Chapter 9
Multi-Carrier CDMA

Chapter 9

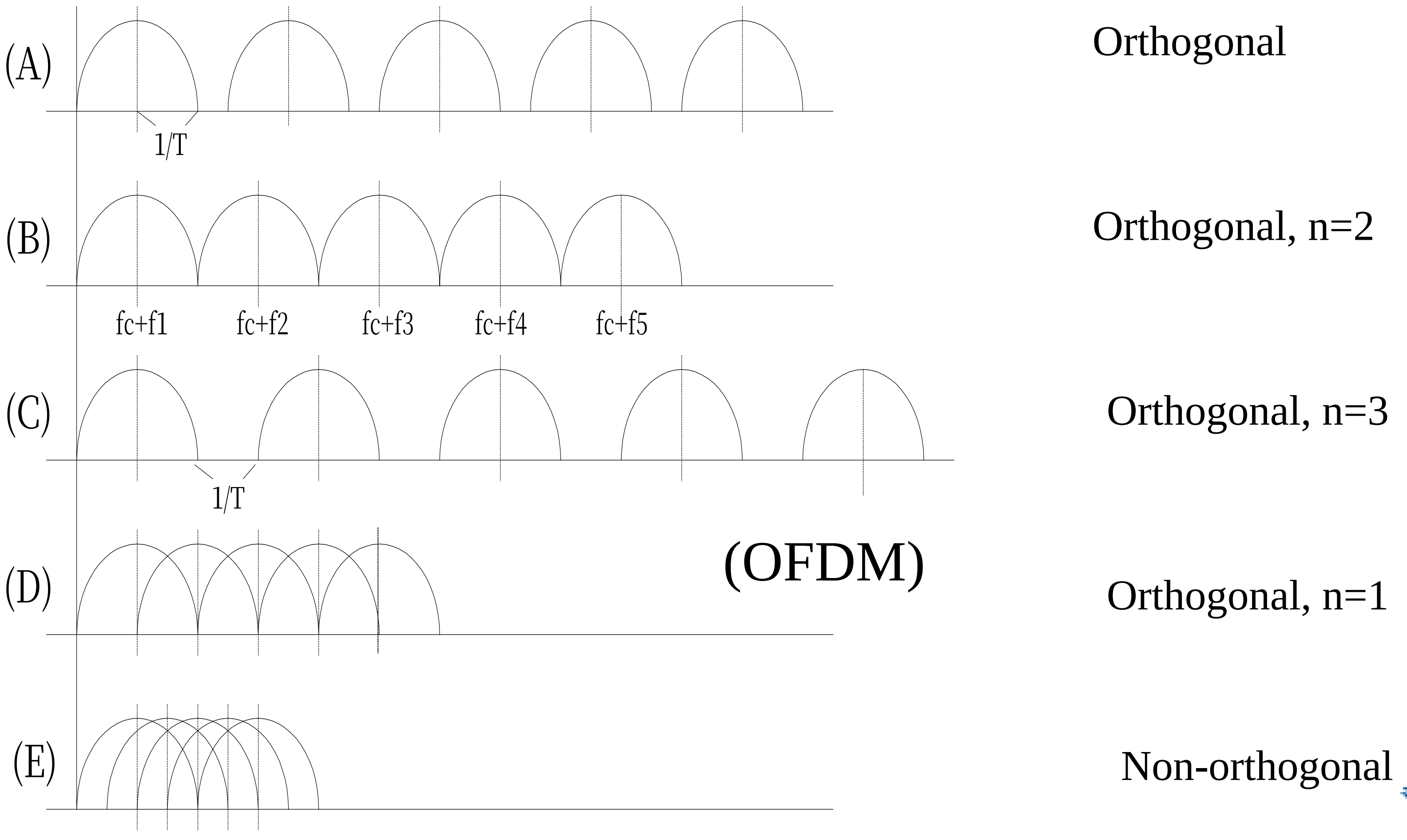
- 9 Multi-carrier CDMA
  - 9.1 Introduction
  - 9.2 Family of Multi-carrier CDMA Systems
    - 9.2.1 MC-CDMA System
    - 9.2.2 Multi-carrier DS-CDMA System
    - 9.2.3 Multi-Tone CDMA System
    - 9.2.4 System features comparison
  - 9.3 Differences between OFDM and MC-CDMA

9.1 Introduction

- **Transmit high data rate in a mobile environment**
  - **Multi-carrier Transmission**
- **Multi-carrier transmission and OFDM**
  - **Multi-carrier Transmission**
    - **Multi-carrier concept**
    - **Orthogonality**
  - **OFDM**
    - **Using FFT device without increasing the transmitter and receiver complexities**
    - **High spectral efficiency due to minimally densely subcarrier spacing**

9.1 Introduction

☞ Multicarrier Concept



9.1 Introduction

☞ Orthogonality

Definition

Time domain

$$\int_{-\infty}^{\infty} x_1(t)x_2^*(t)\,dt = 0$$

$\Leftrightarrow$

Frequency domain

$$\int_{-\infty}^{\infty} X_1(f)X_2^*(f)\,df = 0$$

Bandpass signal

$$x_m(t) = \cos(2\pi(f_c + f_m)t) = \mathrm{Re}\left(e^{i2\pi(f_c+f_m)t}\right) = \mathrm{Re}\left(x_{lm}(t)\cdot e^{i2\pi f_c t}\right)$$

where $x_{lm}(t) = e^{i2\pi f_m t}$ **is the equivalent lowpass signal of** $x_m(t)$

$$\gamma_{12} = \int_0^T e^{i2\pi f_1 t}(e^{i2\pi f_2 t})^* dt = \int_0^T e^{i2\pi(f_1-f_2)t} dt = \frac{\sin(\pi\Delta f T)}{\pi\Delta f} e^{i\pi\Delta f T}$$

if $\Delta f T = n$ **,*n* is non-zero integer, i.e.** $\Delta f = \frac{n}{T}$ **, then** $\gamma_{12} = 0$ **.**

9.1 Introduction

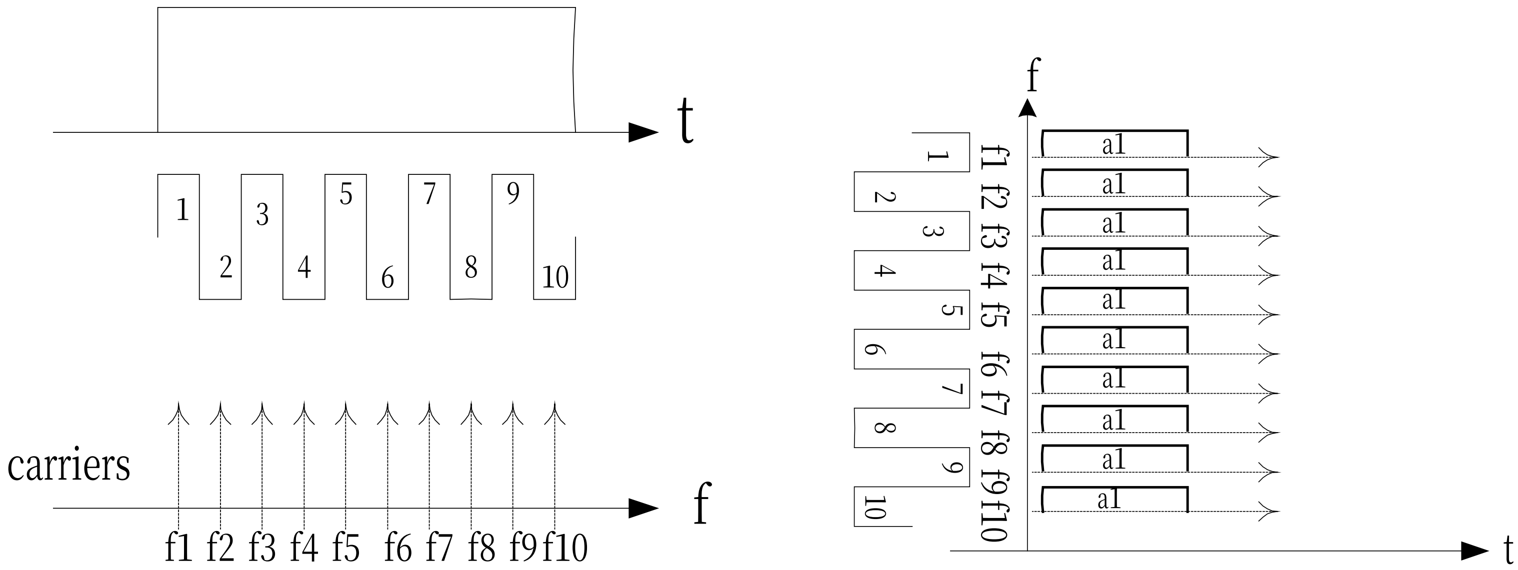
- **Three types of multiple access schemes**
  - **Combination of CDMA and Multi-carrier modulation techniques**
    - **MC-CDMA System**
    - **Multi-carrier DS-CDMA System**
    - **Multi-Tone CDMA System**

9.2 Family of Multi-carrier CDMA Systems

- **Frequency domain spreading + multi-carrier modulation**
  - **MC-CDMA scheme**
- **Time domain spreading + multi-carrier modulation**
  - **Multi-carrier DS-CDMA scheme**
  - **MT-CDMA scheme**

9.2 Family of Multi-carrier CDMA Systems

- ☞ **Frequency domain and Time domain spreading**



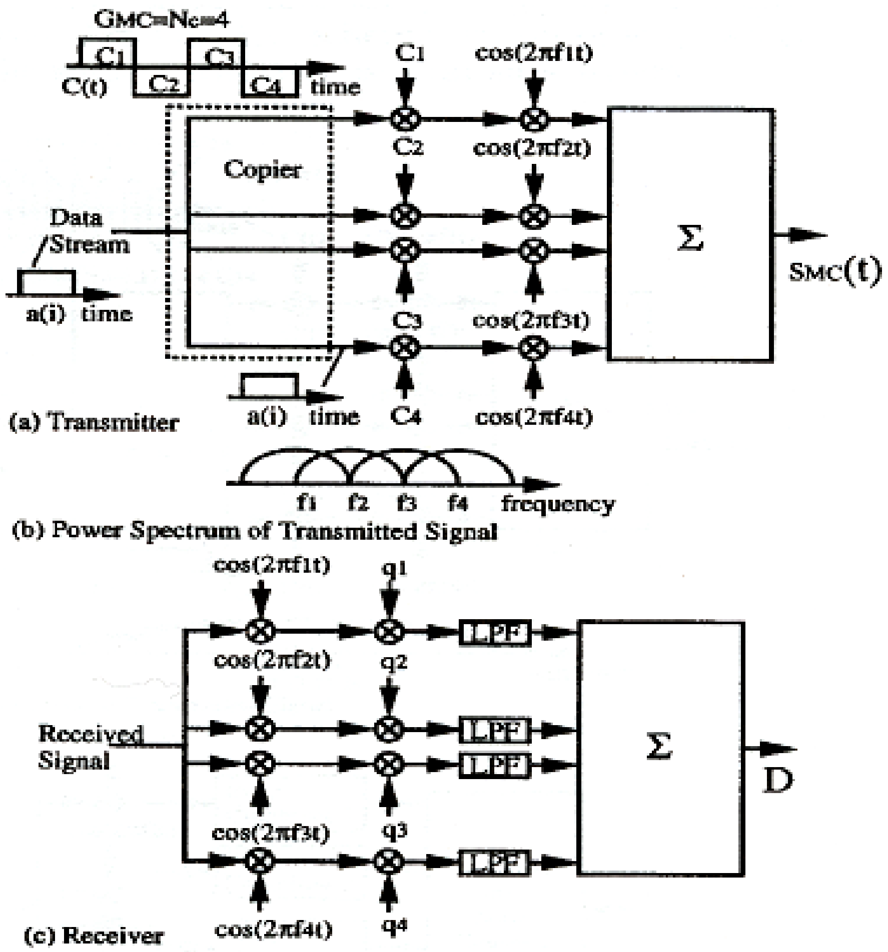
9.2.1 MC-CDMA System

MC-CDMA System

- **Frequency domain spreading**
- **The resulting spectrum of each subcarrier can satisfy the orthogonality condition with the minimum frequency separation.**
- **In a (synchronous) down-link mobile radio communication channel, we can use Hadamard Walsh codes as an optimum orthogonal set.**
- **It can be implemented by OFDM technique.**
- **It's a potential candidate for the 4th wireless communication system.**

9.2.1 MC-CDMA System

☞ MC-CDMA System



$$s^j_{MC}(t) = \sum_{i=-\infty}^{+\infty} \sum_{m=1}^{G_{MC}} a^j(i) c^j_m \cdot p_s(t - iT_s) \cos\{2\pi(f_0 + m\Delta f)t\}$$

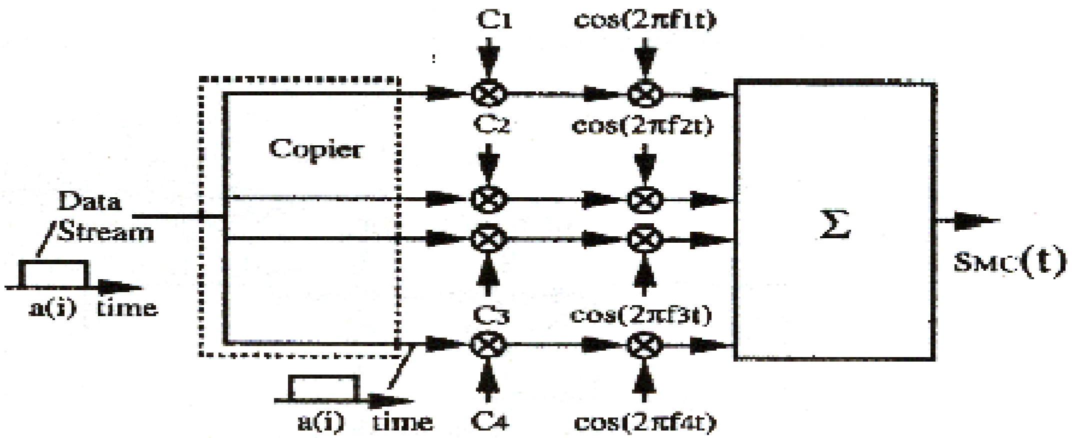
$$\Delta f = \frac{1}{T_S}$$

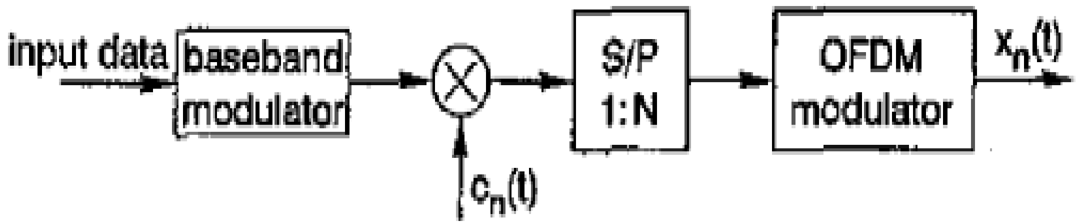
$$D^{j'} = \sum_{m=1}^{G_{MC}} q^{j'}_m y_m ;$$

$$y_m = \sum_{j=1}^{J} z^j_m a^j c^j_m + n_m ;$$

9.2.1 MC-CDMA System

☞ **MC-CDMA System**



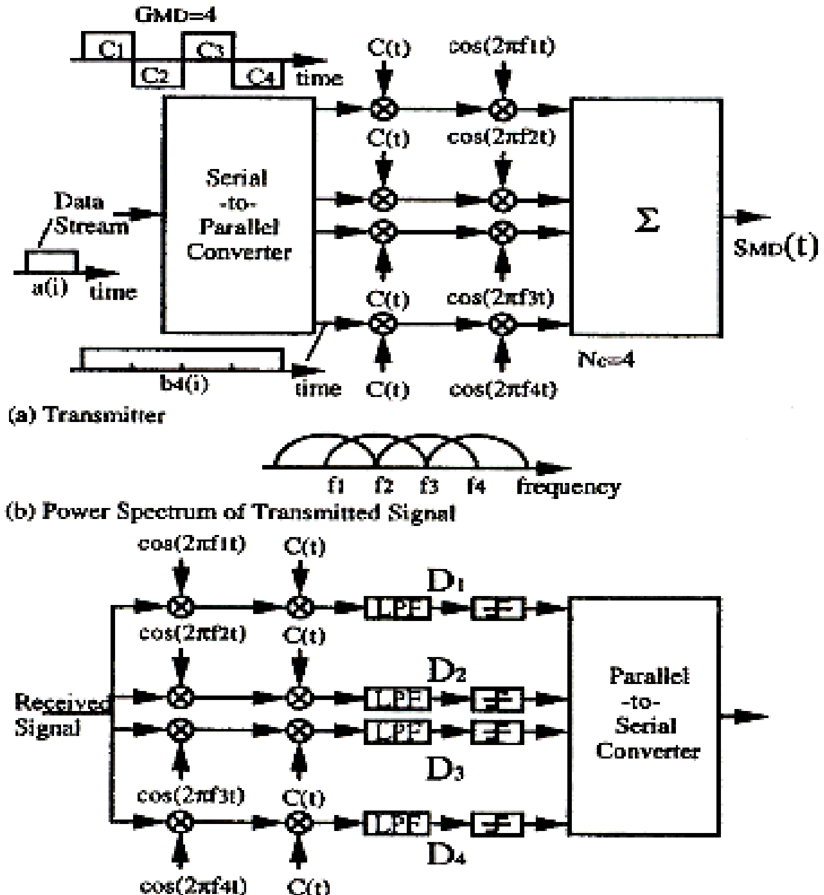


9.2.2 Multi-carrier DS-CDMA System

- **Multi-carrier DS-CDMA system**
  - **Time domain spreading**
  - **The resulting spectrum of each subcarrier can satisfy the orthogonality condition with the minimum frequency separation.**
  - **This scheme can lower the data rate in each subcarrier so that a large chip time make it easier to synchronize the spreading sequences.**
  - **The multicarrier DS-CDMA scheme is originally proposed for a up-link communication channel, because this characteristic is effective for establishment of a (quasi-) synchronous channel.**
  - $N_c = G_{MD}$

9.2.2 Multi-carrier DS-CDMA System

☞ **Multi-carrier DS-CDMA system**



(a) Transmitter
(b) Power Spectrum of Transmitted Signal
(c) Receiver

$$s^j_{MD}(t) = \sum_{i=-\infty}^{+\infty}\sum_{k=1}^{N_c}\sum_{m=1}^{G_{MD}} b^j_k(i)\, c^j_m \cdot p_c(t-(m-1)T_c - iT'_s) \cdot \cos\{2\pi(f_0+k\Delta f')t\}$$

$$T_C = \frac{N_C T_S}{G_{DS}}$$

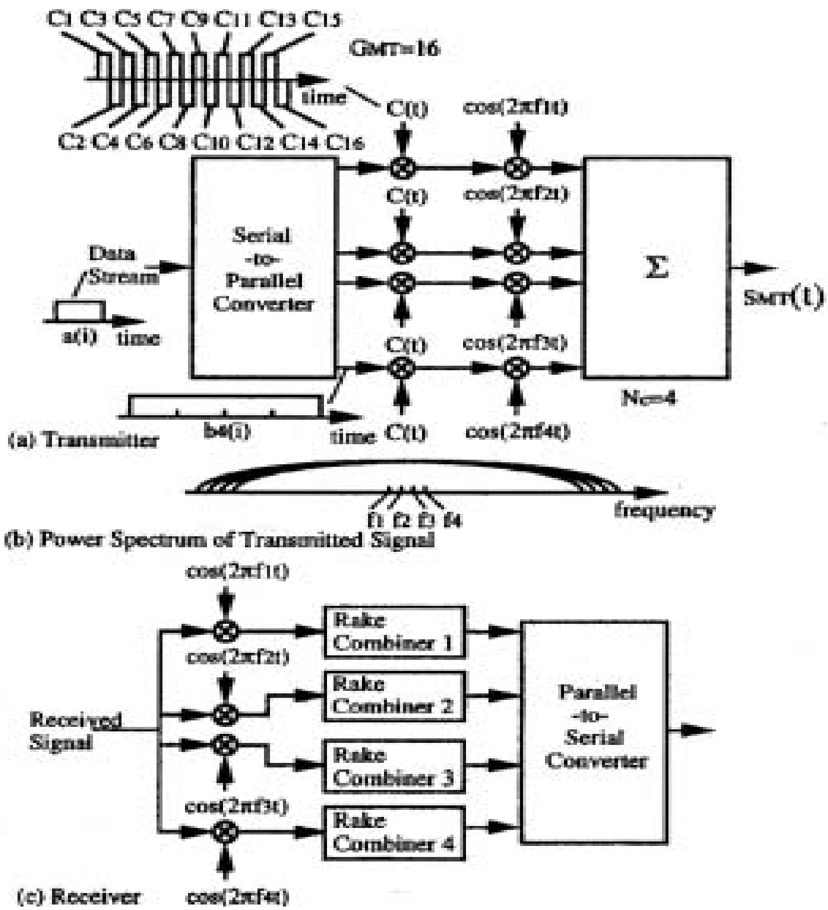
$$\Delta f' = \frac{1}{T_C}$$

9.2.3 Multi-Tone CDMA System

- **Multi-Tone CDMA (MT-CDMA) system**
  - **Time domain spreading**
  - **The resulting spectrum of each subcarrier no longer satisfies the orthogonality condition.**
  - **The MT-CDMA scheme uses longer spreading codes in proportion to the number of subcarriers, as compared with a normal DS-CDMA scheme.**
  - **The MT-CDMA system can accommodate more users than the DS-CDMA system.**
  - $N_c < G_{MD}$

9.2.3 Multi-Tone CDMA System

☞ **Multi-Tone CDMA (MT-CDMA) system**

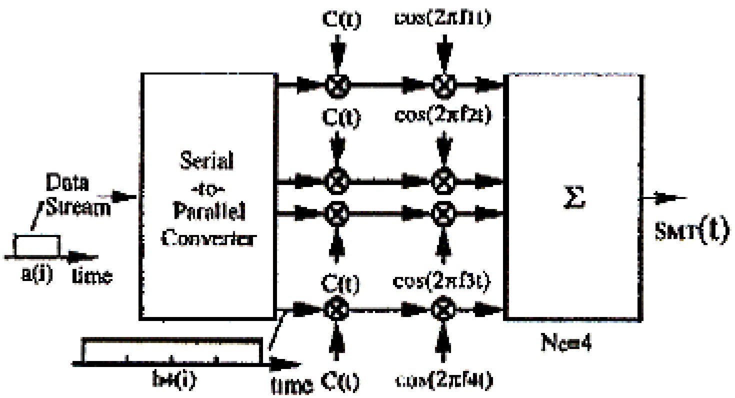


$$s^j_{MT}(t) = \sum_{i=-\infty}^{+\infty}\sum_{k=1}^{N_c}\sum_{m=1}^{G_{MT}} b^j_k(i)c^j_m \cdot p_c(t-(m-1)T_c - iT'_s) \cdot \cos\{2\pi(f_0 + k\Delta f'')t\},$$

$\Delta f''$ $(= 1/T_s)$ is the subcarrier separation.

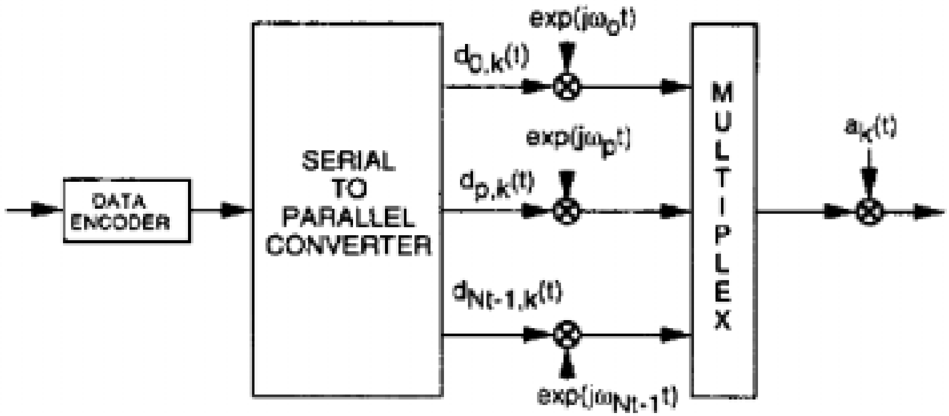
9.2.3 Multi-Tone CDMA System

☞ Multi-Tone CDMA (MT-CDMA) system



$$s^j_{MT}(t) = \sum_{i=-\infty}^{+\infty} \sum_{k=1}^{N_c} \sum_{m=1}^{G_{MT}} b^j_k(i) c^j_m \cdot p_c(t-(m-1)T_c - iT'_s) \cdot \cos\{2\pi(f_0 + k\Delta f'')t\},$$

f'' $(= 1/T_s)$ is the subcarrier separation.



9.2.4 System Features Comparison

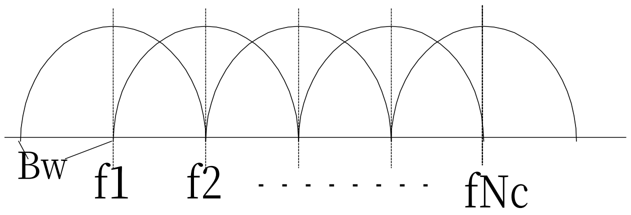
☞ **System features comparison**

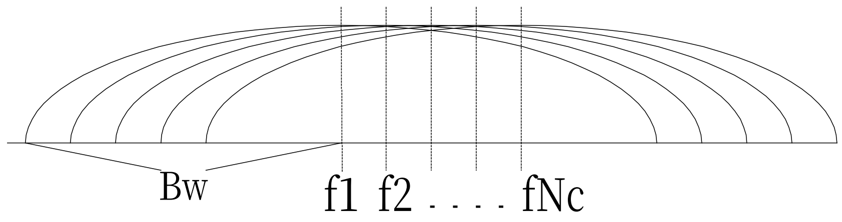
Access Scheme	Symbol Duration at Subcarrier	The Number of Subcarriers	Processing Gain	Chip Duration	Subcarrier Separation	Required Bandwidth
DS-CDMA	T_s	(1)	G_{DS}	T_s/G_{DS}		G_{DS}/T_s Nyquist Filter with Roll-off Factor ≈ 0
MC-CDMA	T_s	$N_c = G_{MC}$	$G_{MC} \approx G_{DS}$		$1/T_s$	$(G_{DS}+1)/T_s$
Multicarrier DS-CDMA	N_cT_s	N_c	$G_{MD} = G_{DS}$	N_cT_s/G_{DS}	$G_{DS}/(N_cT_s)$	$(N_c+1)/N_c \cdot G_{DS}/T_s$
MT-CDMA	N_cT_s	N_c	$G_{MT} = N_cG_{DS}$	T_s/G_{DS}	$1/(N_cT_s)$	$(N_c-1)/(N_cT_s)$ $+2G_{DS}/T_s$

9.2.4 System Features Comparison

System features comparison

- **MC-CDMA Bw=1/Ts , B=(Nc+1)/Ts**
- **Multi-carrier DS-CDMA Bw=** $G_{DS}/(N_cT_s)$**, B=** $(N_c+1) \times G_{DS}/(N_cT_s)$
- **MT-CDMA Bw=** G_{DS}/T_s **, B=** $2\,G_{DS}/T_s + (N_c-1)/N_cT_s$





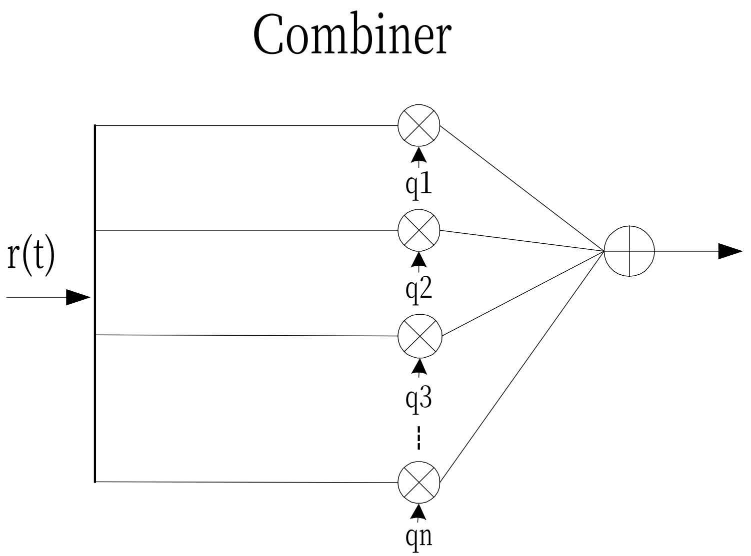
9.2.4 System Features Comparison

- **Receiver structures**
  - **DS-CDMA scheme**
  - **MC-CDMA scheme**
    - **9 different structures**
  - **Multicarrier DS-CDMA**
    - **Compose of Nc normal coherent (Non-Rake) receivers**
  - **MT-CDMA**
    - **Compose of Nc Rake combiners**
  - **Detection strategies comparison**

9.2.4 System Features Comparison

Diversity and combining schemes

- **Diversity**
- **Combiner**
  - **Selection diversity**
  - **Equal gain combining**
  - **maximum ratio combining**
  - **Orthogonality restoring combining**
  - **MMSE combining**
  - **……….**



9.2.4 System Features Comparison

- **Receiver structures**
  - **MC-CDMA system**
    - **1.Orthogonality Restoring Combining (ORC)**
      - **choosing the gain q_m as** $q_m^{j'} = c_m^{j'} z_m^* / |z_m|^2$

$$D^{j'} = \sum_{m=1}^{G_{MC}} q_m^{j'} y_m, \qquad y_m = \sum_{j=1}^{J} z_m^j a^j c_m^j + n_m,$$

$$D^{j'} = a^{j'} + \sum_{m=1}^{G_{MC}} c_m^{j'} z_m^* / |z_m|^2 n_m$$

, z_m is the complex envelope of the m-th subcarrier

      - **Noise enhancement**

9.2.4 System Features Comparison

- **Receiver structures**
  - **MC-CDMA system**
    - **2.Controlled Equalization (CE)**

$$D^{j'} = \sum_{m=1}^{G_{MC}} q_m^{j'} y_m, \qquad y_m = \sum_{j=1}^{J} z_m^j a^j c_m^j + n_m,$$

$$D^{j'} = \sum_{m=1}^{G_{MC}} c_m^{j'} z_m^* / |z_m|^2 u(|z_m| - \gamma)(\sum_{j=1}^{J} z_m^j a^j c_m^j + n_m)$$

$$q_m^{j'} = c_m^{j'} z_m^* / |z_m|^2$$

9.2.4 System Features Comparison

- **Receiver structures**
  - **MC-CDMA system**
    - **3.Equal Gain Combining (EGC) and Maximum Ratio Combining (MRC)**

$$q_m^{j'} = \begin{cases} c_m^{j'} z_m^{j'*} / |z_m^{j'}| & (EGC) \\ c_m^{j'} z_m^{j'*} & (MRC) \end{cases}$$

      - MRC maximizes the output SNR

9.2.4 System Features Comparison

- **Receiver structures**
  - **MC-CDMA system**
    - **4.Minimum Mean Square Error Combining (MMSEC)**

$$\widehat{a^{j'}} = \sum_{m=1}^{G_{MC}} q_m^{j'} y_m$$

$$\left(a^{j'} - \widehat{a^{j'}}\right) \cdot y_{m'}^* = 0 \quad \left(m' = 1, 2, \cdots, G_{MC}\right).$$

$$q_m^{j'} = c_m^{j'} z_m^* / \left(J|z_m|^2 + N_0\right),$$

9.2.4 System Features Comparison

- Receiver structures
  - MC-CDMA system
    - 5.Maximum Likelihood Multi-User Detection (MLMUD)
      - Find a set of a^j,(j=1,2,….,J) to minimize the following likelihood function Λ

$$\Lambda = \sum_{m=1}^{G_{MC}} |y_m - \sum_{j=1}^{J} z_m^j a^j c^j(m)|^2$$

9.2.4 System Features Comparison

- **Receiver structures**
  - **MC-CDMA system**
    - **6.EGC-EGC Multi-User Detection**
      - **First using EGC to estimate a set of a^j,(j=1,2,….,J,j≠j')**
      - **And then estimates the $a^{j'}$ by EGC after removing the MAI from the received signal**

$$D^{j'} = \sum_{m=1}^{G_{MC}} c_m^{j'} z_m^* / |z_m| (y_m - \sum_{\substack{j=1 \\ j \neq j'}}^{J} z_m^j \widehat{a^j} c_m^j + n_m)$$

9.2.4 System Features Comparison

- **Receiver structures**
  - **MC-CDMA system**
    - **7.ORC-MRC Multi-User Detection (O-M MUD)**
    - **8. CE-ML Multi-User Detection (C-M MUD)**
    - **9.Decorrelating and MMSE interference Canceller (DIC and MMSEIC)**

9.2.4 System Features Comparison

- **Receiver structures**
  - **MT-CDMA system**
    - **DFE - Decision Feedback Equalizer**
    - **LE - Linear Equalizer**
    - **JEIC - Joint multiple access Interference Canceller/Equlizer**

9.2.4 System Features Comparison

☞ Detection strategies comparison

Access Scheme	Detection Strategy	Up-Link	Down-Link
DS-CDMA	Rake Combiner	o	o
	MUD	o	
MC-CDMA	ORC		o
	CE		o
	EGC	o	o
	MRC	o	o
	MMSEC		o
	ML MUD		o
	E-E MUD		o
	O-M MUD		o
	C-M MUD		o
	DIC		o
	MMSEIC		o
Multicarrier DS-CDMA	Non-Rake Receiver	o	
MT-CDMA	Rake Combiner	o	
	DFE	o	
	LE	o	
	JEIC	o	

9.2.4 System Features Comparison

- **Bit error rate comparison**
  - **BER lower bound**

$$BER_{LB} = \left(\frac{1-\mu}{2}\right)^2 \sum_{l=0}^{1} \binom{l+1}{l} \left(\frac{1+\mu}{2}\right)^l$$

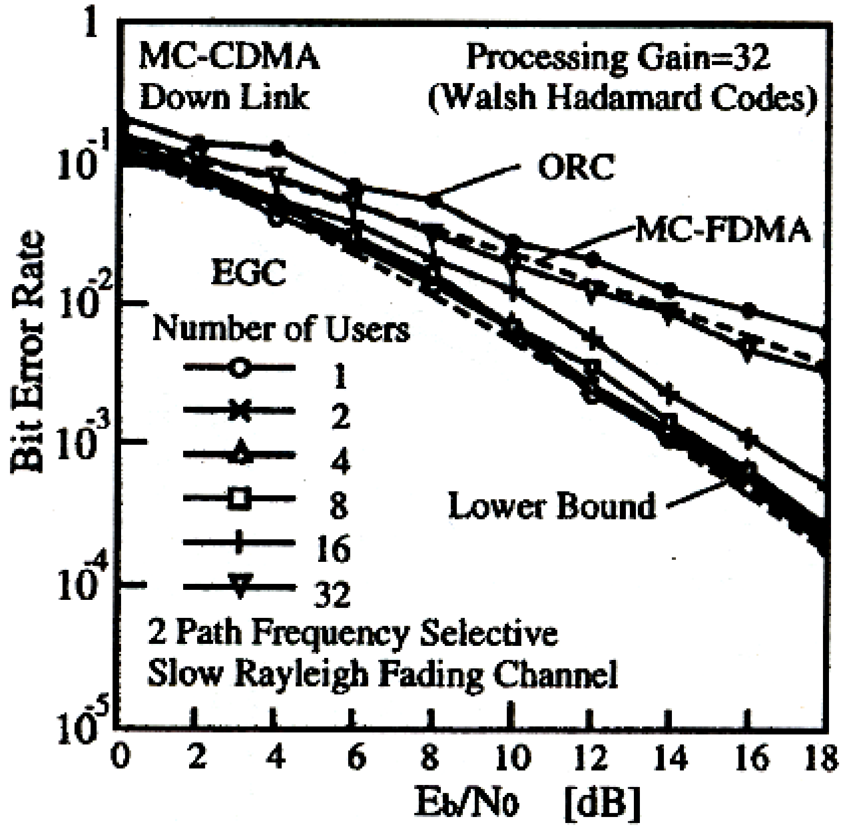
$$\mu = \sqrt{\frac{E_b/N_0}{2+E_b/N_0}}.$$

  - **BER of an MC-FDMA**

$$BER_{MC-FDMA} = \frac{1}{2}\left(1-\sqrt{\frac{E_b/N_0}{1+E_b/N_0}}\right)$$

9.2.4 System Features Comparison

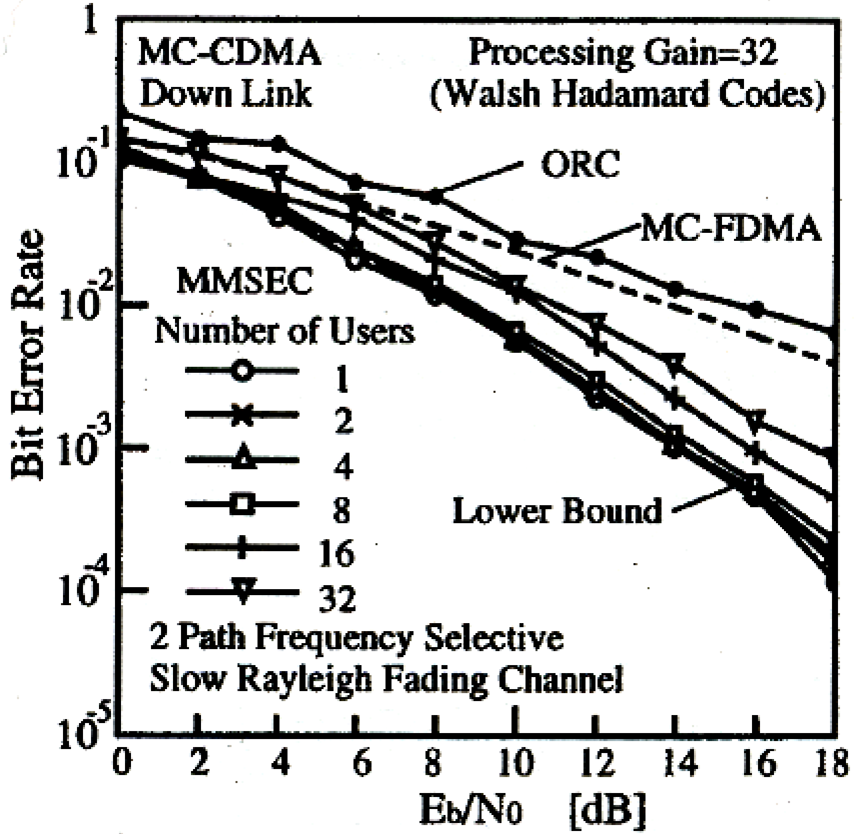
☞ **BER performance**



BER performance of MC-CDMA scheme with EGC

9.2.4 System Features Comparison

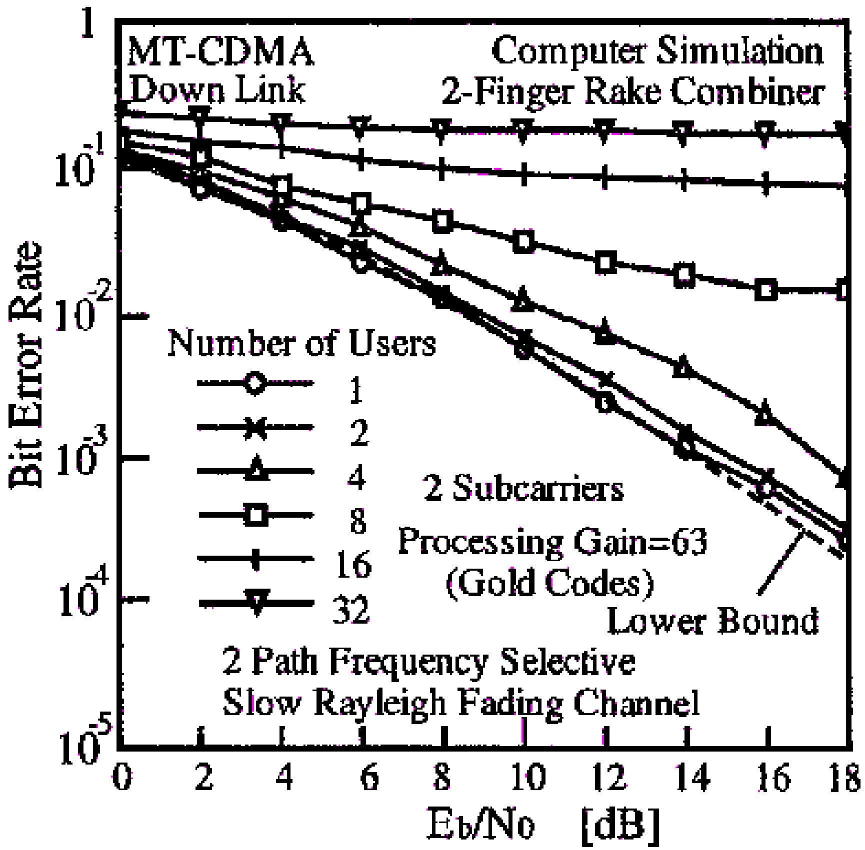
☞ **BER performance**



BER performance of MC–CDMA scheme with MMSEC

9.2.4 System Features Comparison

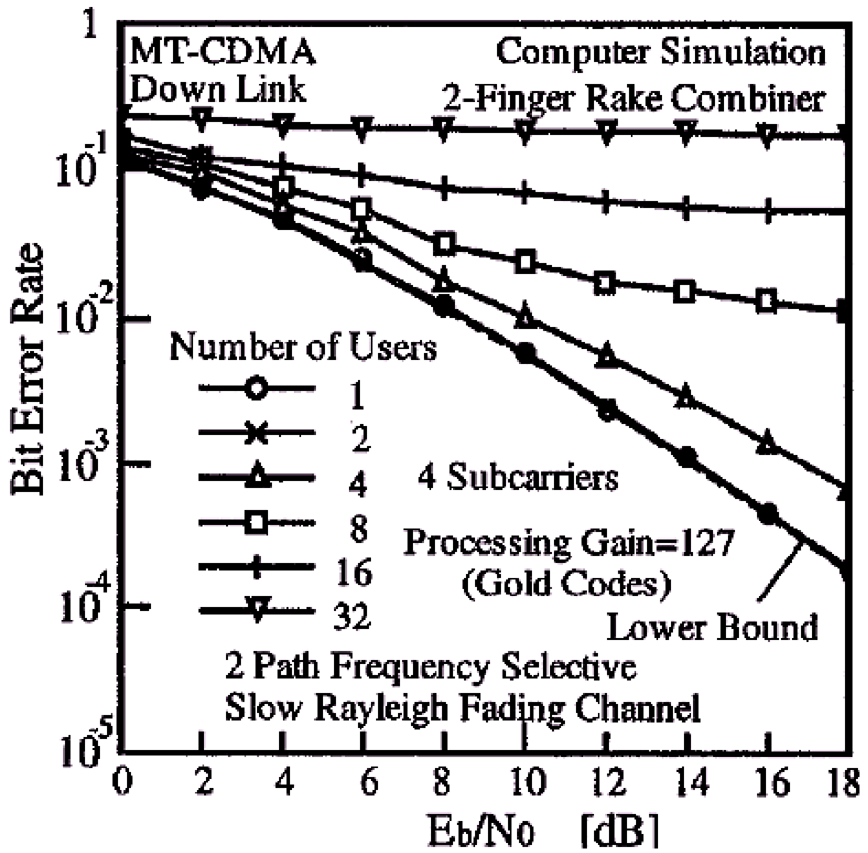
☞ **BER performance**



BER performance of MT–CDMA scheme with 2 subcarriers

9.2.4 System Features Comparison

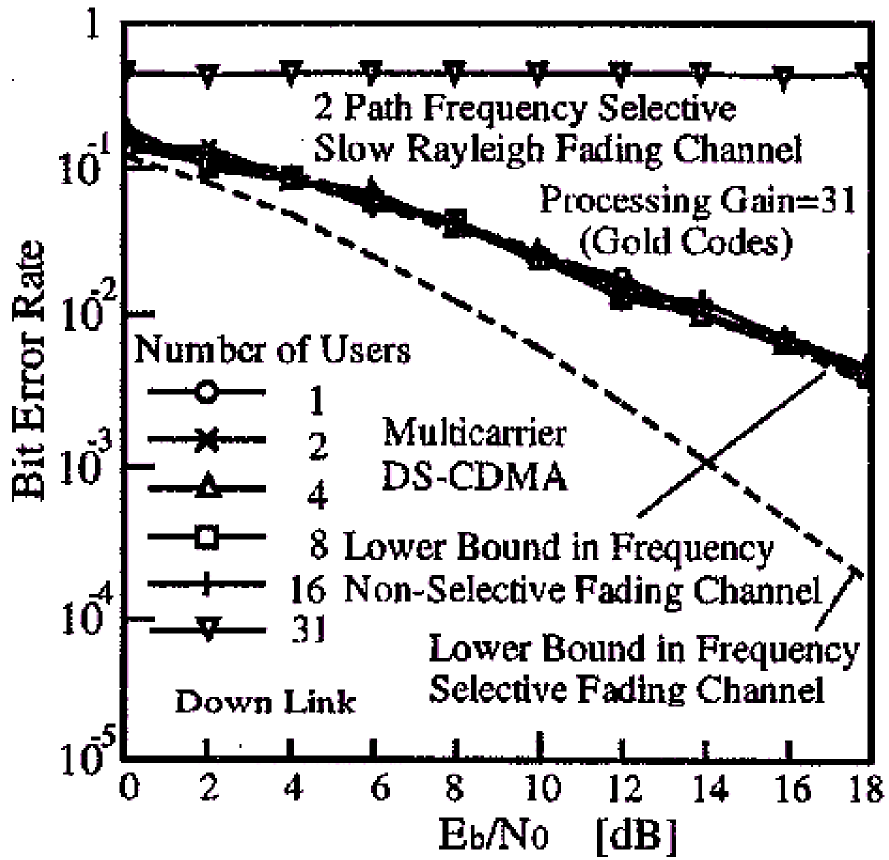
☞ **BER performance**



BER performance of MT–CDMA scheme with 4 subcarriers

9.2.4 System Features Comparison

☞ **BER performance**



BER performance of Multicarrier DS−CDMA scheme

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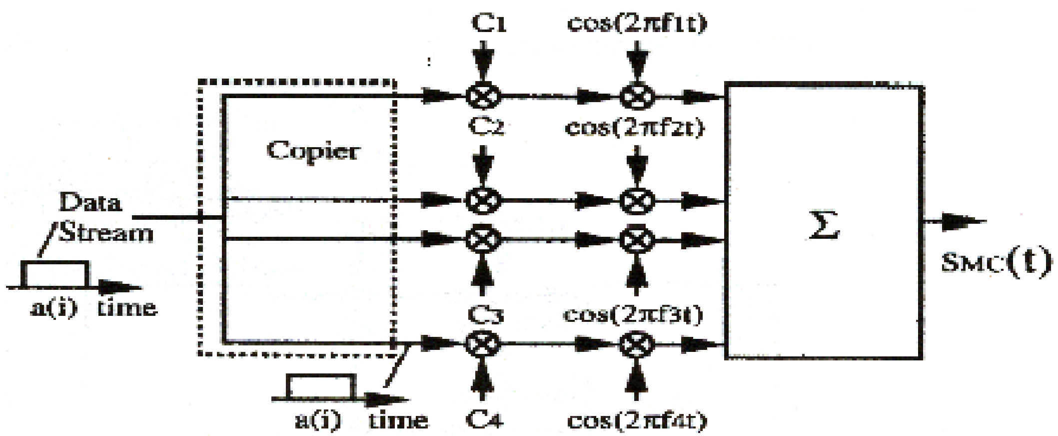
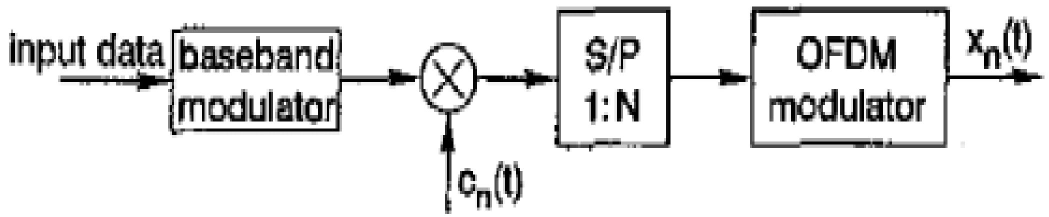
Wireless Comm. Lab.

9.3 Differences between OFDM and MC-CDMA

- MC-CDMA system is a CDMA based on a combination of CDMA and OFDM signaling.
  - OFDM-CDMA
  - MC-CDMA can be implemented by OFDM technique.





9.3 Differences between OFDM and MC-CDMA

- MC-CDMA spreads the signal in the frequency domain according to the code.
- MC-CDMA can view as employing the frequency diversity method.
- MC-CDMA performs better than DS-CDMA in Downlink level. But performs even worse in Uplink level.
- MC-CDMA has gained much attention, because the signal can b easily transmitted and received using the fast Fourier transform (FFT) device without increasing the transmitter and receiver complexities and it is potentially robust to channel frequency selectivity with a good frequency use efficiency.

- **[1]Richard van Nee Ramjee Prasad,** ***OFDM Wireless Multimedia Communication*****, Artech House Boston London**
- **[2]Ahmad R.S.Bahai and Burton R. Saltzberg** ***Multi-carrier Digital Communications Theory and Applications of OFDM*****, Kluwer Academic/Plenum Publishers.**
- **[3] L. Hanzo, W. Webb and T. Keller,** ***Single- and multi-carrier quadrature amplitude modulation – Principles and applications for personal communications, WLANs and broadcasting*****, John Wiley & Sons, Ltd, 2000.**
- **[4] rasad, R.; Hara, SP. "An overview of multi-carrier CDMA," Spread Spectrum Techniques and Applications Proceedings, 1996., IEEE 4th International Symposium on , Volume: 1 , 1996 Page(s): 107 - 114 vol.1**