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Lecture-5: Multi- Antenna OFDM Systems

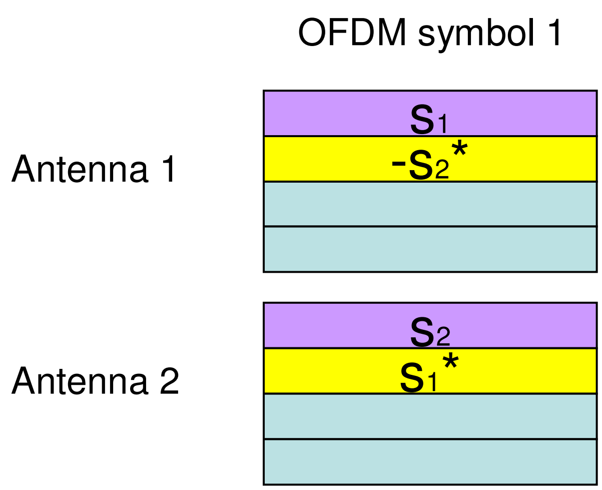
1. Diversity Techniques in OFDM
2. Receive Diversity in OFDM Systems
3. **Transmit Diversity in OFDM Systems**
4. Spatial Multiplexing (MIMO-OFDM)
5. Smart Antenna Technique: Beamforming

Transmit Diversity

- Time diversity ➔ Delay diversity
- S-T Diversity ➔ STBC, STTC
- S-F Diversity ➔ SFBC, SFTC
- S-T-F Diversity ➔ STFBC

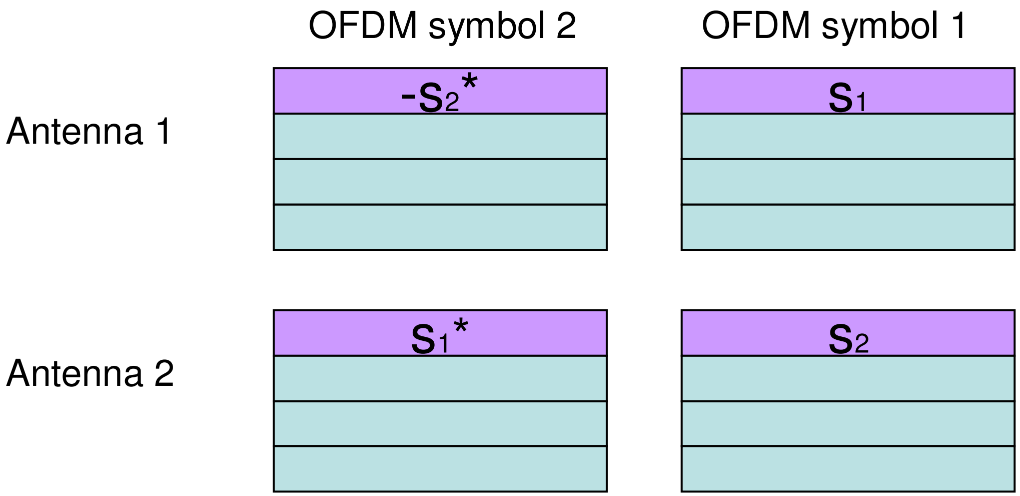
7. Spatial diversity coding for MIMO-OFDM

- In MIMO system the Alamouti scheme realizes full spatial diversity gain in the absence of channel knowledge at the transmitter.
- This requires that the channel remains constant over at least two consecutive symbol periods
- In MIMO-OFDM the coding is performed in the frequency rather than in time
- Symbols s1 and s2 are transmitted over antennas 1 and 2 on tone n and symbols –s2* and s1* are transmitted over antennas 1 and 2 on tone n+1



7. Spatial diversity coding for MIMO-OFDM

- Any pair of tones could be used as long as the associated channels are equal i.e. the channel requirement is different from the MIMO case
- An alternative technique is to use diversity coding on a per-tone basis across OFDM symbols in time but then the channel should be constant during two consecutive OFDM symbols
- This is not usually true due to the long duration of OFDM symbols



Space-Time Block Code - II

- The received signals are

$$y_1 = \alpha_1 x_1 + \alpha_2 x_2 + \eta_1$$
$$y_2 = -\alpha_1 x_2^* + \alpha_2 x_1^* + \eta_2 .$$

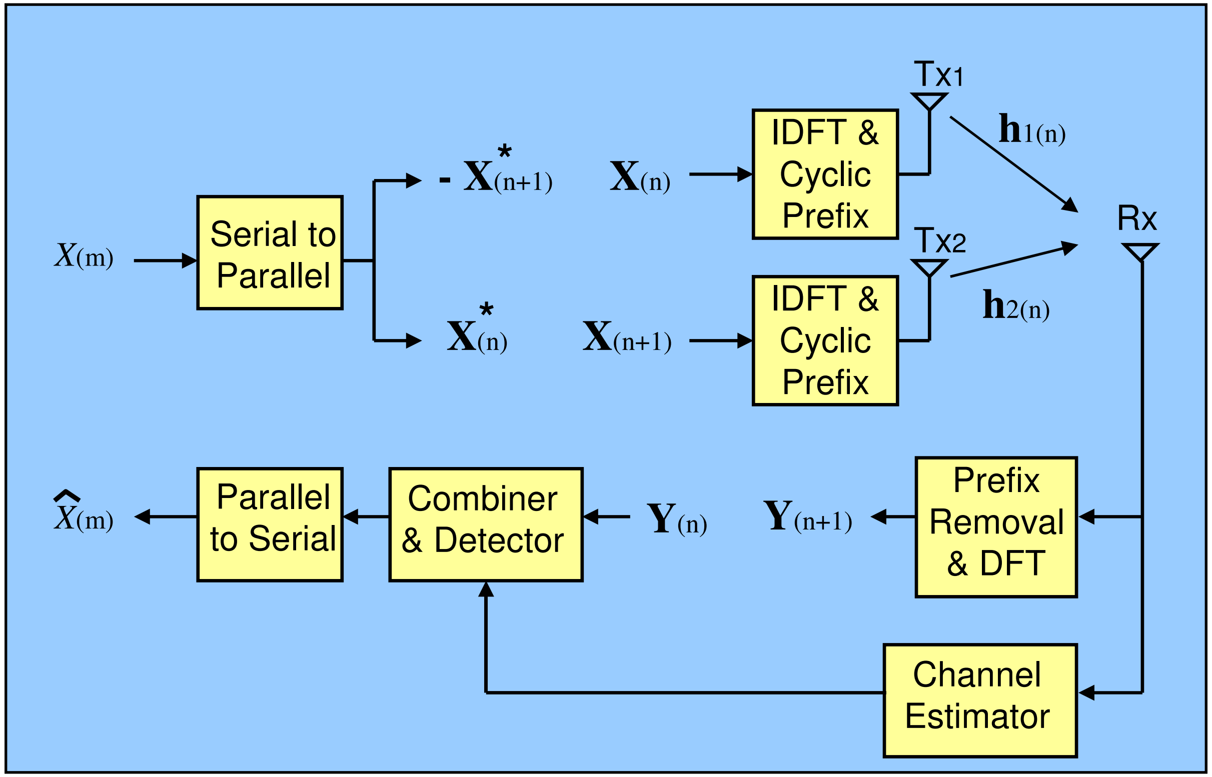
- Calculate the decision variables as

$$\hat{x}_1 = \alpha_1^* y_1 + \alpha_2 y_2^* = \left(|\alpha_1|^2 + |\alpha_2|^2\right) x_1 + \alpha_1^* \eta_1 + \alpha_2 \eta_2^*$$
$$\hat{x}_2 = \alpha_2^* y_1 - \alpha_1 y_2^* = \left(|\alpha_1|^2 + |\alpha_2|^2\right) x_2 - \alpha_1 \eta_2^* + \alpha_2^* \eta_1 .$$

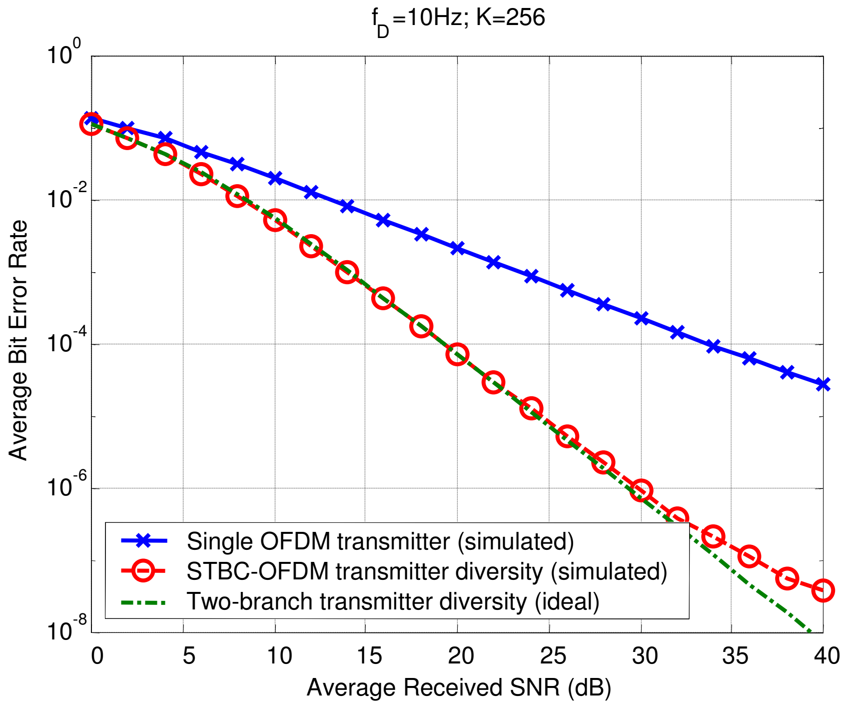
- Similar to that of a two-branch maximal ratio combining receiver diversity system!

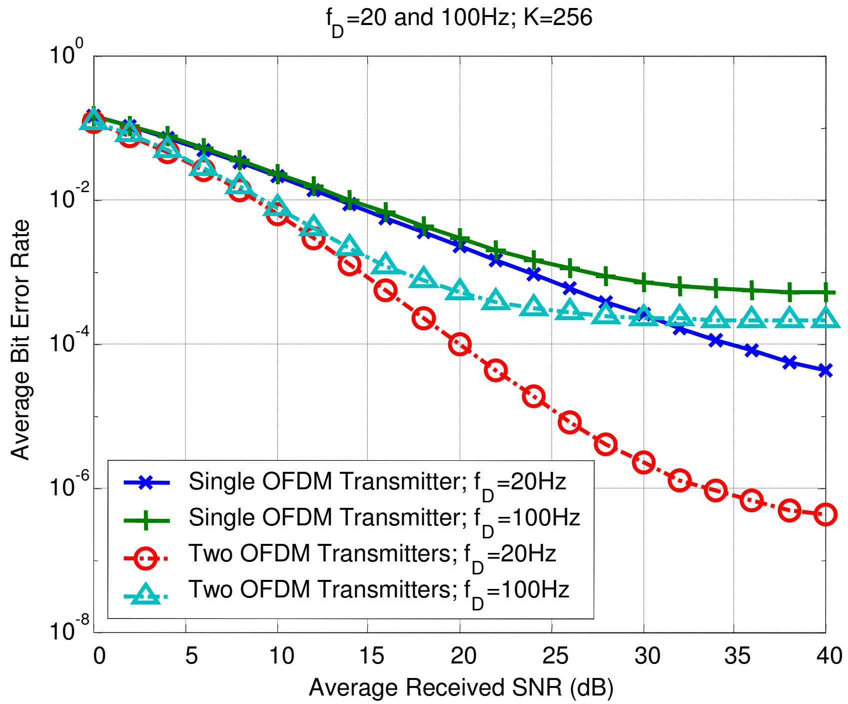
Space-Time Block-Coded OFDM - I

- Space-time coding on two adjacent blocks of data symbols, i.e., $\mathbf{X}(n)$ and $\mathbf{X}(n+1)$.



STBC-OFDM Simulation Results

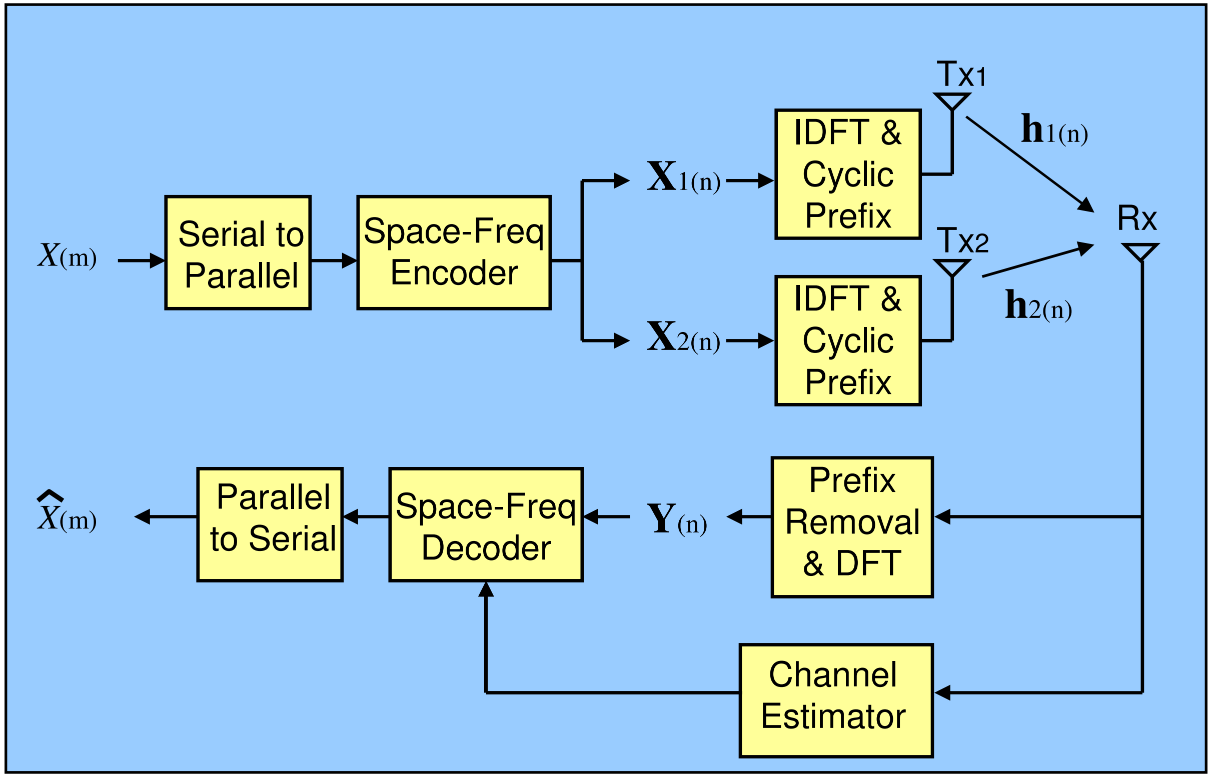




- STBC-OFDM achieves near optimal diversity gain in slow fading.
- Still outperforms non-diversity OFDM system at f_D=100Hz.

Space-Frequency Block-Coded OFDM - I

- Coding on adjacent DFT frequency bins of each block of $\mathbf{X}(n)$.



Space-Frequency Block-Coded OFDM - II

- Space-frequency encoder codes each data vector $\mathbf{X}(n)$,

$$\mathbf{X}(n) = \left[X(n,0) \;\; X(n,1) \cdots X(n,K-2) \;\; X(n,K-1) \right]^T,$$

into two vectors $\mathbf{X_1}(n)$ and $\mathbf{X_2}(n)$ as

$$\mathbf{X}_1(n) = \left[X(n,0) \;\; -X^*(n,1) \cdots X(n,K-2) \;\; -X^*(n,K-1) \right]^T,$$

$$\mathbf{X}_2(n) = \left[X(n,1) \quad X^*(n,0) \cdots X(n,K-1) \quad X^*(n,K-2) \right]^T$$

or in terms of the even and odd polyphase vectors as

$$\mathbf{X}_{1,e}(n) = \mathbf{X}_e(n) \quad , \quad \mathbf{X}_{1,o}(n) = -\mathbf{X}_o{}^*(n)$$

$$\mathbf{X}_{2,e}(n) = \mathbf{X}_o(n) \quad , \quad \mathbf{X}_{2,o}(n) = \mathbf{X}_e{}^*(n).$$

Space-Frequency Block-Coded OFDM - III

- The demodulated vector is

$$\mathbf{Y}(n) = \mathbf{\Lambda}_1(n)\mathbf{X}_1(n) + \mathbf{\Lambda}_2(n)\mathbf{X}_2(n) + \mathbf{Z}(n),$$

or, equivalently, as

$$\begin{aligned}\mathbf{Y}_e(n) &= \mathbf{\Lambda}_{1,e}(n)\mathbf{X}_{1,e}(n) + \mathbf{\Lambda}_{2,e}(n)\mathbf{X}_{2,e}(n) + \mathbf{Z}_e(n)\\ \mathbf{Y}_o(n) &= \mathbf{\Lambda}_{1,o}(n)\mathbf{X}_{1,o}(n) + \mathbf{\Lambda}_{2,o}(n)\mathbf{X}_{2,o}(n) + \mathbf{Z}_o(n)\end{aligned}.$$

- Calculate

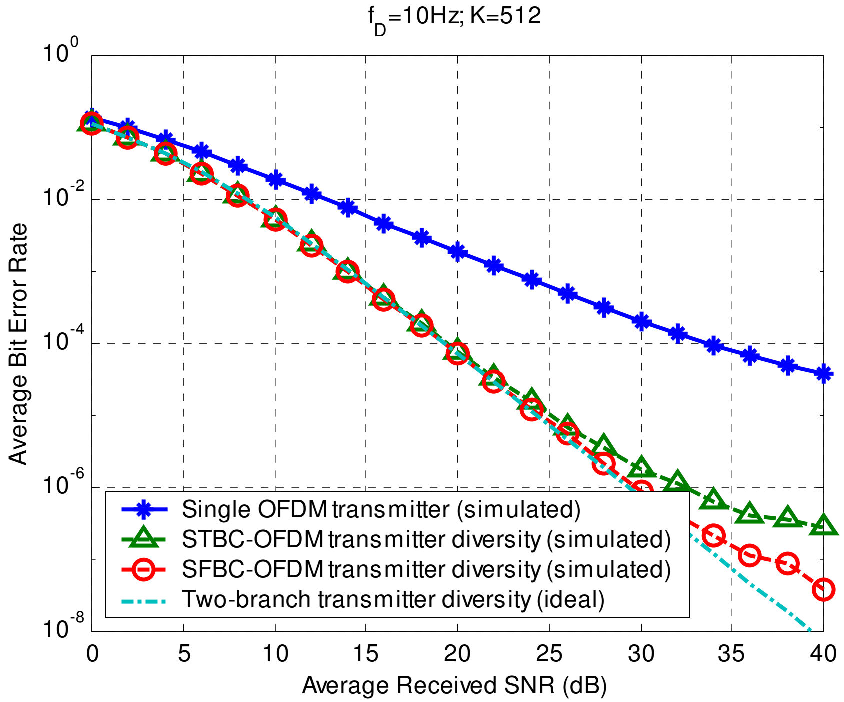
$$\begin{aligned}\hat{\mathbf{X}}_e(n) &= \mathbf{\Lambda}^*_{1,e}(n)\mathbf{Y}_e(n) + \mathbf{\Lambda}_{2,o}(n)\mathbf{Y}^*_o(n)\\ \hat{\mathbf{X}}_o(n) &= \mathbf{\Lambda}^*_{2,e}(n)\mathbf{Y}_e(n) - \mathbf{\Lambda}_{1,o}(n)\mathbf{Y}^*_o(n)\end{aligned}.$$

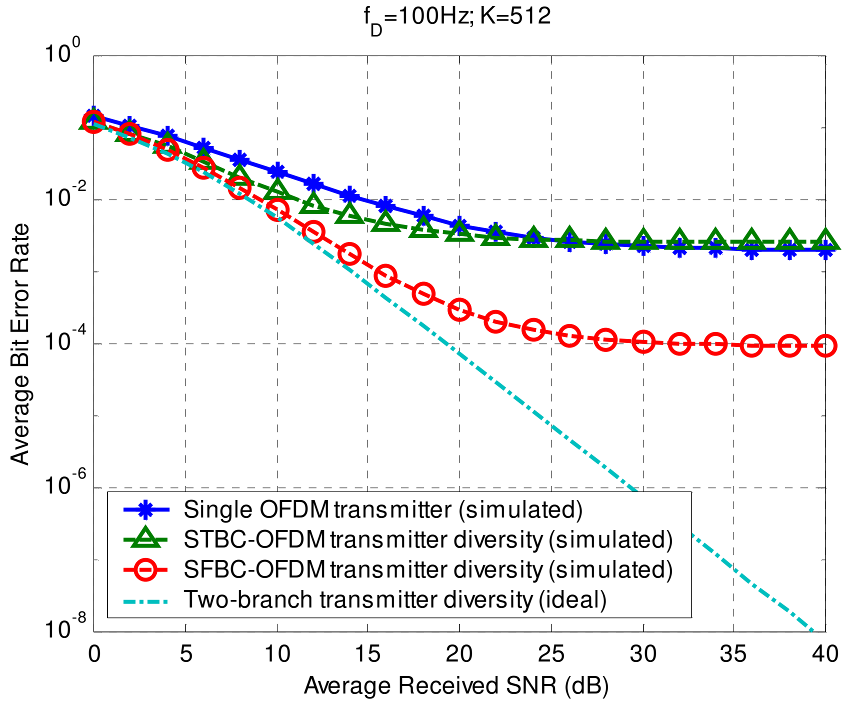
- Assuming $\mathbf{\Lambda}_{1,e}(n) \approx \mathbf{\Lambda}_{1,o}(n)$ and $\mathbf{\Lambda}_{2,e}(n) \approx \mathbf{\Lambda}_{2,o}(n)$,

yields

$$\begin{aligned}\hat{\mathbf{X}}_e &= \left(\left|\mathbf{\Lambda}_{1,e}\right|^2 + \left|\mathbf{\Lambda}_{2,e}\right|^2\right)\mathbf{X}_e + \mathbf{\Lambda}^*_{1,e}\mathbf{Z}_e + \mathbf{\Lambda}_{2,o}\mathbf{Z}^*_o\\ \hat{\mathbf{X}}_o &= \left(\left|\mathbf{\Lambda}_{1,o}\right|^2 + \left|\mathbf{\Lambda}_{2,o}\right|^2\right)\mathbf{X}_o + \mathbf{\Lambda}^*_{2,e}\mathbf{Z}_e - \mathbf{\Lambda}_{1,o}\mathbf{Z}^*_o\end{aligned}.$$

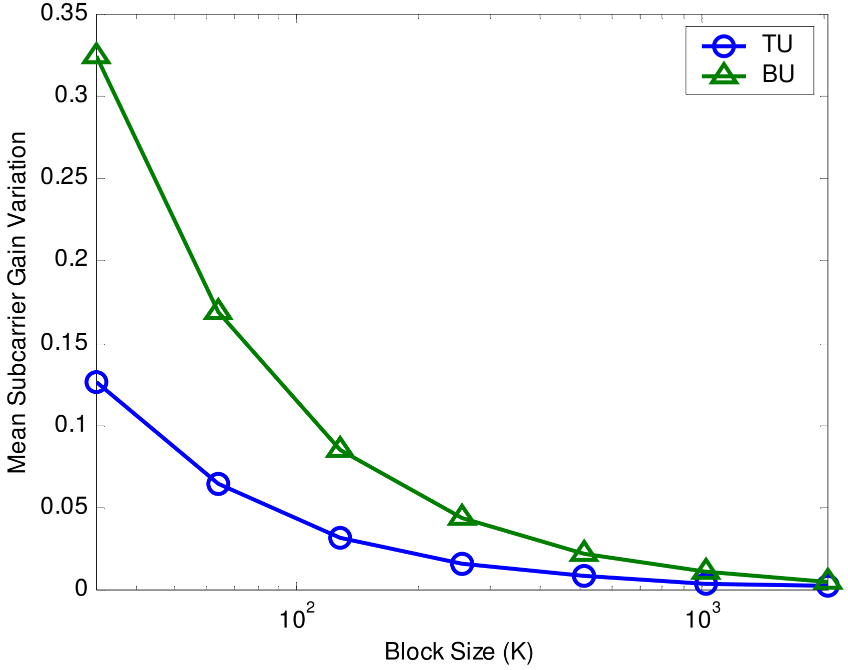
SFBC-OFDM Simulation Results - I

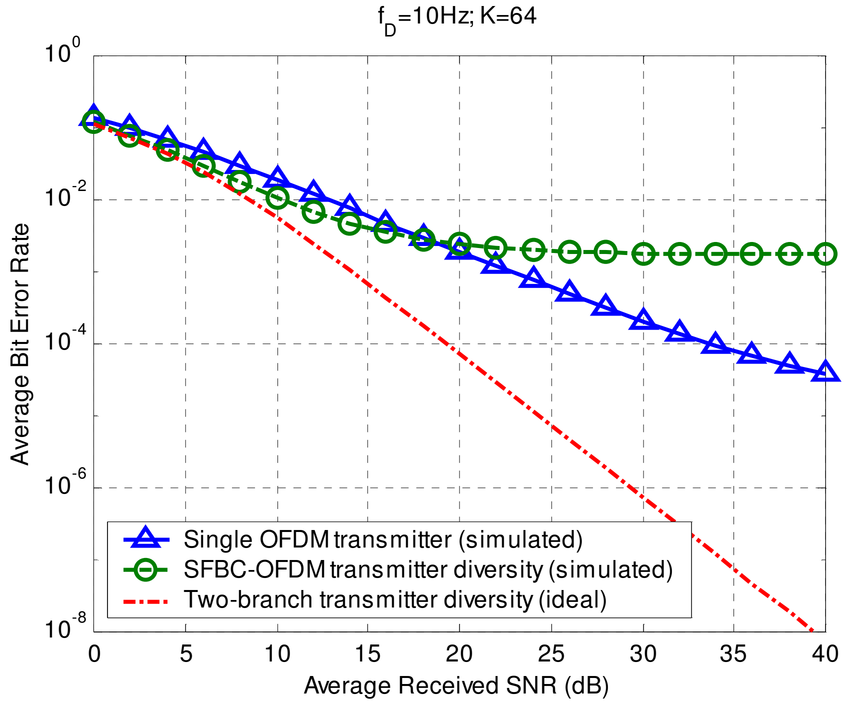




- SFBC-OFDM achieves similar diversity gain as STBC-OFDM in slow fading.
- SFBC-OFDM performs better in fast fading.

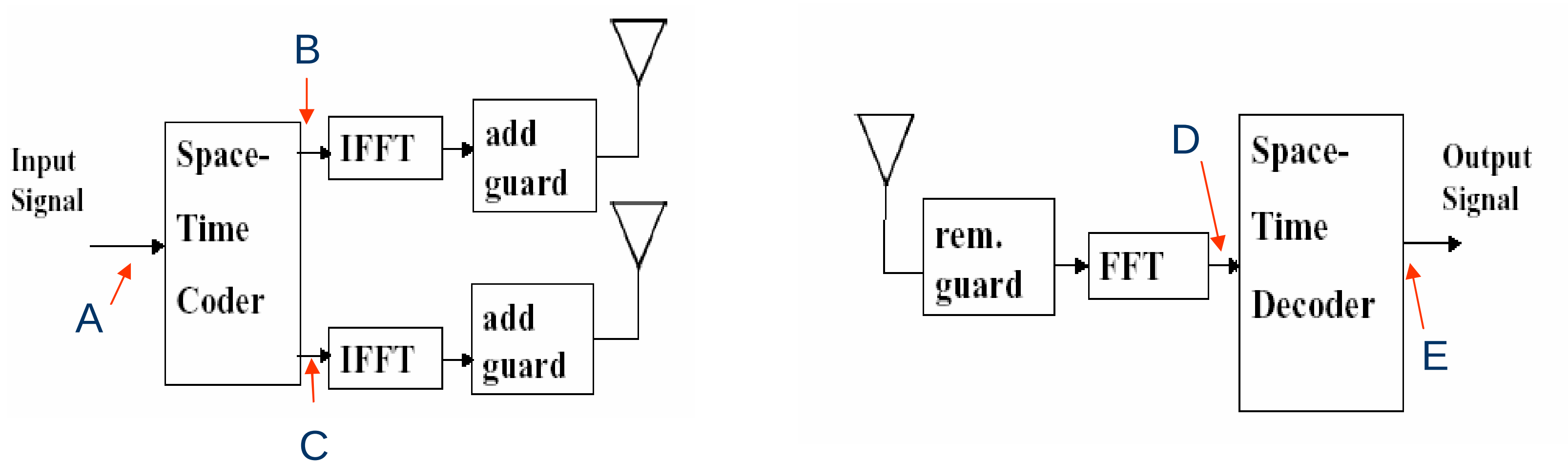
SFBC-OFDM Simulation Results - II





- STBC-OFDM is more sensitive to channel gain variation over time.
- SFBC-OFDM is more sensitive to channel gain variation over frequency.

ST(F)BC Decoding



	Time/Tone index	
	i	i+1
A	s_1	s_2
B	s_1	$-s_2^*$
C	s_2	s_1^*
D	$h_1 s_1 + h_2 s_2$	$-h_1 s_2^* + h_2 s_1^*$
E	$\|\|H[k]\|\|^2 s_1$	$\|\|H[k]\|\|^2 s_2$

[Paulraj 03]

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5. Smart Antenna Technique: Beamforming

What is a MIMO System??

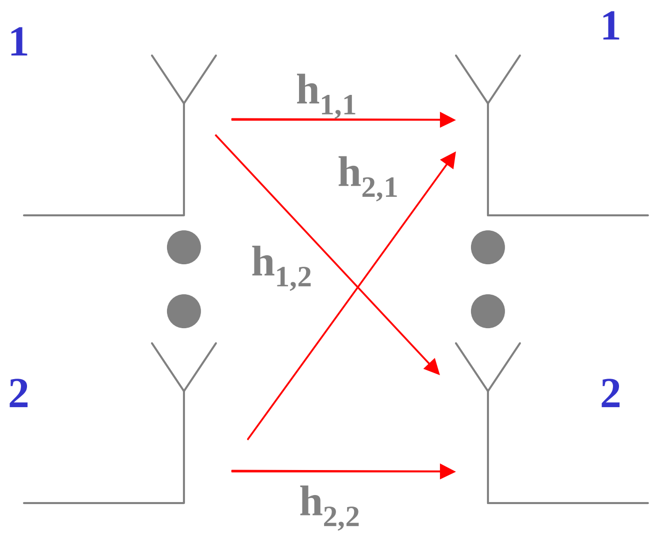
- What are MIMO systems ?

A MIMO system consists of several antenna elements, plus adaptive signal processing, at both transmitter and receiver, the combination of which exploits the spatial dimension of the mobile radio channel.

Benefits

- higher capacity (bits/s/Hz):
  - spectrum is expensive; number of BS is limited
- better transmission quality
- Increased coverage
- Improved user position estimation

Narrowband MIMO Channel Model



- Frequency flat channel model

$$H = \begin{bmatrix} h_{1,1} & h_{1,2} \\ h_{2,1} & h_{2,2} \end{bmatrix}$$

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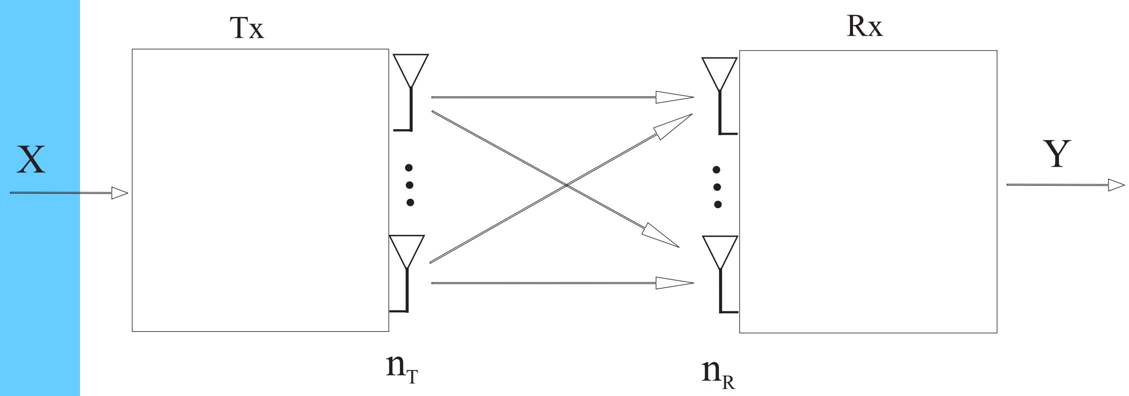
Wideband MIMO Channel Model

- Channel measurements typically show large delay spreads.
- Insufficient antenna spacing or lack of scattering cause individual antennas to be correlated.
- Geometry of Ricean component has a direct bearing on multiplexing gain.

- Broadband channel is frequency selective :

$$H(\tau) = \begin{bmatrix} h_{1,1}(\tau) & h_{1,2}(\tau) & \dots & h_{1,N_T}(\tau) \\ h_{2,1}(\tau) & h_{2,2}(\tau) & \dots & h_{2,N_T}(\tau) \\ \mathrm{M} & \mathrm{M} & \mathrm{M} & \mathrm{M} \\ h_{N_R,1}(\tau) & h_{N_R,2}(\tau) & \dots & h_{N_R,N_T}(\tau) \end{bmatrix}$$

MIMO System Model



AWGN

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

with

$$r = \begin{bmatrix} r_1 & r_2 & \dots & r_{N_R} \end{bmatrix}^T \quad \dots \; \mathrm{N}_R \times 1 \text{ receive signal vector}$$

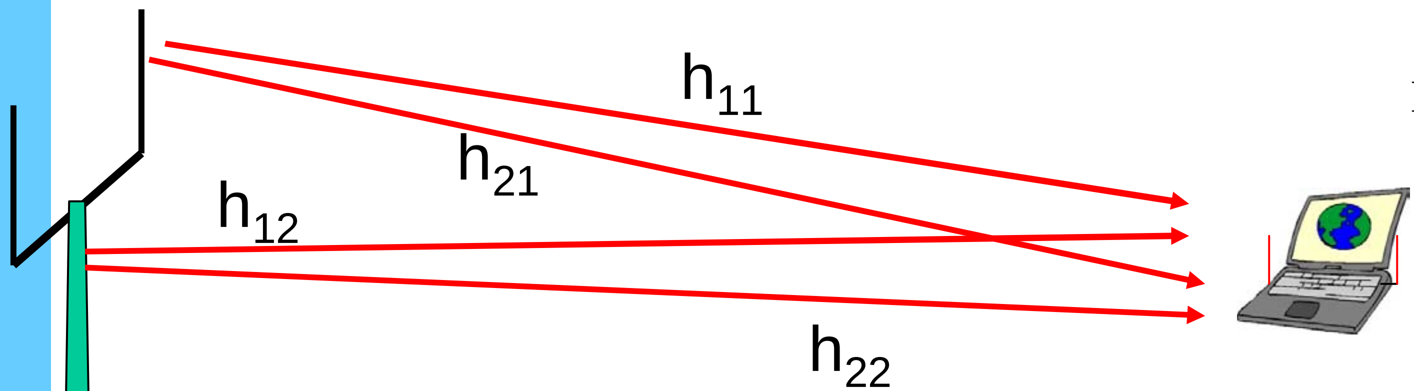
$$x = \begin{bmatrix} x_1 & x_2 & \dots & x_{N_T} \end{bmatrix}^T \quad \dots \; \mathrm{N}_T \times 1 \text{ transmit signal vector}$$

$$n = \begin{bmatrix} n_1 & n_2 & \dots & n_{N_R} \end{bmatrix}^T \quad \dots \; \mathrm{N}_R \times 1 \text{ noise vector}$$

$$\mathrm{H} \; \dots \; \mathrm{N}_R \times \mathrm{N}_T \text{ channel transfer matrix}$$

$$\text{Noise: } n_i : \; \mathrm{CN}\left(0, \sigma_R^2\right) \text{ with } \mathrm{E}\left\{nn^H\right\} = \sigma_R^2 I_{M_R}$$

Capacity of MIMO System



$$H = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$$

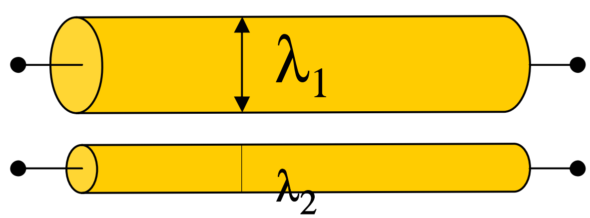
$$C_{diversity} = \log_2 \det[\mathbf{I} + (P_T/2\sigma^2)\cdot \mathbf{HH}^\dagger] =$$

$$= \log_2\left[1 + \frac{P_T}{2\sigma^2}\lambda_1\right] + \log_2\left[1 + \frac{P_T}{2\sigma^2}\lambda_2\right]$$

Where the λ_i are the eigenvalues to $\mathbf{HH}^\dagger$

Interpretation:

Transmitter



Receiver

m=min(N_R, N_T) parallel channels, equal power allocated to each "pipe"

Lecture-6 Outline:
Multi-Carrier Based Multiple Access Schemes

1. **Introduction**
2. Basics of OFDMA
3. OFDMA in Uplink
4. OFDM-CDMA
5. Discussion about Access Techniques

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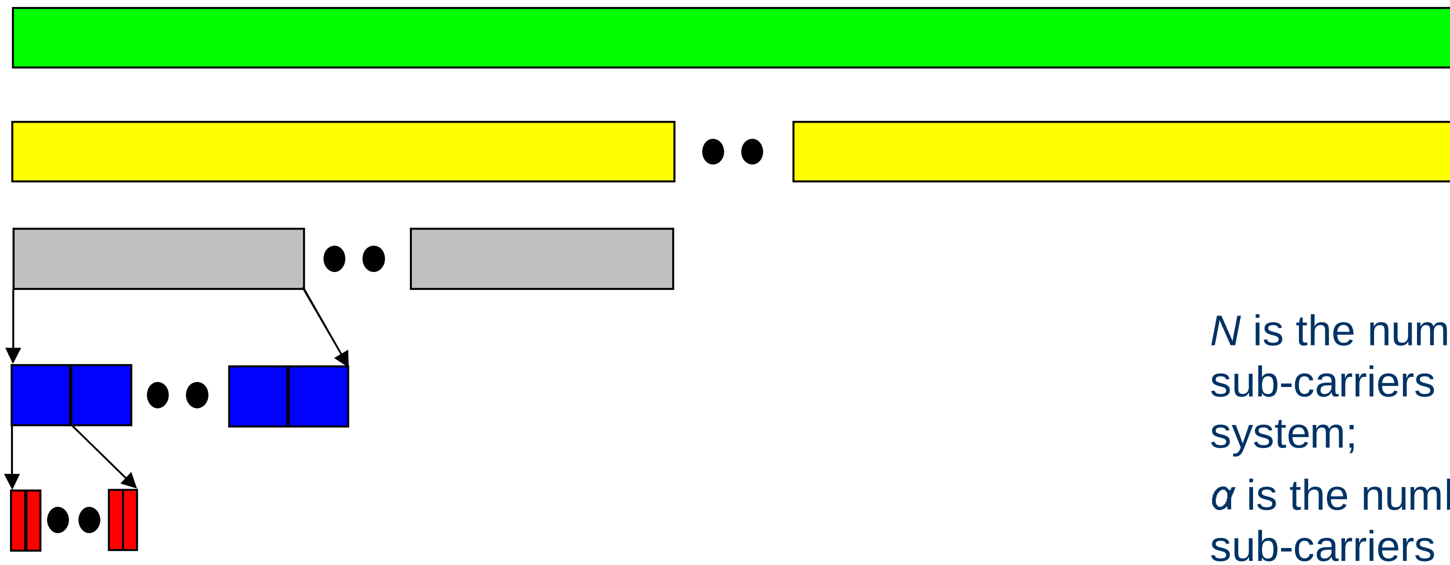
Useful Definitions



Total Available spectrum, W

OFDM system band, B, equivalent to FFT bandwidth

Sub-band bandwidth, consists of few sub-channels

Sub-channel bandwidth, $\Delta f_{sch} = \alpha * \Delta f$

Sub-carrier bandwidth, $\Delta f = B/N$

N is the number of sub-carriers in the system;

α is the number of sub-carriers in one sub-channel

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Introduction

- In recent years, OFDM has gained prominence in high data rate WLAN
- Though OFDM provides efficient transmission scheme at high data rate, it does not possess any inherent multi-user capability
- The objective of this lecture is to understand the methods to instantiate multiple access communications via the multi-carrier approach
- The concentration will be on cellular systems based on multi-carrier techniques, thus access techniques for downlink (DL) and uplink (UL) will be presented.

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Basic Multiple Access Techniques

- Multiple access schemes are used to allow many users to share simultaneously a finite amount of spectrum.
- The sharing of spectrum is required to achieve high capacity by simultaenously allocating the available bandwidth to multiple users.
- For high quality communicatios, this must be done without severe degradation in the performance of the system.
- There are many access techniques , some of them are
  - ✓ Frequency Division Multiple Access (FDMA)
  - ✓ Time Division Multiple Access (TDMA)
  - ✓ Space Division Multiple Access (SDMA)
  - ✓ Spread Spectrum Multiple Access (SSMA)
    - ✓ Code Division Multiple Access (CDMA)
    - ✓ Frequency Hope Multiple Access (FHMA)

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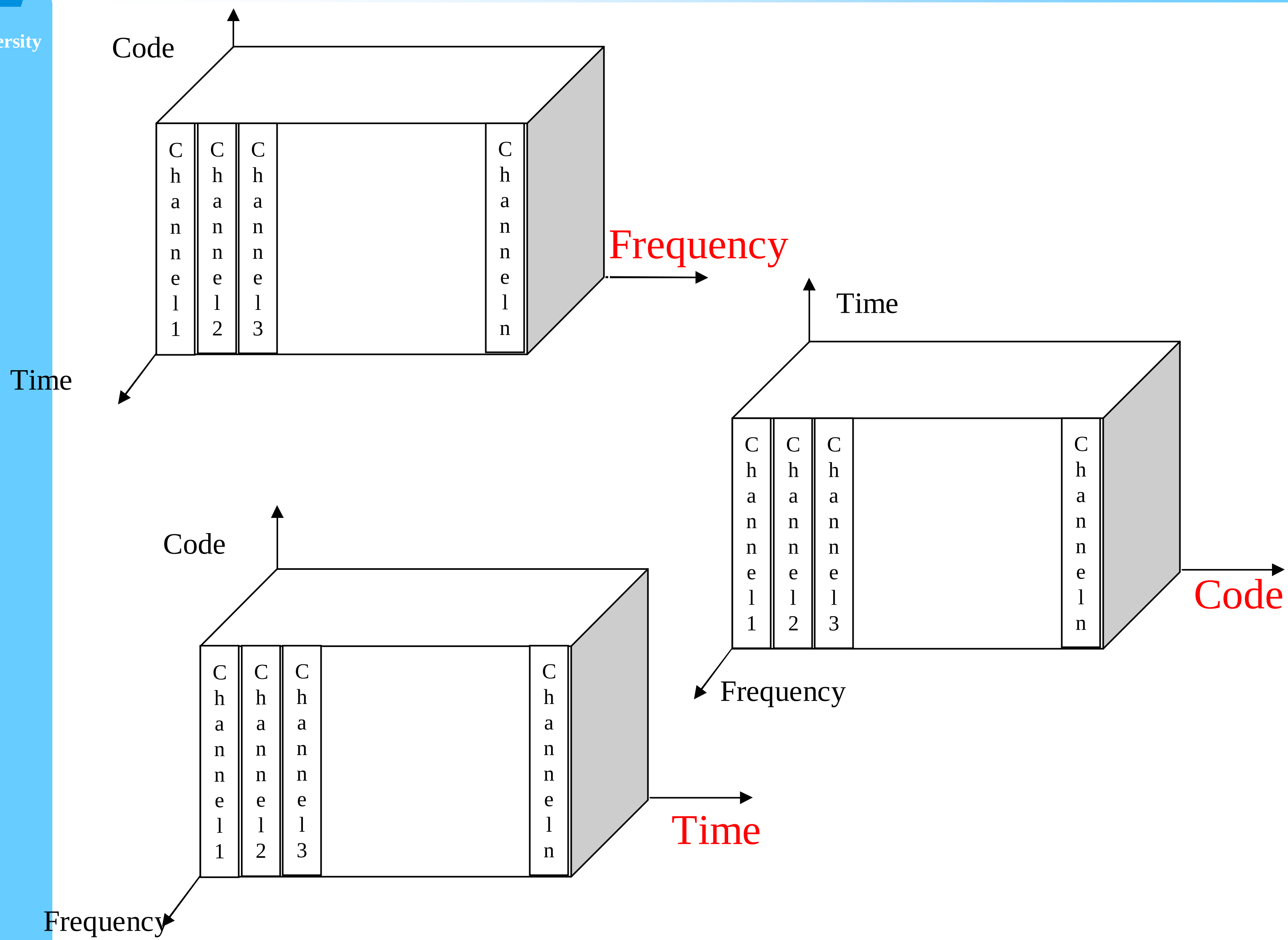
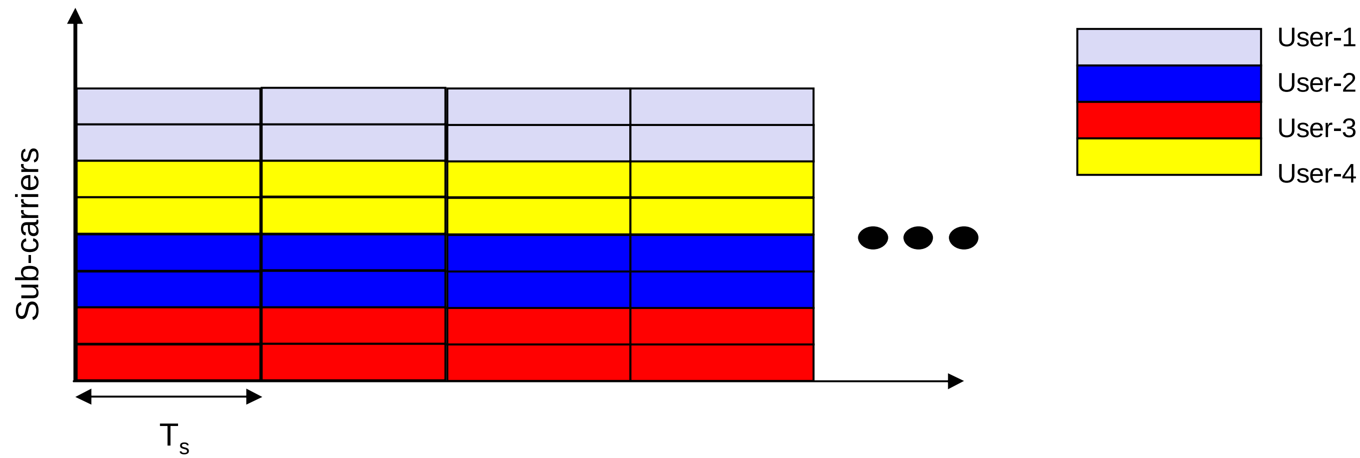
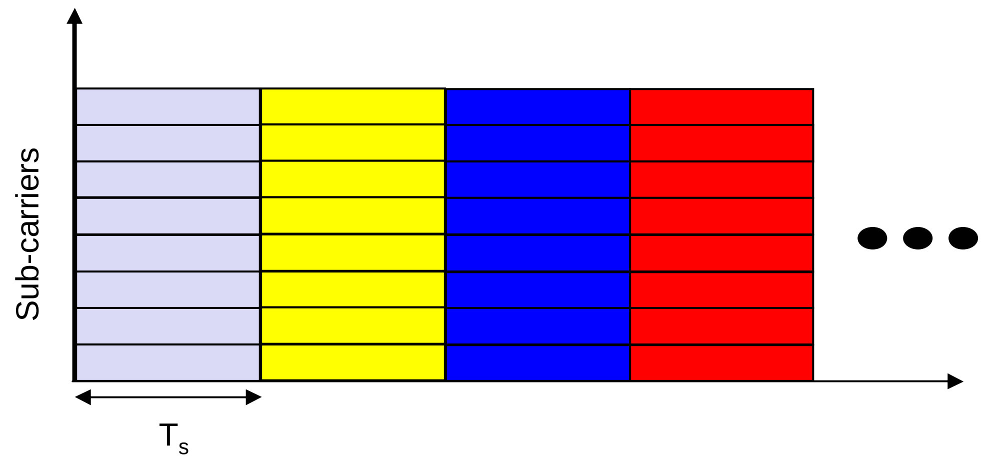
Basic FDMA, TDMA & CDMA Schemes



Basic Multiple Access in OFDM Systems (1)

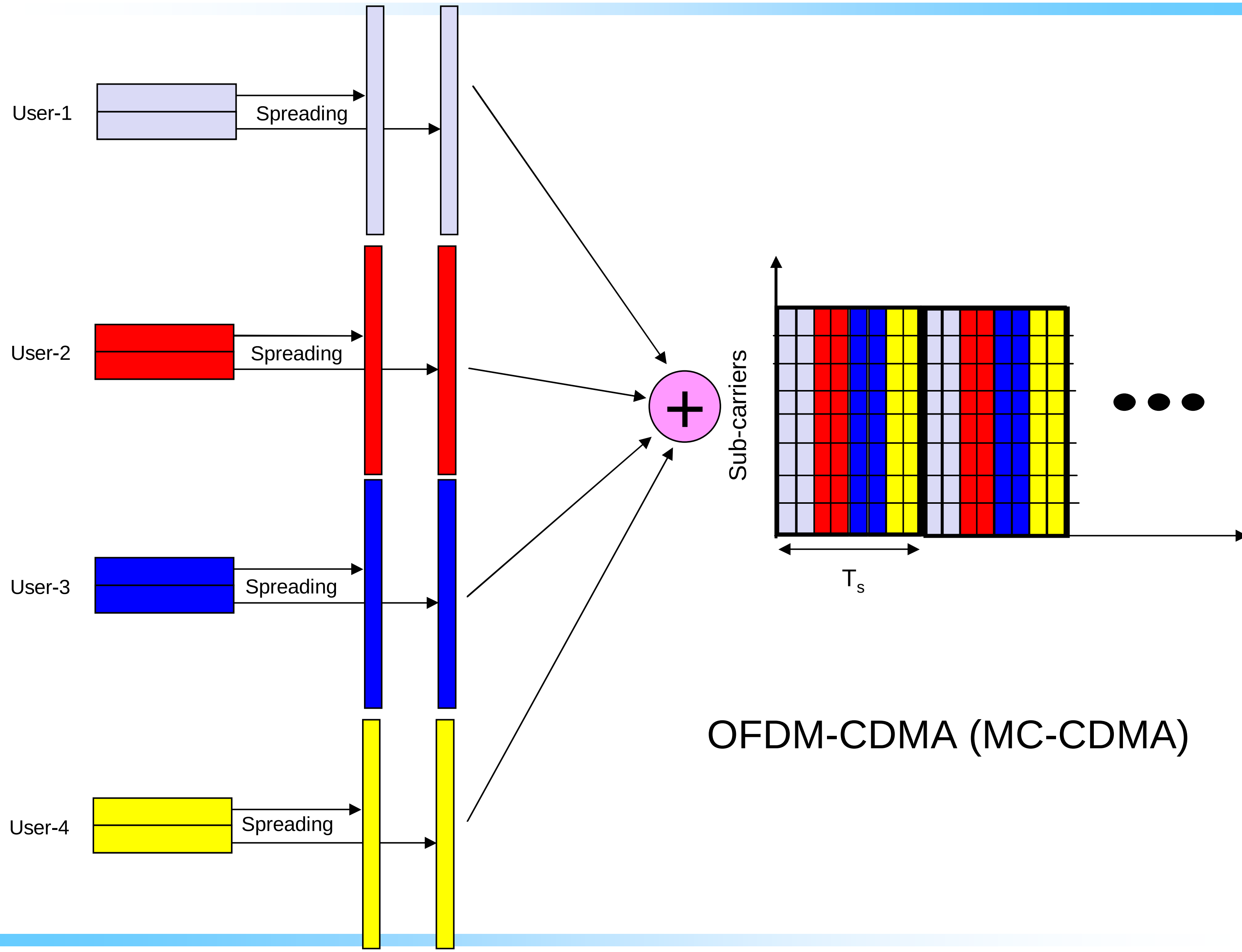


OFDMA (OFDM-FDMA)

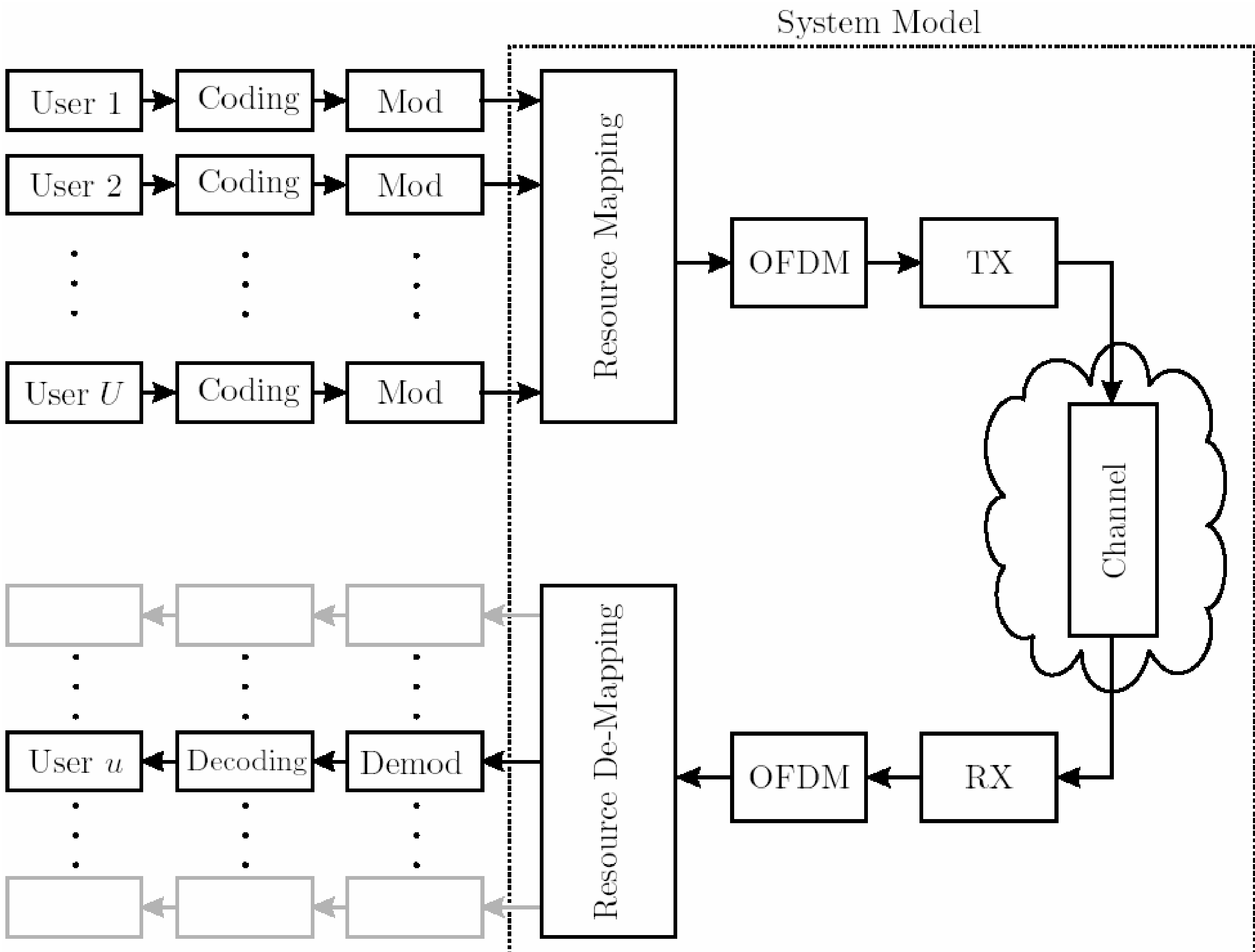


OFDM-TDMA

Basic Multiple Access in OFDM Systems (2)



Generic OFDM Based Multiple Access Model (1)



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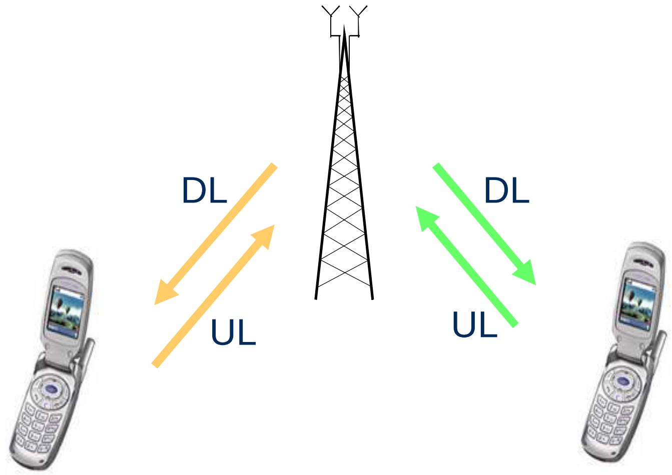
Downlink and Uplink Scenario



- One transmitter and multiple receiver in DL
- DL is similar to broadcast systems
- Several transmitters and one receivers in UL. Thus, UL is an ideal multi-access channel.
- All transmitters have unique time and frequency offset, thus, UL system design is more difficult than DL.
- For future systems, asymmetric traffic distribution between UL and DL is expected. Thus, the access technique should be able to support high data rate in DL and a moderate data rate in UL.

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Available Techniques

- For Seamless Area Coverage, Multi-cell Structure is necessary.

  ➡ **CDMA** achieves the best spectrum efficiency.

- For High Throughput, Single-cell Structure is suitable because it avoids inter-cell interference.

  ➡ **OFDM** achieves the best spectrum efficiency.

However

- Each scheme is not best in the other cell structure.

- For the flexible area coverage and service deployment with lower cost, both Multi-cell and Single-cell environments should be supported with maximum throughput.

Source:
NTT DoCoMo 2002

Need for **New Wireless Access Scheme** that covers **both environments.**

Lecture-6 Outline:
Multi-Carrier Based Multiple Access Schemes

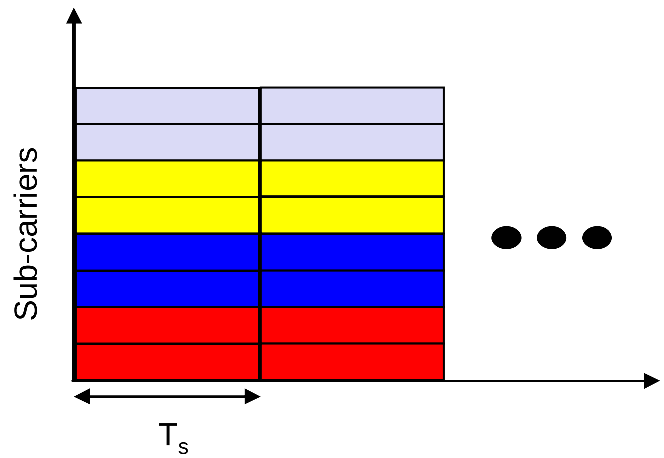
1. Introduction
2. **Basics of OFDMA**
3. OFDMA in Uplink
4. OFDM-CDMA
5. Discussion about Access Techniques

OFDMA

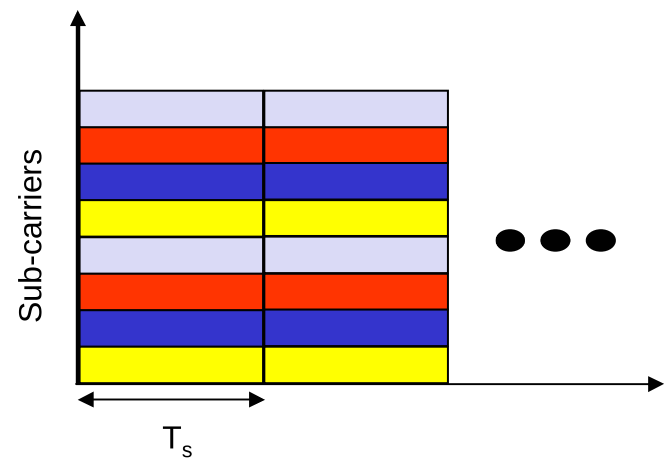
A fraction of OFDM sub-carriers is assigned to a user in a contiguous or interleaved manner

Blocked OFDMA: simple but possible throughput degradation due to channel fading

Interleaved OFDMA: attains channel diversity but there is need for 'stricter' synchronization



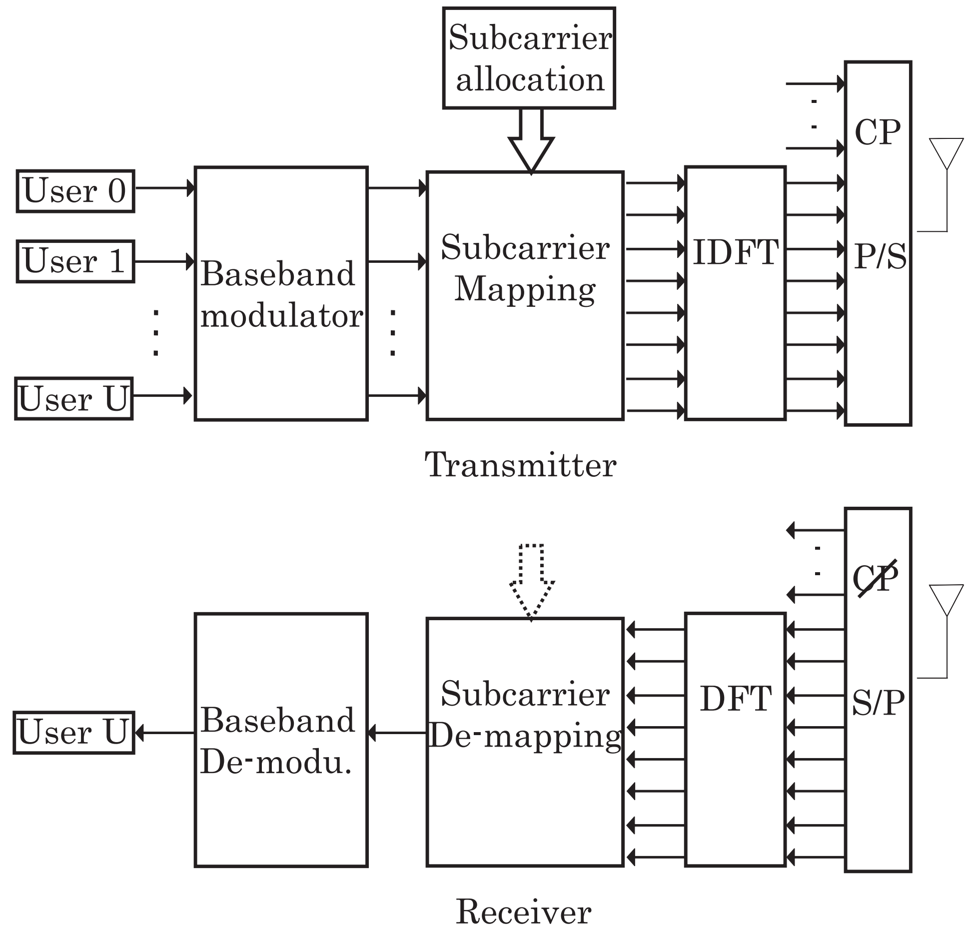
Blocked OFDMA



Interleaved OFDMA

OFDMA Transceiver Architecture

- User data is modulated with a baseband modulated scheme
- Baseband modulated symbols are assigned to sub-carriers, using the assignment map defined by the subcarrier allocation scheme, then OFDMA symbol is transmitted.
- Data of u^{th} user can be received by knowledge of the subcarrier assignment



OFDMA: Specific Features

- Very simple scheme to implement
- In downlink OFDMA has all the advantages and disadvantages of basic OFDM, with the addition of multiple access capability. Thus, a high peak data rate can be achieved in DL through OFDMA.
- In uplink time and frequency synchronization becomes important (We will discuss this later in details).
- OFDMA with high user mobility: When some of the users are moving with a high speed, then the coherence time is small and Doppler effect is severe, then special measure needs to be taken due to the relation between channel coherence time and OFDM symbol duration

Static and Dynamic Sub-carrier Allocation

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Each user can have a pre-determined set of sub-carriers for the duration of connection in Static Sub-carrier Allocation (SSA).

Alternatively, number of sub-carriers can be varied based on the current traffic, user the channel and the required user data rate to transmit in Dynamic Sub-carrier Allocation (DSA).

SSA : ☺ Simple to implement

☺ Minimal signaling overhead

☹ No frequency diversity is achieved

☹ Sub-optimal throughput, at times may be below the expected rate

DSA: ☺ Optimized throughput

☹ Channel State Information (CSI) of all the users for all sub-carriers are required in real-time.

☹ Signaling overhead is increased compared to SSA.

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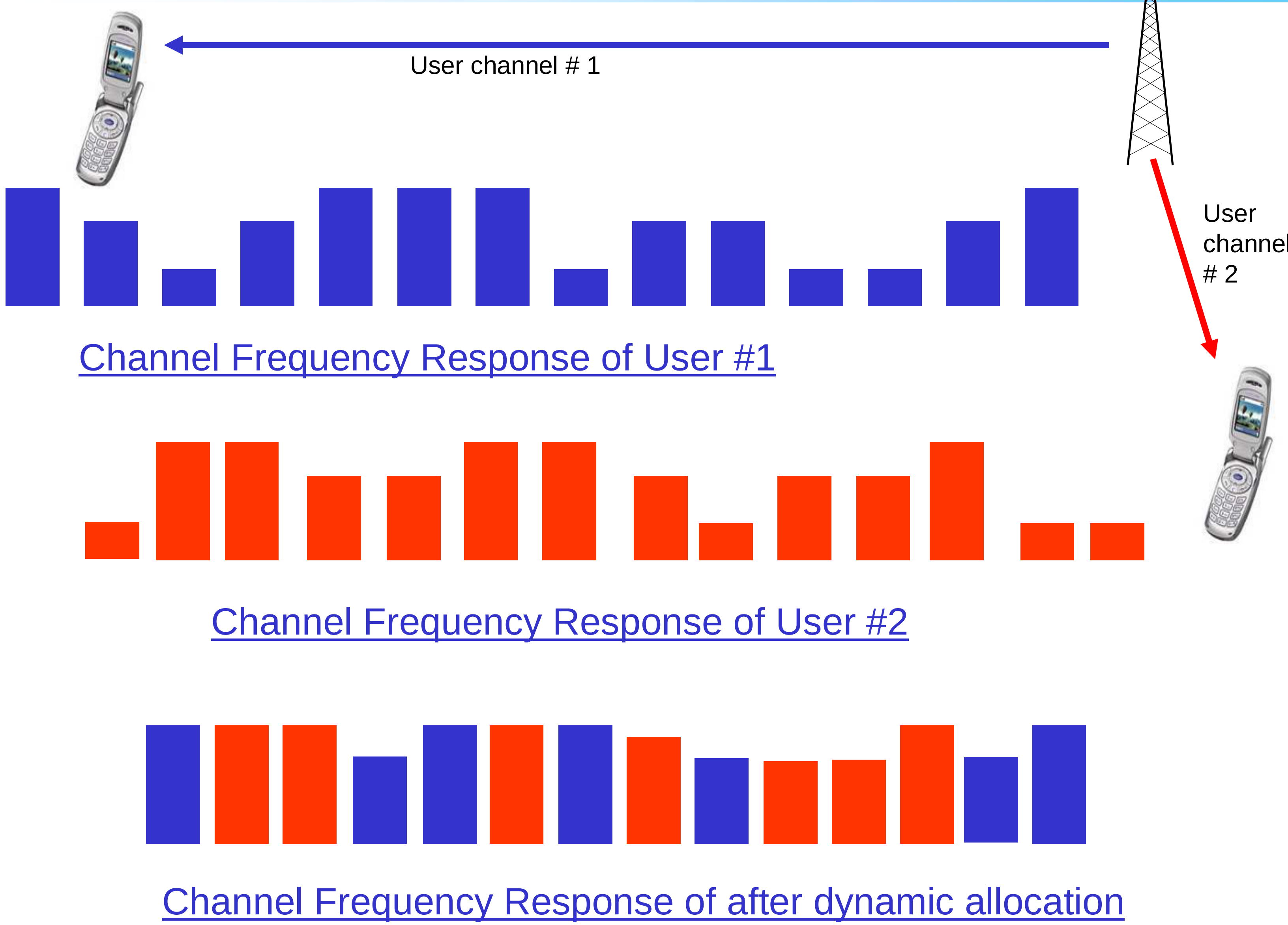
Dynamic Sub-carrier Allocation



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Dynamic Allocation Algorithm

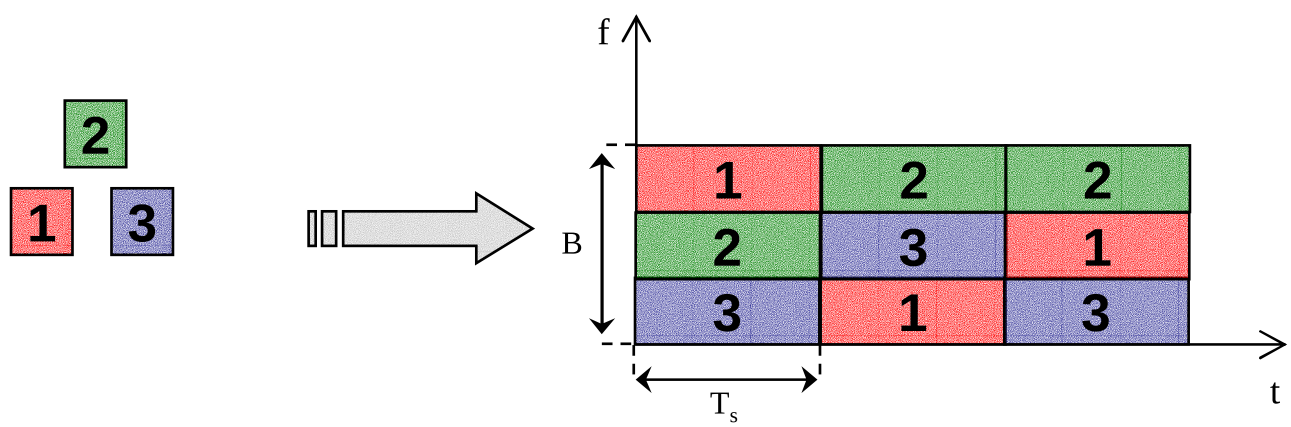
- For sub-carrier allocation specific algorithms are required at the base station to assign the sub-carriers.

- The objective functions of the allocation algorithms can be either thorough optimization or QoS or both.

- Some of the well-known algorithms are:
  - ➔ Round Robin Scheduling
  - ➔ Max C/I based Scheduling
  - ➔ Proportional Fair Scheduling

Round Robin and Max C/I in Brief

	RR	Max C/I	Mixed
User order	Random	Best Throughput	Random
Sub-channel Allocation	Random	Best Throughput	Best Throughput



Practicality of Dynamic Sub-carrier Allocation

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- DSA can be impractical especially when
  - Coherence time is very low, that the channel time variability is high
  - Large number of sub-carriers are present in DFT window
  - Large number of users require simultaneous services in the system

- This is because
  - excessive signaling is required when CSI related to large number of sub-carriers and large number of users are transmitted to BS
  - the required computation time of scheduling algorithm will be very high.

- One alternative to DSA is sub-carrier hopping.

Sub-Carrier Hopped OFDMA (SCH-OFDMA)

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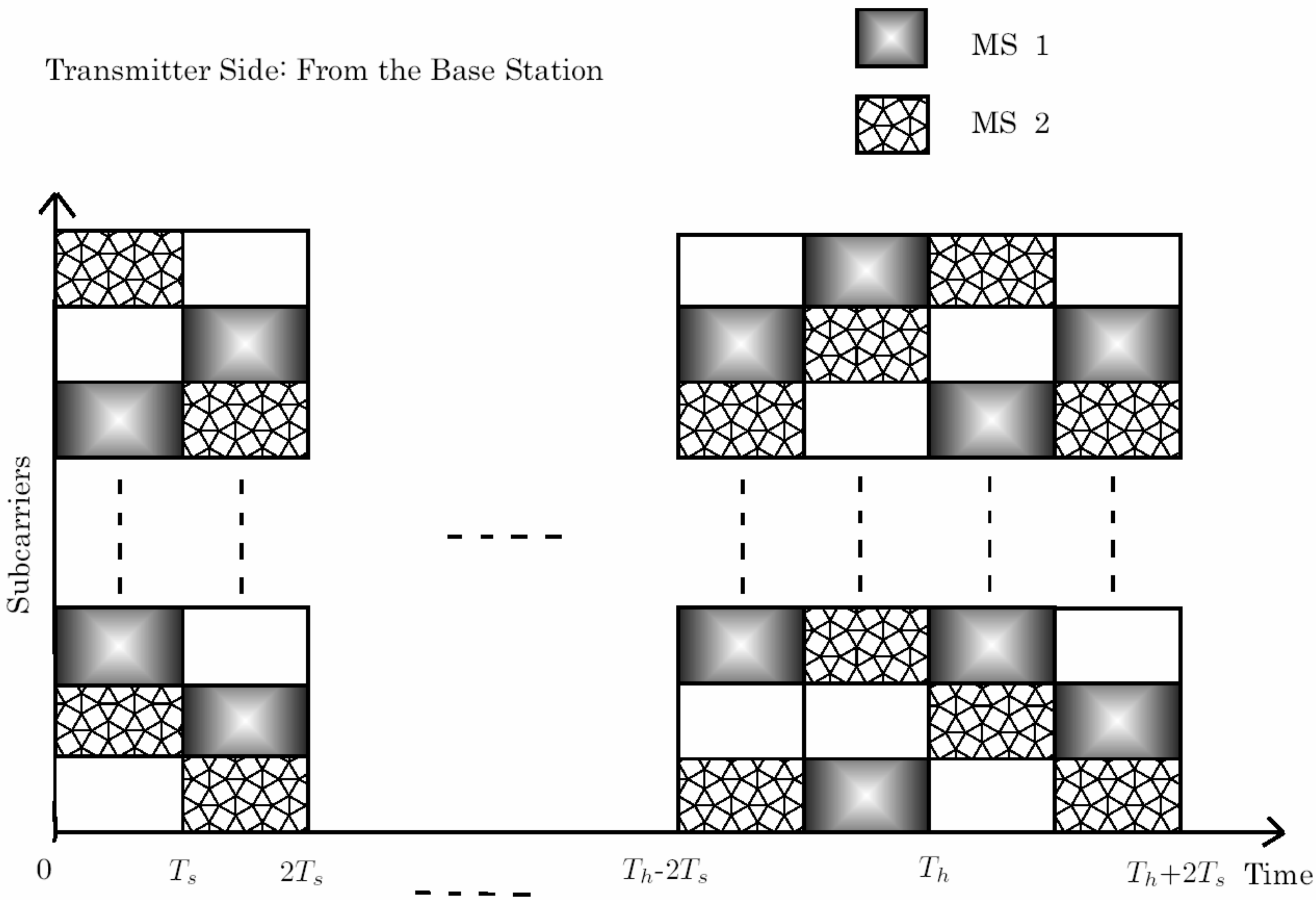
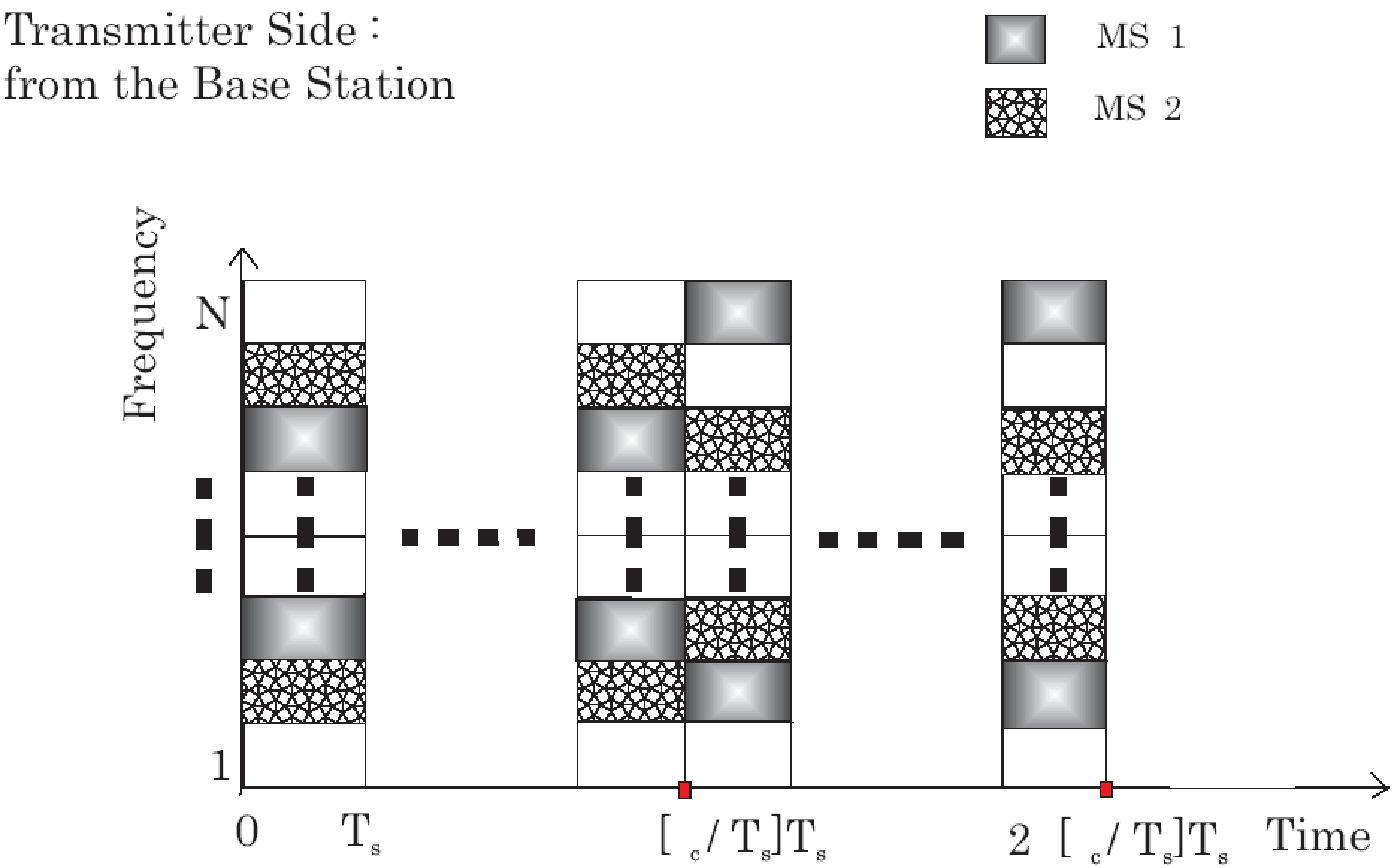
- Users hop between sub-carriers from OFDMA symbol to symbol in SCH-OFDMA.
- When users hop after every OFDMA symbol, then we call it Fast SCH-OFDMA (FSCH-OFDMA). Similarly, when users hop after some OFDMA symbols, then we call it Slow SCH-OFDMA.
- Using SCH-OFDMA
  - Minimizes the inter-cell interference
  - Averages the impact of fading among users
  - Does not require CSI for sub-carrier allocation anymore.
  - Near Far resistance
- Definitely, the throughput is reduced compared to dynamic allocation with the knowledge of CSI, but greatly enhanced compared to static allocation

Time- Frequency Diagram of FSCH-OFDMA



Time- Frequency Diagram of SSCH-OFDMA



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SCH-OFDMA: Specific Features

- Orthogonal hopping sequences used among users
  - ➔ no Intra-cell interference
- Each BS has an orthogonal hop-set compared to neighboring cells
  - ➔ Inter-cell interference can be prevented
- Orthogonal sub-carriers and perfect synchronization
  - ➔ no ICI within each cell
- If CP larger than maximum excess delay ➔ no ISI
- If $T_s < T_c$, then sub-carrier indices allocated to each user change faster than the channel, then the '*bad*' sub-carriers are distributed among users
  - ➔ error rate of each user is reduced

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Choosing Hopping Rate

Since in outdoor coherence time is smaller than in indoor, SSCH tends to coincide with FSCH

Receiver has to hop synchronously with the transmitter to recover the transmitted information

In DL it is easier to synchronize compared with UL, since in the DL transmissions experience a single common channel to reach a user, while in UL there are several channels from users to the BS

SSCH has lower signaling complexity for synchronization than FSCH, since hops occur less frequently

SCH-OFDMA Based System: Flash OFDM

- "Fast Low-latency Access with Seamless Handoff (FLASH) OFDM'' proposed by Flarion Inc.
- Flash-OFDM uses FSCH in the downlink and SSCH in the uplink.
- Approved in IEEE 802.16a WMAN and under consideration in IEEE 802.20 system.

Carrier frequency	≤ 3.5 GHz
Channel bandwidth	1.25 MHz
Sub-carrier separation	11.25 kHz
Available sub-carriers	113
Symbol duration	100 μs
Cyclic prefix duration	11.1 μs
Baseband modulation	QPSK or 16-QAM
DL Data rate	>4Mbps
UL Data rate	>800kbps
SSCH in UL	Once every 7 symbols

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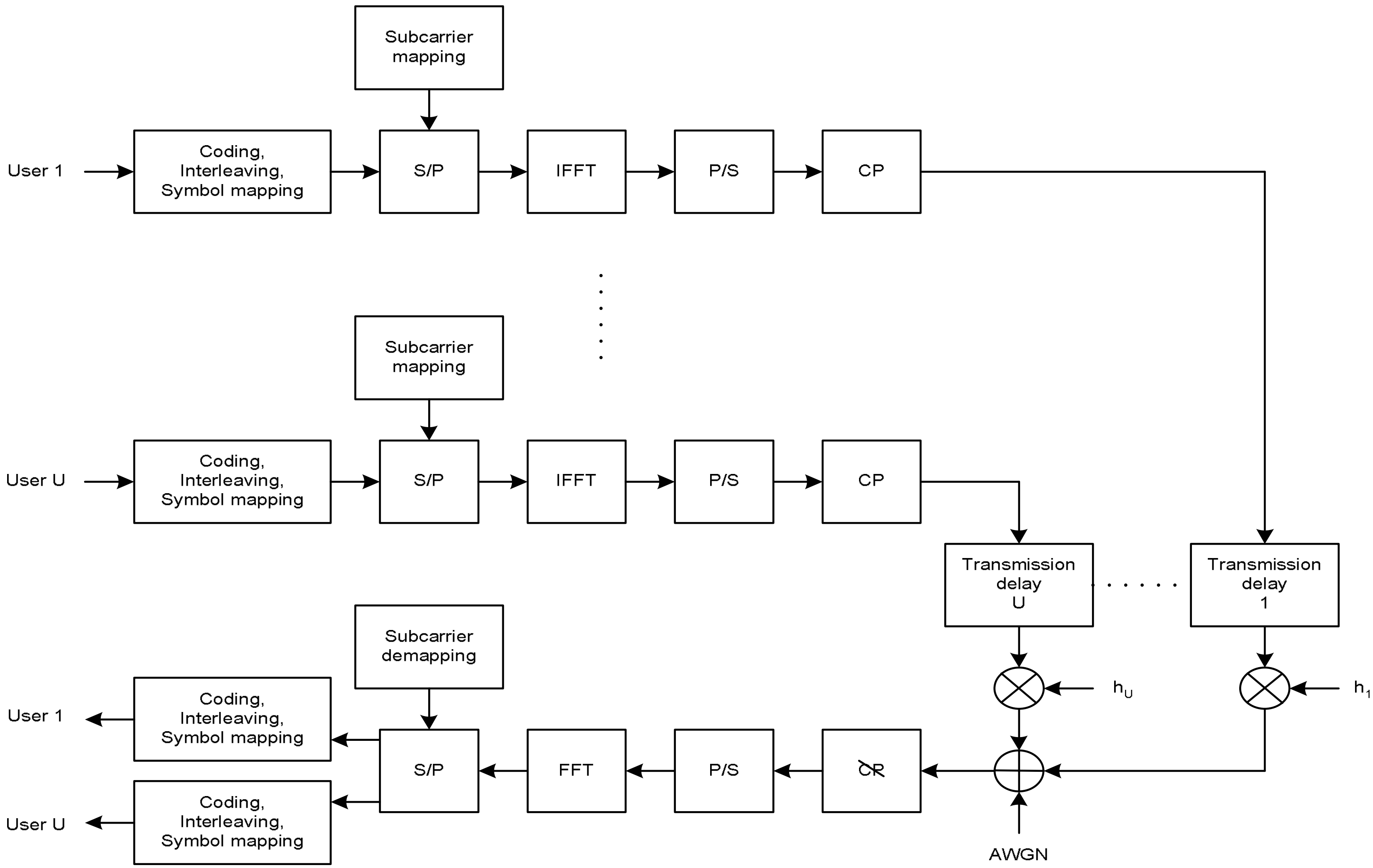
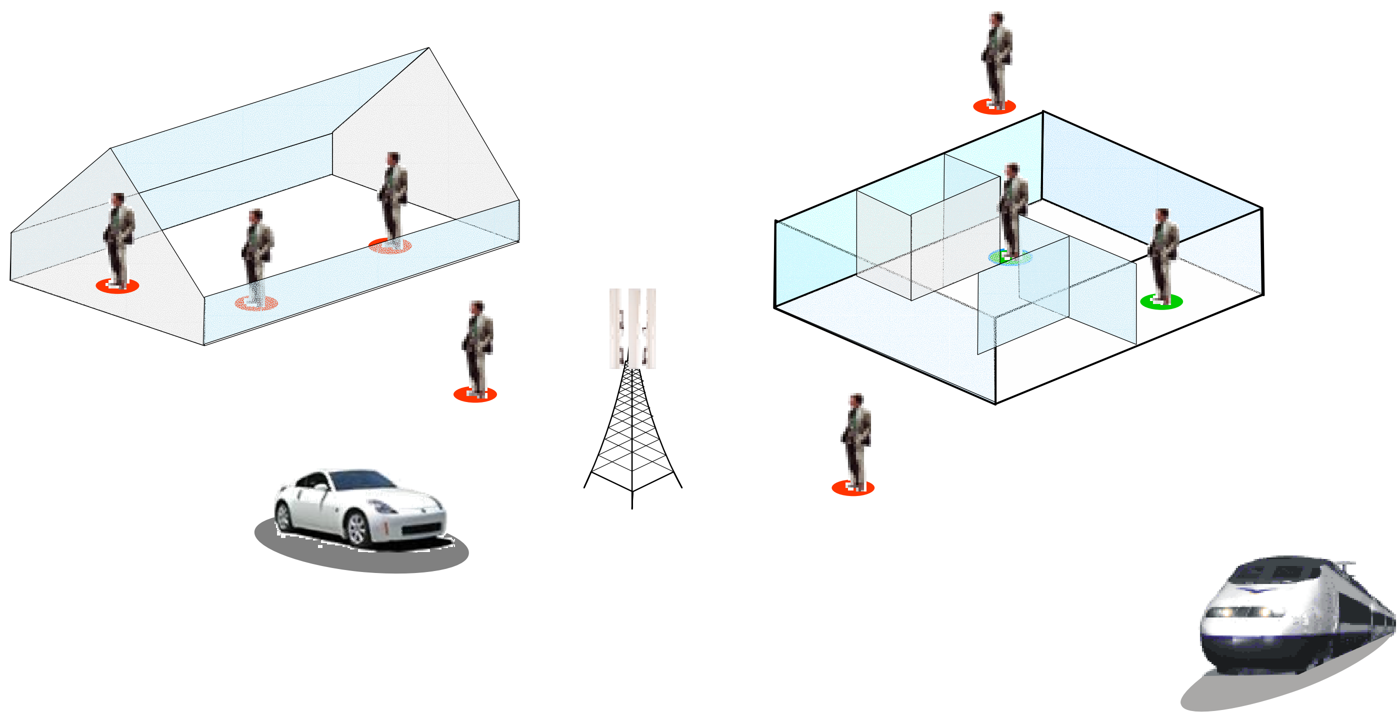
Lecture-6 Outline:
Multi-Carrier Based Multiple Access Schemes

1. Introduction
2. Basics of OFDMA
3. **OFDMA in Uplink**
4. OFDM-CDMA
5. Discussion about Access Techniques

Conventional System Model for Uplink OFDMA



Typical User in Wide Area Cellular Systems



- ❑ Different types of wireless channel, i.e. different coherence time and coherence bandwidth is expected from different user
- ❑ The physical distance of a user can be very large in large cells

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OFDMA Uplink Scenario

- Users are transmitting from distant locations to BS with
  - different timing offset (DFT window de-synchronization)
  - different carrier frequency offset (oscillator mismatch)
  - different Doppler frequency (due to user motion)
- Carrier frequency offset = MS oscillator offset + BS oscillator mismatch and total frequency offset = carrier frequency offset + Doppler spread
- Timing offset = f(maximum delay spread, propagation path delay)
- These offsets are unique to all users, and each user’s offset needs to be resolved separately.

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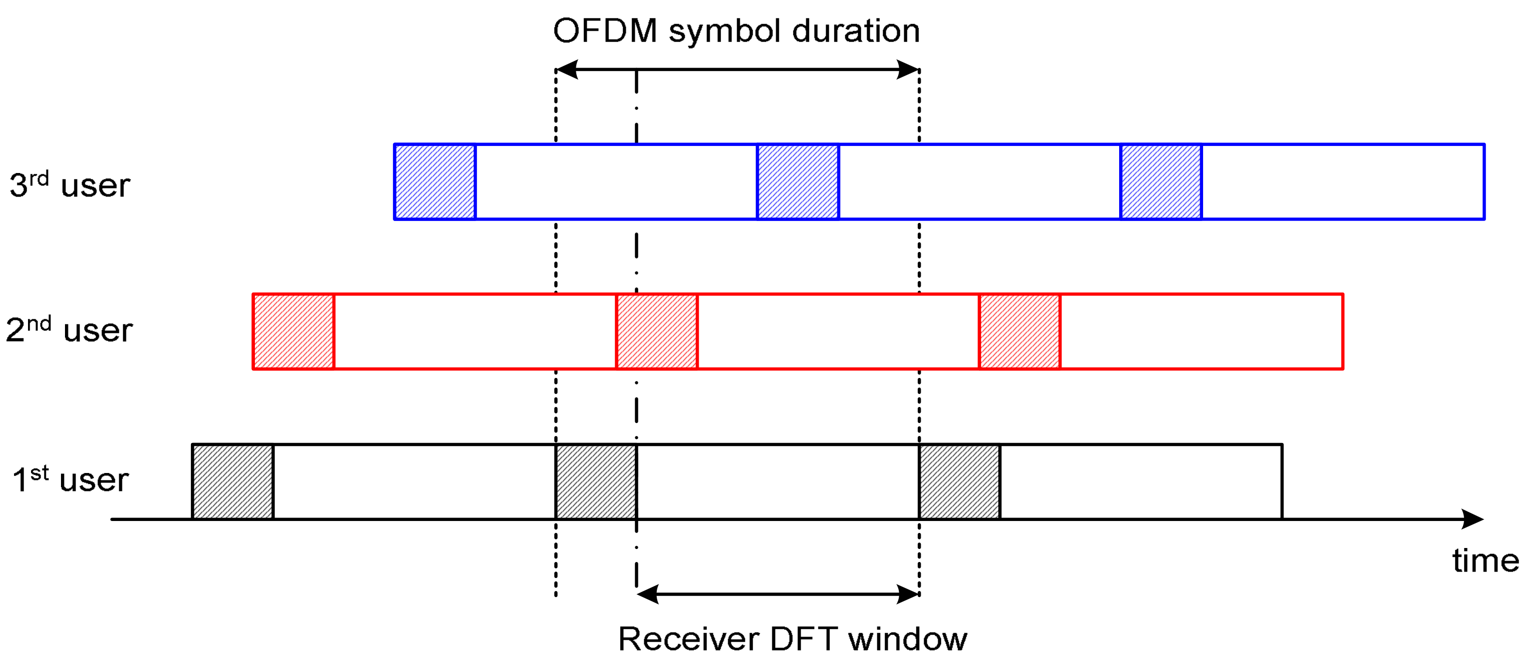
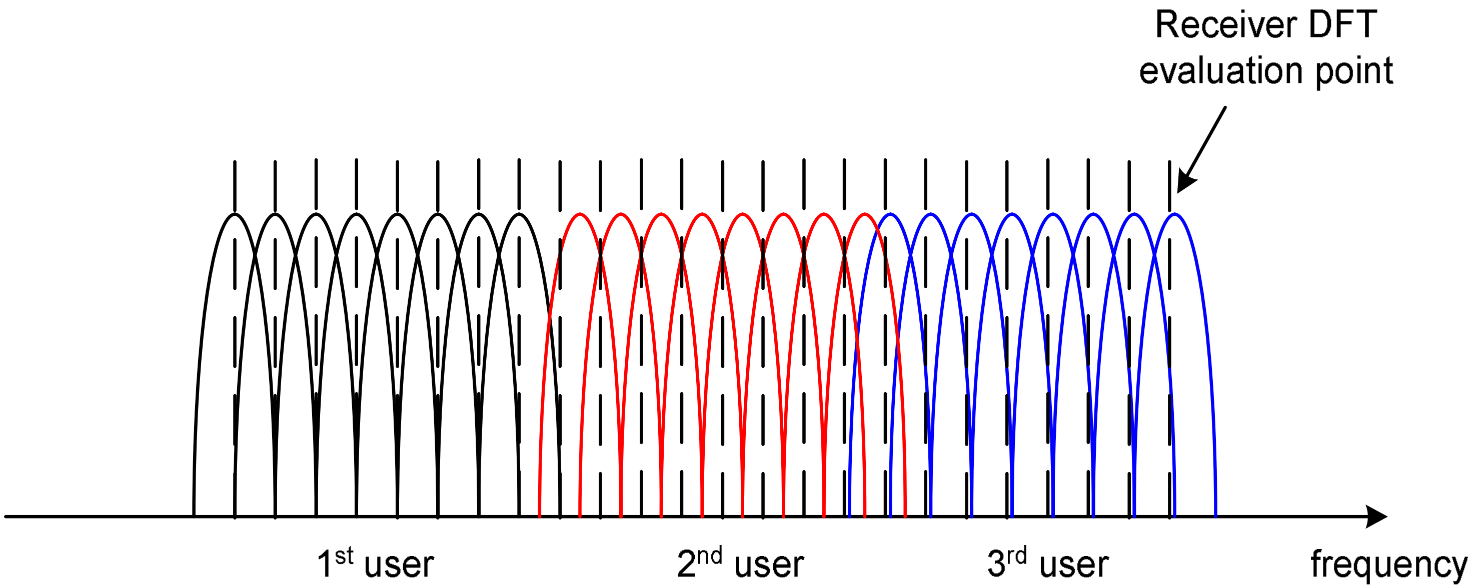
Timimg Synchronization

- All incoming signals must be aligned with BS's FFT window, otherwise both ICI and ISI are introduced
- The relatively different delays between incoming signals reduce OFDM's robustness to delay spread
- Multiuser timing synchronization is not always possible



Frequency Synchronization in Uplink



- Each MS experiences different frequency error and Doppler spread, which resulted in different frequency offset
- Frequency offset can cause ICI and MUI at the receiver, and also reduce the received power
- Frequency offset correction for all users is not possible, as correction for one would misalign the others

Some Known Solutions for Uplink OFDMA Issues

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Increasing the CP interval to account for differential delays:

→ Induce SNR loss and reduce system throughput

Timing and frequency synchronization is done at MS:

- BS performs estimation and sends feedback information to MS,
- MS adjusts its timing and frequency base to account for the mis-matches,

→ Require established connection between MS and BS, which is not applicable in some scenarios (e.g. random access)

Multi-user detection and separation before individual time- and frequency-estimation and correction

- Work for both contiguous and non-contiguous subcarrier allocation schemes

→ However, this method require much more processing power at BS for multi-user detection, separation and decoding

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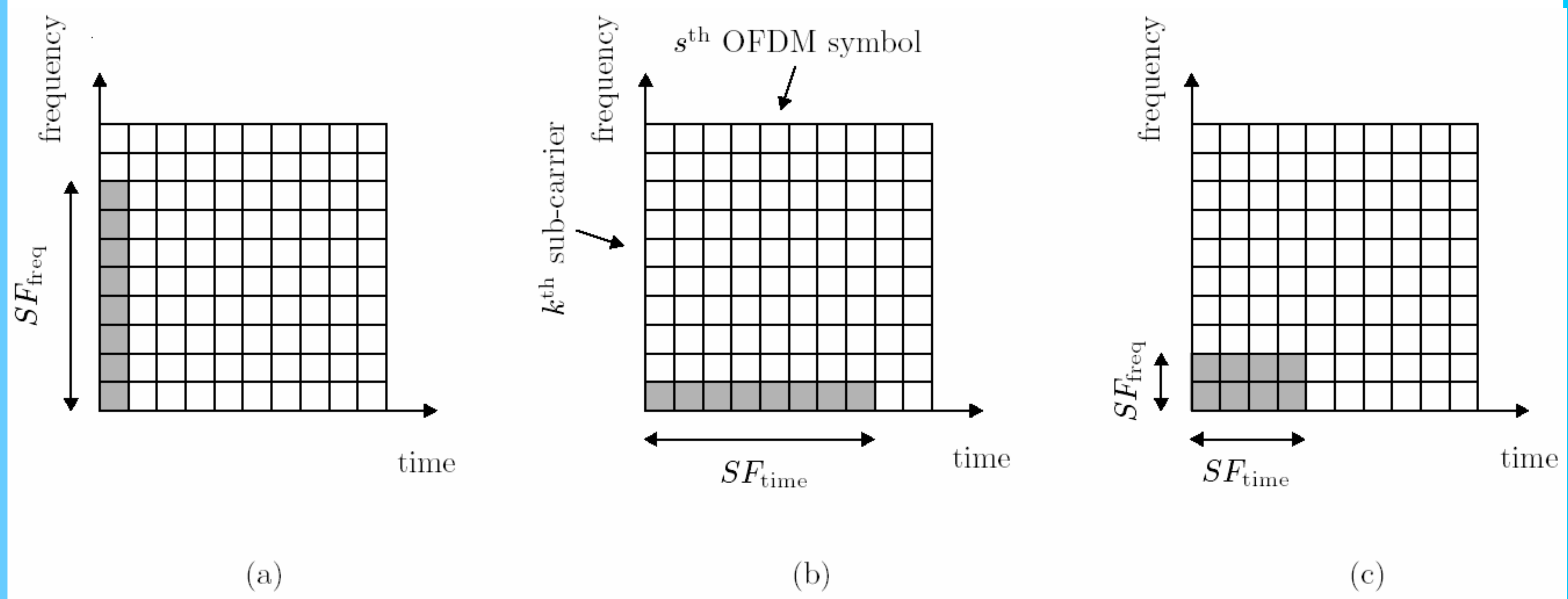
OFDM-CDMA: Main Idea (1/2)

- OFDM overcomes ISI effect of multi-path frequency selective wireless channel, while CDMA provides frequency diversity and multi-user access scheme
- The idea of sharing time, frequency and energy between different users can be depicted in the figures



(a) Frequency-domain spreading; (b) Time-domain spreading; (c) Time-Frequency localized spreading, all with SF=8

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OFDM-CDMA: Main Idea (2/2)

- Only time and frequency domain in the figure. Each data symbol is spread either in frequency domain, or time domain or in both. Coding plane is not shown for clarity.

- In figure, spread chips of a symbol occupy contiguous sub-carriers. In practice, chips of different symbols can be interleaved to achieve frequency diversity.

- At the very first phase in 1993, three slightly different schemes were independently proposed:
  - MC-CDMA (Yee, Linnartz, Fettweis, and others)
  - Multi-Carrier DS-CDMA (DaSilva and Sousa)
  - Munti-Tone CDMA (Vandendorpe)

- Number of symbols to be transmitted in one OFDM symbol is an implementation issue, related to traffic load, system requirement and transmission scenario.

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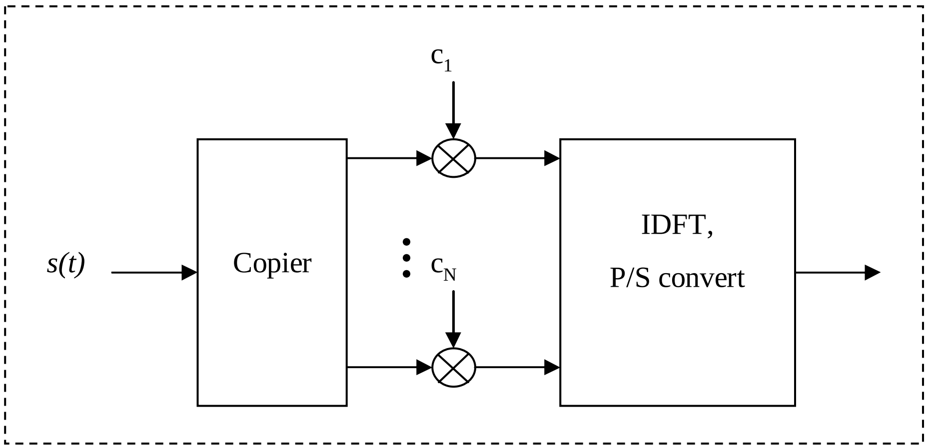
MC-CDMA (Multi-Carrier CDMA)

- MC-CDMA implements frequency domain spreading via orthogonal codes, thus, several users transmit over the same subcarrier. The transmitter spreads the data, then modulates a different subcarrier with each chip, thus spreading in frequency domain is realized.
- MC-CDMA has been so far hailed to be a very efficient in DL. Asynchronous UL has a severe effect on orthogonal codes
- If $c(t)=[c_1, c_2, \ldots, c_N]$ represents the spreading code for an arbitrary user, the transmitter structure is:



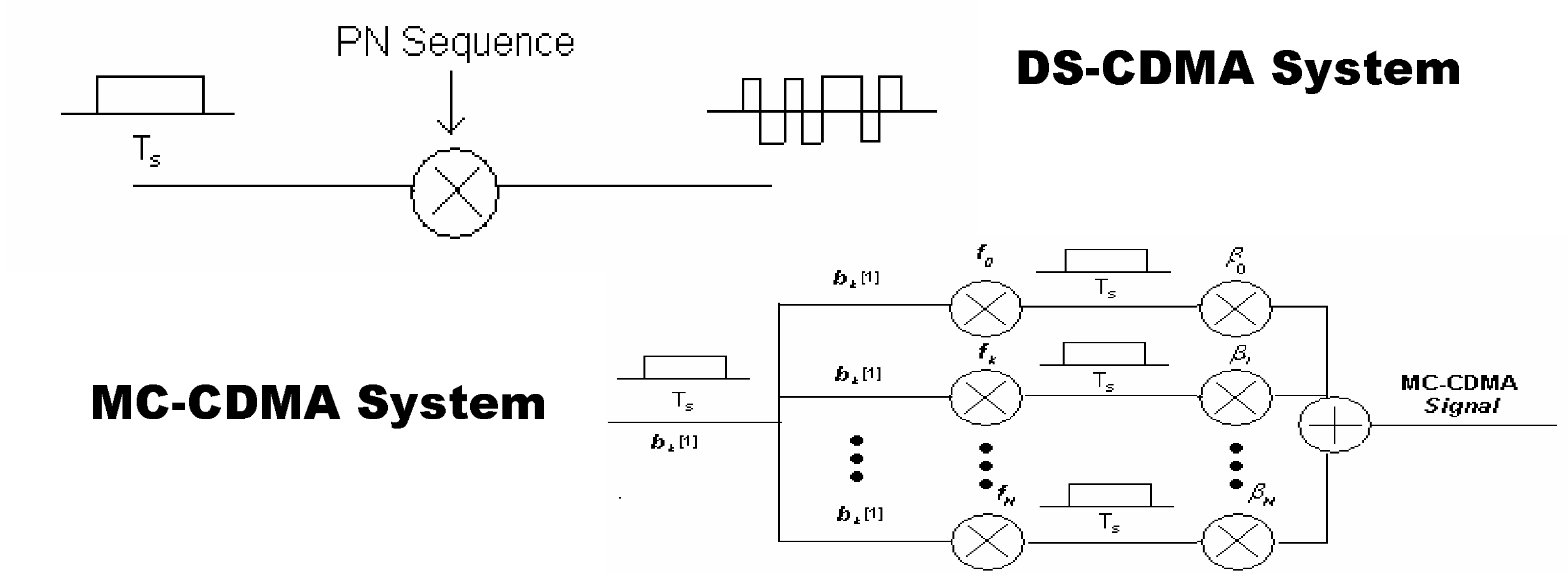
DS-CDMA and MC-CDMA

MC-CDMA has similar structure as DS-CDMA except:

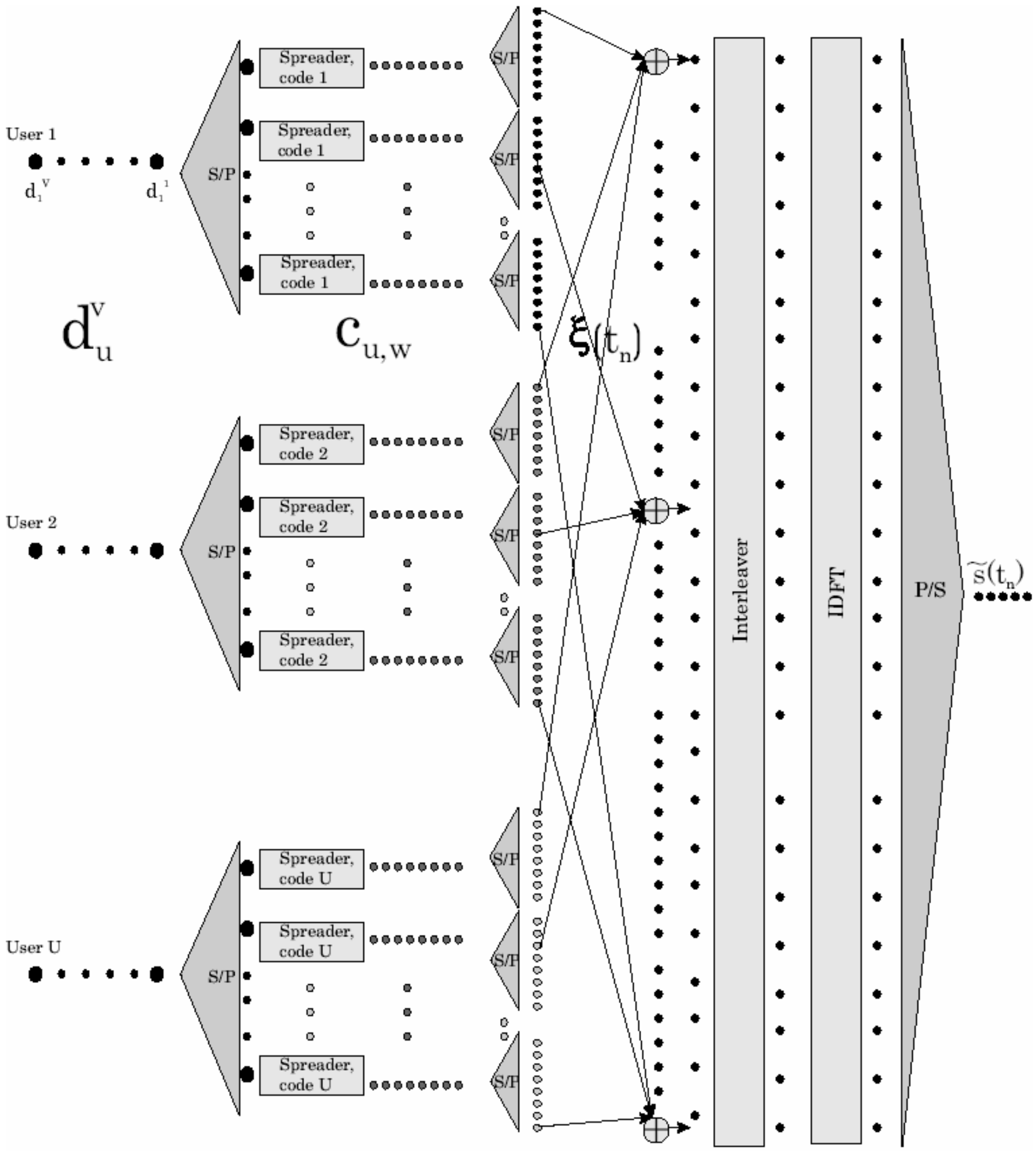
- ❑ Spreading codes is applied in frequency domain.
- ❑ Signal is transmitted over several sub-carriers that constitute the entire spectrum. Therefore, same amount of bandwidth is used for both the system

Since spreading codes is applied in frequency domain, information bits are not chopped into smaller chips.

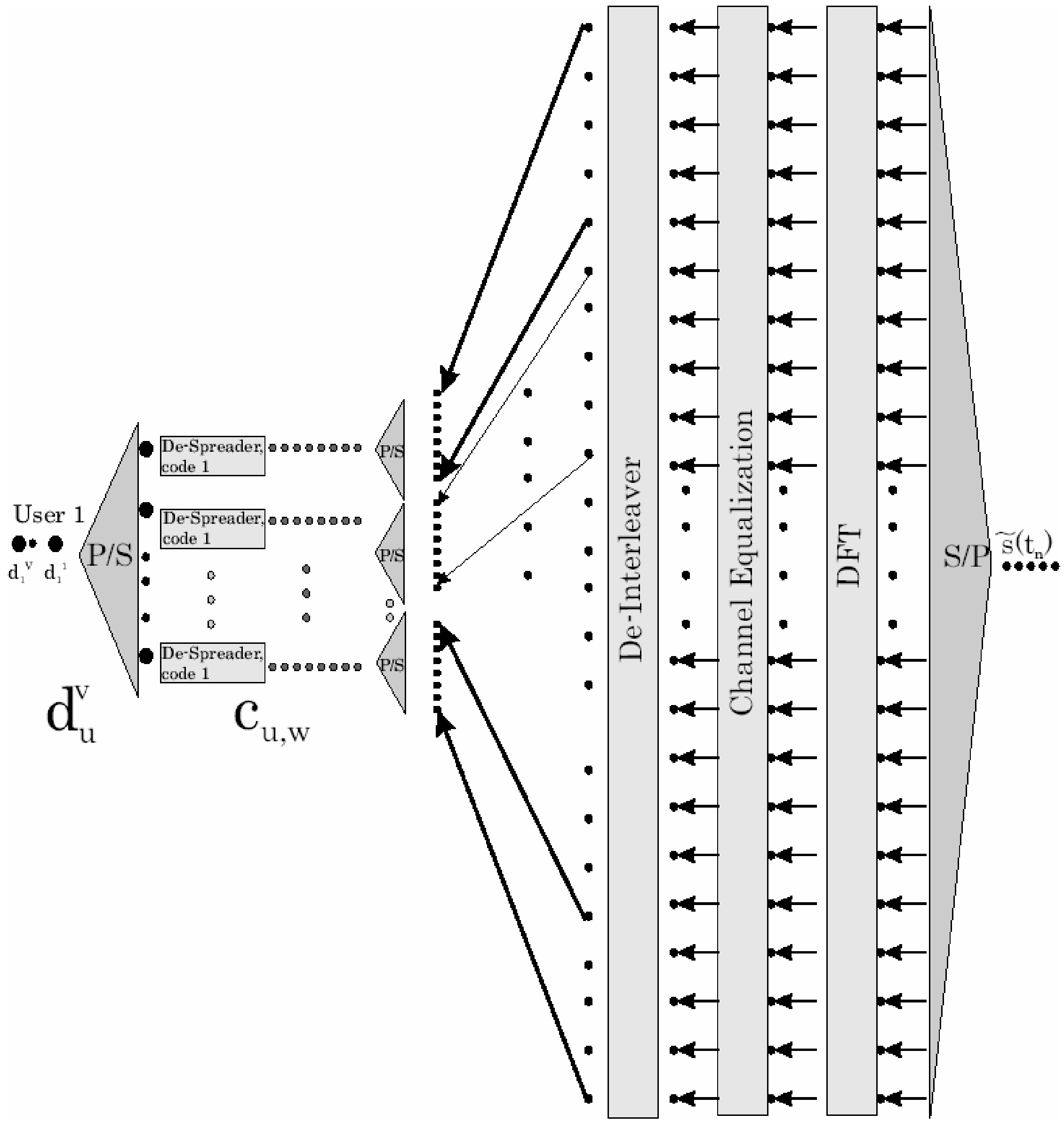
Therefore, the each bit is longer than the chip in DS-CDMA system. So, MC-CDMA is less sensitive to the channel coherence bandwidth.



Downlink MC-CDMA Transmitter



Downlink MC-CDMA Receiver



MC-CDMA: Specific Features

- It is one of the candidates that can be used as one of the future DL access schemes, since it provides high frequency diversity, low complex equalization and high spectral efficiency
- Variation of the scheme: OFDMA-CDM ➔one user is given a set of sub-carriers. All the data symbols that the user has to transmit are spread and transmitted over those sub-carriers only.
- OFDMA-CDM does not introduce MAI as MC-CDMA does, but it introduces self-interference, it can be a viable scheme for UL in small indoor scenarios
- OFDMA-CDM with Frequency Hopping avoids near far effect or asynchronous transmission (might be OK for UL)

Time Domain Spreading and Multi-carrier Modulation

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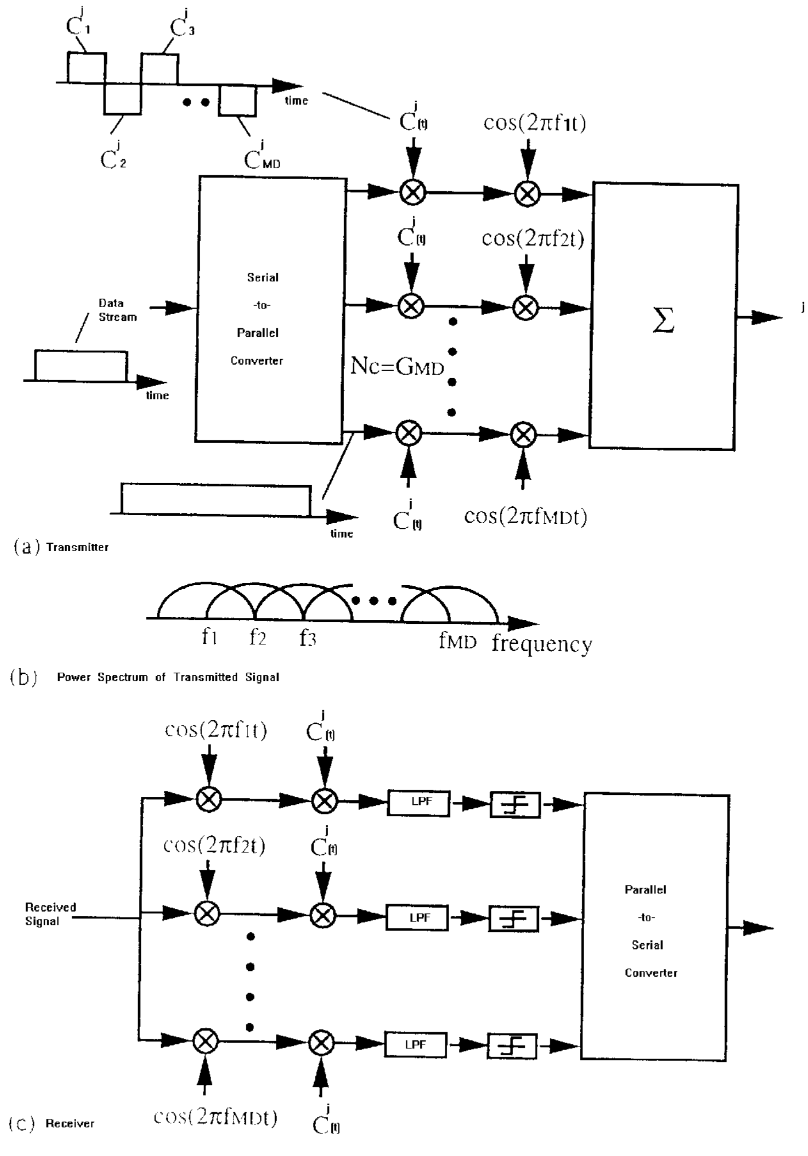
- Two schemes that combines time domain spreading on multi-carrier modulation are:
  - Multi-Carrier DS-CDMA Scheme
  - Multi-Tone CDMA Scheme

- Multi-Carrier DS-CDMA transmitter spreads the serial-to-parallel(S/P)-converted data streams using a given spreading code in the time domain so that the resulting spectrum of each subcarrier satisfies the orthogonality condition with the minimum frequency separation. This scheme can lower the data rate in each subcarrier so that a large chip time makes it easier to synchronize the spreading sequences.

- The MC-DS-CDMA scheme is originally proposed for a uplink communication channel, because this characteristic is effective for the establishment of a quasi-synchronous channel.

Multicarrier DS-CDMA



- Spreads the S/P converted data, then modulates a different subcarrier with each stream (spreading in time domain).
- If $c(t)=[c_1, c_2, \ldots, c_N]$ represents the spreading code for an arbitrary user, the transmitter structure is shown in the figures.
- In the receiver, DFT demodulation can be used.

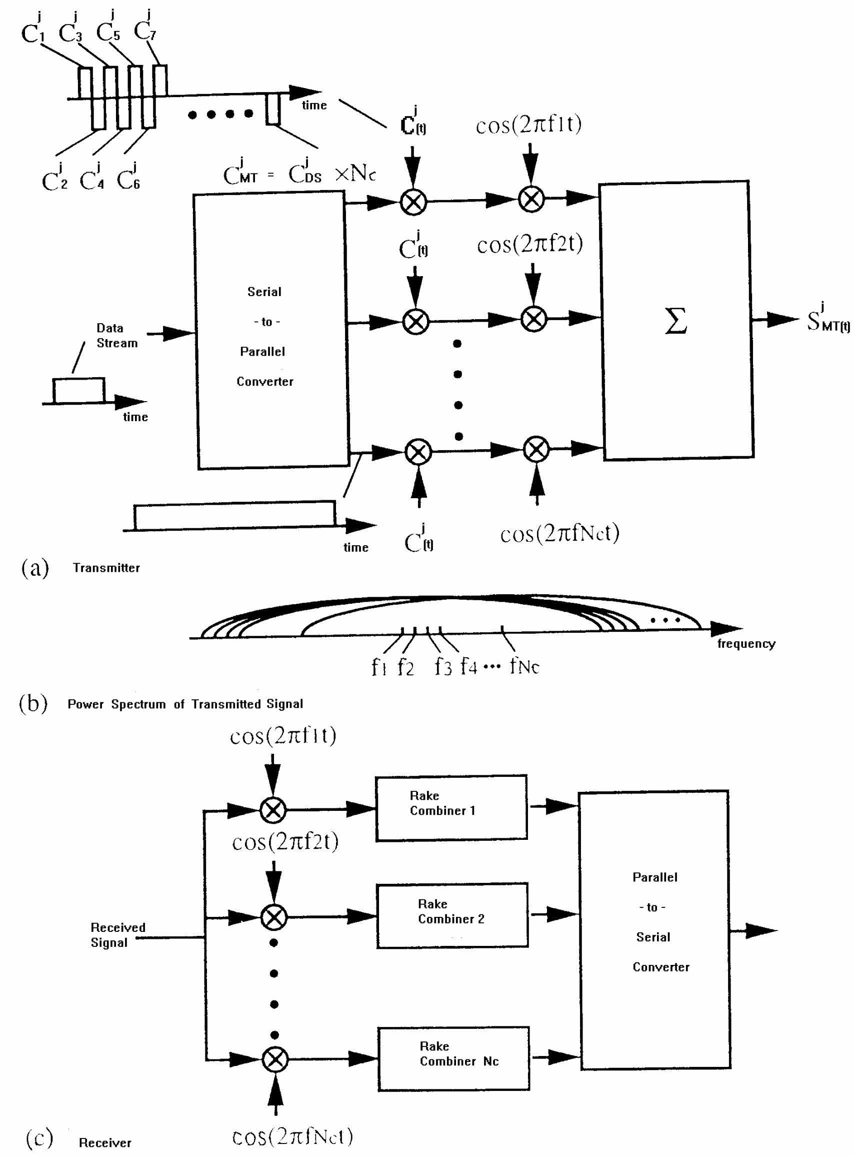
MT-CDMA scheme

(a)Transmitter

(b)Power spectrum of its transmitted signal

(c)Receiver

MT-CDMA is very similar to MC-DS-CDMA, only that the orthogonality between the sub-carriers are lost in MT-CDMA, thus DFT demodulation cannot be used.



BEP Comparison in a Downlink Channel with 2-path i.i.d. Multipath Delay Profile (1/2)

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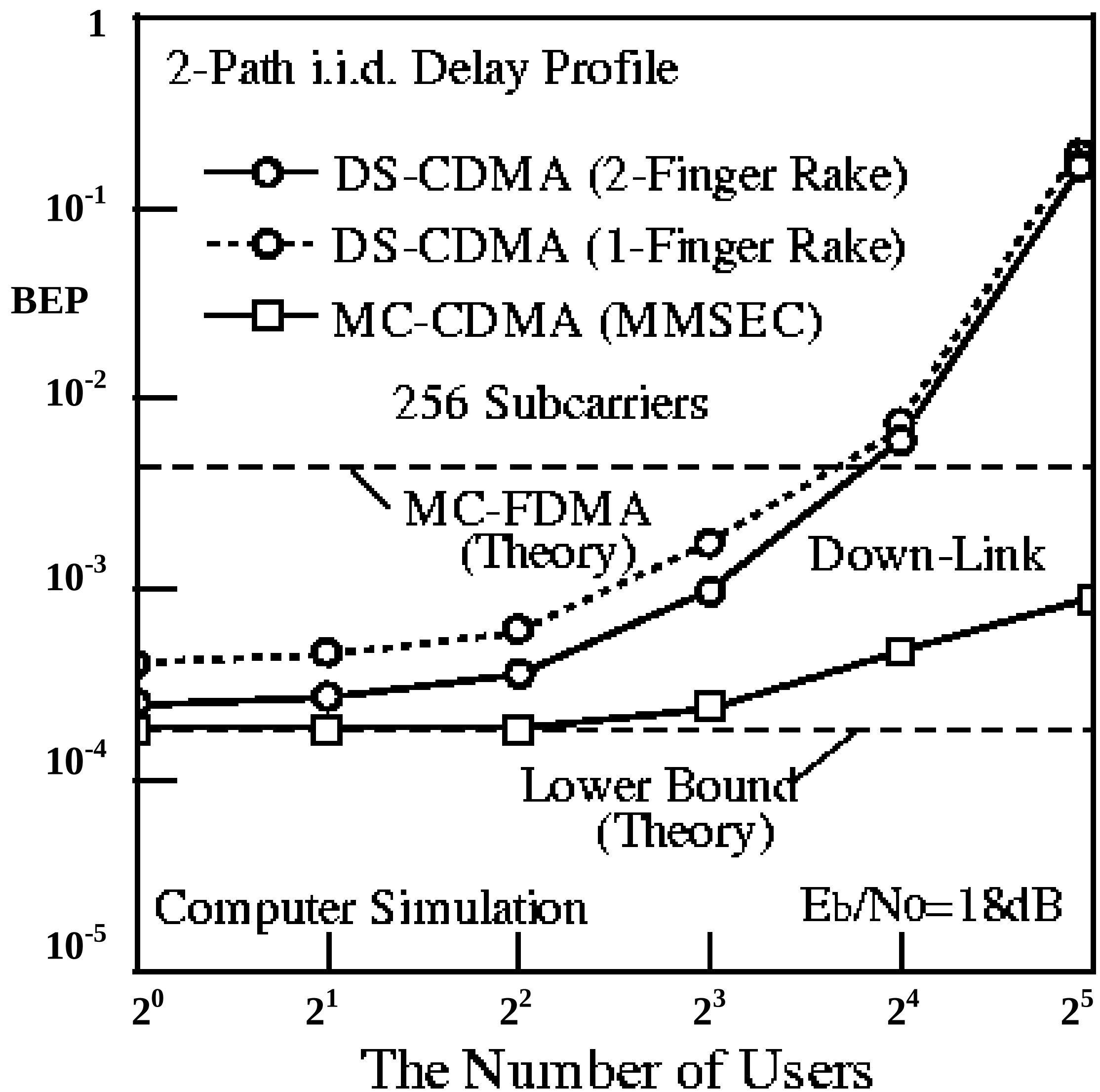
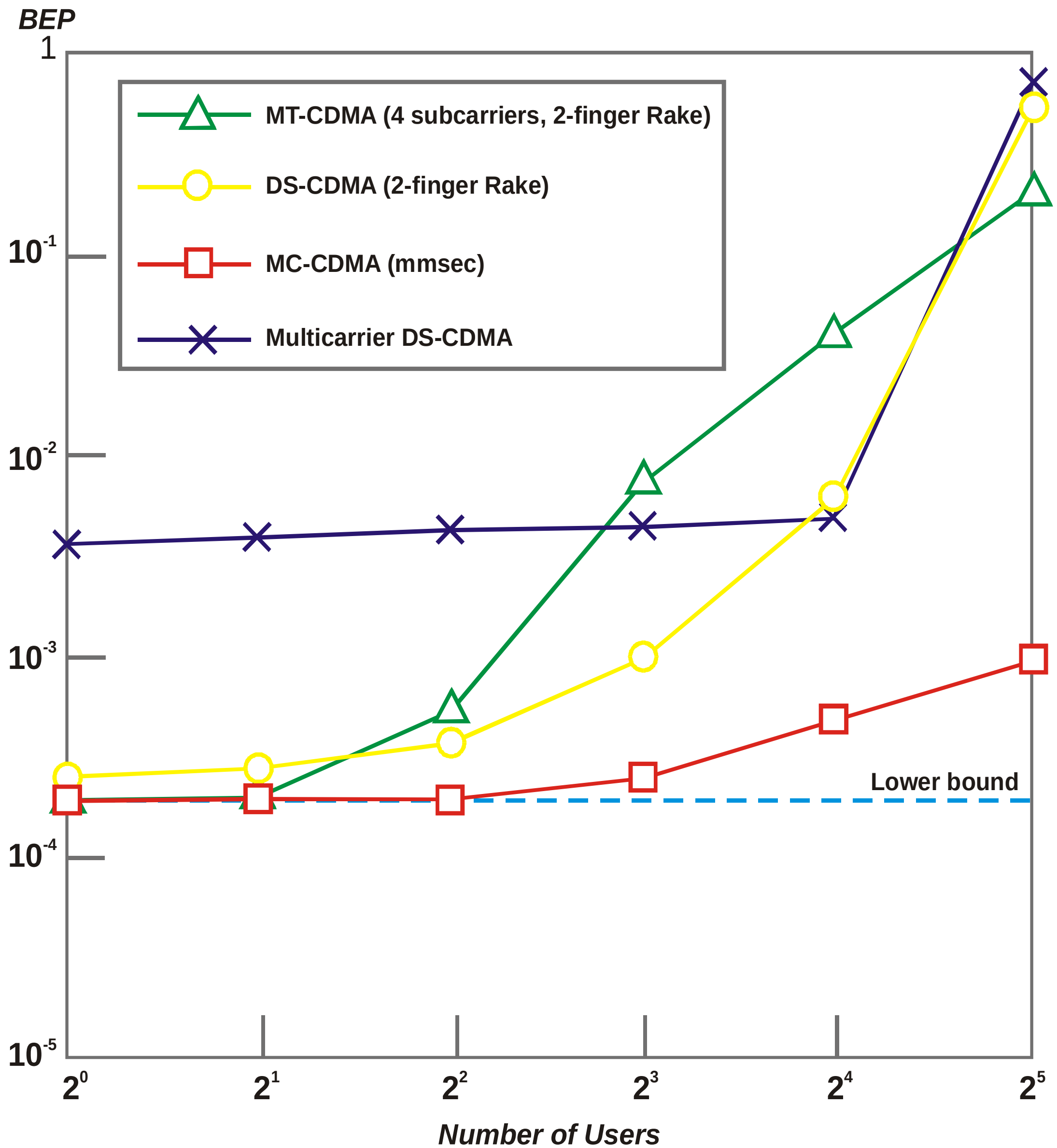


BEP Comparison (2/2)



Assumptions:

- RMS delay spread τ_{rms} = 20nsec,
- Max. Doppler frequency (f_D) = 10Hz,
- Transmission rate (R) = 3Msymbols/sec (BPSK format)
- Walsh Hadamard codes with K_{MC} = 32 for the MC-CDMA system,
- Gold codes with K_{DS} = 31 for the DS-CDMA system
- E_b/N_0 = 18 dB

Comments on Performance Comparison (1/2)

- ❑ MC-CDMA system has no major advantage over DS-CDMA system in terms of required bandwidth, because the bandwidth of MC-CDMA signal spectrum is almost the same as that of DS-CDMA signal spectrum.
- ❑ In terms of transmission performance, the BEP lower bound of MC-CDMA system is all the same as that of DS-CDMA system. Therefore, If we make every effort to improve the BEP in each system, there is no difference in the attainable BEP as long as the same channel is used.
- ❑ DS-CDMA system cannot always employ all the received signal energy scattered in the time domain, whereas MC-CDMA system can effectively combine all the received signal energy scattered in the frequency domain, although it requires much complexity in the receiver structure such as subcarrier synchronization.

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Comments on Performance Comparison (2/2)

- The MMSEC-based MC-CDMA must be a promising scheme in a down-link channel, although estimation of the noise power as well as subcarrier condition is required.
- In the up-link application, a multi-user detection is required because the code orthogonality among users is totally distorted by the channel frequency selectivity.

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General Comments about the Schemes

- OFDMA with DSA is throughput optimal compared to all other scheme in DL. But implementing DSA may require excessive signaling. In UL, OFDMA requires special care because of time and frequency misalignment among multiple users.
- OFDM-TDMA is another simple scheme which can be implemented with less signaling compared to OFDMA. It can be a good solution for UL. Supporting real-time burst traffic is a problem in this technique.
- MC-CDMA performs very good in DL, but it suffers from MAI. So, OFDMA-CDM can be even better for DL. For UL, OFDM-CDMA based schemes are probably not a good solution due to loss of orthogonality and MAI.
- Compared to OFDMA and OFDM-TDMA, OFDM-CDMA is better in terms of frequency reuse factor. Reuse of factor of 1 Is possible in OFDM-CDMA, but at least 3 is required in OFDMA for a reasonable performance.

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Outdoor Scenario: Channel Characteristics

1. Large cell radius
2. Large number of users
3. High mobility (high Doppler)
4. Large RMS delay spread
5. Wide distribution of user transmit power
6. Handover (re-synchronization of transceivers, signaling)
7. Inter-Cell interference

Outdoor Scenario: General Comment

- If orthogonal codes are used while spreading the signals, inter-cell interference cannot be avoided. Choosing PN sequence instead can be an effective solution.
- Uplink: none of the schemes discussed so far can be considered the best possible. Thus there is a possibility of finding some new access schemes which perform better than the considered ones
- Downlink: inter-cell interference is the main concern
- Downlink: OFDMA with some form of DSA and/or OFDMA-CDM is a preferred choice, with its advantage of frequency diversity.
- Before suggesting any access, more detailed system level analysis with several impairments are required.

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Indoor Scenario: Channel Characteristics

1. Small cell
2. Relatively small number of users
3. Very little handover problem
4. Low mobility, channel static for a long period so algorithms can be implemented for large number of symbols blocks
5. AMC and feedback systems can work in this environment
6. User transmit power uniformly distributed so little problem in power management
7. Low delay spread, and Large coherence bandwidth
8. Interference from Bluetooth networks, home networks, ISM band devices

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Indoor Scenario: General Comment

- Inter-cell interference is not an issue, but the inter-network interference is still present for unlicensed technologies.
- OFDMA is a simple scheme and since not many users are present, signaling is not very high in such a situation.
- OFDMA and even OFDM-TDMA performance are expected to be quite good.
- OFDM-CDMA is supposed to have the best quality, since it can exploit frequency diversity.
- OFDMA-CDM is still a good option for DL.

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Conclusion

- There are numerous other multiple access schemes that are not presented in this lecture.
- The goal is to give a high-level overview and overall understanding, thus, no mathematical expressions are presented. Interested students can refer to relevant references.
- Multiple access techniques for 4G is hot topic for research now.
- Do contact us, if you are interested in the topics discussed in the lectures.