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# Frequency-domain Wireless Signal Processing

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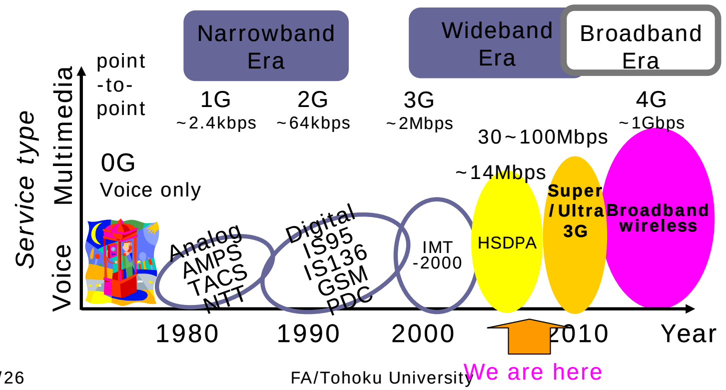
## OUTLINE

- Evolution into 4G
- Frequency-domain Equalization for Taking Advantage of Channel Selectivity
- Broadband MA Schemes Based on Frequency-domain Signal Processing



# Evolution into 4G

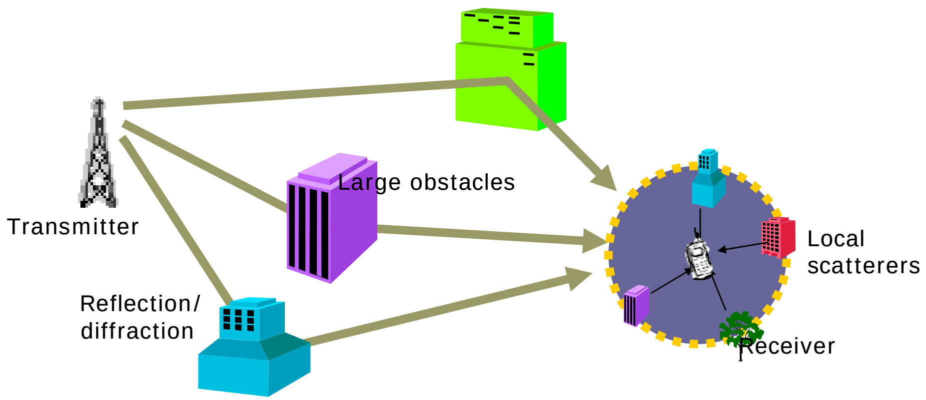
- In 4G systems, a peak data rate of around 1Gbps is demanded.
  - Available radio bandwidth may be limited to 100MHz.
  - Some advanced wireless techniques to achieve more than 10bps/Hz/BS are necessary; e.g., multi-input/multi-output (MIMO) antenna techniques, powerful error control, etc.






# Wireless Propagation Channel

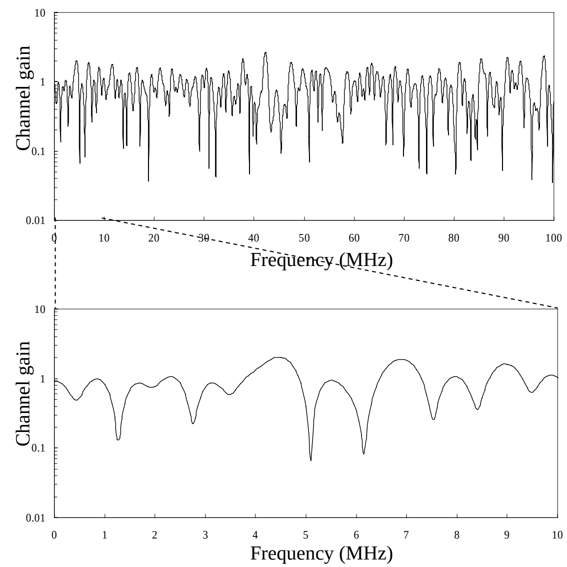
- In terrestrial wireless communications, the transmitted signal is reflected or diffracted by large buildings between transmitter and receiver, creating a number of propagation paths having different time delays.






# Frequency-selective Channel

- For broadband signal transmission, the transfer function of wireless channel varies over the signal bandwidth.
- Challenge is to transmit data at high speed (around 1 Gbps) with high quality over such a severe frequency-selective channel.




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

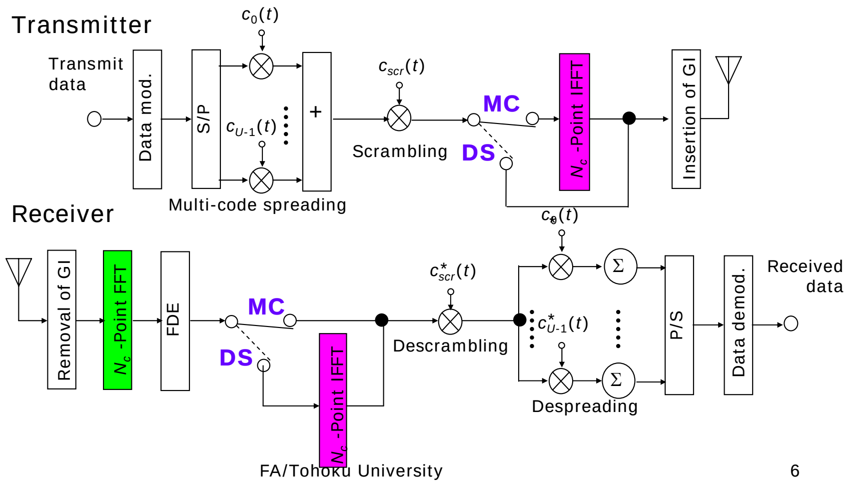
# Frequency-domain Equalization for Taking Advantage of Channel Selectivity

- Strong inter-symbol interference (ISI) can be produced by the severe frequency-selectivity of the channel.
- This has been long time a big problem for achieving high speed and high quality data transmissions.
- Equalization techniques play an important role to remove ISI and improve the transmission performance.
- Single-carrier (SC) system has been using a time-domain equalization technique, but this can be helpful only in a channel with a moderate number of paths.
- Multicarrier (MC) system representing OFDM carries the transmitting data symbol sequence by a number of orthogonal subcarriers. Simple one-tap frequency-domain equalization (FDE) can provide a good transmission performance in a severe frequency-selective channel.
- One-tap FDE can also be applied to SC system including DS-CDMA to significantly improve the transmission performance.



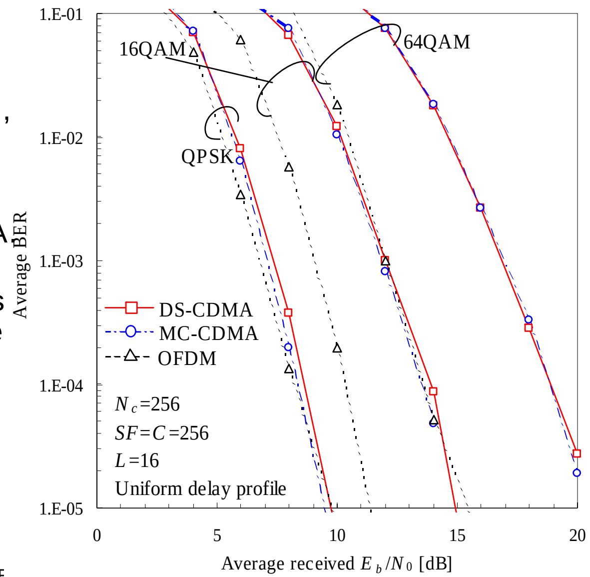
# CDMA Transmitter / Receiver

- One-tap FDE can take advantage of the channel frequency-selectivity and achieve an improved BER performance irrespective of DS- or MC-CDMA.
- Their transmitter/receiver structures also are similar.
  - Transmitter
  - Receiver





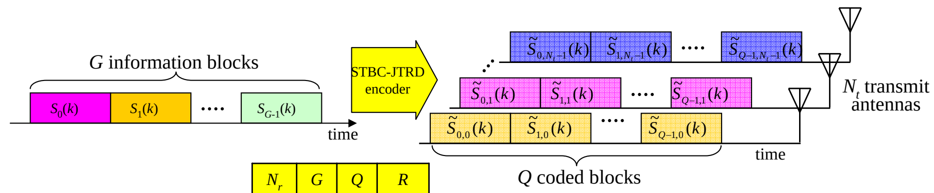

- MC- and DS-CDMA performances coincide for all the modulation levels.
- For 16QAM and 64QAM, however, OFDM provides a better BER performance than either MC- or DS-CDMA.
- This performance degradation of CDMA is owing to the inter-code interference (ICI) produced by the channel frequency-selectivity.






# Space-Time Block Coded Transmit Diversity

- Frequency-domain equalization can also be incorporated into space-time block coded transmit diversity.
- One such a transmit diversity is space-time block coded joint transmit/receive diversity (STBC-JTRD) which can use an arbitrary number of transmit antennas while limiting the maximum number of receive antennas to 4.




| $N_r$ | $G$ | $Q$ | $R$ |
|---|---|---|---|
| 1 | 1 | 1 | 1 |
| 2 | 2 | 2 | 1 |
| 3 | 3 | 4 | 3/4 |
| 4 | 3 | 4 | 3/4 |

- $G$ and $Q$ (hence, the coding rate, $R$) depend on the number of receive antennas, $N_r$, not on the number of transmit antennas, $N_t$.


- H. Tomeba, K. Takeda, and F. Adachi, "Space-time block coded joint transmit/receive diversity in a frequency-nonselective Rayleigh fading channel," IEICE Trans. Commun., Vol. E89-B, No. 8, pp. 2189-2195, Aug. 2006.
- H. Tomeba, K. Takeda, and F. Adachi, "Frequency-domain space-time block coded-joint transmit/receive diversity for the single carrier transmission," Proc. the 10th ICCS, pp. 1-5, Singapore, 30 Oct. - 1 Nov. 2006.

# Frequency-domain STBC-JTRD for $N_r$=2 ($G$=$Q$=2)

- Encoding

$$\left(\tilde{S}_{0,n_t}(k),\tilde{S}_{1,n_t}(k)\right)=\sqrt{\frac{N_c}{\sum_{n_r=0}^{N_r-1}\sum_{n_t=0}^{N_t-1}\sum_{k=0}^{N_c-1}|w_{n_r,n_t}(k)|^2}}\begin{pmatrix}S_0(k)w_{0,n_t}(k)+S_1(k)w_{1,n_t}(k)\\ S_0^*(k)w_{1,n_t}(k)-S_1^*(k)w_{0,n_t}(k)\end{pmatrix}^T$$

where $w_{nr,nt}(k)$ is the MMSE pre-equalization weight, given as

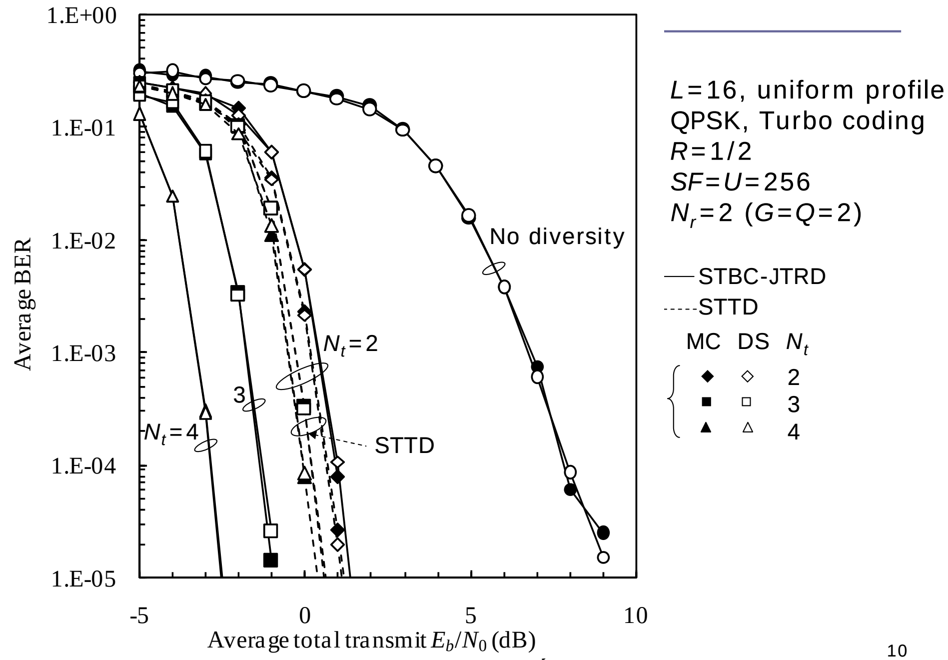
$$w_{n_r,n_t}(k)=H^*_{n_r,n_t}(k)\Bigg/\left(\frac{1}{N_r}\sum_{n_r=0}^{N_r-1}\sum_{n_t=0}^{N_t-1}|H_{n_r,n_t}(k)|^2+\left(\frac{U}{SF}\frac{E_s}{N_0}\right)^{-1}\right)$$

and $H_{nr,nt}(k)$ is the channel gain between the $n_t$th transmit antenna and the $n_r$th receive antenna at the $k$th subcarrier.

- Decoding (for $t$=0~$N_c$–1)

$$\left(\hat{r}_0(t),\hat{r}_1(t)\right)=\begin{pmatrix}r_{0,0}(t)+r_{1,1}^*(N_c-t)\\ r_{0,1}(t)-r_{1,0}^*(N_c-t)\end{pmatrix}^T$$

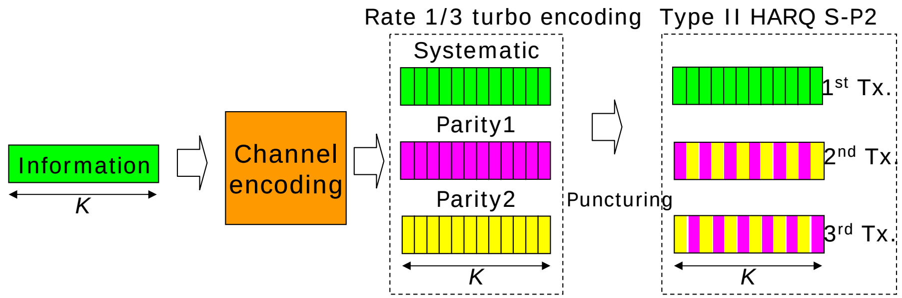







# Hybrid ARQ (HARQ) with Incremental Redundency(IR)

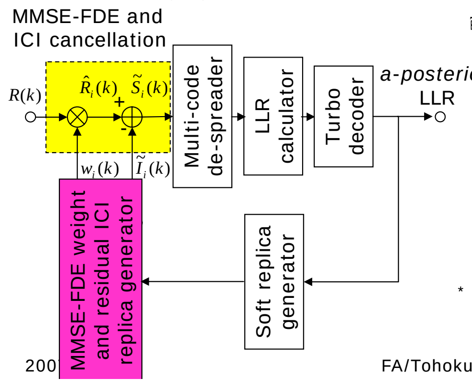
- An automatic repeat request (ARQ) combined with the channel coding, called hybrid ARQ (HARQ), is an inevitable technique, since an error-free transmission must be guaranteed for packet data services.
- HARQ combined with FDE can take advantage of the channel frequency-selectivity and can significantly improve the throughput.

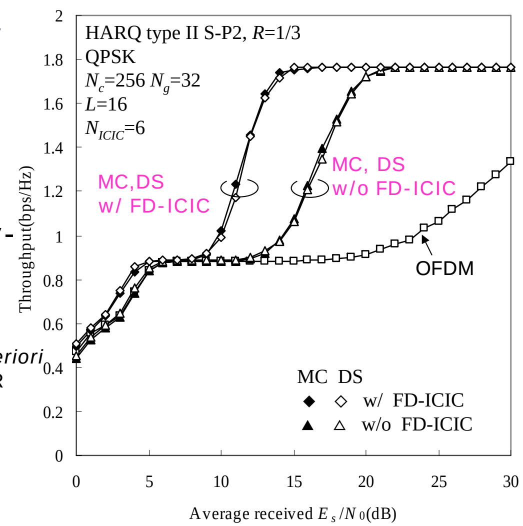





# HARQ w/FDE & ICI Cancellation

- Joint use of FDE and ICI cancellation significantly improves the throughput.
- MC- and DS-CDMA provide better throughput than OFDM due to the frequency-diversity gain.

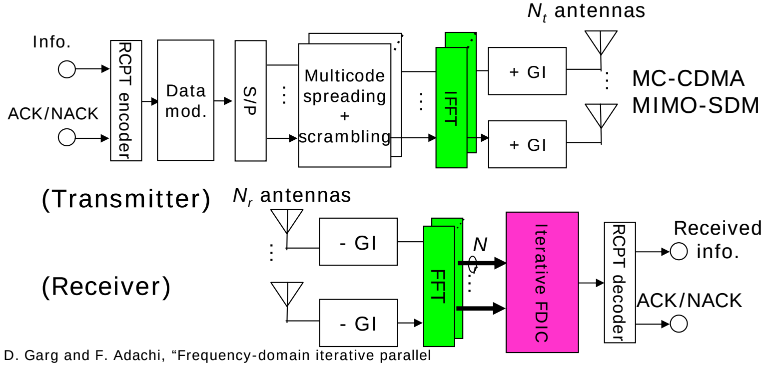



* K. Fukuda, A. Nakajima, and F. Adachi, "LDPC-coded HARQ throughput performance of MC-CDMA using ICI cancellation," to be presented at The 65th IEEE VTC07-fall, Baltimore, USA, 30 Sept.-3 Oct. 2007.

# Frequency-Domain SDM

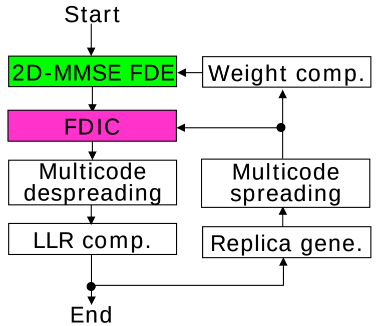
- MIMO space division multiplexing (SDM) is a promising technique to increase the throughput with limited frequency bandwidth.
- To achieve the frequency-diversity gain, joint MMSE-FDE/parallel interference cancellation (PIC) is repeated for signal detection. This is called iterative FDIC.

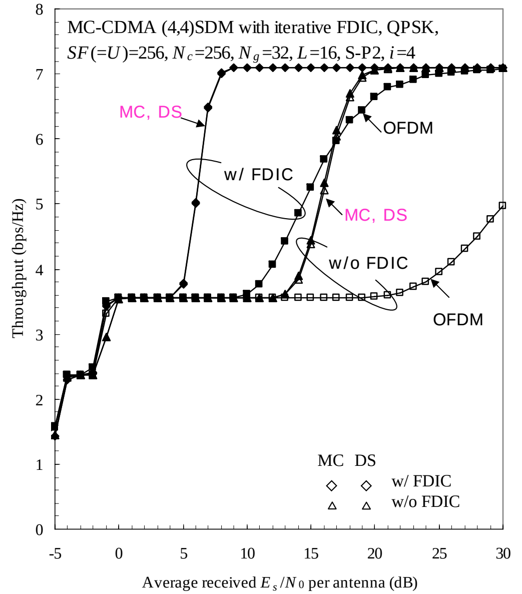



* A. Nakajima, D. Garg and F. Adachi, "Frequency-domain iterative parallel interference cancellation for multicode DS-CDMA-MIMO multiplexing," Proc. IEEE VTC'05 Fall, Dallas, U.S.A., 26-28 Sept. 2005.



- Iterative FDIC can improve throughput for both CDMA and OFDM, but is more effective for CDMA.



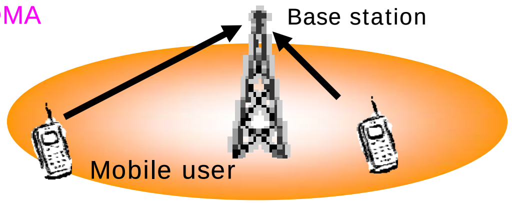




- A. Nakajima, D. Garg and F. Adachi, "Frequency-domain iterative parallel interference cancellation for multicode DS-CDMA-MIMO multiplexing," Proc. IEEE VTC'05 Fall, Vol.1, pp. 73-77, Dallas, U.S.A., 26-28 Sept. 2005.
- A. Nakajima and F. Adachi, "Iterative FDIC using 2D-MMSE FDE for turbo-coded HARQ in SC-MIMO multiplexing," IEICE Trans. Commun. Vol. E90-B, No.3, pp.693-695, Mar. 2007.



# Broadband MA Schemes Based On Frequency-domain Signal Processing

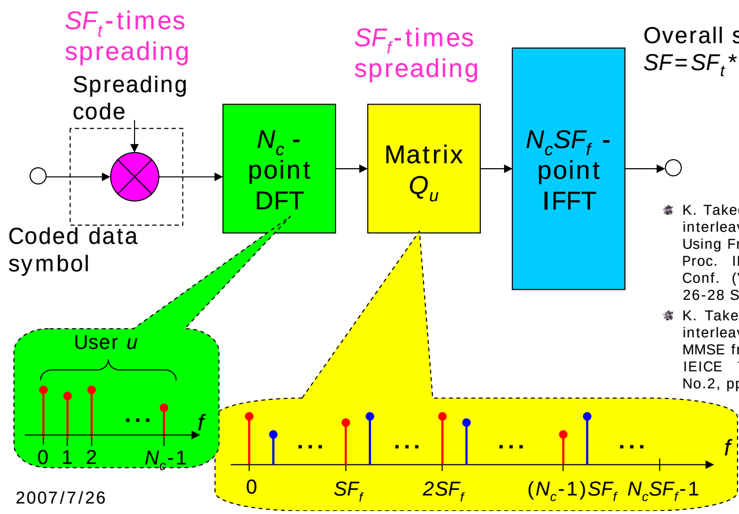
- Uplink capacity is limited by MAI resulting from asynchronous users.
- For the uplink applications, SC is more suitable than MC because of its lower PAPR property.
- Two approaches:
  - Frequency-domain approach separates users so that their spectra do not overlap in the frequency-domain
    →Frequency-domain interleaved spread spectrum SCMA
  - Time-domain approach separates users thanks to code orthogonality property of block spreading (users' spectra are overlapped)
    →2D block spread CDMA






# Frequency-domain interleaved SSMA

- Spread spectrum SC signal is first transformed into frequency-domain signal and then, mapped to different subcarriers, similar to SC-FDMA.

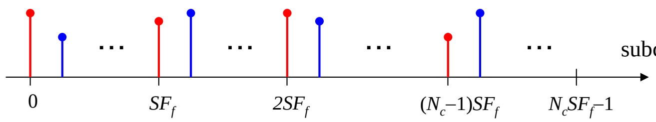



Overall spreading factor $SF=SF_t*SF_f$

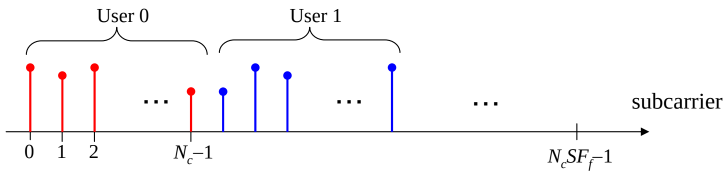
- K. Takeda and F. Adachi, " Frequency-interleaved CDMA Uplink Transmission Using Frequency-domain Equalization," Proc. IEEE 62nd Vehicular Technol. Conf. (VTC2005-Fall), Dallas, U.S.A., 26-28 Sept. 2005.
- K. Takeda and F. Adachi, "Frequency-interleaved spread spectrum with MMSE frequency-domain equalization," IEICE Trans. Commun., Vol.E90-B, No.2, pp.260-268, Feb. 2007.

# Orthogonal Interleave Patterns

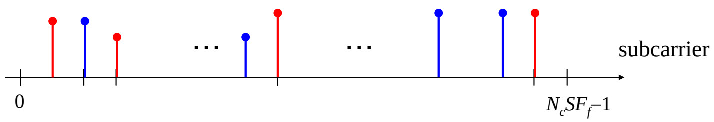
- Equal-spacing pattern




- Localized pattern

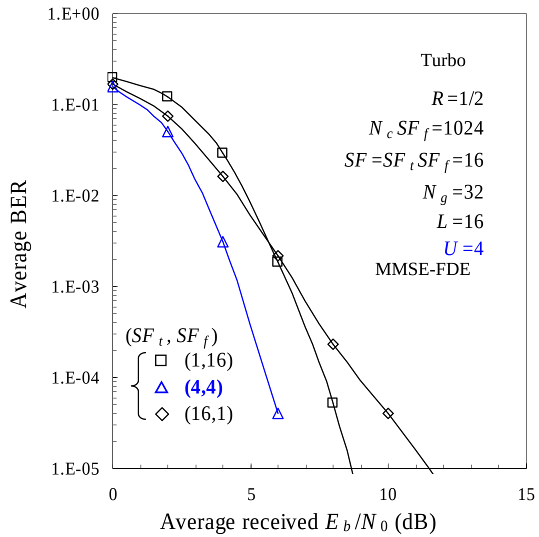



- Random pattern





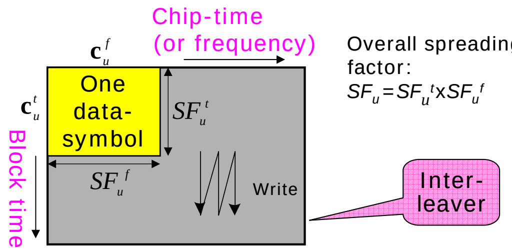

- $(SF_t, SF_f) = (SF/U, U)$ gives the best BER performance for the given overall spreading factor $SF = SF_t * SF_f$ since
  - MAI can be mitigated by preventing the spectrum overlap
  - chip-time spreading factor $SF_t$ can be maximized so that the residual ISI can be minimized.






# 2D Block Spread CDMA

- 2D block spread CDMA uses a product code of two orthogonal spreading codes, $\boldsymbol{c}_u^t$ and $\boldsymbol{c}_u^f$, of spreading factors, $SF_u^t$ and $SF_u^f$, respectively.
  - Block-time spreading code $\boldsymbol{c}_u^t$ allows MAI-free multi-access
  - Chip-time (or frequency) spreading code $\boldsymbol{c}_u^f$ allows reduction of the residual ISI after FDE.
- MAI-free code combination is $(SF_u^t, SF_u^f) = (U, SF/U)$
- $\boldsymbol{c}_u^t$ and $\boldsymbol{c}_u^f$ codes can be chosen from orthogonal variable spreading factor (OVSF) codes.



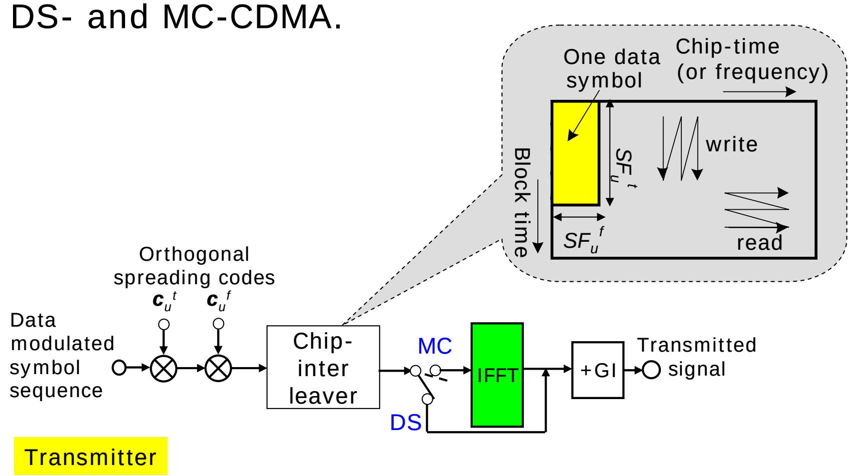

Overall spreading factor: $SF_u = SF_u^t \times SF_u^f$

$\mathbf{C}_u = \mathbf{c}_u^t (\mathbf{c}_u^f)^T$


L. Le and F. Adachi, " 2-dimensional OVSF Spreading for Chip-interleaved DS-CDMA Uplink Transmission," Proc. WPMC05, Aalborg, Denmark, 19-22 Sept. 2005.
L. Liu and F. Adachi, "2-dimensional OVSF spread/chip-interleaved CDMA," IEICE Trans. Commun., Vol. E89-B, No. 12, pp. 3363-3375, Dec. 2006.



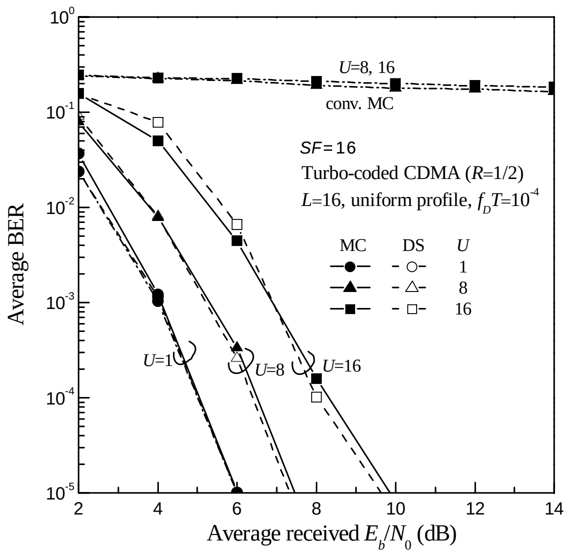

- 2D block spreading can be introduced into both DS- and MC-CDMA.





L. Liu and F. Adachi, "2-dimensional OVSF spread/chip-interleaved CDMA," IEICE Trans. Commun., Vol. E89-B, No. 12, pp. 3363-3375, Dec. 2006.

- $(SF_u^t, SF_u^f) = (U, SF/U)$ gives the best uplink performance since
  - MAI can be mitigated, without using a sophisticated MUD, thanks to orthogonal block-time spreading
  - chip-time spreading factor $SF_u^f$ can be maximized so that the residual ISI can be minimized.






# Conclusion

- 4G systems are a broadband packet network and requires Giga-bit wireless technology of around1Gbps transmission capability.
- Frequency-domain signal processing is an important technique to achieve the goal.
  - Either MC or SC with FDE can be used since both can provide similar performance.
  - Frequency-domain HARQ and MIMO can be used to take advantage of the channel frequency-selectivity.
- Network issue
  - Power problem is an important technical issue in 4G networks. Some fundamental change needs to be introduced to the wireless network.
  - E.g., multi-hop virtual cellular network, collaborative network, distributed antenna network, etc.



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