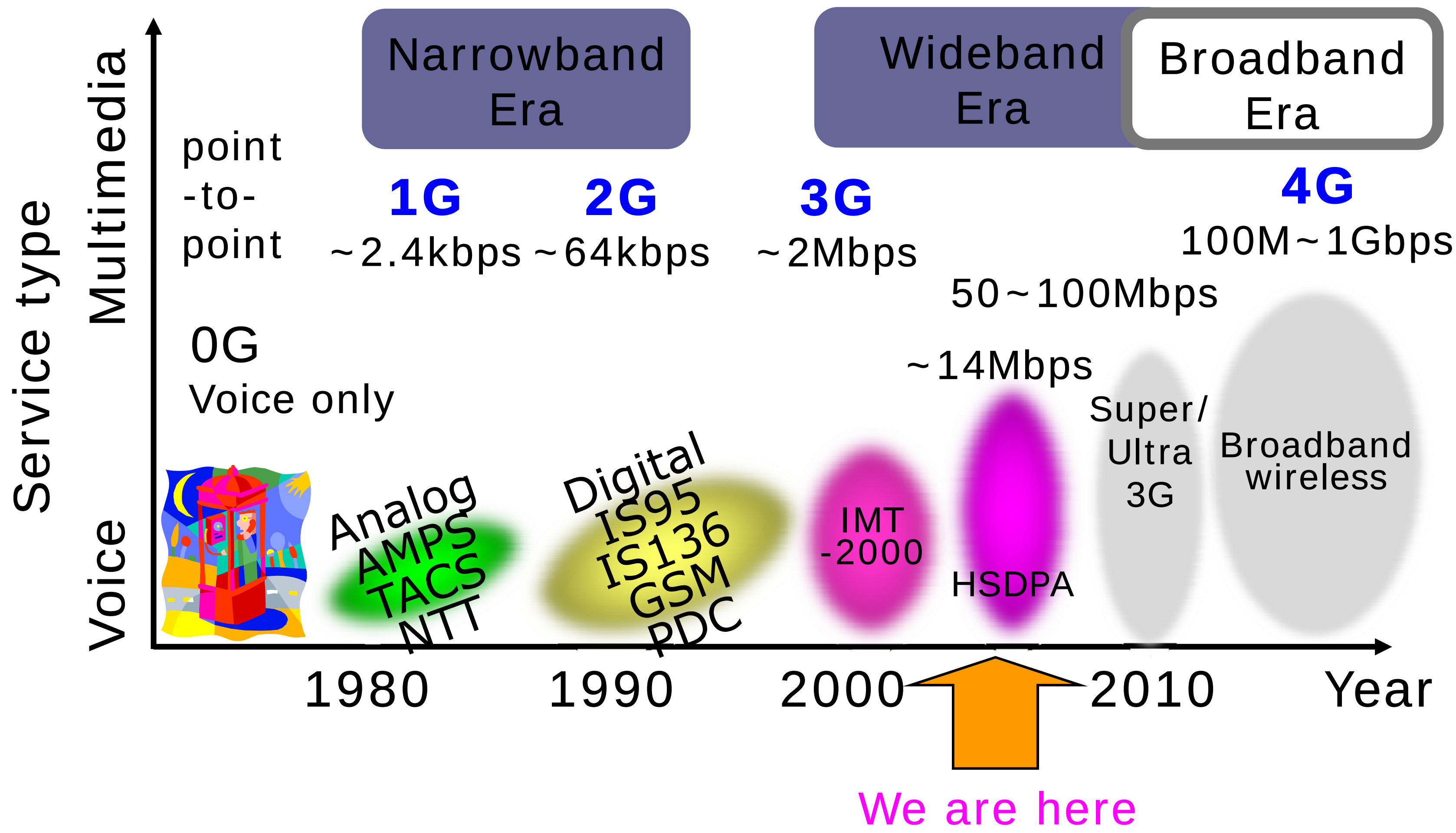
F. Adachi, "Wireless past and future - evolving mobile communications systems," IEICE Trans. Fundamentals, vol. E84-A, pp. 55-60, Jan. 2001.

Wireless Evolution

- Every one wants to communicate instantly with anyone, any time, from anywhere
  - Arrival of ubiquitous society: communication is available everywhere
  - This is only possible by wireless. Wireless is indispensable in our forthcoming ubiquitous society
- Every 10 years, a new wireless technology has come up and changed our society
- 1980's: from "point-to-point" to "anytime, anywhere" communication
  - 1G systems (analog)
- 1990's: from voice to "data"
  - 2G systems (digital)
  - Access to the Internet
- 2000's: →"wideband data"
  - 3G systems and then 3.5G systems (high speed packet)
- 2010's: → "broadband, ubiquitous"
  - 4G systems
  - Roaming across heterogeneous networks

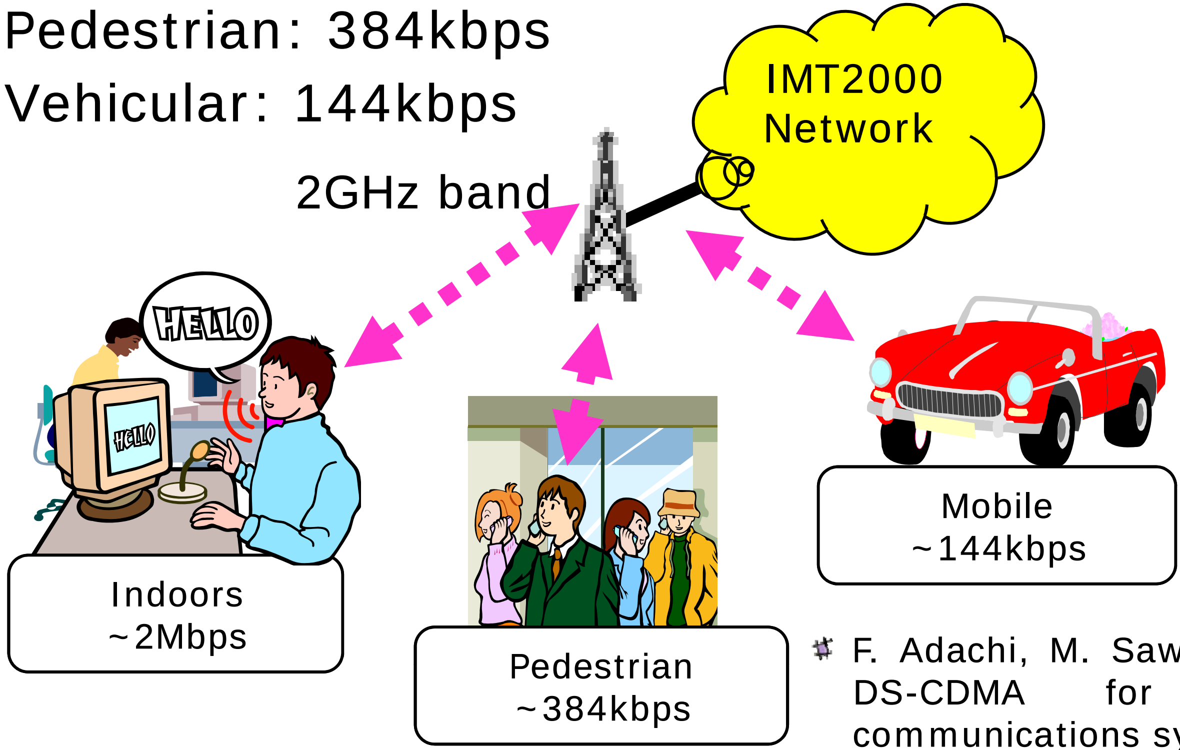
Wireless Evolution

- Cellular systems have evolved from narrowband to wideband wireless networks
- Now on the way to broadband wireless networks



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



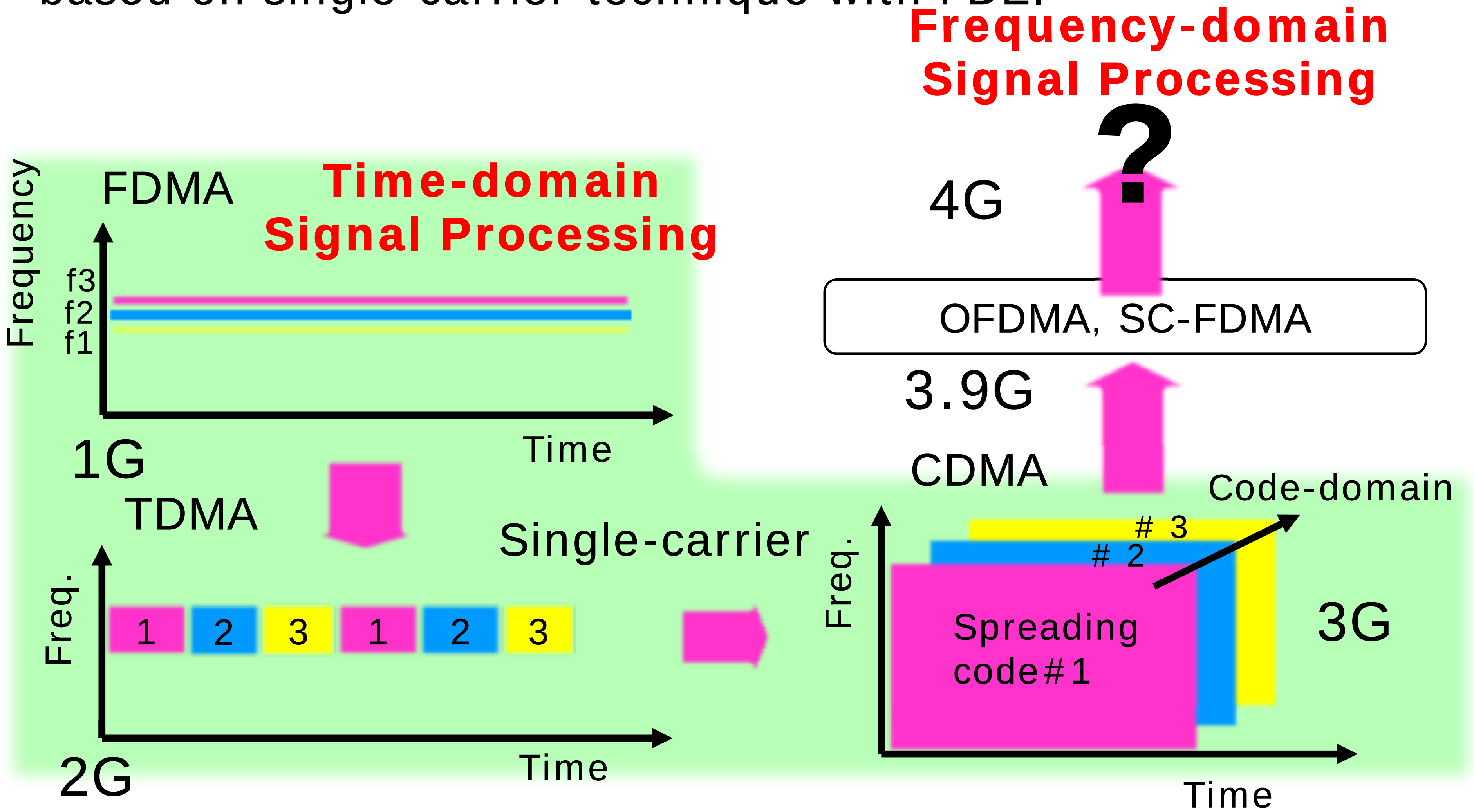
F. Adachi, M. Sawahashi and H. Suda, “Wideband DS-CDMA for next generation mobile communications systems,” IEEE Commun. Mag., vol. 36, pp. 56-69, Sept. 1998.

3.5G and 3.9G Systems

- 3G systems will continue to evolve to meet the demands of (internet-related) broadband wireless services and substantially strengthen its downlink data rate capability
  - High-speed downlink packet access (HSDPA), called 3.5G systems of ~14Mbps/5MHz, started in Japan in 2006
  - Even 3.5G of 14Mbps data rate capability will sooner or later become insufficient
  - A 3.9G close to 4G will appear to provide broadband services of 50~100Mbps/20MHz using the 3G bands
- 4G systems are expected to provide much faster services of a peak data rate of 100M~1Gbps
- ITU allocated the spectrum for 4G systems in Dec. 2007
  - 450~470MHz/790~806MHz/2.3~2.4GMHz/3.4G~3.6GHz
  - 4G development will start soon
  - 4G systems will appear in around 2015

Shift From Single-Carrier Only to Multi-Carrier / Single-Carrier

- In 3.9G, wireless downlink access will be based on multi-carrier technique including OFDMA, while uplink access based on single-carrier technique with FDE.



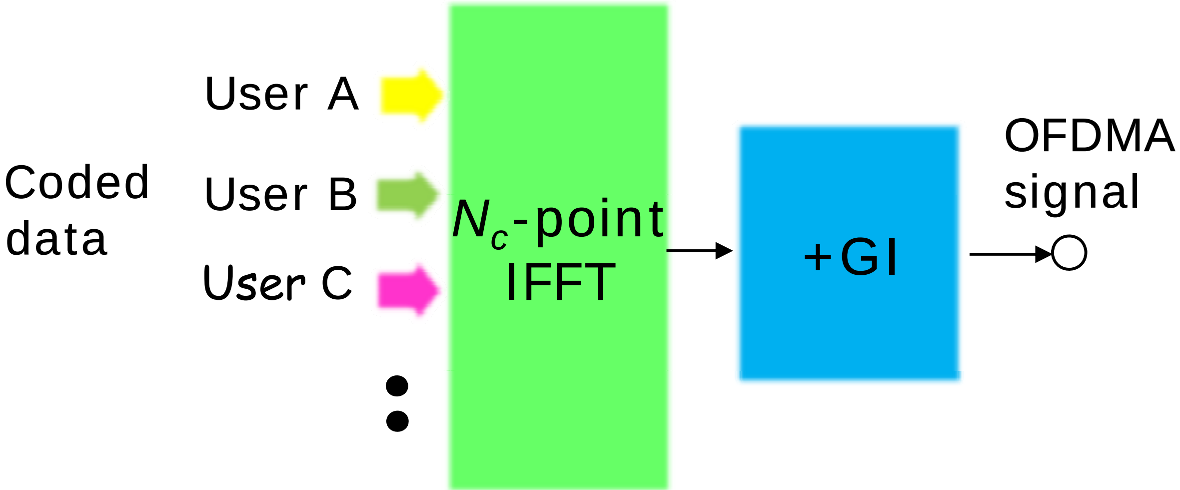
Wireless Access of 3.9G (LTE)

- Different multi-access techniques between downlink and uplink (this is the first time in its history)
  - Downlink: OFDMA, ~100Mbps
  - Uplink: SC-FDMA, ~50Mbps
- Scheduling for packet access
  - Multiuser diversity in wireless channel
  - Hybrid ARQ using incremental redundancy (IR) strategy
  - Non real time services

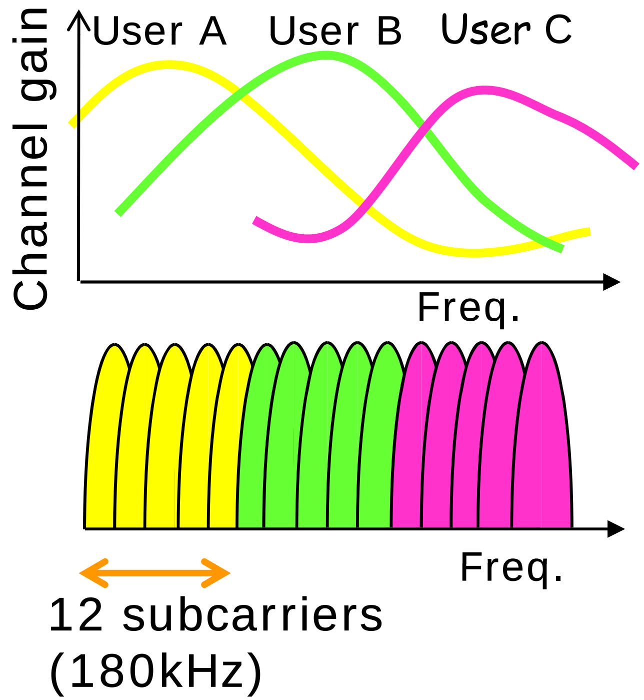
	Downlink	Uplink
Bandwidth(MHz)	1.4/3/5/10/15/20	
IFFT/FFT block size	128/256/512/1024/1536/2048	
Multi-access	OFDMA	SC-FDMA
Scheduling	Multi-user diversity gain	
ARQ	Turbo-coded IR-HARQ	

Downlink OFDMA

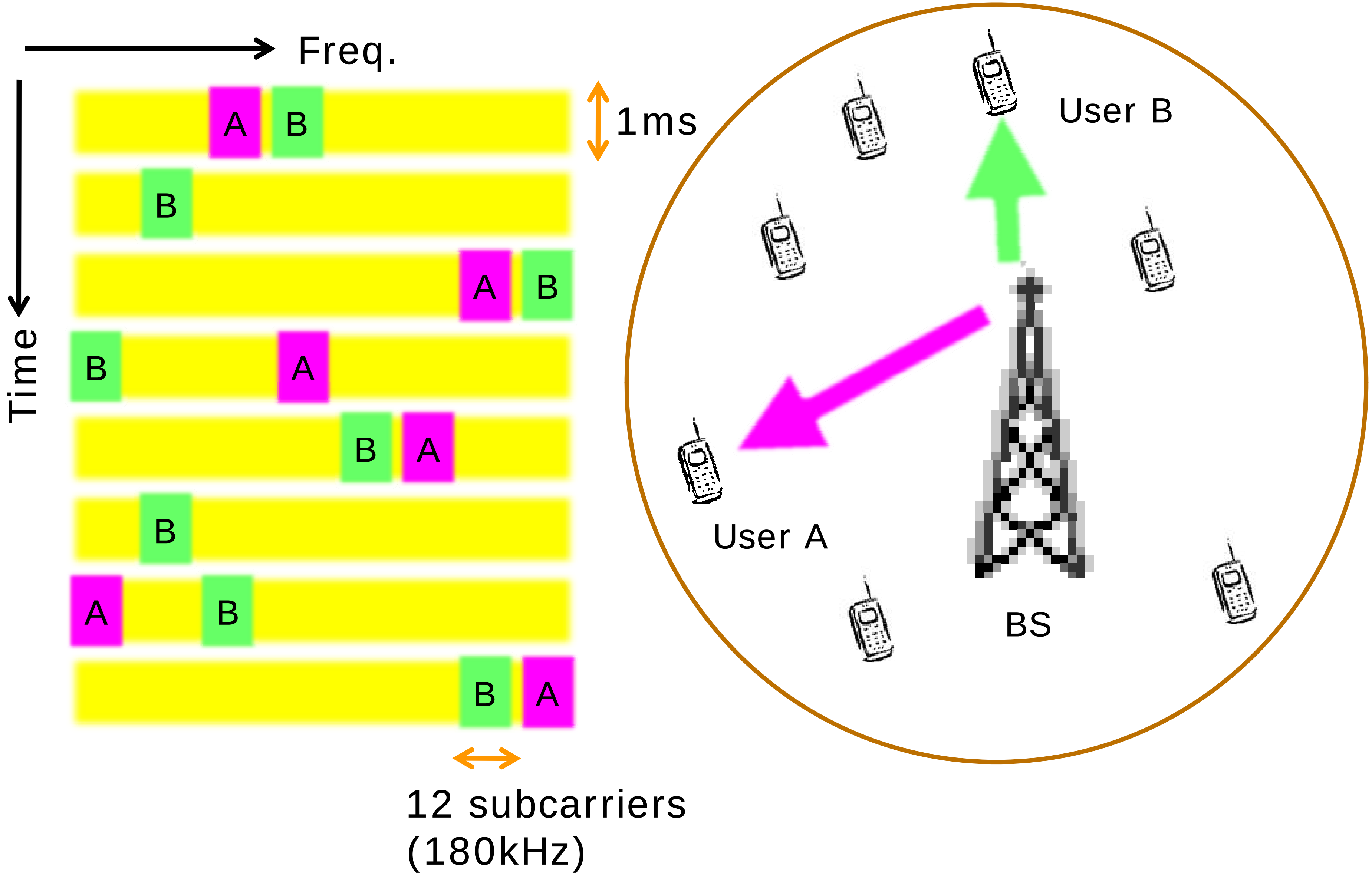
- Resource allocation: one or more resource blocks of 1msec and 12 subcarriers (180kHz) each are allocated according to each user's channel condition (scheduling) to obtain multiuser diversity gain
- Proportional fairness (PF)* scheduling can maximize the throughput while keeping fairness among users



Freq./time -domain scheduling

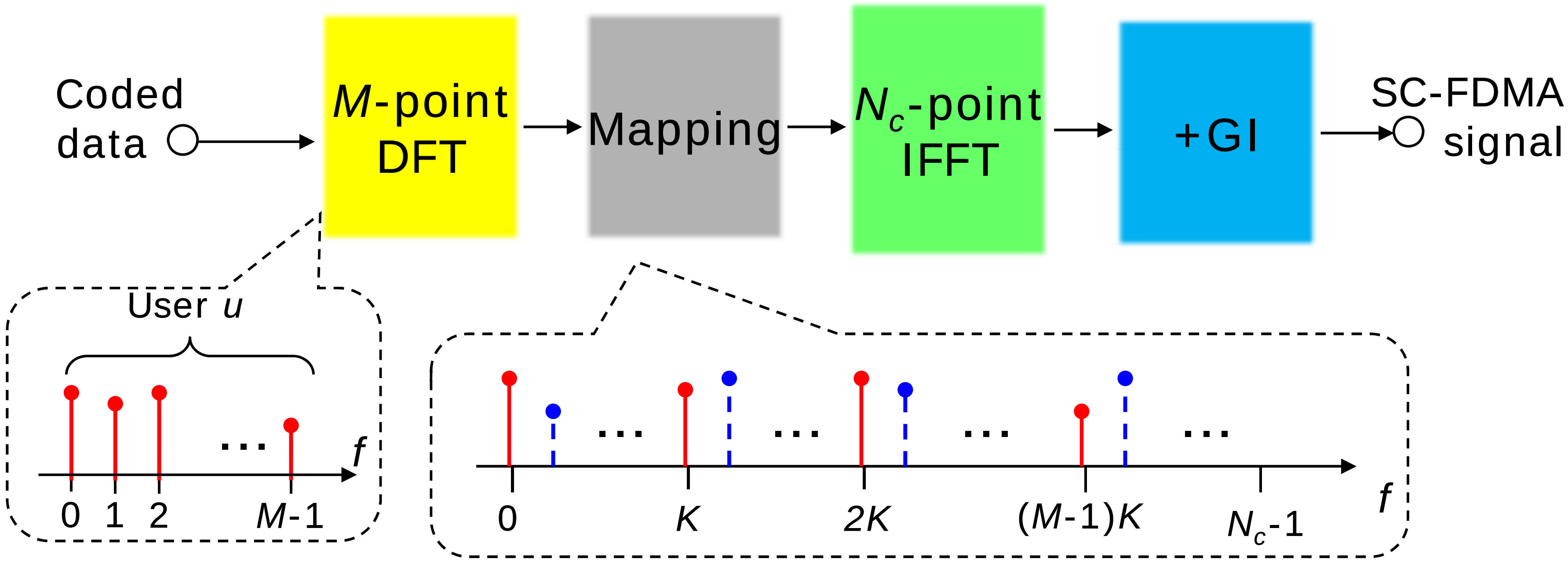


* A. Jalali, R. Padovani, and R. Pankaj, "Data throughput of CDMA-HDR a high efficiency-high data rate personal communication wireless system," Proc. IEEE VTC 2000-Spring, vol. 3, pp. 1854 - 1858, Tokyo, 15-18May 2000.

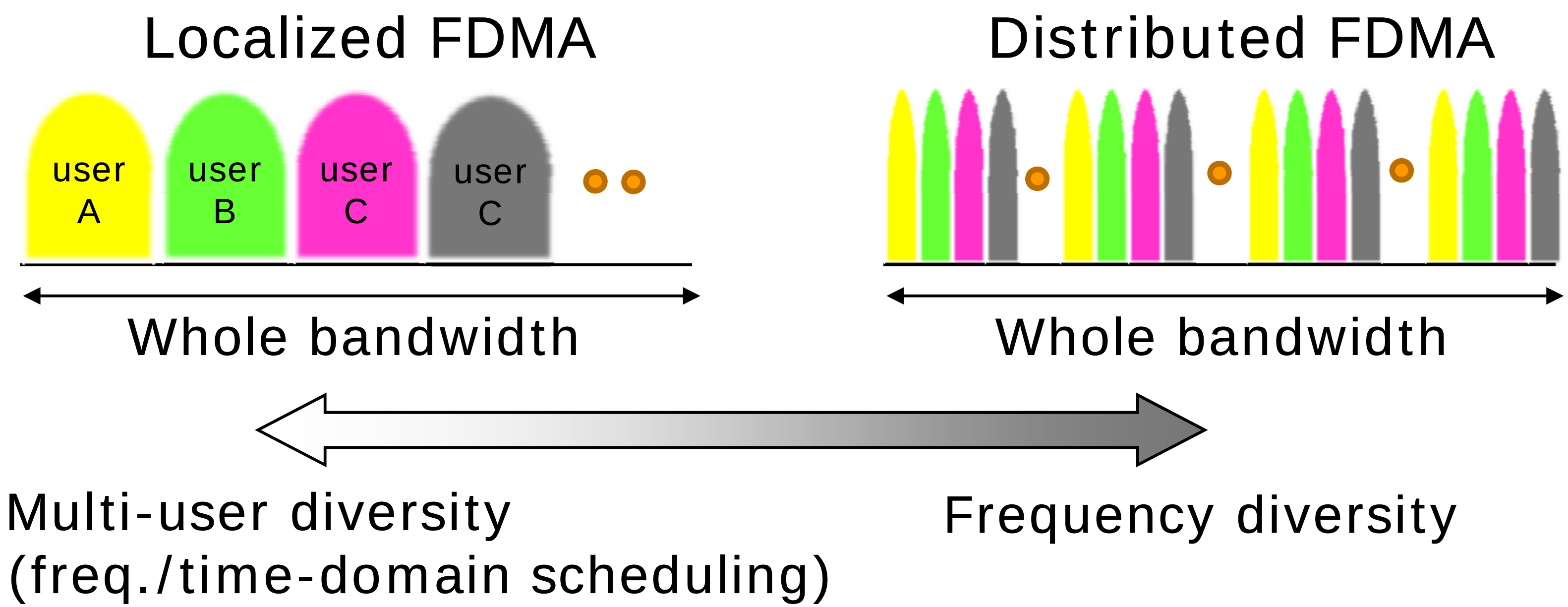

Freq.
Time
A
B
B
A
B
B
A
B
A
B
A
B
B
A
1ms
12 subcarriers
(180kHz)
User B
User A
BS

Uplink SC-FDMA

- For uplink, peak to average power ratio (PAPR) is a big factor to decide the access technique
- To reduce the peak transmit power of mobile power amplifiers, SC-FDMA with FDE is a good choice
  - Block transmission is used. Each block is transformed by DFT into frequency-domain signal which is then mapped onto broad bandwidth in such a way that users' spectra are not overlapped.
  - To reduce PAPR of SC-FDMA signal, equidistance spectrum mapping is used



- Two types of equidistance spectrum mapping
  - Localized FDMA
  - Distributed FDMA
- Advantage of localized FDMA
  - Multi-user diversity gain, similar to downlink OFDMA, can be obtained
  - According to each user's channel condition, one or more resource blocks of 1msec and 12 subcarriers (180kHz) each is allocated



Technical Issues for 4G

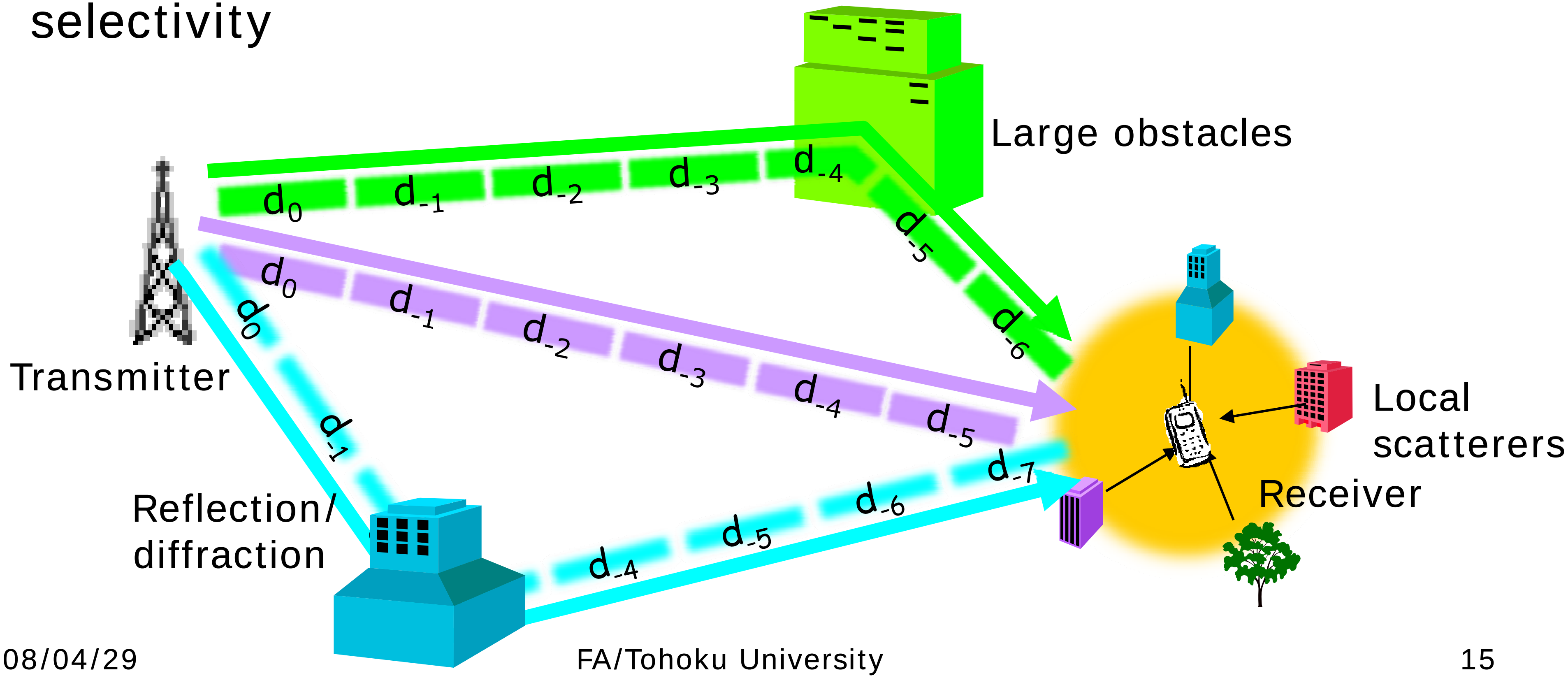
- For a peak data rate of ~1Gbps/100MHz, there are two important technical issues to address
- Channel problem
  - Wireless channel is extremely frequency-selective and produces strong inter-symbol interference (ISI). Some advanced equalization technique is necessary
  - A very high frequency-efficient transmission technique is necessary to achieve the cellular frequency efficiency of more than 10bps/Hz/BS
- Power problem
  - For a very high rate transmission, a huge transmit power is required if the same communication range in distance as in the present cellular systems is kept
  - To keep the transmit power the same as in the present systems, fundamental change is necessary in wireless access network architecture

Channel & Power Problems

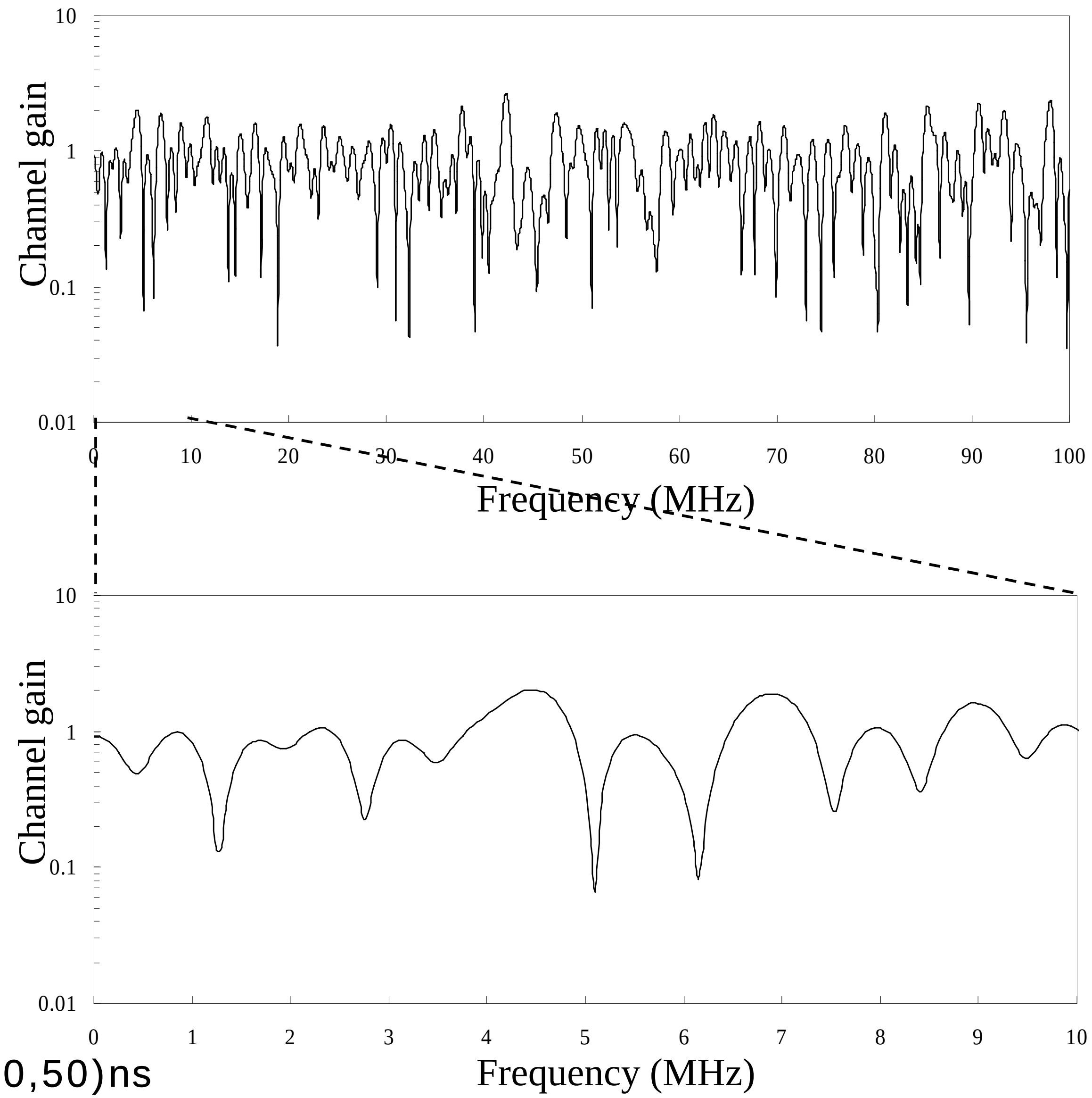
- There will be two important technical issues which should be solved before 4G systems will appear
- Channel problem is a consequence of the presence of multipaths having different time delays
- Power problem is a consequence of high data rates

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 1Gbps transmission, 1bit time length is equivalent to the distance of 0.3 m. So, many distinct multipaths exist, thereby extremely enhancing the channel frequency-selectivity



- For broadband data transmission, the transfer function of wireless channel is not constant and varies over the signal bandwidth
- Challenge is to transmit data at high speed (close to 1 Gbps) with high quality over such a severe frequency-selective channel



L=16
Uniform power delay profile
l-th path time delay=100l + [-50,50)ns

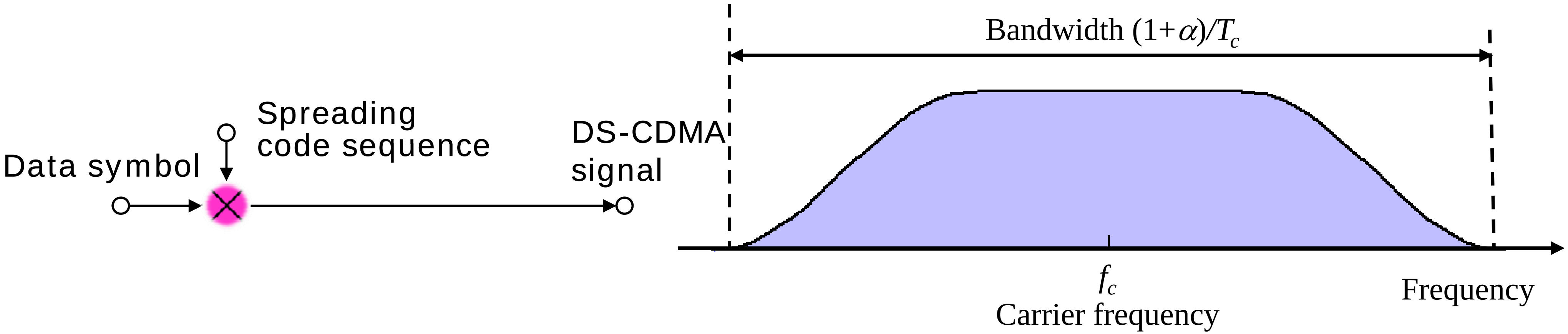
Multi-carrier vs Single-carrier

- In 3G systems, DS-CDMA (or single-carrier CDMA) is adopted for both uplink and downlink since it is a very flexible multi-access technique
- Which will be an optimal wireless access technique in a severe frequency-selective channel, single-carrier CDMA or multicarrier CDMA or OFDMA for 4G systems?

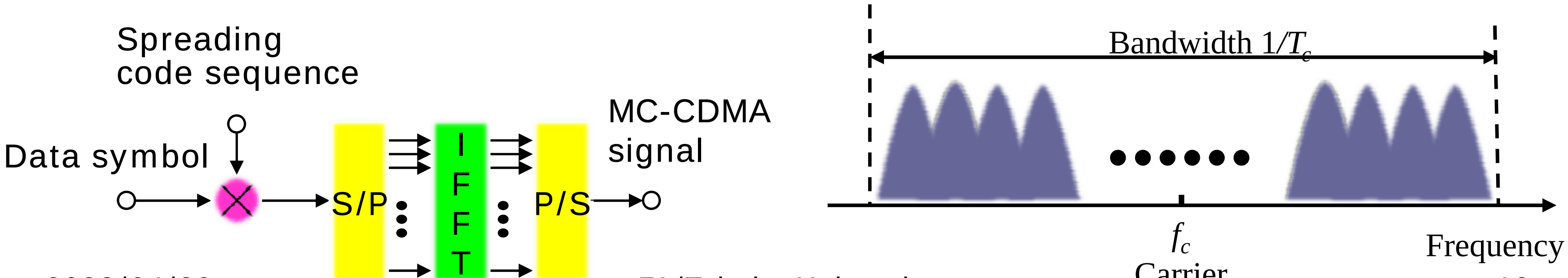
F. Adachi, D. Garg, S. Takaoka, and K. Takeda, "Broadband CDMA techniques," IEEE Wireless Commun. Mag., Vol. 12, No. 2, pp. 8-18, April 2005

MC vs SC

- CDMA can overcome the channel frequency-selectivity and even improve the transmission performance, yet retaining multi-access capability.
  - DS-CDMA: Time-domain spreading
  - MC-CDMA: Frequency-domain spreading
- DS-CDMA: single-carrier/time-domain spreading

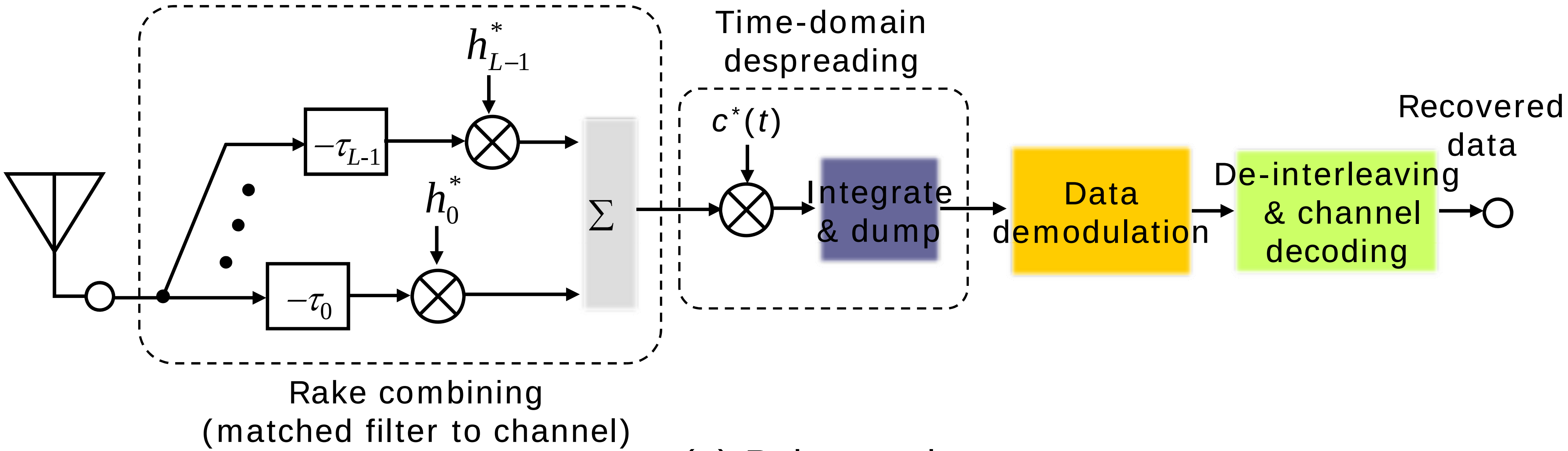


- MC-CDMA: multi-carrier/frequency-domain spreading



Rake Receiver for DS

- Receivers of present 3G systems use time-domain rake combining, which is a channel matched filter.
- Rake combining can improve the BER performance if the channel frequency-selectivity is not too strong (or the number *L* of resolvable paths is not too large).

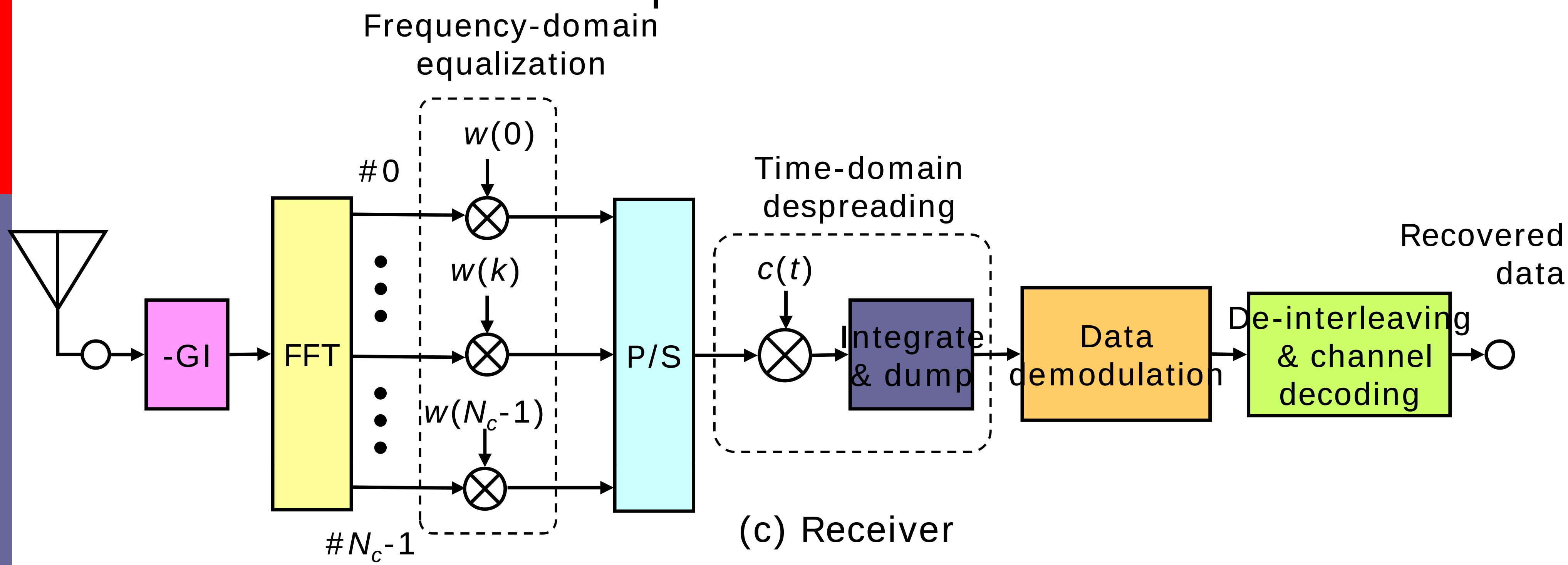


(c) Rake receiver

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.

Frequency-domain Equalization for MC

- Frequency-domain equalization (FDE) is used to exploit the frequency selectivity of the channel.
- FDE based on the minimum mean square error (MMSE) criterion can provide the best downlink performance.
- MMSE-weight minimizes the mean square error (MSE) between the transmit subcarrier component and the received distorted component.

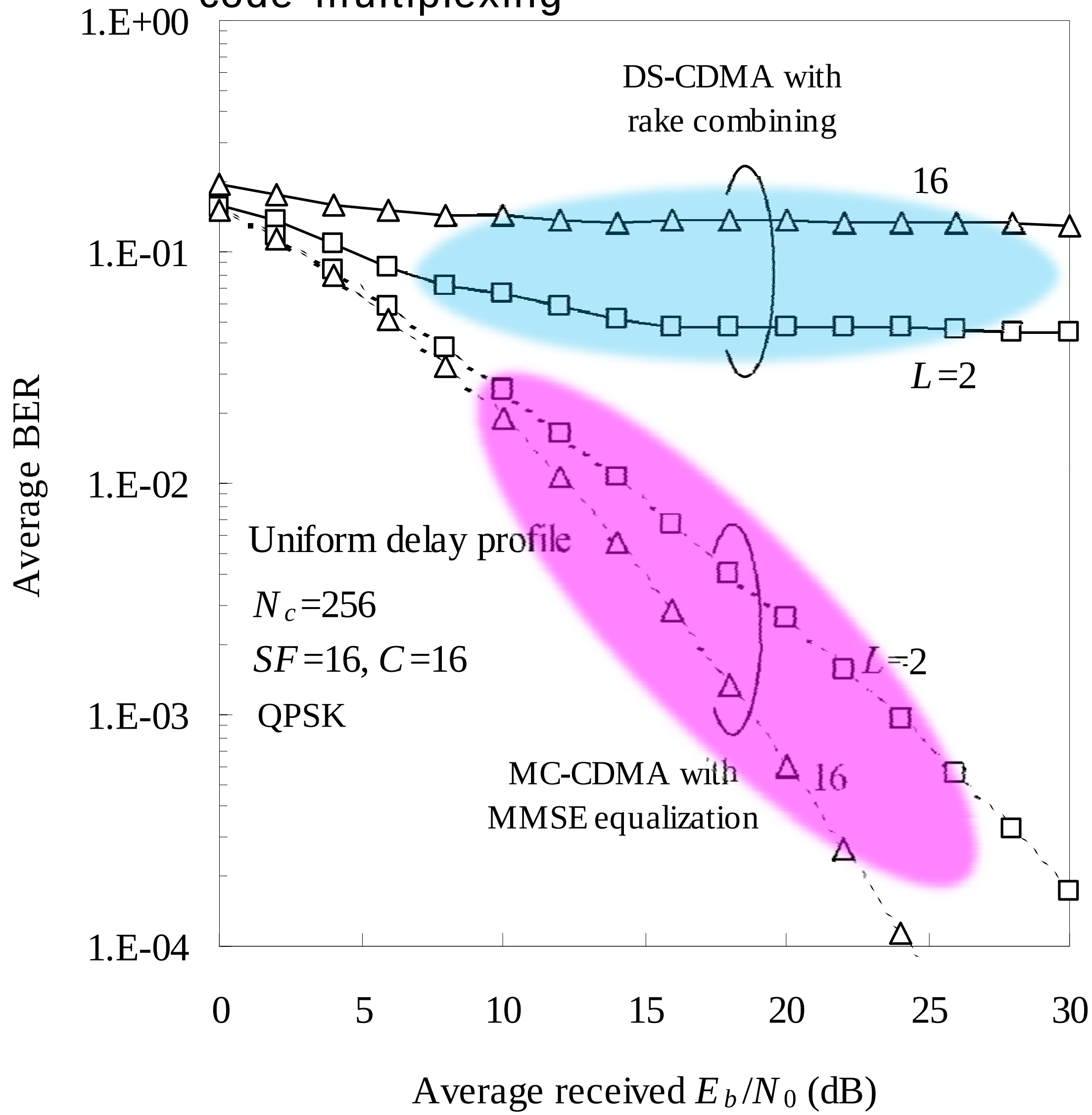


(c) Receiver

DS with Rake vs. MC with FDE

- As the number of resolvable paths increases, the channel frequency-selectivity gets stronger and hence, the achievable BER performance of DS-CDMA with rake combining significantly degrades due to strong IPI
  - Even with $L=2$, a high BER floor appears resulting from IPI 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

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



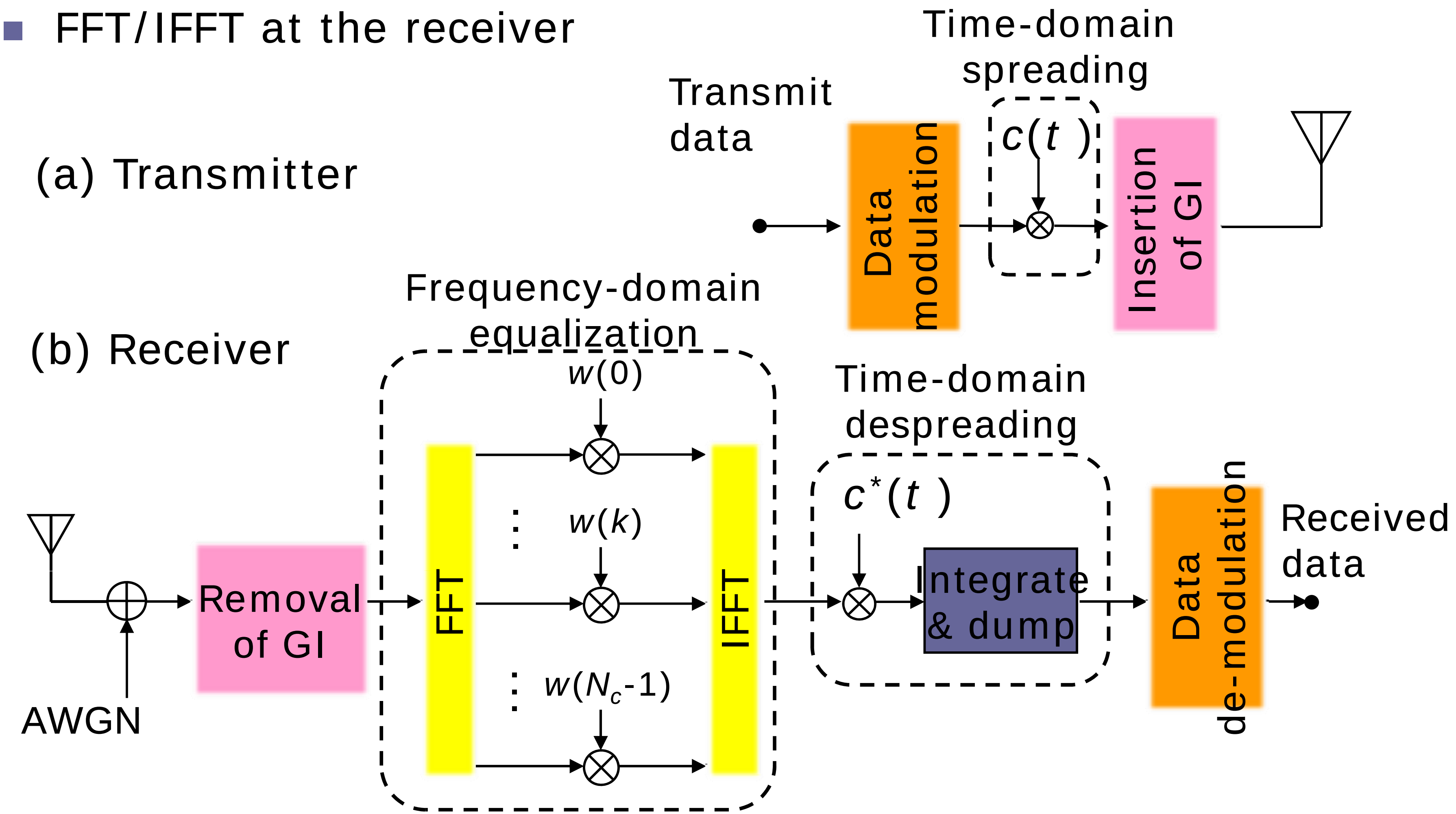
Application of Frequency-domain Equalization (FDE) to DS-CDMA

- One-tap FDE can replace rake combining to have much improved performance

⌗ 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

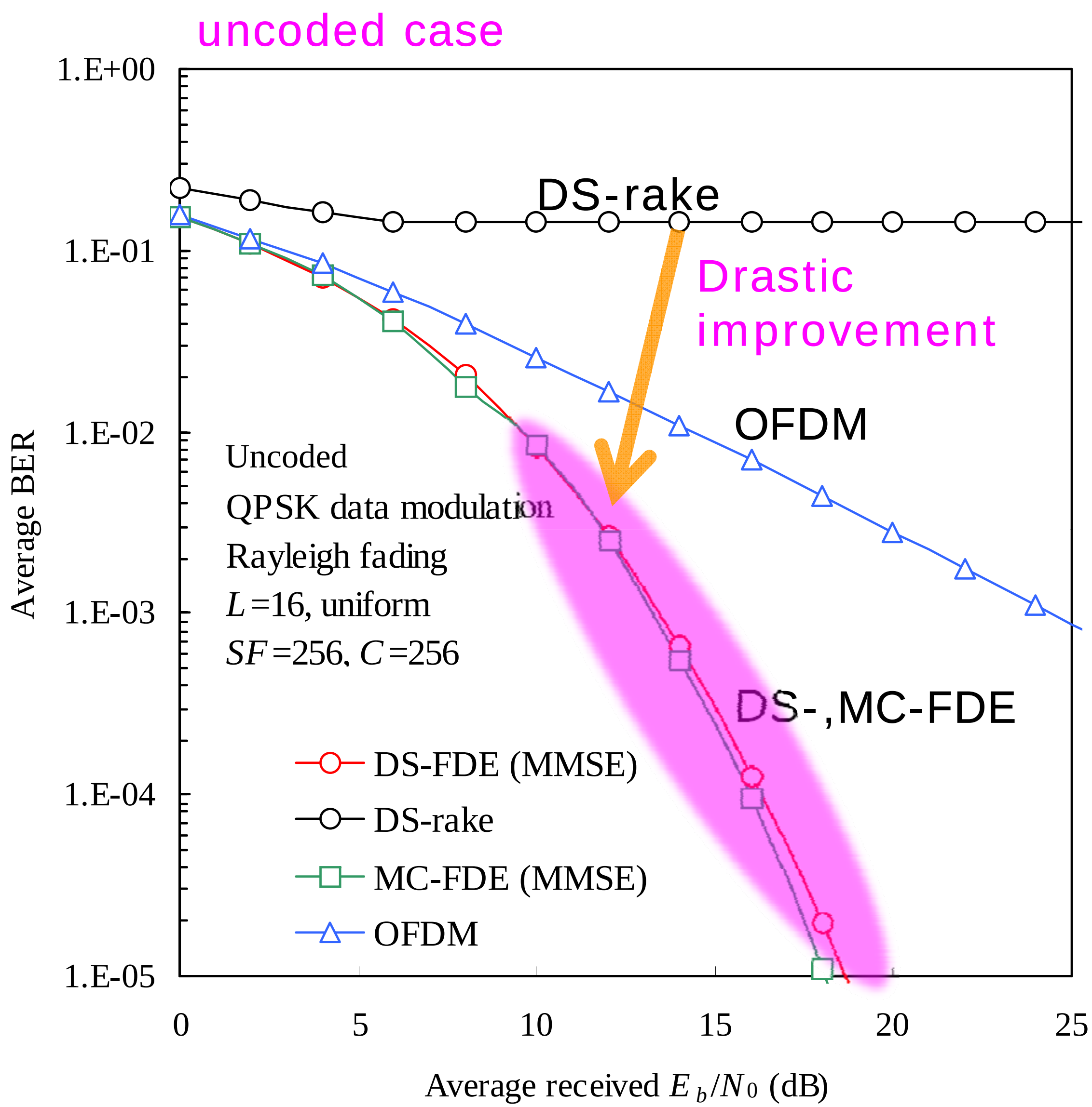
Frequency-domain Equalization (FDE)

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



Downlink Performance Comparison

- FDE can achieve
  - significantly better performance than rake receiver
  - better BER performance than OFDM even for full code-multiplexing (no. of users, *C*, is equal to *SF*=256)



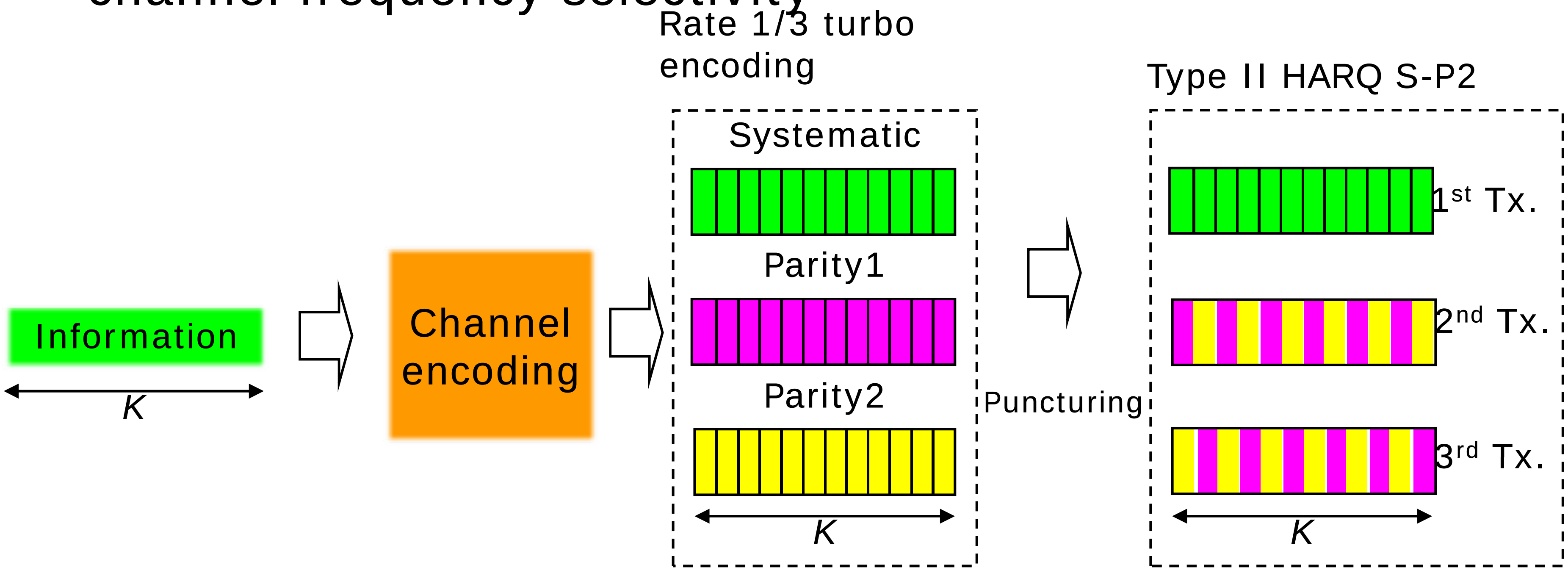
High-speed Packet Access

- Packet services will dominate in 4G systems
- For packet transmissions, some form of error control is necessary to satisfy the quality requirement
- Hybrid ARQ w/incremental redundancy (IR) strategy is a promising technique

- D. Garg and F. Adachi, "Throughput comparison of turbo-coded HARQ in OFDM, MC-CDMA and DS-CDMA with frequency-domain equalization," IEICE Trans. Commun., Vol.E88-B, No.2, pp.664-677, Feb. 2005.
- D. Garg and F. Adachi, "Packet Access using DS-CDMA with frequency-domain equalization," IEEE Journal of Select. Areas in Commun., Vol. 24, No. 1, pp. 161-170, Jan. 2006.

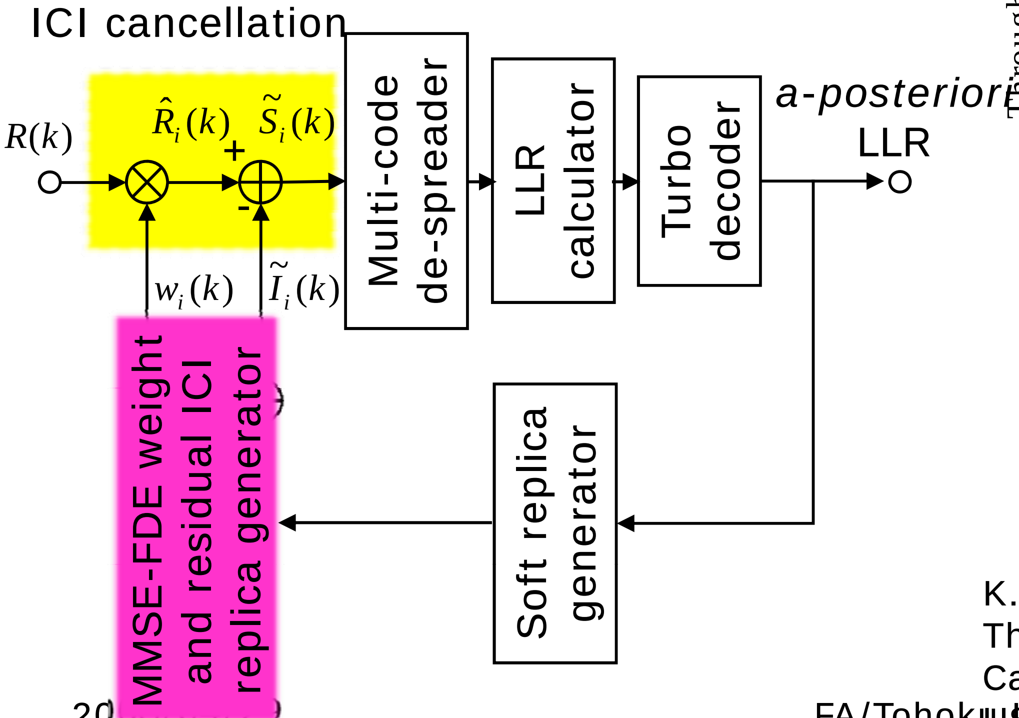
Hybrid ARQ (HARQ) with Incremental Redundancy(IR)

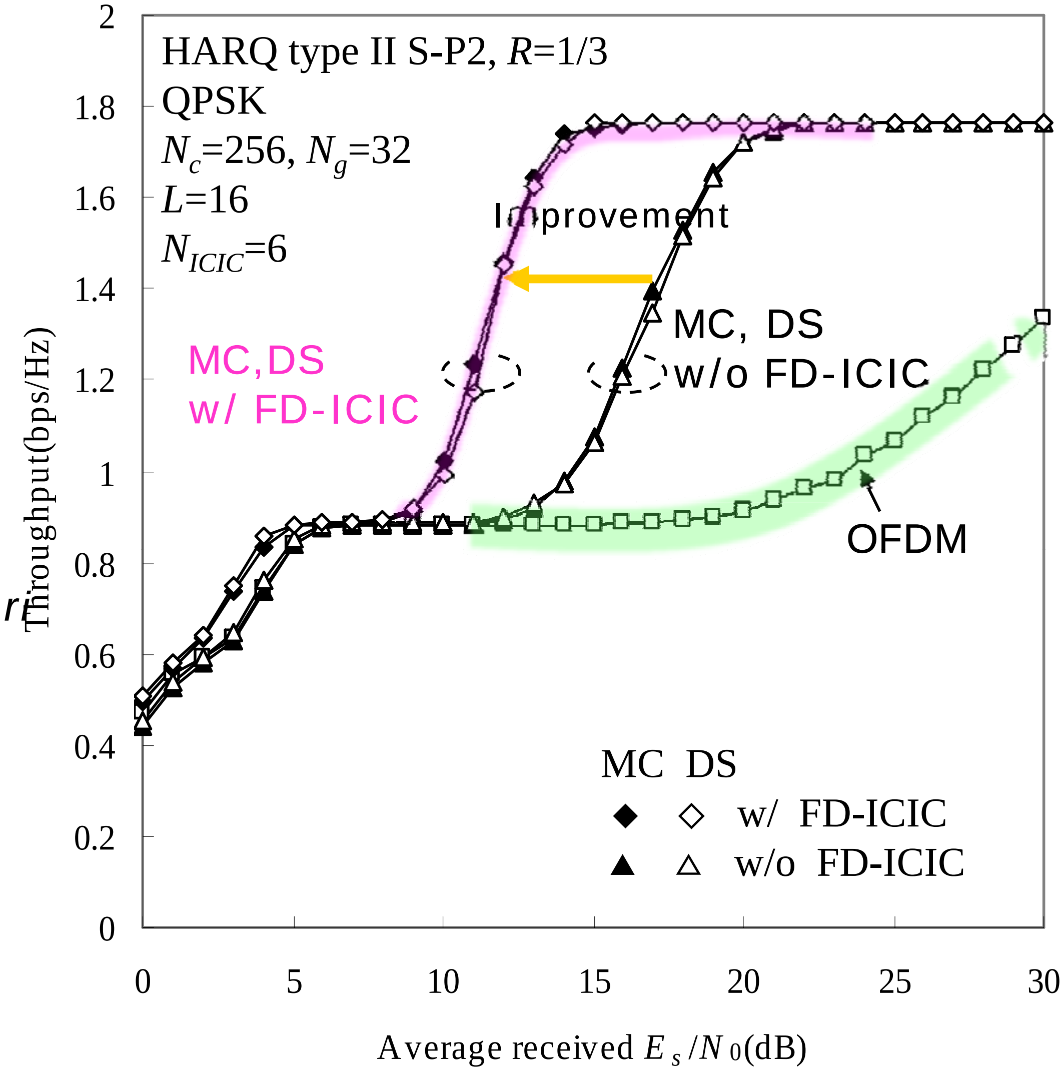
- An automatic repeat request (ARQ) combined with the channel coding, called hybrid ARQ (HARQ), is an inevitable technique, since an error-free transmission must be guaranteed for packet data services
- HARQ combined with FDE is a very promising error control technique for DS- and MC-CDMA
- HARQ combined with FDE can take advantage of the channel frequency selectivity



- ICI cancellation significantly improves the throughput performance.
  - Much better throughput than OFDM in a high E_s/N_0 region.
  - Almost the same throughput as OFDM in a low E_s/N_0 region.

MMSE-FDE and ICI cancellation





K. Fukuda, A. Nakajima, and F. Adachi, “LDPC-coded HARQ Throughput Performance of MC-CDMA using ICI Cancellation,” Proc. The 65th IEEE VTC07-fall, Baltimore, USA, 30 Sept.-3 Oct. 2007.

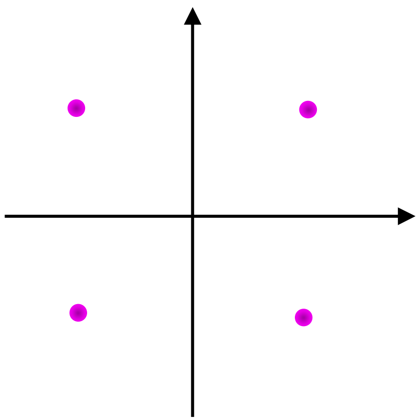
MIMO Antenna Technology

- Equivalent to 10bps/Hz/BS when using single-frequency reuse of 100MHz bandwidth

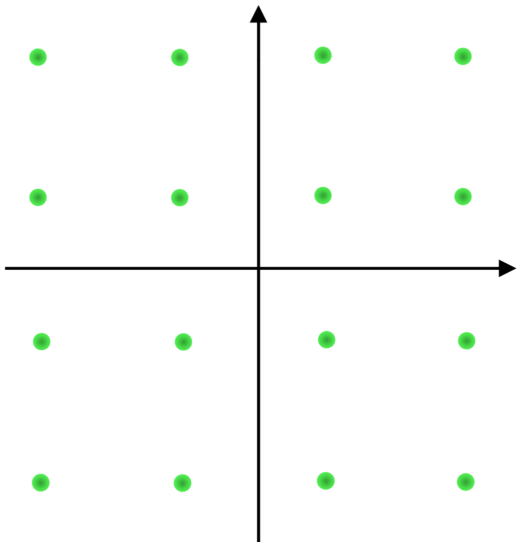
- Next generation (4G) wireless systems are expected to provide broadband packet data services of up to around 100M~1Gbps.
- However, available bandwidth is limited. Probably, the available bandwidth is less than 100MHz.
  - In December 2007, ITU allocated 3.4~3.6GHz band for 4G services.
- It is necessary to develop a highly spectrum efficient wireless transmission technology of around 10bps/Hz/BS.
- Multiple-input/multiple-output (MIMO) antenna technology will play an important role to realize 4G systems.

How To Achieve 1Gbps?

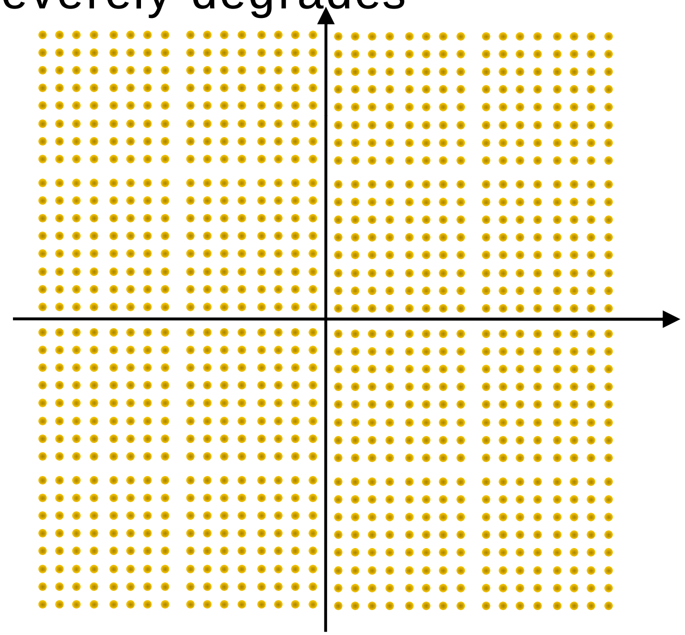
- 4G target of peak data rate is ~1Gbps, but the available bandwidth may be 100MHz/system in 4G (3.4~3.6GHz band)
- 1Gbps/100MHz/BS=10bps/Hz/BS
  - If we want to achieve this goal by multi-level modulation, 1024QAM is required
  - However, the achievable BER performance severely degrades



4QAM (2bps/Hz)



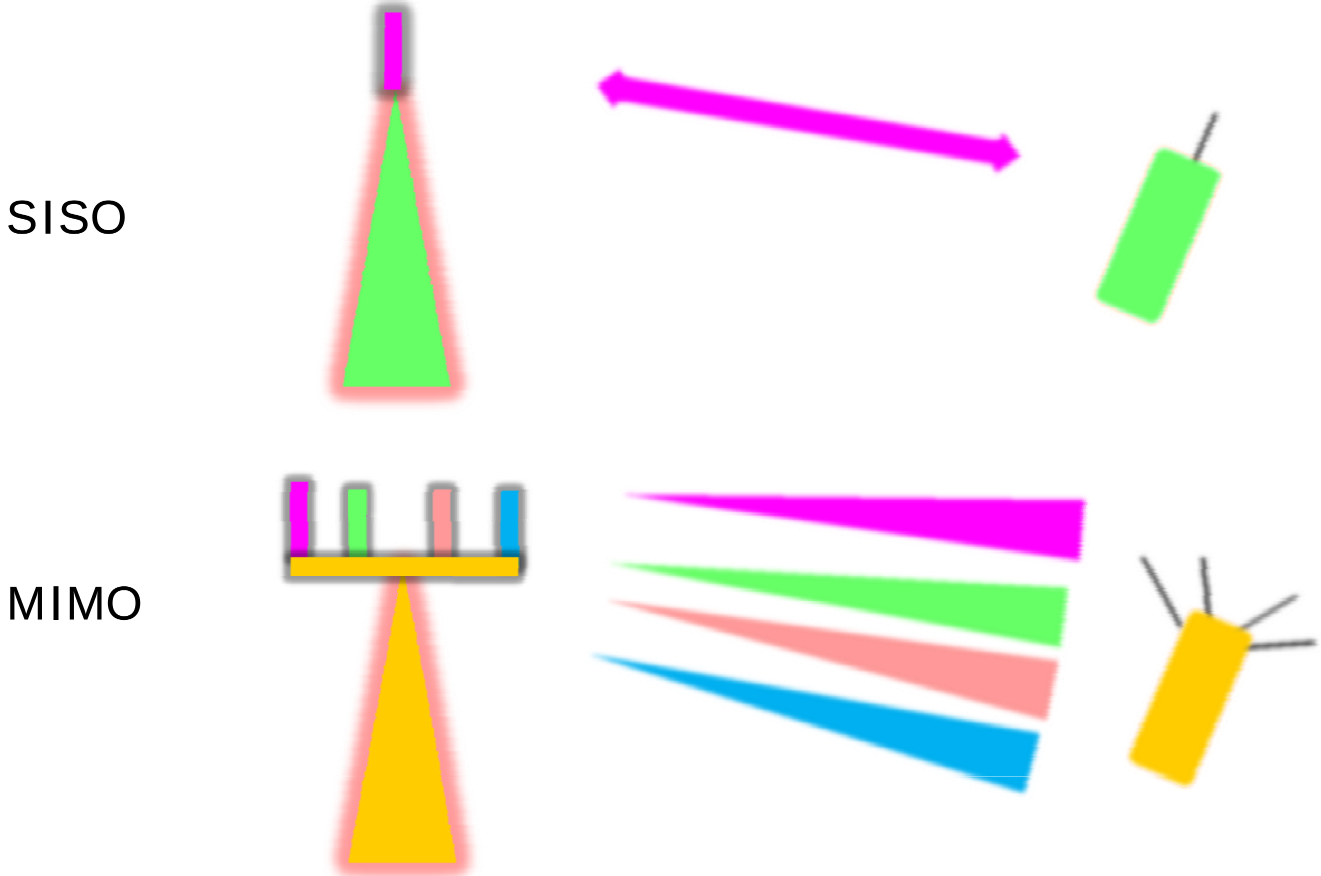
16QAM (4bps/Hz)



1024QAM (10bps/Hz)

MIMO SDM

- It may be almost impossible to use a higher level modulation such as 1024QAM to achieve 10bps/Hz/BS.
- MIMO technology can achieve such a high spectrum efficiency by using many antennas at both stations.



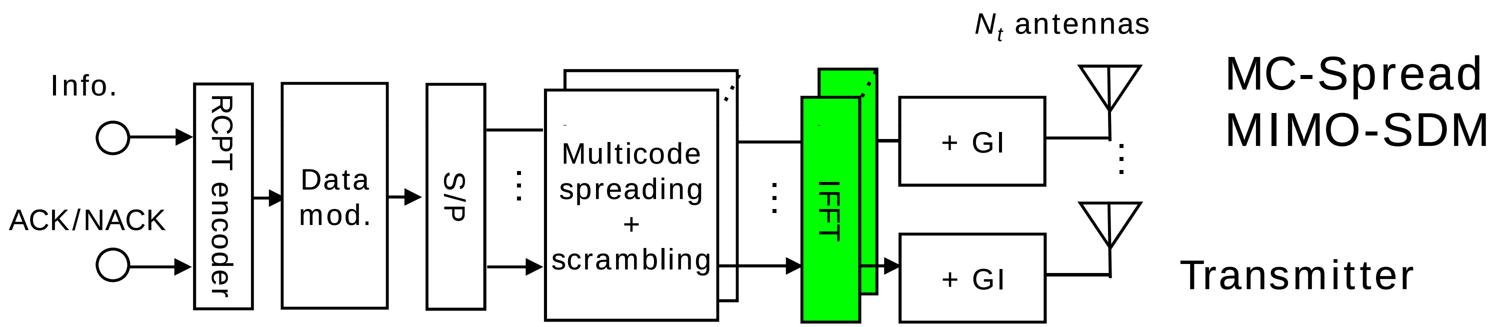
Single-Carrier Frequency-domain SDM

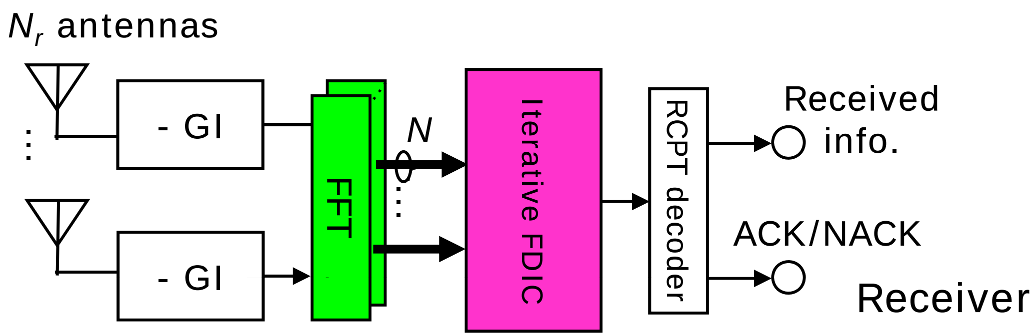
- Severe frequency-selective fading
  - So far, frequency nonselective fading channel has been assumed for AAA, STTD, and MIMO. But, for broadband wireless, severe frequency selective fading occurs.
  - They can be combined with DS-CDMA and MC-CDMA with frequency-domain equalization and a much better transmission performance can be achieved due to frequency diversity effect.
- Limitation on no. of antennas
  - Only one or two antennas (probably at most 4 antennas) may be available at a terminal in practice.
- Joint iterative frequency-domain 2D equalization (FDE) and parallel interference cancellation (PIC) for SC transmission
  - The data rate increase without bandwidth expansion is achieved while achieving frequency diversity gain.

- 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.

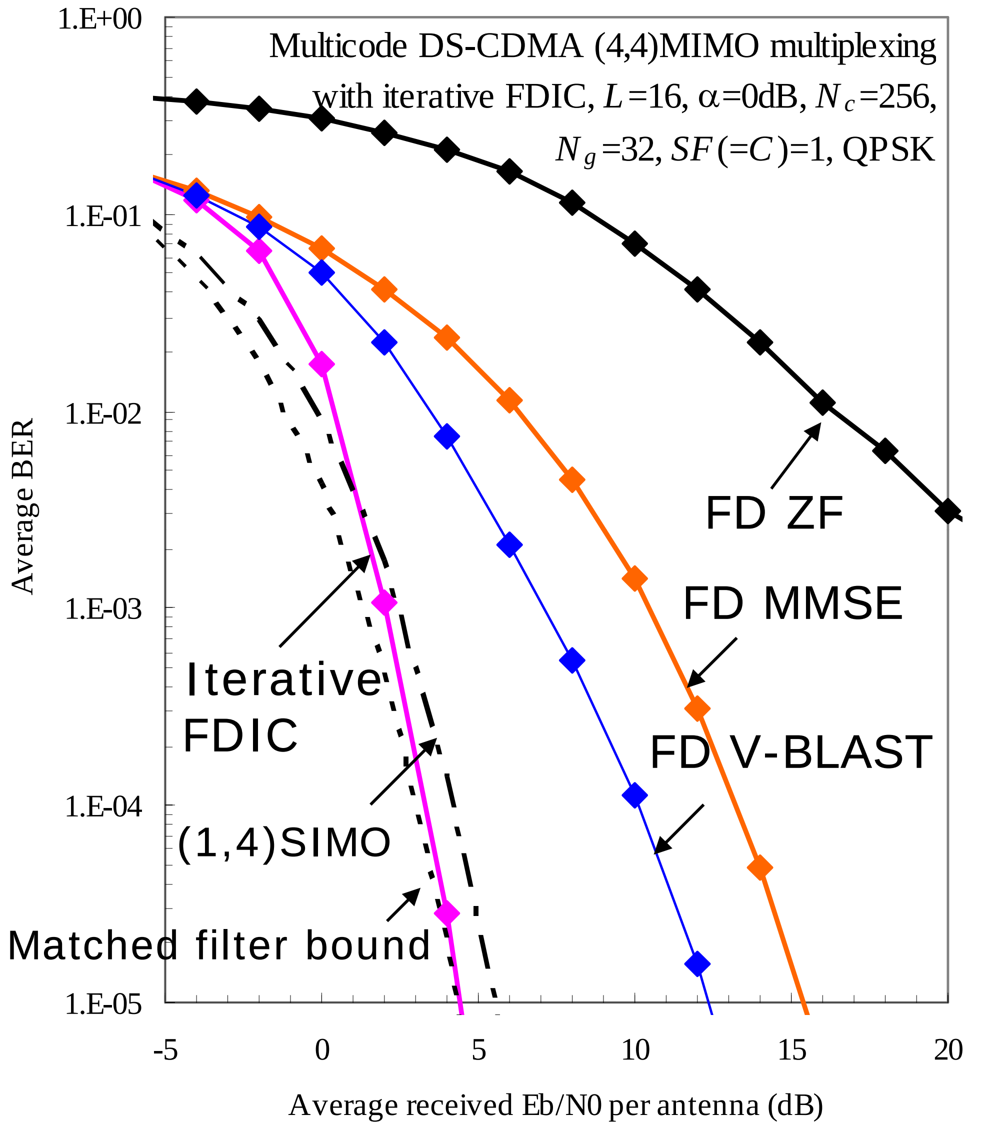
Spread MIMO SDM

- Frequency-domain iterative interference cancellation (FDIC) can be introduced to Spread MIMO SDM.
- Joint MMSE frequency-domain equalization (FDE) and parallel interference cancellation (PIC) is repeated for de-multiplexing while achieving frequency-diversity gain.



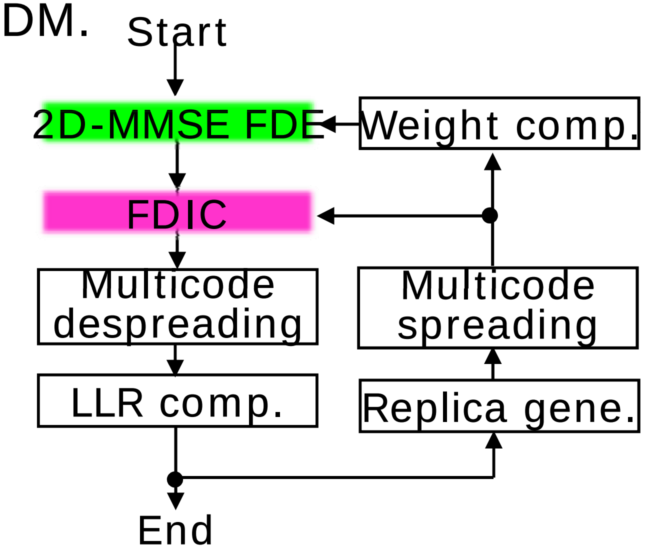


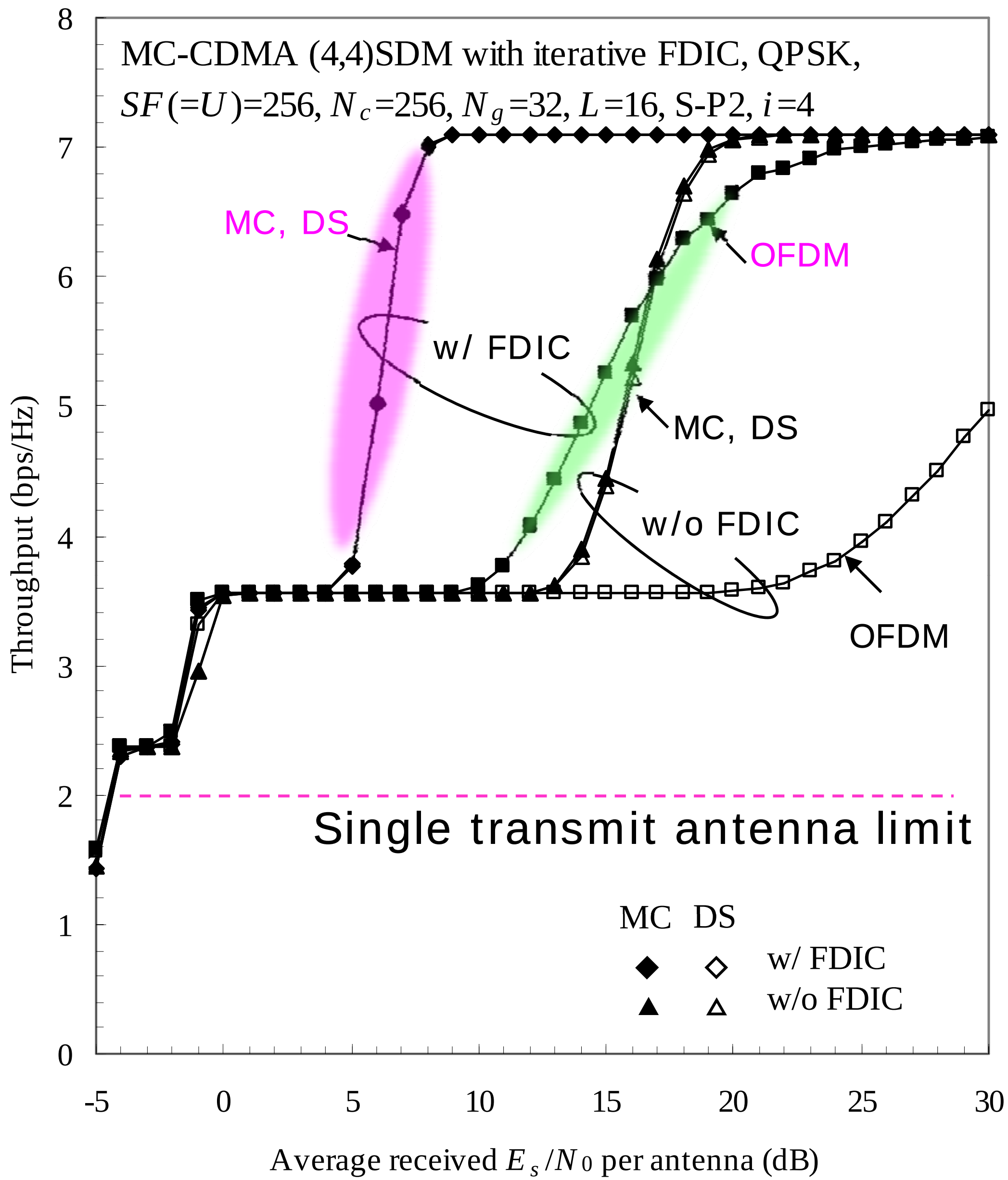
A. Nakajima, D. Garg and F. Adachi, "Frequency-domain iterative parallel interference cancellation for multicode DS-CDMA-MIMO multiplexing," Proc. IEEE VTC'05 Fall, Dallas, U.S.A., 26-28 Sept. 2005.


Multicode DS-CDMA (4,4)MIMO multiplexing
with iterative FDIC, L=16, α=0dB, Nc=256,
Ng=32, SF(=C)=1, QPSK
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
Average BER
-5
0
5
10
15
20
Average received Eb/N0 per antenna (dB)
FD ZF
FD MMSE
FD V-BLAST
Iterative
FDIC
(1,4)SIMO
Matched filter bound

Throughput of Spread MIMO SDM

- Close-to-1Gps (peak) access is required, but the available bandwidth is limited (e.g. 100MHz). MIMO SDM is a promising technique to achieve such a data rate.
- Spread MIMO SDM w/FDIC 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.

A New Approach In Mobile Networks

- Another important technical issue for the realization of high data rate 4G mobile networks is the significant reduction of the transmit power from a mobile terminal (MT)

E. Kudoh and F. Adachi, "Power and Frequency Efficient Wireless Multi-hop Virtual Cellular Concept," IEICE Trans. Commun., Vol.E88-B, No.4, pp.1613-1621, Apr. 2005.

Transmit Power Problem

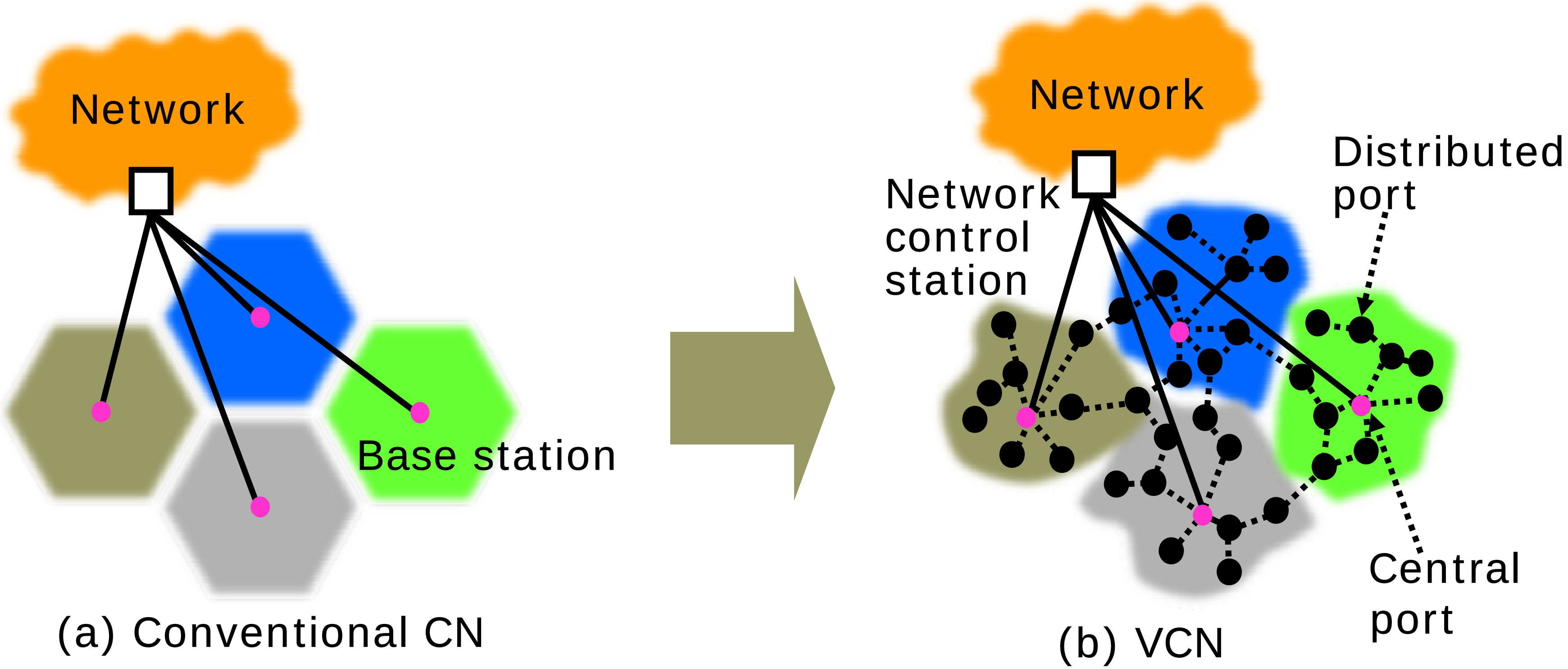
- Links for high speed data services are severely power-limited
  - Peak power is in proportion to "transmission rate" x "$f_c^{2.6}$ [Hata-formula]" where f_c is the carrier frequency
  - Let's consider the peak transmit power for 100Mbps@5GHz at a communication range of 1,000m. We assume the required transmit power for 8kbps@2GHz is 1Watt
  - The required peak transmission power is

    100Mbps/8kbps x $(5GHz/2GHz)^{2.6}$ =135,000 times, that is 135kWatt. Obviously, this cannot be allowed
  - To keep the transmission power at 1Watt level, the communication range should be reduced by about 29 times (e.g., 1,000m → 34m cell) if the propagation path loss exponent is 3.5
- Fundamental change is necessary in wireless access network

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

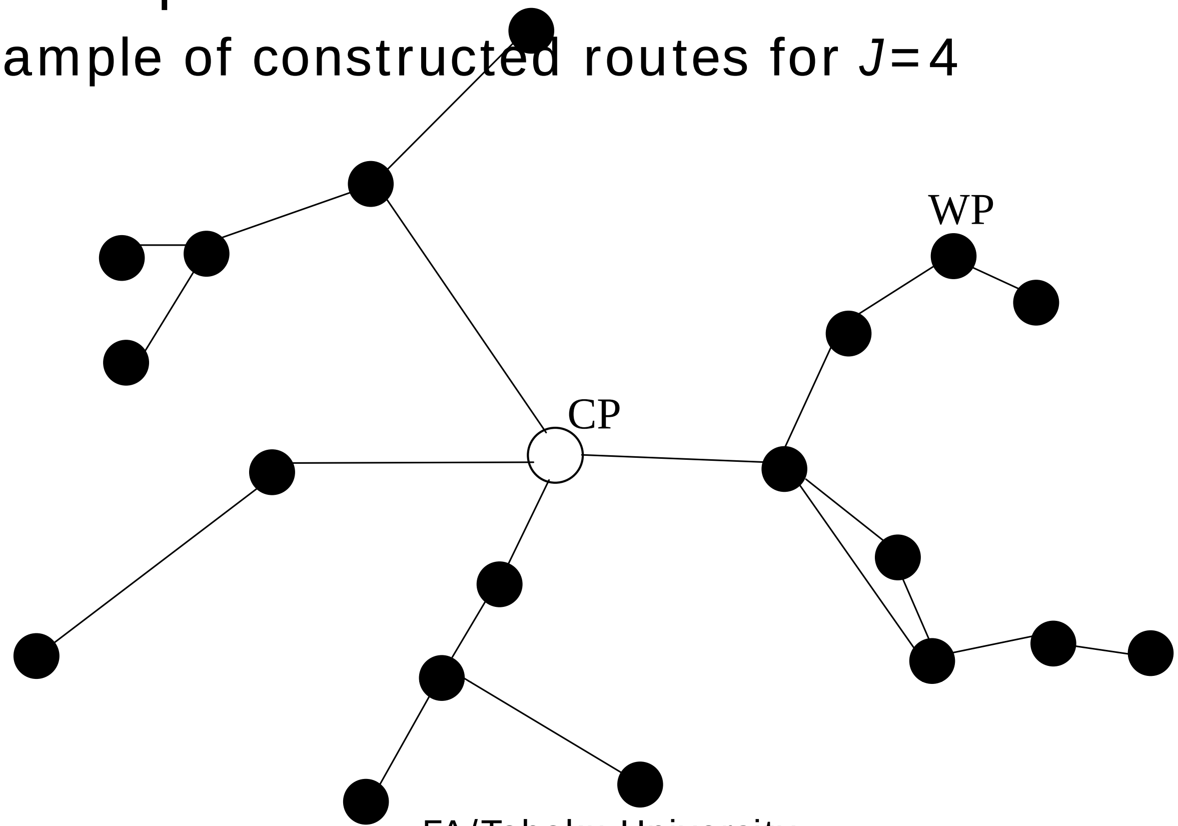
Multi-hop Virtual Cellular Network (VCN)

- Virtual cellular network (VCN) is suitable for non-real time packet communication
- Virtual cell consisting of many distributed wireless ports
  - One port (central port) acts a gateway to the network
  - Mobile terminal and central port are connected using wireless multi-hop relay technique



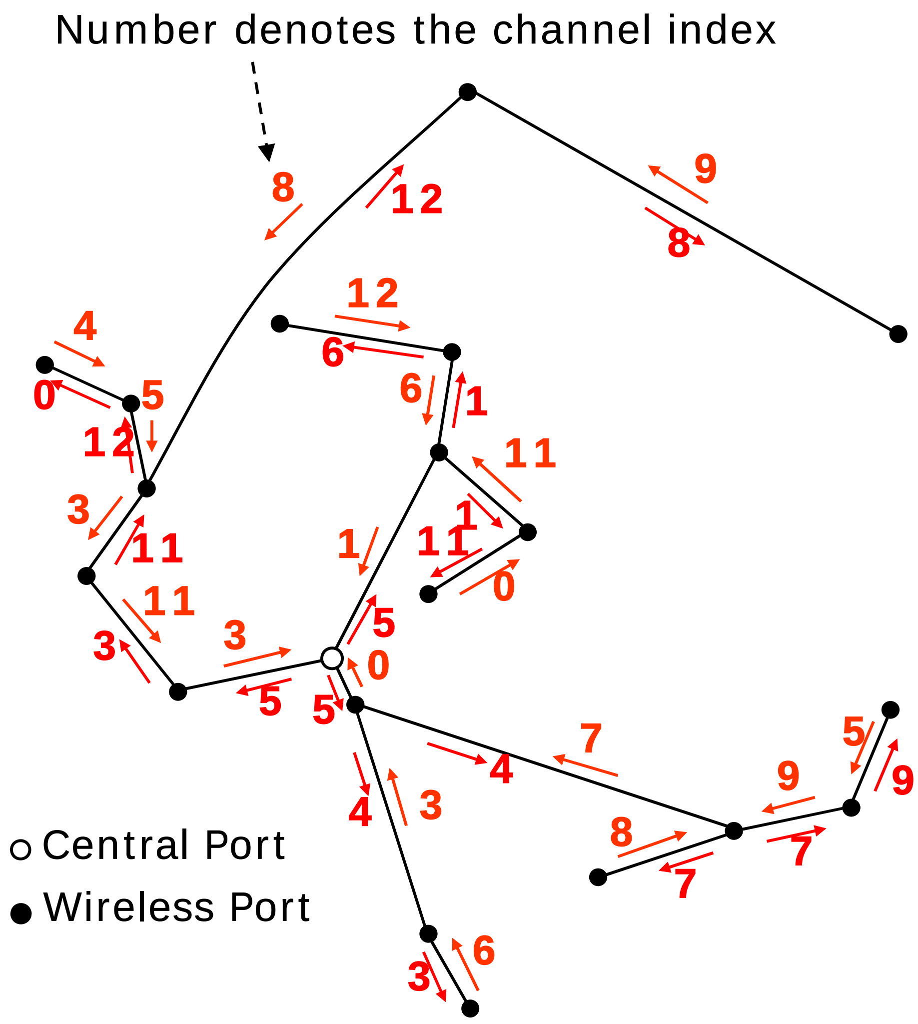
Multi-hop Route Construction

- Multi-hop routes connecting wireless end-ports (WPs) and central port (CP) are constructed based on the total transmit power minimization criterion
  - The interference to other multi-hop routes can be minimized.
- To avoid excessive transmission delay, the maximum number of hops is limited to J
  - An example of constructed routes for $J=4$



Dynamic Channel Allocation

- Channel allocation is an important technical issue to efficiently reuse the limited channel resources
- In VCN, a distributed dynamic channel allocation (DCA) will be a solution
- Channel segregation DCA (CS-DCA) is promising
  - Each WP learns about its favorite channels in a distributed manner without requiring any propagation channel information in advance



Y. Furuya and Y. Akaiwa, “Channel segregation, a distributed adaptive channel allocation scheme for mobile communication systems”, IEICE Trans., vol.E74, no.6, pp.1531-1537, June 1991.

Conclusion

- 4G systems are a broadband packet network which requires Giga-bit wireless technology of 100M~1Gbps capability (=10bps/Hz/BS for a 100MHz system bandwidth)
- Wireless multi-access technique
  - Frequency-domain signal processing plays an important role to achieve the goal
  - Besides OFDMA and SC-FDMA in 3.9G, either DS- or MC-CDMA with FDE can also be a promising candidate for 4G
  - Frequency-domain HARQ and MIMO SDM can be used to take advantage of the channel frequency-selectivity
- Network issue
  - Power problem is an important technical issue in 4G network. Some fundamental change needs to be introduced to the wireless network
  - E.g., multi-hop virtual cellular network, distributed antenna network, MIMO cooperative network, etc.

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