Orthogonal Frequency Division Multiplexing (OFDM)

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OFDM

- OFDM also known as
  Multi-Carrier or Multi-Tone Modulation
- DAB-OFDM
  Digital Audio Broadcasting
- DVD-OFDM
  Digital Video Broadcasting
- ADSL-OFDM
  Asynchronous Digital Subscriber Line
- Wireless Local Area Network
  IEEE-802.11a, IEEE-802.11g
  ETSI BRAN (Hyperlan/2)

Sidebar 1.1 A Brief History of OFDM

Although OFDM has become widely used only recently, the concept dates back some 40 years. This brief history of OFDM cites some landmark dates.

1966: Chang shows that multicarrier modulation can solve the multipath problem without reducing data rate [4]. This is generally considered the first official publication on multicarrier modulation. Some earlier work was Holsinger's 1964 MIT dissertation [5] and some of Gallager's early work on waterfilling [6].

1971: Weinstein and Ebert show that multicarrier modulation can be accomplished using a DFT [7].

1985: Cimini at Bell Labs identifies many of the key issues in OFDM transmission and does a proof-of-concept design [8].

1993: DSL adopts OFDM, also called discrete multitone, following successful field trials/competitions at Bellcore versus equalizer-based systems.

1999: The IEEE 802.11 committee on wireless LANs releases the 802.11a standard for OFDM operation in 5GHz UNI band.

2002: The IEEE 802.16 committee releases an OFDM-based standard for wireless broadband access for metropolitan area networks under revision 802.16a.

2003: The IEEE 802.11 committee releases the 802.11g standard for operation in the 2.4GHz band.

2003: The multiband OFDM standard for ultrawideband is developed, showing OFDM's usefulness in low-SNR systems.

Networks …

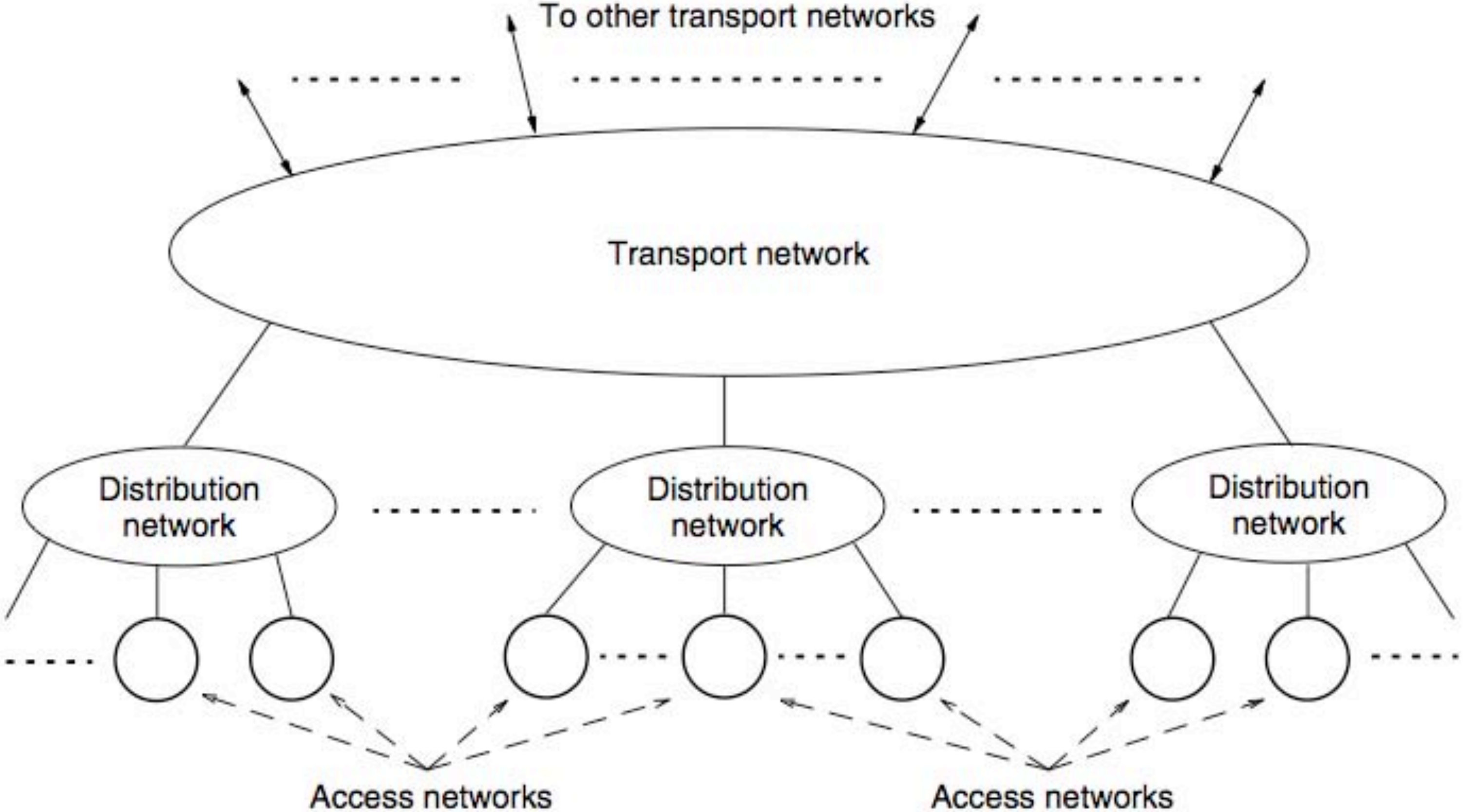
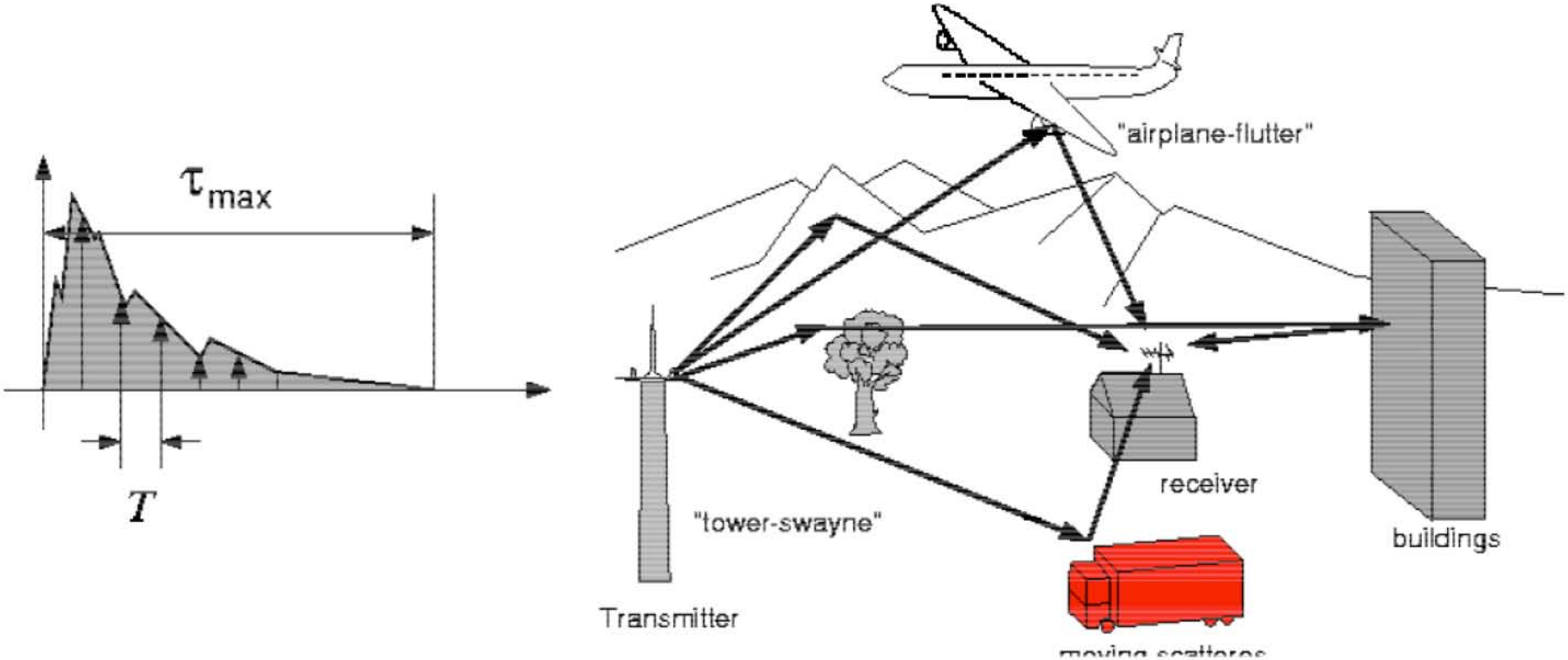


Figure 1.1 Telecommunications network hierarchy

Basic Wireless Propagation



Line Of Sight propagation (LOS)

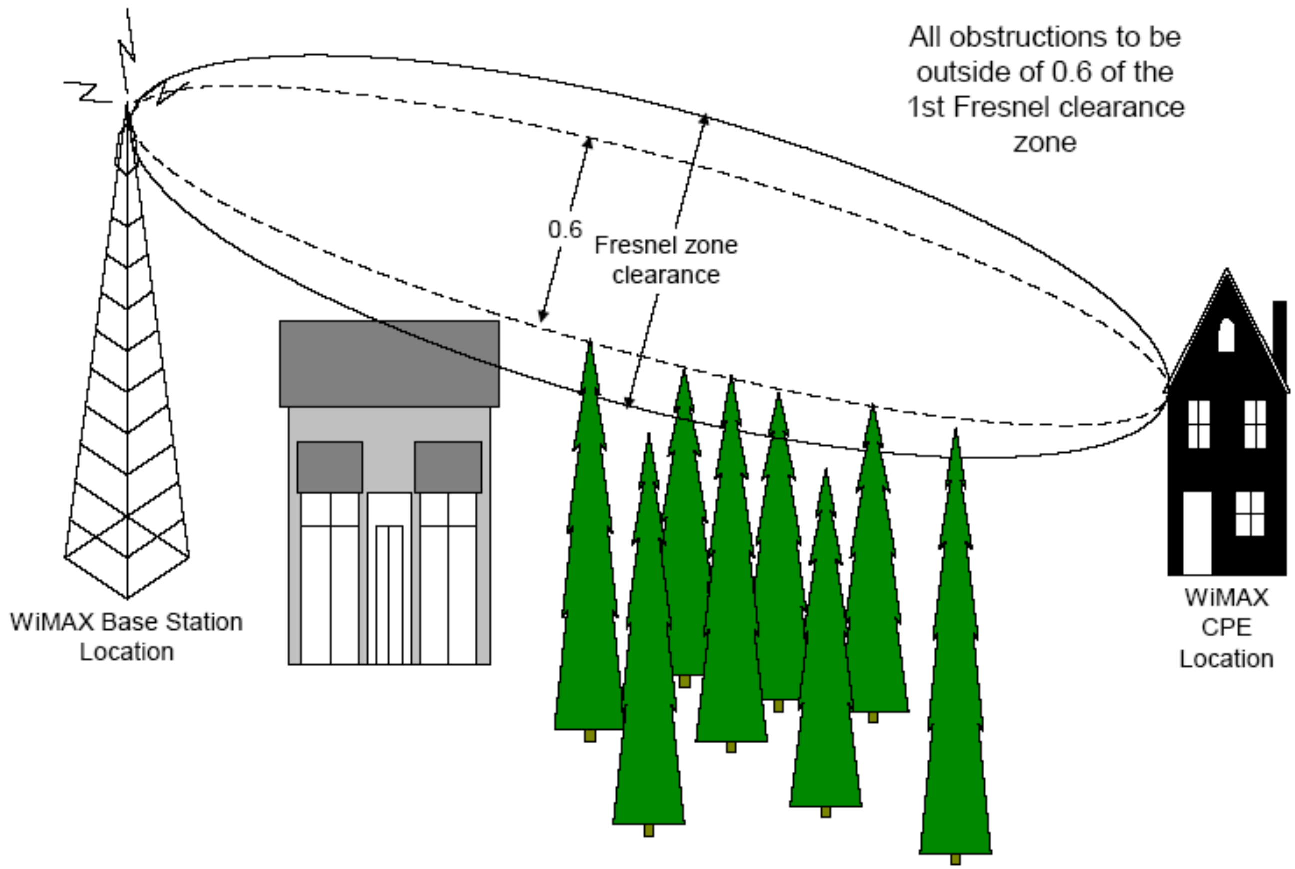


Figure 1 LOS Fresnel zone

Multipath

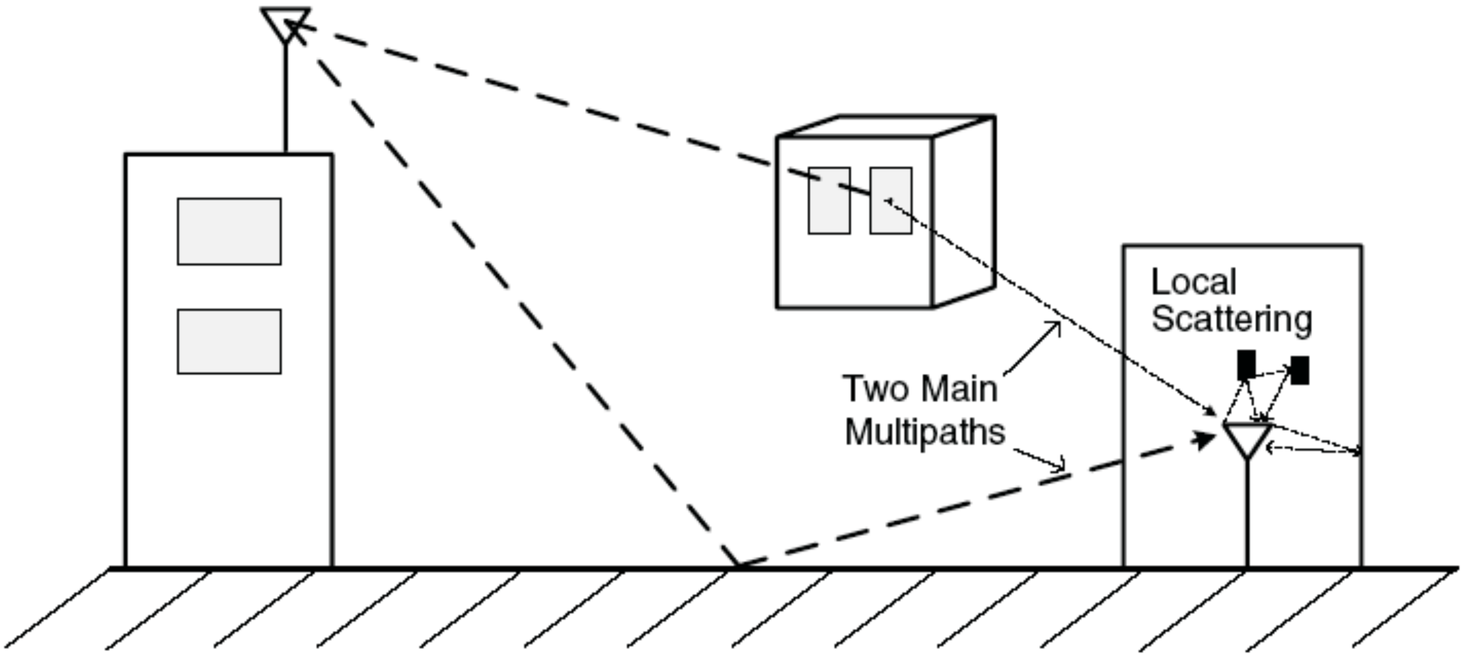


Figure 3.10 A channel with a few major paths of different lengths, with the receiver seeing a number of locally scattered versions of those paths

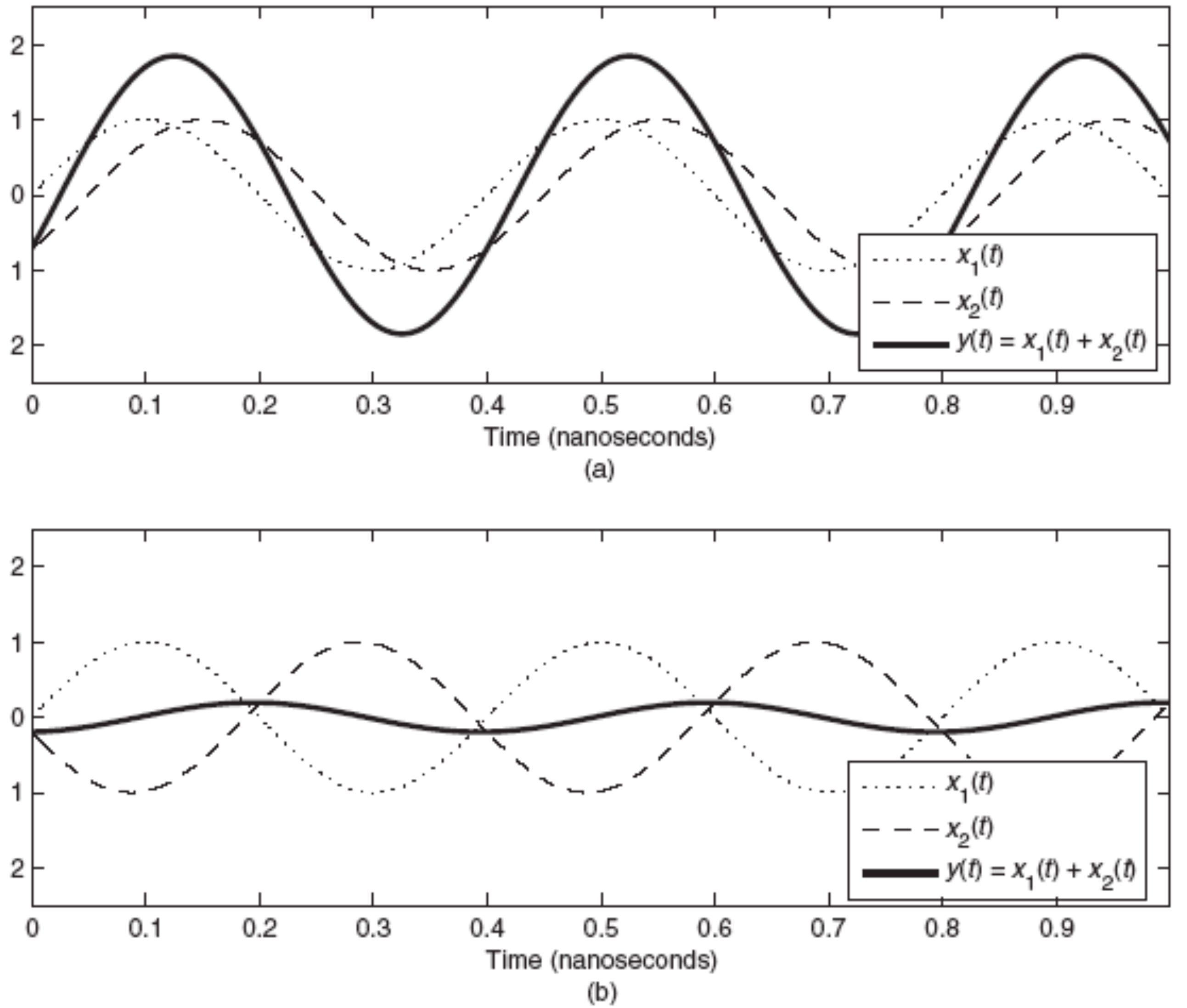


Figure 3.11 The difference between (a) constructive interference and (b) destructive interference at $f_c = 2.5$GHz is less than 0.1 nanoseconds in phase, which corresponds to about 3 cm.

Shadowing

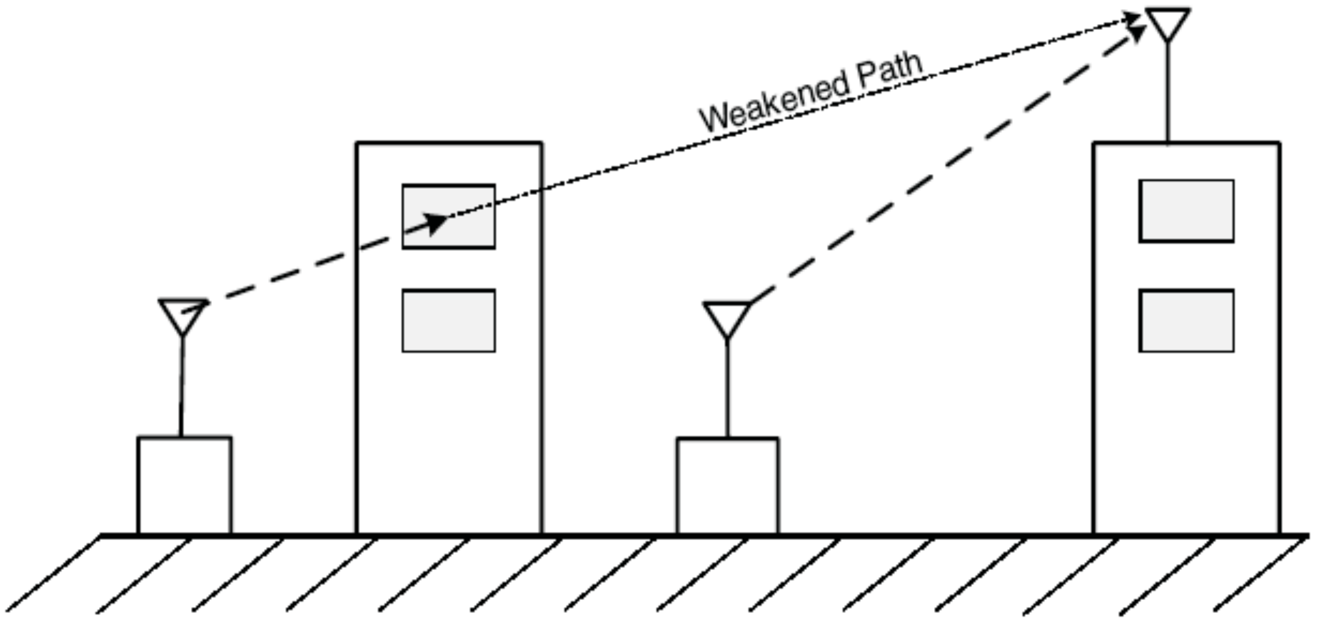


Figure 3.3 Shadowing causes large random fluctuations about the pathloss model: Figure from [28], courtesy of IEEE.

Pathloss + shadowing + fading

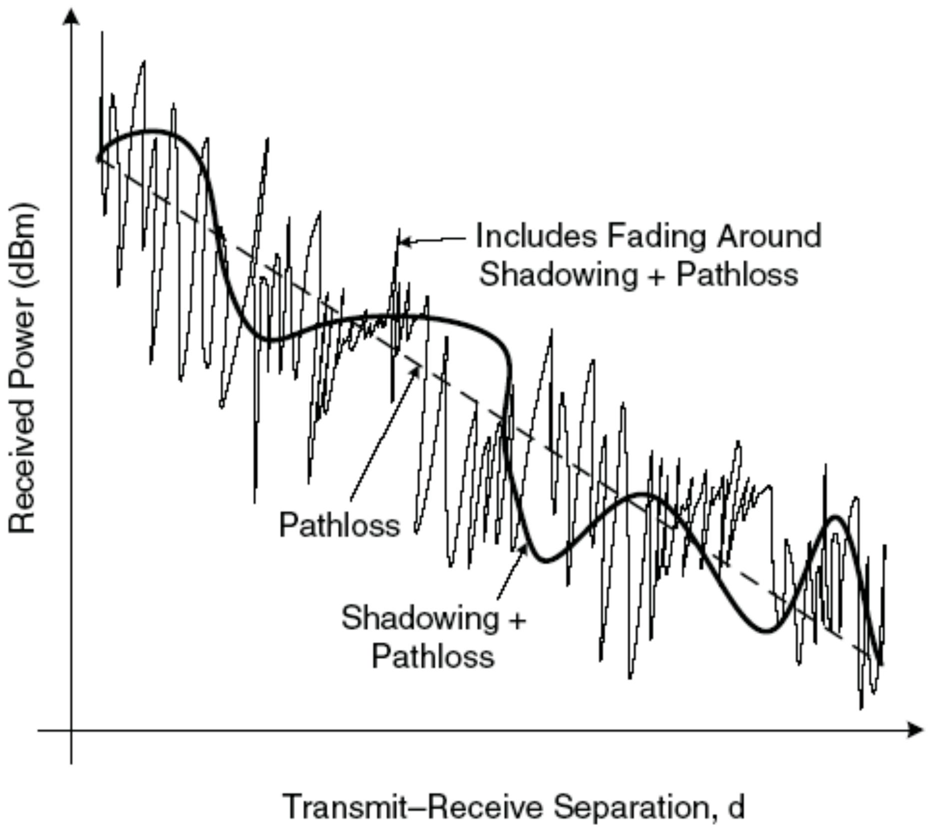
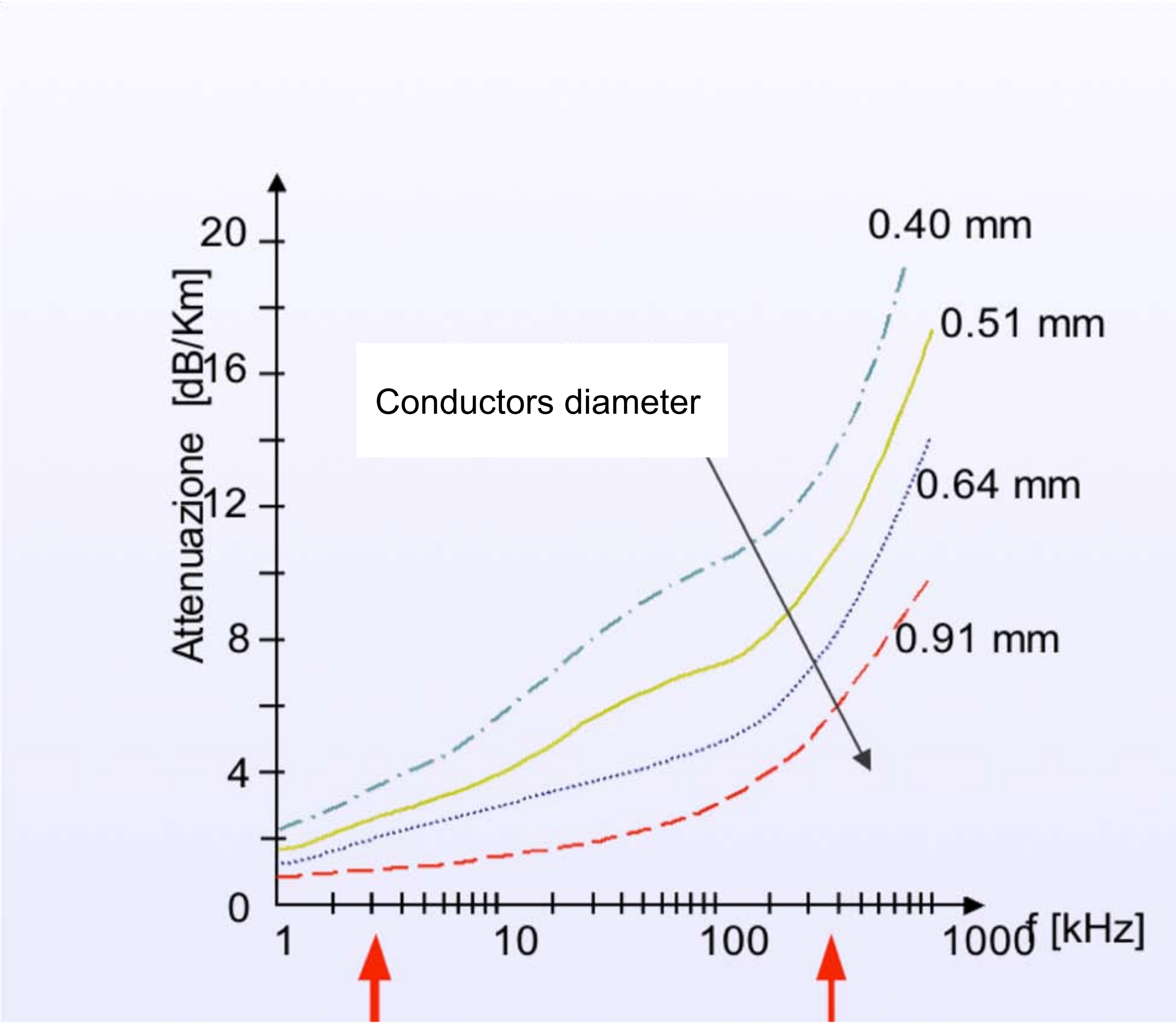
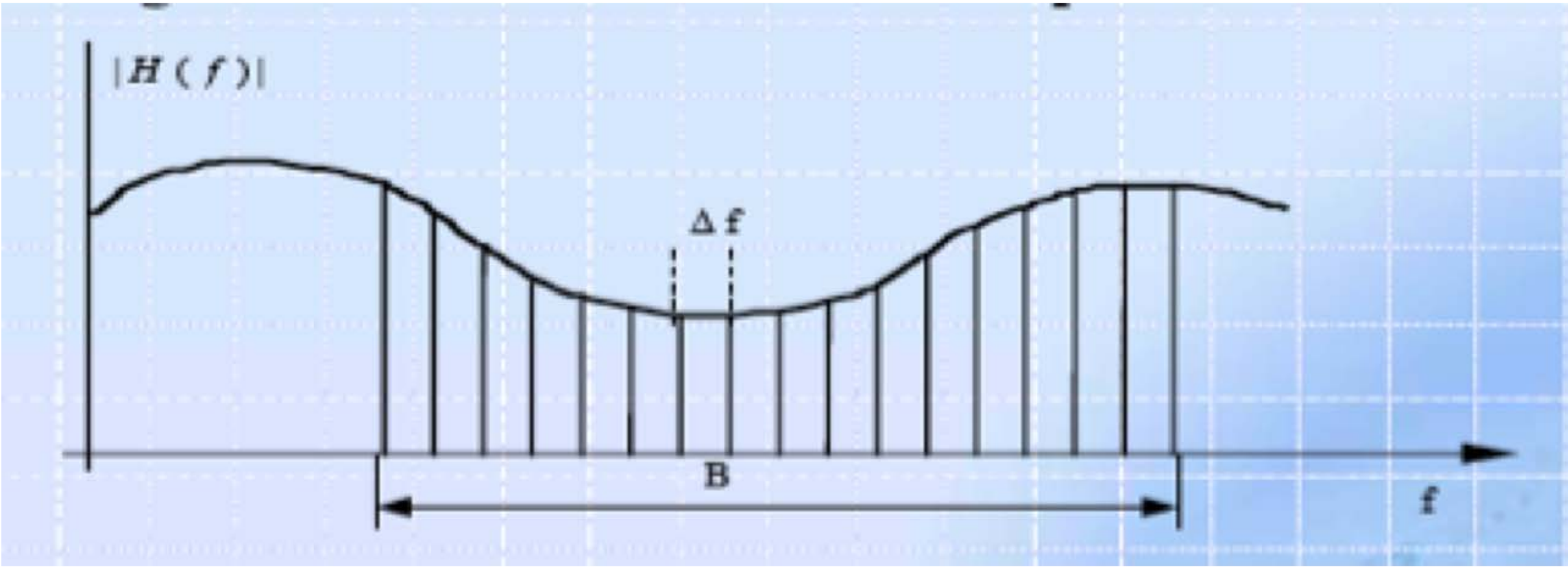


Figure 3.13 Plot showing the three major trends: pathloss, shadowing ,and fading all on the same plot: empirical, simulated, or a good CAD drawing

ADSL: Attenuation (dB/km) in case of copper twisted-pairs telephone cable (also a strong non-ideal channel)

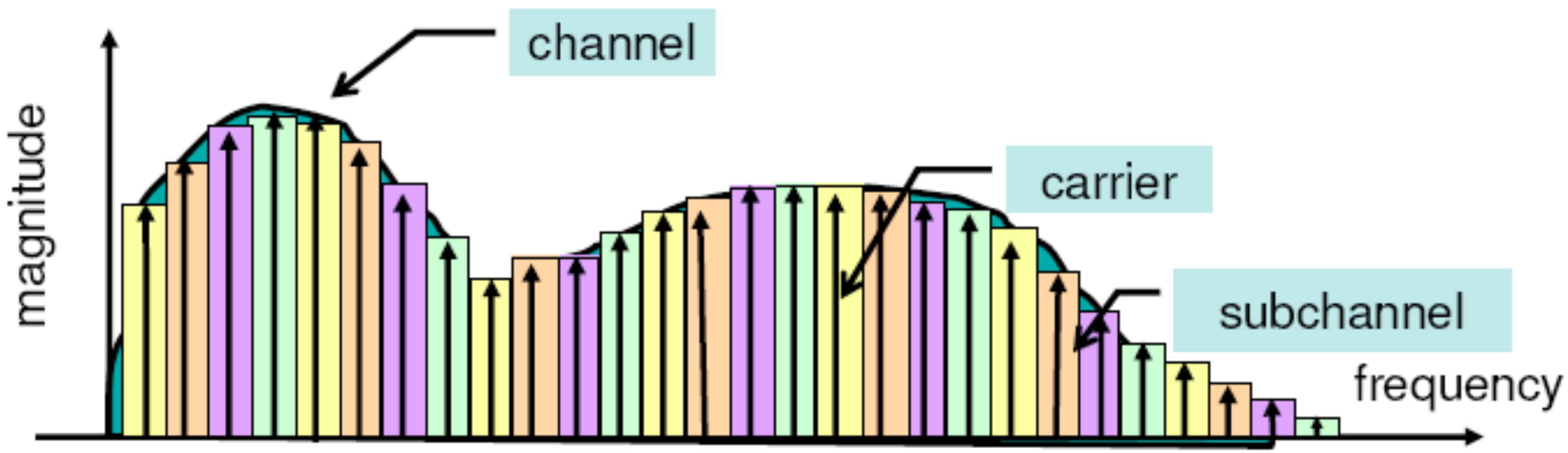


The basic idea of OFDM

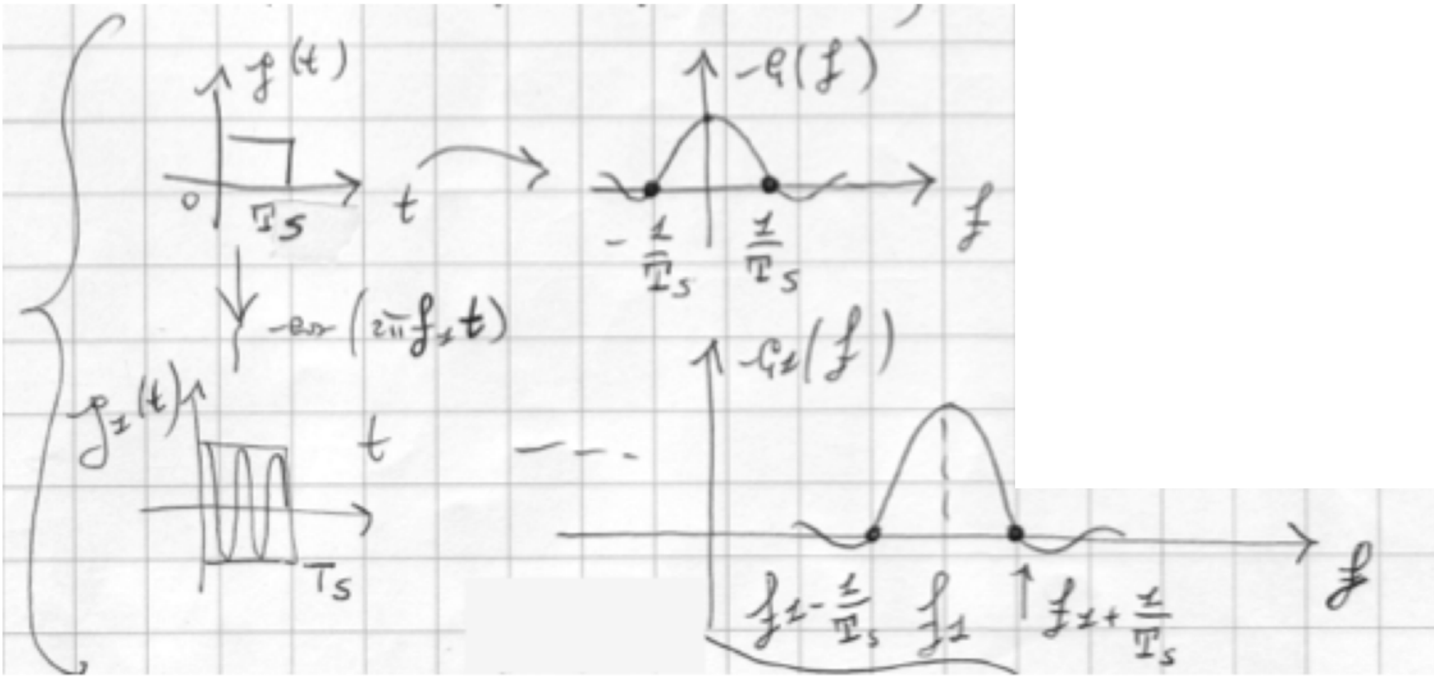


1) We sub-divide the non-ideal channel into many sub-channels
2) If N is big, every sub-channel can be considered as a flat-fading sub-channel (more easily equalized)
3) It is more easier to get closer to Shannon bounds in case of real channels (also Shannon divided the non-ideal channel in many sub-channels …)

- Frequency-selective channel is divided into flat fading subchannels
- Fast serial data stream is transformed into slow parallel data streams
  - Longer symbol durations

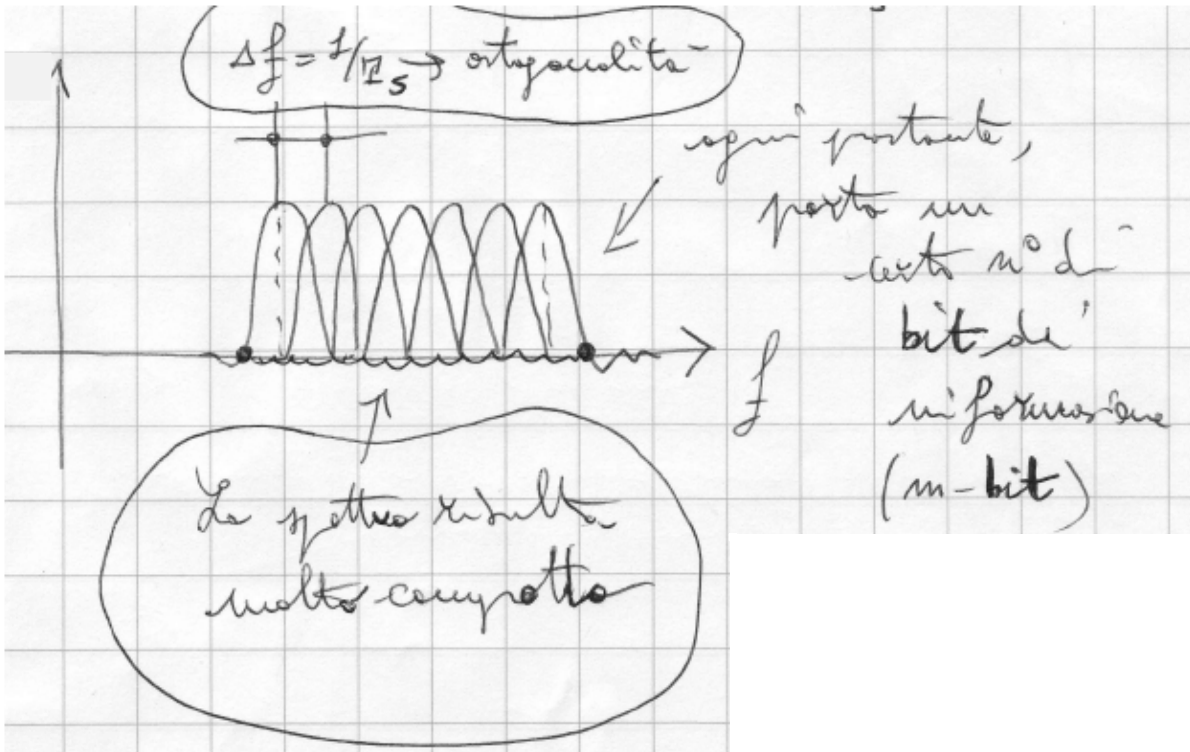


Classic QAM modulation



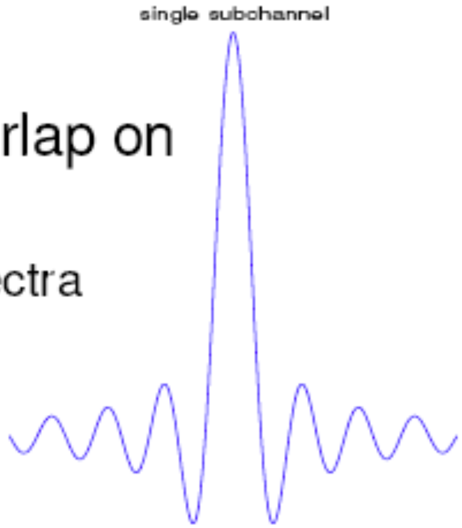
With a single carrier the spectrum is not very compact (at least, with p(.)=rect(.) shaping)

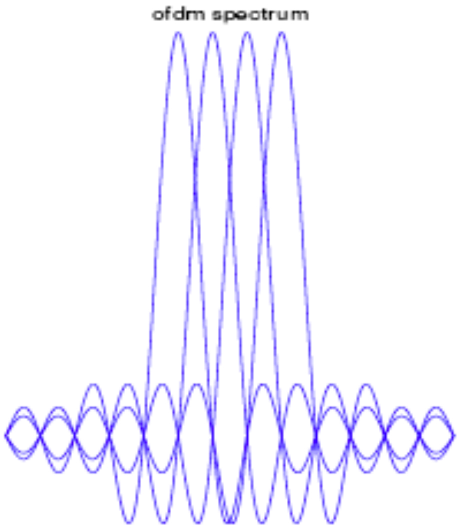
GENERAL OFDM IDEA



1) We use a lot (e.g., thousands) of different (orthogonal carriers), and the resultant spectrum will be much more compact …
2) Every carrier carries m information bits …
3) Delta_f=1/Ts guarantees the orthogonality among the carriers …

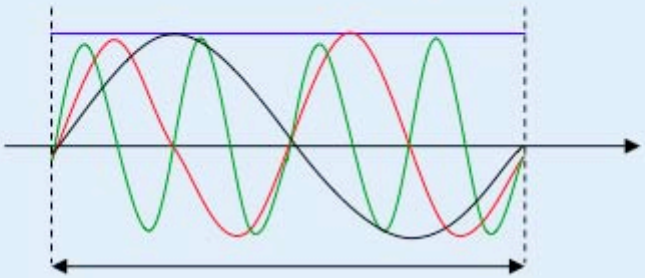
- Subchannel spacings are selected so, that they are mathematically orthogonal to each other
  - FDM → OFDM
- Subchannels overlap on each other
  - Sinc -shaped spectra

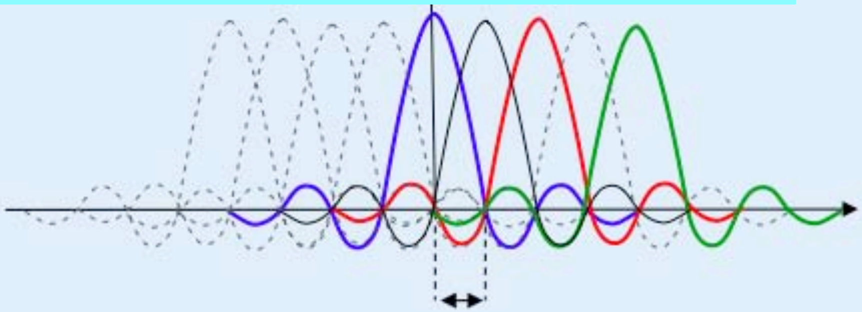


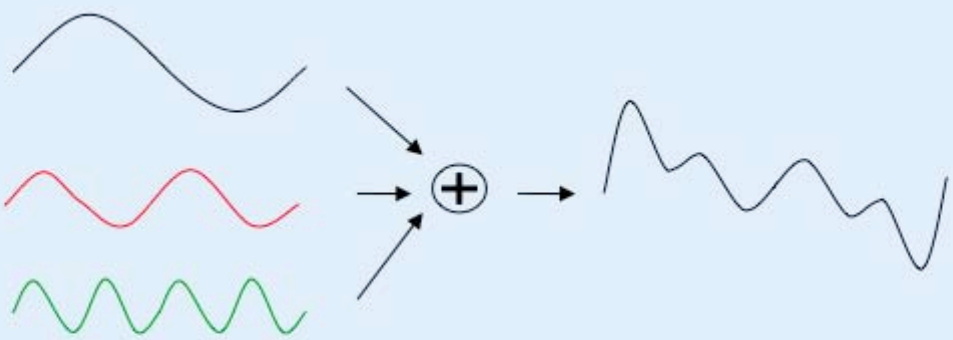


Basic principle: time domain

Many orthogonal sinusoidal carriers (windowed in time) are amplitude modulated and then added together (IDFT)

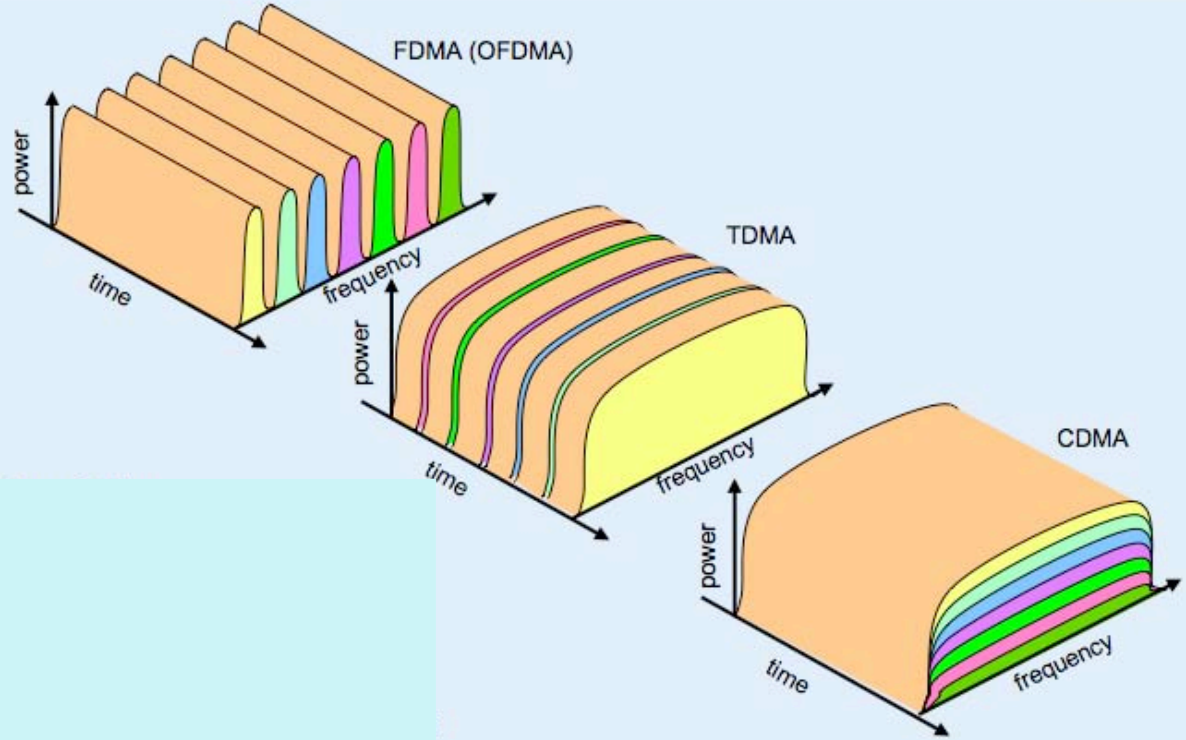






Multiple access techniques

FDMA, TDMA e CDMA



OFDM spectrum

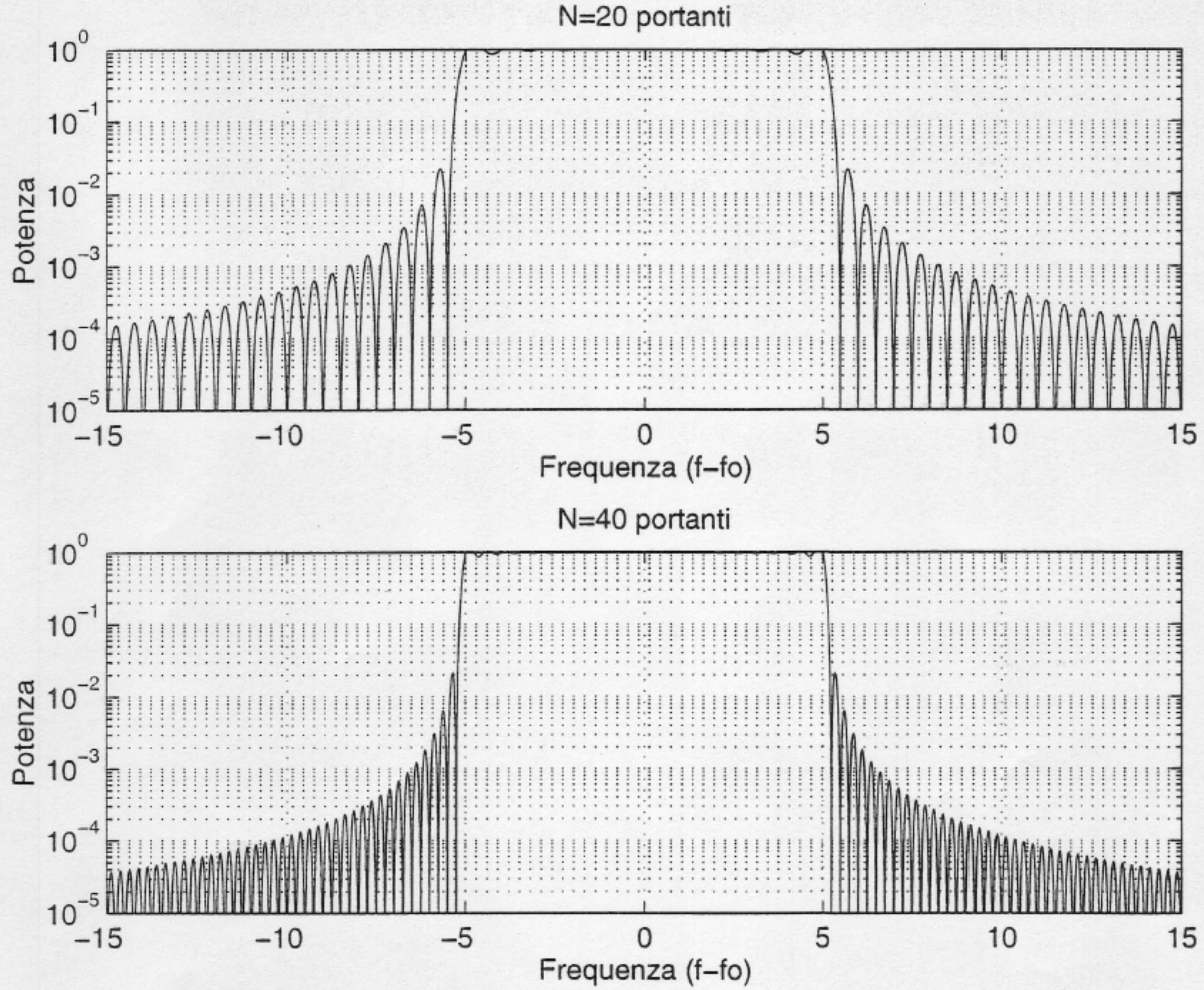


Figura 2.8: Spettro del segnale OFDM per N=20 e N=40.

OFDM spectrum

How change the spectrum according to the number of subcarriers

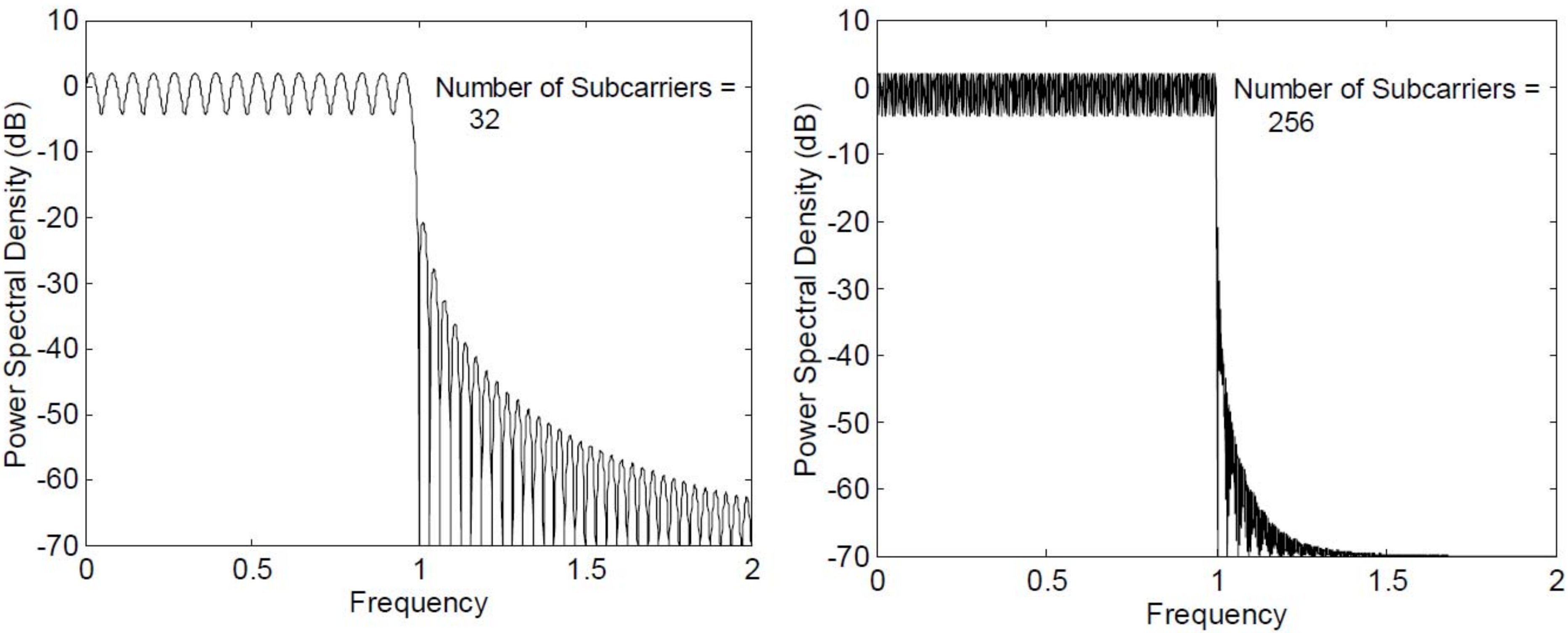
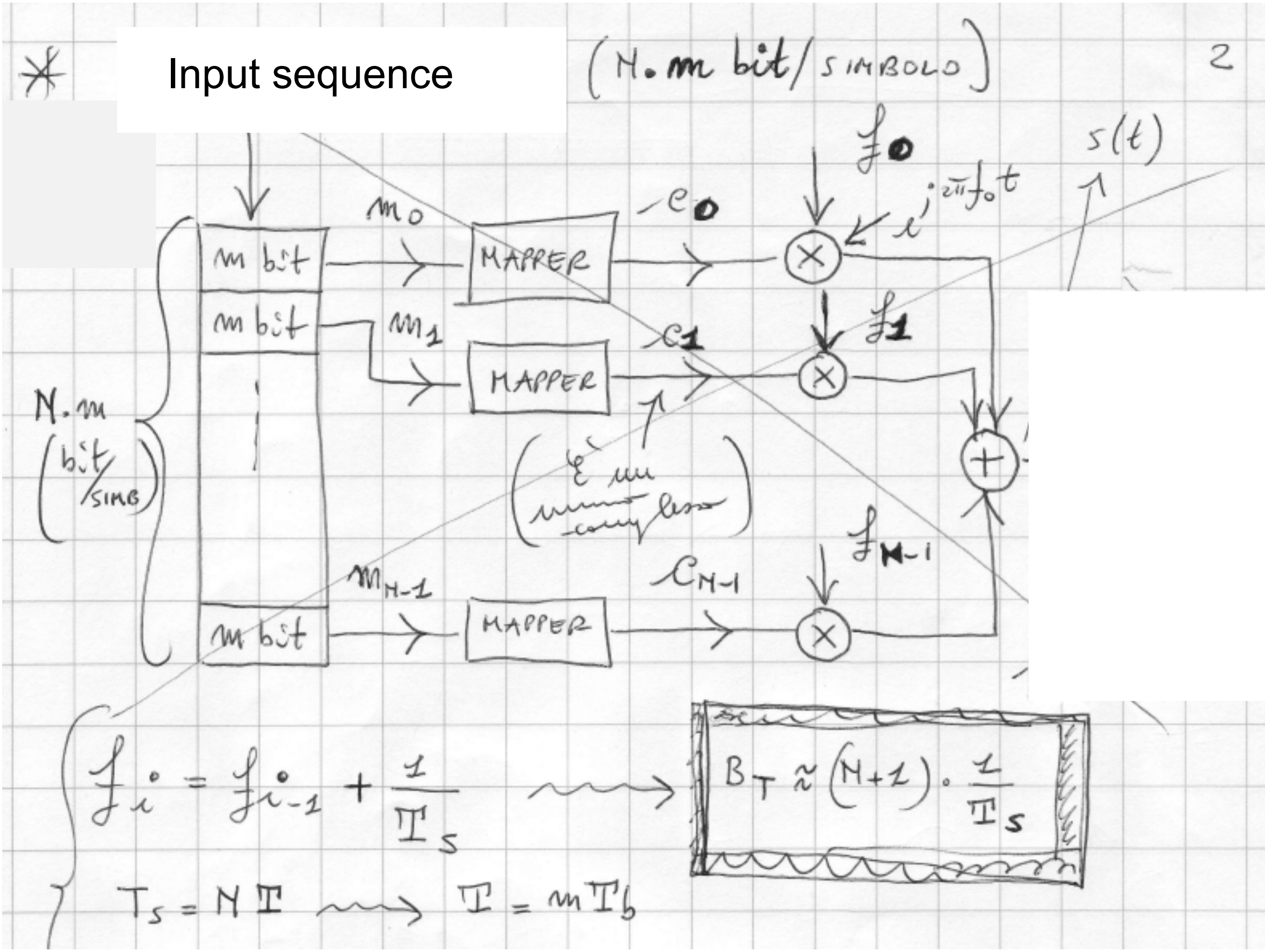
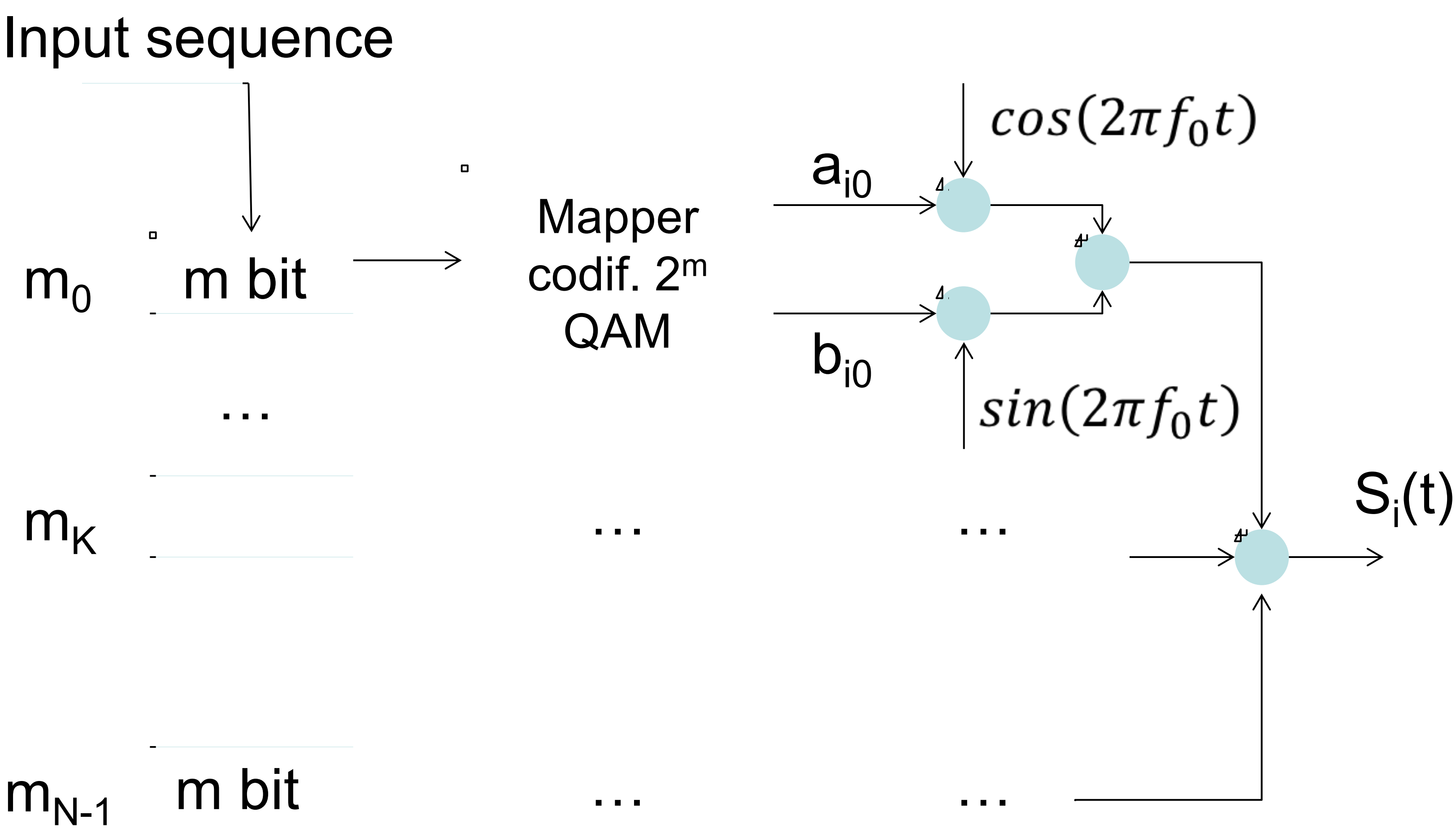


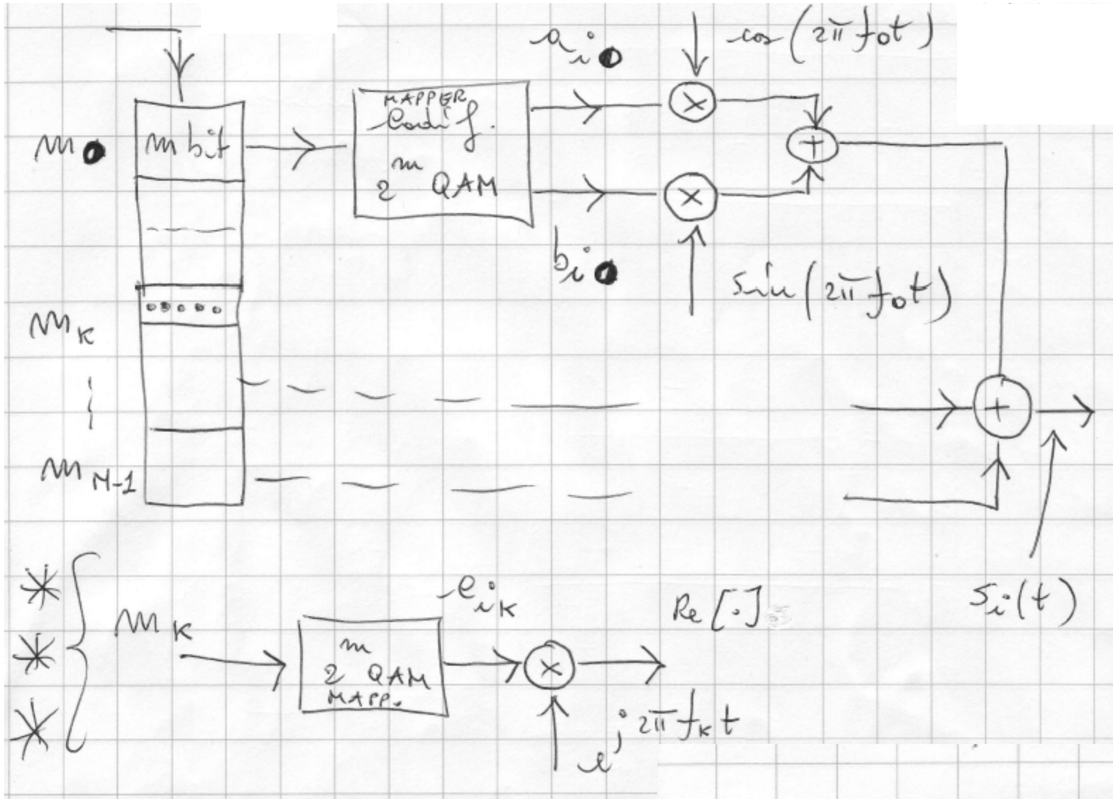
Figure 1.7 – Example of modulation using 32 carriers and 256 carriers

Basic block diagram



Transmitter block



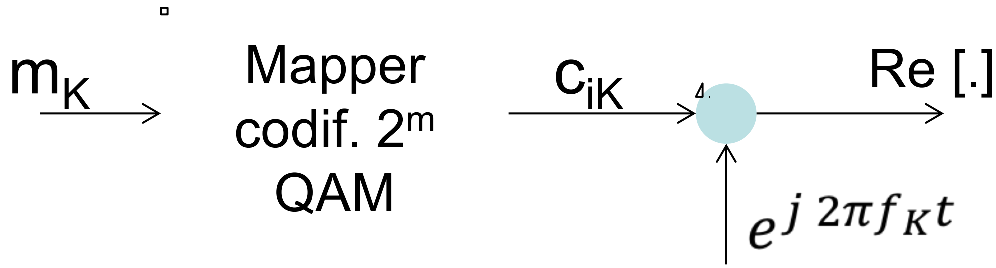


3

$$e_1 = a_1 + j\,b_1 \;, \quad e^{j 2\pi f_1 t} = \cos(2\pi f_1 t) + j \sin(2\pi f_1 t) =$$

$$e_1 e^{j 2\pi f_1 t} = \overbrace{a_1 \cos(2\pi f_1 t)}^{Re[\cdot]} + \cancel{j\,b_1 \cos(\cdot)} + \cancel{j\,a_1 \sin(\cdot)} - \underbrace{b_1 \sin(2\pi f_1 t)}_{Re[\cdot]} =$$

Transmitter block



$$f_i = f_{i-1} + \frac{1}{T_S} \quad \rightarrow \quad B_T \approx (N+1)\frac{1}{T_S}$$

$$T_S = N\,T \quad \rightarrow \quad T = m\,T_b$$

$$c_1 = a_1 + jb_1 \quad e^{j2f_1t} = \cos(2\pi f_1 t) + j\,sin(2\pi f_1 t)$$

$$c_1 \cdot e^{j2f_1t} = a_1\cos(2\pi f_1 t) + \cancel{jb_1\,sin(2\pi f_1 t)} - b_1\cos(2\pi f_1 t) + \cancel{ja_1\,sin(2\pi f_1 t)}$$

Re[.] Re[.]

OFDM signal expression

$$s_i(t) = \mathrm{Re}\left[\sum_{k=0}^{N-1} c_{ik}\, e^{j2\pi f_k t} \cdot \mathrm{rect}\left(\frac{t - T_s/2 - iT_s}{T_s}\right)\right]$$

si(t): i-th ofdm symbol,

$$\left(f_k = f_0 + \frac{k}{T_s}\right)$$

f0 = first carrier freq.

$$* \quad f_k = f_c + \frac{1}{T_s}\cdot\left(k - \frac{N-1}{2}\right), \quad k = 0, 1, \dots, N-1$$

fc = central frequency

OFDM signal expression

$$s_i(t) = Re\left(\sum_{k=0}^{N-1} c_{i\,k}\, e^{j2\pi f_k t} \cdot rect\left(\frac{t - \frac{T_S}{2} - i\,T_S}{T_S}\right)\right)$$

Where:

- $s_i(t)$ is the i-th OFDM symbol
- $f_k = f_0 + \frac{k}{T_S}$ and f_0 is the first carrier frequency

- Note that $f_k = f_c + \frac{1}{T_S} \cdot \left(k - \frac{N-1}{2}\right)$ with k = 0, 1, … , N-1

  (f_c means central frequency)

Consider a specific symbol: e.g., $s_1(t)$)

$$s_1(t) = \mathrm{Re}\left[\sum_{k=0}^{M-1} c_{1k}\, e^{j2\pi f_k t}\right] \mathrm{rect}(\cdot)$$

$$\sum_{k=0}^{M-1} c_{1k} \exp\left[j2\pi t\frac{\left(k-\left(\frac{M-1}{2}\right)\right)}{T_s} + j2\pi f_c t\right] =$$

$$= \underbrace{\sum_{k=0}^{M-1} c_{1k} \exp\left[j2\pi \frac{kt}{T_s}\right]}_{u_1(t)} \exp[\cdot]\, e^{j2\pi f_c t}$$

non dipende da k e viene recuperata con il sinc. di fase della portante

$t = mT$

$\tilde{u}_1(t) \rightarrow$ è l'inviluppo complesso di $u_1(t)$

$$\tilde{u}_1(mT) = \sum_{k=0}^{M-1} c_{1k} \exp\left[j2\pi \frac{km}{M}\right]; \quad m = 0, 1, \ldots, M-1.$$

$t = m\frac{T_s}{M}$

This term, independ from k, will be recovered with the carrier phase syncr.

u1{tilde}(t) = complex envelop of u1(t)

Analysis of a symbol

Consider a specific symbol (such as $s_1(t)$):

$$s_1(t) = Re\left(\sum_{k=0}^{N-1} c_{1\,k}\, e^{j2\pi f_k t}\right) \cdot rect\left(\frac{t - \frac{T_S}{2} - kT_S}{T_S}\right) =$$

$$\underbrace{\sum_{k=0}^{N-1} c_{1\,k}\, e^{\left[j2\pi t \frac{k - \left(\frac{N-1}{2}\right)}{T_S} + j2\pi f_c t\right]}}_{u_1(t)} = \underbrace{\sum_{k=0}^{N-1} c_{1\,k} e^{\left[j2\pi \frac{k\,t}{T_S}\right]} e^{\left[-j2\pi t \frac{\left(\frac{N-1}{2}\right)}{T_S}\right]}}_{\widetilde{u_1}(t)} e^{j2\pi f_c t}$$

This term, independent form k, will be recovered with the carrier phase syncr.

$\widetilde{u_1}(t)$ is the complex envelop of $u_1(t)$ and since t = nT

$$\widetilde{u_1}(nT) = \sum_{k=0}^{N-1} c_{1\,k}\, e^{\left[j2\pi \frac{k\,n}{N}\right]} \quad with\ n=0,1,\ldots,N-1 \quad and\ t = n\frac{T_S}{N}$$

DFT & IDFT

It's interesting recalling the DFT (Discrete Fourier Transform) and the IDFT (Inverse Discrete Fourier Transform) formulas:

- DFT

$$X(k) = \sum_{i=0}^{N-1} x(i) e^{-j2\pi ik/N} \qquad k = 0, 1, \dots, N-1$$

- IDFT:

$$x(n) = \frac{1}{N} \sum_{k=0}^{N-1} X(k) e^{\frac{j2\pi nk}{N}} \qquad n = 0, 1, \dots, N-1$$

$$\tilde{u}_1(\underbrace{nT}_{t = n\frac{T_s}{N}}) = \sum_{0}^{N-1} {}_k\, c_{1k} \exp\left[j 2\pi \frac{kn}{N}\right] \; ; \; n = 0, 1, \ldots, N-1.$$

$$\tilde{u}_1(nT) \rightsquigarrow N \cdot \mathrm{IDFT}\{c_{1k} \ldots\}, \quad n, k = 0, 1, \ldots, N-1$$

Sampling with Tc …

Campioniamo il segnale con

$$T_c = T = \frac{T_s}{N} = m T_b$$

Il segnale viene generato nel dominio delle freq. e trasformato nei tempi con la IDFT

The signal is generated in the f domain, and antri-traf. in the time domain by using the IDFT

$$\widetilde{u_1}(n\,T) = \sum_{k=0}^{N-1} c_{1\,k}\, e^{\left[j2\pi \frac{k}{N} n\right]} \qquad n = 0, 1, \dots, N-1$$

Remembering that $t = n\,\frac{T_S}{N}$

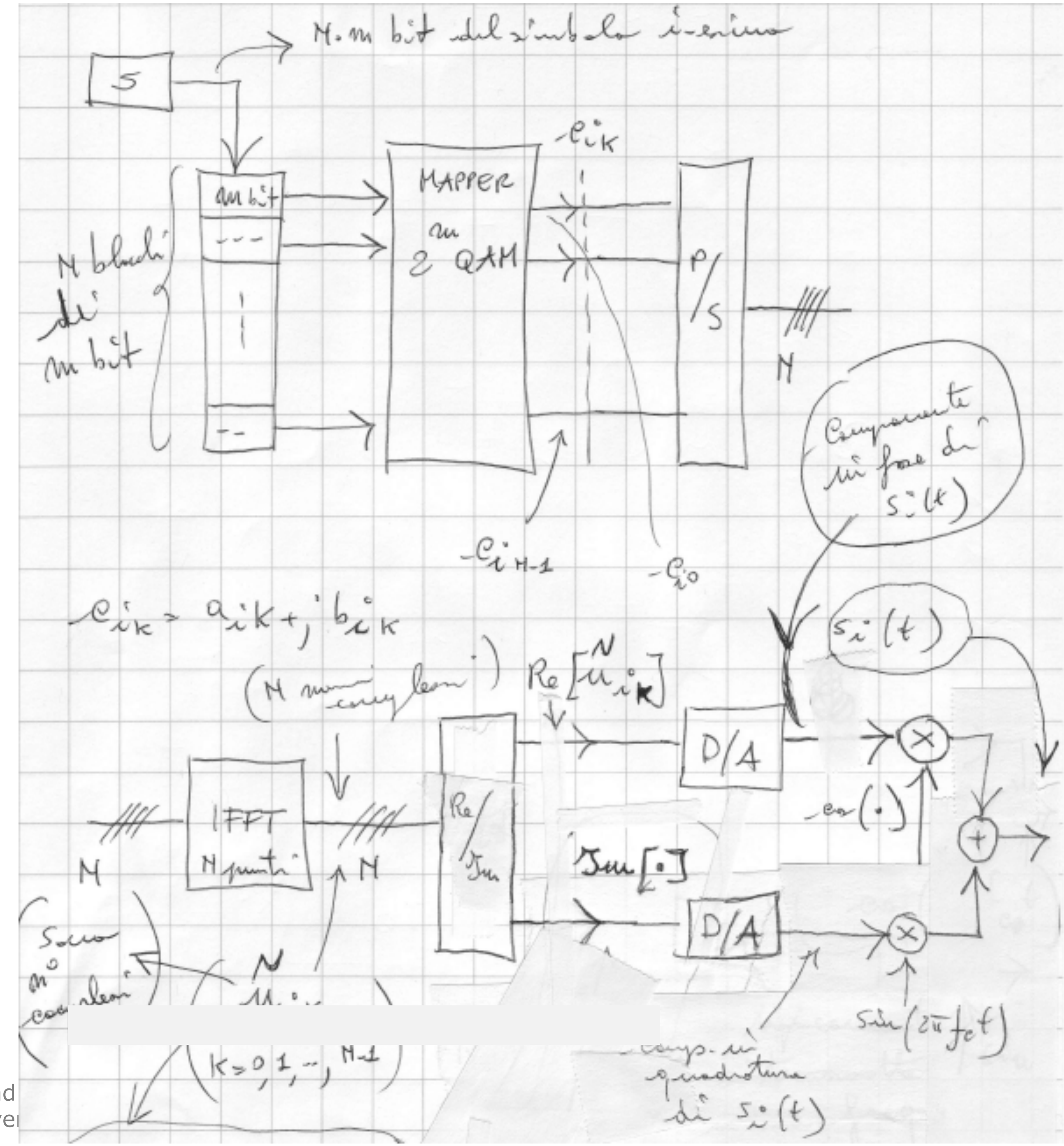
Sampling with $T_C = T = \frac{T_S}{N} = mT_b$

$$\widetilde{u_1}(nT) \rightarrow N \cdot IDFT\left\{c_{1,k}, \dots\right\} \qquad n, k = 0, 1, \dots, N-1$$

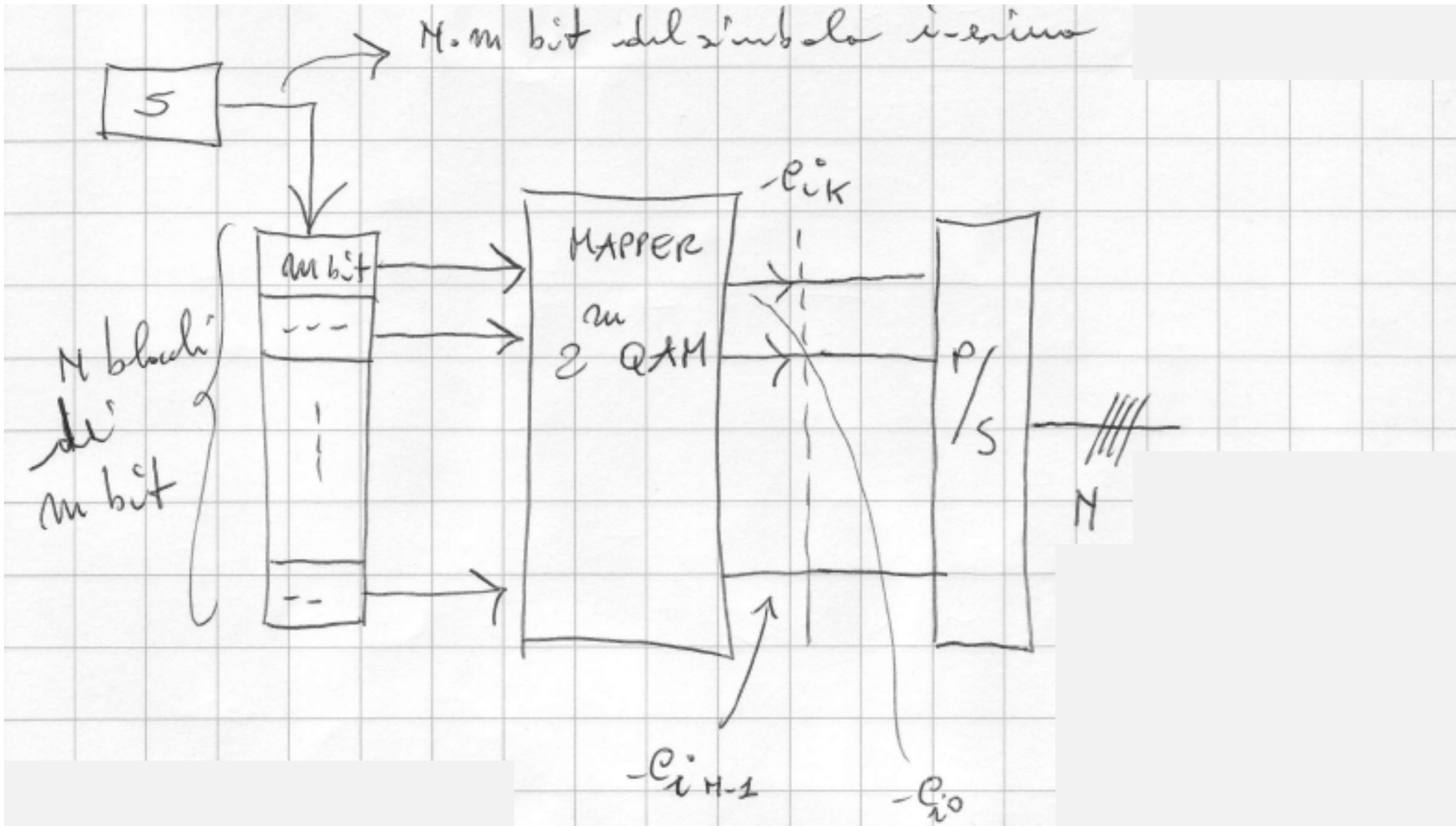
$$\{c_{1\,0}, c_{1\,1}, \dots\} \longrightarrow \text{IDFT} \longrightarrow \{u_{1\,0}, u_{1\,1}, \dots, u_{1\,N-1}\} \longrightarrow \text{D / A} \longrightarrow \widetilde{u_1}(t)$$

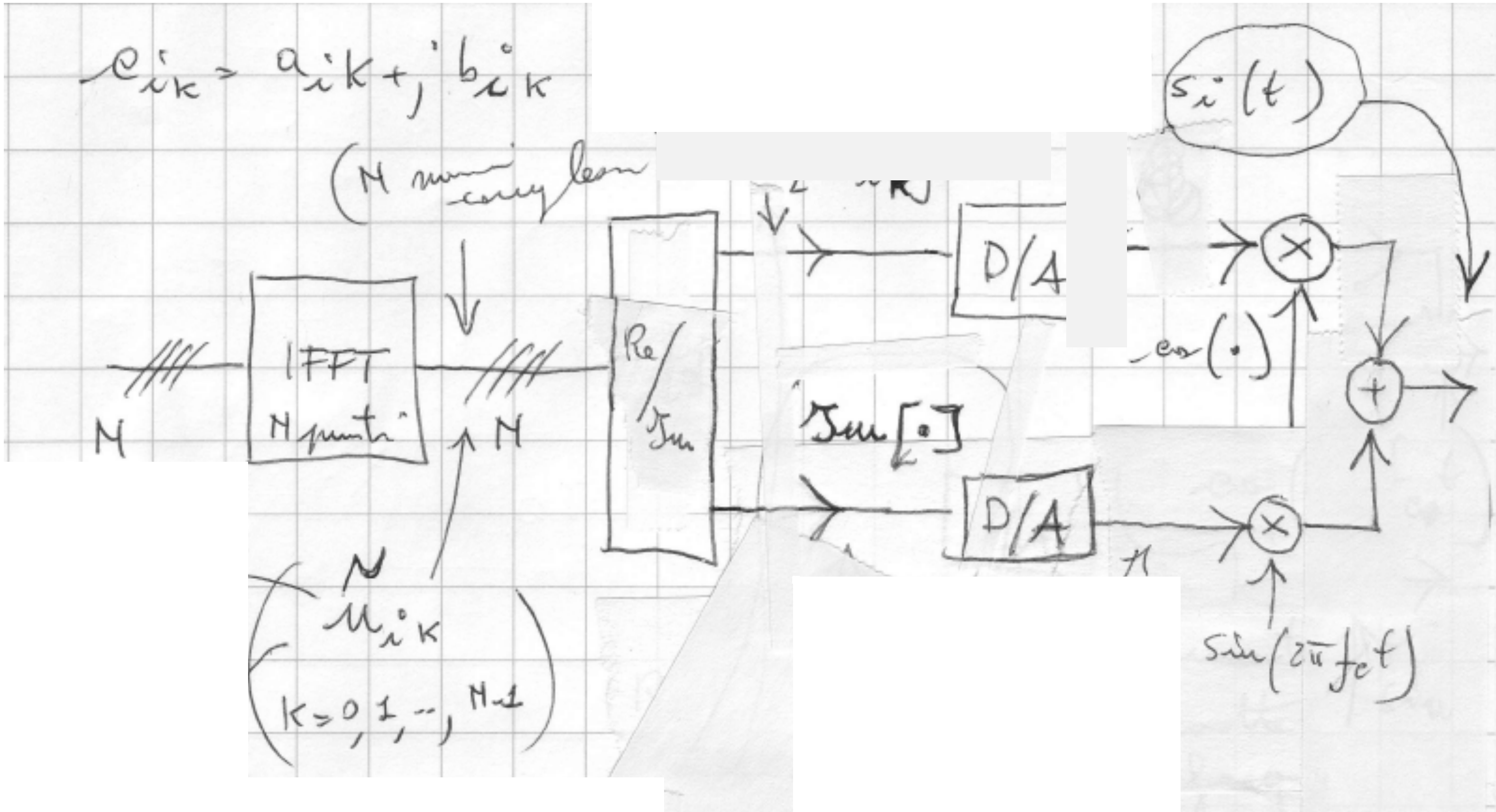
Each m bit has a $c_{1\,i}$ It's a complex vector

Note that the signal $\{u_{1\,0}, u_{1\,1}, \dots, u_{1\,N-1}\}$ is generated in the frequency domain and then anti transformed in the time domain by using the IDFT.


N·m bit del simbolo i-esimo
S
N blocchi di m bit
m bit
MAPPER
2^m QAM
c_{ik}
P/S
N
$c_{i\,N-1}$
c_{i0}
Componente in fase di $s_i(t)$
$c_{ik} = a_{ik} + j\, b_{ik}$
(N numeri complessi)
$Re[\overset{N}{u}_{ik}]$
$s_i(t)$
IFFT
N punti
N
Re/Im
$Im[\cdot]$
D/A
D/A
$\cos(\cdot)$
$\sin(2\pi f_c t)$
comp. in quadratura di $s_i(t)$
$K = 0, 1, \ldots, N-1$

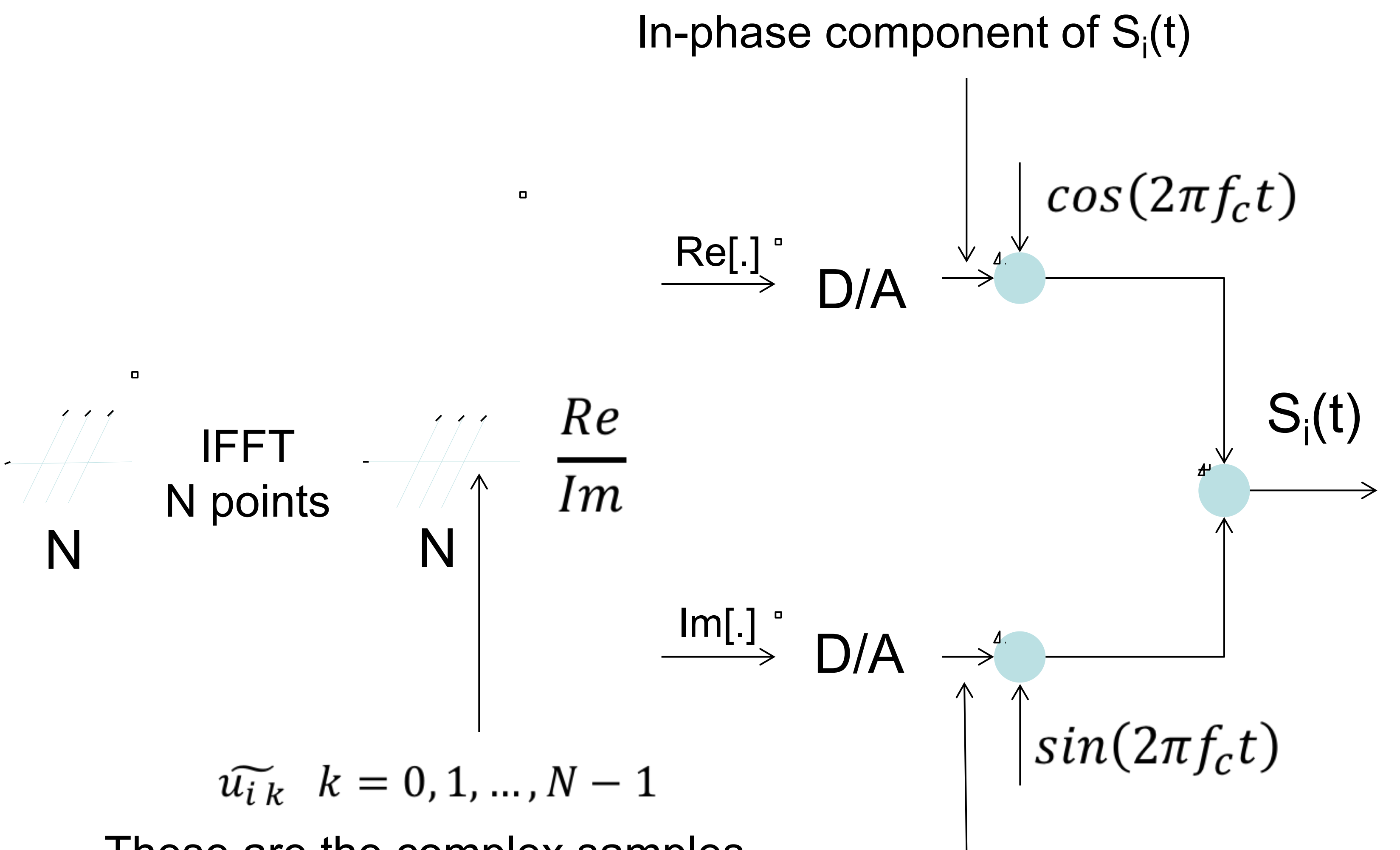
Block diagram: more details …





This are the complex samples
of the transmitted signal

Block diagram: more details

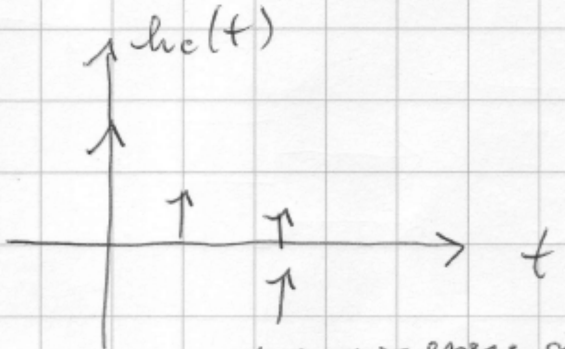


$\widetilde{u_{i\,k}} \quad k = 0, 1, \ldots, N-1$

These are the complex samples of the transmitted signal

Guard Interval and Cyclic Prefix

If the channel presents a lot of multiple paths, there is a long "echo" (assume its max. duration is Delta) …
in this case, it is better to have Ts >> Delta, and to introduce a guard interval (of duration >= Delta) to reduce the inter symbol interference …
The introduced spectral inefficiency is proportional to Delta/Ts …



possono essere anche molto lontani tra di loro (anche 600 μsec)

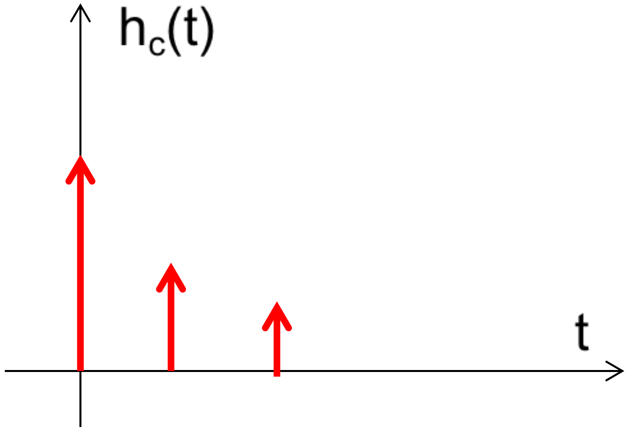
* L'effetto dell'eco arriva dopo tanto tempo

↳ conviene avere Ts elevati → OFDM

↓ intervallo di GUARDIA

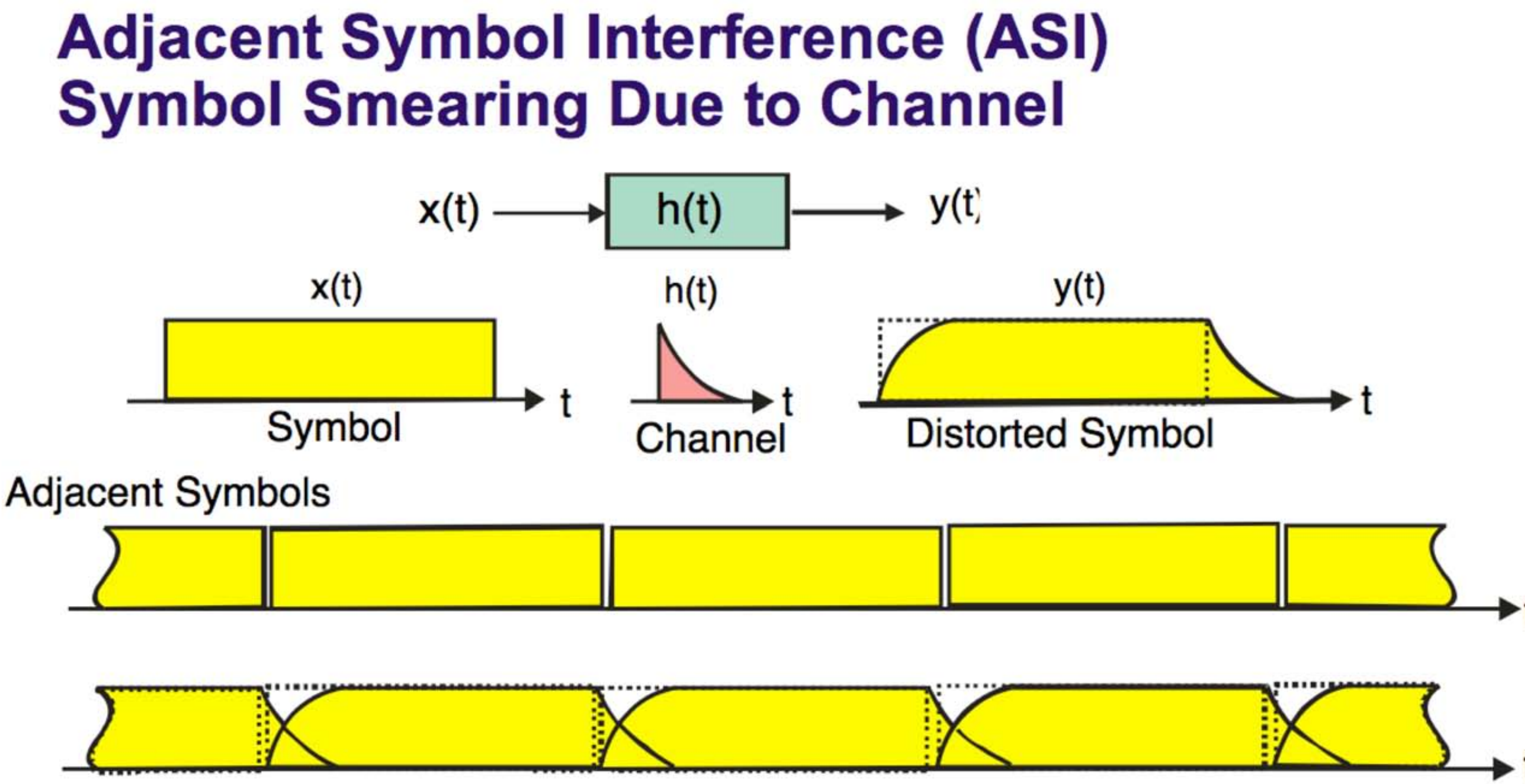
Guard interval & Cyclic prefix

If the channel presents a lot of multiple paths, there's a long "echo" (assume its maximum duration is Δ)



In this case, it's better to have $T_S \gg \Delta$, and to introduce a guard interval (of duration $\geq \Delta$) to reduce the Inter Symbol Interference.

The introduced spectral inefficiency is proportional to $\frac{\Delta}{T_S}$.


Adjacent Symbol Interference (ASI)
Symbol Smearing Due to Channel
x(t)
h(t)
y(t)
x(t)
t
Symbol
h(t)
t
Channel
y(t)
t
Distorted Symbol
Adjacent Symbols
t
t

Interferences

The main interferences present in this modulation are Inter Symbol Interference (ISI) and Inter Carrier Interference (ICI) due to the proximity of symbols (Adjacent Symbol Interference (ASI)).

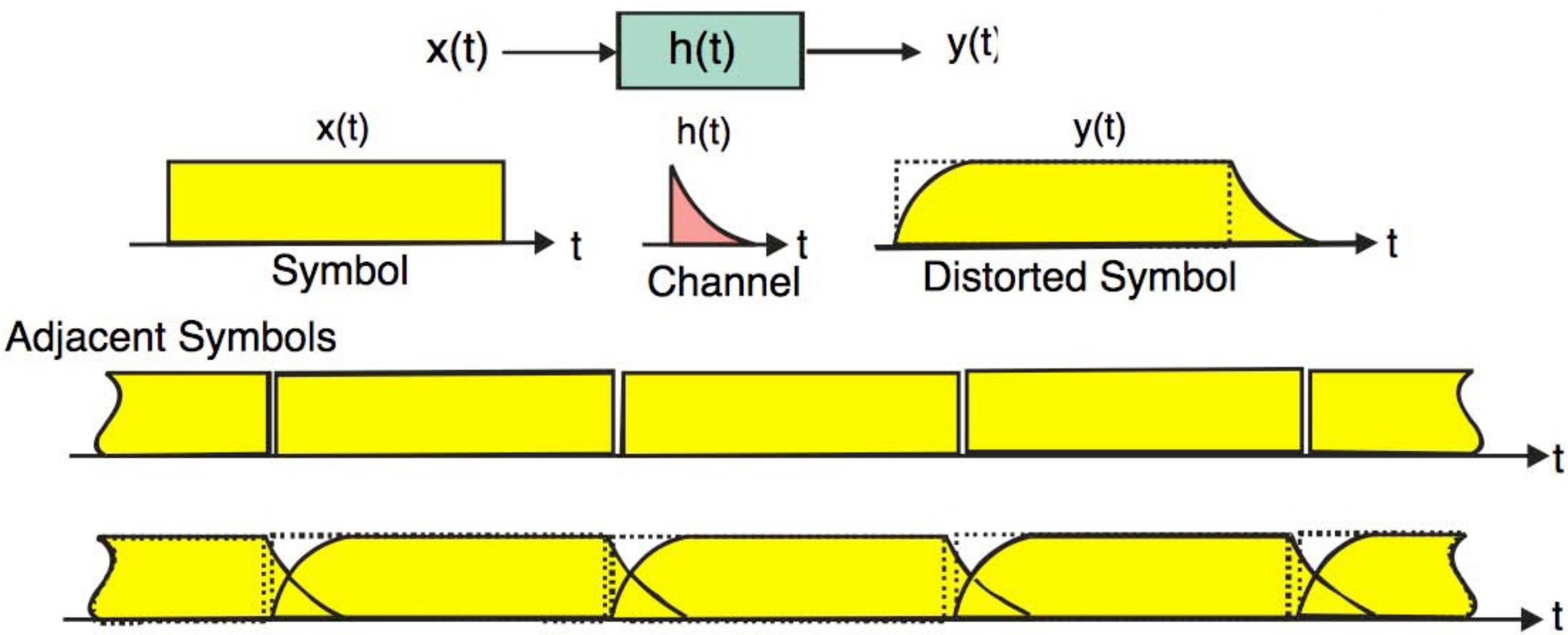
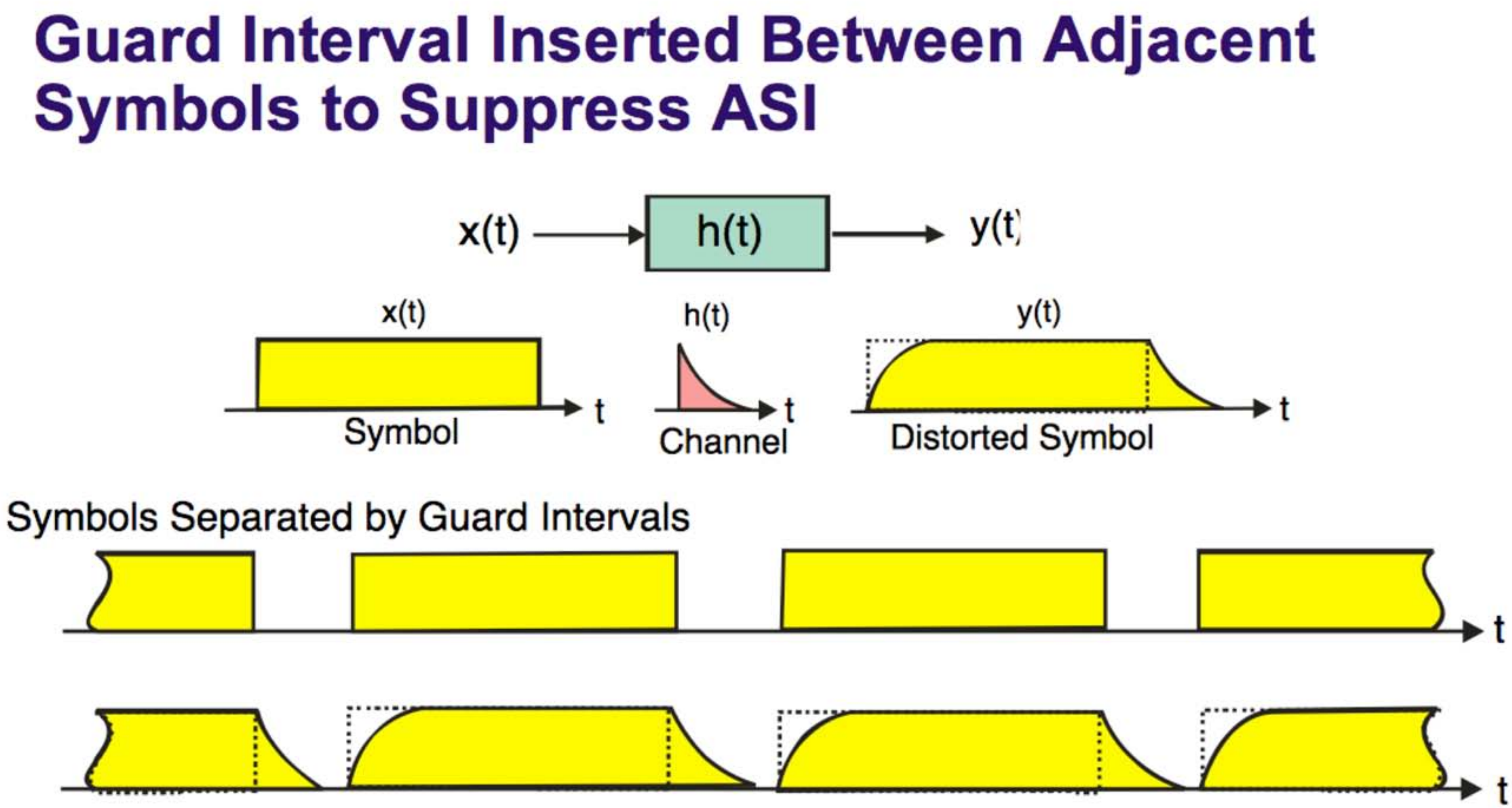


Figure 1.9 – Example of transmission with interferences

Insertion of a Guard Interval (GI)



Better solution: Cyclic Prefix

The key principle is the introduction of a cyclic prefix as a GI, whose length should exceed the maximum excess delay of the multipath propagation channel . Due to the cyclic prefix, the transmitted signal becomes periodic, and the effect of the time-dispersive multipath channel becomes equivalent to a cyclic convolution, discarding the GI at the receiver. Due to the properties of the cyclic convolution, the effect of the multipath channel is limited to a pointwise multiplication of the transmitted data constellations by the channel TF, or the FT of the channel IR; that is, the SCs remain orthogonal

The only drawback of this principle is a slight loss of effective transmit power, as the redundant GI must be transmitted. Usually, the GI is selected to have a length of one tenth to a quarter of the symbol period, leading to an SNR loss of 0.5 to 1 dB

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Cyclic prefix

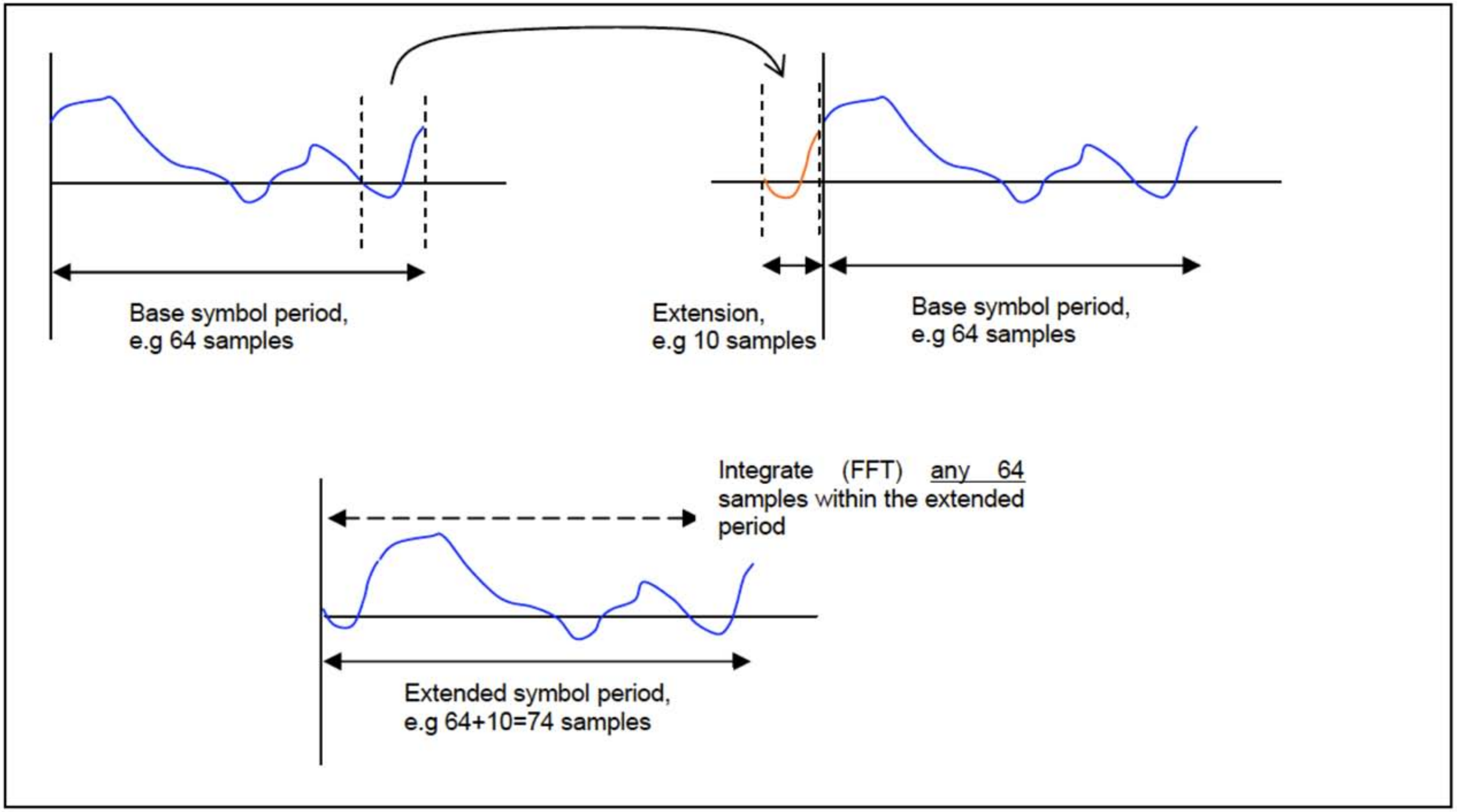
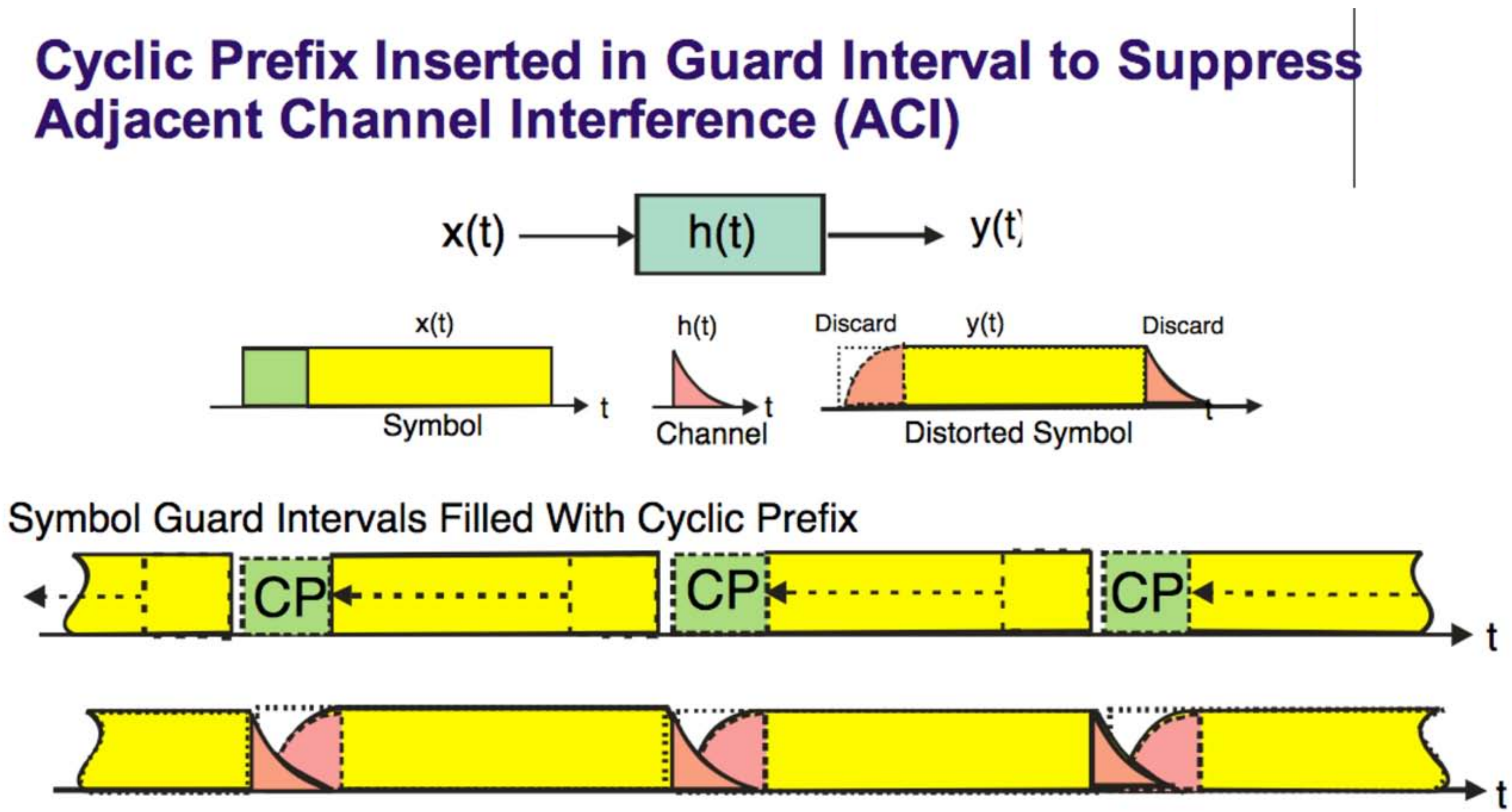
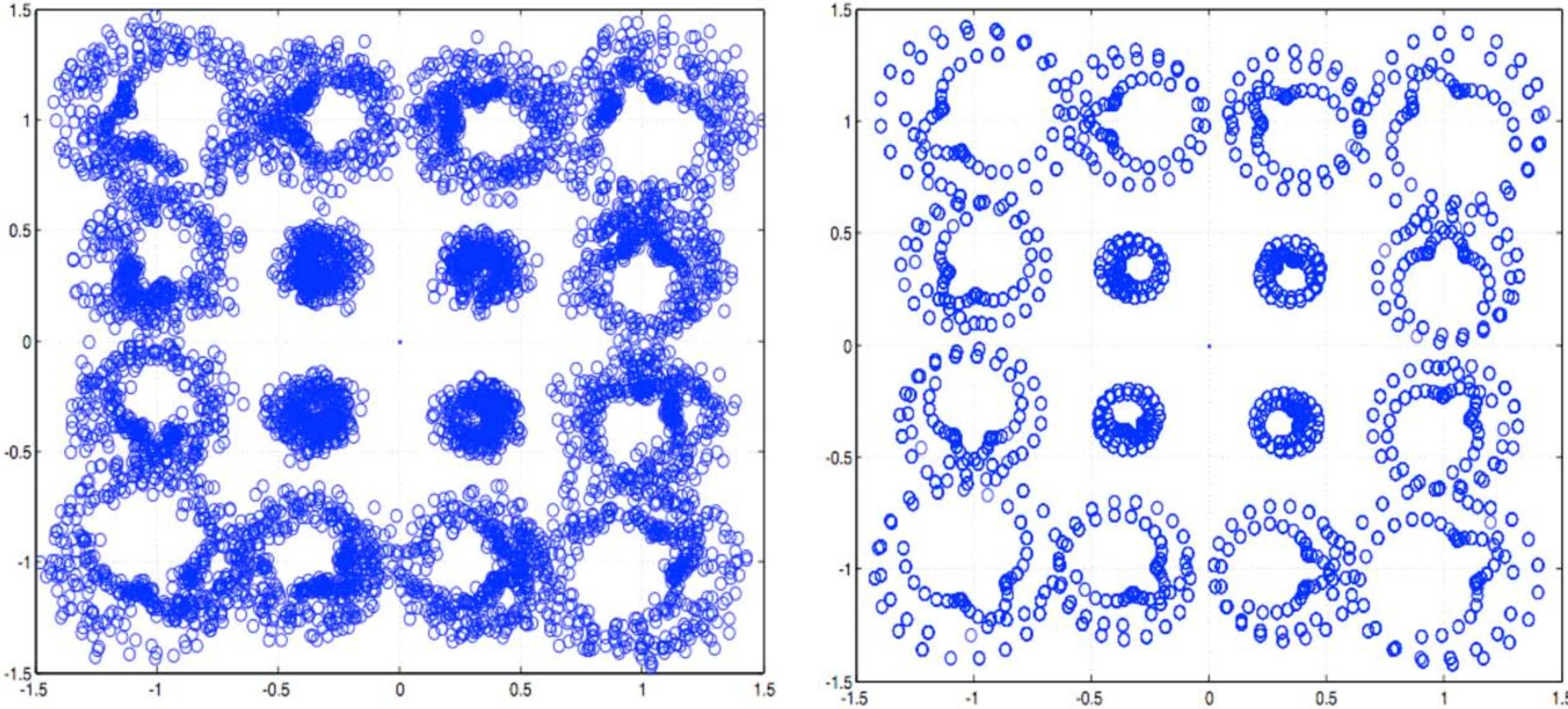


Figure 10: Guard Period via Cyclic Extension

Cyclic prefix



Overlaid Constellations , All Frequencies, Without and With Cyclic Prefix



Final block diagram

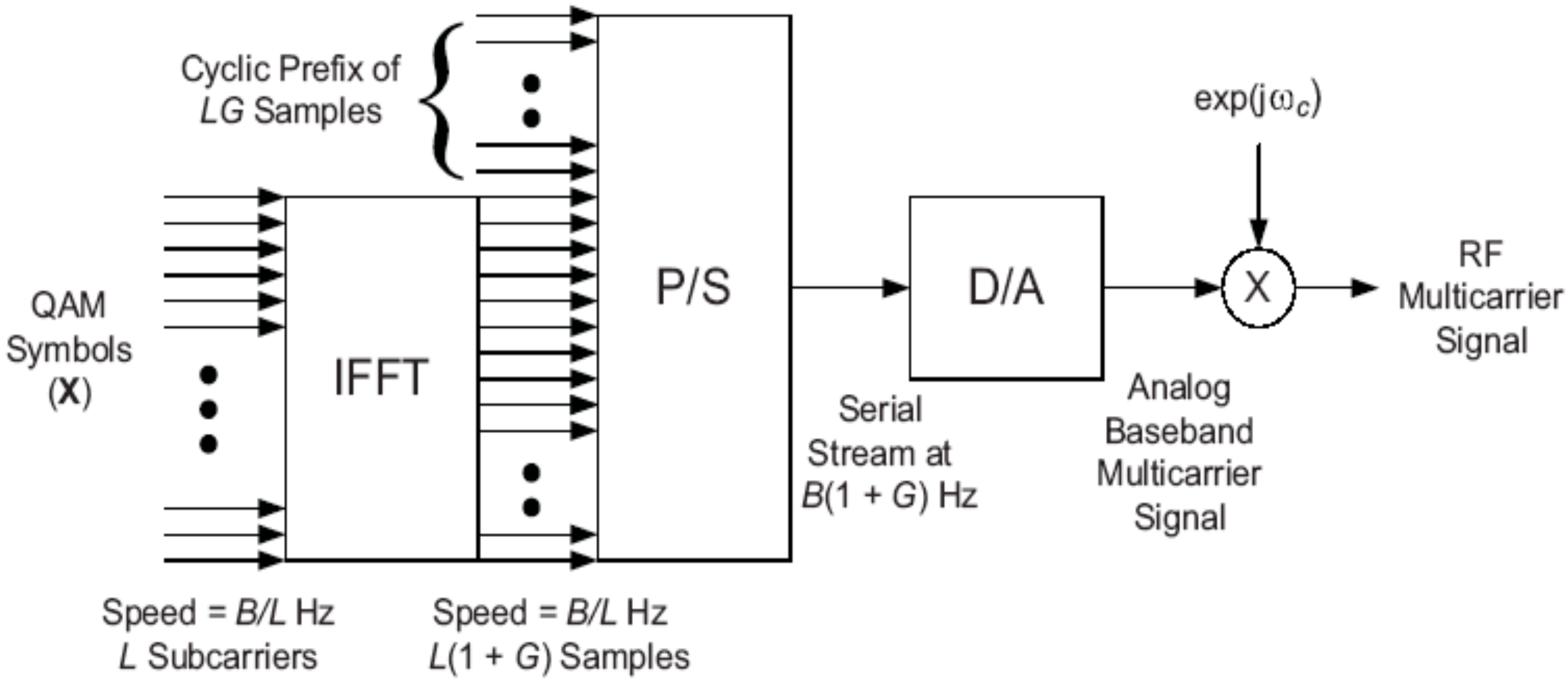


Figure 4.8 Closeup of the OFDM baseband transmitter

Equalization in the frequency domain (one of the key points in OFDM)

$$c'_{ik} = c_{ik} \cdot H_{ik}$$

simb. ricevuto

simb. tx

$H(f)$ del canale!!!

(eq. in banda base ...)

* Portanti pilota per la stima dei valori H_{ik} !!!

$$c_{ik} = \frac{c'_{ik}}{\hat{H}_{ik}}$$

This is an equal. carried out using DFT, therefore it compensate for a “circular convolution”.
Therefore, circular prefix (forcing also the channel to carry out a circ. conv.), give the best performance.

The channel estimation is performed in the freq. domain using the so called “Pilot carriers”.

Equalization in the frequency domain

This aspect is one of the key points in OFDM:

$$c'_{i\,k} = c_{i\,k} \cdot H_{i\,k}$$

Rx impulse Tx impulse Channel's H(t) (baseband eq.)

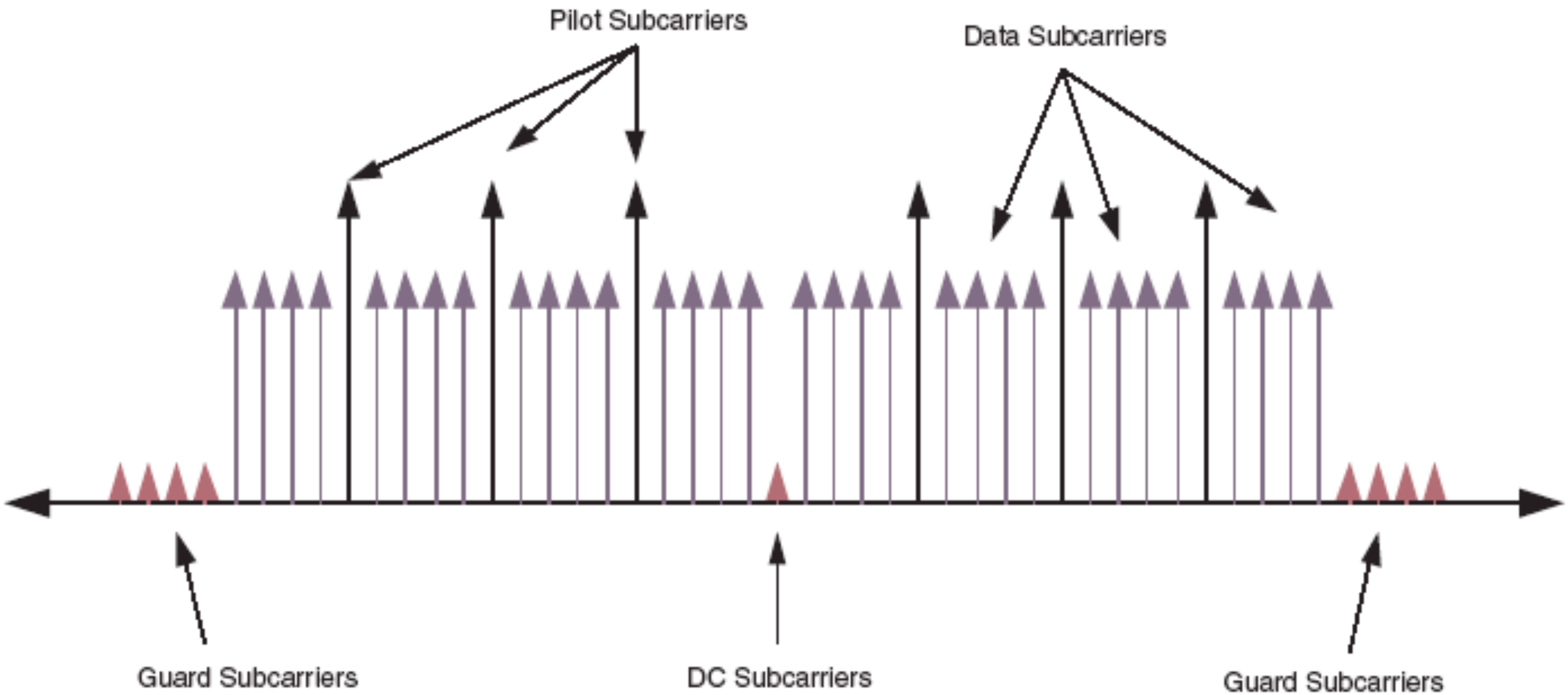
$$c''_{i\,k} = \frac{c'_{i\,k}}{\widehat{H_{i\,k}}}$$

This is an equalization carried out using DFT, therefore it compensate for a "circular convolution".

The use of circular prefix (forcing also the channel to carry out a circular convolution) gives the best performance.

The channel estimation is performed in the frequency domain using the so called "Pilot carriers".

Pilot subcarrier (channel estimation)



Frequency-domain representation of OFDM symbol

Shannon limit & water-pouring

Claude E. Shannon (1948):

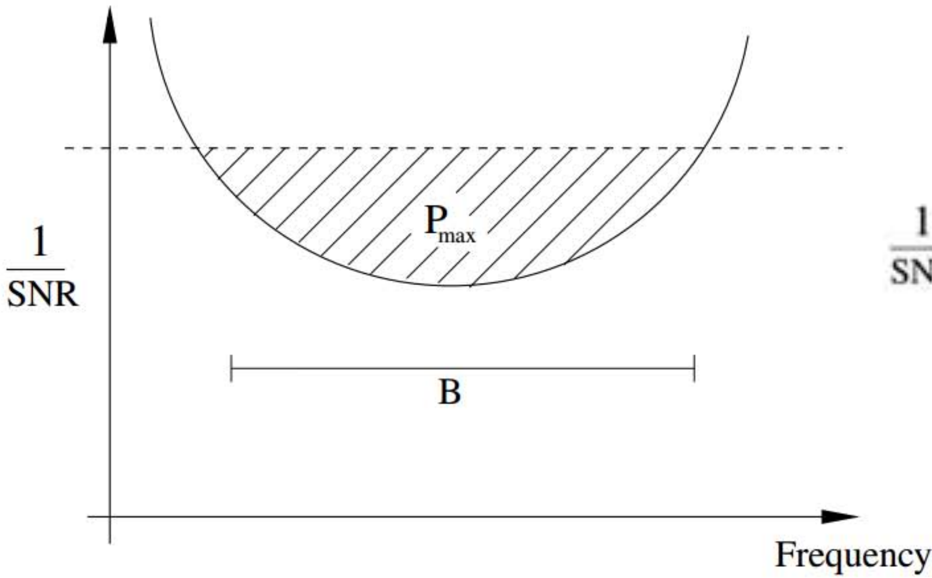
$$C = W\ log_2\left(\frac{P+N}{N}\right)$$

where:

- C = channel capacity (bit/sec)
- W = bandwidth (Hz)
- P = Signal power (Watts)
- N = Noise power (Watts)

~ 3 bps/Hz per every 10 dB SNR

Water-pouring



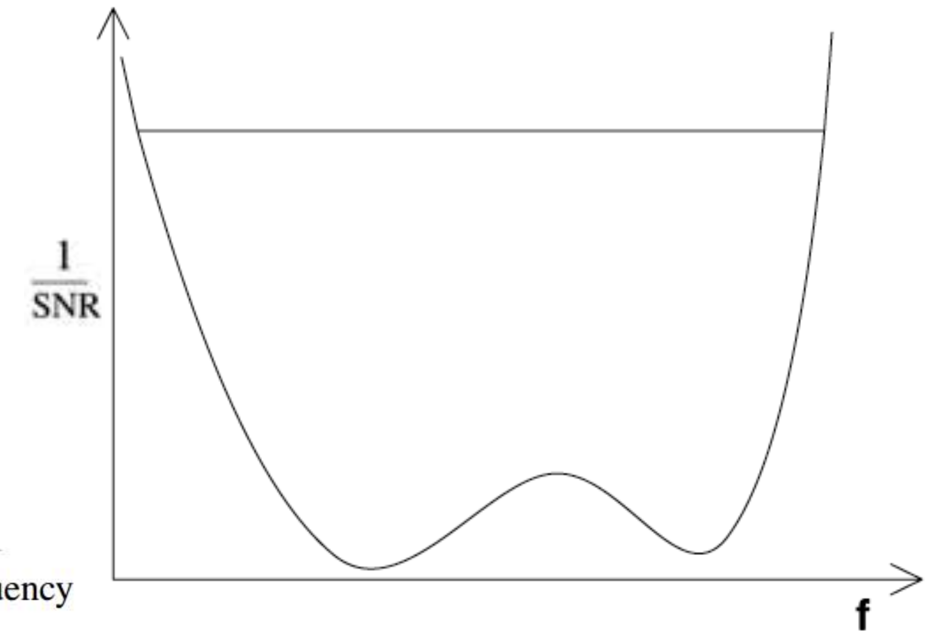
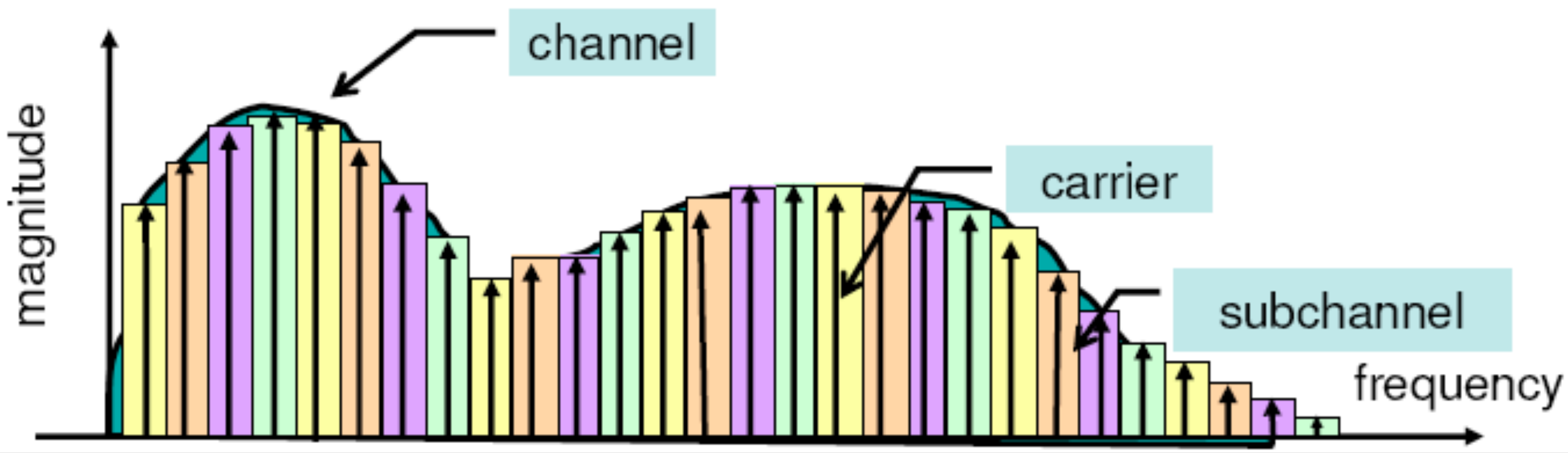


Figure 1.17 – Principle of information theory's ”water-pouring” approach

$$C = \int_0^{\infty} log_2 \left(1 + \frac{S_s(f)\, C(f)}{N_0(f)}\right) df$$

Water-pouring

- Frequency-selective channel is divided into flat fading subchannels
- Fast serial data stream is transformed into slow parallel data streams
  - Longer symbol durations



सहजं कर्म कौन्तेय सदोषमपि न त्यजेत् ।
सर्वारम्भा हि दोषेण धूमेनाग्निरिवावृताः ॥

saha-jaṁ karma kaunteya
sa-doṣam api na tyajet
sarvārambhā hi doṣeṇa
dhūmenāgnir ivāvṛtāḥ

Every endeavor is covered by some fault, just as fire is covered by smoke. Therefore one should not give up the work born of his nature, even if such work is full of fault.

—*The Bhagvad-Gita* (18.48)

Advantages Vs Disadvantages

OFDM advantages

- Efficiently deals with multi-path fading
- Efficiently deals with channel delay spread
- Enhanced channel capacity
- Adaptively modifies modulation density
- Robustness to narrowband interference

OFDM disadvantages

- OFDM sensitive to small carrier frequency offsets
- OFDM exhibits high peak to average power ratio
- OFDM sensitive to high frequency phase noise
- OFDM sensitive to sampling clock offsets

Problematiche OFDM

* Sincronizzazione → recupero fase della portante

* $f_x(\alpha)$ → è una gaussiana (delle z su una portante si guasta) → il Tx. toglierà dei picchi → spettro si allarga ...
(fattore di picco elevato)

* (Eq. nel dominio delle freq.
↳ tempo di guardia
spreco un po' di tempo e un po' di energia per la tx. del prefisso-circolare ..)

* Le non linearità distorcono il segnale in modo significativo ....
e anche le "SPALLE" dello spettro subiscono un incremento notevole ....

OFDM Main Problems:

1)Synchronization is a critical issue (freq. and phase);

1)The ofdm signal pdf (gaussian) show a very large "peak factor" (it is therefore needed a linear system with large dynamics);

1)The power spectrum is also strongly influenced by the non-linearities.

2)There are some spectral inefficiencies due to insertion of the guard interval (cyclic prefix)

OFDM main problems

- The synchronization required to recovery precisely the carrier is a critical issue (both for frequency and phase);
- The OFDM signal pdf “$f_x(\alpha)$” (gaussian) shows a very large “peak factor” which requires a linear system with a large dynamics;
- The power spectrum is also strongly influenced by the non-linearities;
- There are some spectral inefficiencies due to insertion of the guard interval : it’s wasted a bit of time and energy to transmit the cyclic prefix.

Amplifier in-out characteristics

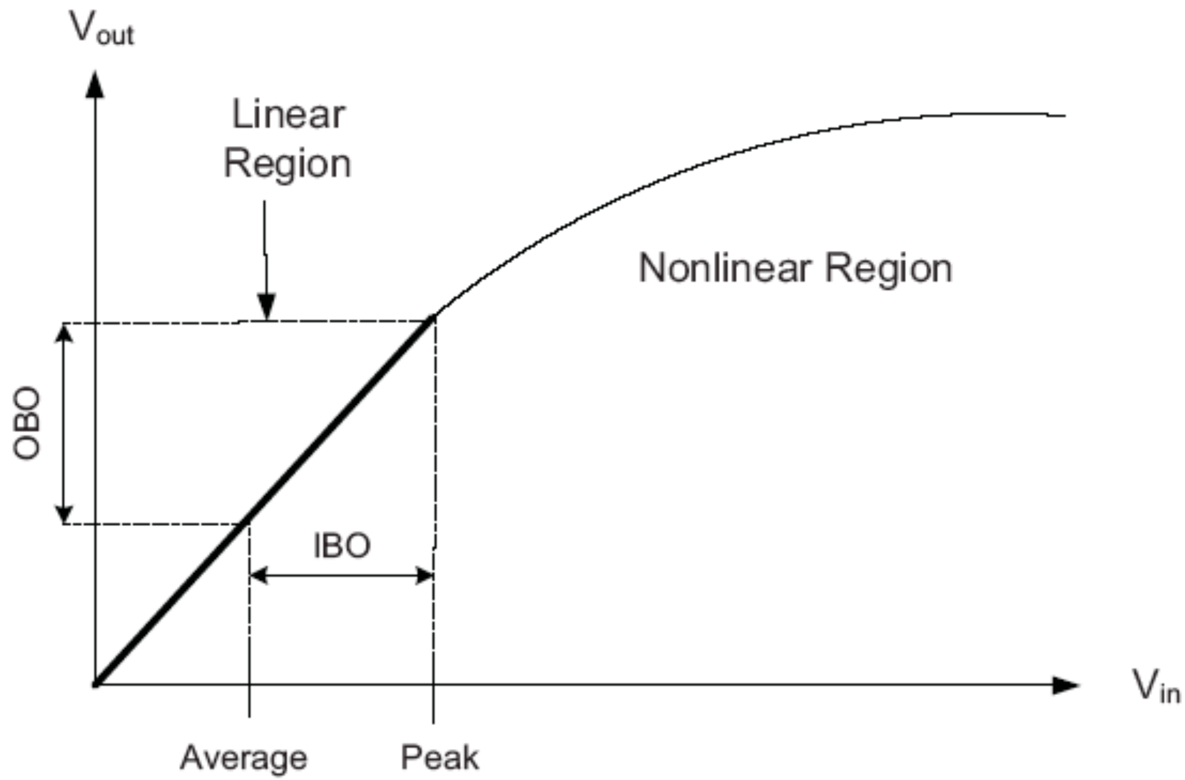


Figure 4.12 A typical power amplifier response. Operation in the linear region is required in order to avoid distortion, so the peak value must be constrained to be in this region, which means that on average, the power amplifier is underutilized by a back-off amount.

Prob. Density Function (PDF) of OFDM signal

The pdf of a sum of nearly independent random variables approximate a Gaussian distribution (central limit theorem). Therefore the “peak factor” is very big (10 dB).

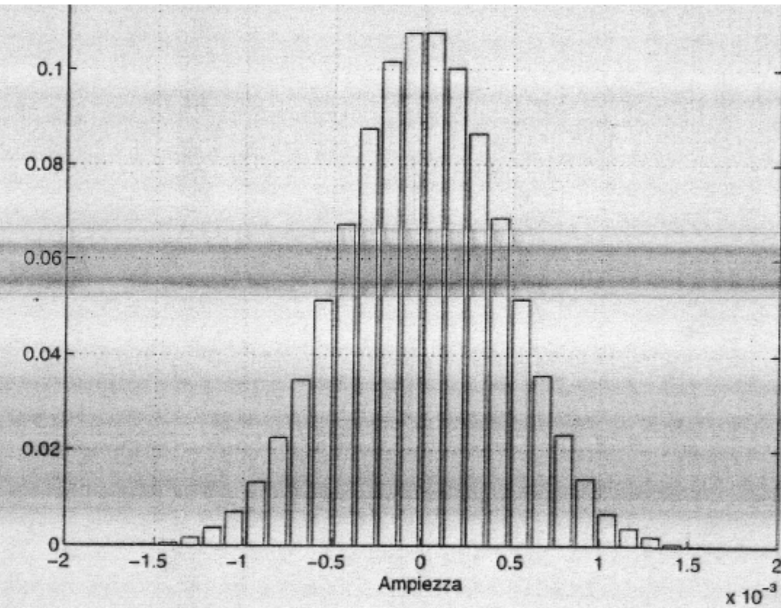


Figura 6.23: Densità di probabilità della parte reale delle ampiezze del segnale OFDM.

Prob. of Error (P(E))

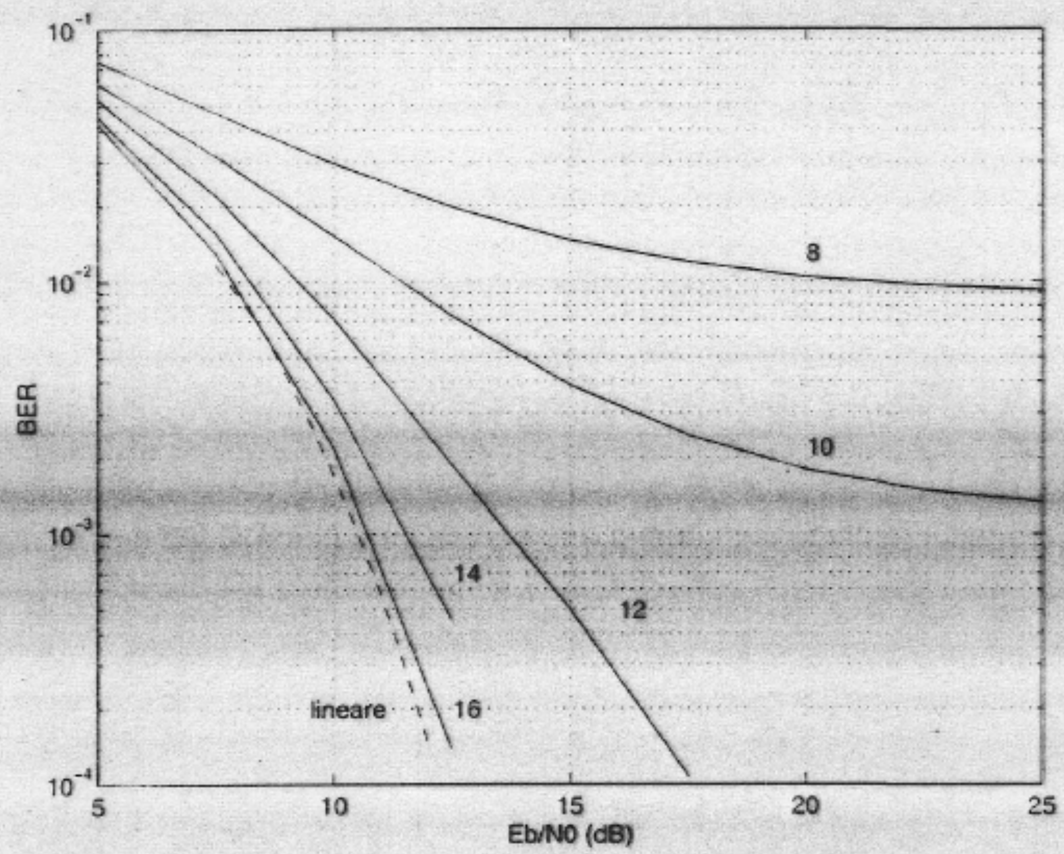


Figura 6.10: Prestazioni del sistema OFDM-16QAM con TWTA in funzione del valore di *Input Back-Off*.

P(E)

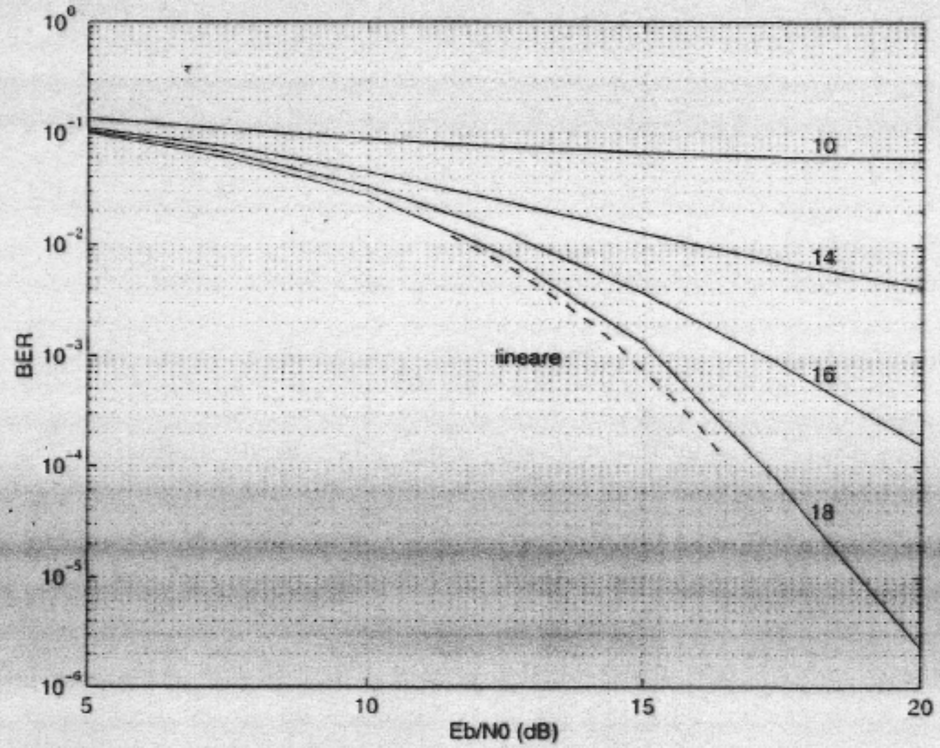


Figura 6.11: Prestazioni del sistema OFDM-64QAM con TWTA in funzione del valore di *Input Back-Off*.

P(E)

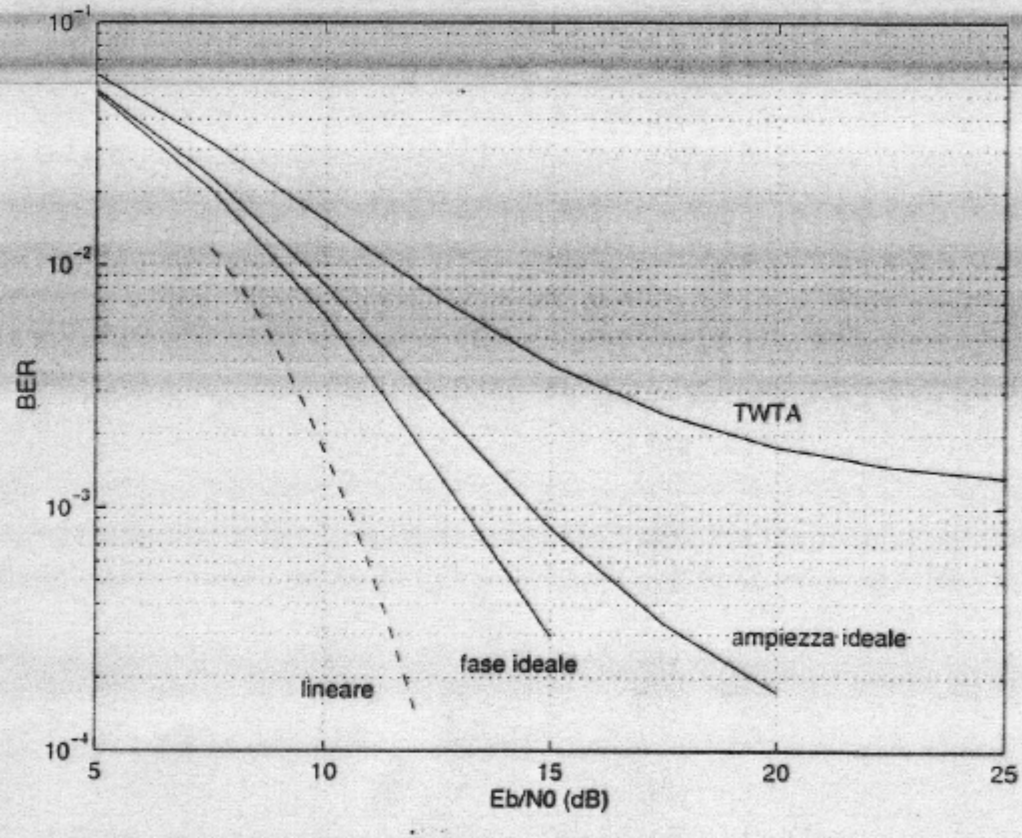


Figura 6.12: Effetti delle non linearità di fase e di ampiezza (IBO=10 dB).

Spectral mask

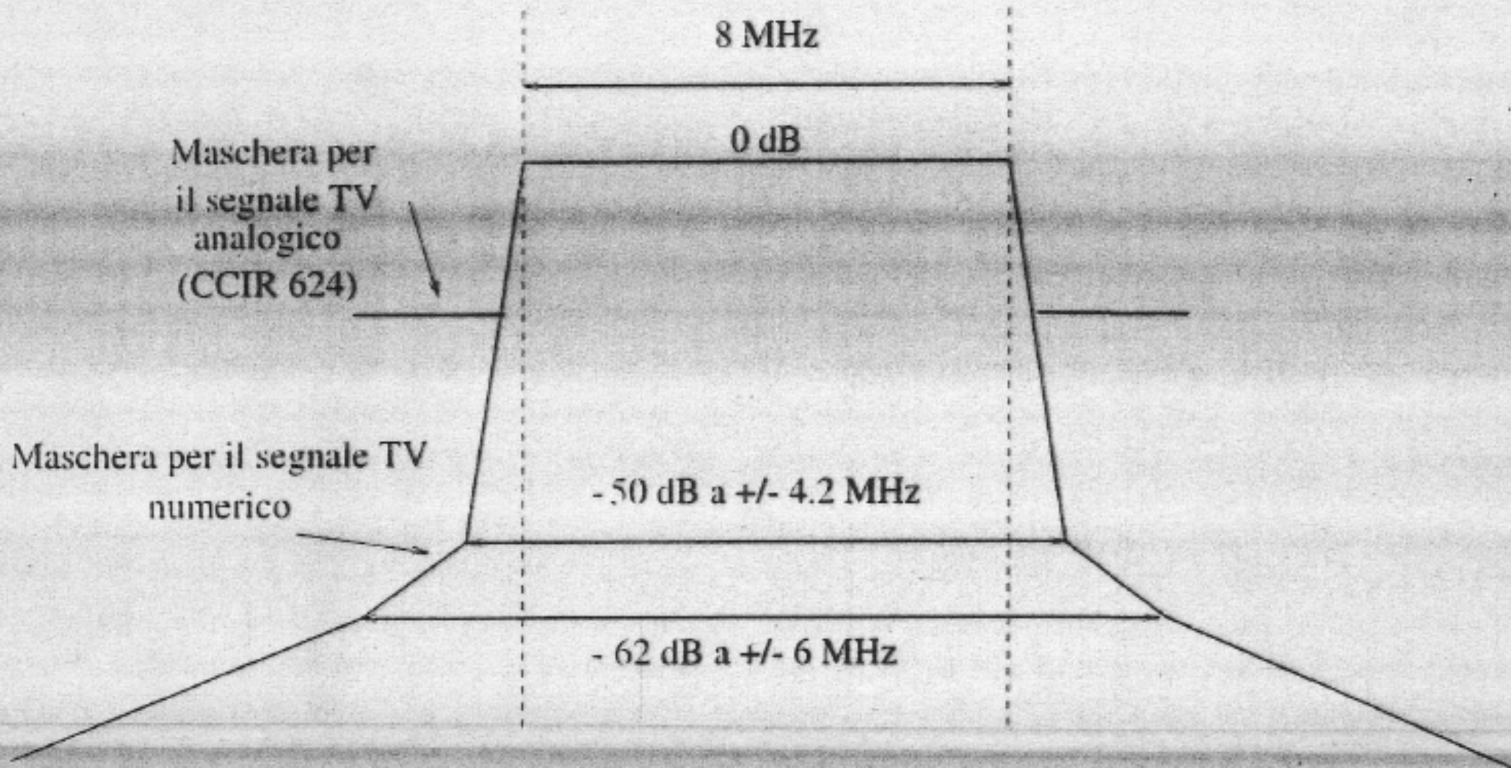


Figura 5.12: Requisiti della maschera dello spettro per il segnale televisivo analogico e numerico.

Spectral mask

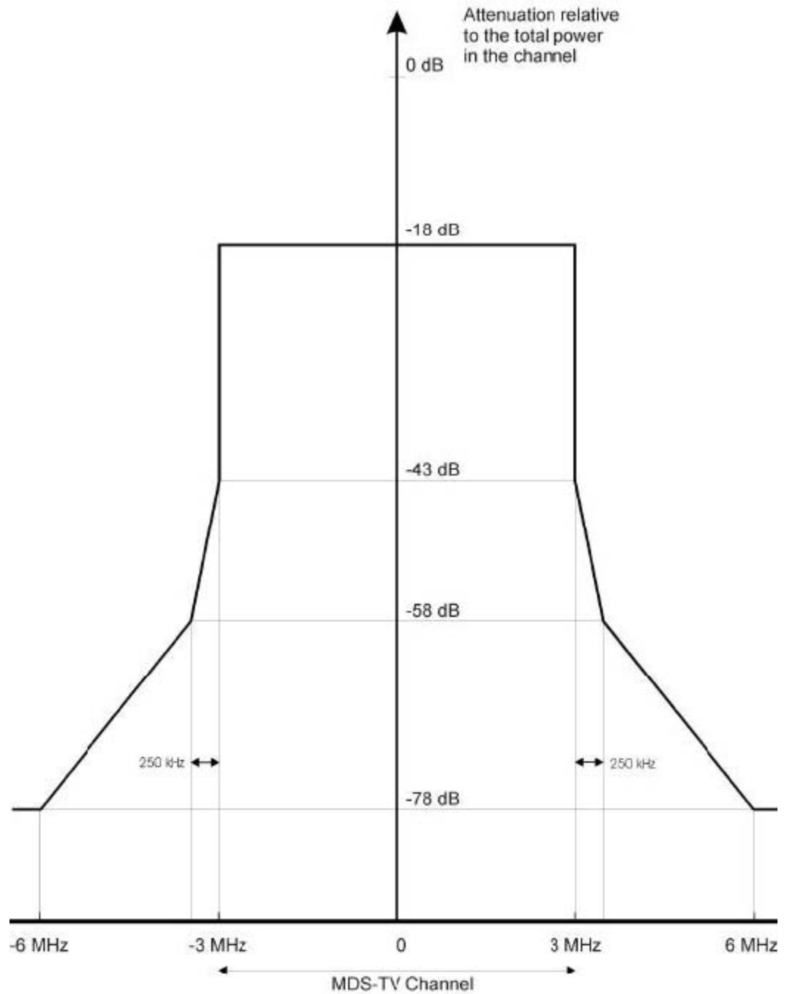


Figure 1.9 – Spectral mask for the digital MDS-TV (Multipoint Distribution Television Systems (Canada)) channel

Spectrum modifications

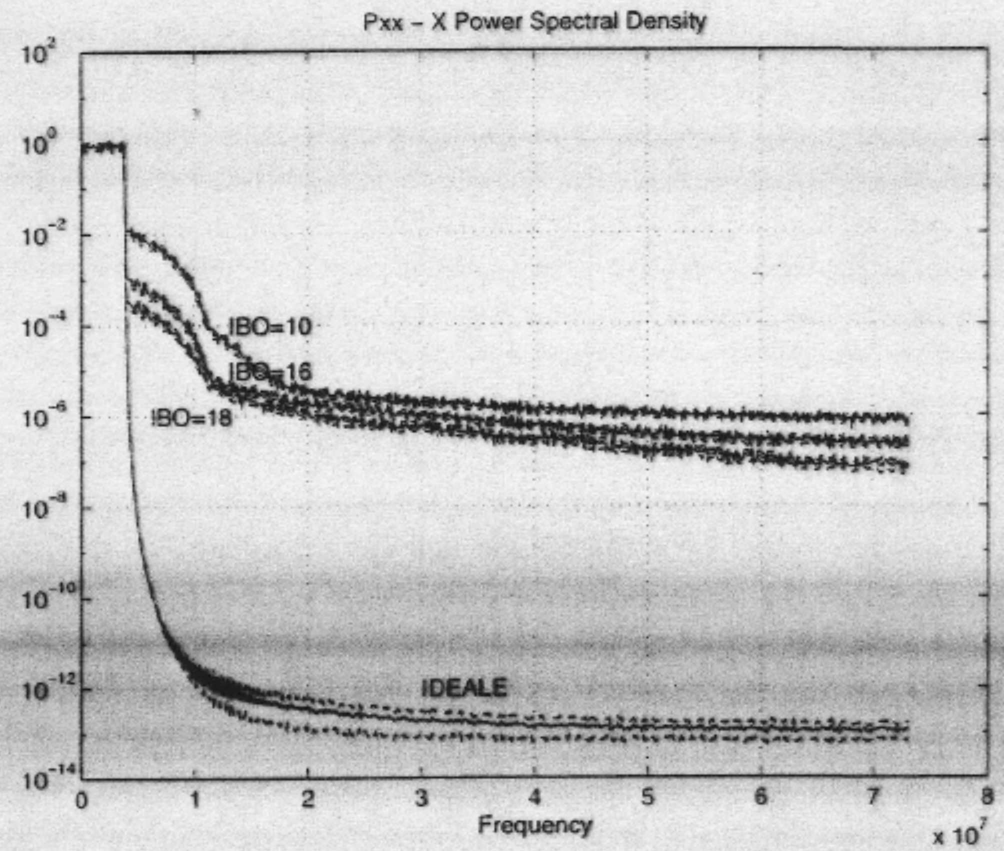
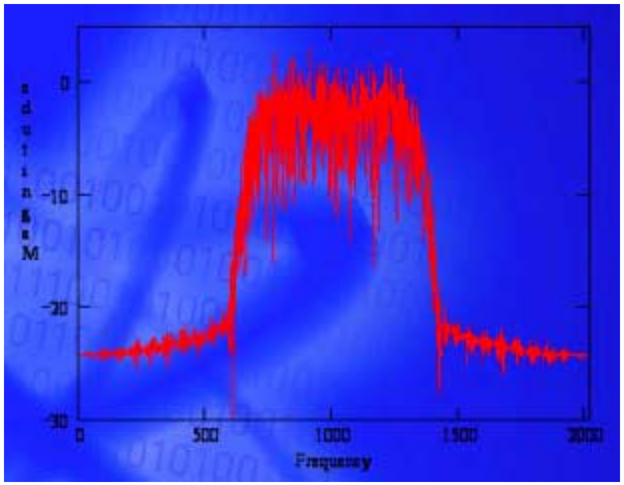


Figura 6.20: Spettro di potenza del segnale OFDM-64QAM ideale e con amplificatore TWT in funzione di diversi valori di IBO.

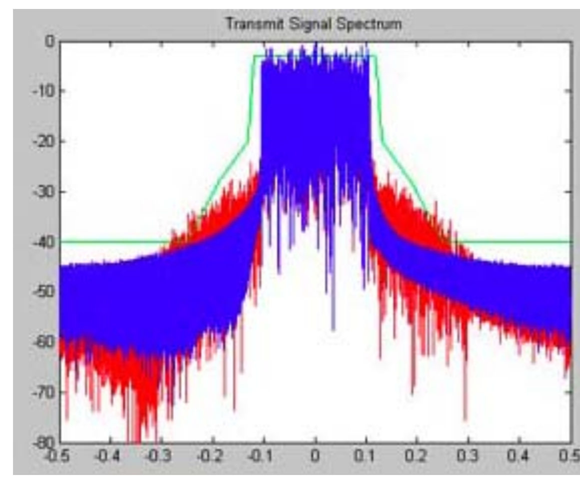
Spectrum modification

Practical signal spectra



Single carrier signals require filtering for spectral containment. This signal has narrow roll-off regions which requires long filters.

OFDM spectra have naturally steep sides, especially with large N. The PAPR is often higher, which may result in more spectral regrowth. The blue trace is an unfiltered OFDM signal with 216 subcarriers. The red trace includes the effects of a non-linear Power Amplifier.



Spectrum modifications

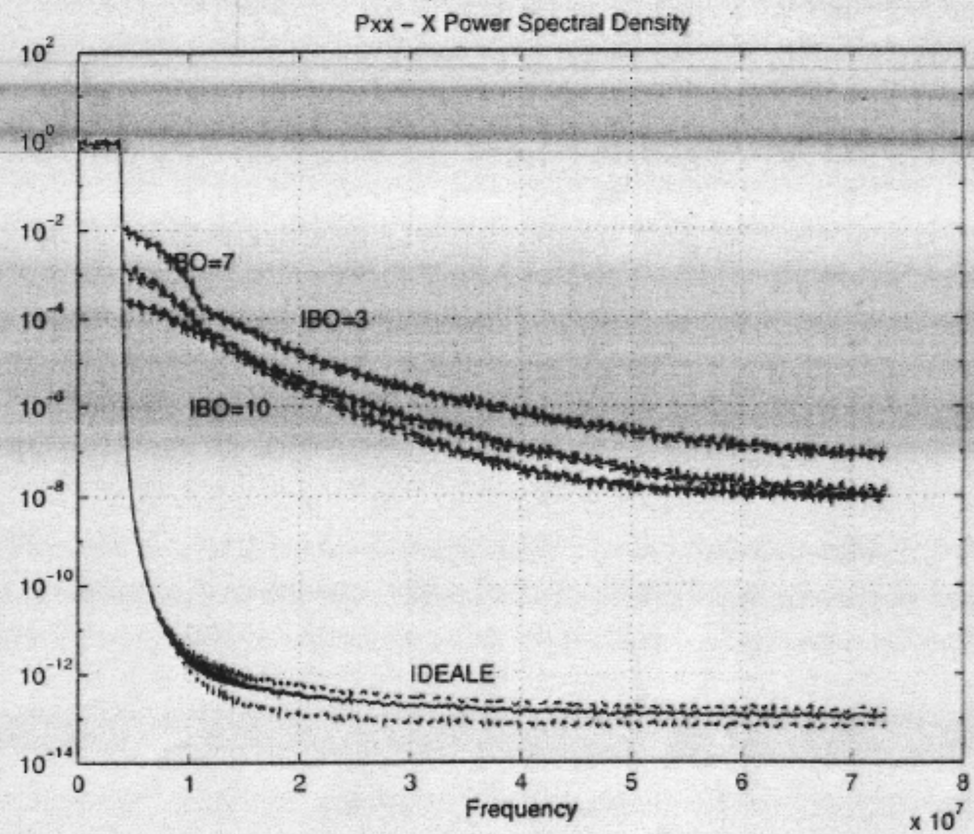


Figura 6.21: Spettro di potenza del segnale OFDM-64QAM ideale e con amplificatore SSP in funzione di diversi valori di IBO.

Applications

- 1. DAB, DVB
- 2. Wireless systems: WiFi, WiMax, 4G, …
- 3. Domotic, Digital Power Lines (DPL)
- 4. Modem: ADSL, VDSL, …
- 5. Ultra Wide Band (UWB)
- 6. Many more …

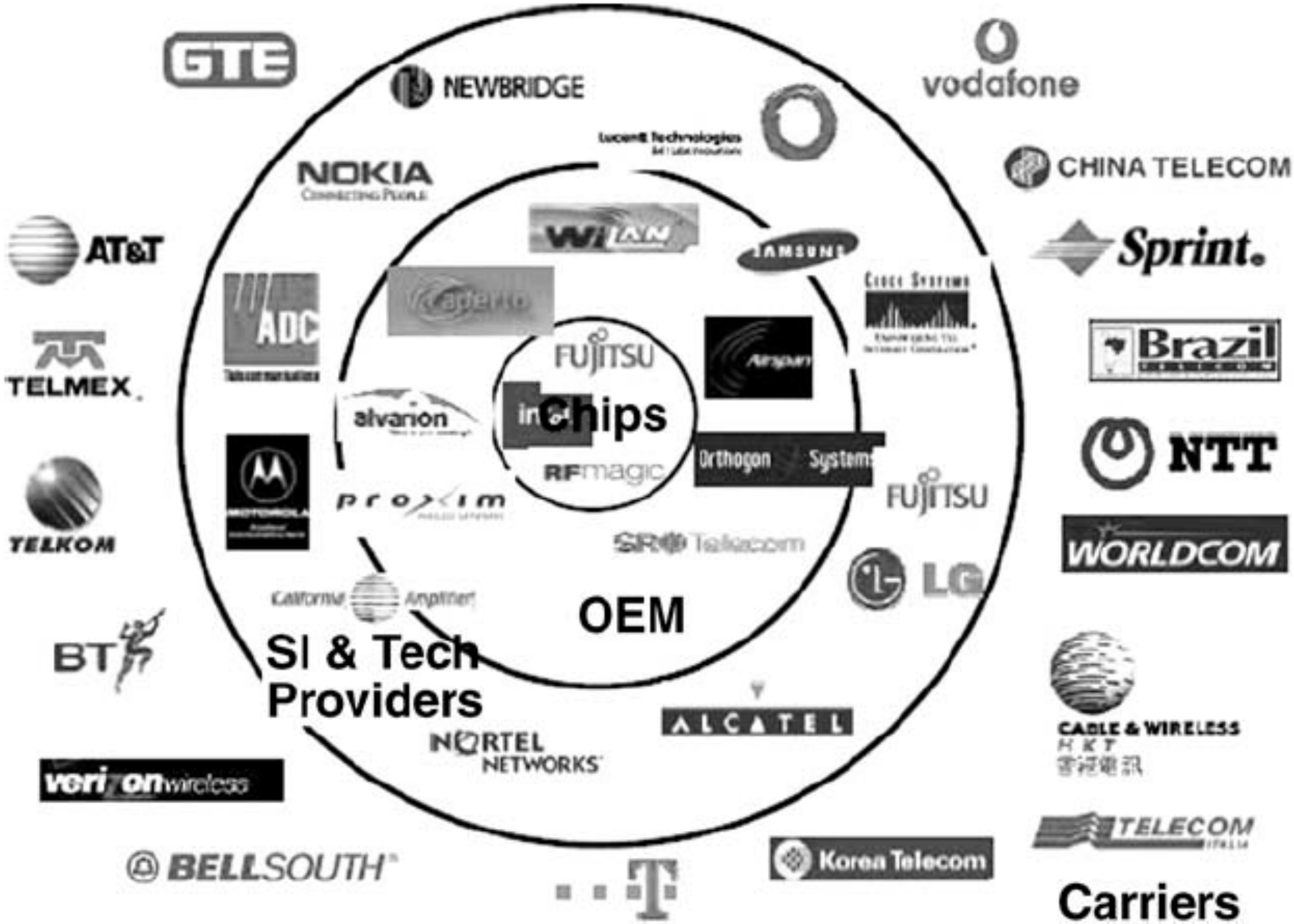


Figure 9.14 WiMAX industry structure

Wireless Local Area Network (WLAN)

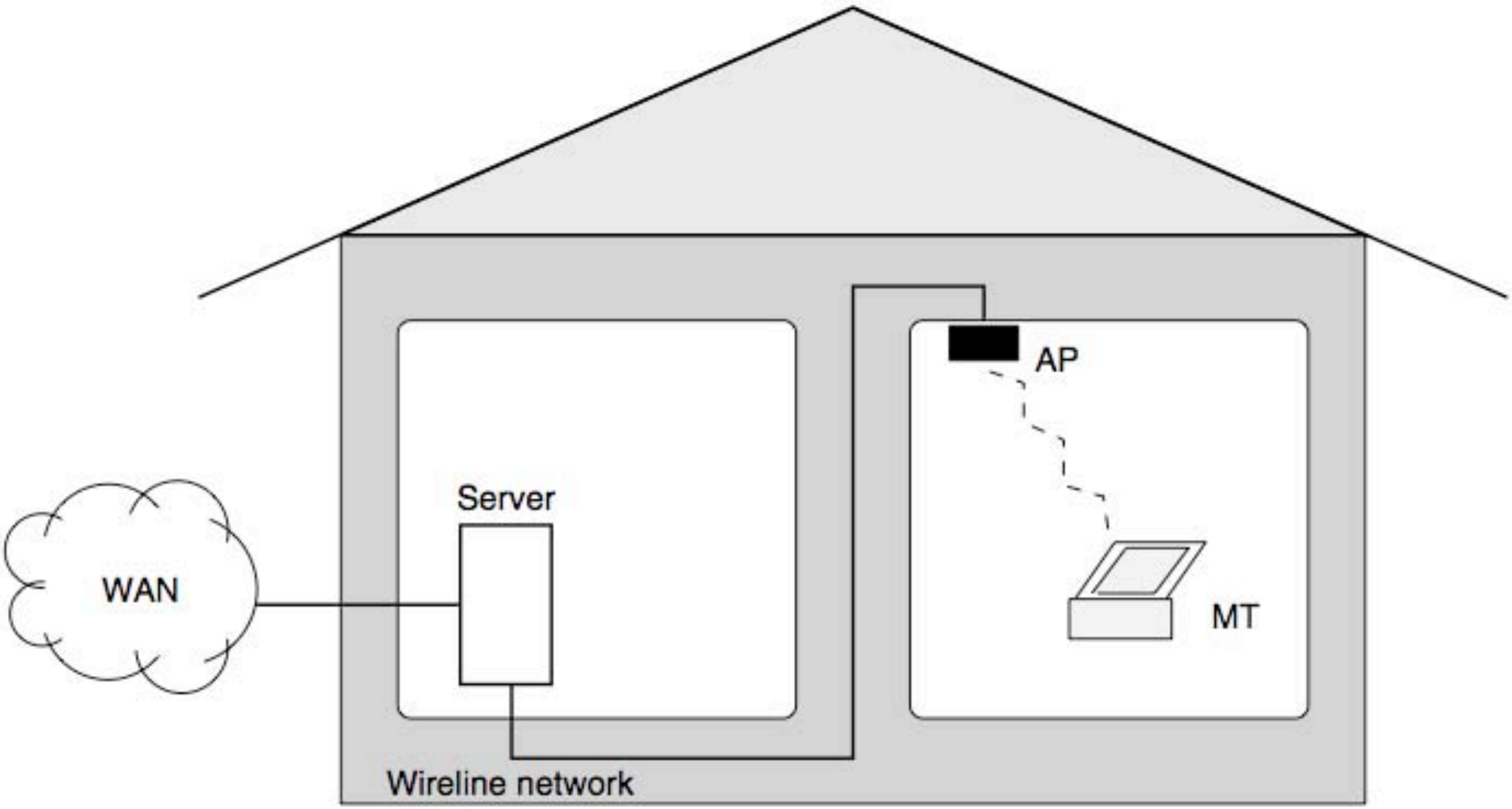
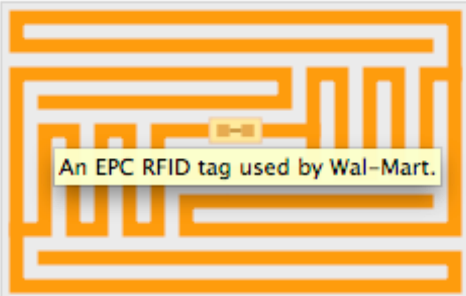


Figure 2.4 Structure of Wireless Local Area Networks – WLAN

RFID



An EPC RFID tag used by Wal-Mart.

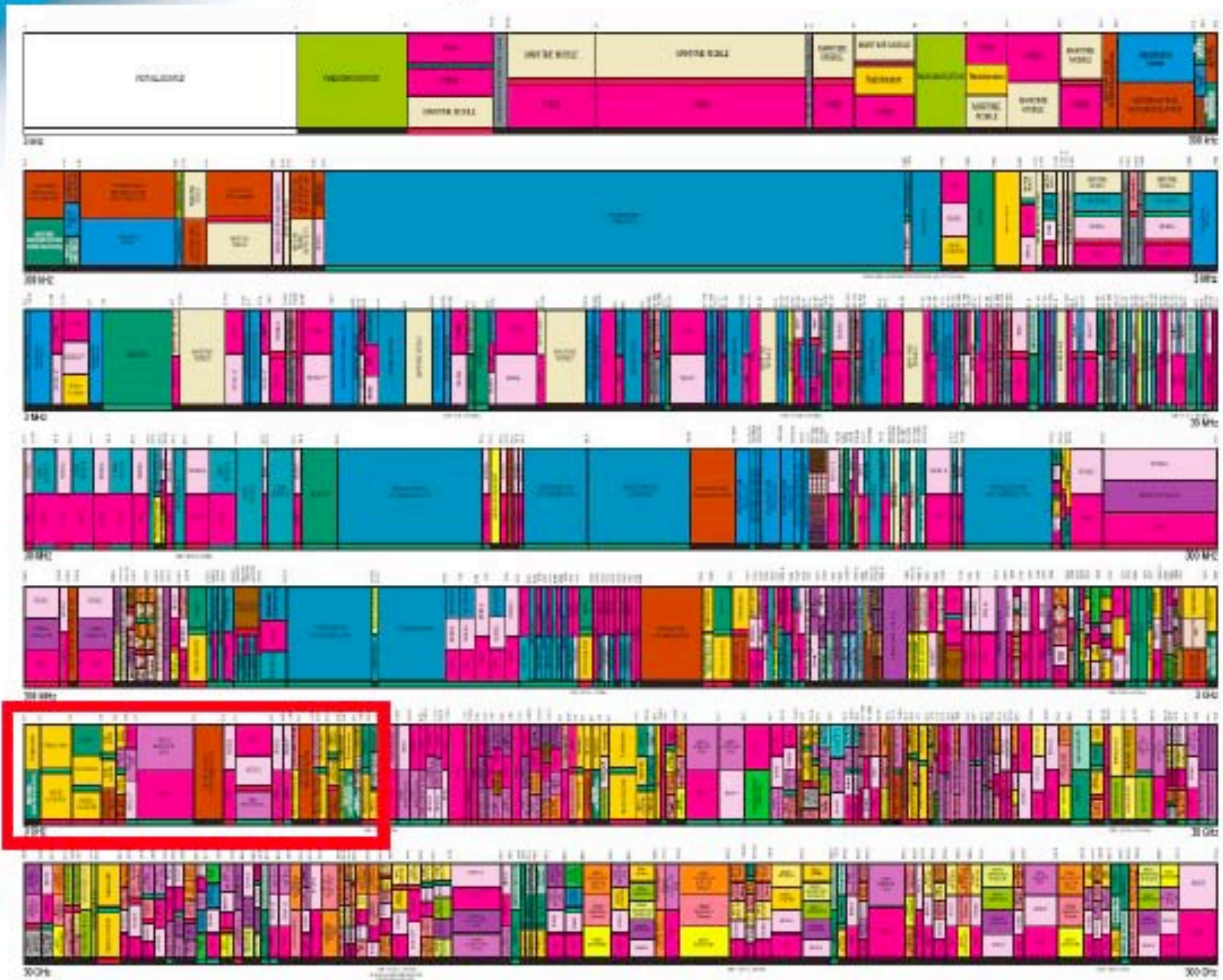
RFID tags used in libraries: square book tag, round CD/DVD tag and rectangular VHS tag.

An Electronic Road Pricing gantry in Singapore. Gantries such as these collect tolls in high-traffic areas from active RFID units in vehicles.

PayPass RFID chip removed from a MasterCard.

An RFID tag used for electronic toll collection.

U.S. Frequency Allocation Chart



4G?

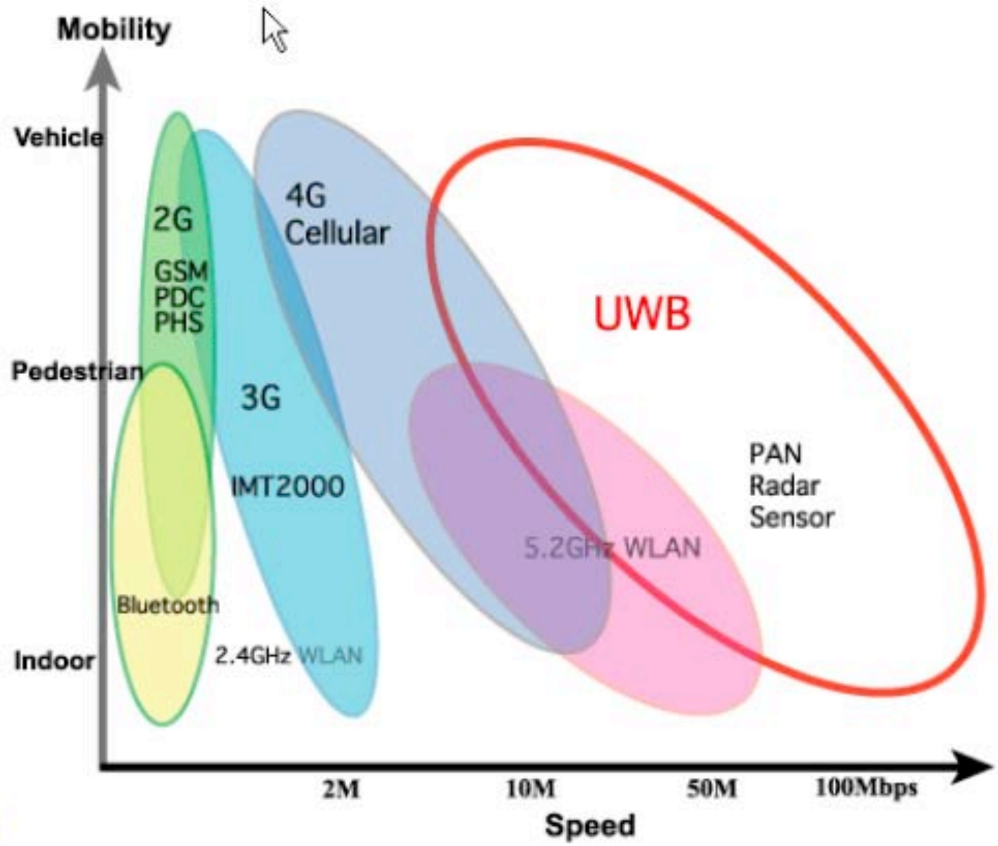
UWB-Ultra Wide Band

Spark Gap transmitter

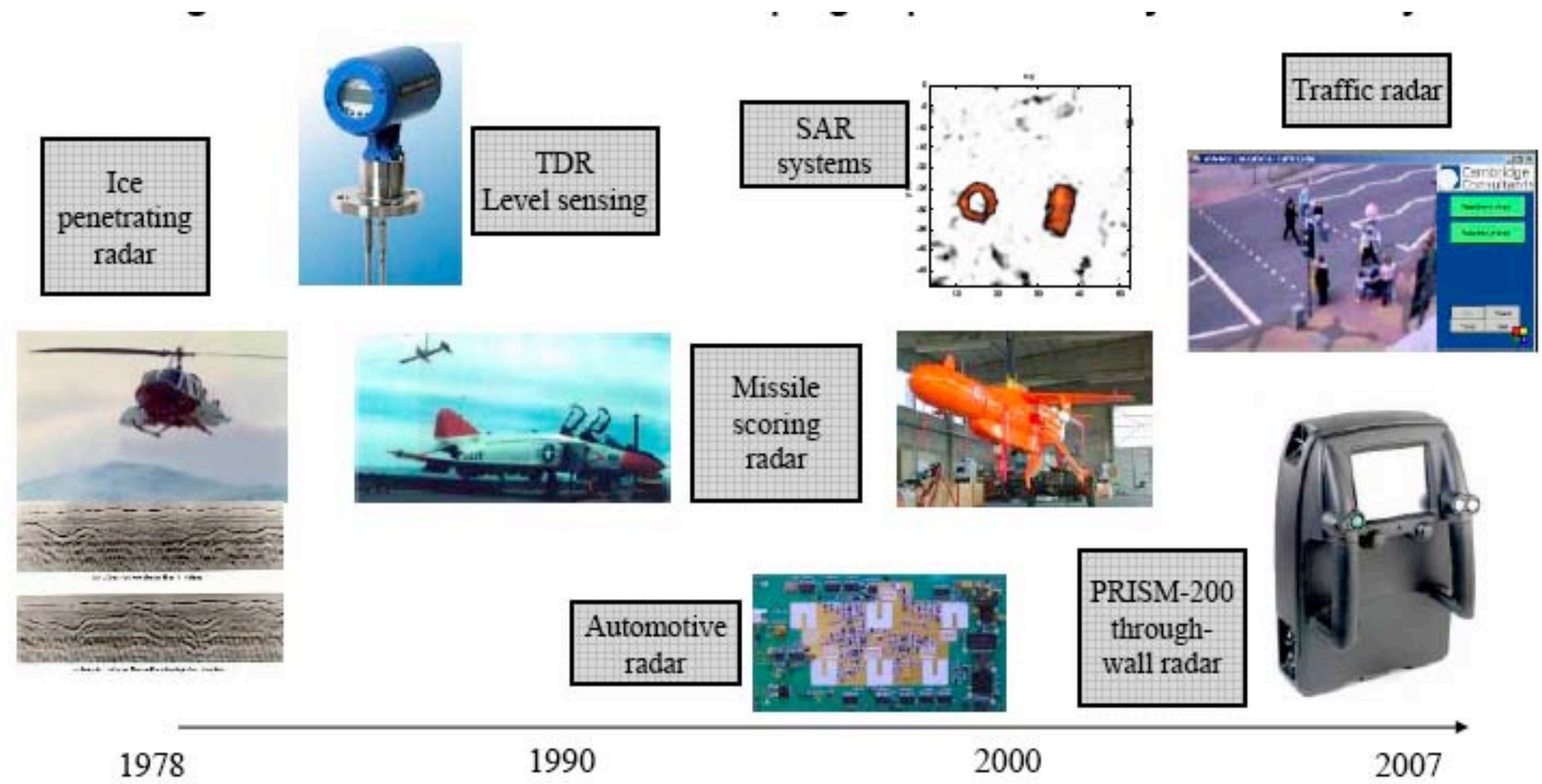
The first UWB radio was developed by Guglielmo Marconi in the late 1800's.

Was used to transmit Morse code through the airwaves.

Where does it fit?



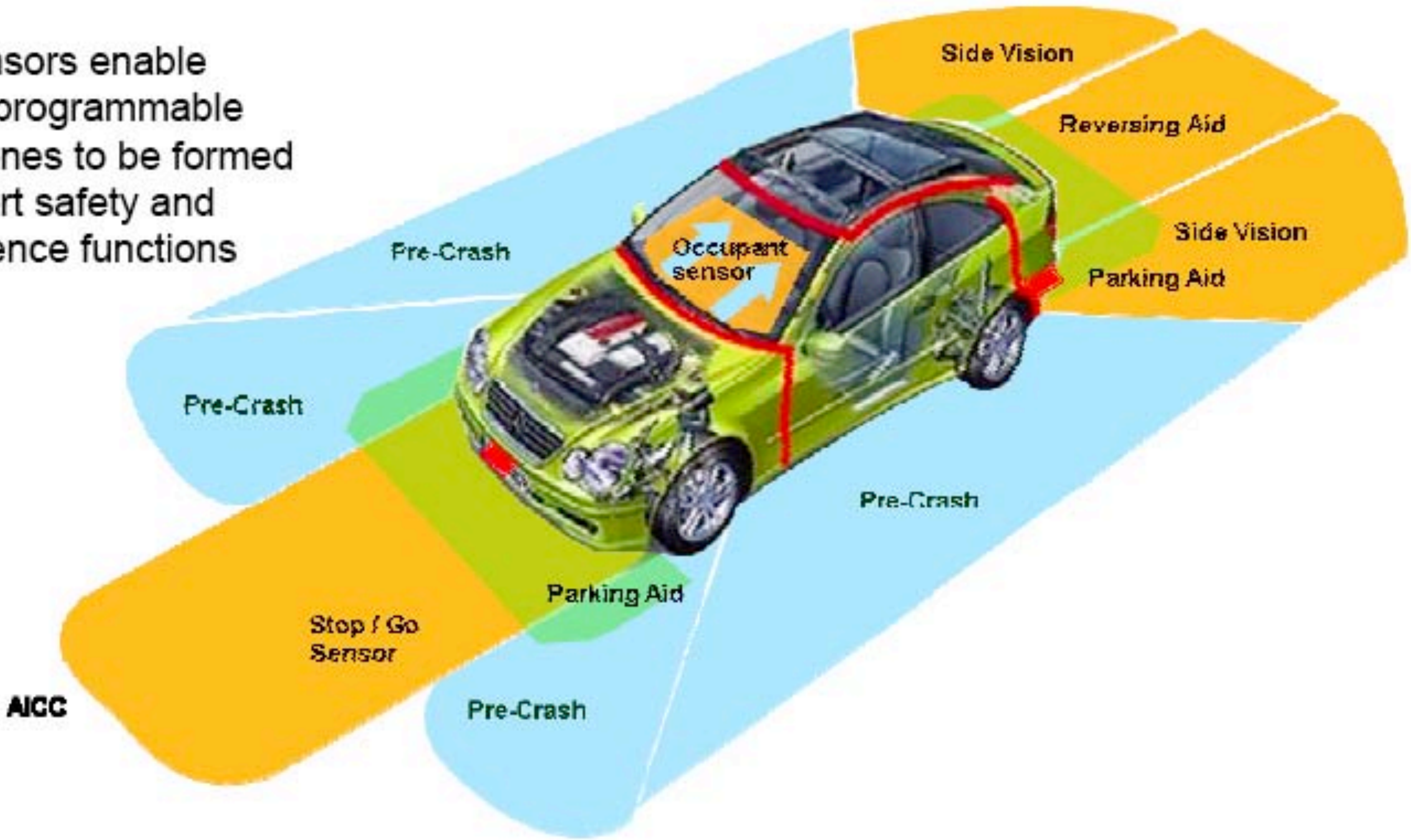
UWB


Ice penetrating radar
TDR Level sensing
SAR systems
Traffic radar
Missile scoring radar
Automotive radar
PRISM-200 through-wall radar
1978
1990
2000
2007

UWB

Car safety – pre-crash protection, reversing, blind-spot coverage, parking aid

- Four sensors enable thirteen programmable alarm zones to be formed to support safety and convenience functions



UWB


MEMBER COMPANIES
AUTHORS
alereon
FOCUS
GENERAL ATOMICS
intel
MITSUBISHI ELECTRIC
Panasonic
PHILIPS
SAMSUNG ELECTRONICS
STACCATO COMMUNICATIONS
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zero
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UWB Wireless
Verisity
VESTEL
VIA Networking Technologies, Inc.
VIRAGE LOGIC
WiLAN
Wireless Experience
Wisme
WiQuest

Software Defined Radio

- Goal: allow a single device to implement many different standards by simply loading different software

- Advantage: very flexible and adaptive

- Disadvantage: High power consumption
  - Rule of Thumb:
    - *ASIC 10X more efficient than DSP*
    - *DSP 10X more efficient than general purpose μP*

- Other challenges include RF implementation

- Again, expect a general trend towards software, instead of new software radios out of nowhere

Cognitive Radio Concept

FCC NPRM adopted Dec 17, 2003, ET-03-108*
FCC NPRM adopted May 14, 2004 (*to be published*)

[Cognitive radio technologies] include, among other things, the ability of devices to determine their location, sense spectrum use by neighboring devices, change frequency, adjust output power, and even alter transmission parameters and characteristics.

(*Paragraph 1)

A cognitive radio (CR) is a radio that can change its transmitter parameters based on interaction with the environment in which it operates. This interaction may involve active negotiation or communications with other spectrum users and/or passive sensing and decision making within the radio.

(*Paragraph 10)

Cognitive Radio Concept

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(*Paragraph 10)

Cognitive Radio

- On long term, the most disruptive spectrum sharing scheme is the Cognitive Radio
- The radio functionality for advanced flexible spectrum use is demanding, as it requires a considerable amount of intelligence from the transmitting device.
- Cognitive*) or smart radios could possess the required capabilities for flexible spectrum use

- sensing over wide frequency band
- identifying both other users of that band as well as the available transmission opportunities
- coordinating the actual use of the radio band by communicating with other devices
- conforming to spectrum pooling etiquettes to ensure that no harmful interference is caused to other users

Cognitive Radio

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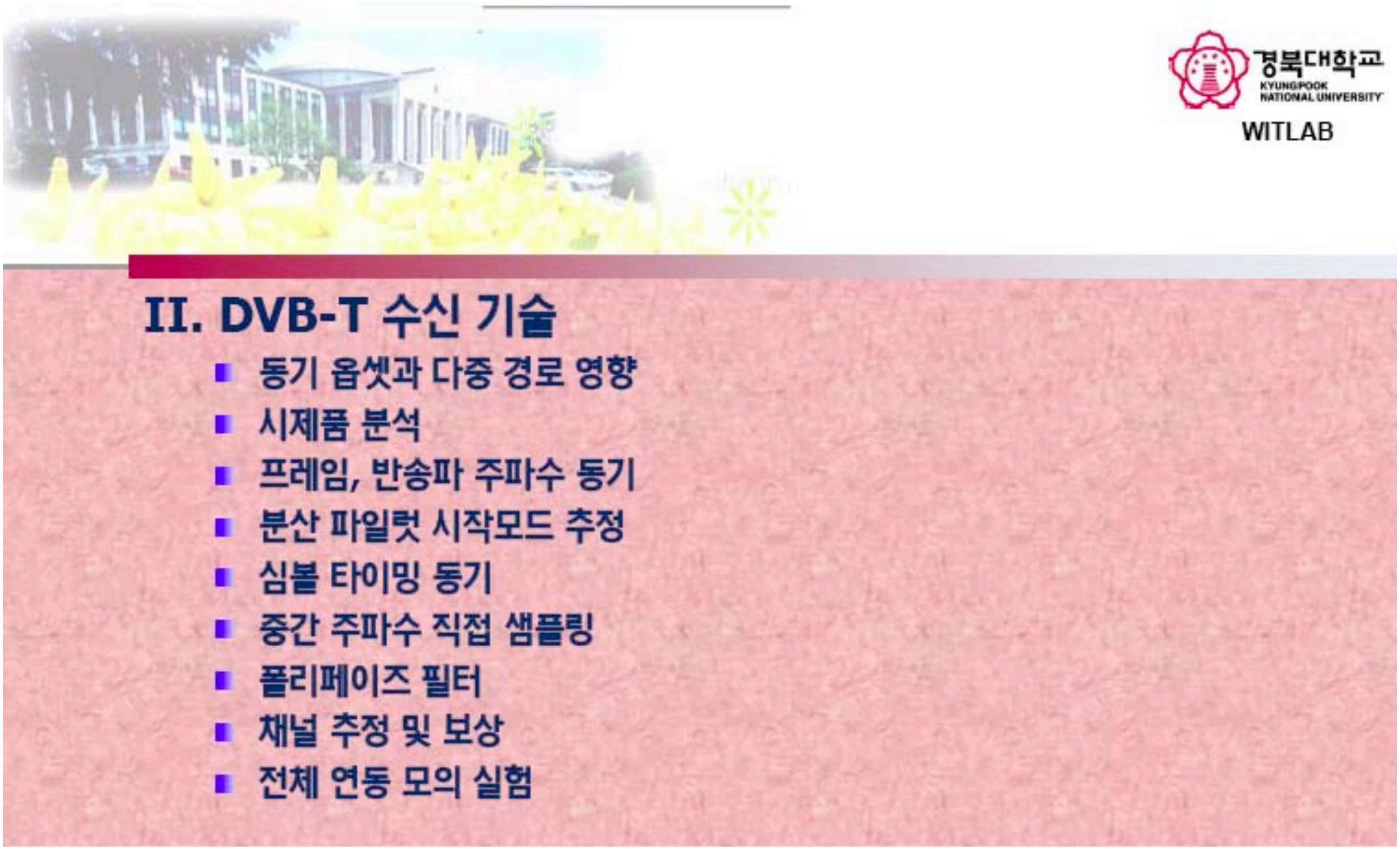
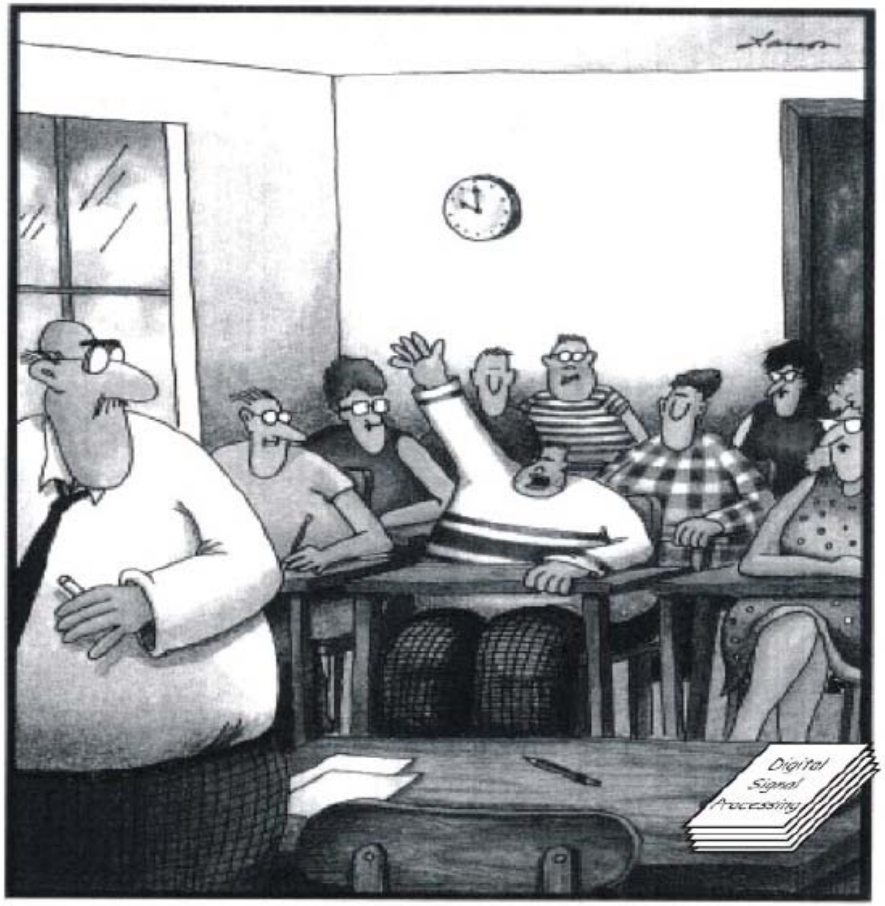
Conclusions



That's all folks



"Professor Migliorati, may I be excused?

My brain is full!"