SYSTEM ARCHITECTURE
ADVANCED SYSTEM ARCHITECTURE
LUO Chapter18.1 and 18.2

Introduction to OFDM

2013/Fall-Winter Term
Monday 12:50

Room# 1-322 or 5F Meeting Room

Instructor: Fire Tom Wada, Professor

What is OFDM?

- OFDM
  =Orthogonal Frequency Division Multiplexing

- Many orthogonal sub-carriers are multiplexed in one symbol
  - What is the orthogonal?
  - How multiplexed?
  - What is the merit of OFDM?
  - What kinds of application?

Outline

- Background, history, application
- Review of digital modulation
- FDMA vs. Multi-carrier modulation
- Theory of OFDM
- Multi-path
- Real OFDM systems examples

Why OFDM is getting popular？

- State-of-the-art high bandwidth digital communication start using OFDM
  - Terrestrial Video Broadcasting in Japan and Europe
    - ISDB-T / DVB-T
  - ADSL High Speed Modem
  - WLAN such as IEEE 802.11a/g/n/ac
  - WiMAX as IEEE 802.16d/e

- Economical OFDM implementation become possible because of advancement in the LSI technology

Brief history of OFDM

- First proposal in 1950's
- Theory completed in 1960's
- DFT implementation proposed in 1970's
- Europe adopted OFDM for digital radio broadcasting in 1987
- OFDM for Terrestrial Video broadcasting in Europe and Japan
- ADSL, WLAN(802.11a)

Digital modulation basics

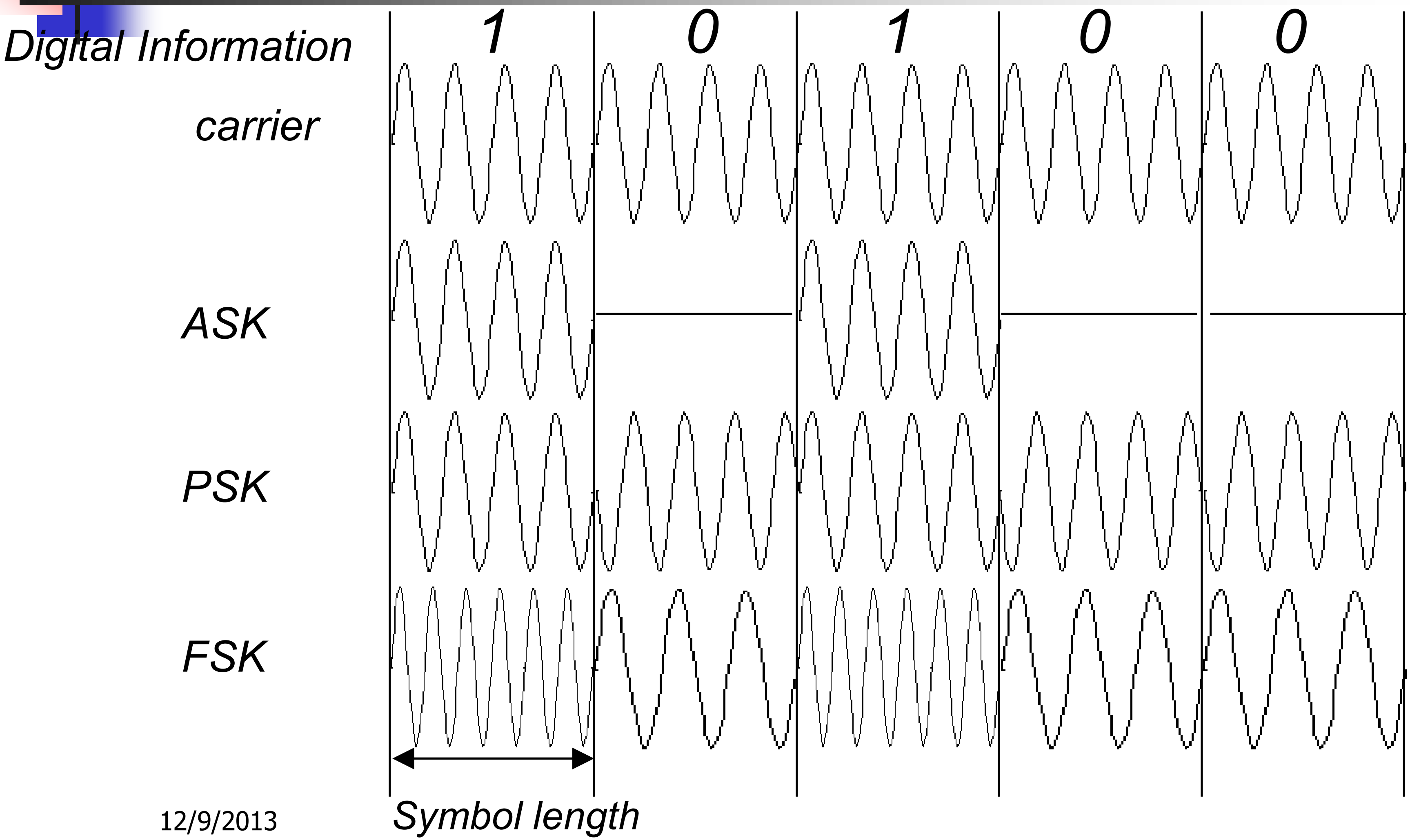
- Digital modulation modulates three parameters of sinusoidal signal.
- A, θ_k fc,

$$s(t) = A \cdot \cos(2\pi \cdot f_c \cdot t + \theta_k)$$

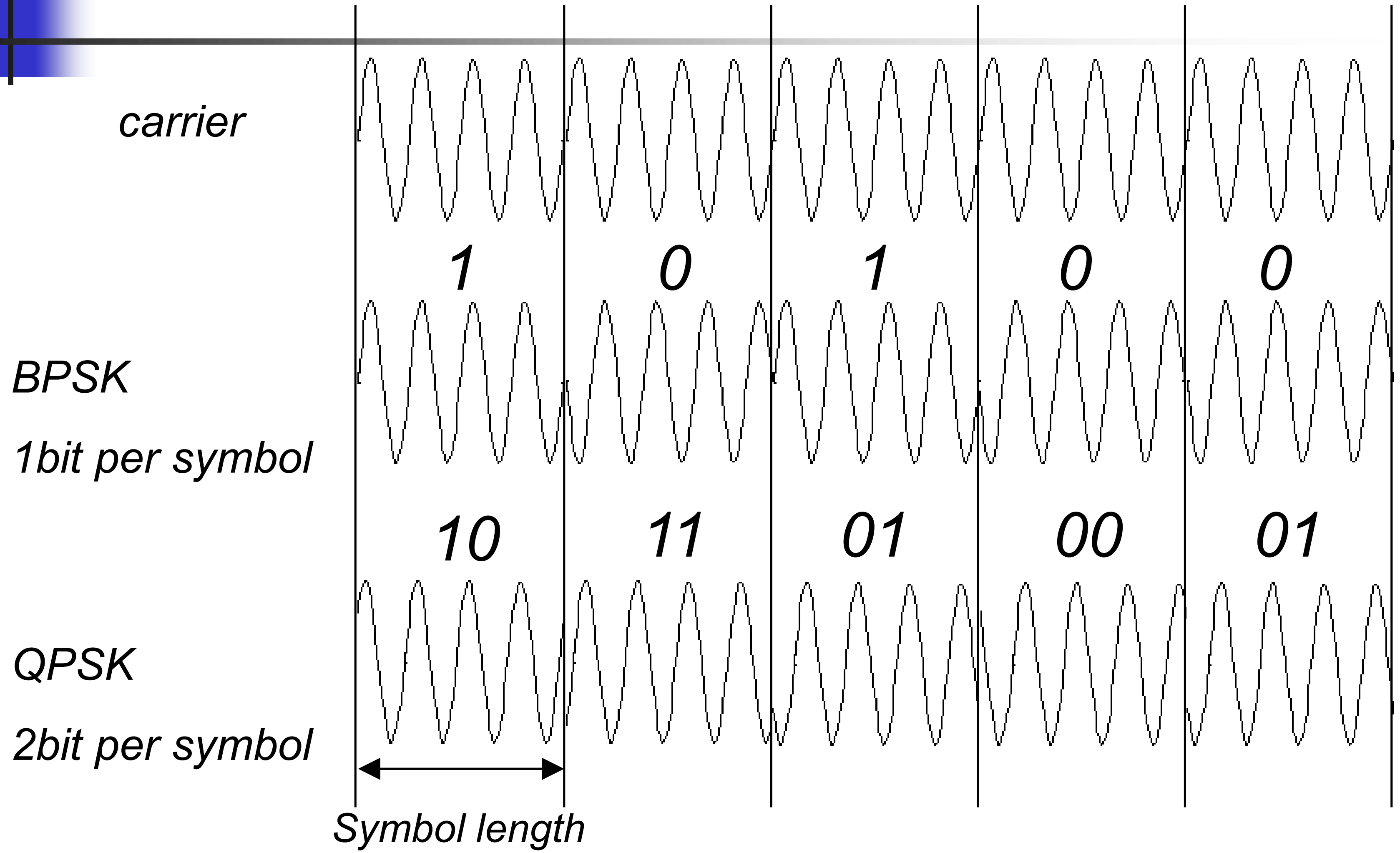
- Three type digital modulation:
  - ASK : Amplitude Shift Keying
  - PSK : Phase Shift Keying
  - FSK : Frequency Shift Keying

OFDM uses combination of ASK and PSK such as QAM, PSK

Symbol Waveform



Multi bit modulation



Mathematical expression of digital modulation

- Transmission signal can be expressed as follows

$$s(t) = \cos(2\pi \cdot f_c \cdot t + \theta_k)$$

$$= \cos\theta_k \cdot \cos(2\pi \cdot f_c \cdot t) - \sin\theta_k \cdot \sin(2\pi \cdot f_c \cdot t)$$

$$a_k = \cos\theta_k, \quad b_k = \sin\theta_k$$

$$s(t) = \mathrm{Re}[(a_k + jb_k)e^{j2\pi fc \cdot t}]$$

- s(t) can be expressed by complex base-band signal $(a_k + jb_k)e^{j2\pi fc \cdot t}$

$e^{j2\pi fc \cdot t}$ *Indicates carrier sinusoidal*

$(a_k + jb_k)$ *Digital modulation*

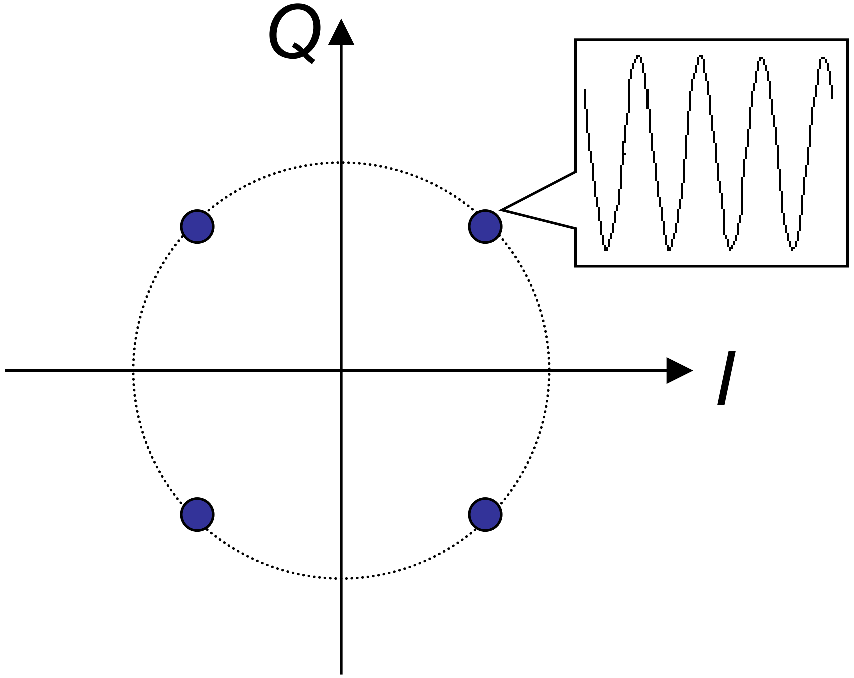
Digital modulation can be expressed by the complex number

Constellation map

- $(a_k + jb_k)$ is plotted on I(real)-Q(imaginary) plane

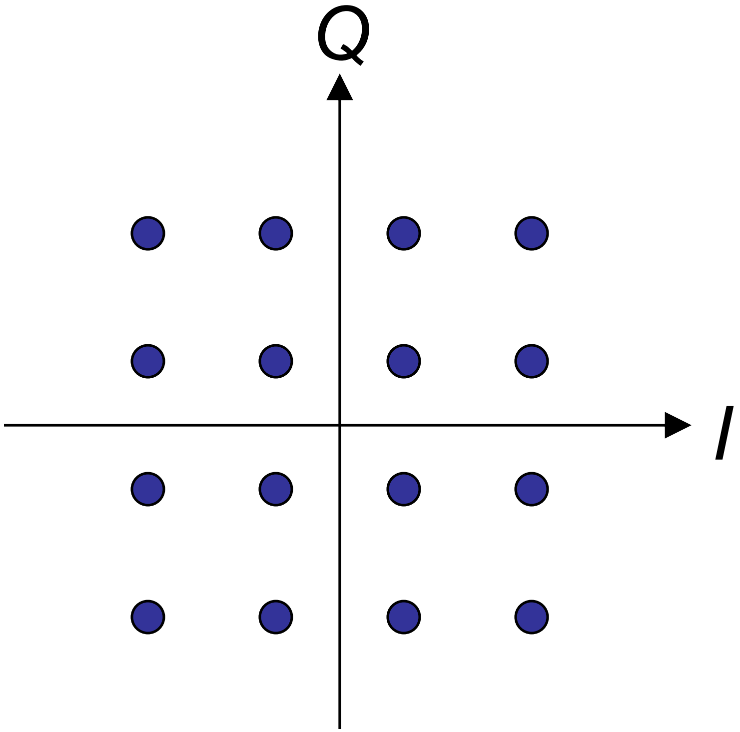
data		a_k	b_k
00	π/4	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$
01	3π /4	$-\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$
11	5π /4	$-\frac{1}{\sqrt{2}}$	$-\frac{1}{\sqrt{2}}$
10	7π /4	$\frac{1}{\sqrt{2}}$	$-\frac{1}{\sqrt{2}}$

QPSK

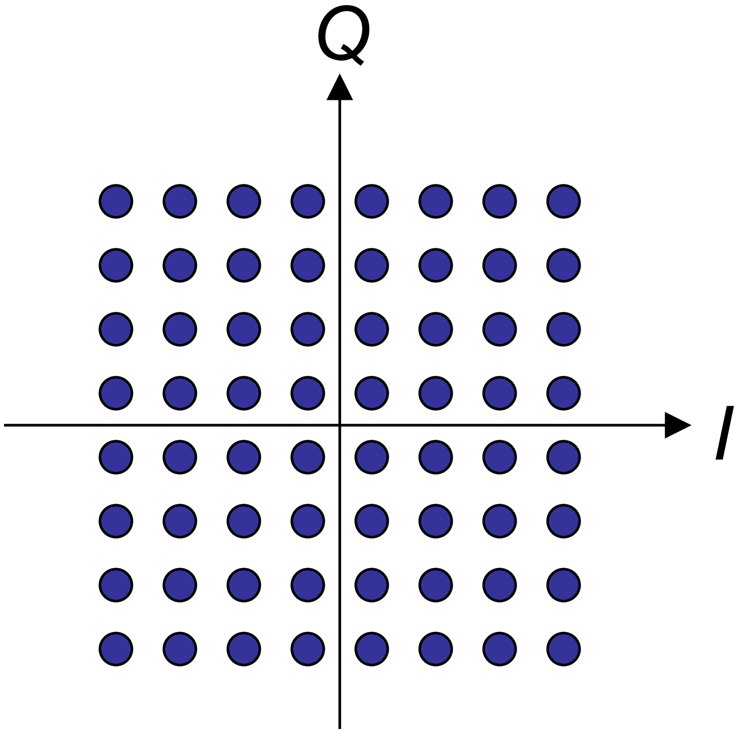


Quadrature Amplitude Modulation (QAM)

16QAM



64QAM

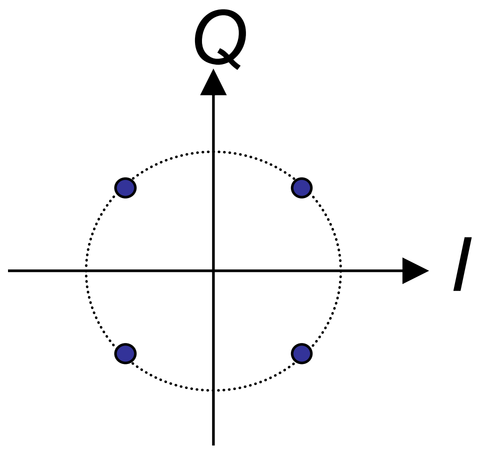


Summary of digital modulation

- Type of modulation: ASK,PSK,FSK,QAM
- OFDM uses ASK,PSK,QAM
- Digital modulation is mathematically characterized by the coefficient of complex base-band signal

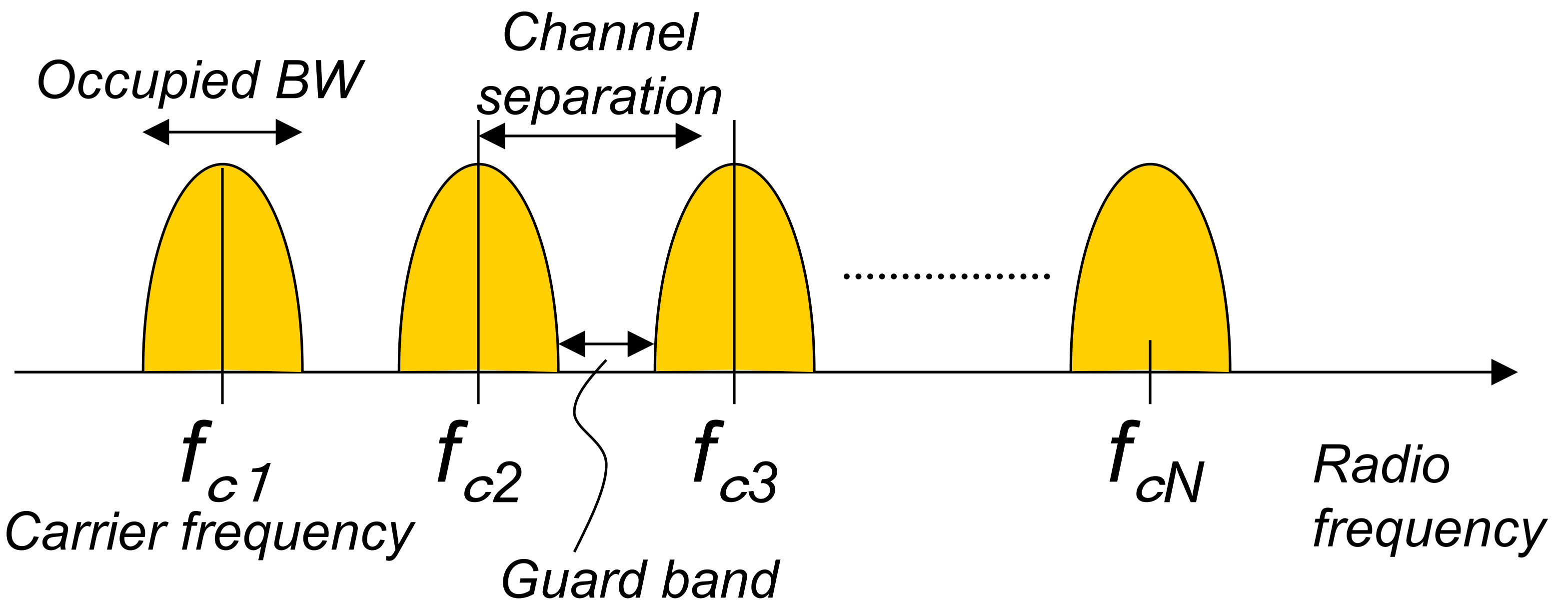
$$(a_k + jb_k)$$

- Plot of the coefficients gives the constellation map



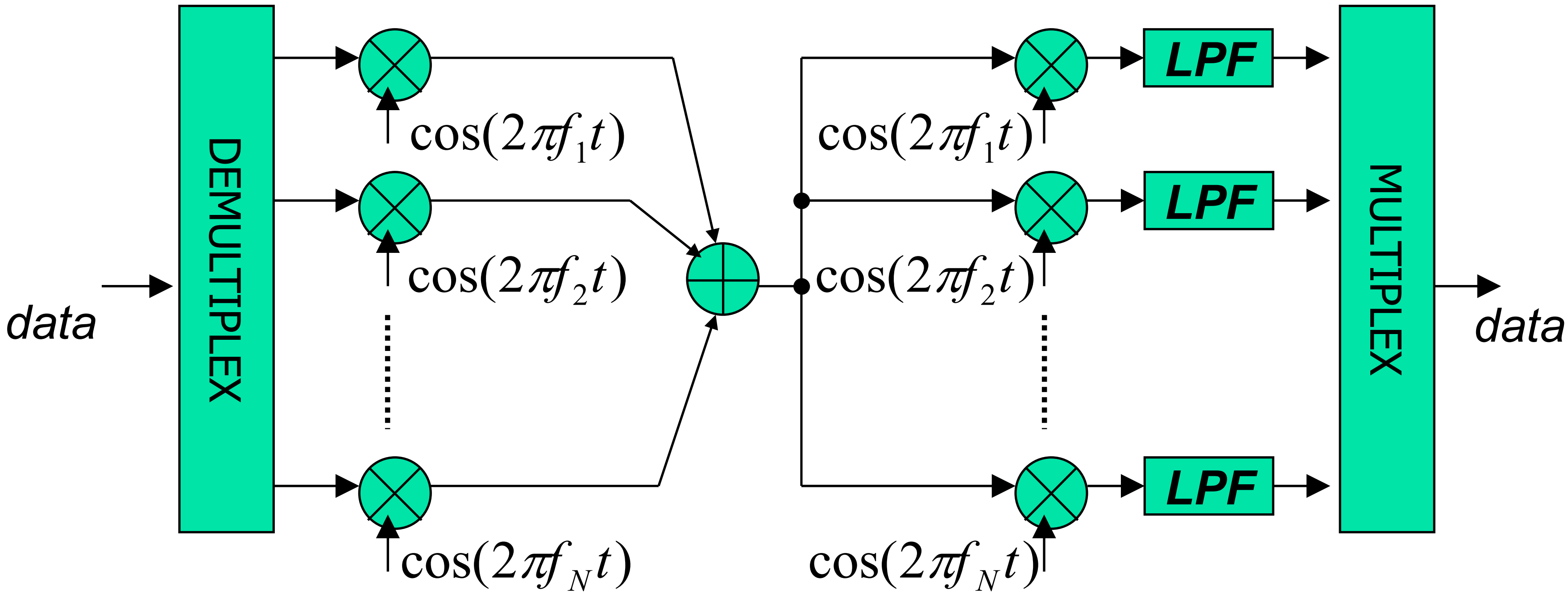
Frequency Division Multiple Access (FDMA)

- Old conventional method (Analog TV, Radio etc.)
- Use separate carrier frequency for individual transmission

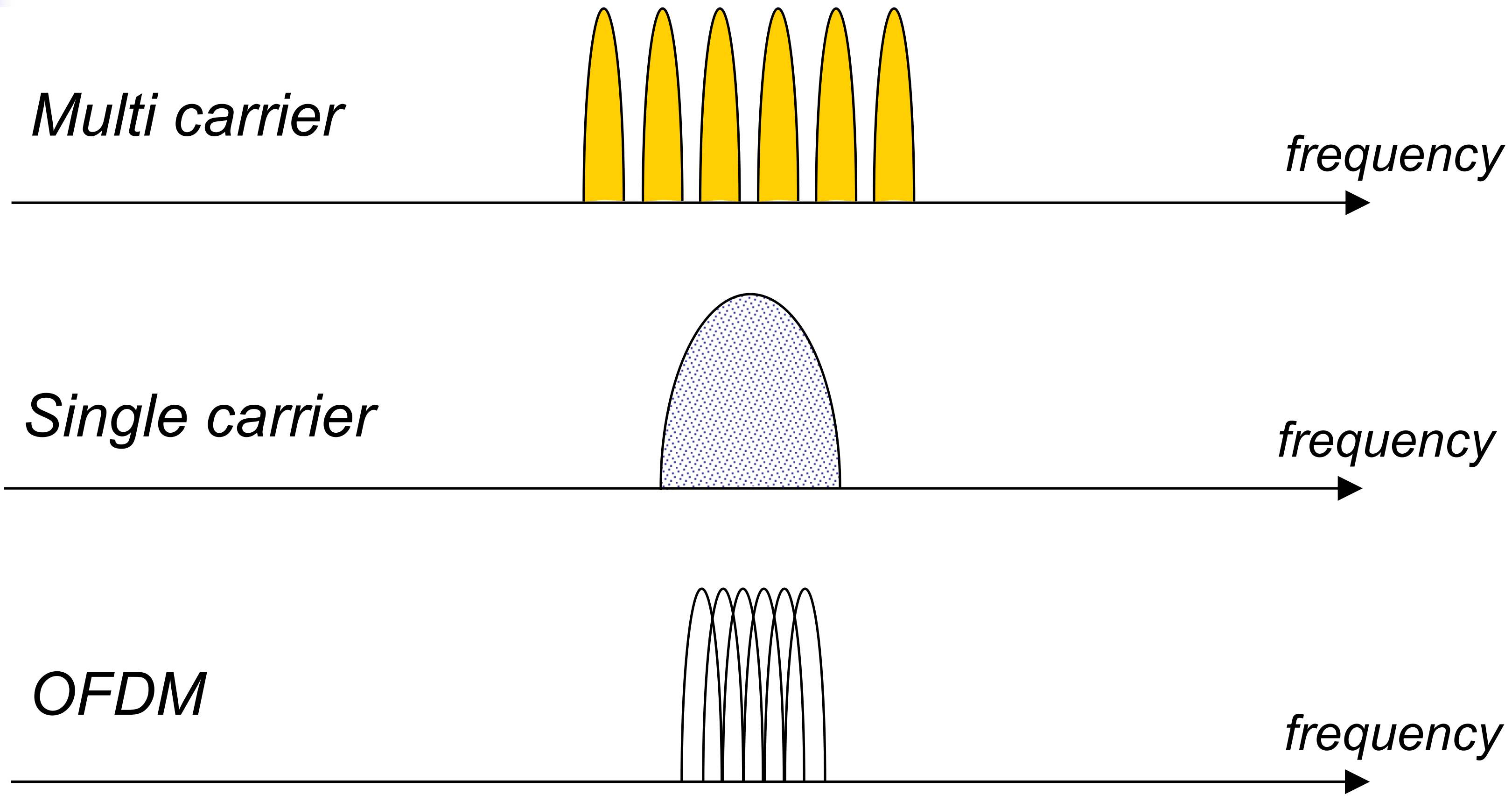


Multi-carrier modulation

- Use multiple channel (carrier frequency) for one data transmission



Spectrum comparison for same data rate transmission

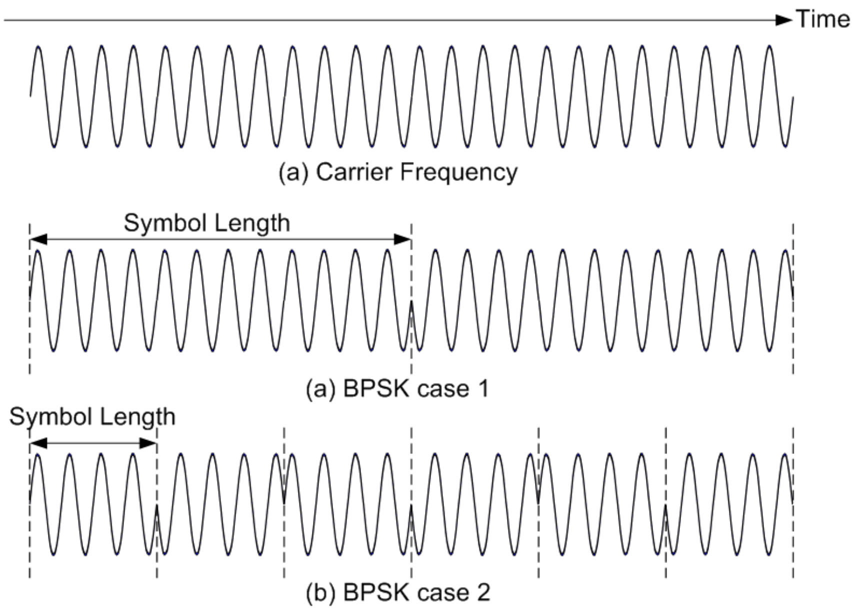


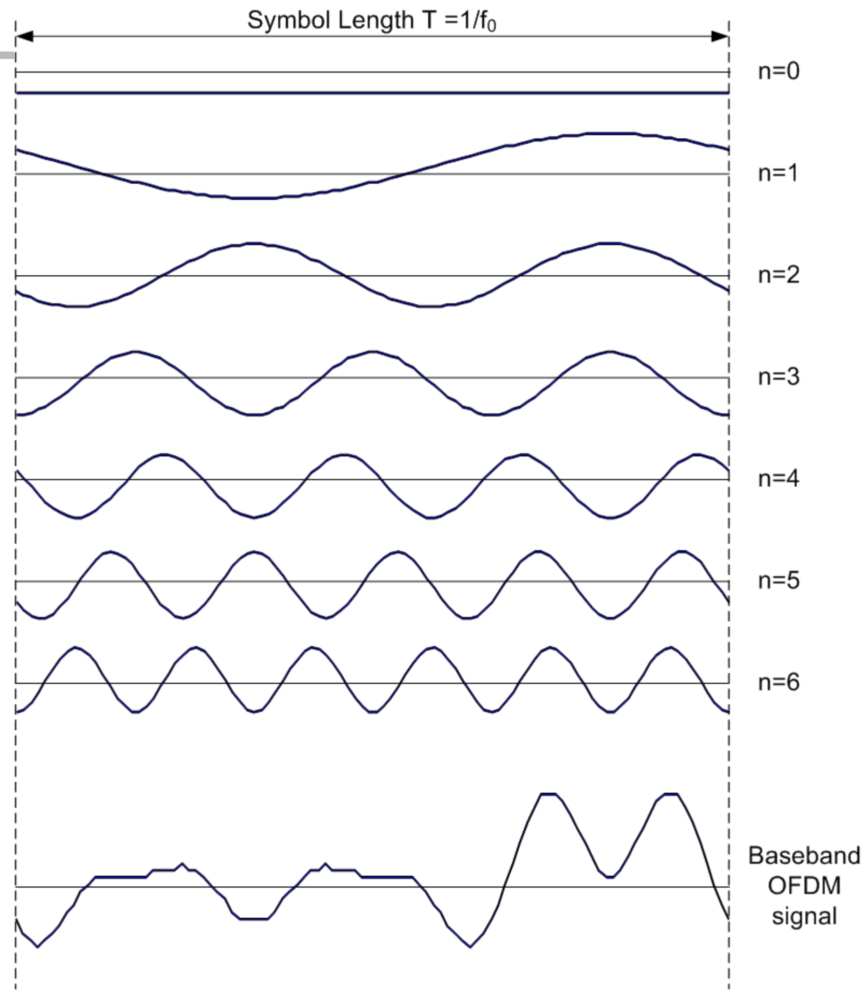
OFDM vs. Multi carrier

- OFDM is multi carrier modulation
- OFDM sub-carrier spectrum is overlapping
- In FDMA, band-pass filter separates each transmission
- In OFDM, each sub-carrier is separated by DFT because carriers are orthogonal
  - Condition of the orthogonality will be explained later
- Each sub-carrier is modulated by PSK, QAM

Thousands of PSK/QAM symbol can be simultaneously transmitted in one OFDM symbol

Single Carrier vs. Multi Carrier

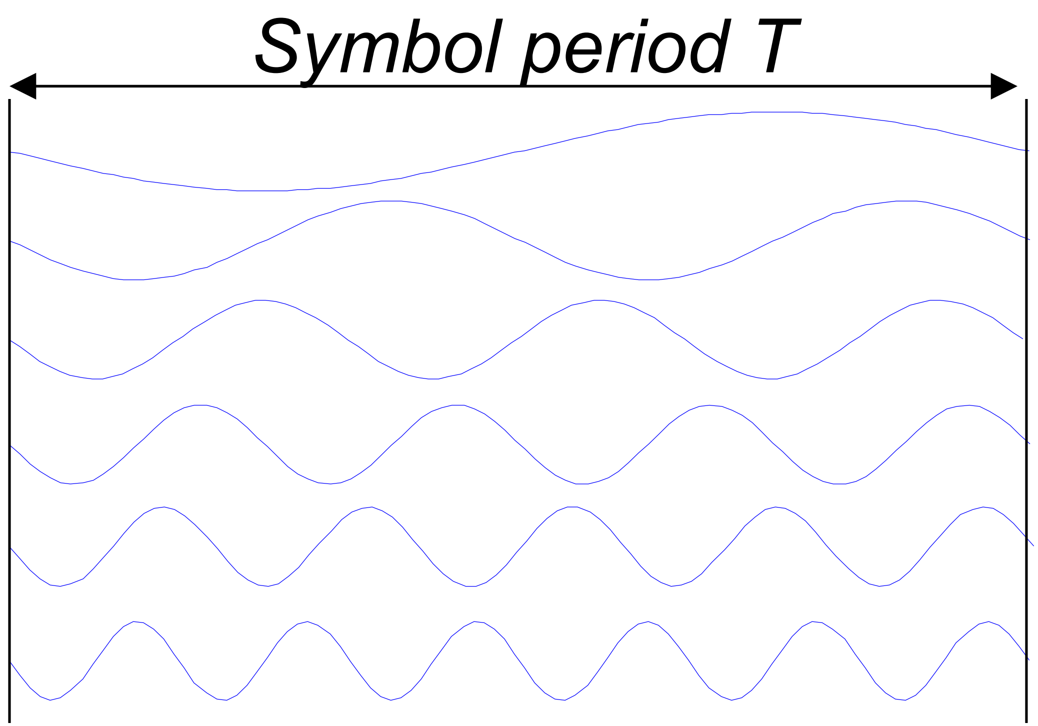




OFDM carriers

- OFDM carrier frequency is n·1/T

$$f_0 = \frac{1}{T}$$



$$\cos(2\pi \cdot 1 \cdot f_0 \cdot t + \theta_1)$$

$$\cos(2\pi \cdot 2 \cdot f_0 \cdot t + \theta_2)$$

$$\cos(2\pi \cdot 3 \cdot f_0 \cdot t + \theta_3)$$

$$\cos(2\pi \cdot 4 \cdot f_0 \cdot t + \theta_4)$$

$$\cos(2\pi \cdot 5 \cdot f_0 \cdot t + \theta_5)$$

$$\cos(2\pi \cdot 6 \cdot f_0 \cdot t + \theta_6)$$

Sinusoidal Orthogonality

- m,n: integer, $T=1/f_0$

$$\int_0^T \cos(2\pi m f_0 t)\cdot\cos(2\pi n f_0 t)dt = \begin{cases} \frac{T}{2} & (m=n) \\ 0 & (m\neq n) \end{cases}$$

$(m\neq n)$ → Orthogonal

$$\int_0^T \sin(2\pi m f_0 t)\cdot\sin(2\pi n f_0 t)dt = \begin{cases} \frac{T}{2} & (m=n) \\ 0 & (m\neq n) \end{cases}$$

$(m\neq n)$ → Orthogonal

$$\int_0^T \cos(2\pi m f_0 t)\cdot\sin(2\pi n f_0 t)dt = 0$$

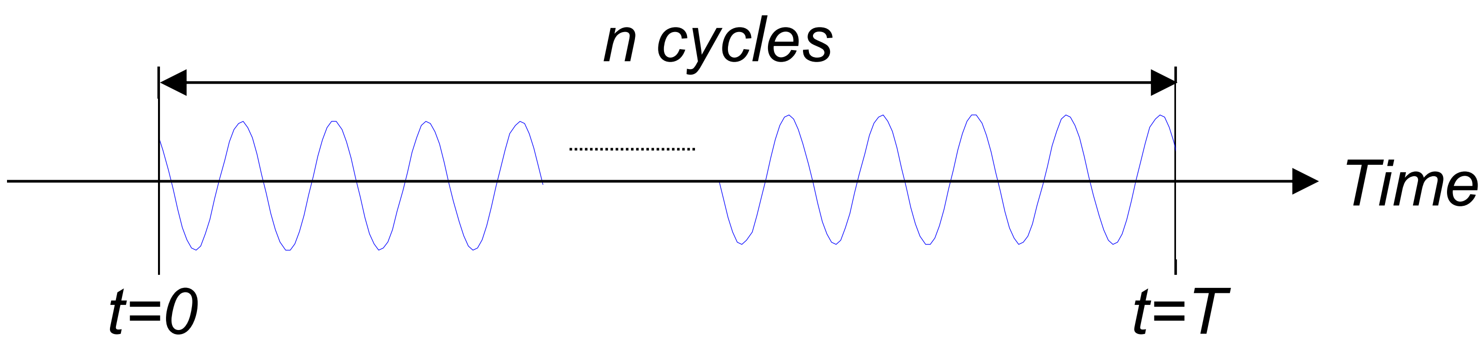
→ Orthogonal

A sub-carrier of $f=nf_0$

$$a_n \cdot \cos(2\pi n f_0 t) - b_n \cdot \sin(2\pi n f_0 t)$$

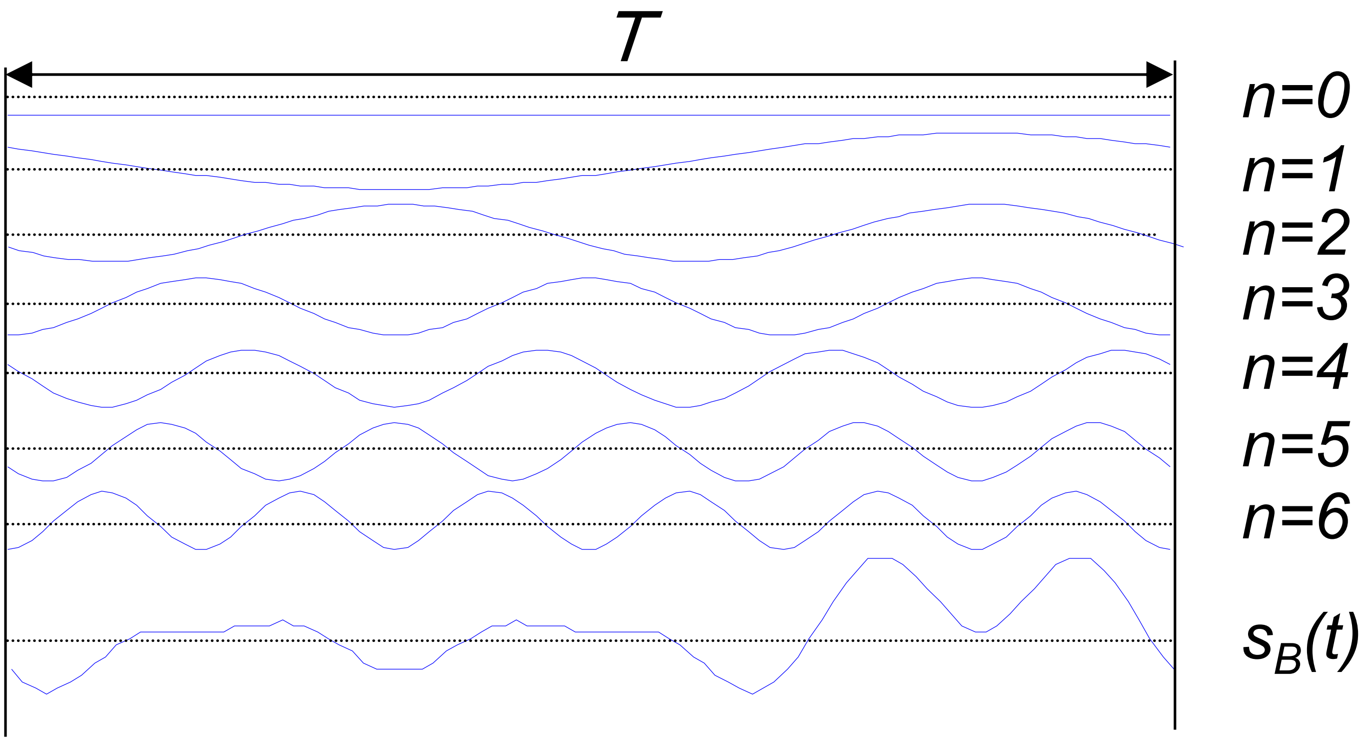
$$= \sqrt{a_n^{\,2} + b_n^{\,2}} \cos(2\pi n f_0 t + \phi_n), \qquad \phi_n = \tan^{-1} \frac{b_n}{a_n}$$

- Amplitude and Phase will be digitally modulated



Base-band OFDM signal

$$s_B(t) = \sum_{n=0}^{N-1} \left\{ a_n \cos(2\pi n f_0 t) - b_n \sin(2\pi n f_0 t) \right\}$$

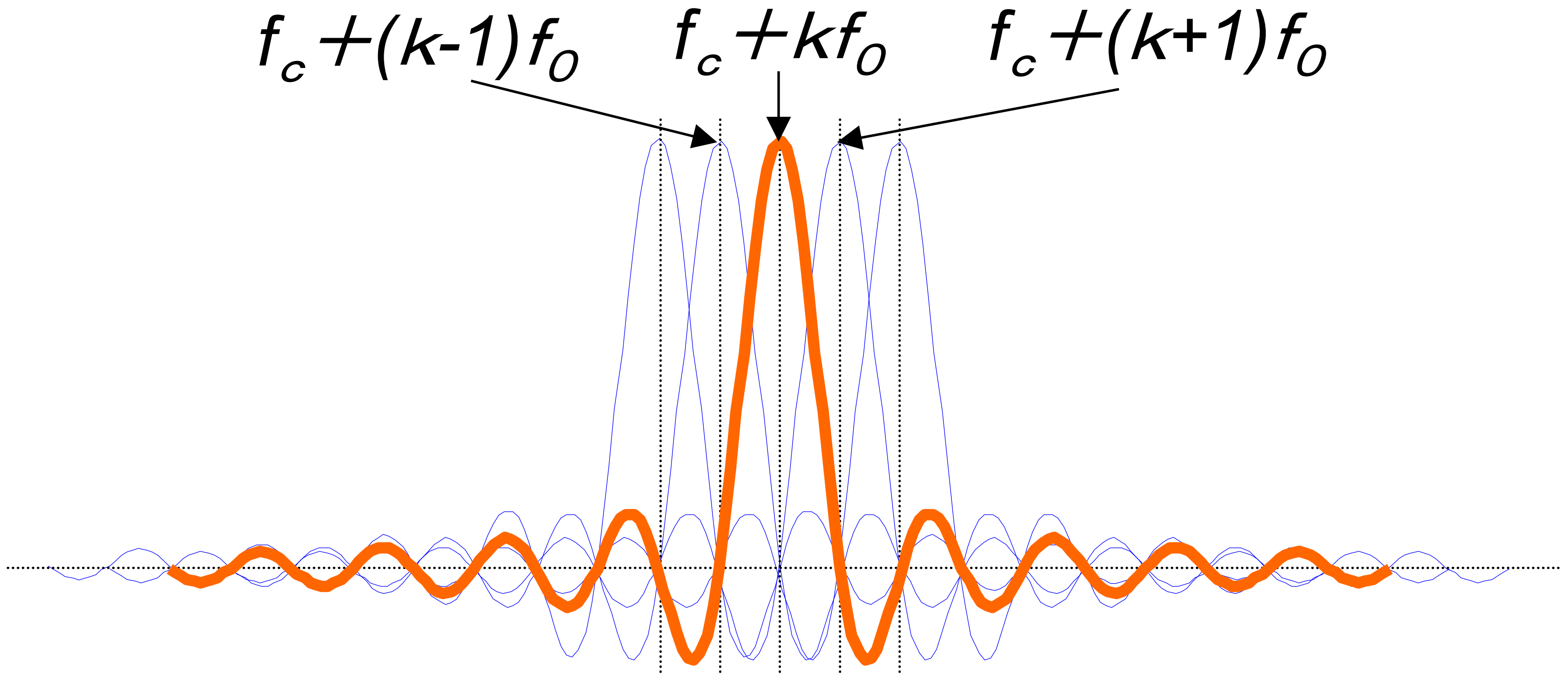


Pass-band OFDM signal

- *$S_B(t)$ is upcoverted to pass-band signal $S(t)$*
- *f_c frequency shift*

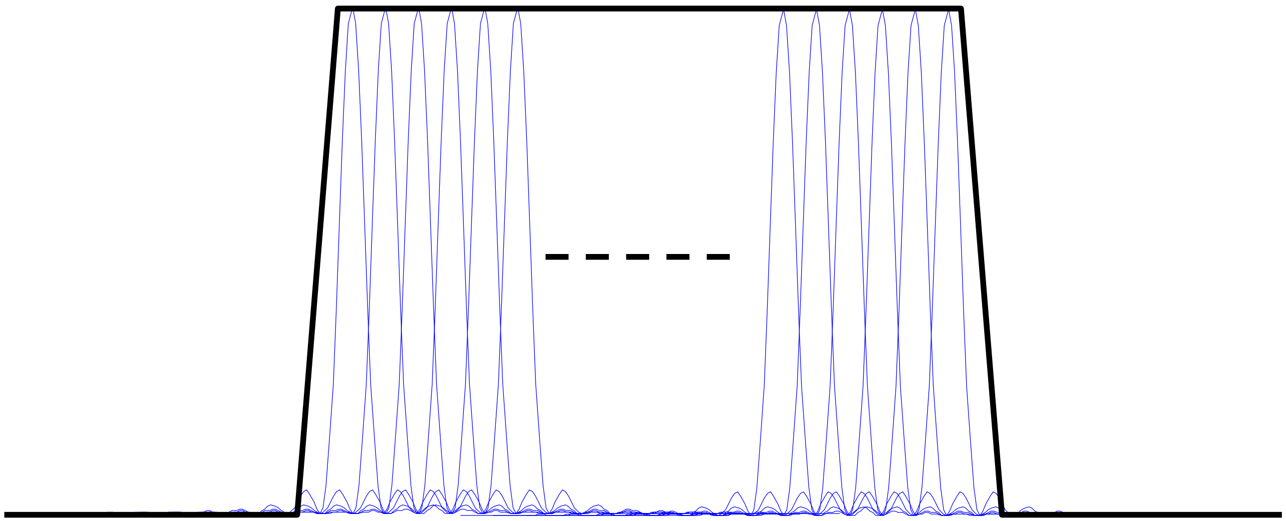
$$s(t) = \sum_{n=0}^{N-1} \left[a_n \cos\left\{ 2\pi (f_c + nf_0) t \right\} - b_n \sin\left\{ 2\pi (f_c + nf_0) t \right\} \right]$$

Actual OFDM spectrum



OFDM power spectrum

- Total Power spectrum is almost square shape



OFDM signal generation

$$s(t)=\sum_{n=0}^{N-1}\left[a_n\cos\left\{2\pi(f_c+nf_0)t\right\}-b_n\sin\left\{2\pi(f_c+nf_0)t\right\}\right]$$

- Direct method needs

  N digital modulators

  N carrier frequency generator

  ➔ Not practical

- In 1971, method using DFT is proposed to OFDM siganal generation

OFDM signal generation in digital domain

- Define complex base-band signal u(t) as follows

$$s_B(t) = \mathrm{Re}[u(t)]$$

$$u(t) = \sum_{n=0}^{N-1} d_n \cdot e^{j2\pi n f_0 t}, \quad d_n = a_n + jb_n$$

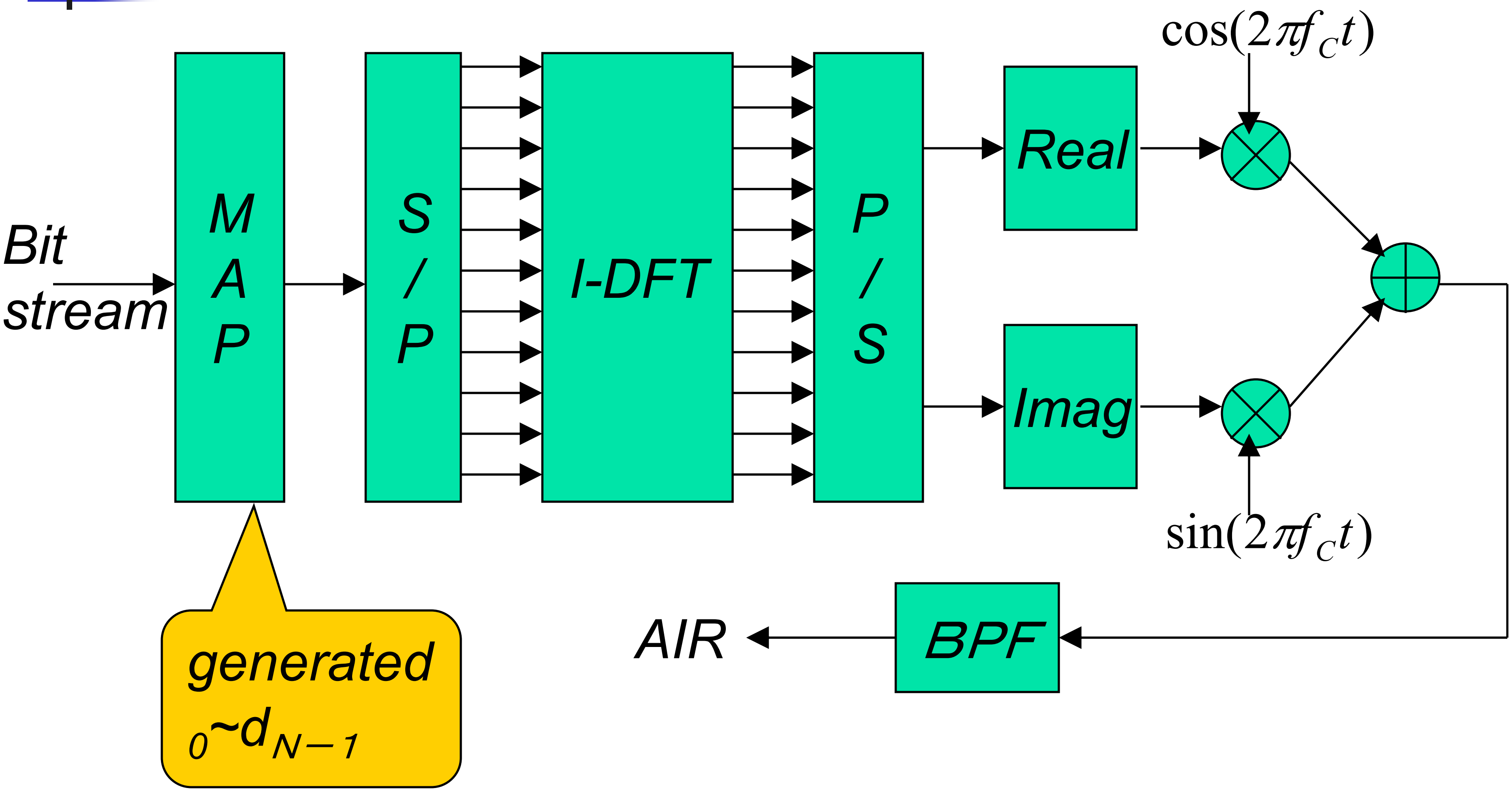
- Perform N times sampling in period T

$$u\left(\frac{k}{Nf_0}\right) = \sum_{n=0}^{N-1} d_n \cdot e^{j2\pi n f_0 \frac{k}{Nf_0}} = \sum_{n=0}^{N-1} d_n \cdot e^{j\frac{2\pi nk}{N}}$$

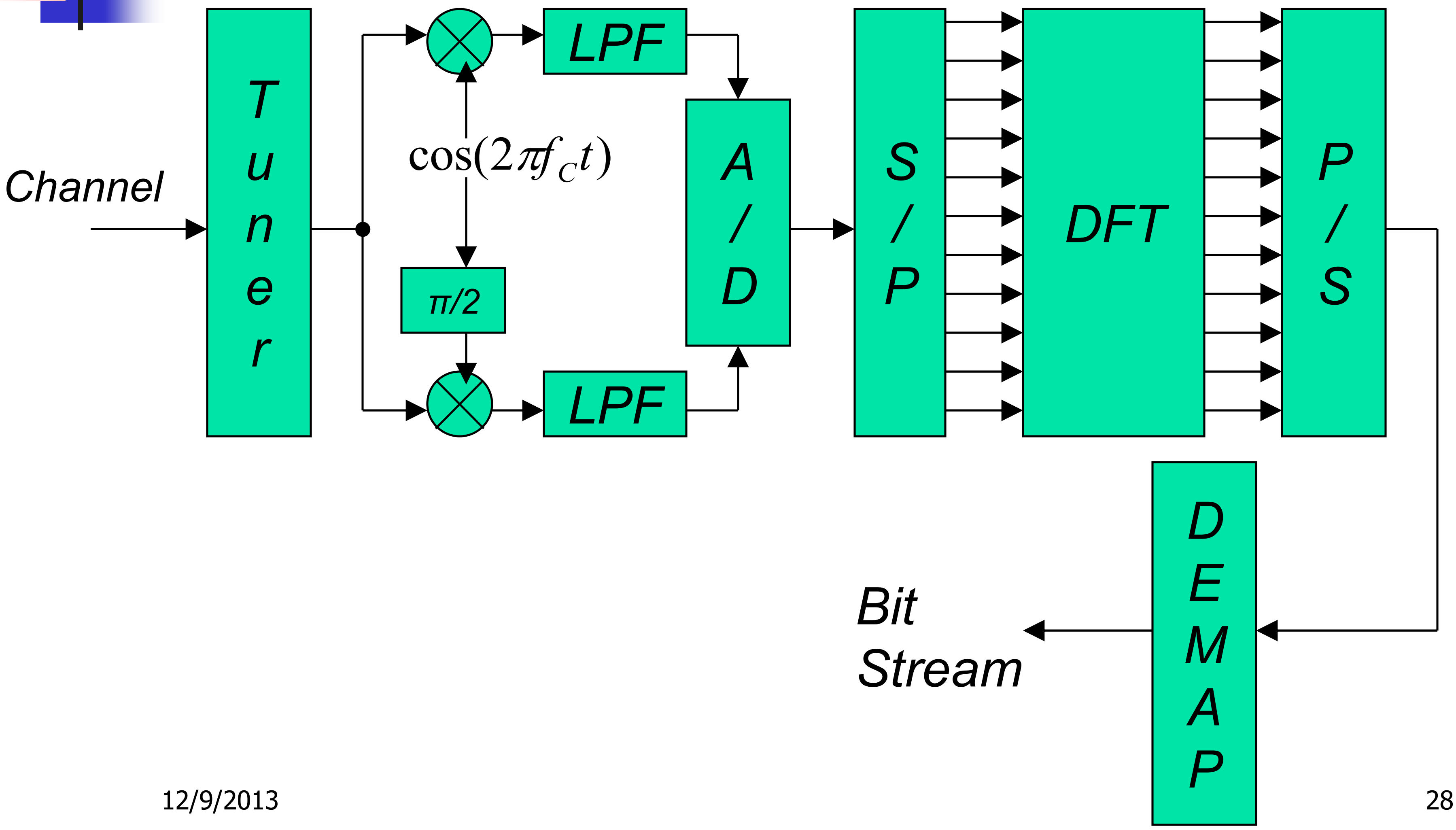
$$= \sum_{n=0}^{N-1} d_n \cdot \left(e^{j\frac{2\pi}{N}}\right)^{nk} \qquad (k = 0,1,2,\cdots,N-1)$$

$u(k) = IFFT\ (d_n) = IFFT(a_n + jb_n)$

OFDM modulator

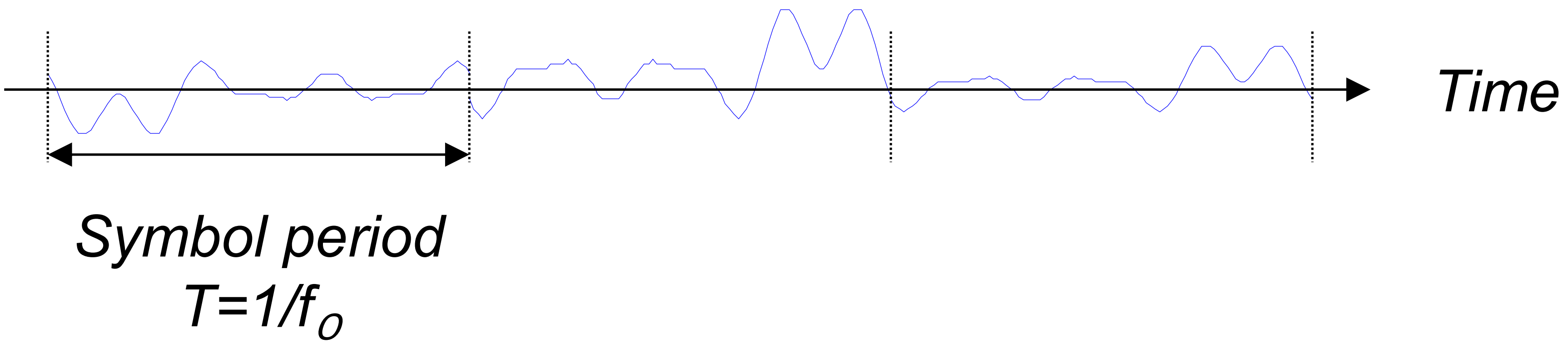


OFDM demodulator (Too simple)



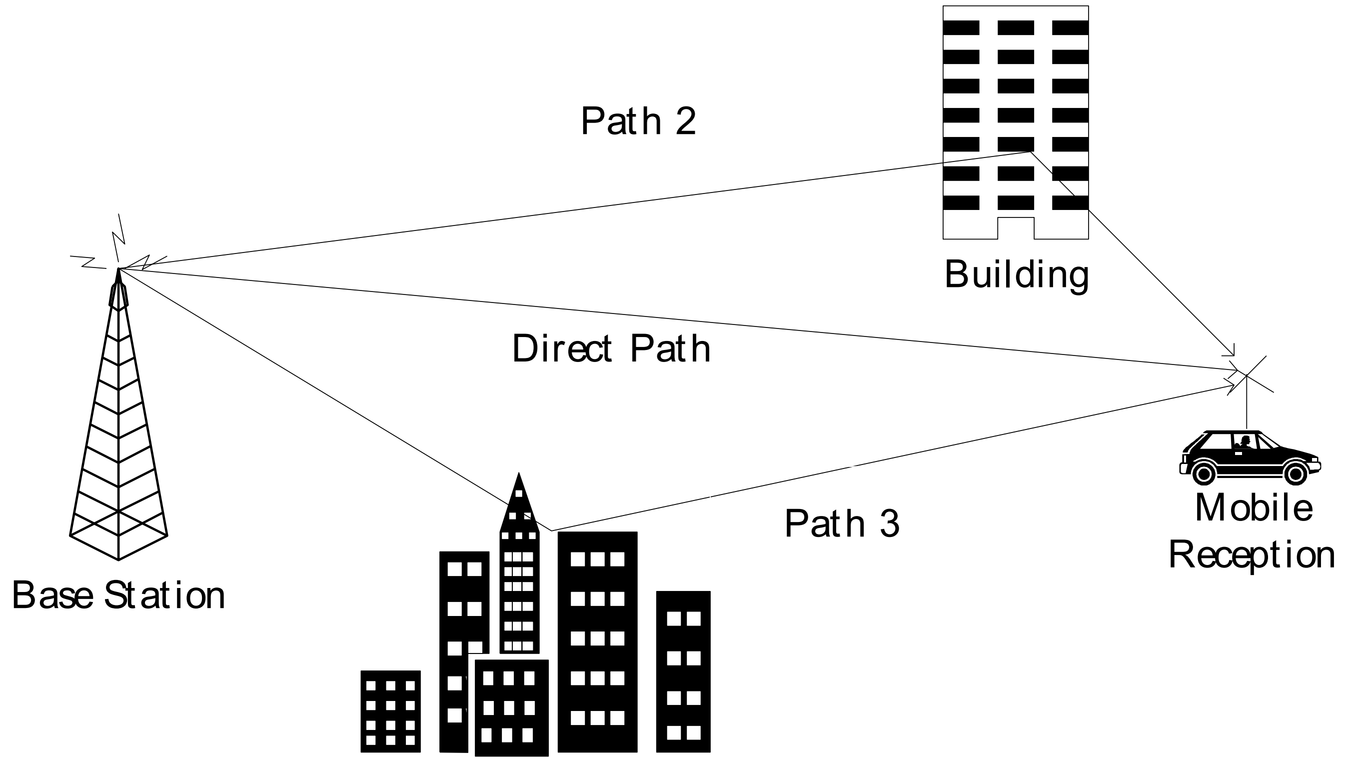
Summary of OFDM signal

- Each symbol carries information
- Each symbol wave is sum of many sinusoidal
- Each sinusoidal wave can be PSK, QAM modulated
- Using IDFT and DFT, OFDM implementation became practical

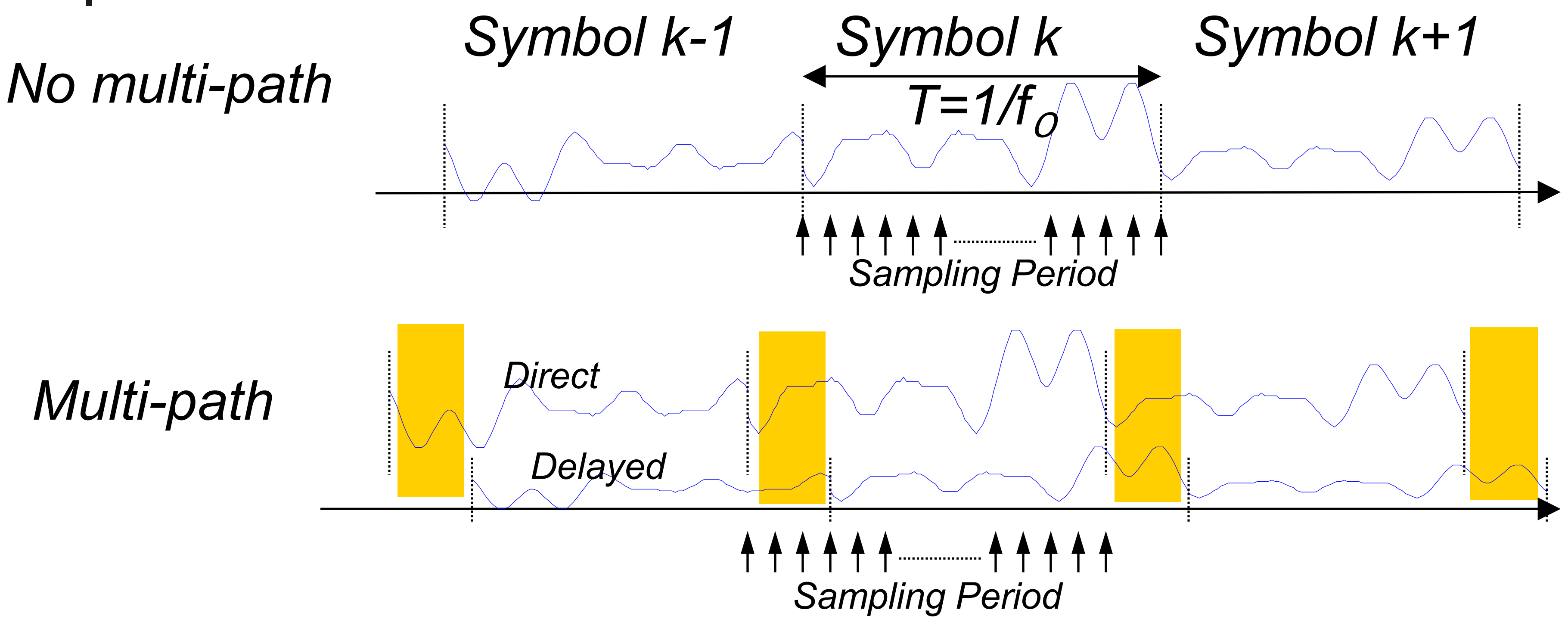


Multi-path

- Delayed wave causes interference

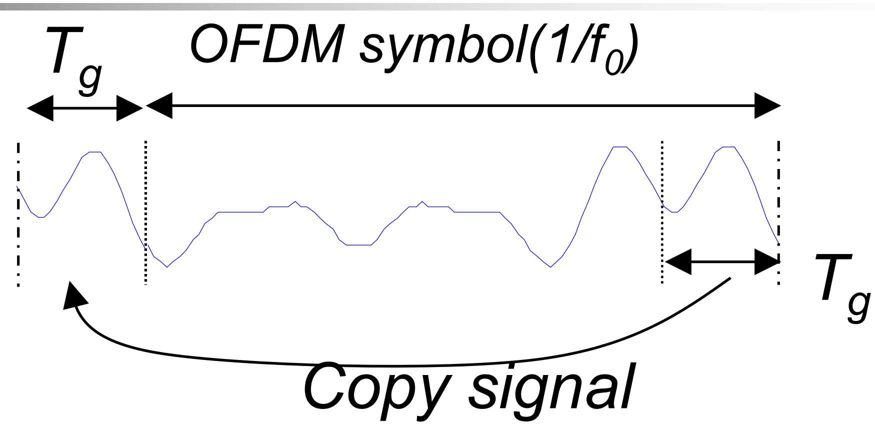


Multi-pass effect

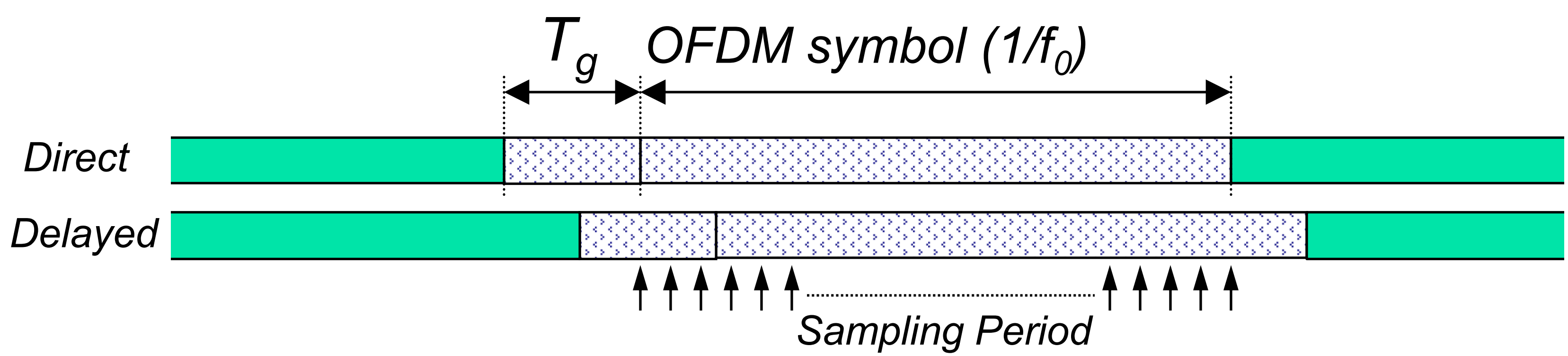


- Inter symbol interference (ISI) happens in Multi-path condition

Guard Interval T_g

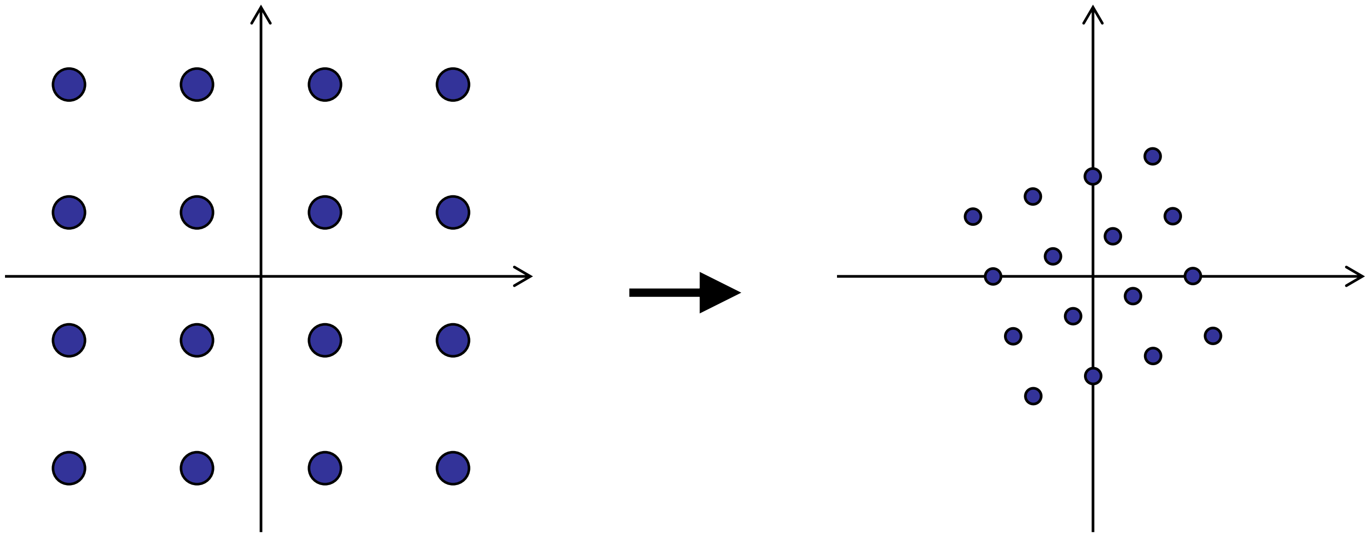


- By adding the Gurard Interval Period, ISI can be avoided



Multi-path

- By adding GI, orthogonality can be maintained
- However, multi-path causes Amplitude and Phase distortion for each sub-carrier
- The distortion has to be compensated by Equalizer



18.2.5 Channel Estimation and Equalizer

- Reception signal $s_R(t)$

$$s_R(t) = \int_{-\infty}^{\infty} h(u)s(t-u)du + n_c(t) \qquad (18.18)$$

- CTF

$$H(f) = \int_{0}^{Tg} h(t)e^{-j2\pi ft}dt \qquad (18.19)$$

- Frequency domain

$$x(k,l) = H(f_c + lf_0)d(k,l) + N_B(k,l) \qquad (18.20)$$

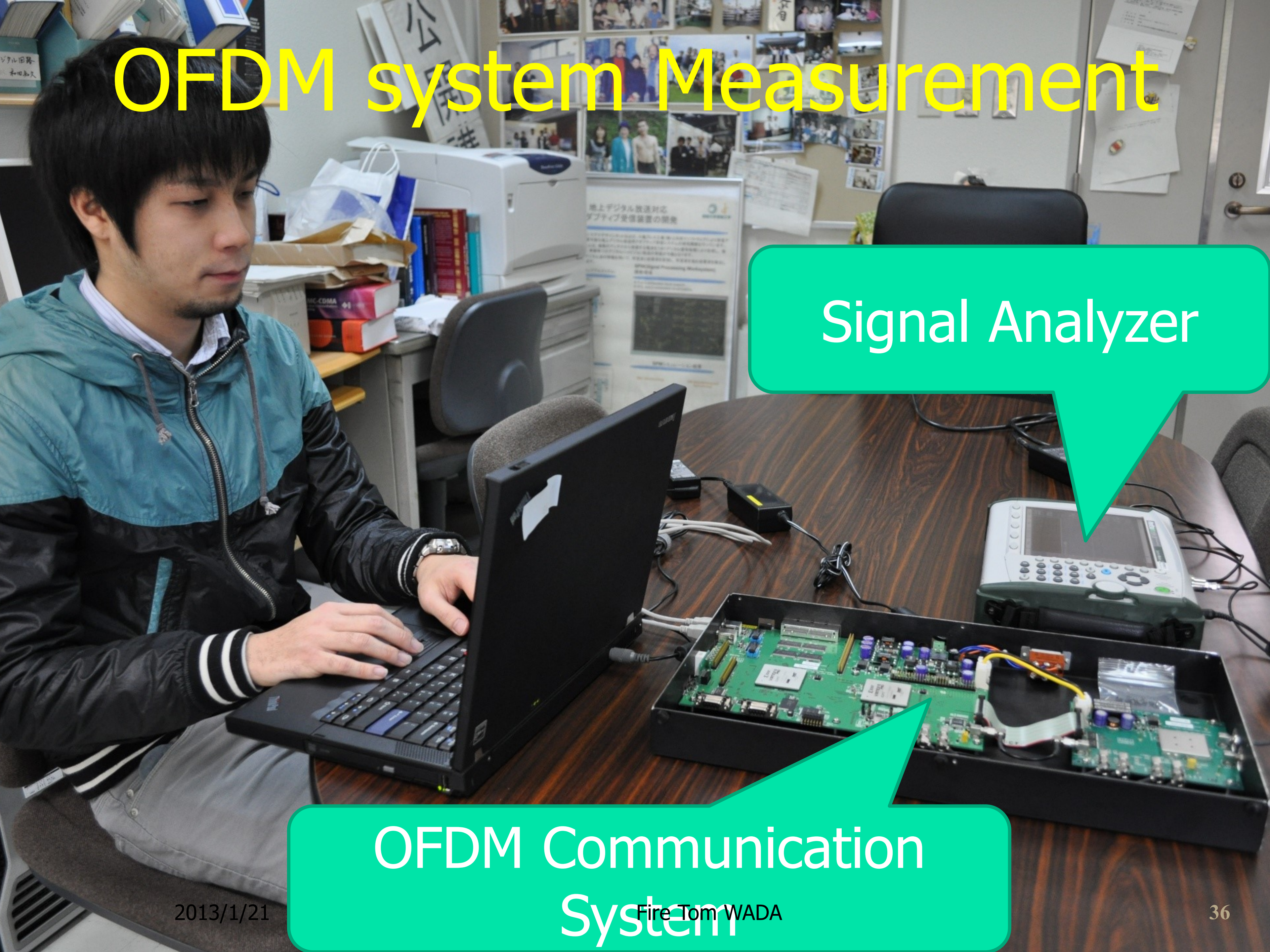
- Equalization

$$\hat{d}(k,l) = \frac{x(k,l)}{H(f_c + lf_0)} = d(k,l) + \frac{N_B(k,l)}{H(f_c + lf_0)} \qquad (18.21)$$

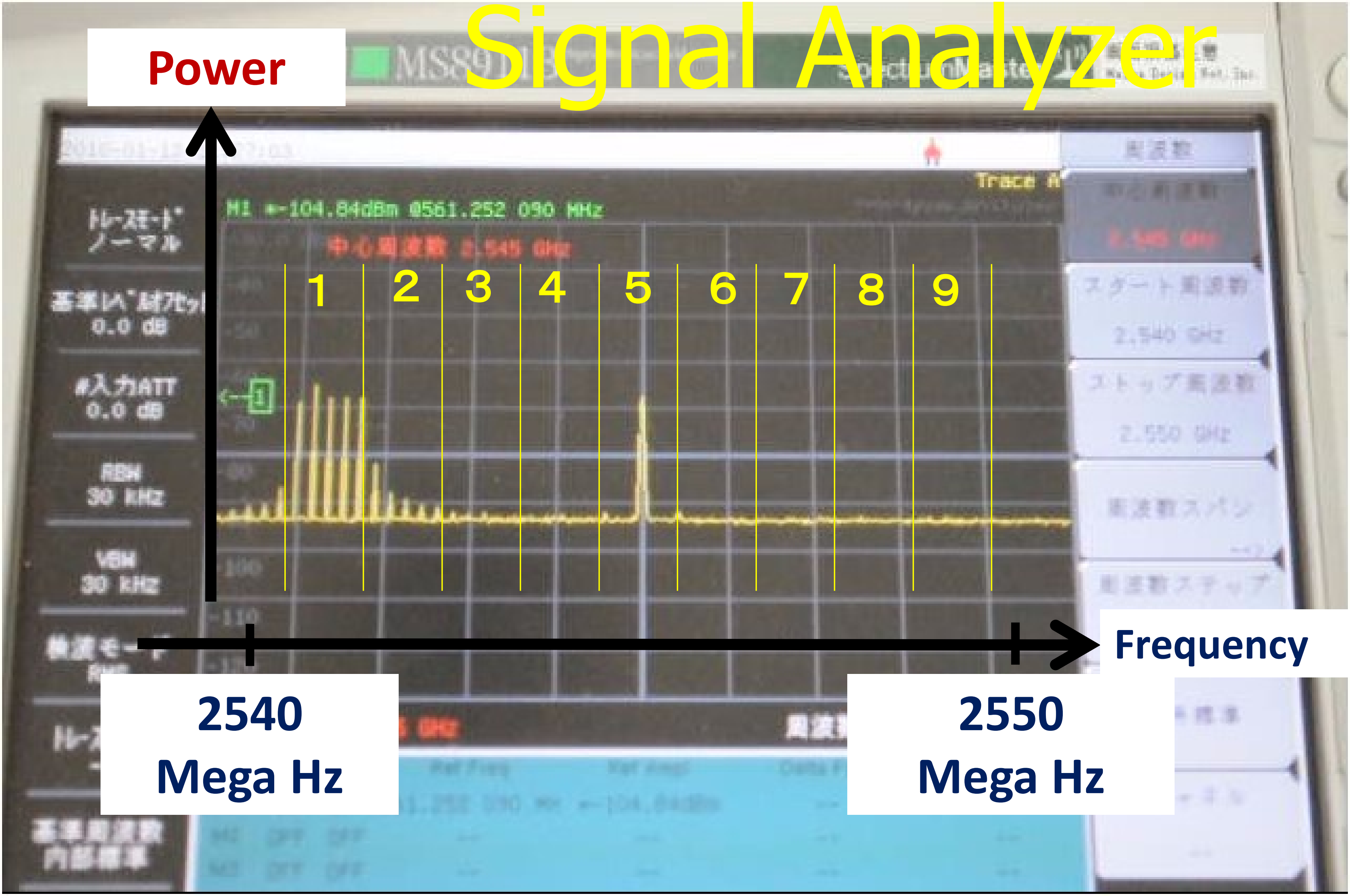
18.2.6
OFDM communication and broadcasting systems

Application of OFDM	Effective OFDM symbol length $1/f_0$
WLAN (802.11g/a/n)	3.2us
XGP (eXtended Global Platform)	26.67us
3.9G mobile phone LTE	66.67 us
WiMAX (802.16e)	102.4us
3.9G mobile phone LTE (Extended mode)	133.33 us
China Digital TV Broadcasting DTMB	500.0us
Europe Digital TV Broadcasting DVB-T	896us (8K mode)
Japan Digital TV Broadcasting ISDB-T	1008us (8K mode)

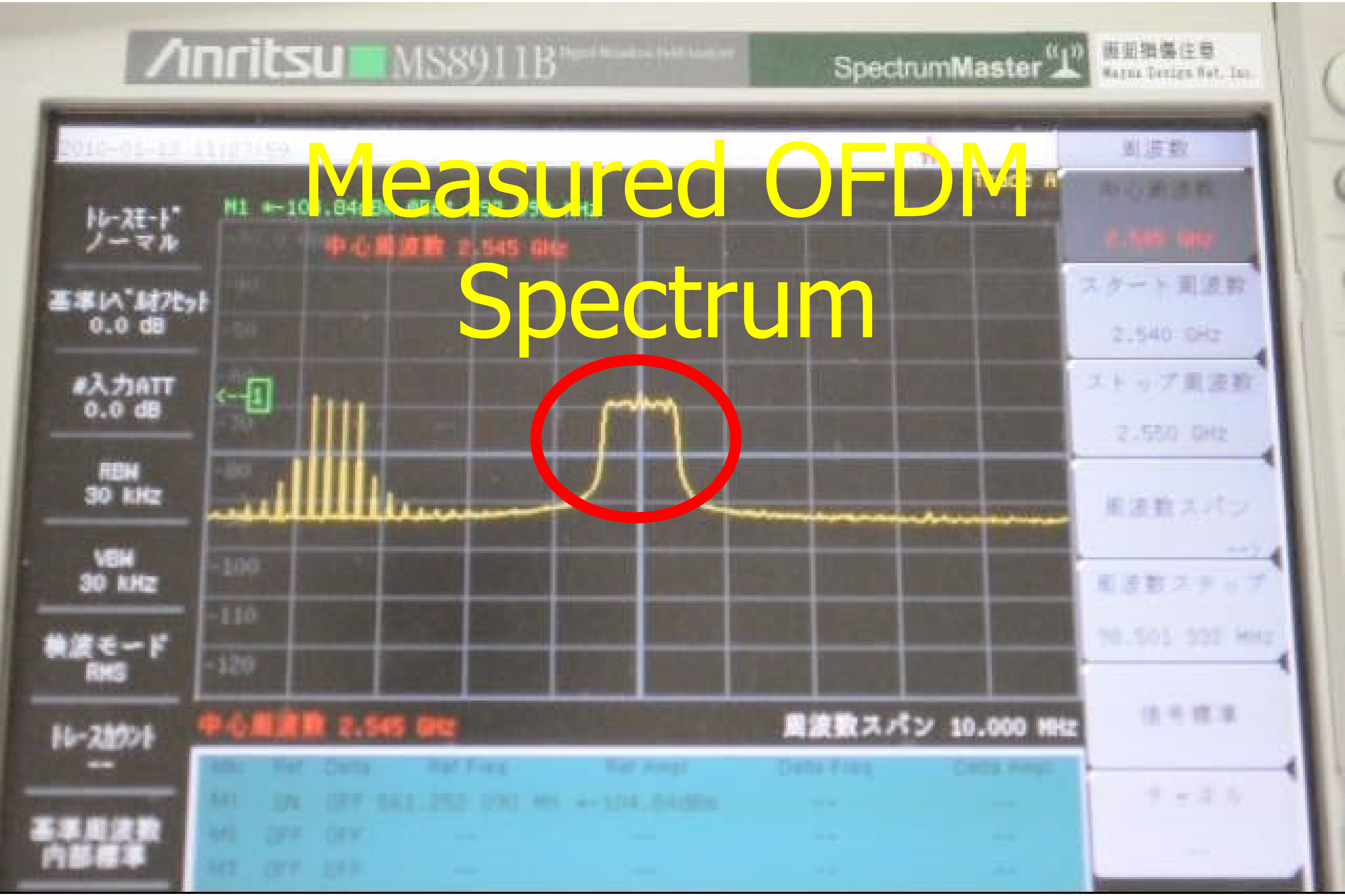
OFDM system Measurement



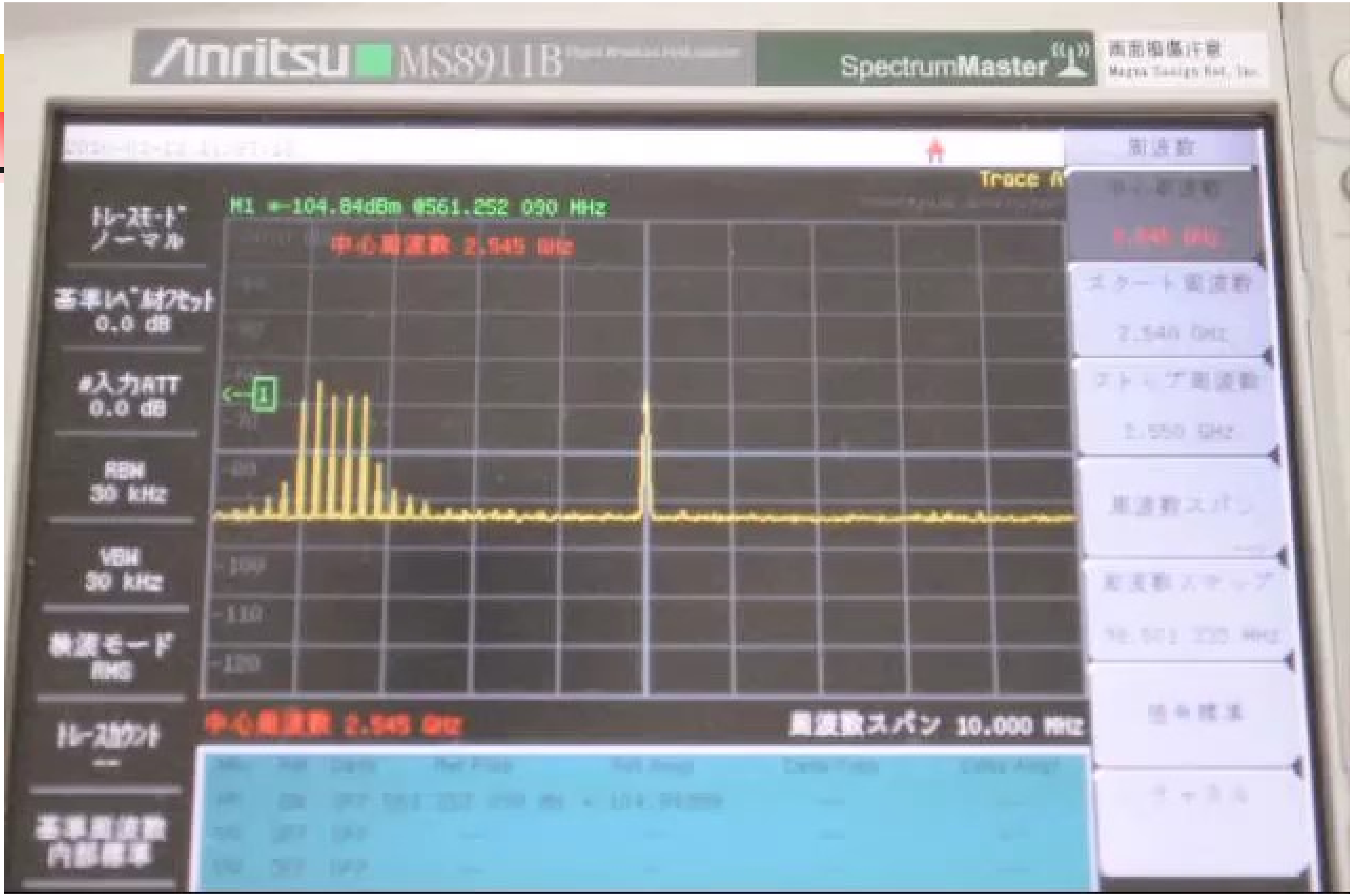
Signal Analyzer



Measured OFDM Spectrum



Video Demo


Anritsu MS8911B
SpectrumMaster
M1 ◆-104.84dBm @561.252 090 MHz
中心周波数 2.545 GHz
トレースモード
ノーマル
基準レベルオフセット
0.0 dB
#入力ATT
0.0 dB
RBW
30 kHz
VBW
30 kHz
検波モード
RMS
トレースカウント
基準周波数
内部標準
周波数スパン 10.000 MHz
Trace A

That's all for introduction

- Feature of OFDM
  1. High Frequency utilization by the square spectrum shape
  2. Multi-path problem is solved by GI
  3. Multiple services in one OFDM by sharing sub-carriers (3 services in ISDB-T)
  4. SFN
  5. Implementation was complicated but NOW possible because of LSI technology progress

REAL OFDM SYSTEMs

1. OFDM WLAN
2. OFDMA transceiver design (LTE)

EXAMPLE 1)

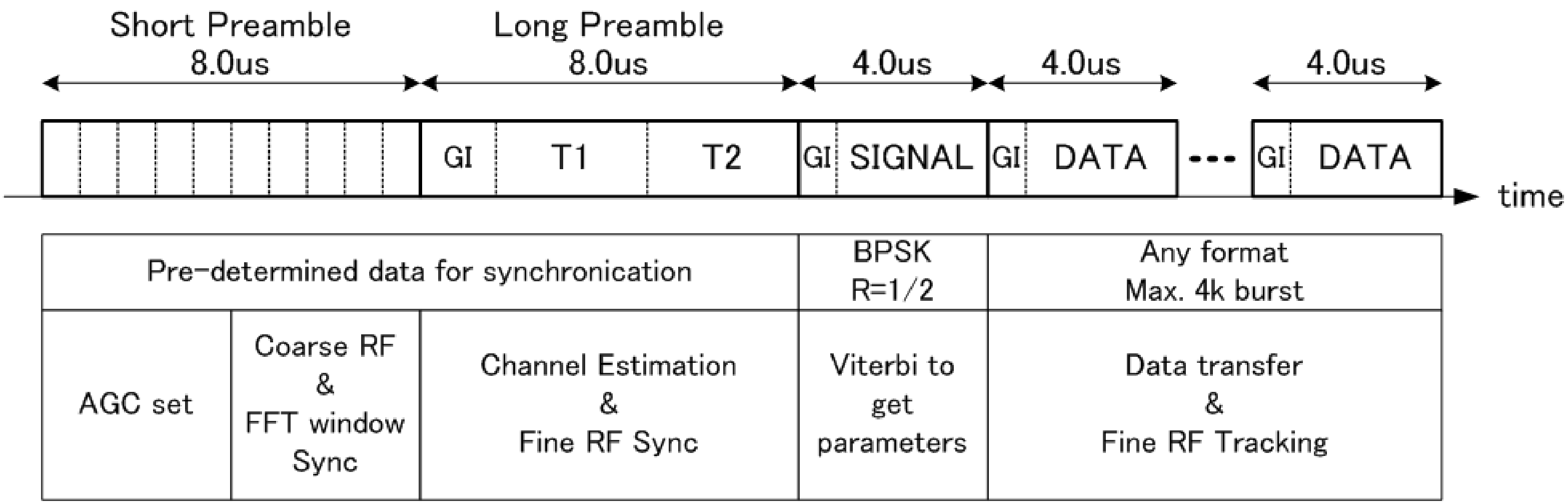
WLAN
Wireless LAN
802.11a/g

OFDM WLAN SYSTEM SPEC

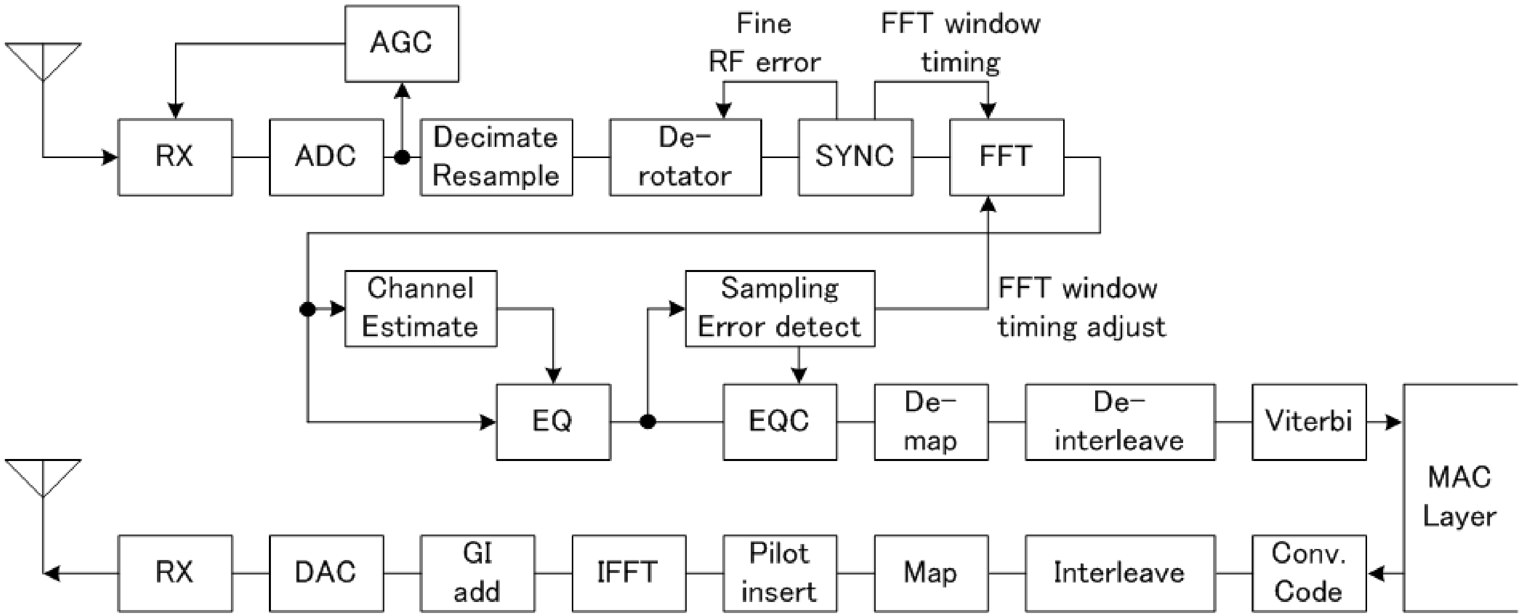
- **802.11a: 5GHz BAND**
- **802.11g: 2.4GHz BAND**

Data rate (Mbps)	6	9	12	18	24	36	48	54
Modulation	BPSK	BPSK	QPSK	QPSK	16QAM	16QAM	64QAM	64QAM
Code rate	1/2	3/4	1/2	3/4	1/2	3/4	2/3	3/4
# of subcarriers	52							
# of pilots	4							
OFDM symbol length	4us (effective symbol=3.2us)							
Guard Interval length	0.8us							
Subcarrier spacing	312.5kHz = 1/3.2us							
Sampling rate	20MHz (50ns)							

WLAN frame format and receiver tasks



WLAN Block Diagram

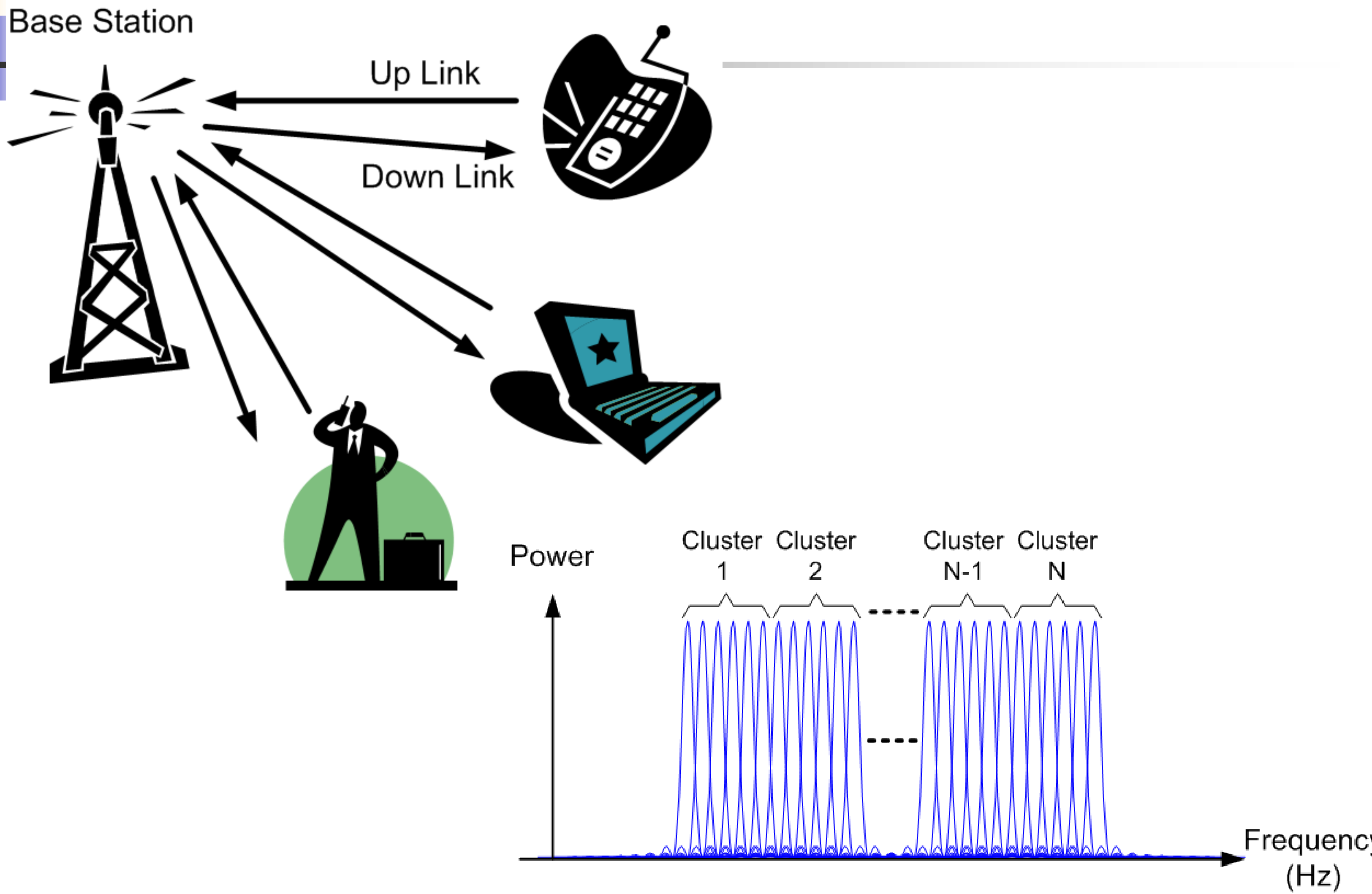


EXAMPLE 2)

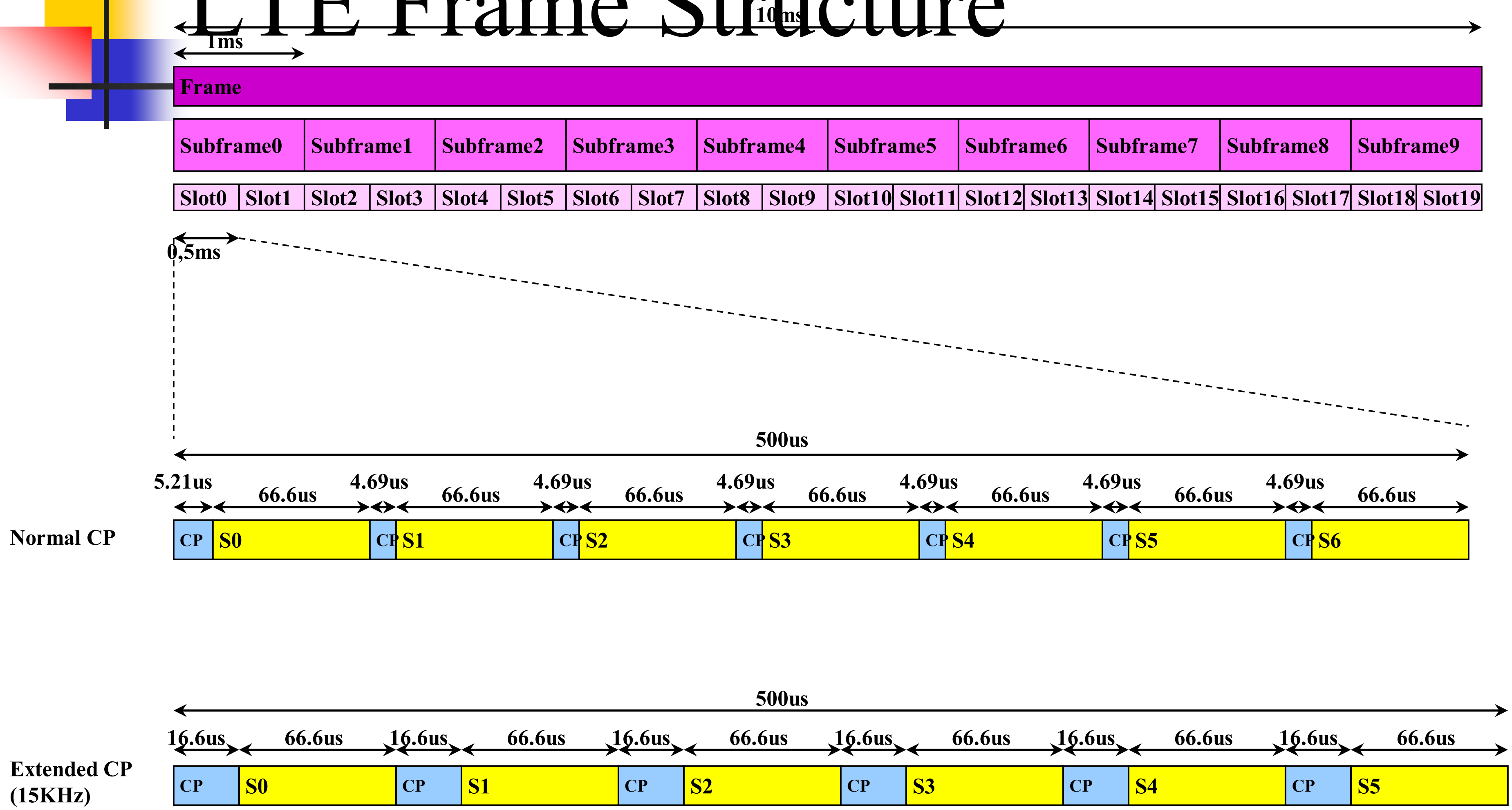
LTE

Long Term Evolution

LTE is OFDMA transceiver

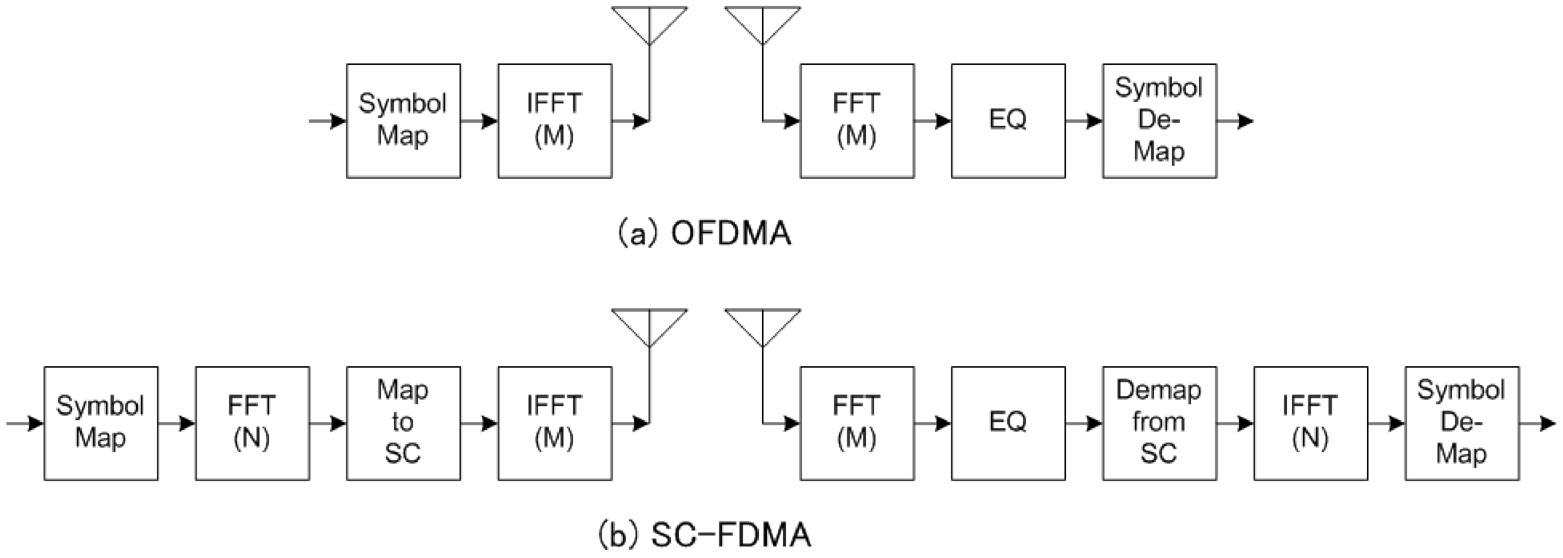


LTE Frame Structure

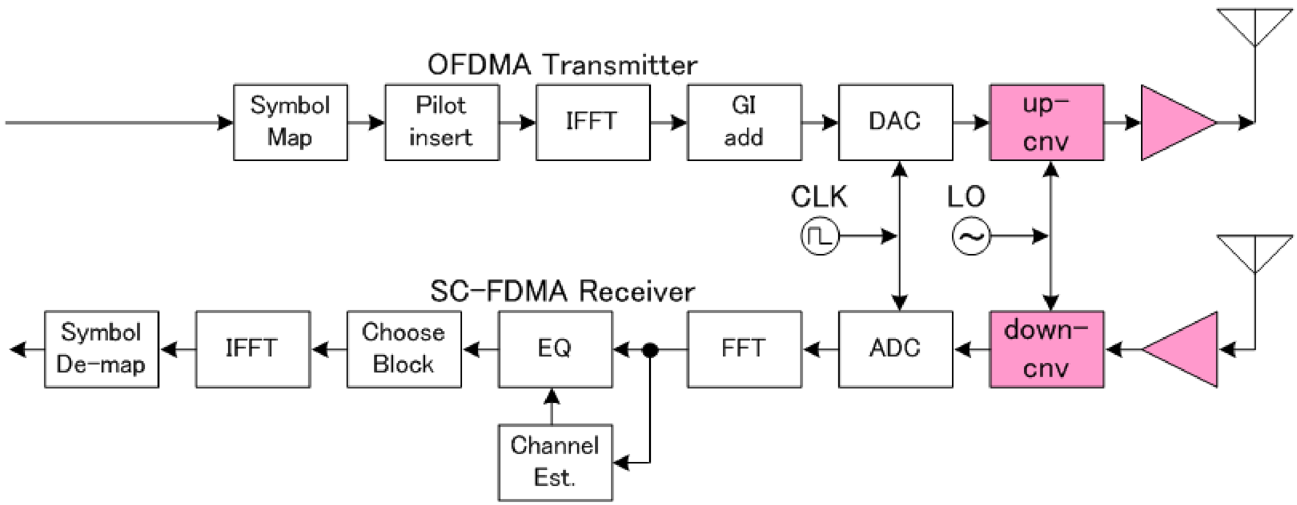


OFDMA and SC-FDMA

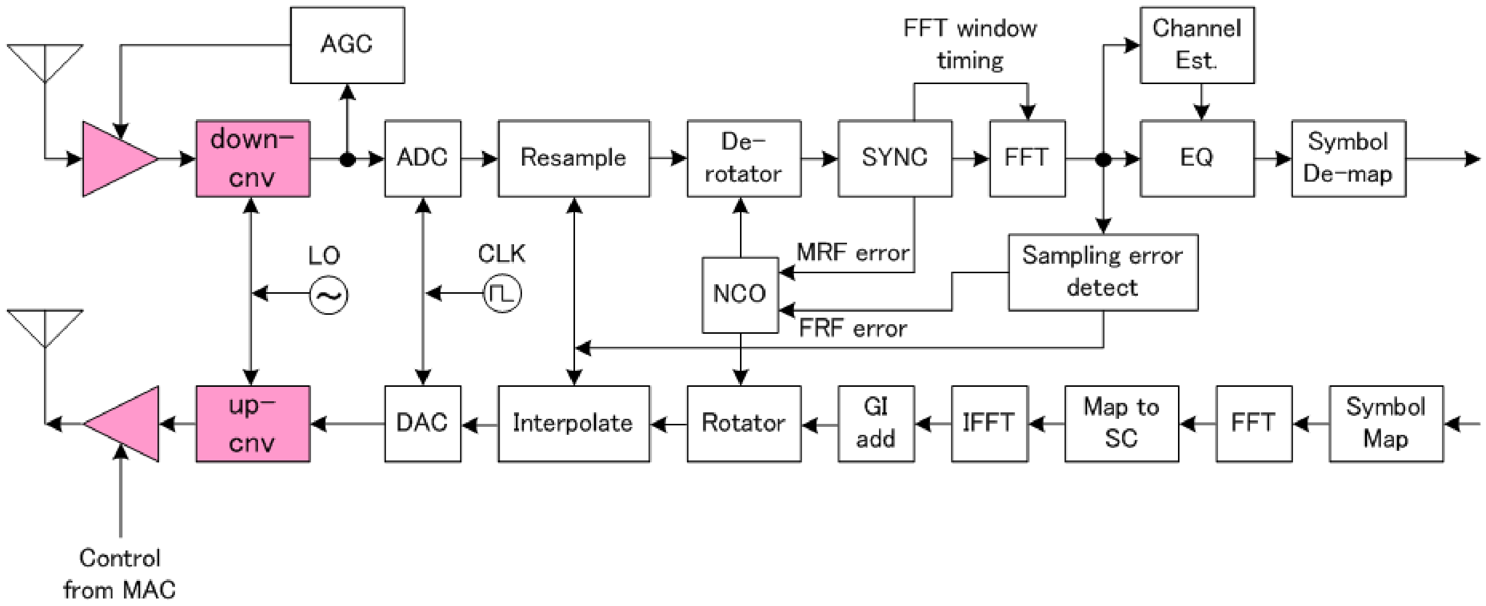
- **Down Link is OFDMA**
- **Up Link us SC-FDMA**



Base Station TX and RX



User Terminal TX and RX



Summary

- High performance Computer and Communication support current IT Society.
- Main stream Technology of High Bandwidth Wireless Communication is based on OFDM method.
- OFDM power spectrum is rectangle then high efficiency is realized.
- WLAN end LTE examples are briefly covered.

Matlab lab on Dec/14th 1:00PM

- Dec/14th Saturday,1pm to 5pm is Matlab lab at computer center, please prepare your login ID