Wireless Communication System

Modul 6 Modulasi Multicarrier

Faculty of Electrical Engineering
Bandung – 2015

Subject

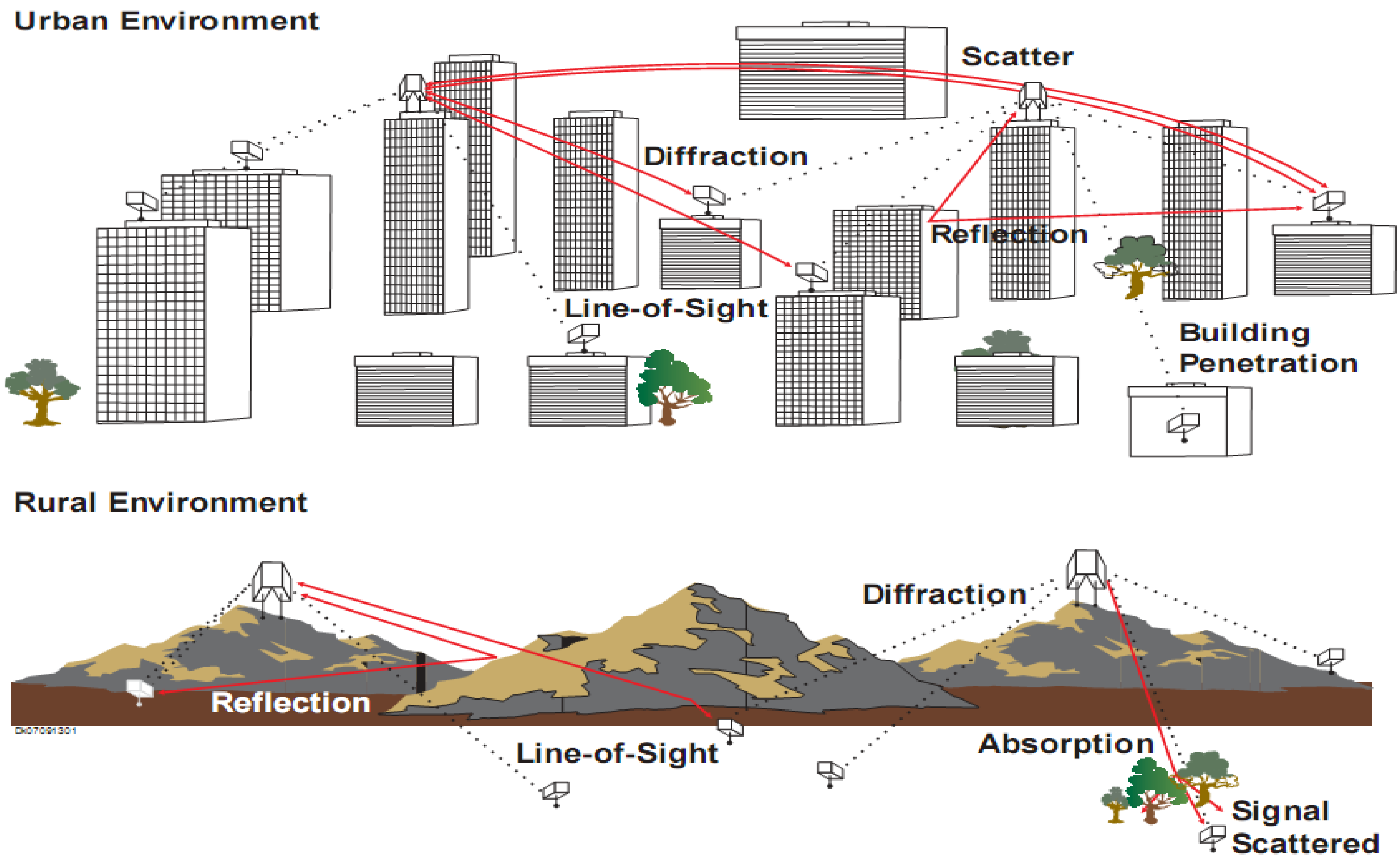
a. Konsep OFDM

b. Konsep OFDMA

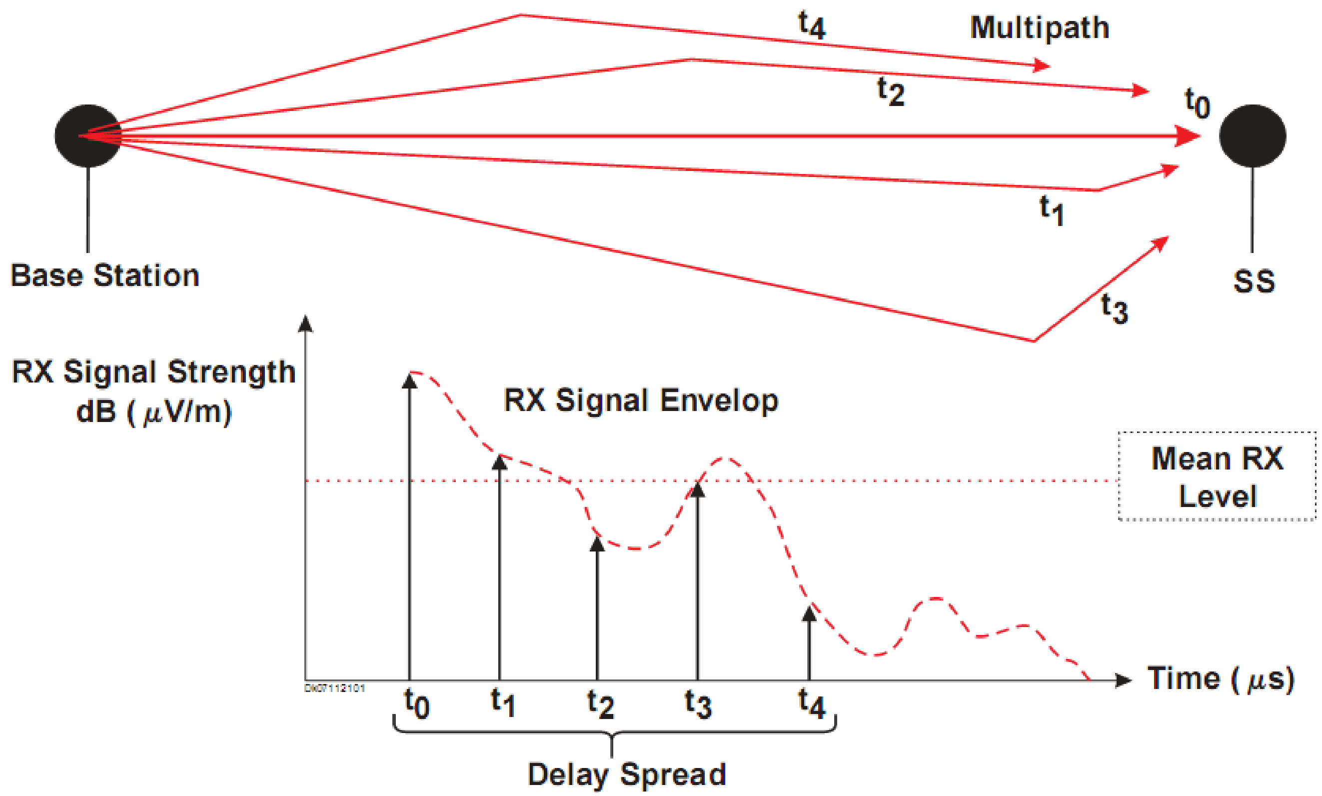
c. Pengenalan SC-FDMA

Konsep OFDM

Propagation Concept: NLOS Performance



Propagation Concept: Mutipath Propagation



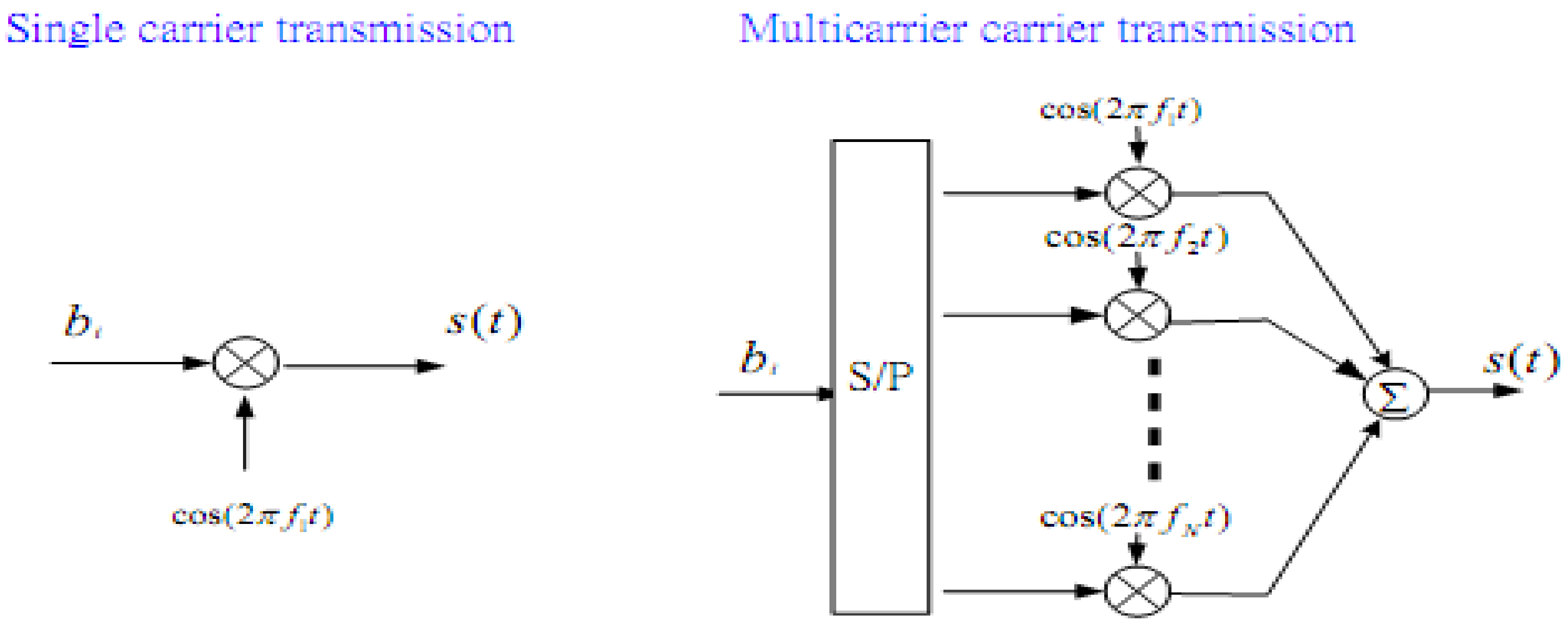
- Sinyal-sinyal multipath datang pada waktu yang berbeda dengan amplitudo dan pergeseran fasa yang berbeda, yang menyebabkan pelemahan dan penguatan daya sinyal yang diterima.
- Propagasi multipath berpengaruh terhadap performansi link dan coverage.
- Selubung (envelop) sinyal Rx berfluktuasi secara acak.

Problems of Mutipath Propagation & High Data Rate

- There are some problems when carrying high data rate via wireless channel, especially frequency selective fading
- OFDM offers the solution for the problems
- OFDM can be seen as multi-carrier transmission (MCM)
- MCM is a principle to transmit data by dividing the data into parallel bit streams
- The parallel bit streams is sometimes called subcarriers or subchannels

- Single carrier transmission
  - The concept of single-carrier is that each user transmits and receives data stream with only one carrier at any time.
- Multicarrier transmission
  - The concept of multi-carrier transmission is that a user can employ a number of carriers to transmit data simultaneously.

- Single and multicarrier transmission



Keterbatasan Modulasi Carrier Tunggal

- Penggunaan suatu carrier tunggal memiliki kelemahan mendasar : durasi cyclic prefix ditentukan oleh maximum expected delay spread .

$$delay_{\max} = T_{CP}$$

- Durasi simbol bisa dibuat seukuran dengan cyclic prefix, namun transmisi data menjadi tinggal setengahnya karena untuk cyclic prefix sehingga sistem menjadi tidak efisien (E kecil)

$$E = \frac{T_{SYMBOL}}{T_{SYMBOL} + T_{CP}}$$

- Selain itu, durasi simbol yang mengecil berarti juga menggunakan spektrum (fs) lebih besar.

$$f_S = \frac{1}{T_S} = \frac{1}{T_{SYMBOL} + T_{CP}}$$

- Untuk peningkatan efisiensi, durasi simbol harus panjang, namun laju simbol menjadi turun.

The Idea

Fig. 1 – (a) A Regular-FDM single carrier – A whole bunch of water coming all in one stream. (b) Orthogonal-FDM – Same amount of water coming from a lot of small streams.

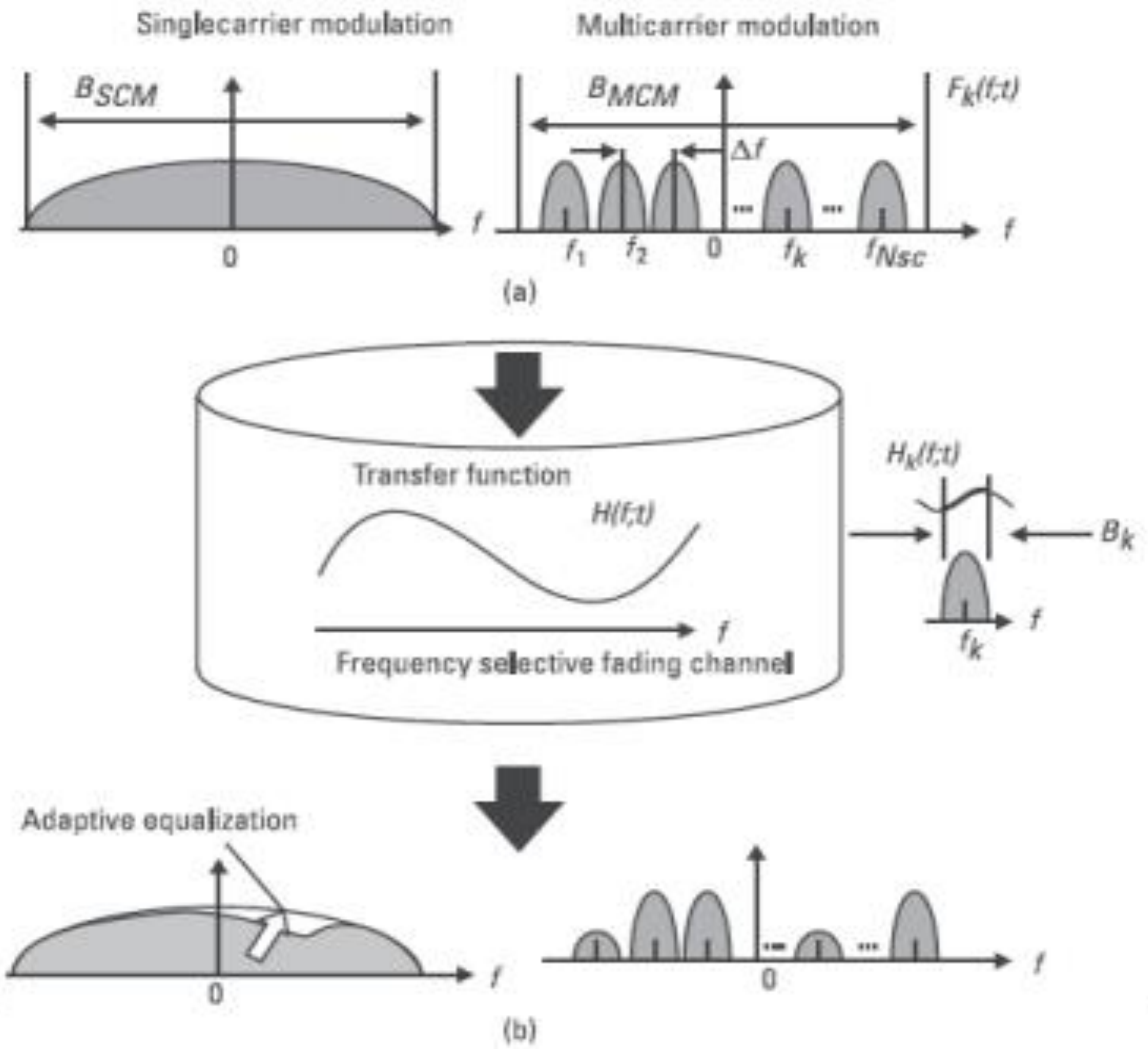
Fig. 2 – All cargo on one truck vs. splitting the shipment into more than one.

- In MCM, we split the data into different streams and transmit using separate *sub-carriers*

What is Multicarrier Modulation?

- Multicarrier modulation is the generic term used for any orthogonal pulse amplitude modulation (OPAM) where the orthogonal pulses are roughly localized in the frequency domain.
- It includes, as special cases, frequency division multiplexing (FDM) and orthogonal FDM (OFDM) and discrete multitone transmission (DMT)
- Now what is orthogonal pulse amplitude modulation (OPAM)?
- Based on our knowledge of modulation, we should be able to understand OPAM very easily and then move on to MCM.

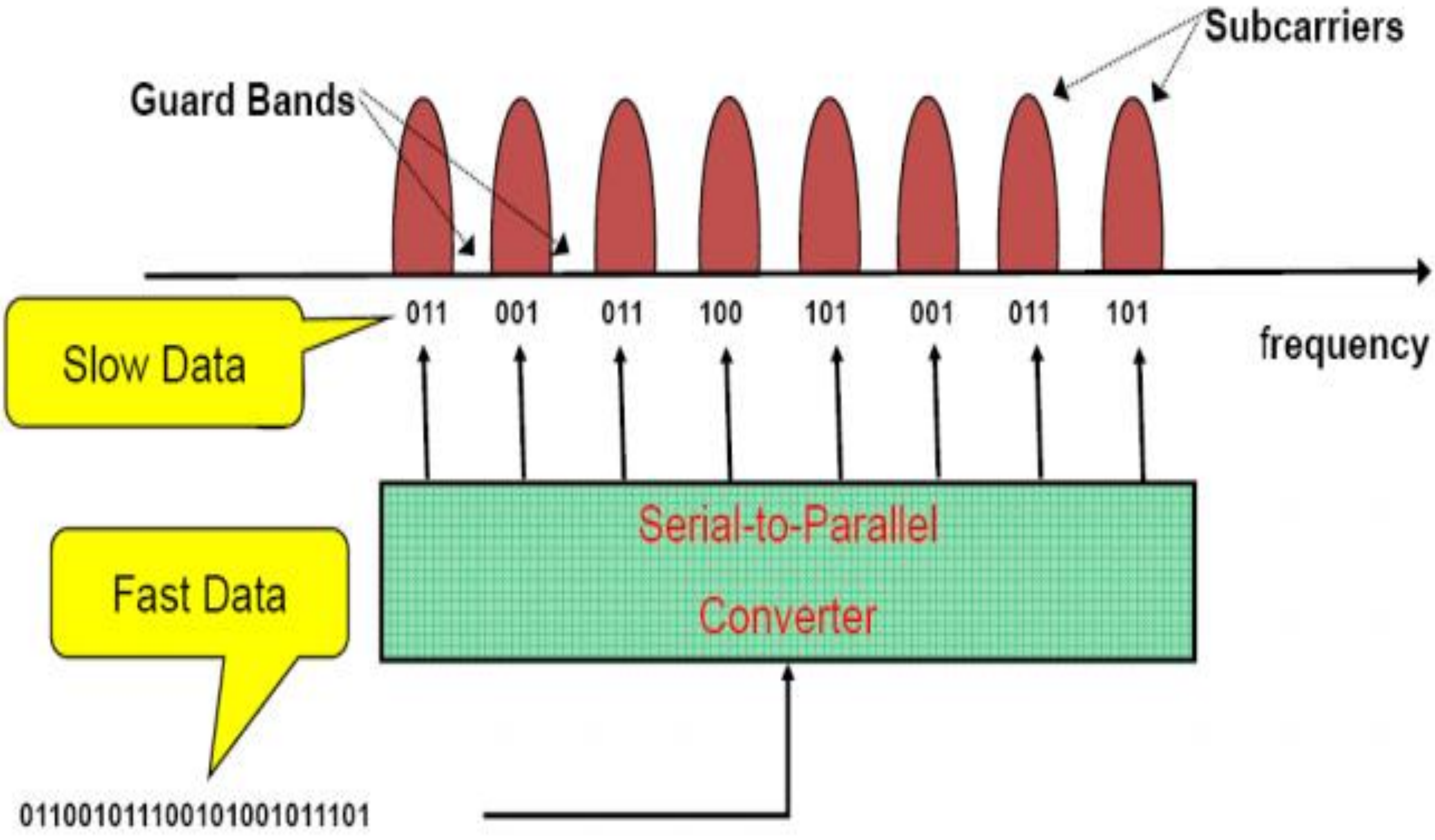
The difference between MCM and SCM



Multicarrier Transmission - Basic Concept

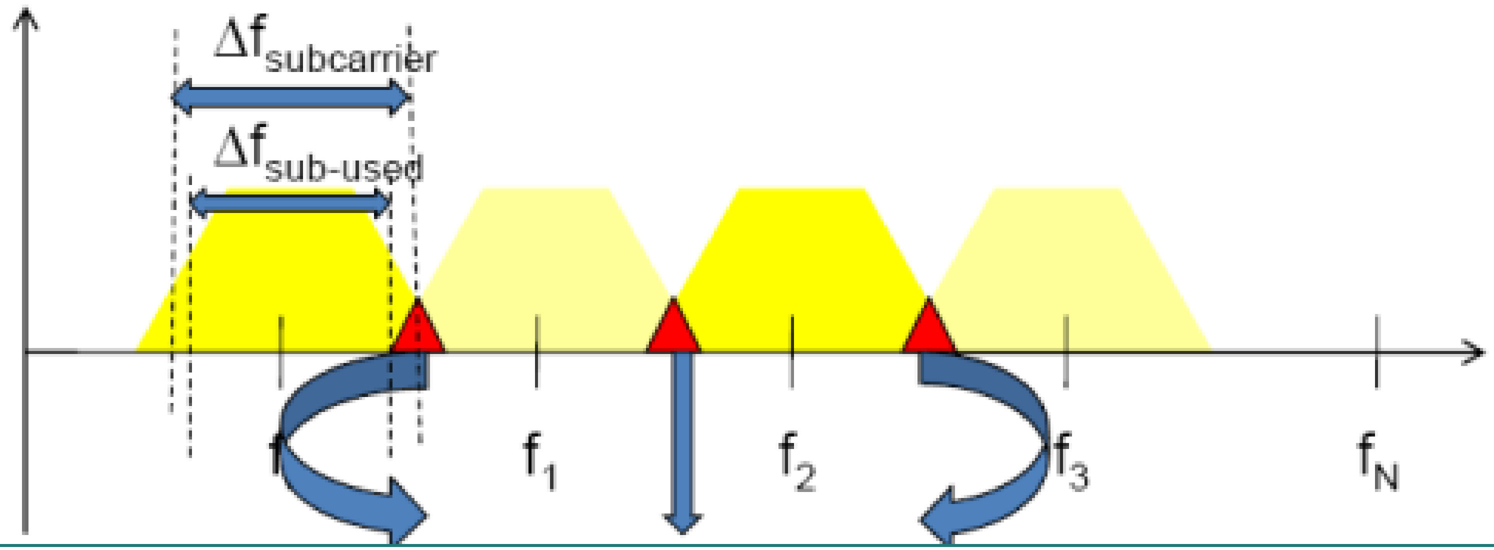
- *Orthogonal Frequency Division Multiplexing* (OFDM) is a multi-carrier modulation scheme
  - First break the data into small portions
  - Then use a number of parallel **orthogonal** sub-carriers to transmit the data
- Conventional transmission uses a single carrier, which is modulated with all the data to be sent

Modulasi Multicarrier



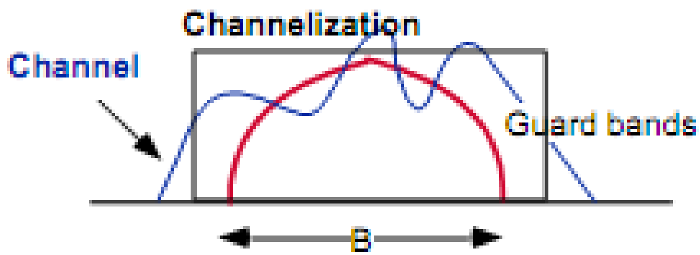
Modulasi Multicarrier

- Frekuensi tengah harus diberi jarak sehingga interference antar carrier yang berbeda atau **Adjacent Carrier Interference ACI minimal** diminimalkan namun tanpa banyak spasi frekuenasi terbuang.
- Tiap carrier menggunakan guard band atas dan bawah untuk proteksi terhadap interferensi carrier sebelah.



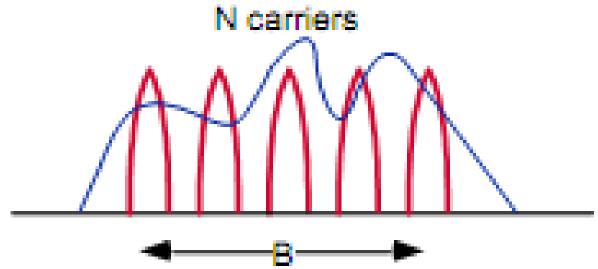
ACI = Adjacent Carrier Interference

Modulation techniques: monocarrier vs. multicarrier



Pulse length ~1/B

– Data are transmitted over **only one carrier**



Pulse length ~ N/B

– Data are shared among **several carriers** and simultaneously transmitted

Similar to FDM technique

Drawbacks

- **Selective Fading**
- **Very short pulses**
- **ISI is compartively long**
- **EQs are then very long**
- **Poor spectral efficiency because of band guards**

Advantages

- **Flat Fading per carrier**
- **N long pulses**
- **ISI is comparatively short**
- **N short EQs needed**
- **Poor spectral efficiency because of band guards**

Furthermore

- It is easy to exploit frequency diversity
- It allows deployment of 2D coding techniques
- Dynamic signaling

To improve the spectral efficiency:

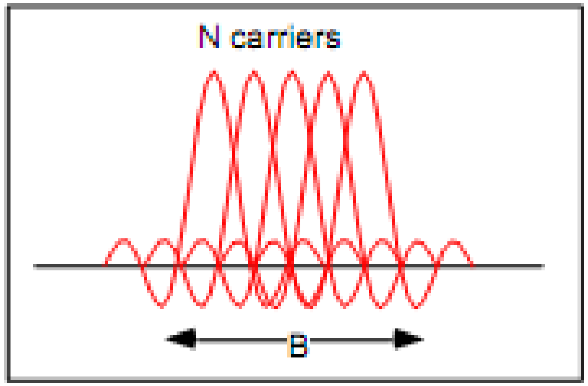
Eliminate band guards between carriers

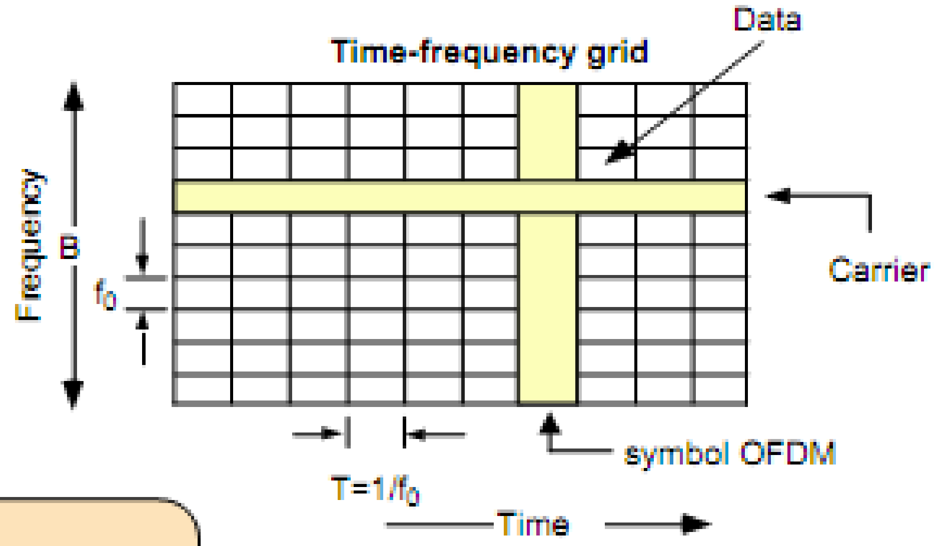
To use orthogonal carriers (allowing spectrum overlapping)

OFDM Concept: Mengapa OFDM

- Sinyal OFDM (Orthogonal Frequency Division Multiplexing) dapat mendukung kondisi NLOS (Non Line of Sight) dengan mempertahankan efisiensi spektral yang tinggi dan memaksimalkan spektrum yang tersedia.
- Mendukung lingkungan propagasi multi-path.
- Scalable bandwidth: menyediakan fleksibilitas dan potensial mengurangi CAPEX (capital expense).

Introduction to OFDM modulation





Features

- No intercarrier guard bands
- Controlled overlapping of bands
- Maximum spectral efficiency (Nyquist rate)
- Easy implementation using FFTs
- Very sensitive time-freq. Synchronization

Intercarrier Separation =
Any integer Multiple of 1/(symbol duration)

Modulation technique

One user utilizes all carriers simultaneously to transmit its data (may be different modulations)

Access techniques (FDMA)

Several users share dynamically the carriers (traffic or service dependent) to access to the system

OFDM

- Peak of spectrum for each sub-band must correspond to zero crossings for all other modulated sub-carriers.
- Interference now avoided in frequency-domain.
- Adjacent sub-carriers spaced exactly 1/T Hz apart when sub-band pulse-rate is 1/T pulses/second.
- Sub-carriers are as close together as they can possibly be without introducing spectral interference.
- Each modulated sub-carrier is ‘orthogonal’ to all others which means that they do not interfere with each other.

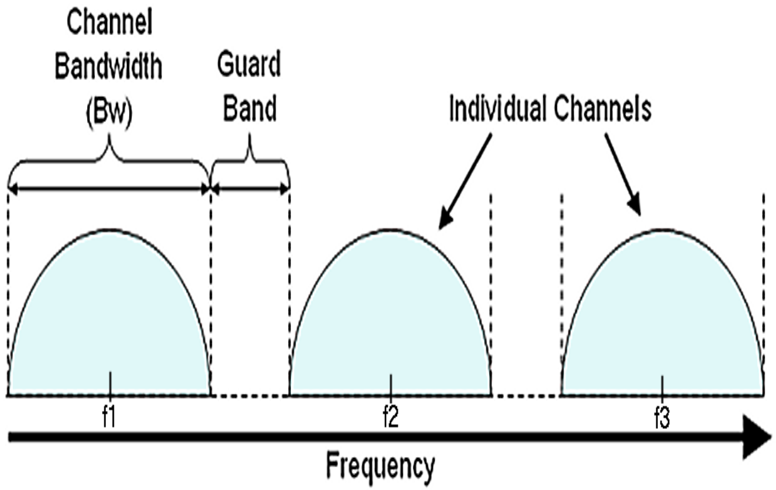
The Multicarrier Modulation Idea (1)

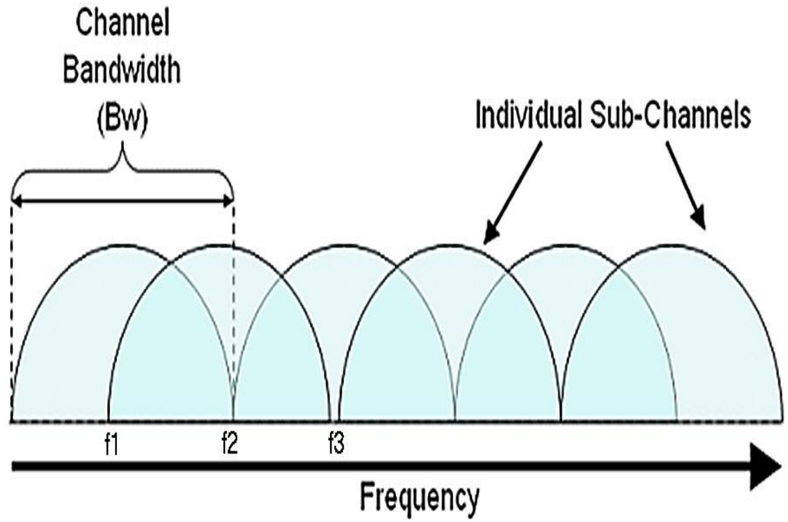
- Suppose we have a fixed channel bandwidth W.
- We are free to increase signal dimensionality N if we simultaneously increase symbol interval T.
- Intuitively we are compensating for reduced symbol rate by increasing the number of symbols per symbol interval.
- How do we choose the set of orthogonal pulses as we increase T?
- One solution: make the bandwidth of each pulse on the order of $1/2T$, satisfying Nyquist rate.
- Then place them at different non-overlapping centre frequencies.
- As T and N increase, this will make only a small portion of the channel transfer function over narrower and narrower bandwidth affect each pulse transmission.

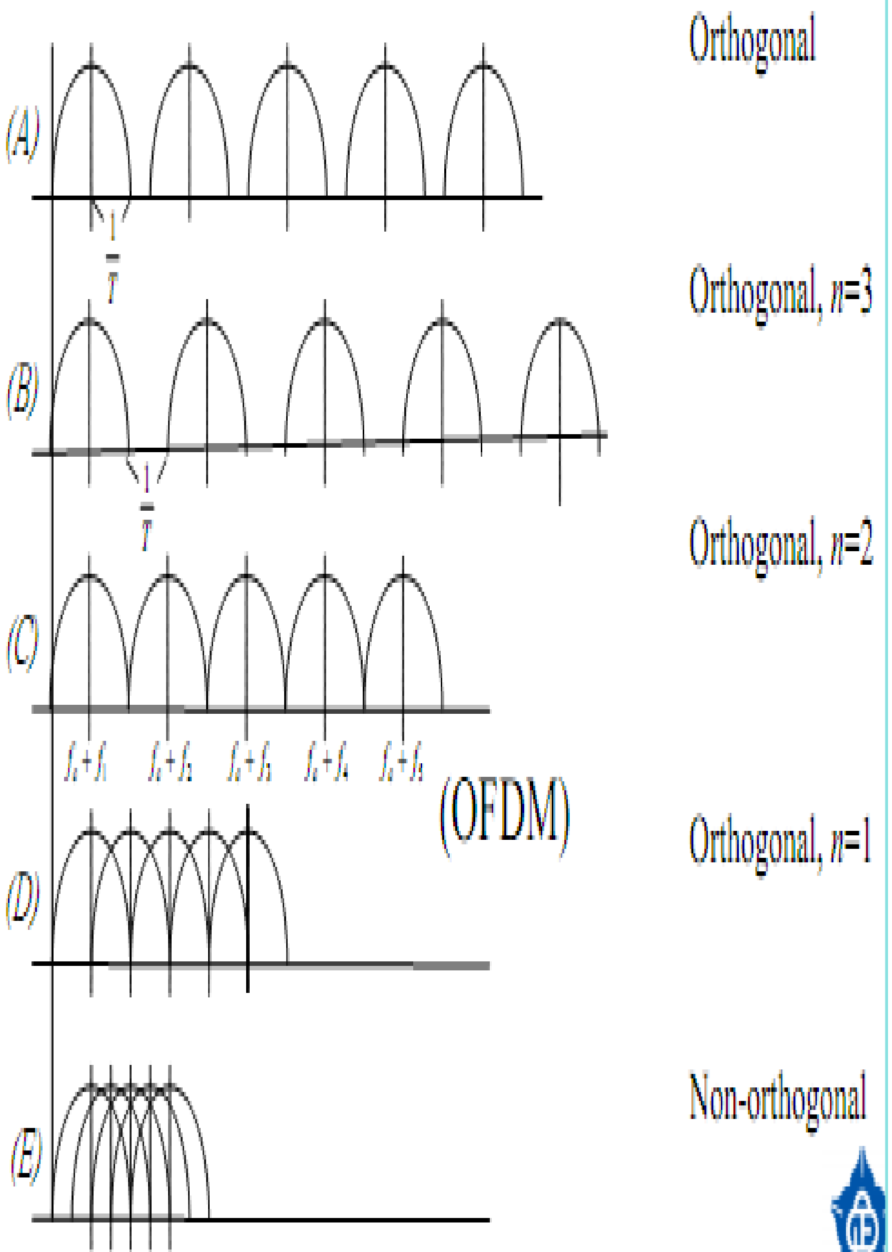
- Eventually, for sufficiently large T the channel transfer function will be constant over the bandwidth of each pulse.
- Therefore, ISI for each pulse will be insignificant.
- By proper MCM system design, we can cleverly avoid ISI.

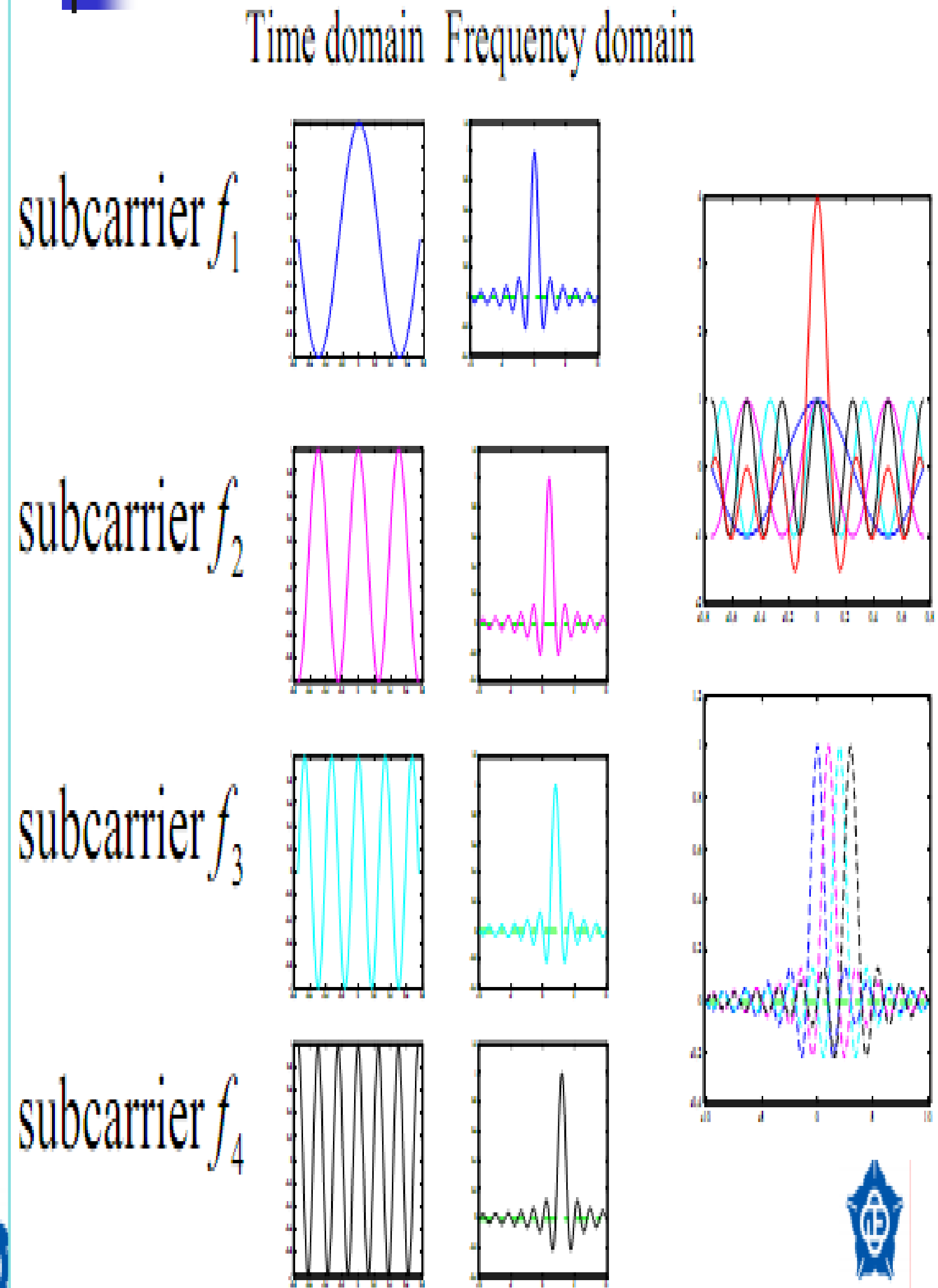
OFDM Basic Concept

- **OFDM is a special case of *Frequency Division Multiplexing* (FDM)**
- **For FDM**
  - **No special relationship between the carrier frequencies**
  - **Guard bands have to be inserted to avoid *Adjacent Channel Interference* (ACI)**
- **For OFDM**
  - **Strict relation between carriers: $f_k = k \cdot \Delta f$ where $\Delta f = 1/T_U$**
    (T_U - symbol period)
  - **Carriers are orthogonal to each other and can be packed tight**






(A)
Orthogonal
(B)
Orthogonal, n=3
(C)
Orthogonal, n=2
(OFDM)
(D)
Orthogonal, n=1
(E)
Non-orthogonal


Time domain
Frequency domain
subcarrier f_1
subcarrier f_2
subcarrier f_3
subcarrier f_4

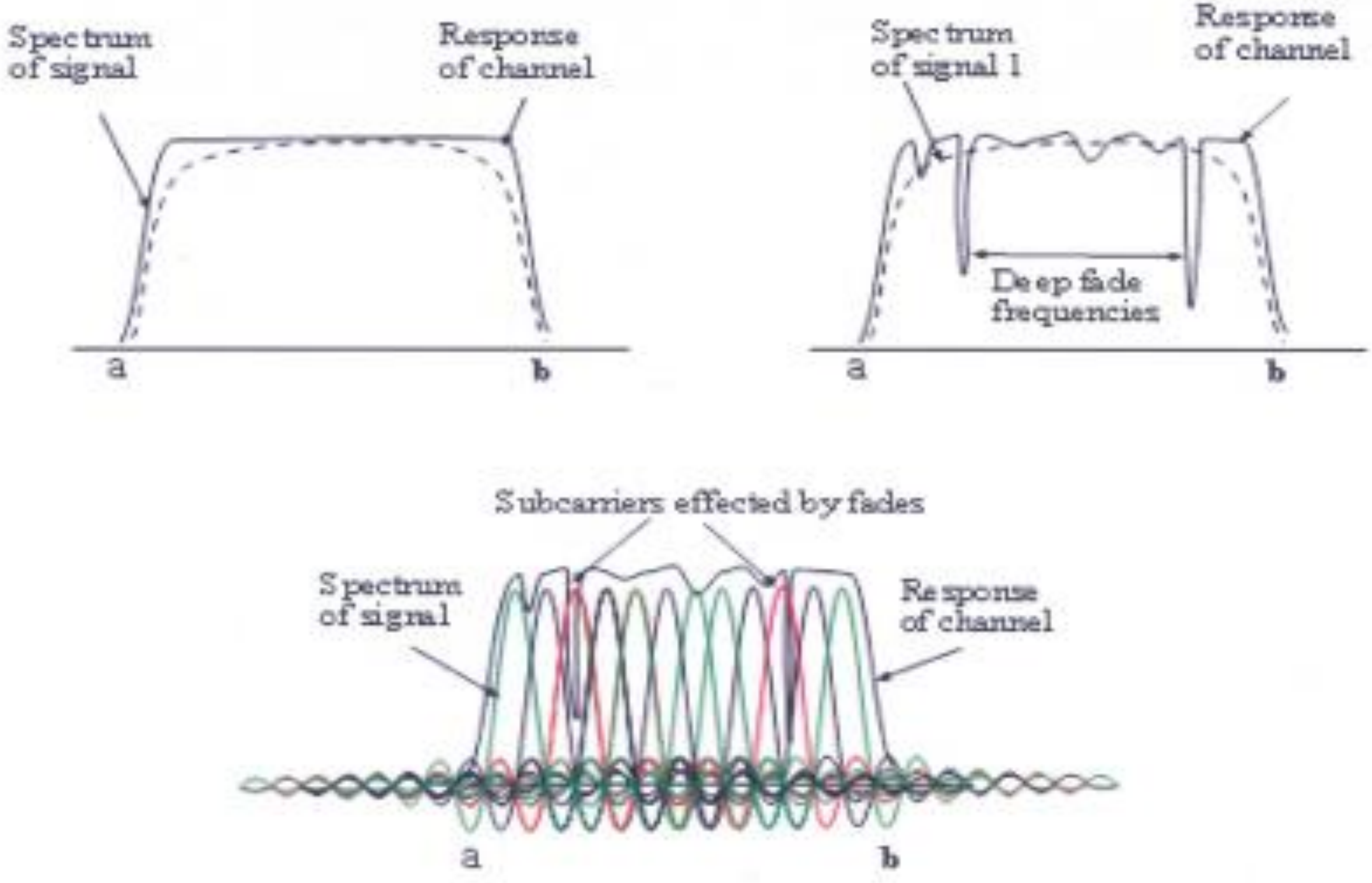
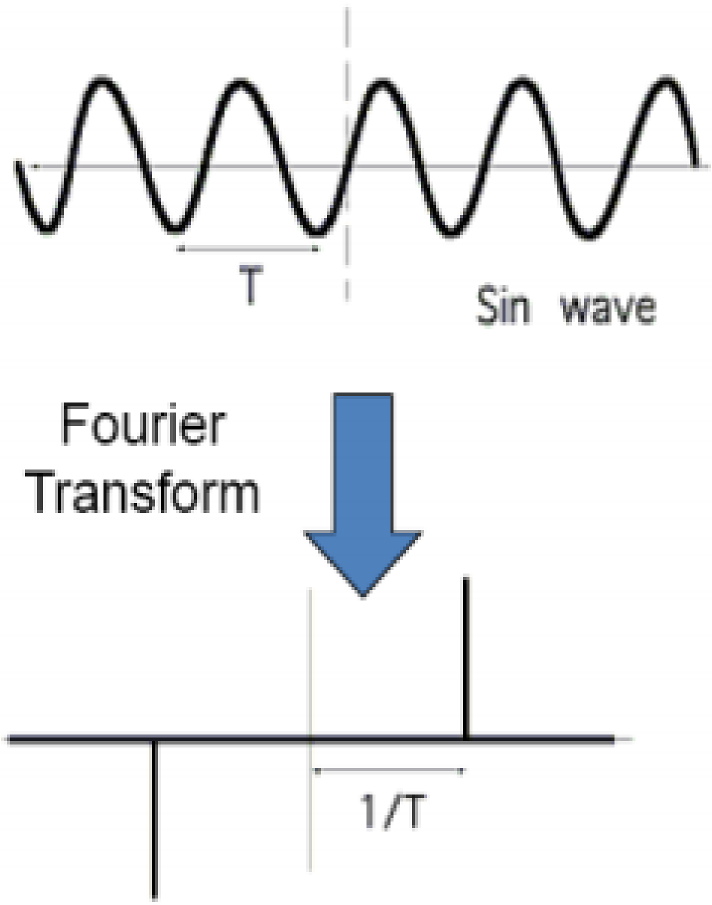


Fig. 20 – (a) The signal we want to send and the channel frequency response are well matched. (b) A fading channel has frequencies that do not allow anything to pass. Data is lost sporadically. (c) With OFDM, where we have many little sub-carriers, only a small sub-set of the data is lost due to fading.

Representasi Kawasan Waktu vs Frekuensi

- Dua penggambaran karakteristik sinyal :
  - Representasi kawasan waktu :
    - Membantu mengenali seberapa panjang durasi suatu simbol It helps
  - Representasi kawasan frekuensi :
    - Untuk memahami kebutuhan spektrum

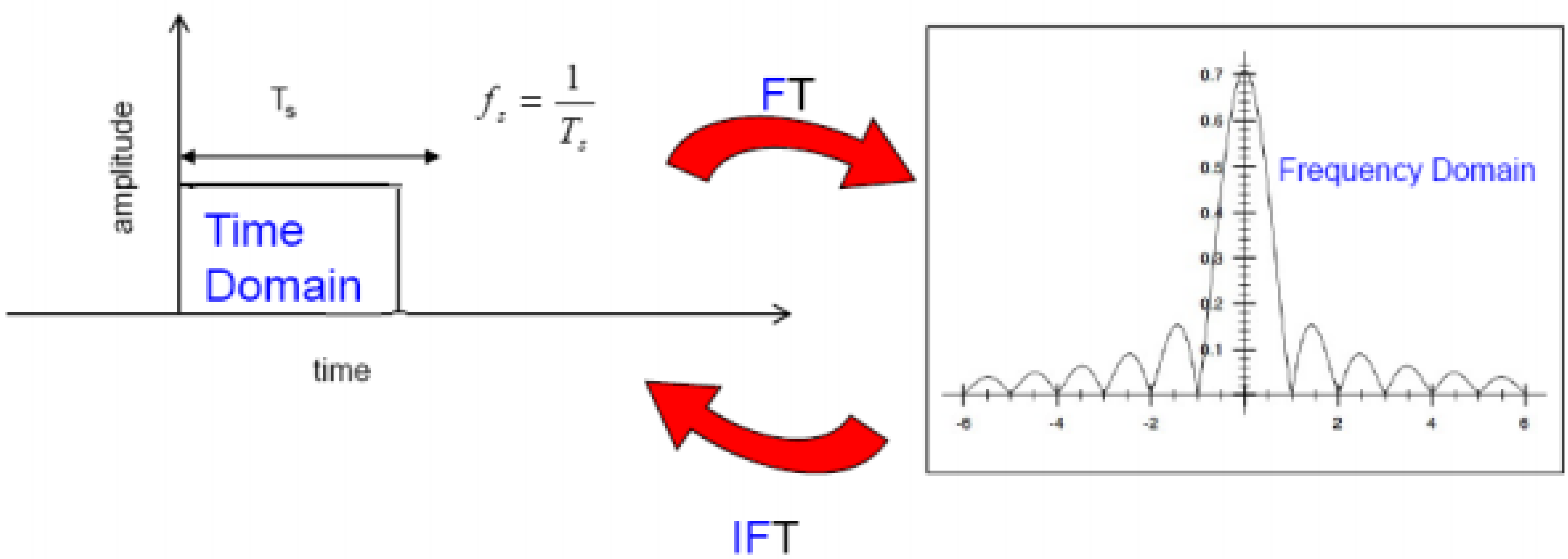
The time domain presentation



The frequency domain presentation

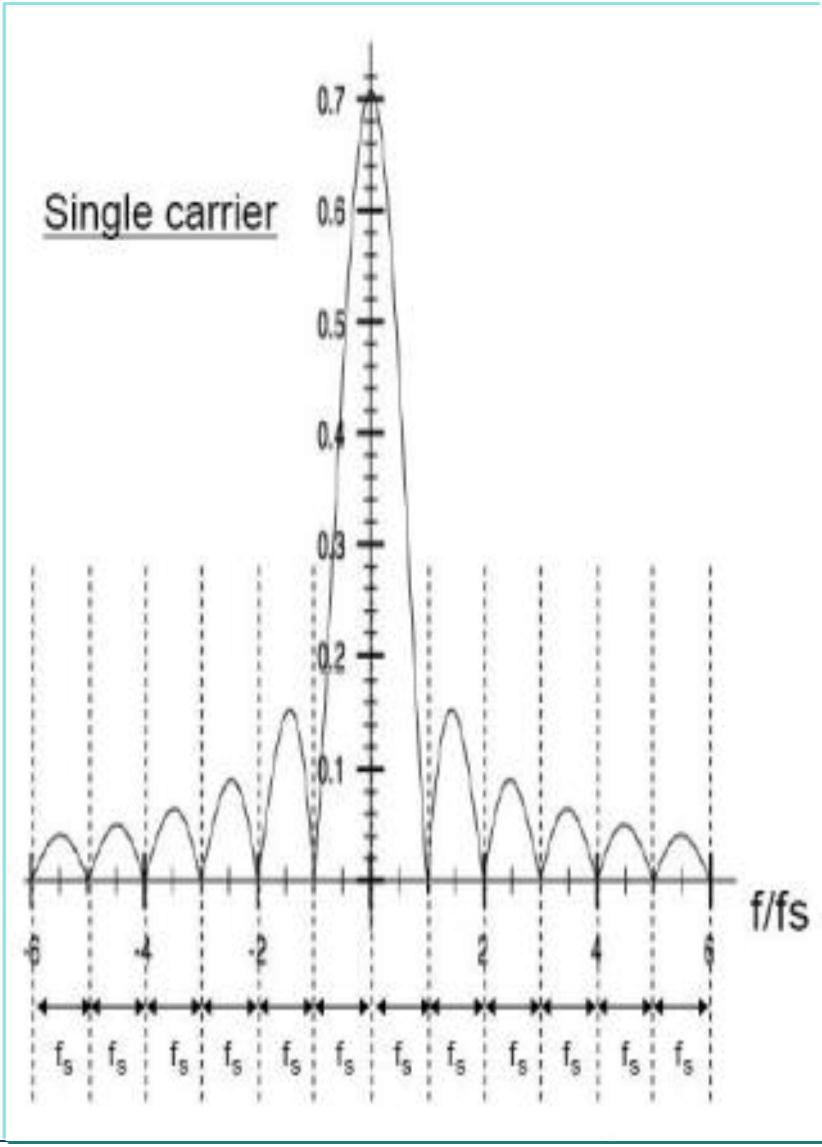
Pulsa Kotak

- Pulsa kotak merupakan pulsa sederhana dalam kawasan waktu.
- Pulsa ini dibentuk dengan cara menaikkan amplituda pada saat t=0 ke maksimum dan setelah suatu durasi waktu Ts amplituda diturunkan kembali ke 0.



OFDM

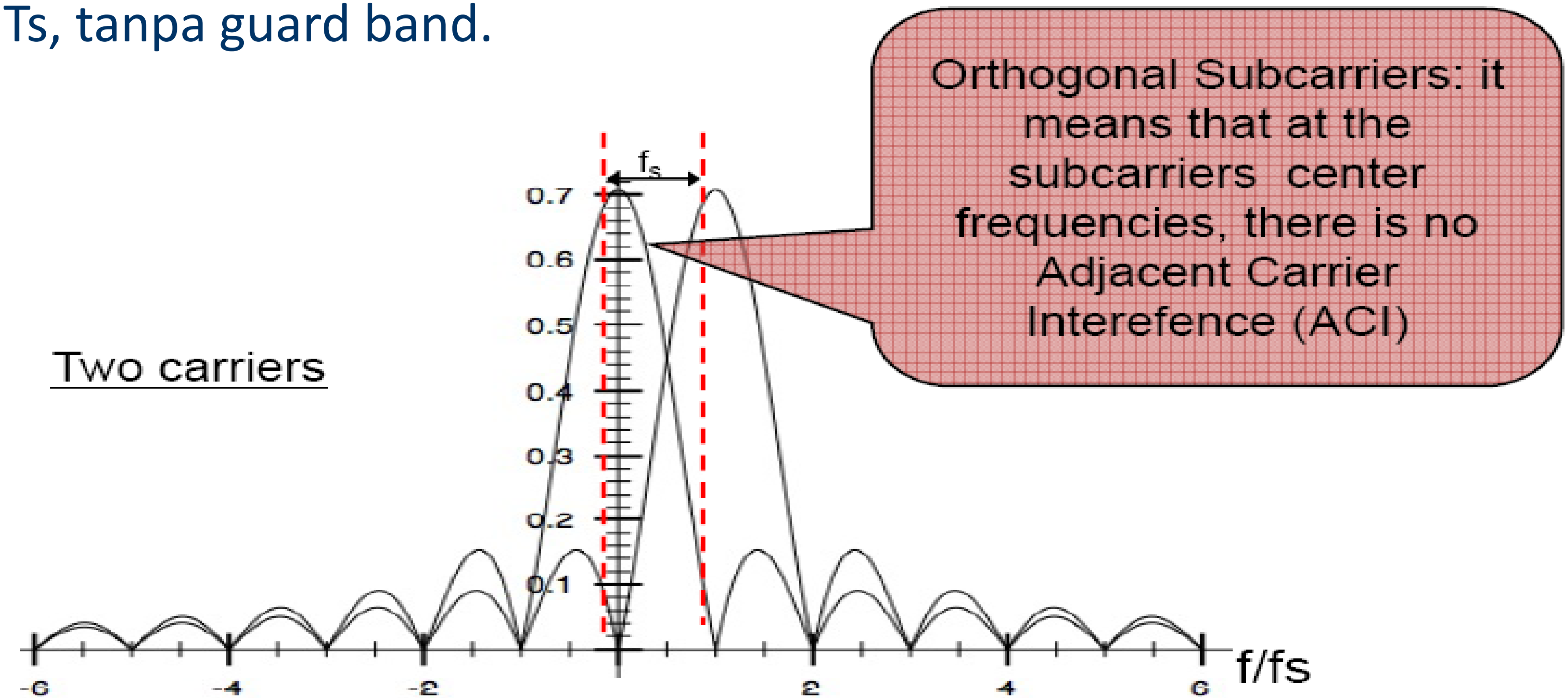
- Suatu pulsa kotak merupakan opsi sinyal yang baik dan mudah diimplementasikan.
- Pulsa kotak dalam kawasan frekuensi memiliki spktrum dengan null terletak pada kelipatan integer dari 1/durasi simbol.
- Puncak daya terletak pada center frequency .



OFDM

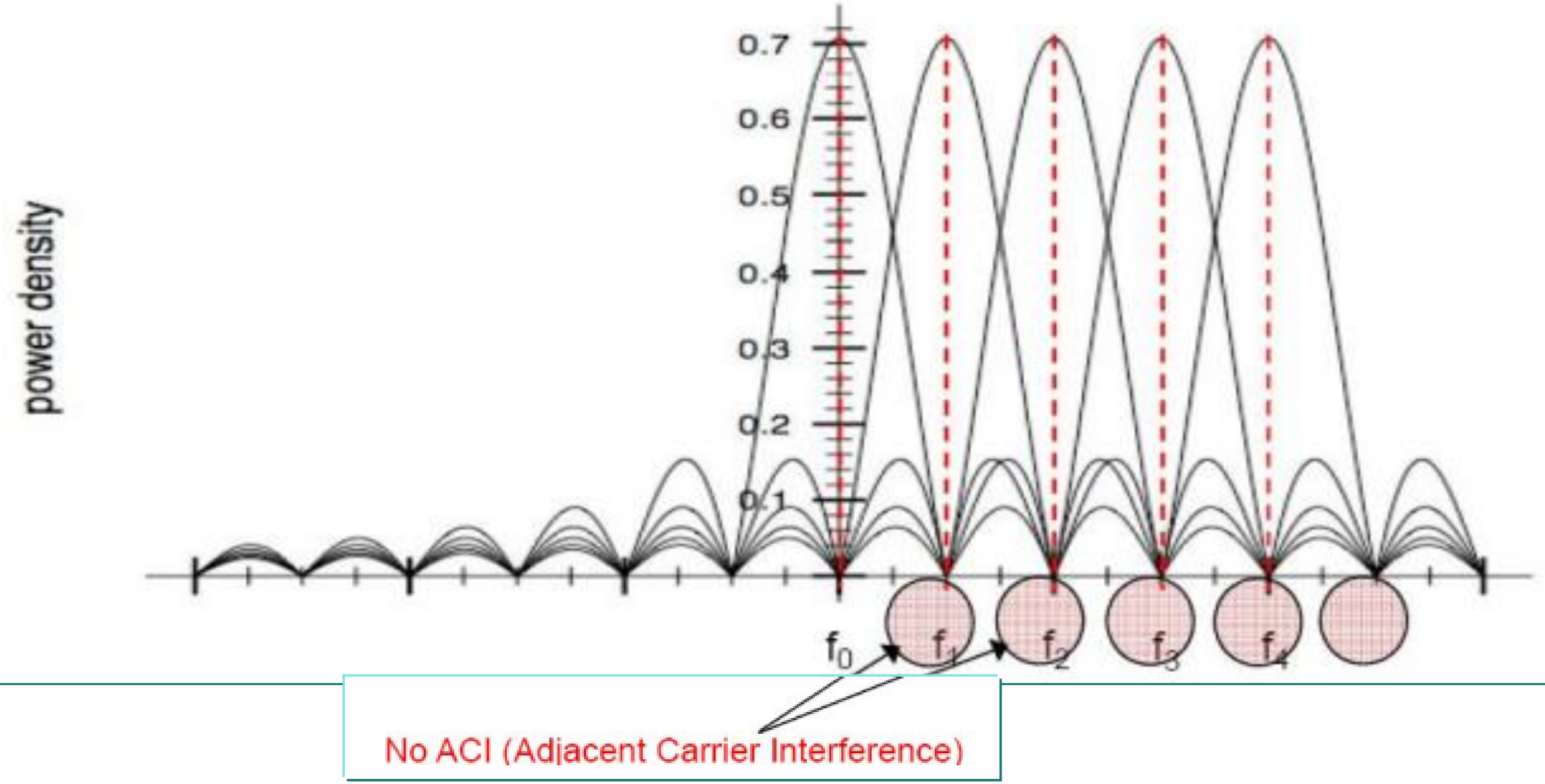
OFDM secara sederhana menempatkan next carrier persis di null pertama dari carrier sebelumnya.

- Sehingga tidak diperlukan pulse shaping
- Antar carrier OFDM carrier menggunakan durasi simbol yang sama Ts, tanpa guard band.



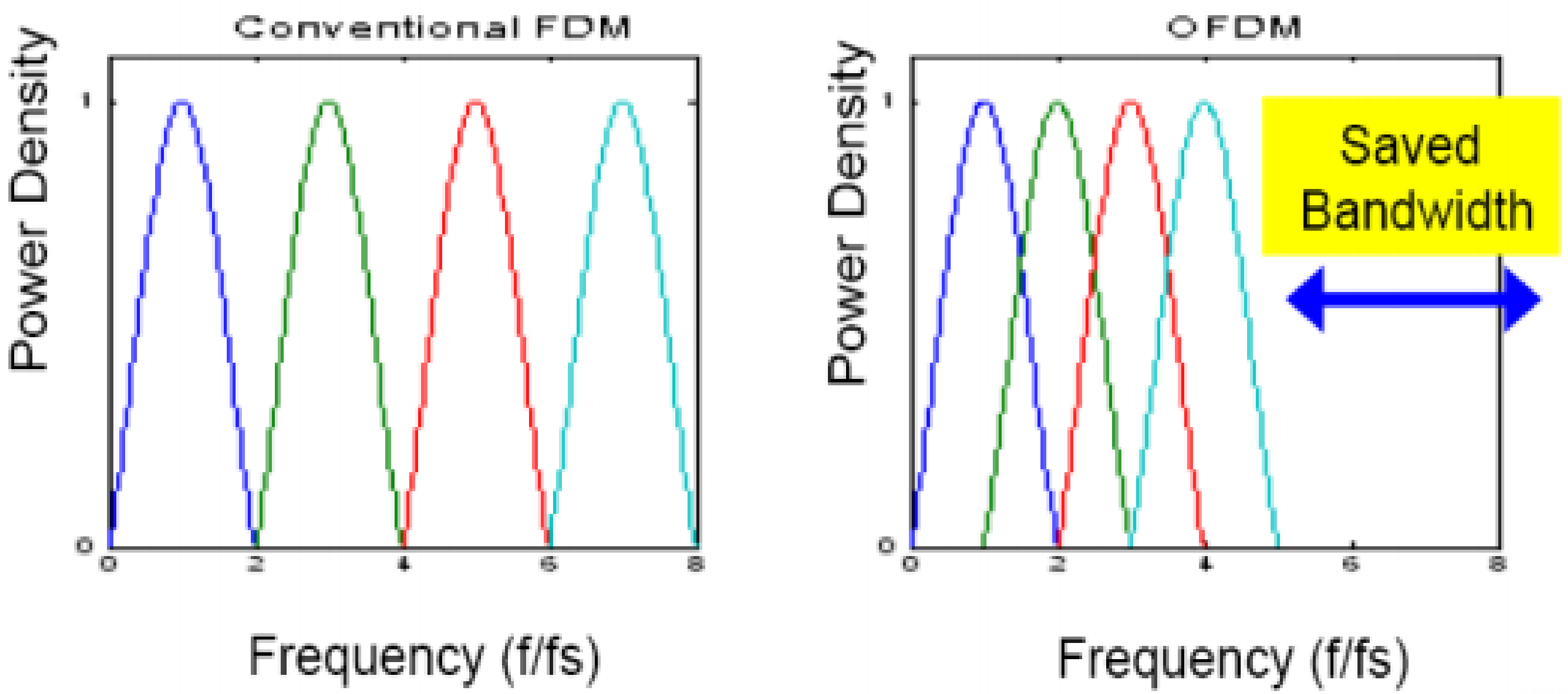
Overlapping Spektrum pada OFDM

$$f_n = f_0 + nf_s = f_0 + n\frac{1}{T_s} \qquad n = \ldots -1, 0, 1, 2 \ldots.$$

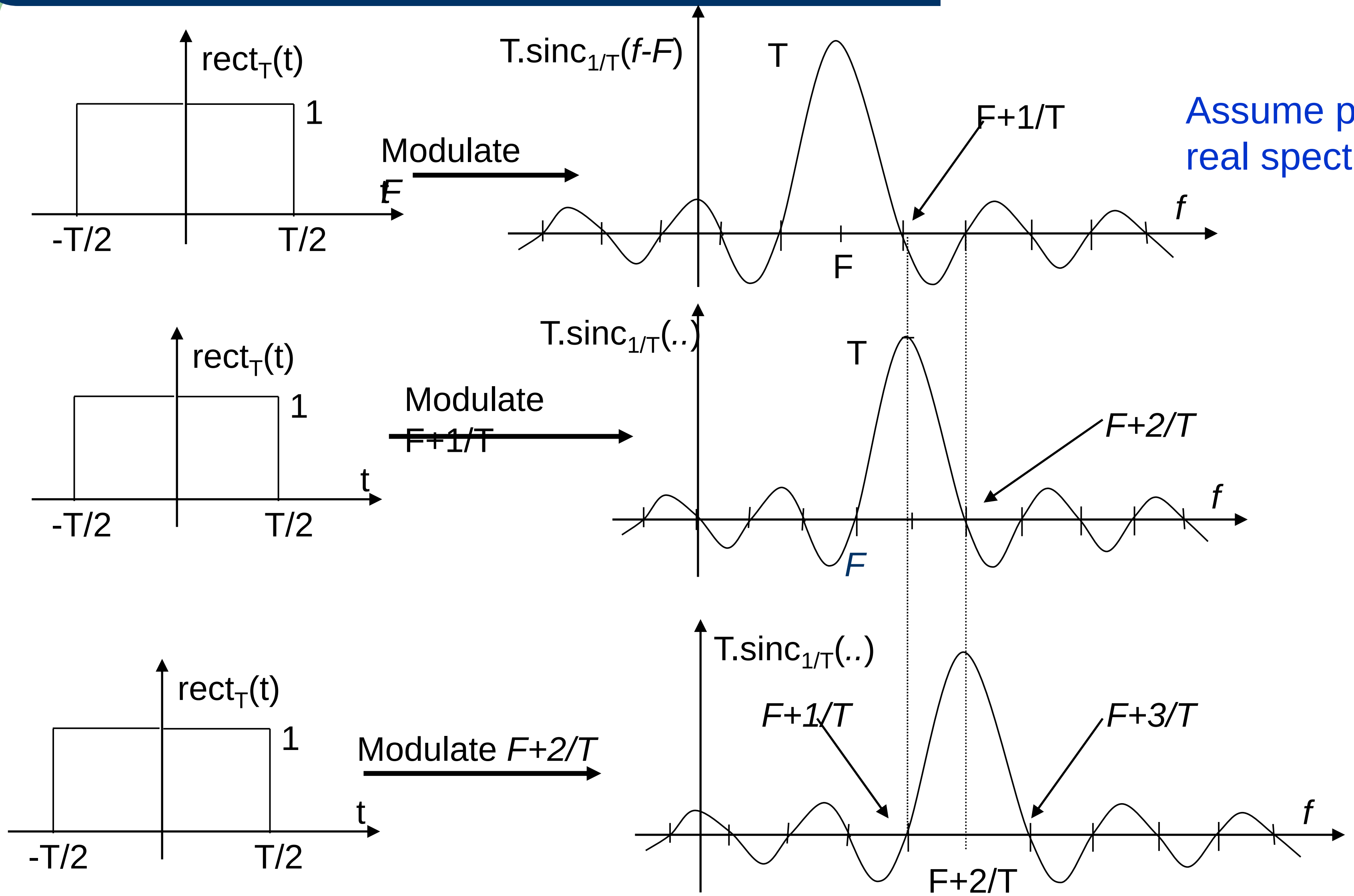


OFDM

- OFDM memungkinkan packaging sejumlah subcarrier kedalam suatu bandwidth yang lebih kompak.



Combining OFDM sub-bands

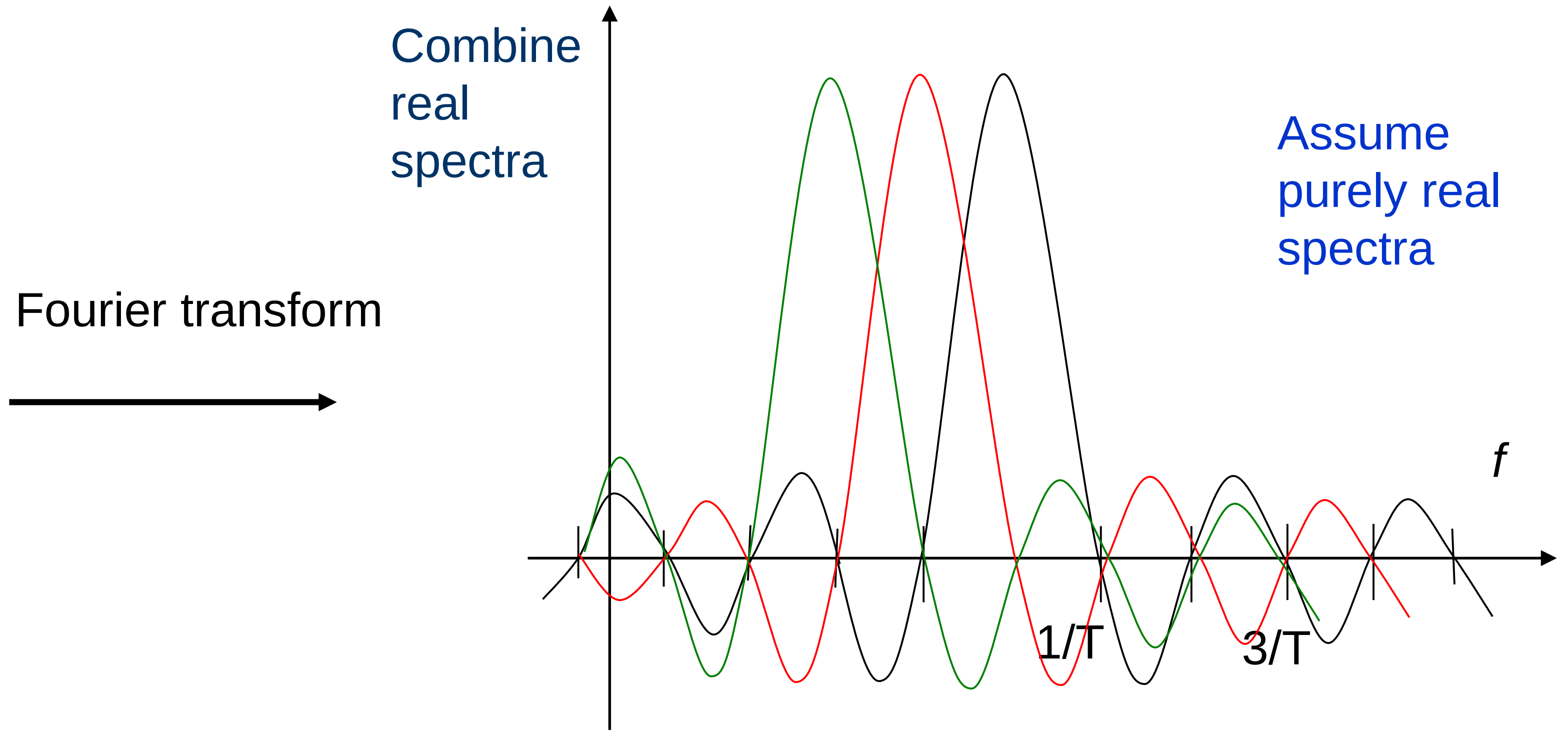


Assume purely real spectrum

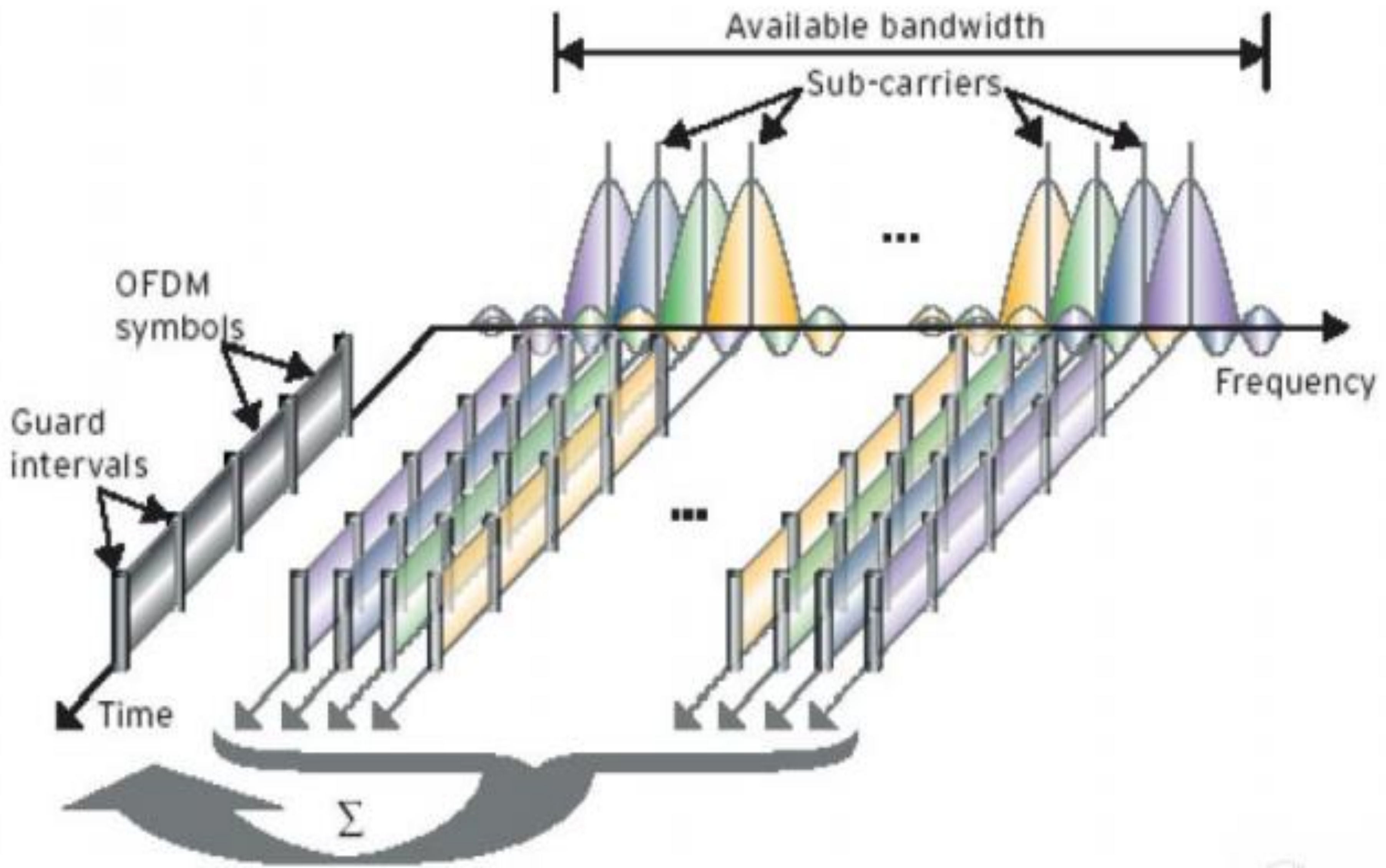
OFDM spectrum

SUM

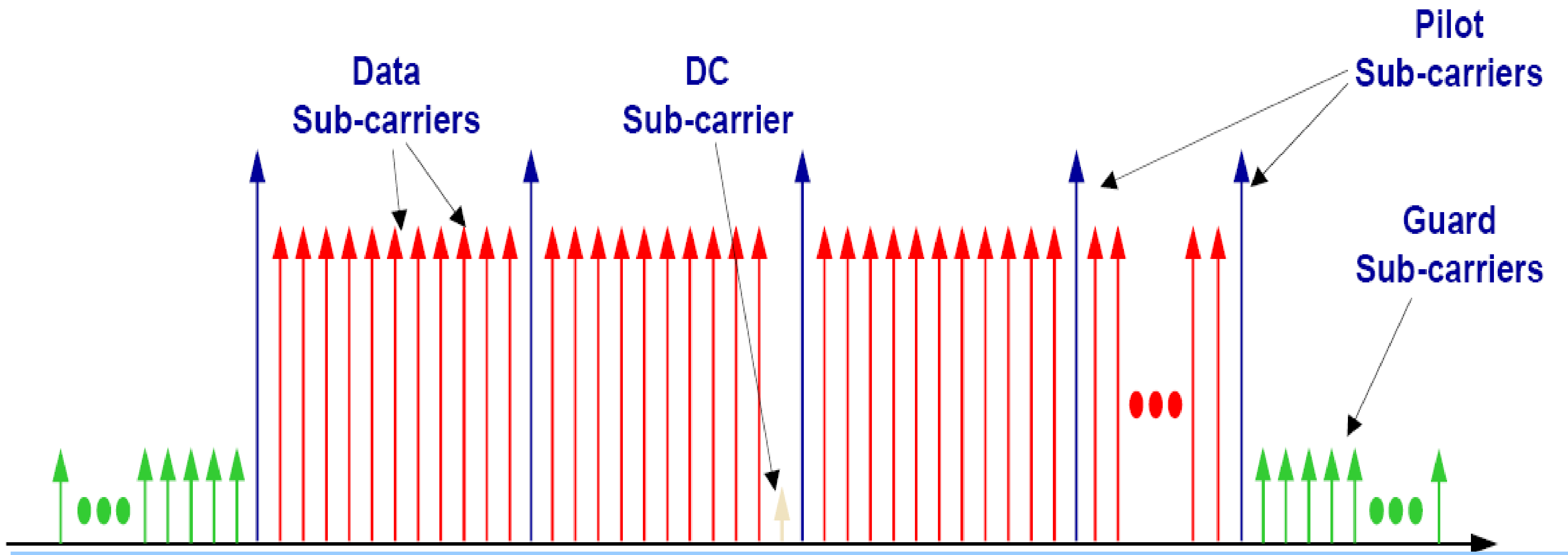
Fourier transform



Sinyal OFDM


Available bandwidth
Sub-carriers
...
OFDM symbols
Guard intervals
...
Frequency
Time
Σ

Tipe Sub-Carrier OFDM



Data Sub-carriers

- Membawa simbol BPSK, QPSK, 16QAM, 64QAM

Pilot Sub-carriers

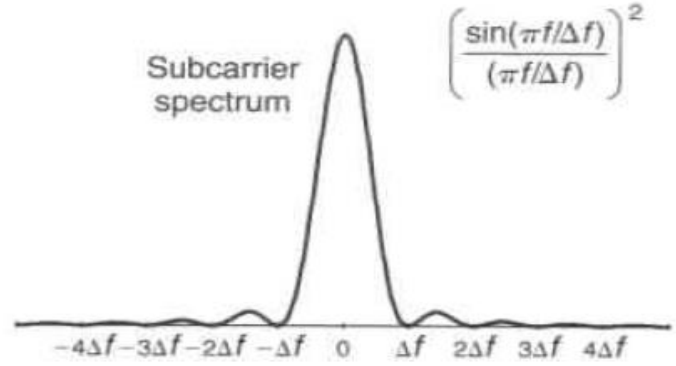
- Untuk memudahkan estimasi kanal dan demodulasi koheren pada receiver.

Null Subcarrier

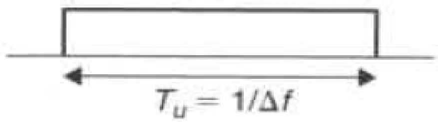
- Guard Sub-carriers
- DC Sub-carrier

OFDM – Signal properties

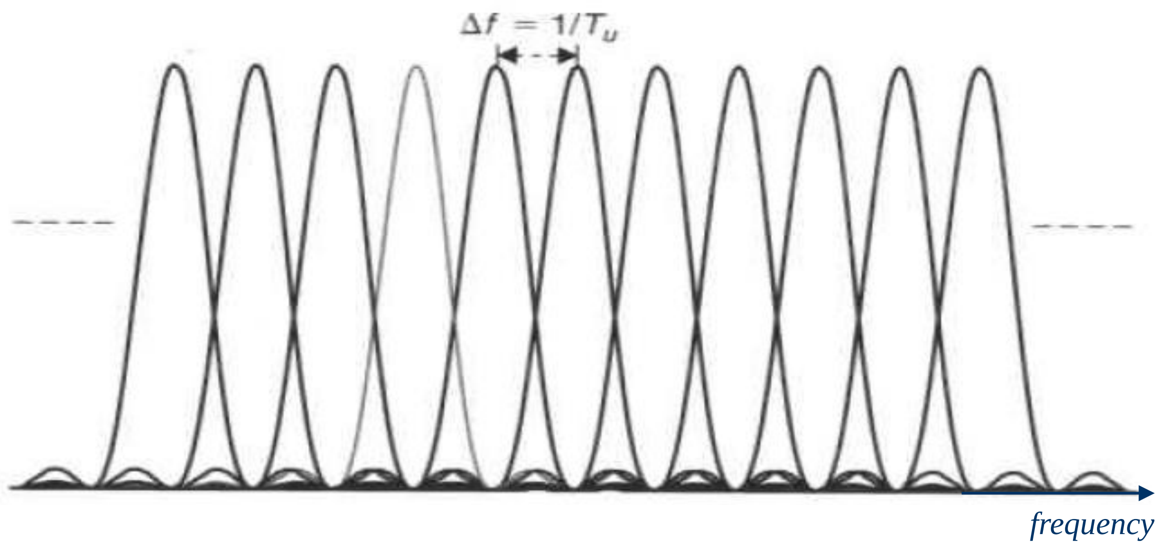
Frequency domain



Time domain

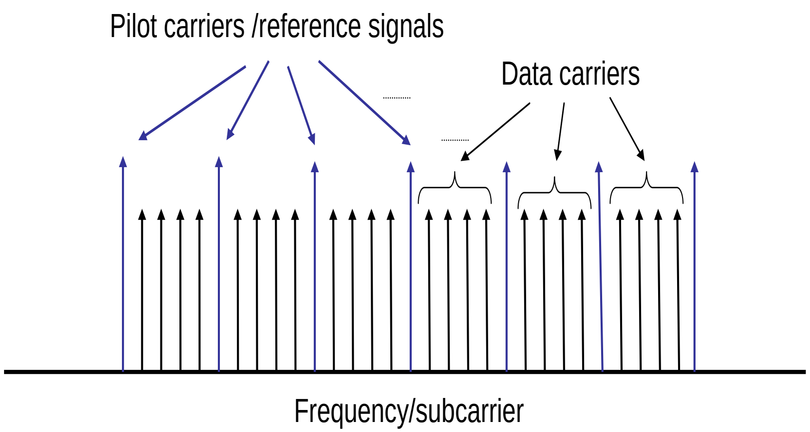


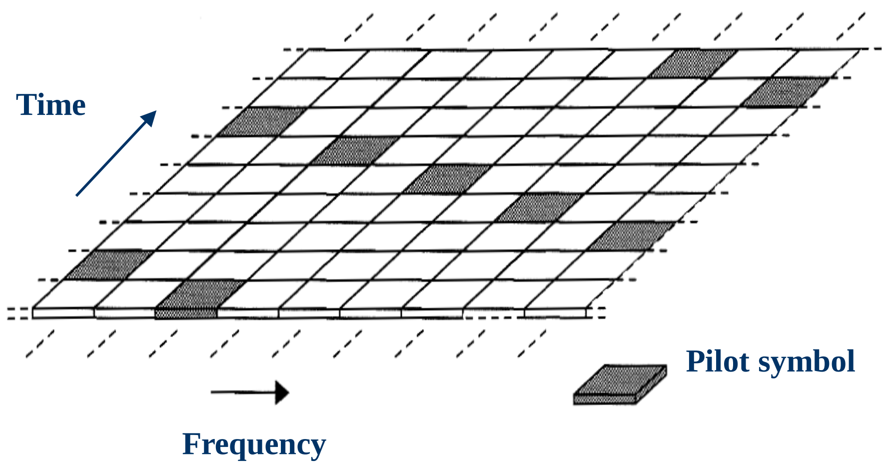
Power Spectrum for OFDM symbol



Channel Estimation_pilot symbols

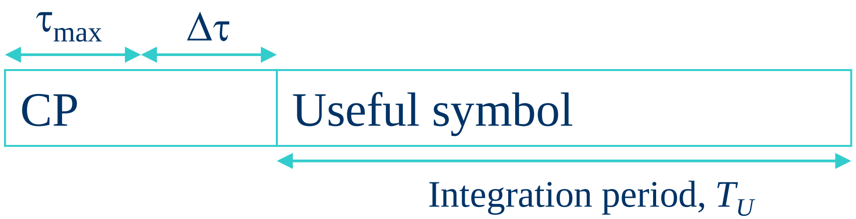
- The channel parameters can be estimated based on known symbols (pilot symbols)
- The pilot symbols should have sufficient density to provide estimates with good quality (tradeoff with efficiency)
- Different estimation methods exist
  - Averaging combined with interpolation
  - *Minimum-mean square error* (MMSE)

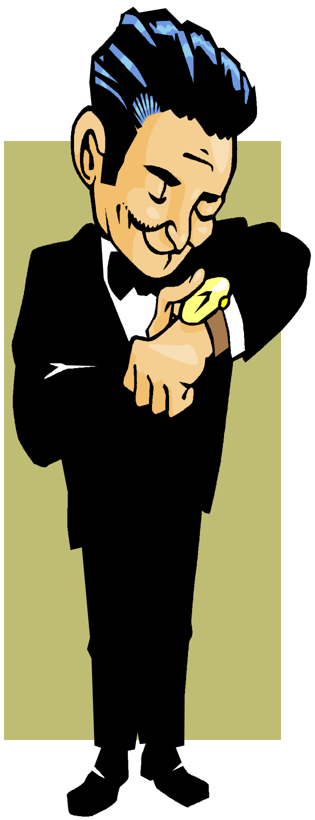




OFDM Synchronization

- Timing recovery
  - No problem if offset is within $\Delta\tau$

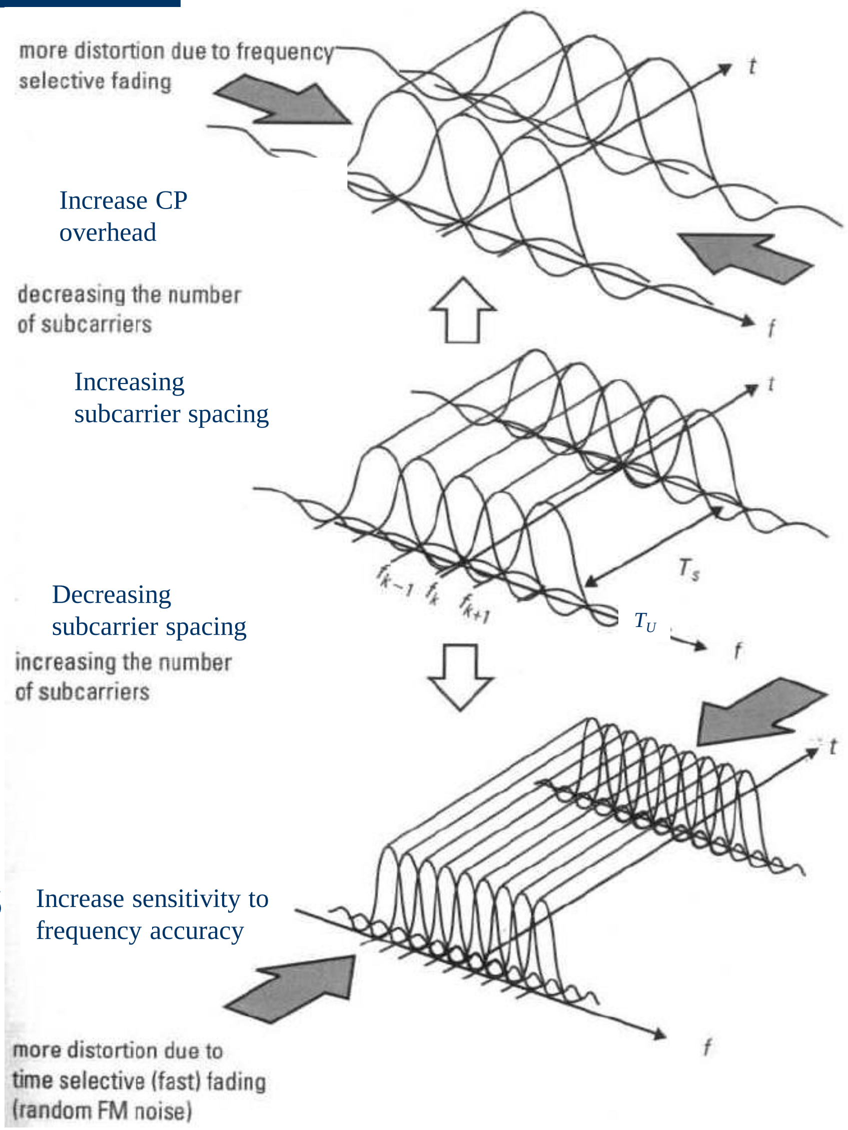




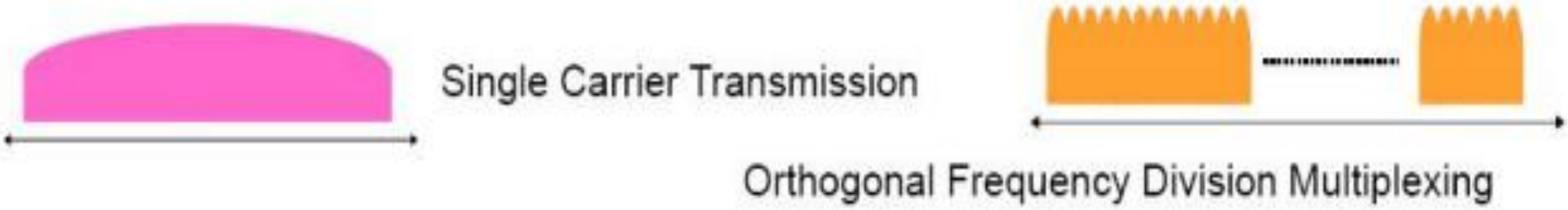
- Frequency synchronization
  - A carrier synchronization error will introduce phase rotation, amplitude reduction and ICI
  - Frequency offsets of up to 2 % of Δf is negligible
  - Even offsets of 5 – 10 % can be tolerated in many situations

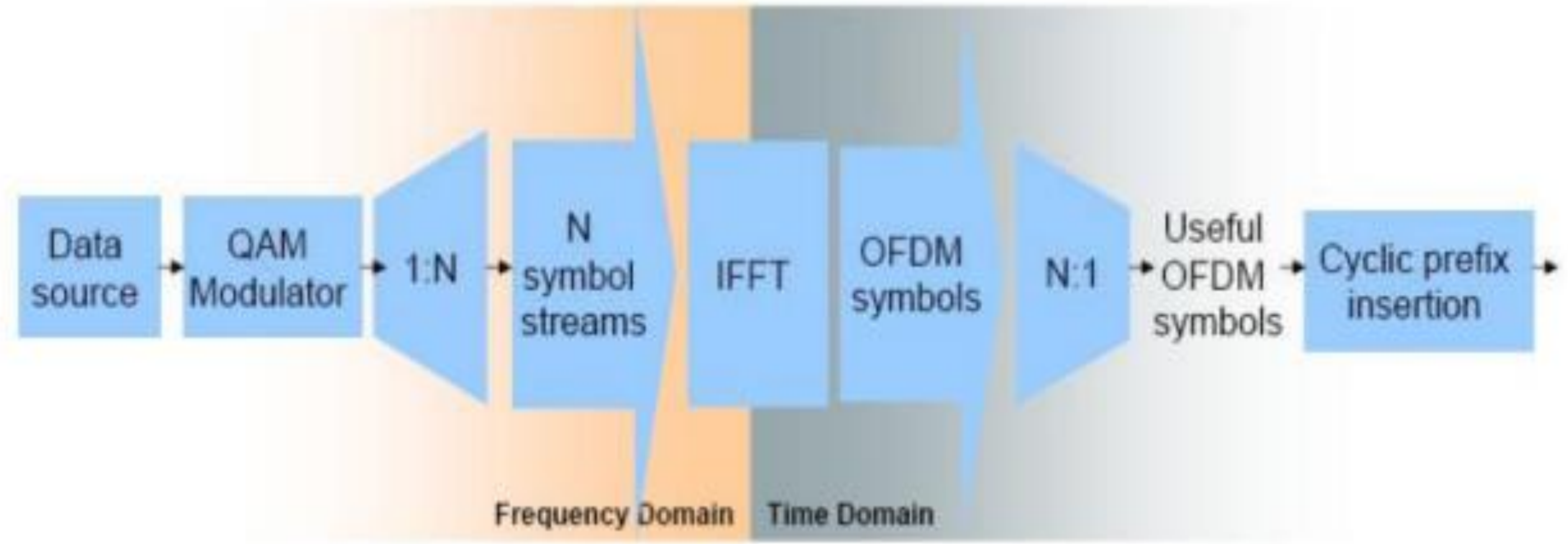
Choosing the OFDM parameters

- Symbol time (T_U) and subcarrier spacing (Δf) are inverse
  - $T_U = 1/\Delta f$
- Consequences of increasing the subcarrier spacing
  - Increase cyclic prefix overhead
- Consequences of decreasing the subcarrier spacing
  - Increase sensitivity to frequency inaccuracy
  - Increasing number of subcarriers increases Tx and Rx complexity



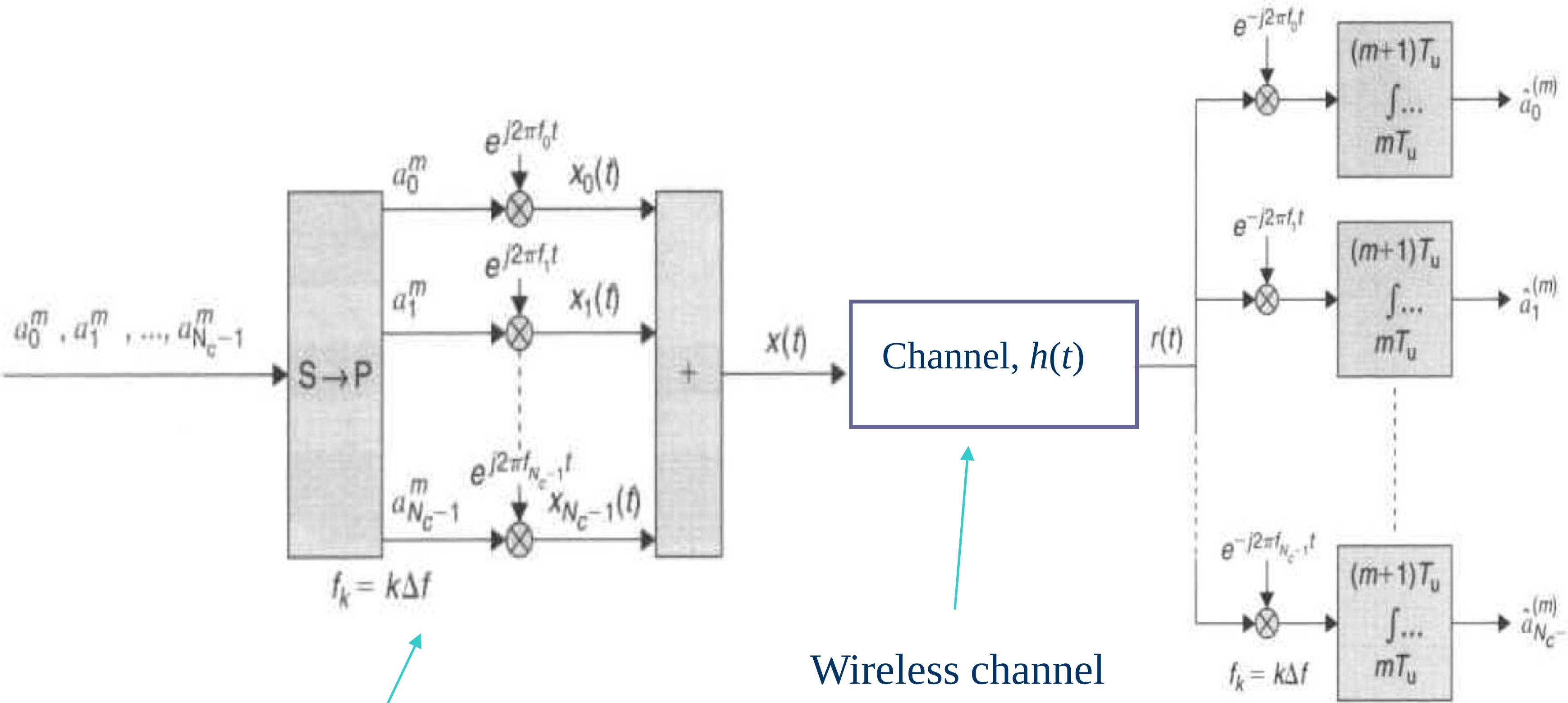
OFDM





OFDM signal generation is based on Inverse Fast Fourier Transform (IFFT) operation on transmitter side. On receiver side, an FFT operation will be used.

OFDM Transmission model

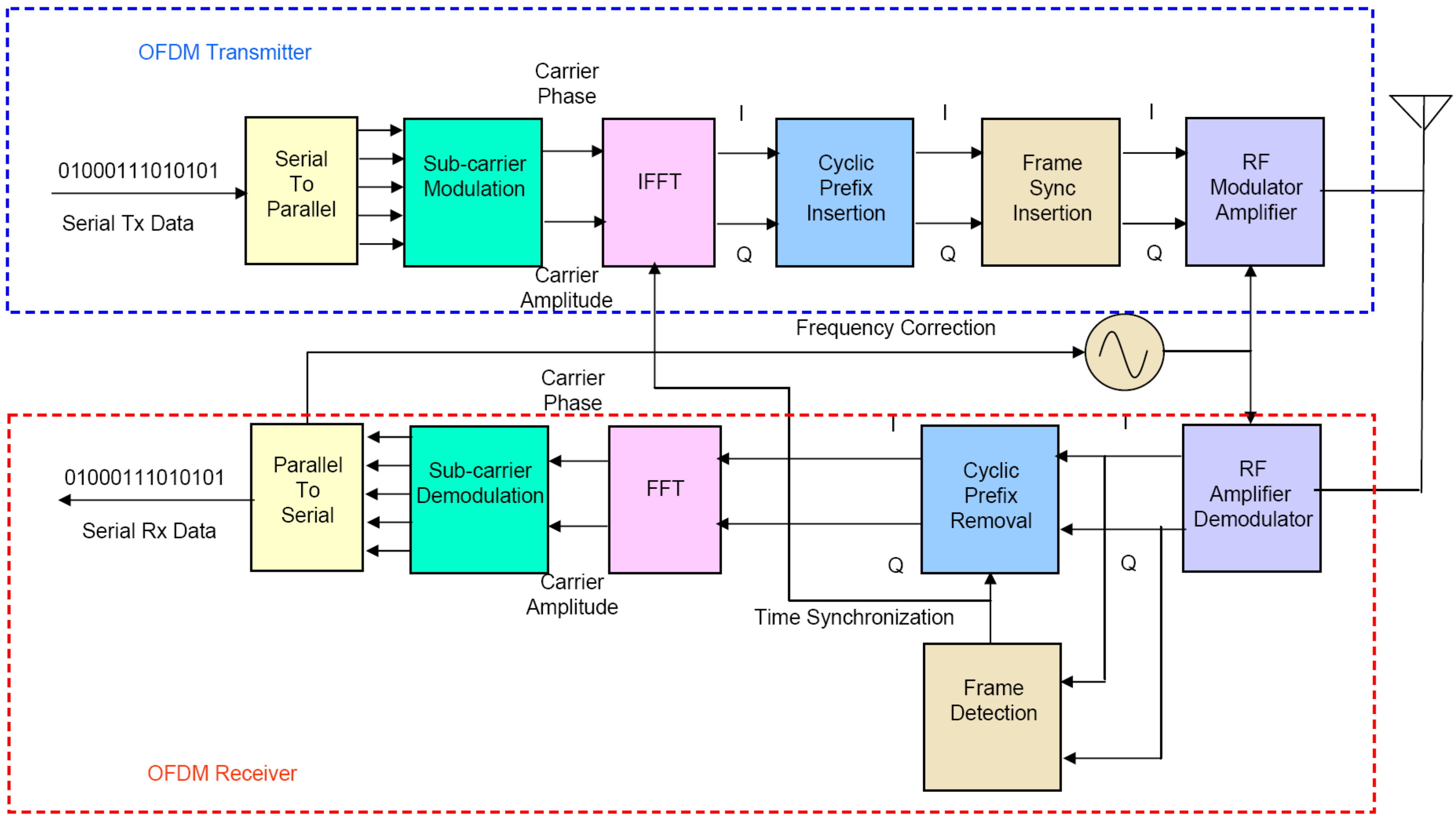


Wireless channel

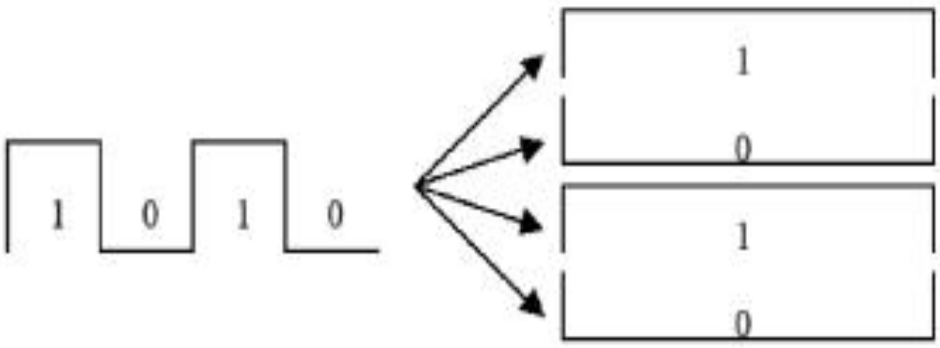
Modulator and transmitter

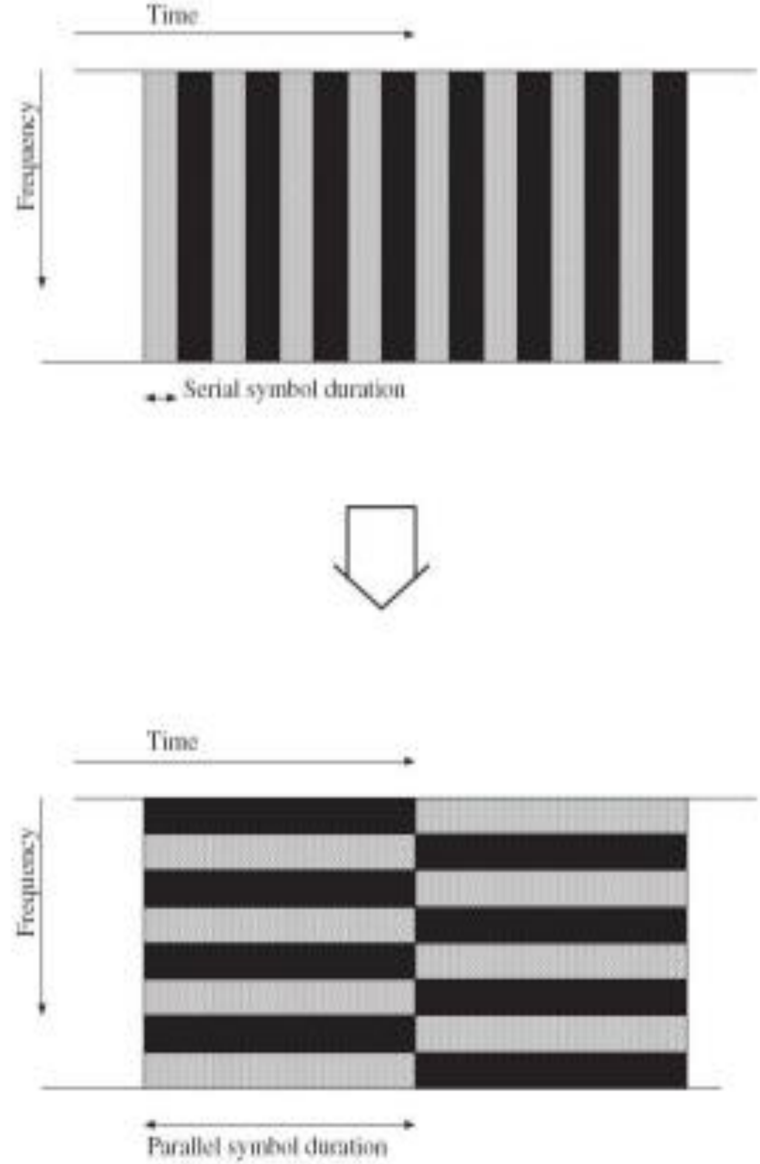
Receiver and demodulator

OFDM Transceiver

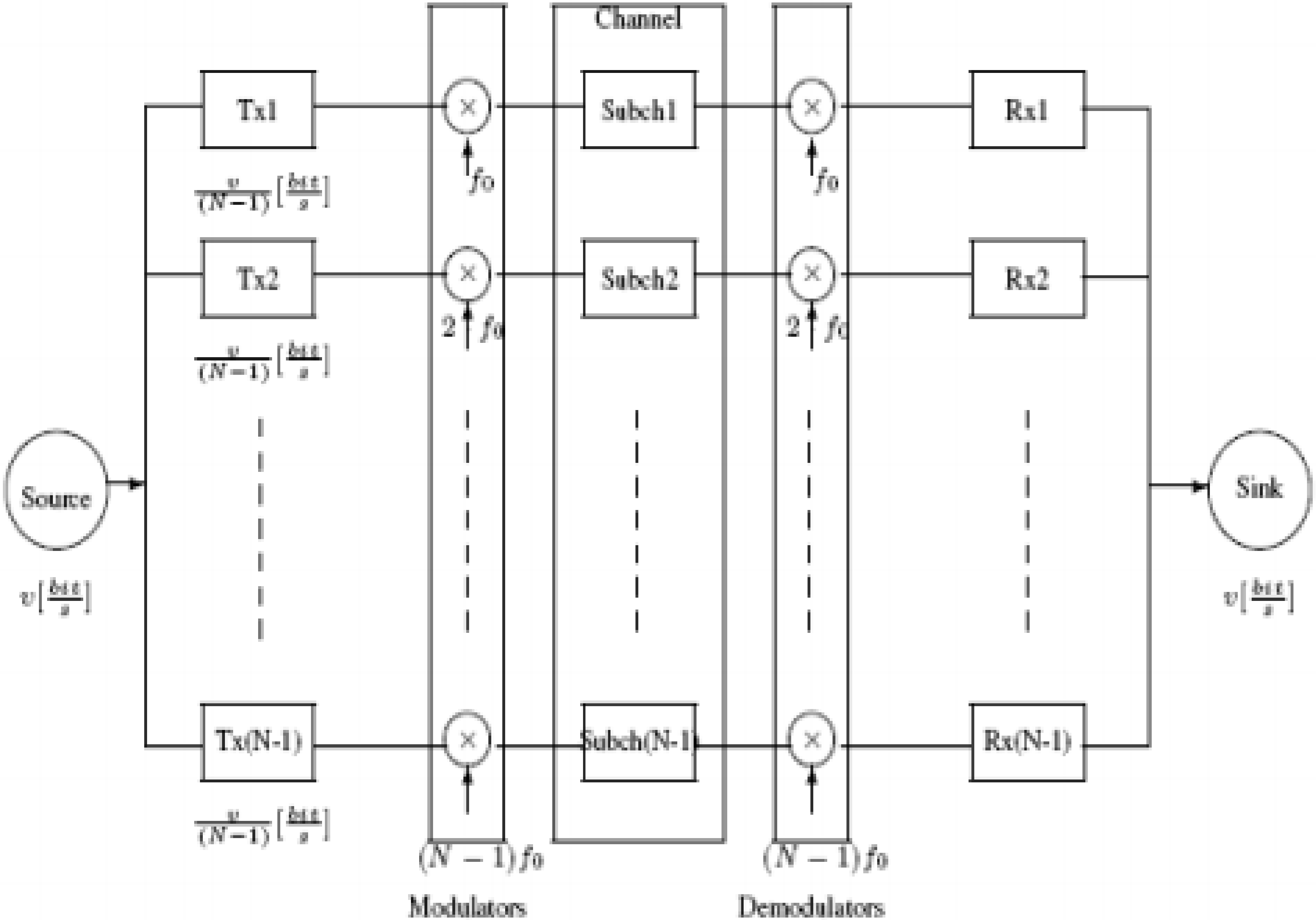


The parallel principle



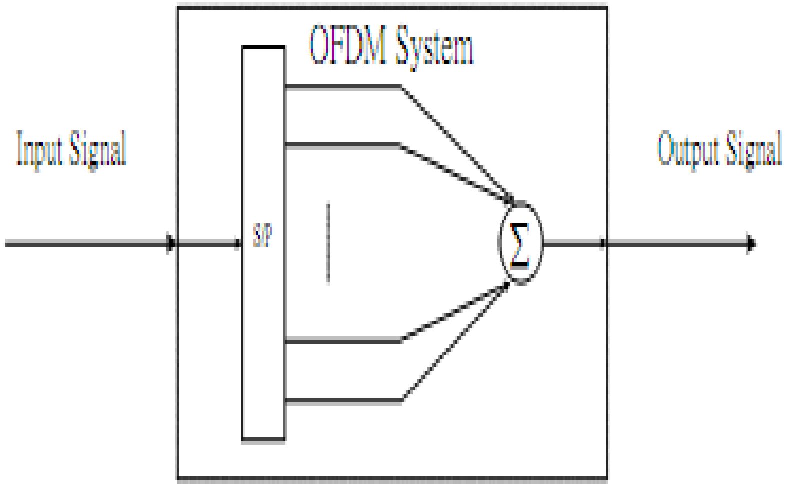


The modem parallel orthogonal

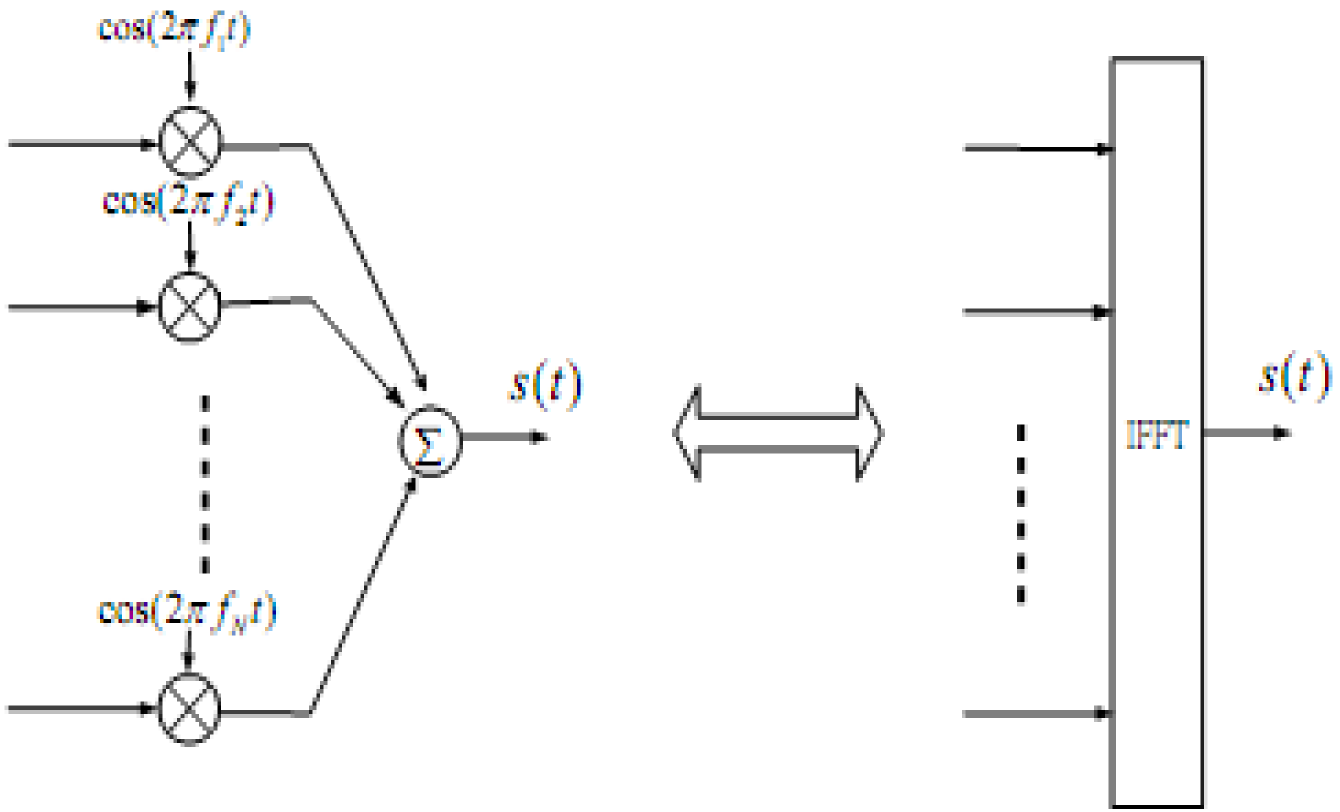


- Because of its high-speed data transmission and effectiveness in combating the frequency selective fading channel, OFDM technique is widely used in wireless communication nowadays.
- Orthogonal frequency division multiplexing (OFDM) is a multi-carrier transmission technique, which divides the available spectrum into many subcarriers, each one being modulated by a low data rate stream.
- OFDM is a special case of multicarrier transmission , where a single data stream is transmitted over a number of lower rate subcarrier[1,4].

- OFDM can be viewed as either a modulation technique or a multiplex technique.
  - Modulation technique
    - Viewed by the relation between input and output signals
  - Multiplex technique
    - Viewed by the output signal which is the linear sum of the modulated signals



- The employment of discrete Fourier transform to replace the banks of sinusoidal generator and the demodulation significantly reduces the implementation complexity of OFDM modems.



OFDM Modulation using FFTs

On line signal

$$x(t)=\sum_{k=0}^{N-1}\sum_{l} c_l^k \,\psi_k(t-lT)$$

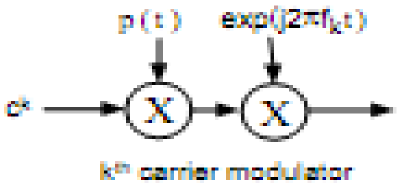
c: data
Ψ: pulse

Orthogonality principle

$$\int_0^T \psi_k(t)\psi_i^*(t)\,dt=\begin{cases}1 \;;\; if\ i=k\\ 0\;;\; if\ i\neq k\end{cases}$$

Let us assume $\psi_k(t)=p(t)e^{j2\pi f_k t}$ and $f_k=k/T$ ⇒ $x(t)=\sum_{k=0}^{N-1}\sum_{l} c_l^k\, p(t-lT)e^{j2\pi f_k t}$

Modulator bank of type



Sampling at $T_s=T/N$

$$x[n]=\sum_{k=0}^{N-1}\sum_{l} c_l^k\ \mathrm{rect}(nT_s-lNT_s)e^{j2\pi knT_s/NT_s}=\sum_{k=0}^{N-1}\sum_{l} c_l^k\ \mathrm{rect}(n-lN)e^{j2\pi kn/N}$$

where $\mathrm{rect}[n-lN]=\begin{cases}1\,;\, lN<n\le(l+1)N\\ 0\,;\quad else\end{cases}$ It can be expressed as

$$x[n]=\sum_{l}\mathrm{rect}[n-lN]\sum_{k=0}^{N-1}c_l^k e^{j2\pi kn/N}=\sum_{l}\mathrm{rect}[n-lN]\,IDFT(\mathbf{c}_l,n)$$

1 OFDM symbol carries N data c

$$x[n]=IDFT(\mathbf{c}_l,n)\ ;\ lN<n\le(l+1)N$$

Block processing

Advantages of OFDM

Spectrally efficient because of orthogonality of the 64 carriers.
Good for channels affected by frequency selective fading because:

(i) Effects of fading, affecting a small range of frequencies, can be spread out using 'interleaving' so that FEC can more easily correct any bit-errors.

(ii) Cyclic extension as a guard-interval, eliminates ISI caused by multi-path propagation. Simpler way of eliminating ISI than pulse-shaping as used in single carrier systems.

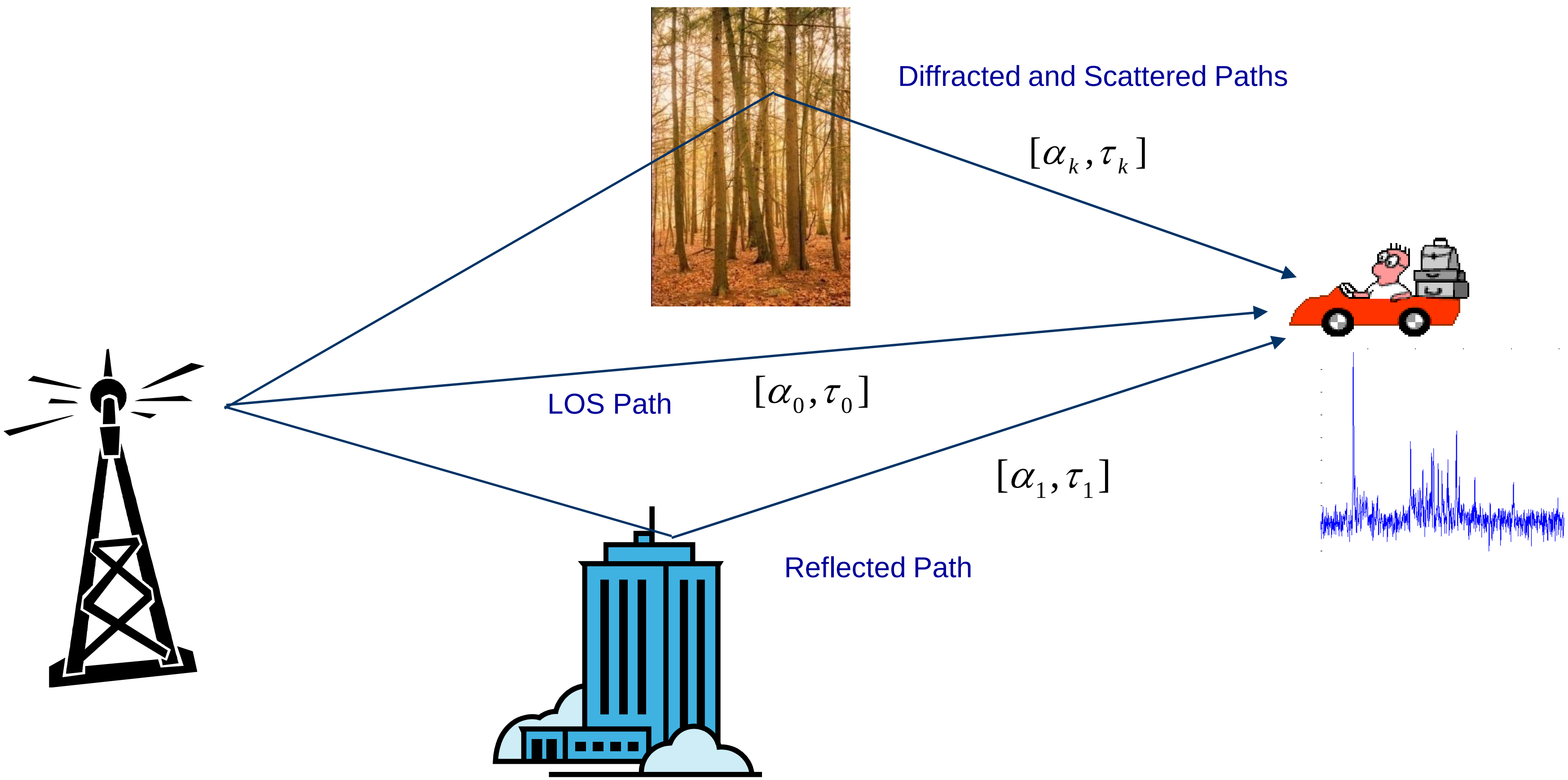
(iii) Equalisation is easier than with single carrier systems which use adaptive filtering. OFDM receiver can amplify real & imag parts of FFT outputs such that they have same amplitudes.

Possible because of the cyclic extension as explained earlier.

Disadvantages of OFDM

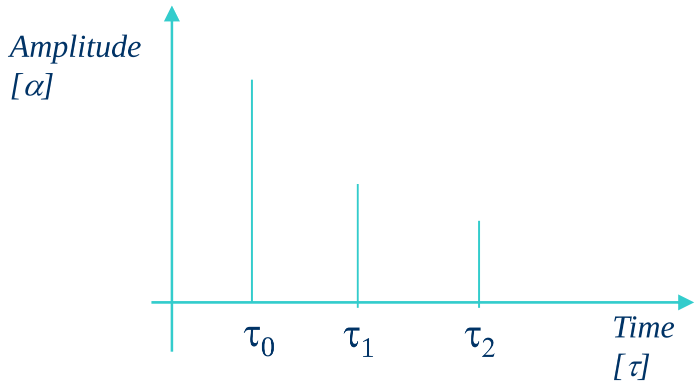
- ‘Peak to mean’ ratio of symbols can be very large by nature of FFT & Inv-FFT. (Amplitudes can become very large in comparison to the mean)
- Shapes OFDM symbols very complex & must be sent & received accurately.
- With QPSK on each sub-carrier, $\approx 10^{29}$ shapes & even more with 64-QAM
- Transmitter & receiver must be linear to preserve shape.
- Definitely not "constant envelope".
- Need ‘class A’ amplifiers: less power efficient than those for constant envelope transmissions.
- Lot of power lost in the amplifiers.
- Not ideal for mobile phones, but fine for mobile computers with bigger batteries that are not sending data continuously.
- Sensitive to ‘Doppler’ frequency shifts.

Effect of Multipath channel

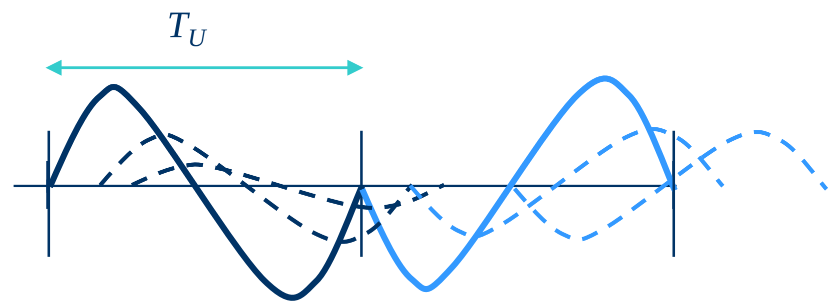


Multipath channel (cyclic prefix)

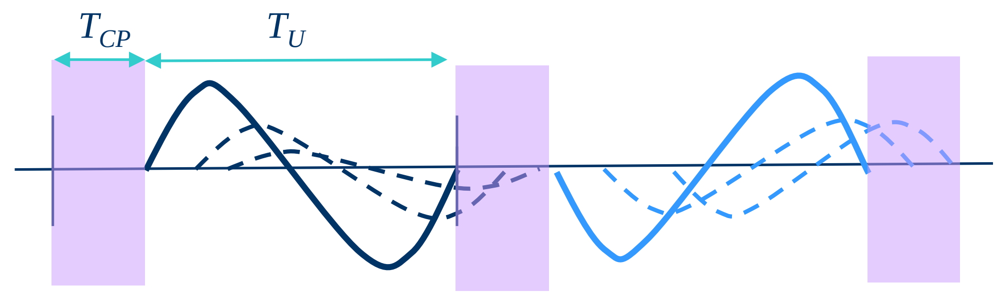
Example multipath profile



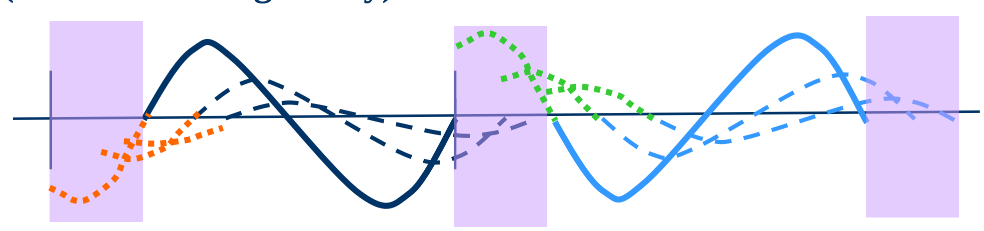
Multipath introduces *inter-symbol-interference* (ISI)



Prefix is added to avoid ISI

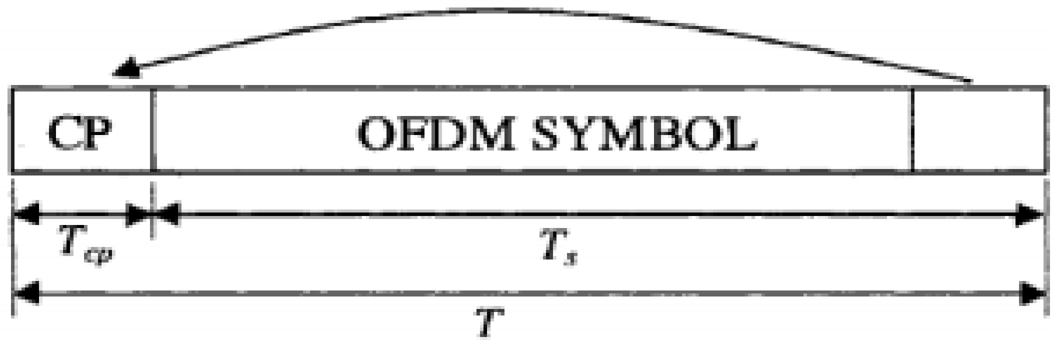


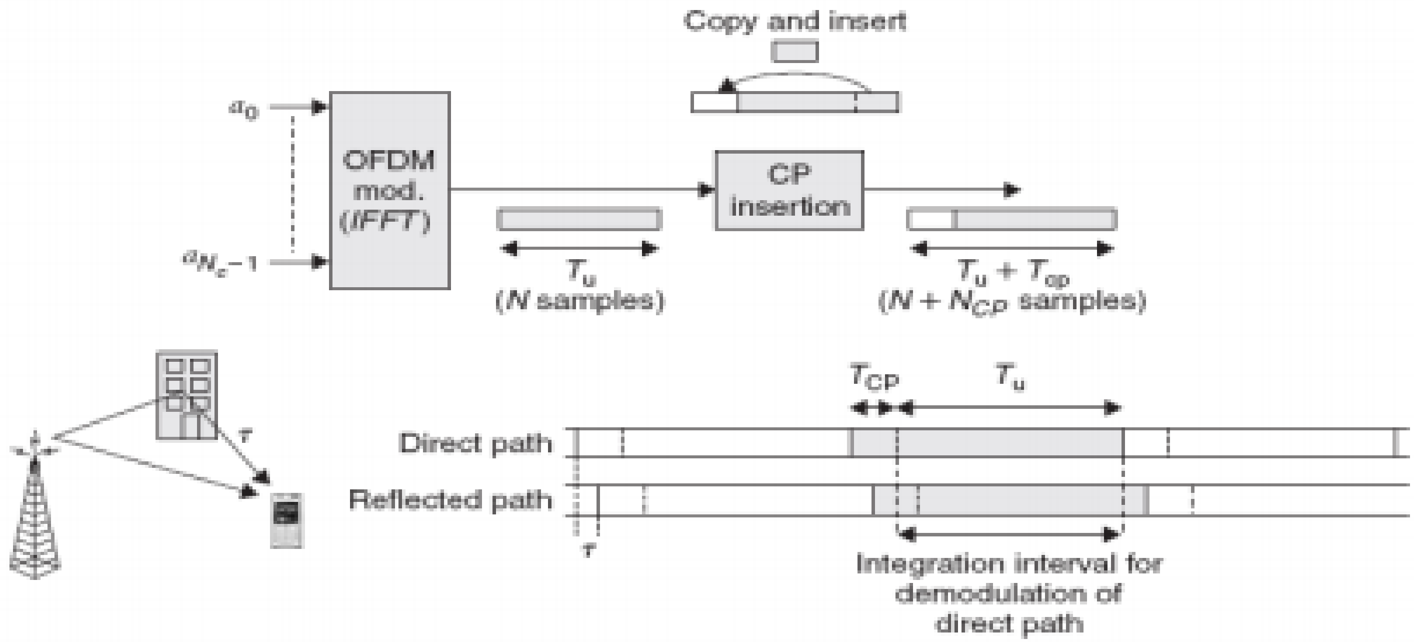
The prefix is made cyclic to avoid *inter-carrier-interference* (ICI) (maintain orthogonality)



Cyclic Prefix

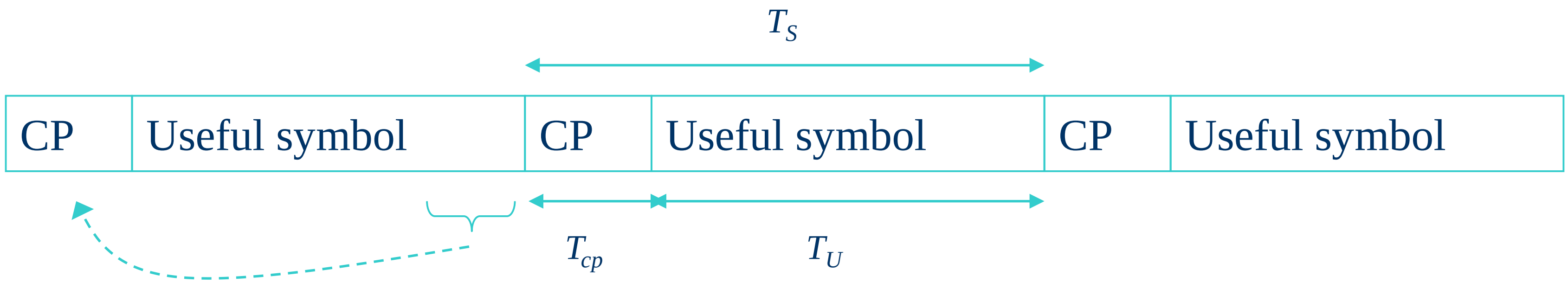
- Principle





Cyclic Prefix for Multipath channel

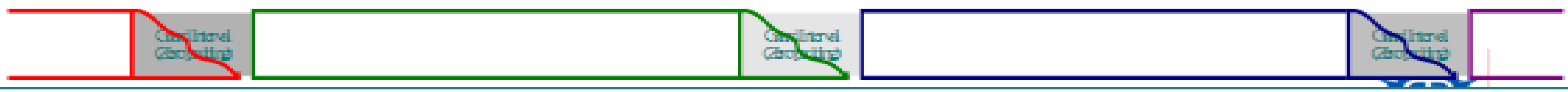
- T_{cp} should cover the maximum length of the time dispersion
- Increasing T_{cp} implies increased overhead in power and bandwidth (T_{cp}/ T_S)
- For large transmission distances there is a trade-off between power loss and time dispersion



- Intersymbol interference is eliminated almost completely by introducing a guard interval with zero padding in every OFDM symbol.

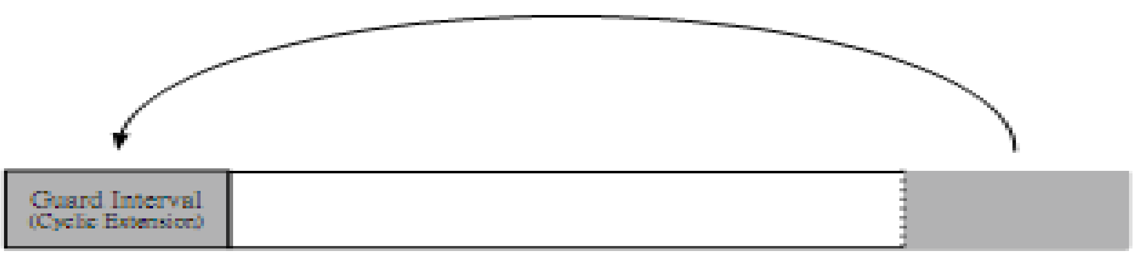
  - Guard interval with zero padding

  - The way to eliminate ISI

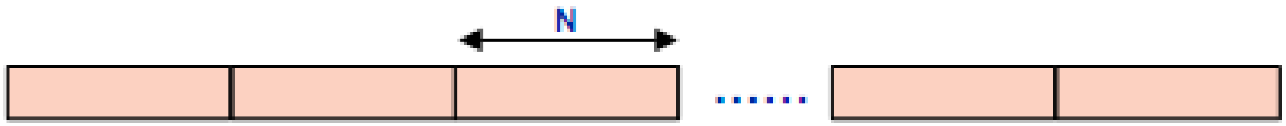


- In the guard time , the OFDM symbol is cyclically extended to avoid intercarrier interference.

  - Guard interval with cyclic extension (cyclic prefix)



Robustness against the channel and ACI improvement



Virtual OFDM symbols within the slot

- With guards (Cyclic prefixes), the channel's time dispersion is avoided

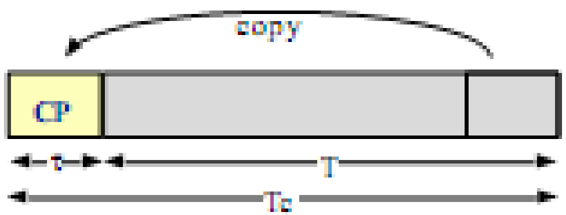
OFDM symbols with time guards (CPs)

- With smooth transitions between symbols, the Adjacent Channel Interference is minimized

OFDM symbols with time guards and shaping (extra time guard)

Drawback: it is implemented by using the **TIME** resource

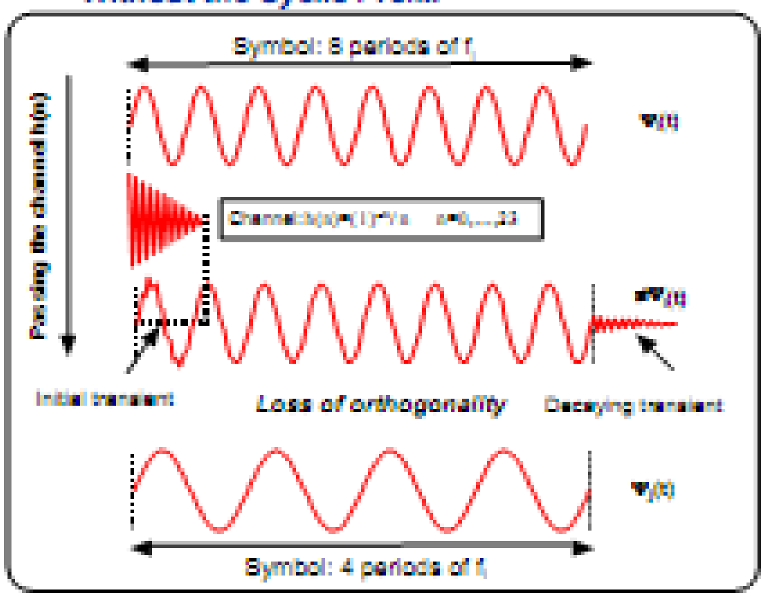
Including a cyclic prefix to the OFDM symbol: 'special' time guards in the symbol transitions



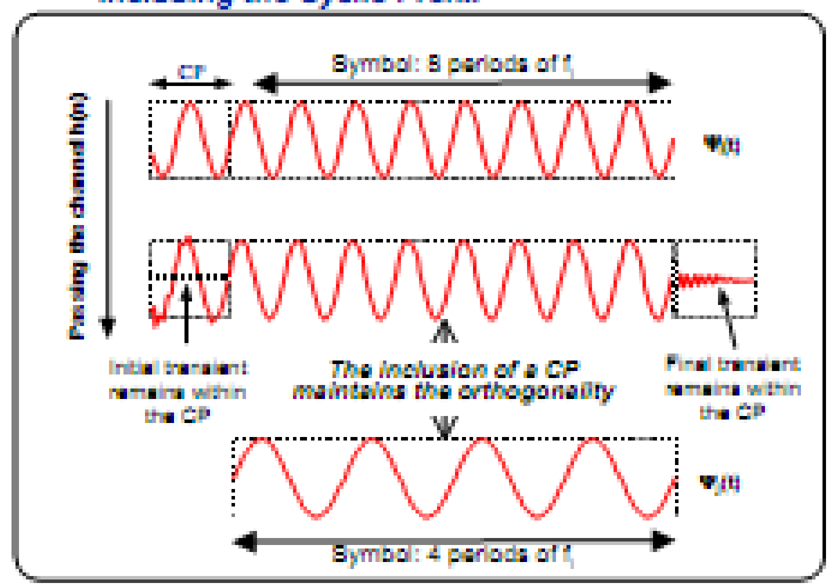
Furthermore, it converts Lineal conv. = Cyclic conv.

(Method: overlap-save)

Without the Cyclic Prefix



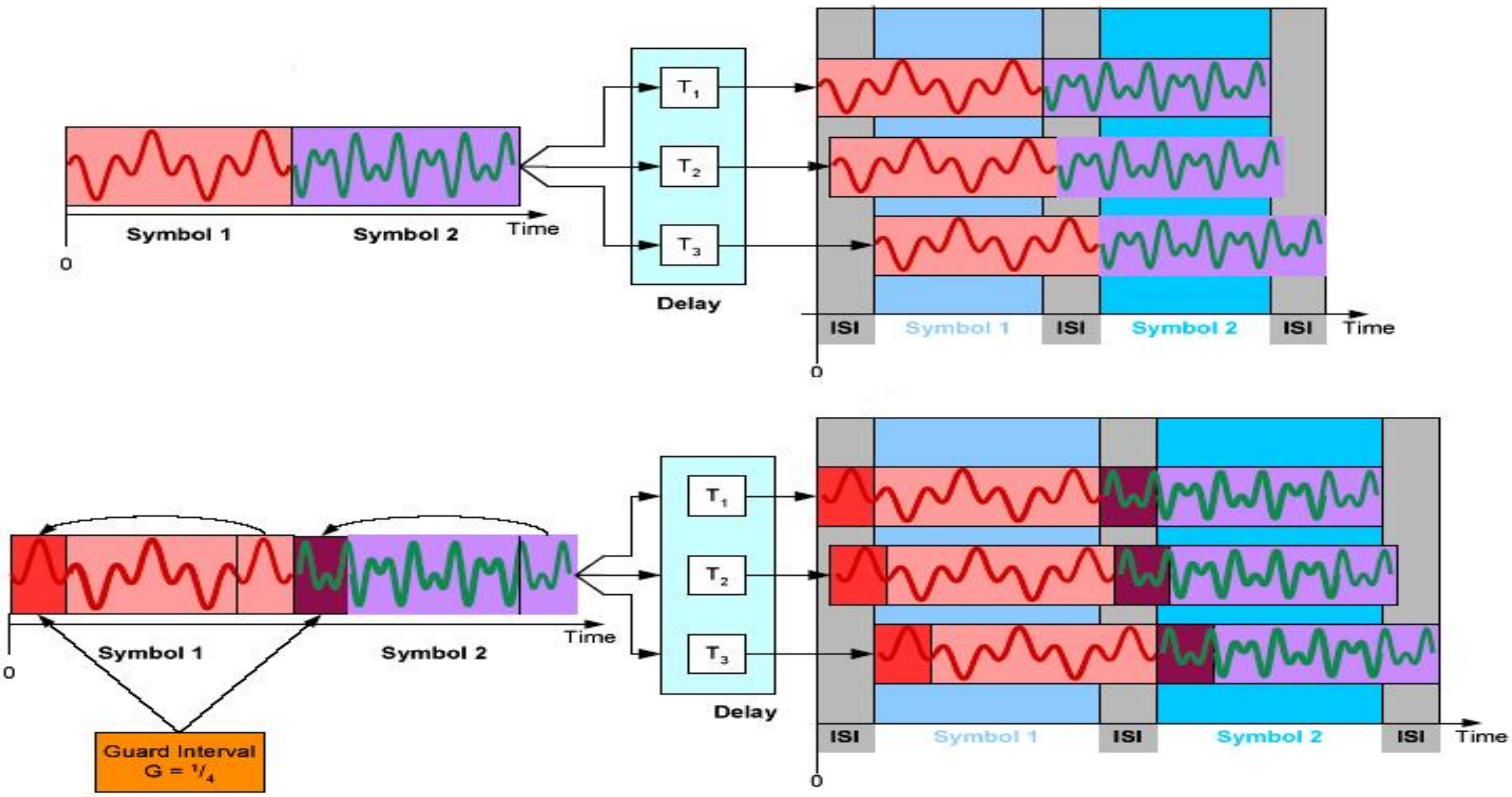
Including the Cyclic Prefix



CP functions:

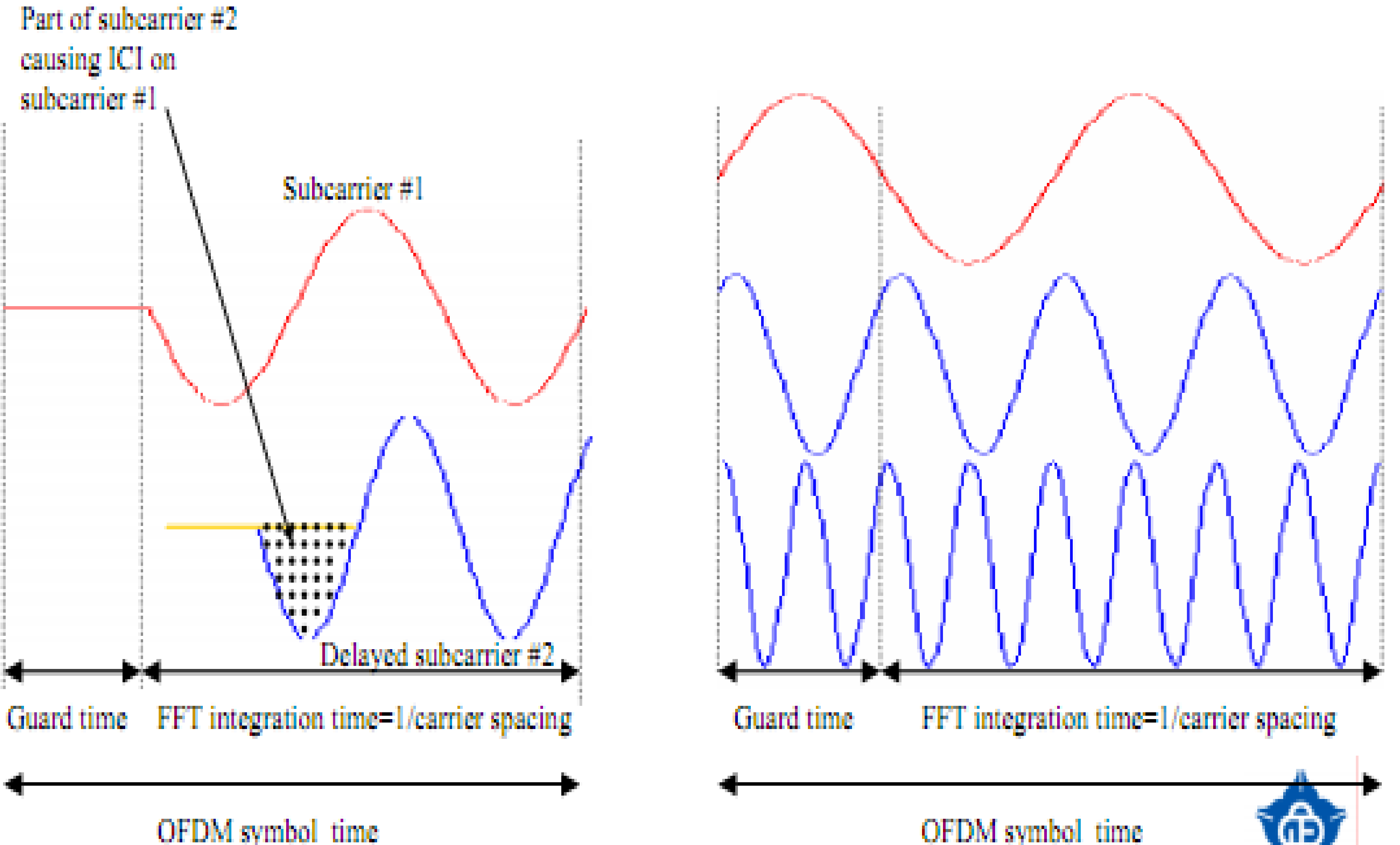
- It **accommodates** the decaying transient of the previous symbol (ISI)
- It **avoids** the initial transient reaches the current symbol (ICI)

Guard Interval (Cyclic Prefix)



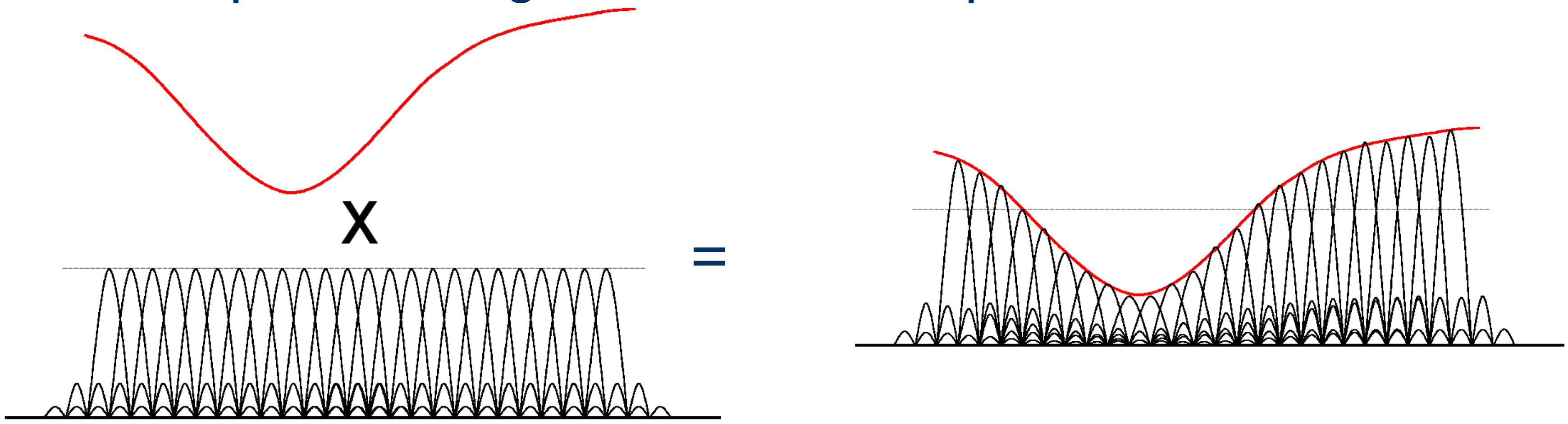
- Untuk mengatasi multipath delay spread
- Guard Interval (cyclic prefix) : 1/4, 1/8, 1/16 or 1/32

The way to avoid ICI

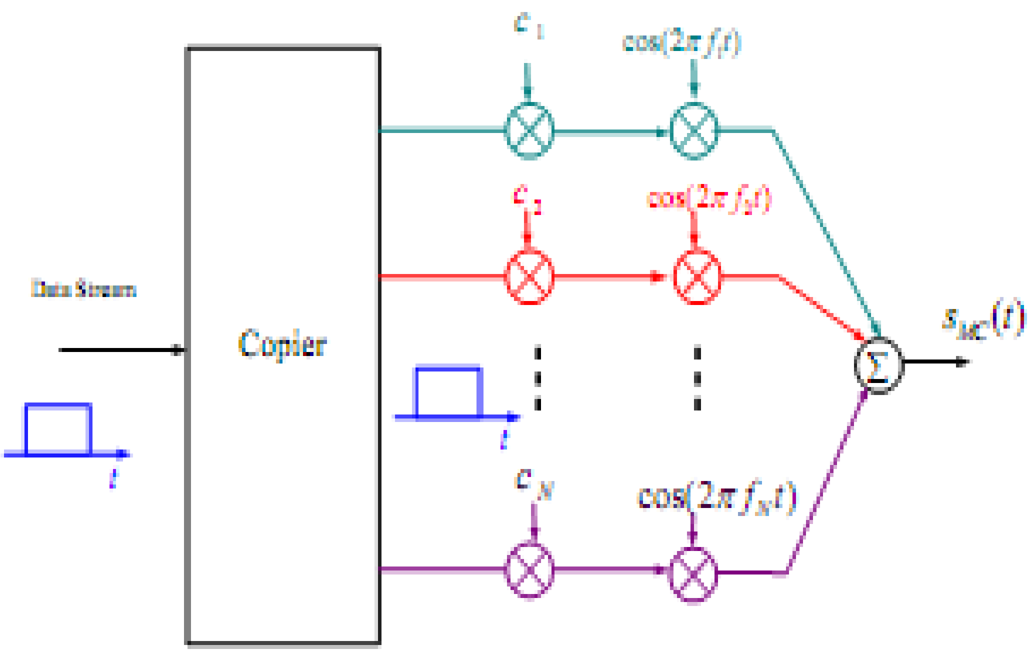


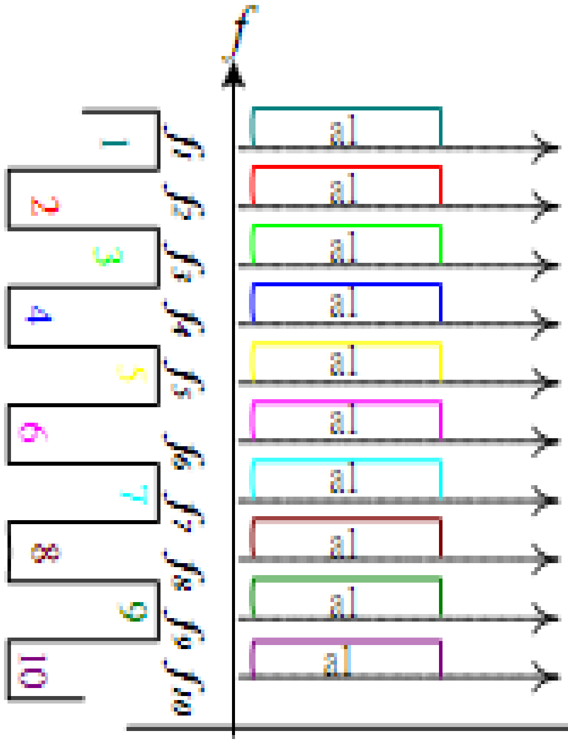
Multipath channel (frequency diversity)

- The OFDM symbol can be exposed to a frequency selective channel
- The attenuation for each subcarrier can be viewed as “flat”
  - Due to the cyclic prefix there is no need for a complex equalizer
- Possible transmission techniques
  - *Forward error correction* (FEC) over the frequency band
  - Adaptive coding and modulation per carrier



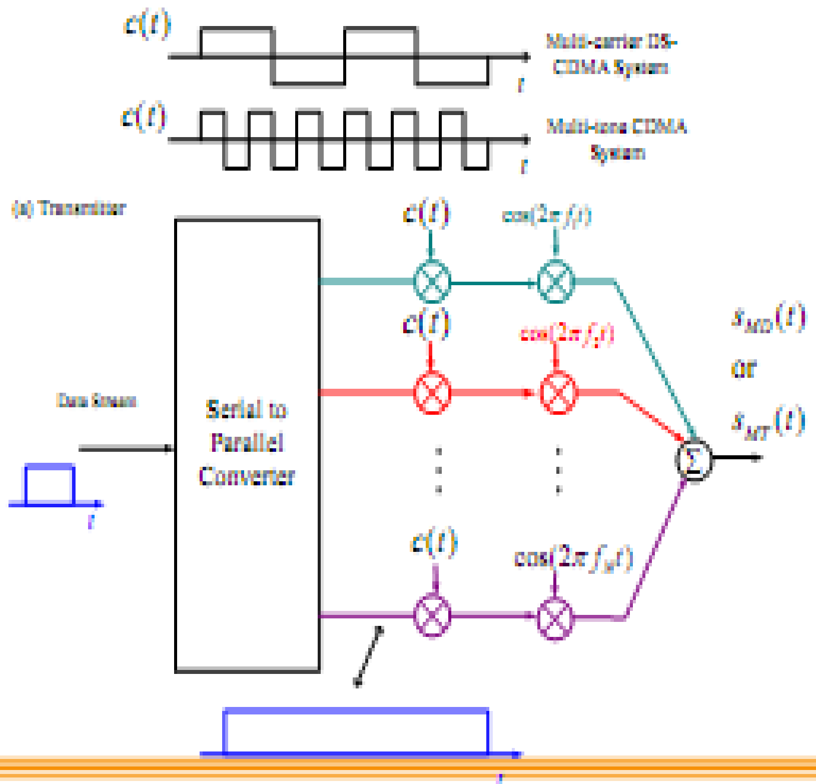
- Multicarrier CDMA system
  - Frequency domain spreading
    - MC-CDMA system
      - The spreading operation in the frequency domain
      - It spreads the original data streams using a given spreading code, and then modulates a different subcarriers with each chip

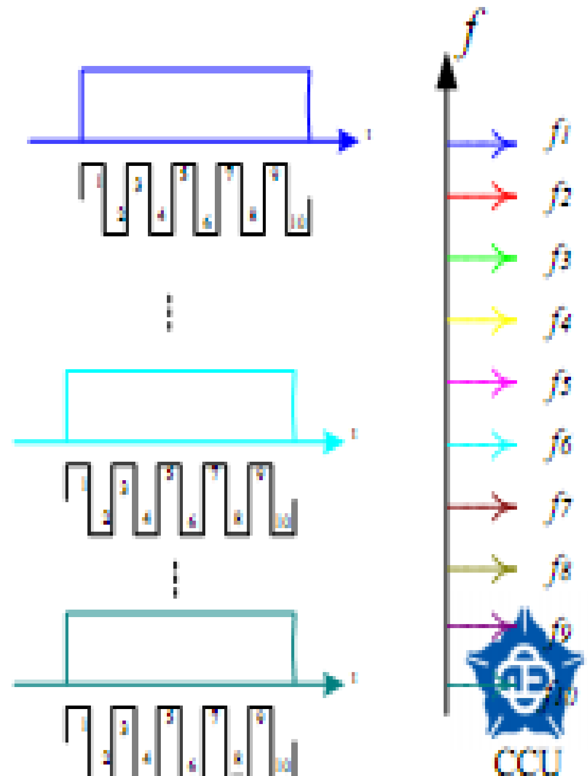




Time domain spreading

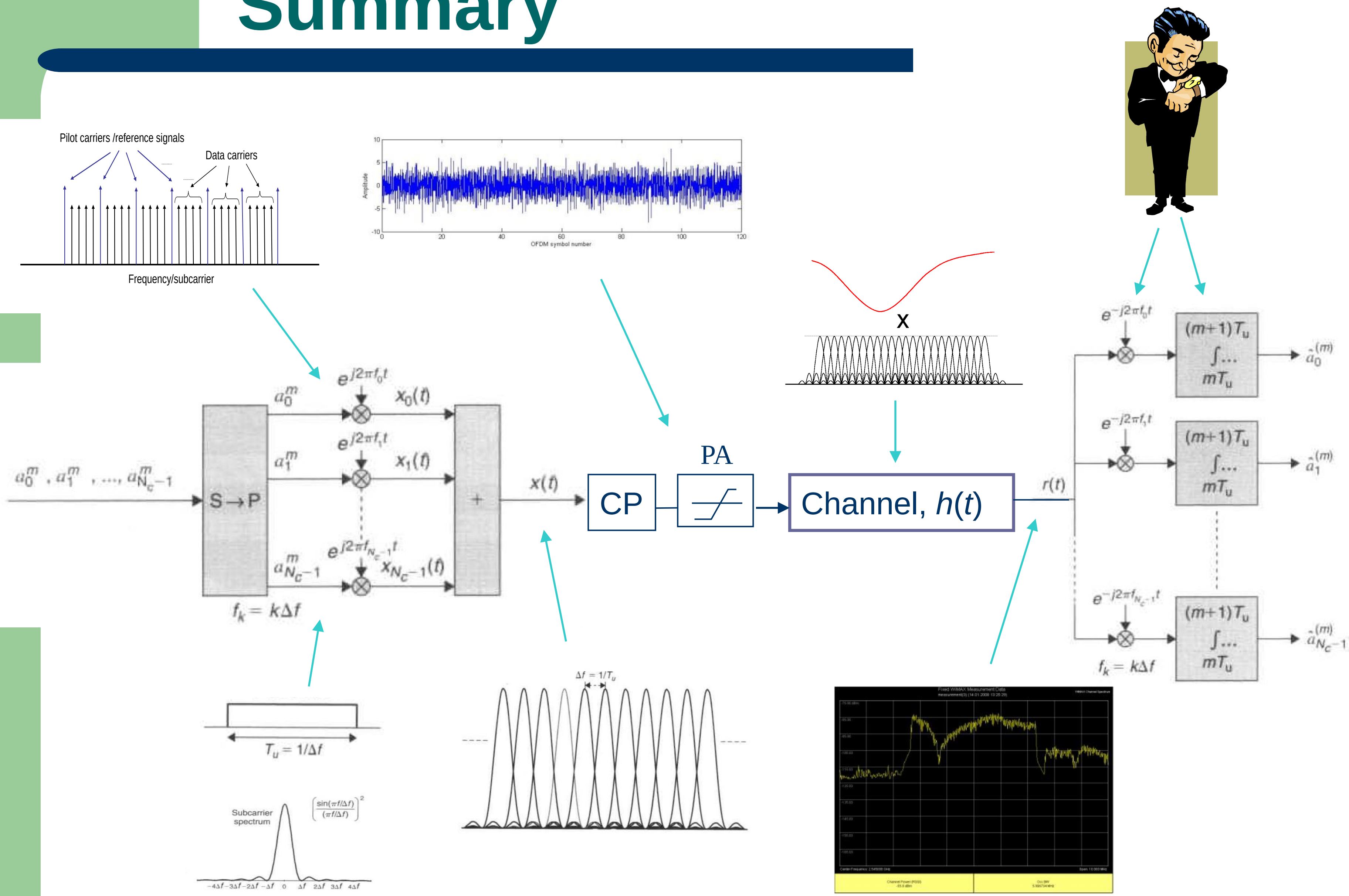
- **Multi-carrier DS-CDMA system**
- **Multi-tone CDMA system**
  - The spreading operation in the time domain
  - It spreads the serial-to-parallel (s/p) converted data streams using a given spreading code, and then modulates a different subcarrier with each data stream.





CCU
Wireless Access Tech. Lab.

Summary



Pilot carriers /reference signals
Data carriers
Frequency/subcarrier
OFDM symbol number
Amplitude
X
PA
CP
Channel, h(t)
S→P
x(t)
r(t)
f_k = kΔf
T_u = 1/Δf
Δf = 1/T_u
Subcarrier spectrum

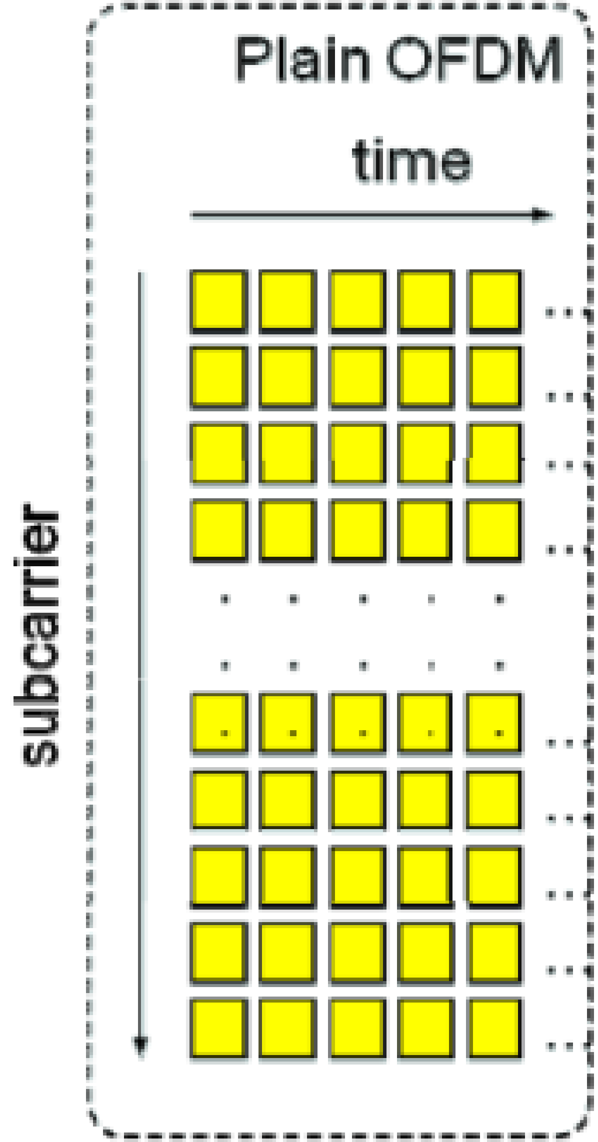
Konsep OFDMA

OFDM dan Multiple Access

- Sampai saat ini, kita baru bicara tentang simple point-to-point atau broadcast OFDM.
- Bagaimana dengan penanganan multi user dimana masing-masing user menggunakan sinyal OFDM ?
- Secara teknis, OFDM dapat dikombinasikan dengan beberapa metode multiple access untuk mendukung layanan multi user:
  - Plain OFDM
  - FDMA/OFDM, TDMA/OFDM, CDMA/OFDM

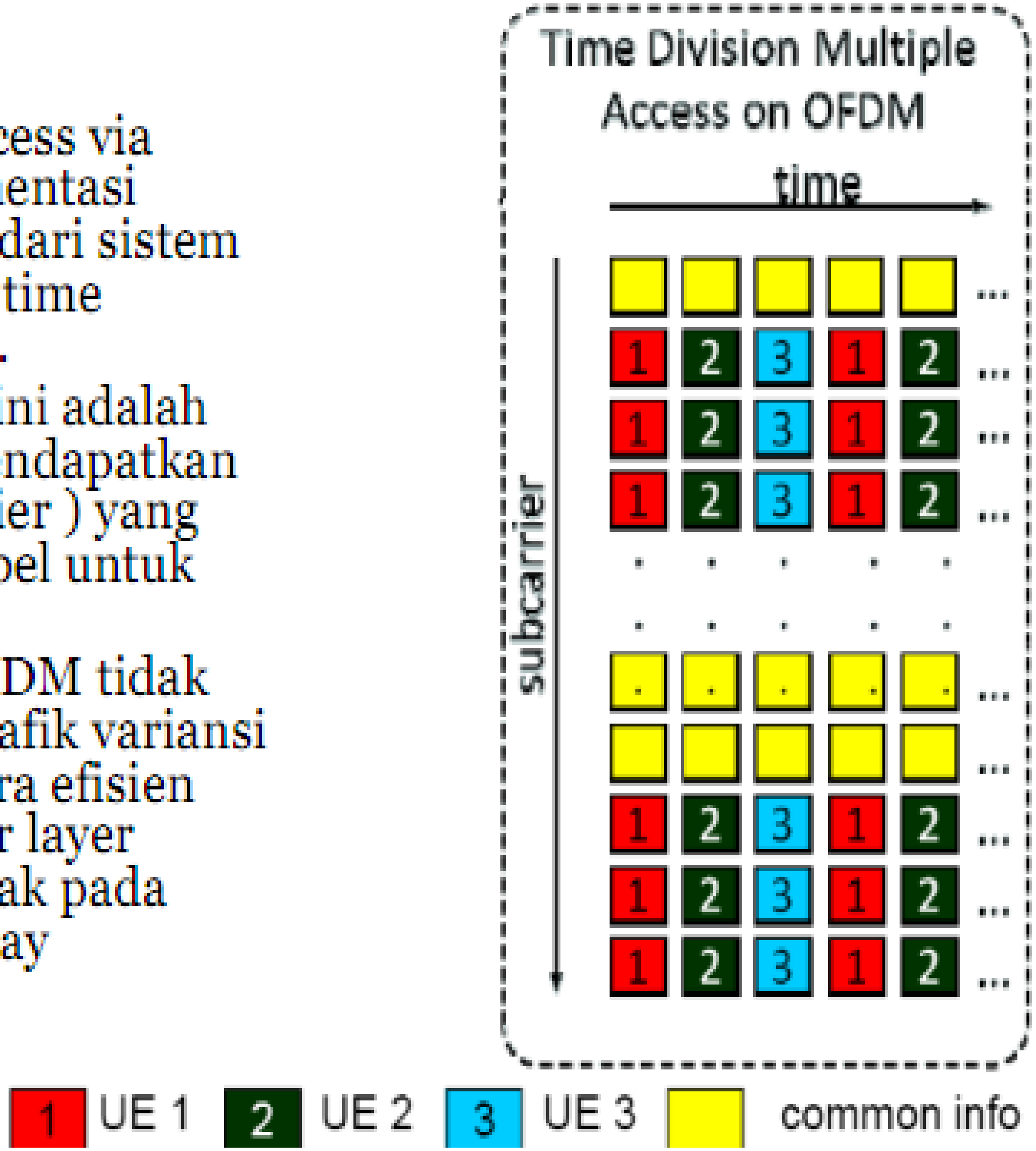
Plain OFDM

- Tidak memiliki mekanisme multipleaccess
- Hanya sesuai untuk aplikasi broadcast/multicast seperti DVB-T/H dengan tanpa kanal feedback



TDMA / OFDM

- Time Division Multiple Access via OFDM merupakan implementasi multiple access sederhana dari sistem OFDM dengan melakukan time multiplexing diatas OFDM.
- Kerugian dari mekanisme ini adalah bahwa setiap user akan mendapatkan jumlah kapasitas (subcarrier) yang sama sehingga tidak fleksibel untuk layanan multi data rate.
- Lebih jauh lagi, TDMA/OFDM tidak sesuai untuk menangani trafik variansi tinggi seperti internet secara efisien tanpa menggunakan higher layer signaling. Hal ini berdampak pada overhead signaling dan delay



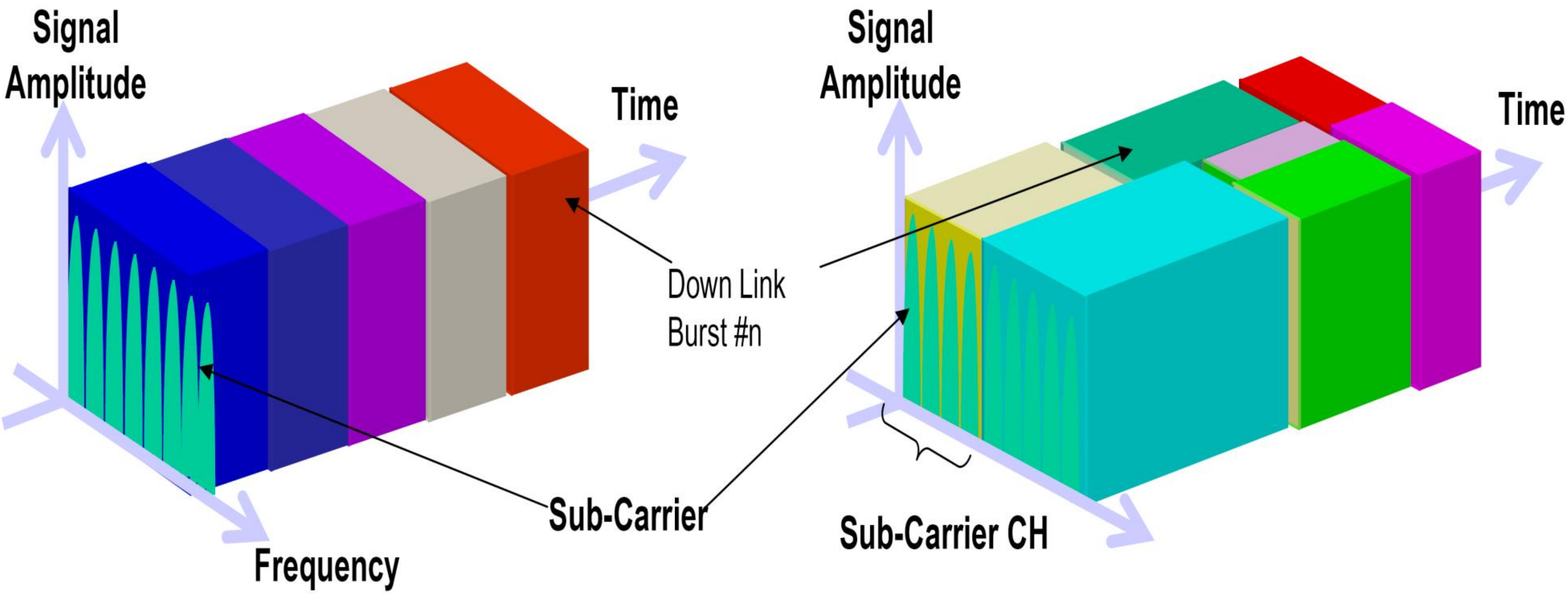
OFDM & OFDMA

OFDM

- Semua subcarrier dialokasikan untuk satu user
- Misal : 802.16-2004

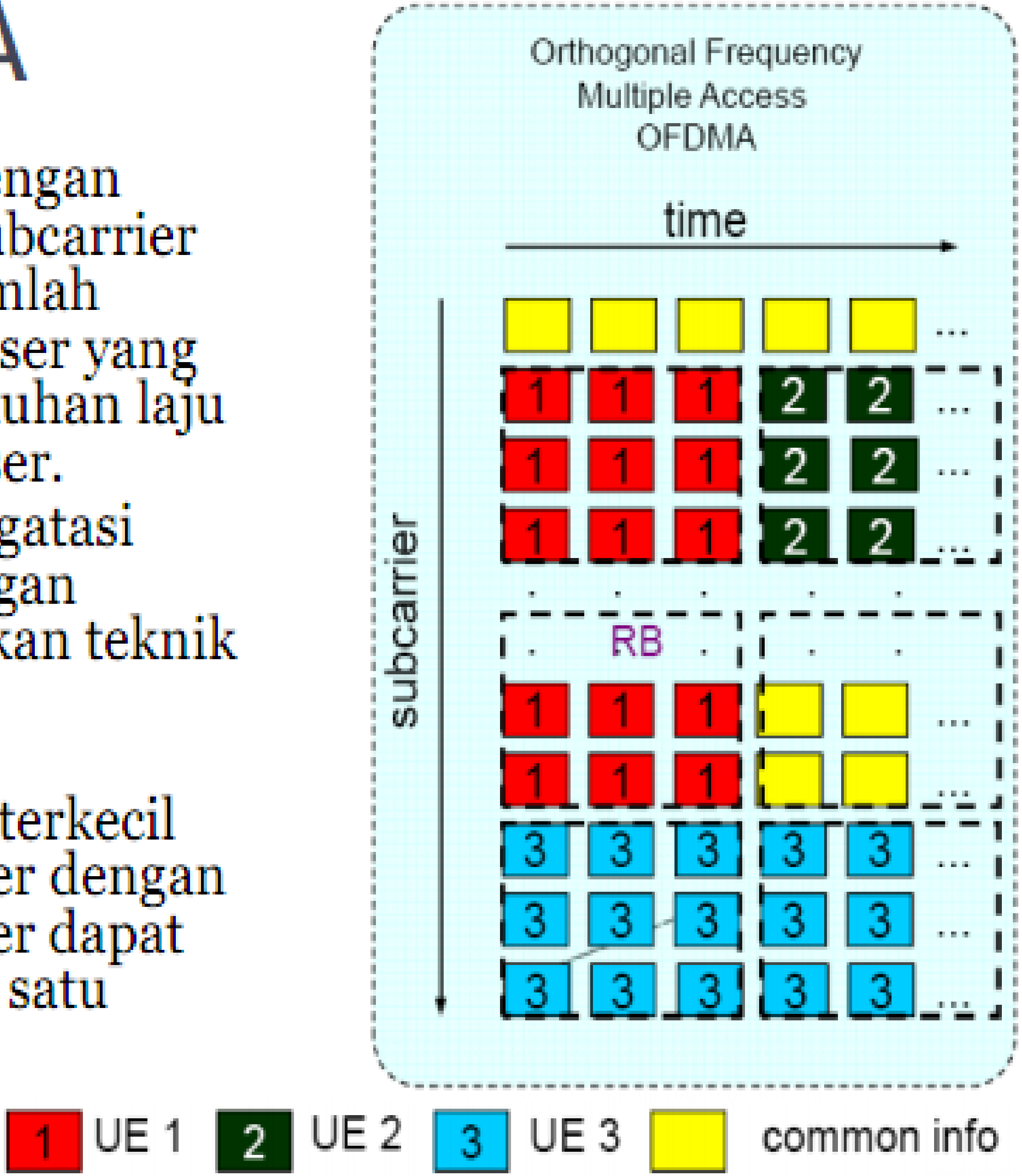
OFDMA

- Subcarrier dialokasikan secara fleksibel untuk banyak user tergantung pada kondisi radio.
- Misal : 802.16e-2005 dan 802.16m



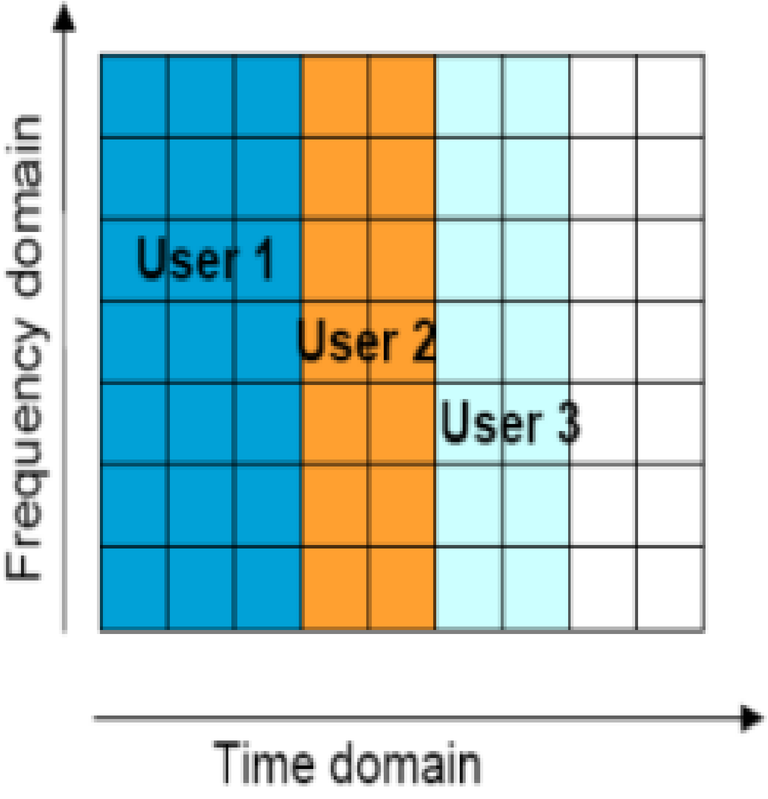
FDMA / OFDMA

- Ide dasarnya adalah dengan penugasan sejumlah subcarrier ke suatu user dan sejumlah subcarrier lain untuk user yang lain berdasarkan kebutuhan laju data masing-maisng user.
- Untuk membantu mengatasi penanganan trafik dengan variansi tinggi, digunakan teknik **resource block atau scheduling block**
- Suatu block adalah set terkecil dari sejumlah subcarrier dengan jumlah tetap. Suatu user dapat dialokasikan lebih dari satu block.

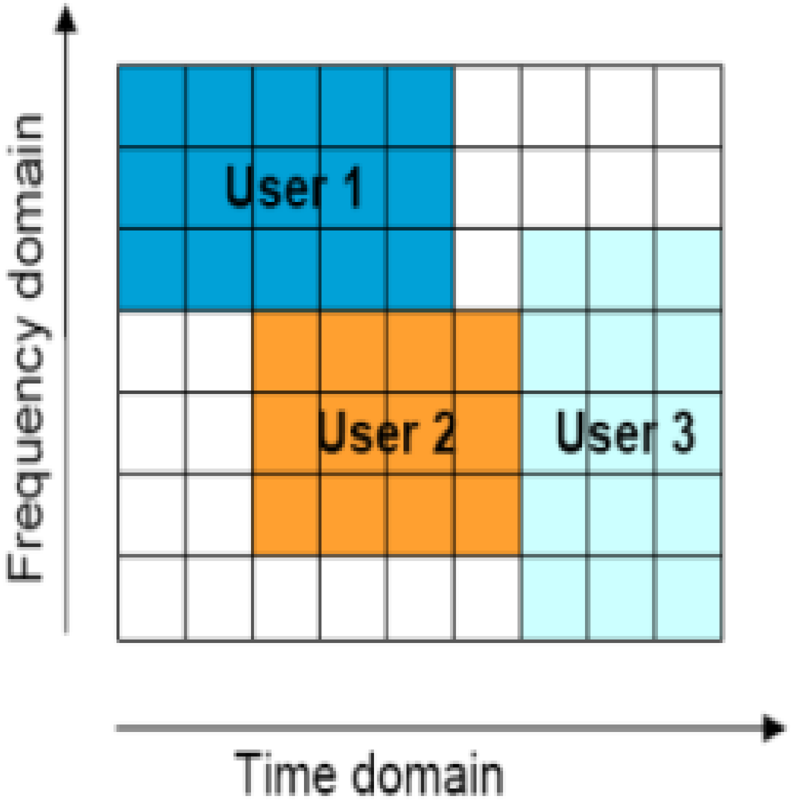


Perbedaan OFDM dan OFDMA

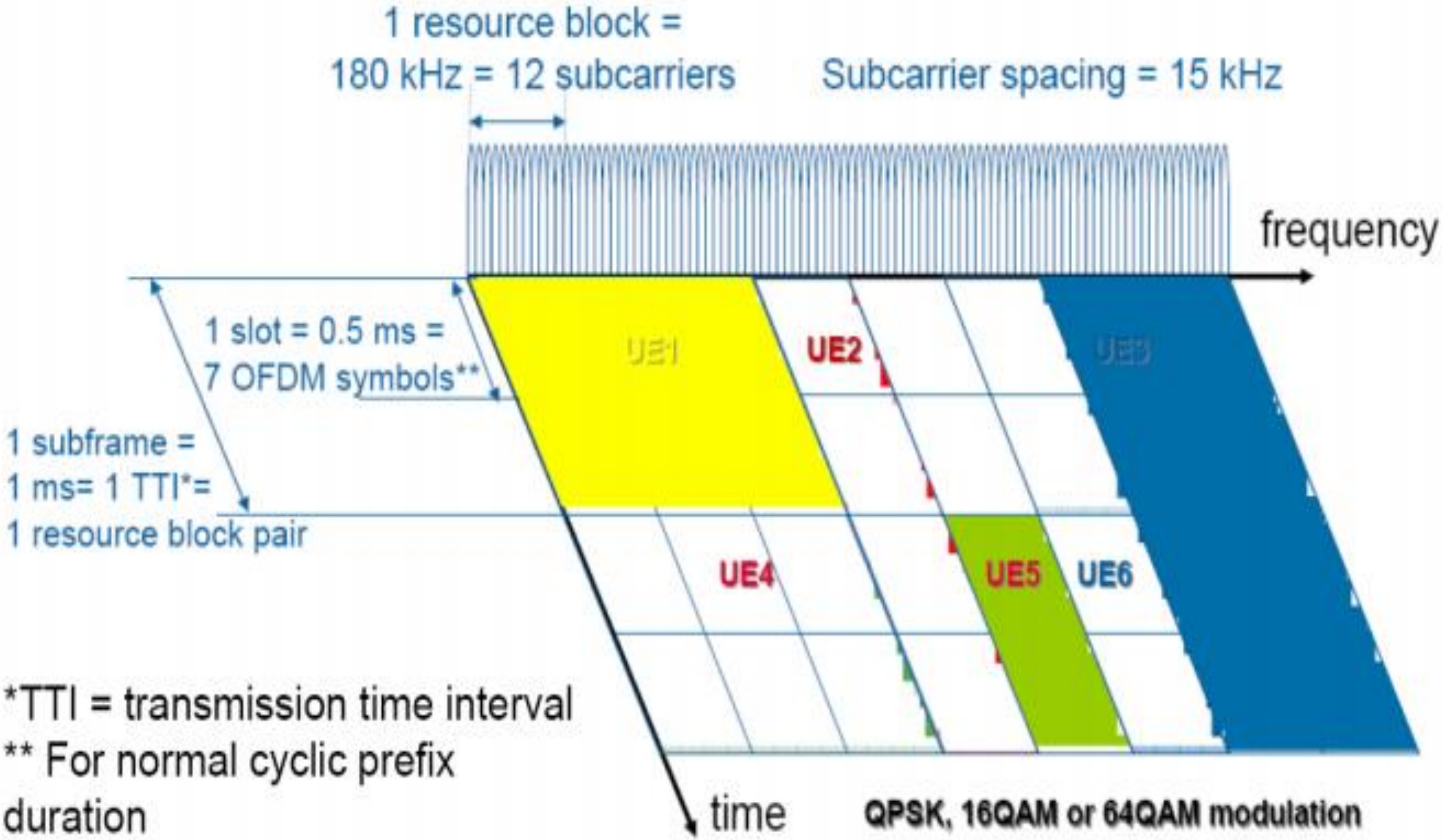
OFDM allocates users in time domain only



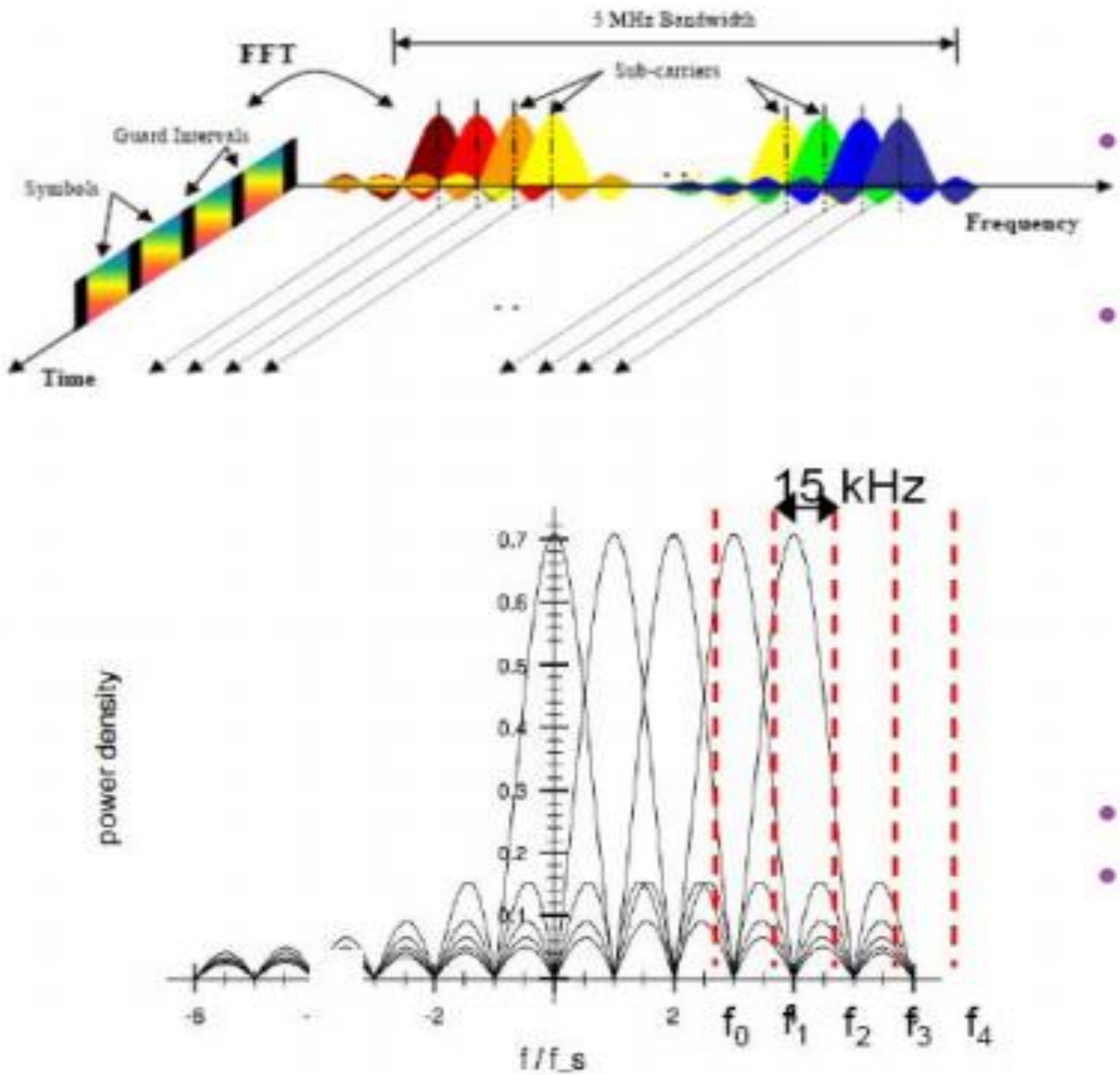
OFDMA allocates users in time and frequency domain



OFDMA Time-Frequency Multiplexing

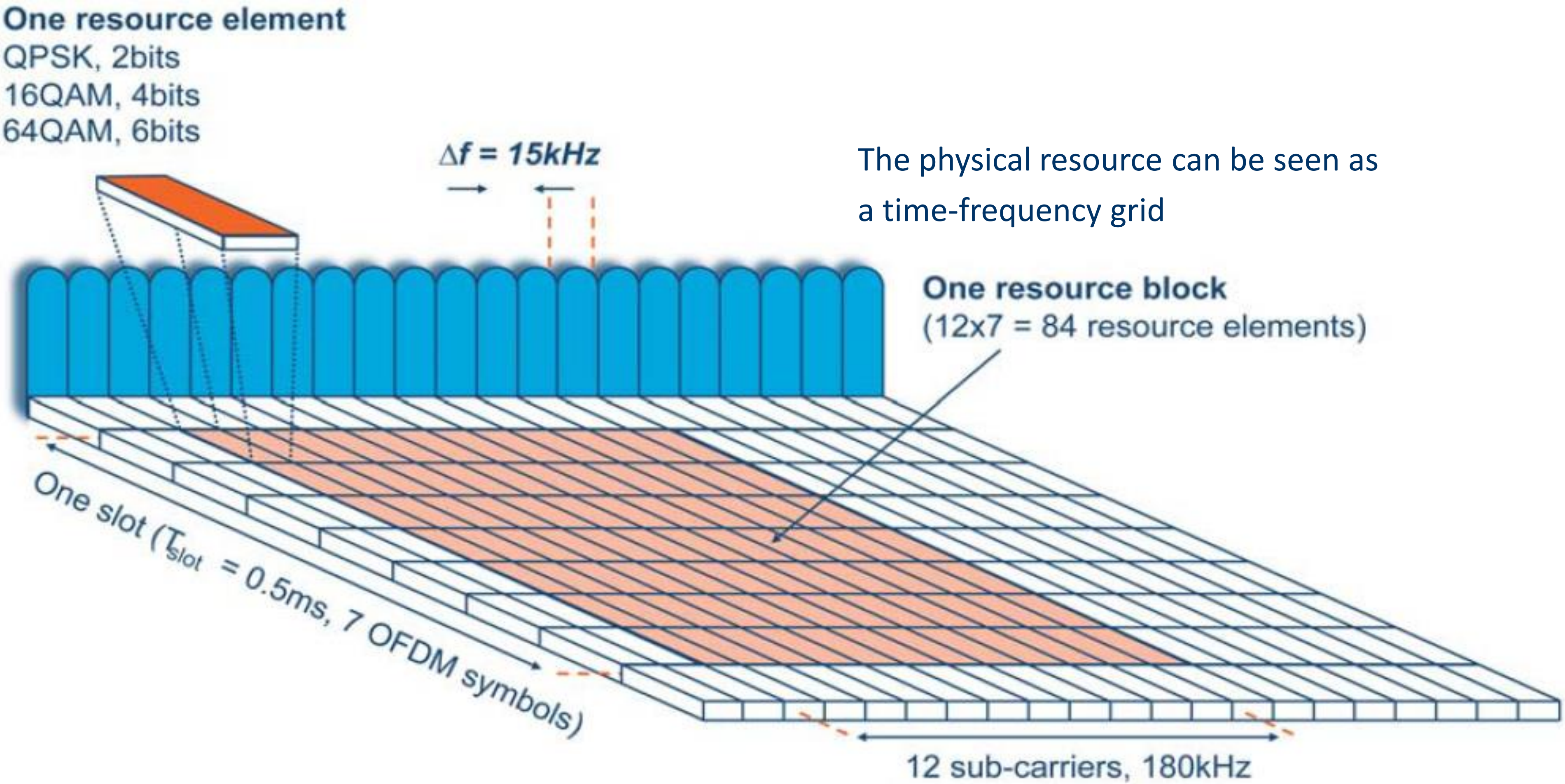


LTE Downlink : OFDMA Konvensional



- LTE menyediakan modulasi QPSK, 16QAM, 64QAM pada arah downlink
- Cyclic prefix digunakan untuk guard interval, dengan beberapa konfigurasi yang berbeda :
  - Normal cyclic prefix dengan 5.2 µs (symbol pertama) / 4.7 µs (symbol lainnya)
  - Extended cyclic prefix dengan 16.7 µs
- 15 kHz subcarrier spacing
- Scalable bandwidth

LTE Downlink Physical Layer Design: Physical Resource



The physical resource can be seen as a time-frequency grid

- LTE uses OFDM (Orthogonal Frequency Division Multiplexing) as its radio technology in downlink
- In the uplink LTE uses a pre=coded version of OFDM, SC-FDMA (Single Carrier Frequency Division Multiple Access) to reduced power consumption

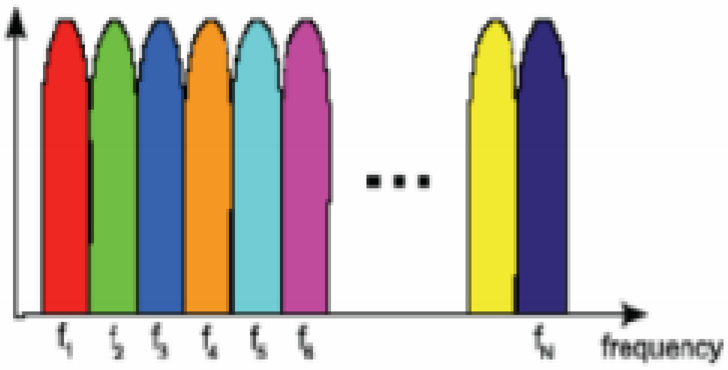
Pengenalan SC FDMA

SC-FDMA

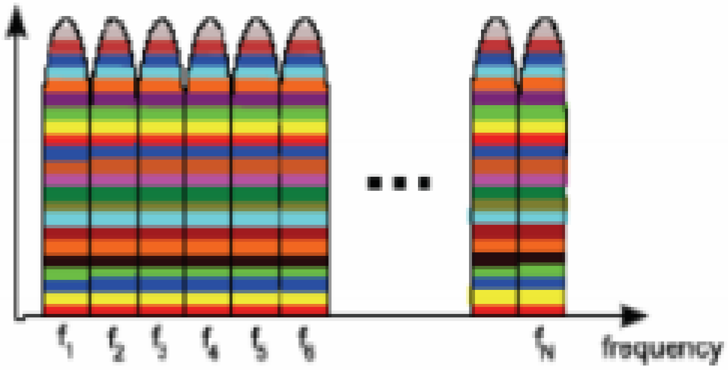
- SC-FDMA :Single Carrier Frequency Division Multiple Access
- SC-FDMA merupakn skema modulasi hybrid yang menggabungkan low PAPR dari sistem single-carrier dengan sifat multipath resistance dan alokasi flexible subcarrier yang diberikan oleh OFDM
- SC menyelesaikan problem PAPR dengan melakukan grouping resouce block untuk mengurangi kebutuhan linearitas penguatan dan konsumis daya sehingga terjadi peningkatan coverage dan kinerja di pinggir sel.
- SC-FDMA menjadi salahsatu opsi WiMAX (802.16d) dan dipakai pada LTE untuk arah uplink.

Bentuk Sinyal SC-FDMA

- Sama seperti sinyal OFDMA, tetapi :
  - Pada OFDMA, tiap sub-carrier hanya membawa informasi yang terkait dengan satu simbol spesifik
  - Pada SC-FDMA, tiap sub-carrier mengandung semua informasi simbol yang terkirim



(a) OFDM subcarriers



(b) DFT-s-OFDM subcarriers

Perbandingan OFDMA dan SC-FDMA