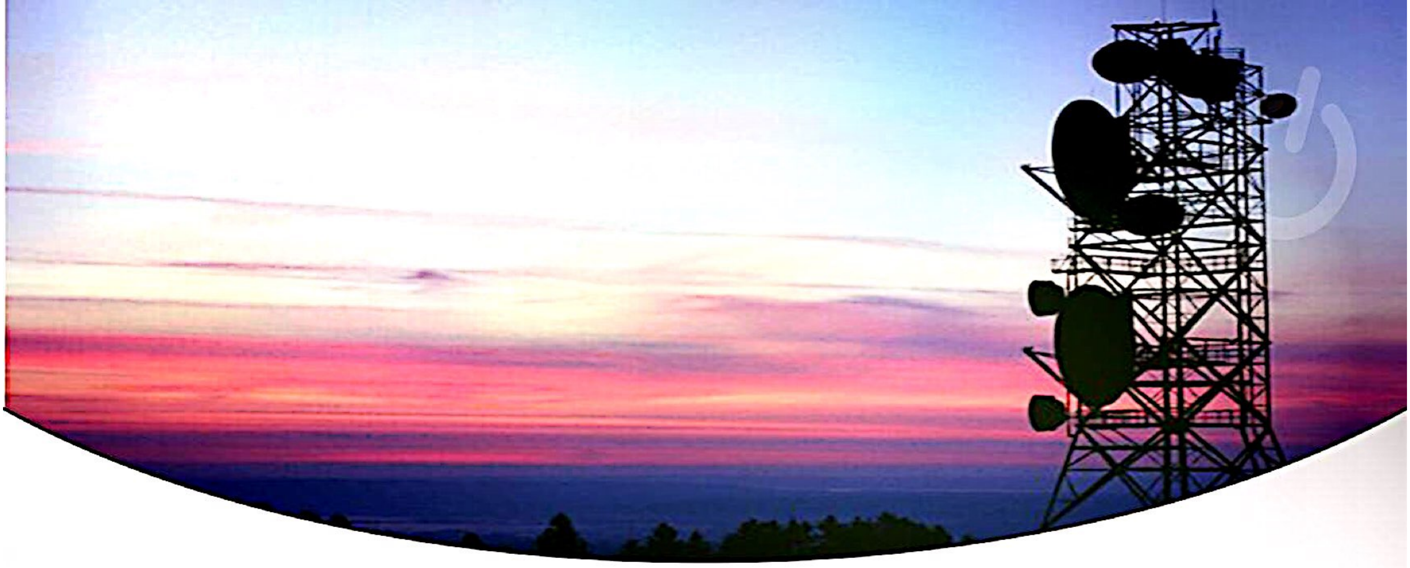

Communications1

Fall017

Dr. Mhmd Hawa

By: Mhmd Abuhashya

www Powerunit-ju.com

Mohammad
Abu Hashya.

24

Lecture 1: Introduction to Communication Systems

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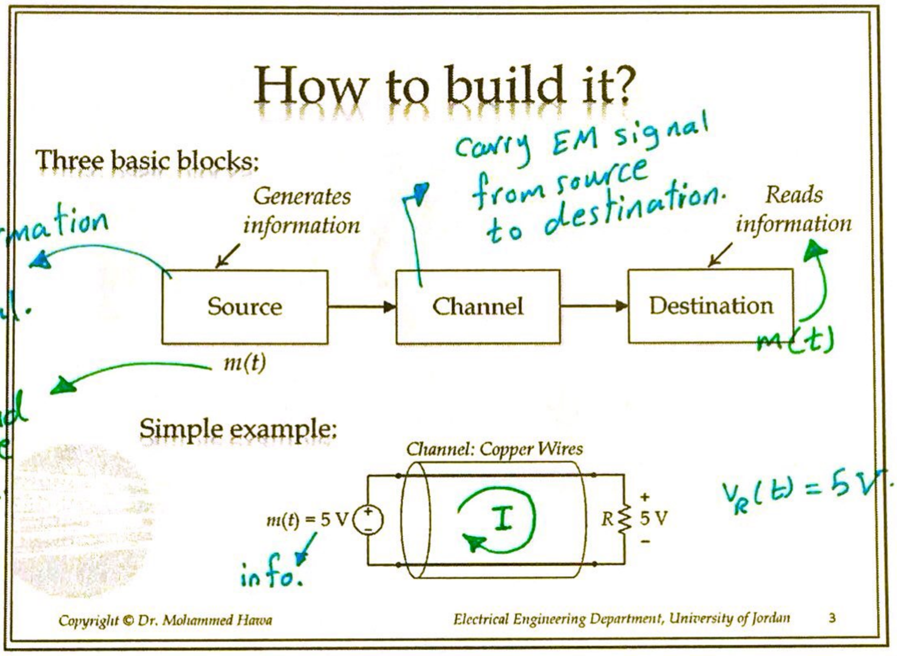
A Communication System

- Purpose of a communication system: Carry information from one point to another.
- A typical communication system consists of three main components:
  - Source
  - Channel
  - Destination



How to build it?

Three basic blocks:

Generates information → Source → Channel → Destination ← *Reads information*

m(t)

Convert information into an EM signal.

Carry EM signal from source to destination.

m(t)

Baseband message signal

Simple example:

Channel: Copper Wires

$m(t) = 5$ V

info.

I

R 5 V

$V_R(t) = 5V$. (Assuming ideal channel)

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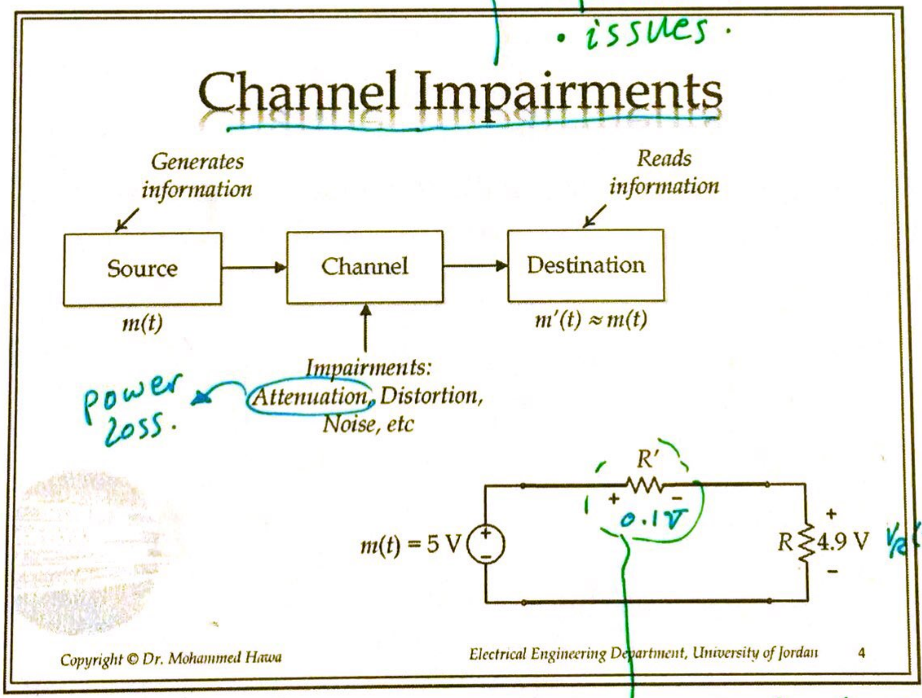
- limitations
- problems
- issues.



Channel Impairments

Generates information → Source → Channel → Destination ← *Reads information*

m(t) *m′(t) ≈ m(t)*

Impairments: Attenuation, Distortion, Noise, etc

power loss.

R′

+ 0.1V −

$m(t) = 5$ V

R 4.9 V

$V_R(t) = 5\frac{R}{R+R'} < 5V$

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→ will absorbe power
→ convert it to heat
, this heat can't be recovered back.
, so power loss.
This called Attenuation.

$V_{DC} = 5V \rightarrow P_{av} = DC^2 = 25W \Rightarrow$ Average value $= DC = 5$

$V_{AC} = 4\cos(\omega_c t) \rightarrow P_{av} = \frac{4^2}{2} = 8W \rightarrow$ Average $= DC =$ Zero.

$V_{out\,DC} = 4.9\,\text{volt} \rightarrow P_{av} = 4.9^2\,W$.

the difference is the Losses.

$m(t)_{average} = DC = \frac{1}{T}\int_T m(t)\,dt$.

P_{av} in $m(t) = \frac{1}{T}\int_T m^2(t)\,dt$.

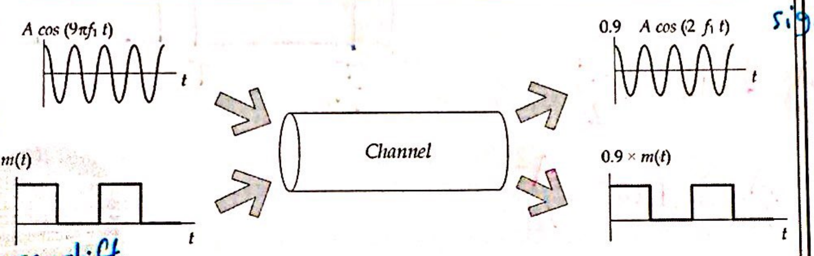
$rms = \sqrt{\frac{1}{T}\int_T m^2(t)\,dt}$

$rms = \sqrt{P_{av}}$

$rms^2 = P_{av}$

Channel Impairments

1. Attenuation: As the signal travels through the channel it loses some of its energy (*power*) as heat in the internal resistance of the channel. We say the signal is attenuated.



signal attenuated.

$A\cos(\underbrace{2\pi f_1}_{=\omega_1} t + \theta)$

amplitude. freq. (HZ) phase-shift. or angle. angular freq. (rad/sec).

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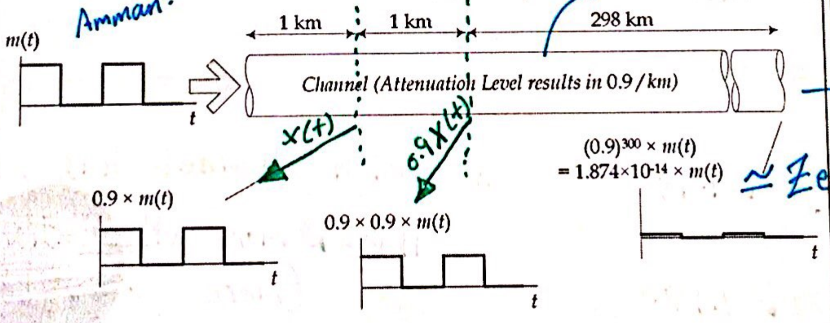
Attenuation

- Attenuation can be problematic for long distance communications (say cross-country).

each time multiply by 0.9. $(0.9)^{300}$

Amman.



Aqaba. → Vout(t) ?

≃ Zero.

Almost Nothing reach Aqaba. (Need solutions!)

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1Km.

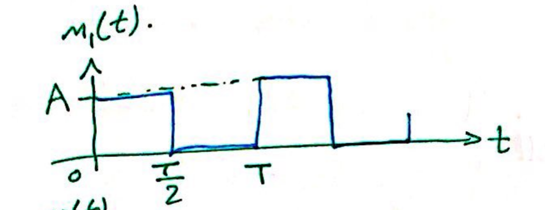
m(t). ch 0.9m(t) → unitless.

$dB = 10\log_{10}(\text{unitless})$

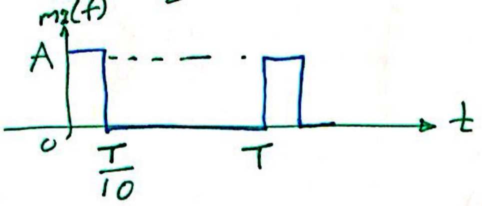
*

Home Work:

1) Find Pav & Average for:



2) Find Pav & Ave. for:



Answers:

1) $Av = \frac{A}{2}$ & $P_{av} = \frac{A^2}{2}$

2) $Av = \frac{A}{10}$ & $P_{av} = \frac{A^2}{10}$

**

1. Attenuation exists for all signal types.
2. " " " all channel types, But its level depends on the exact channel. used.
3. Attenuation Level increases as the channel length increases. (Why?) → Because R′ increases.

5V → (chA) → 4.9V

5V → (chB) → 4.1V.

* Which channel has more attenuation?

CH B → more attenuation.
(more power Loss).

* We care for the channel with less attenuation.

*
**
*memorize the following:

more expensive. ↓

wire Less
copper wires
coax cable
Waveguide & optical fiber.

↑ more Attenuation.

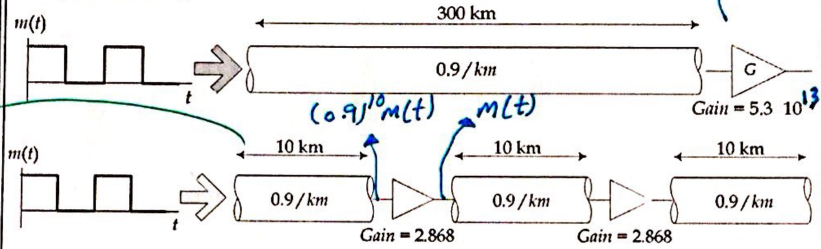
But should be used wisely.

Solutions to Attenuation

Voltage gain = $\frac{1}{(0.9)^{300}}$ $= 5.3 * 10^{13}$

(This will cause a large cost). ∞

(a) Use Amplifiers:



$(0.9)^{10} m(t)$

$m(t)$

gain = $\frac{1}{(0.9)^{10}}$

= 2.868.

(b) Use channels with smaller attenuation levels (e.g., optical fiber) – such channels are usually more expensive.

(c) Digital signals are less susceptible to attenuation (because of threshold detection at the receiver).

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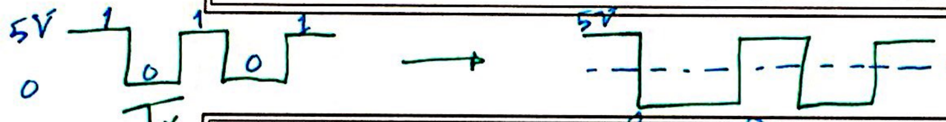


threshold = 2.5V.

Rx don't care for the 5V & 0V.

1 0 1 0 1 Rx

att.

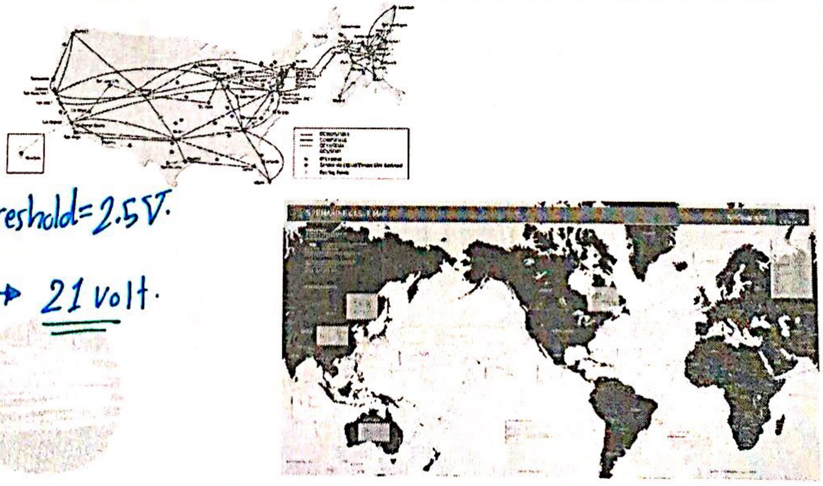
Rx

threshold = 2.5V.

0 16 8 4 2 1

1 0 1 0 1 → 21 volt.

Fiber Cables for Long Distance



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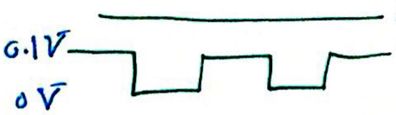
problem when use:



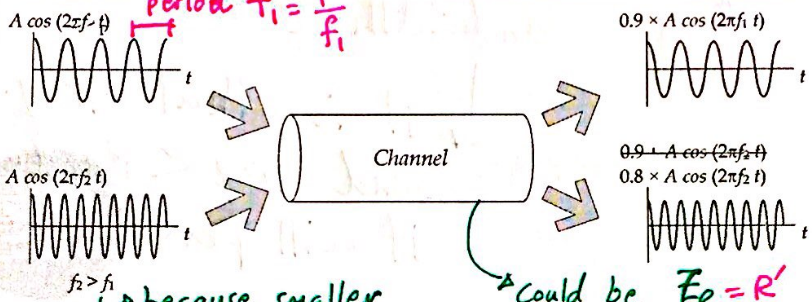
→ 0 0 0 0 0

* Memorize the following:

- For Copper wires you need an amplifier every 5-10Km.
- For Optical fiber you need an amplifier every 50-100Km.

Channel Impairments

2. Linear Distortion: The channel *attenuation* changes according to the transmitted signal *frequency*. Usually higher frequencies are attenuated more. Hence, the channel acts as a LPF that attenuates high frequencies, thus distorting the signal. We say the channel is a filter that has finite (limited) *channel bandwidth*.



period $T_1 = \frac{1}{f_1}$

↳ because smaller period.

could be $Z_R = R'$

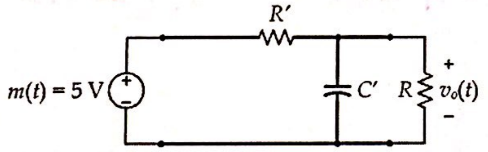
$Z_L = j\omega L$

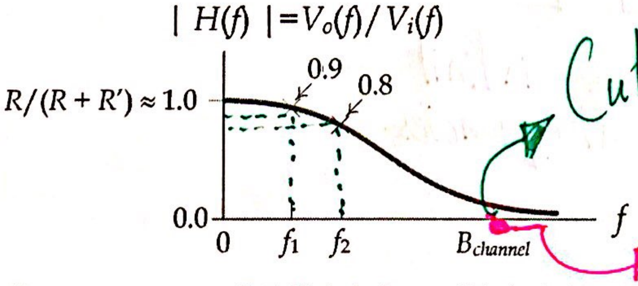
$Z_C = \frac{1}{j\omega C}$

Higher freq.

→ More attenuation.

Linear Distortion: Cause





Cutoff frequancy.

Bandwidth of the channel. B (always in HZ).

low freq ⇒ $Z_C \uparrow$ ⇒ open cct.

High freq ⇒ $Z_C \downarrow$ ⇒ short cct.

⇒ LPF.

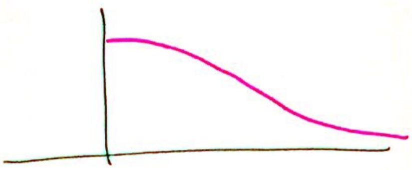
low freq ⇒ pass

High freq ⇒ Rejected.

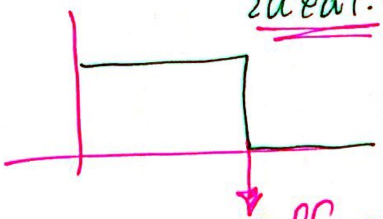
↳ The signal is attenuated. (all of it).

The previous curve called:

※ Attenuation Level:
or freq. Response function.
or freq. Transfer function.



ideal.



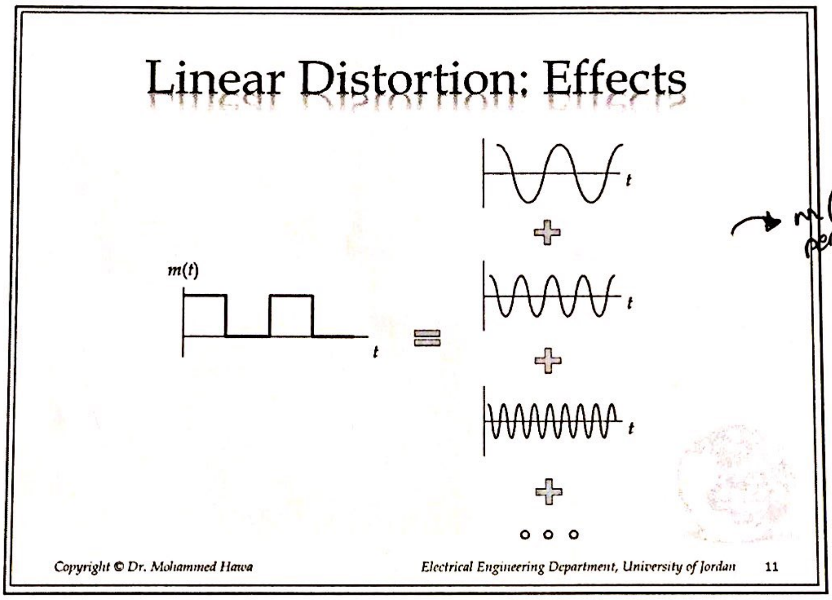
cutoff = Bandwidth. (memorize).

↳ it is that freq., when you send freq < Bandwidth it will pass, o.w reject.

* fourier: $\underset{\text{Periodic}}{m(t)} = \sum_{\infty} \text{Cosines.}$

$\cos(\omega_0 t)$ $\cos(2\omega_0 t)$ $\cos(3\omega_0 t)\ldots$

↳ has infinit frequancies.



Linear Distortion: Effects

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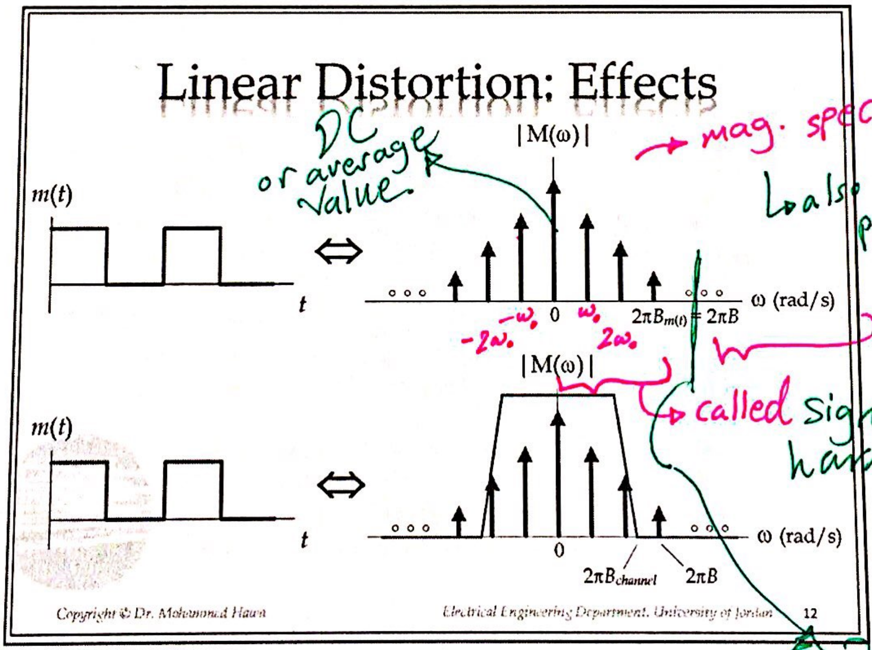
→ m(t) periodic $= \sum_{\infty}$ cosines



Linear Distortion: Effects

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DC or average value

→ mag. spectrum density.

↳ also there is phase spectrum density.

→ insignificant harmonics.

↳ called significant harmonics.

Bandwidth of the signal m(t) $= B = B_{m(t)}$

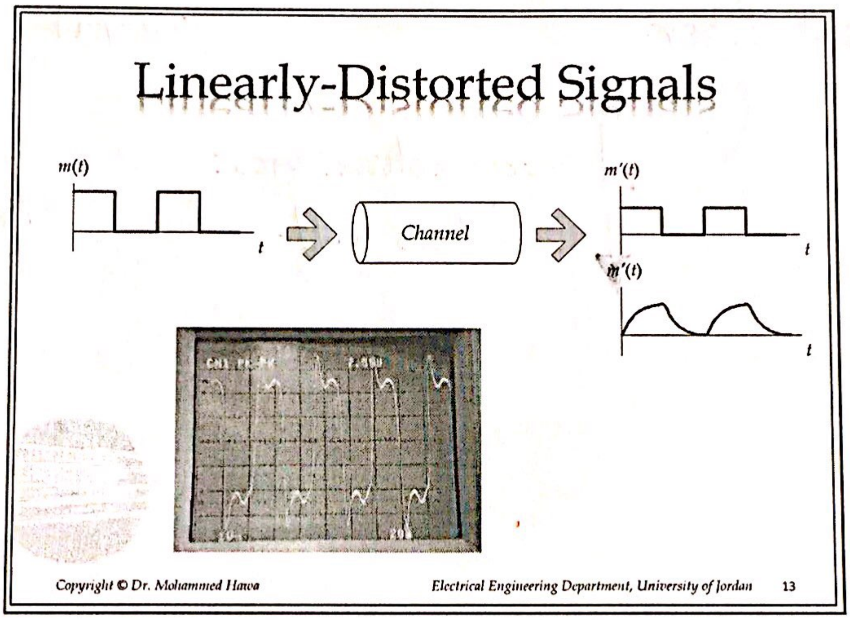
* if we remove one of the insig. signals (No big change).

* " " " . " " " sig. " (Big change).

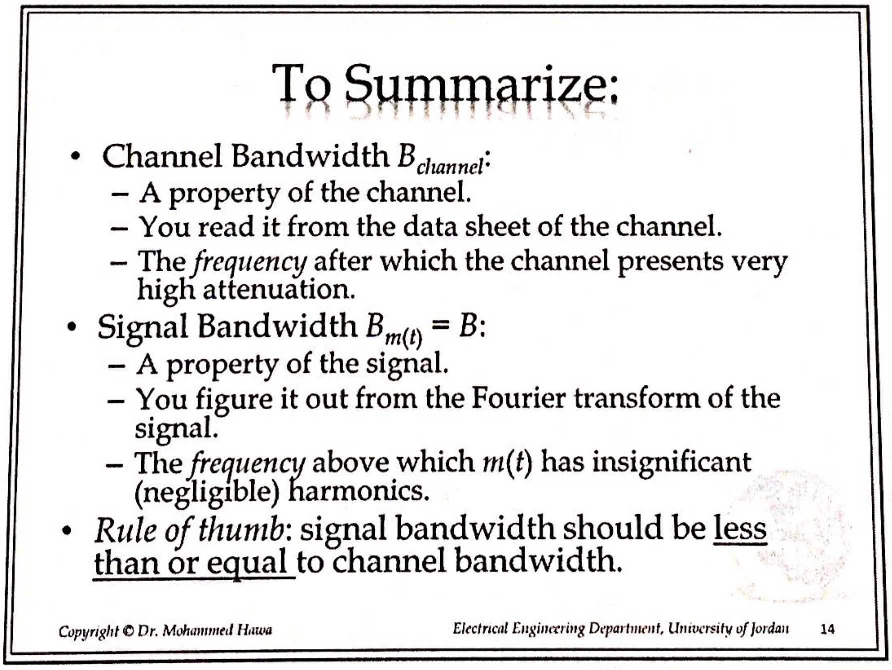
↳ Distortion.

Note that: there is bandwidth of the channel. $B_{channel}$.
// // // // // signal. $B_{m(t)}$.

optical fiber → BPF.



Linearly-Distorted Signals



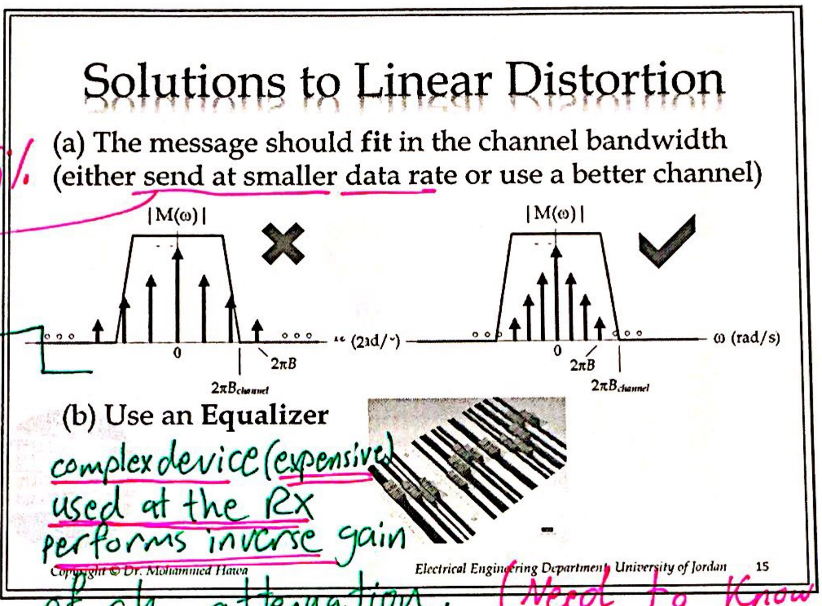
To Summarize:

- Channel Bandwidth $B_{channel}$:
  - A property of the channel.
  - You read it from the data sheet of the channel.
  - The *frequency* after which the channel presents very high attenuation.
- Signal Bandwidth $B_{m(t)} = B$:
  - A property of the signal.
  - You figure it out from the Fourier transform of the signal.
  - The *frequency* above which $m(t)$ has insignificant (negligible) harmonics.
- *Rule of thumb*: signal bandwidth should be less than or equal to channel bandwidth.

			Bandwidth of the channel.
• Copper wires	about	1Km	1-2 MHZ.
• Coax Cable.	〃	〃	1-2GHZ.
• Optical fiber.	〃	〃	several THZ.

more expensive.

Two advantages:
- less att. & - bigger $B_{channel}$.



Solutions to Linear Distortion

(a) The message should **fit** in the channel bandwidth (either send at smaller data rate or use a better channel)

(b) Use an **Equalizer**

complex device (expensive) used at the Rx performs inverse gain of ch. attenuation.

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15

95%

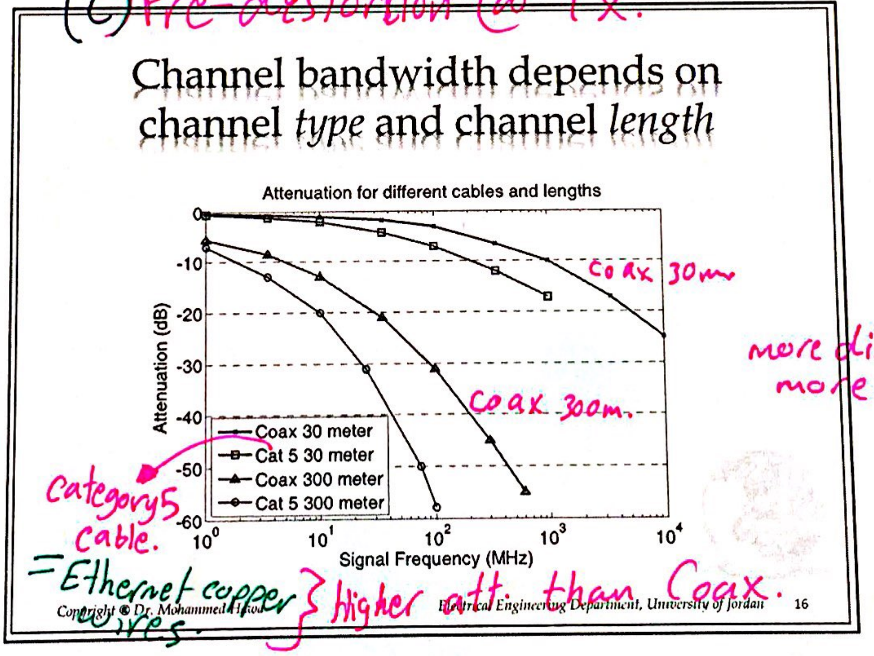
send

instead of

(Need to Know 4 things

memorize these).

(c) Pre-distortion @ Tx.



Channel bandwidth depends on channel *type* and channel *length*

category5 cable. = Ethernet copper wires. } Higher att. than Coax.

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16

more distance. more att.

$\frac{P_{out}}{P_{in}} < 1$

$10\log_{10}\left(\frac{P_{out}}{P_{in}}\right) < 1$ dB.

→ -ve

f↑ ⇒ more att. → Pout smaller → $\log_{10}$ more negative.

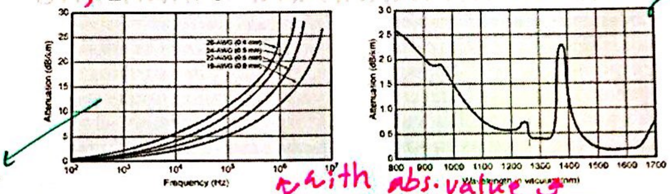
Higher att. → lower curve → Less $B_{channel}$.

* Attenuation, always negative dB.

Ex. what is Att of copper at 10^5 HZ?
-5 dB/Km.

Frequency Response (units of dB)

optical fiber.

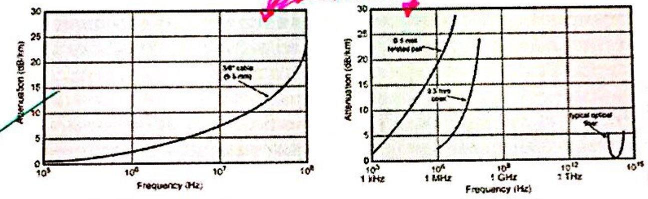


for copper.

(a) Twisted pair (based on [REEV95])

with abs. value ~~[illegible]~~

(c) Optical fiber (based on [FREE02])



for coaxial.

(b) Coaxial cable (based on [BELL90])

(d) Composite graph

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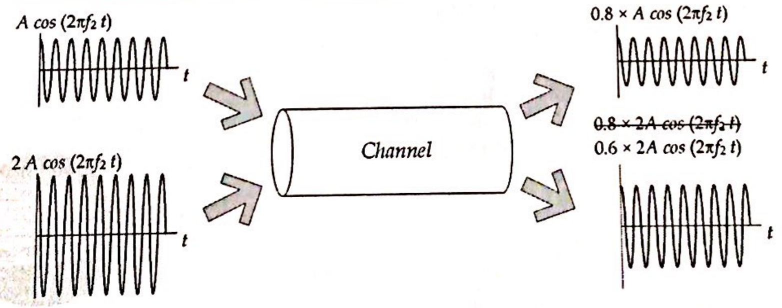
Channel Impairments

3. Non-Linear Distortion: The channel *attenuation* changes according to the transmitted signal *amplitude* and/or *phase*. Usually higher amplitudes are attenuated more. This causes distortion to the signal.



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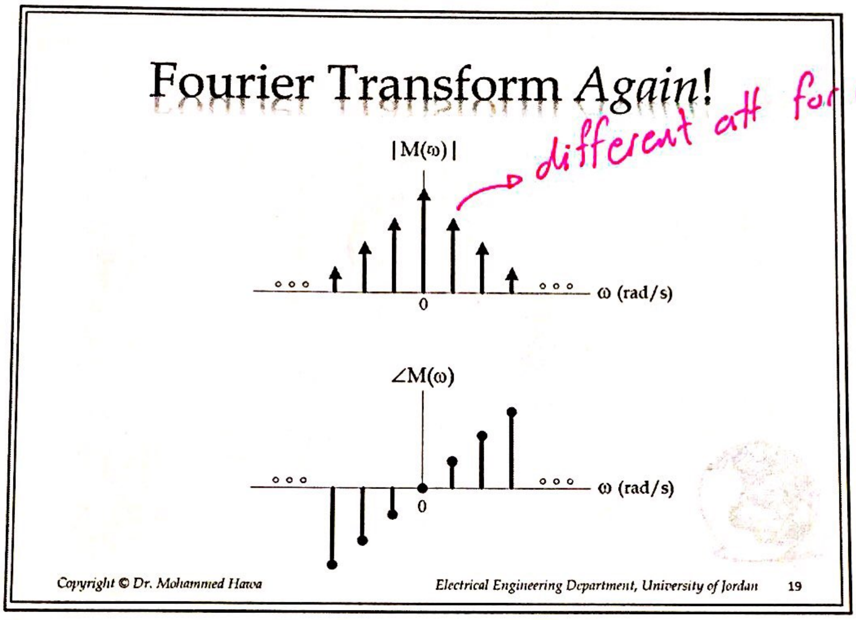
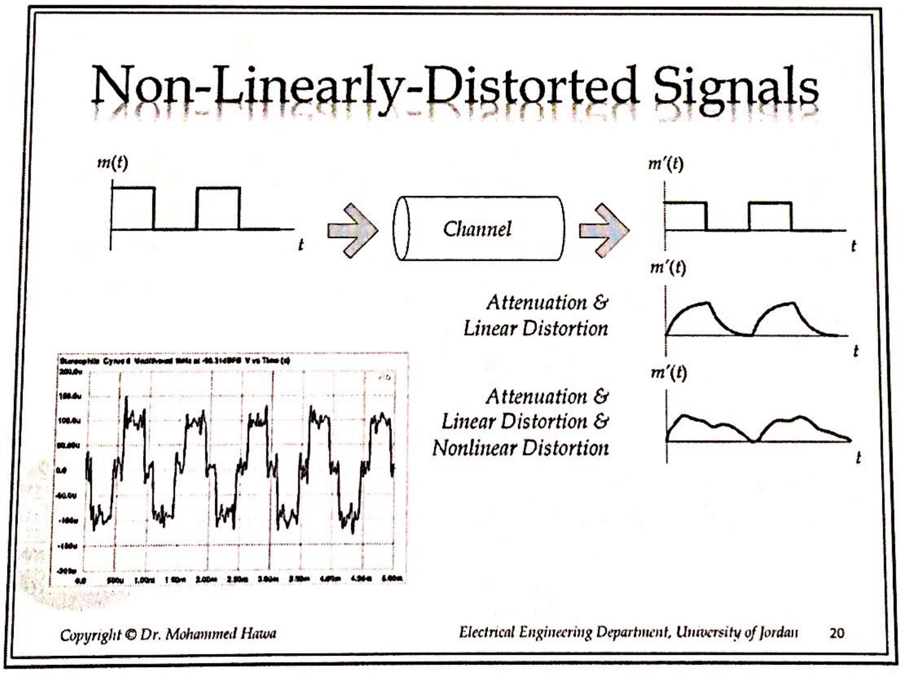
amp↑ => att↑ (depends on the physics of the channel).



Fourier Transform *Again*!

different att for each amp.



Non-Linearly-Distorted Signals

Distorted signals are not desired!

- Solutions to Non-Linear Distortion: Use an Equalizer.

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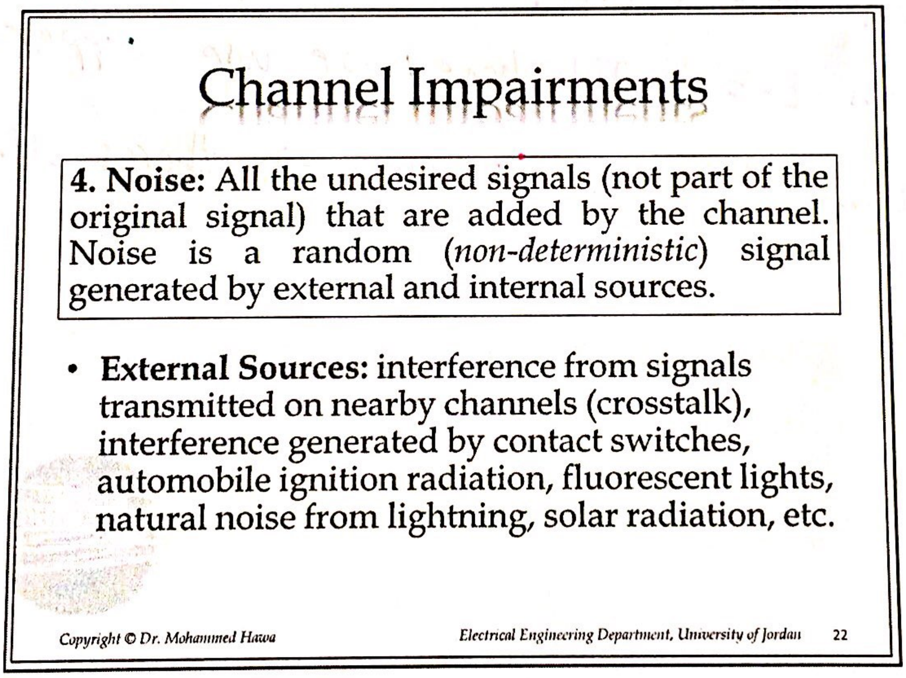

Channel Impairments

4. Noise: All the undesired signals (not part of the original signal) that are added by the channel. Noise is a random (*non-deterministic*) signal generated by external and internal sources.

- **External Sources:** interference from signals transmitted on nearby channels (crosstalk), interference generated by contact switches, automobile ignition radiation, fluorescent lights, natural noise from lightning, solar radiation, etc.

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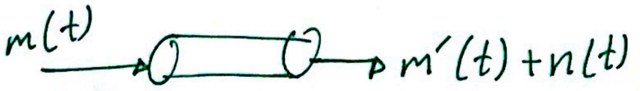


0.5V $\quad$ 0.3V − 0.2V = 0.1V

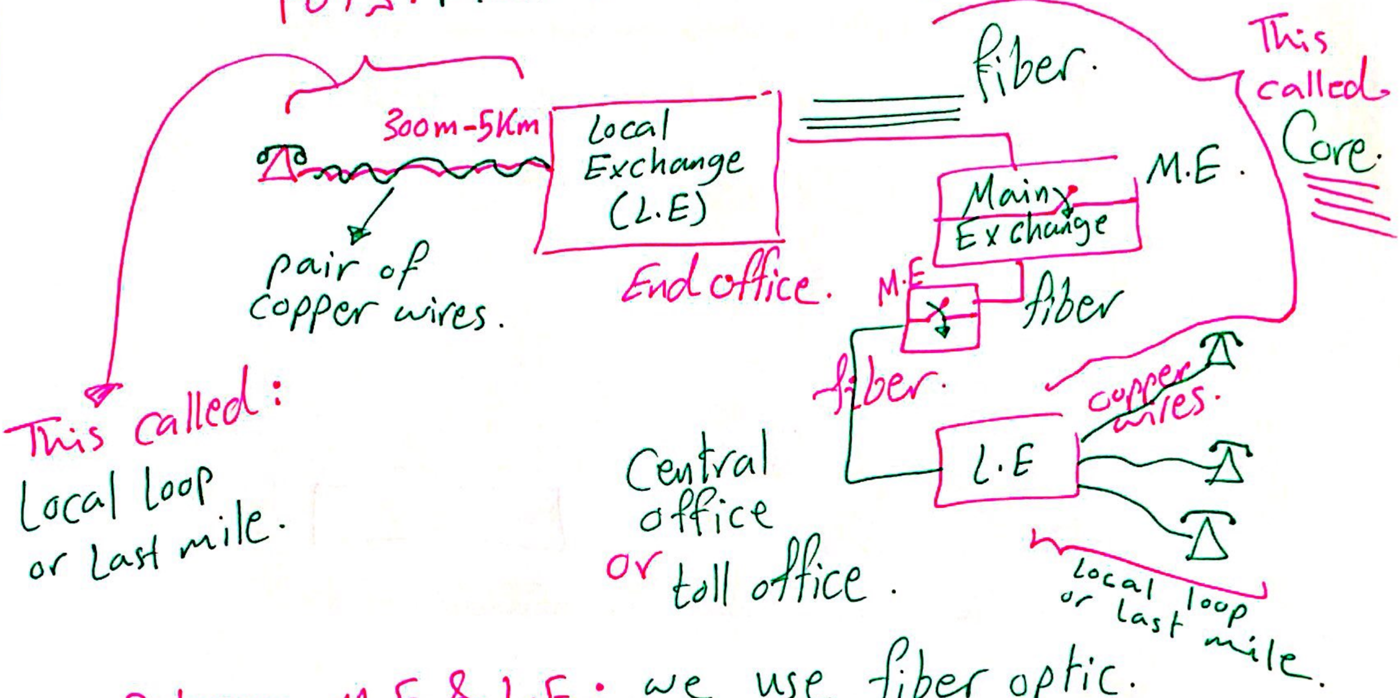
Non-deterministic.

0.5V $\quad$ 0.3V + 0.1V = 0.4V

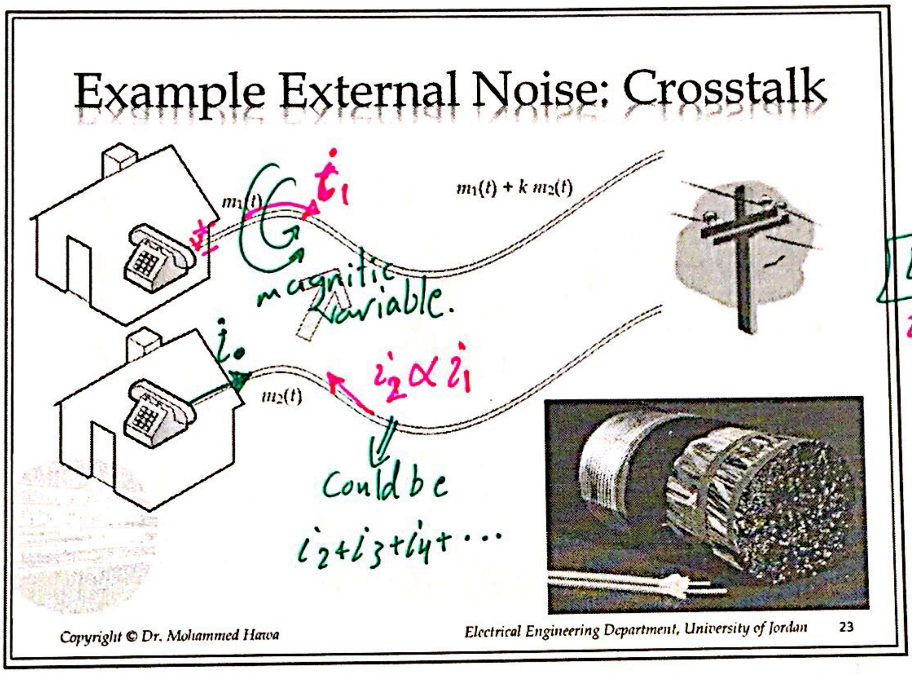
※ Landline telophony Systems:

↳ PSTN: Public switched Telephony Network.

POTS: Plain Old Telephony Service



- Between M.E & L.E: we use fiber optic.
- Between L-E & Telephone: we use copper.
- Between 2 Local Exchanges ⇒ theres M.E.



Example External Noise: Crosstalk

i_1

magnitic variable.

i_0

$i_2 \propto i_1$

Could be

$i_2+i_3+i_4+\dots$

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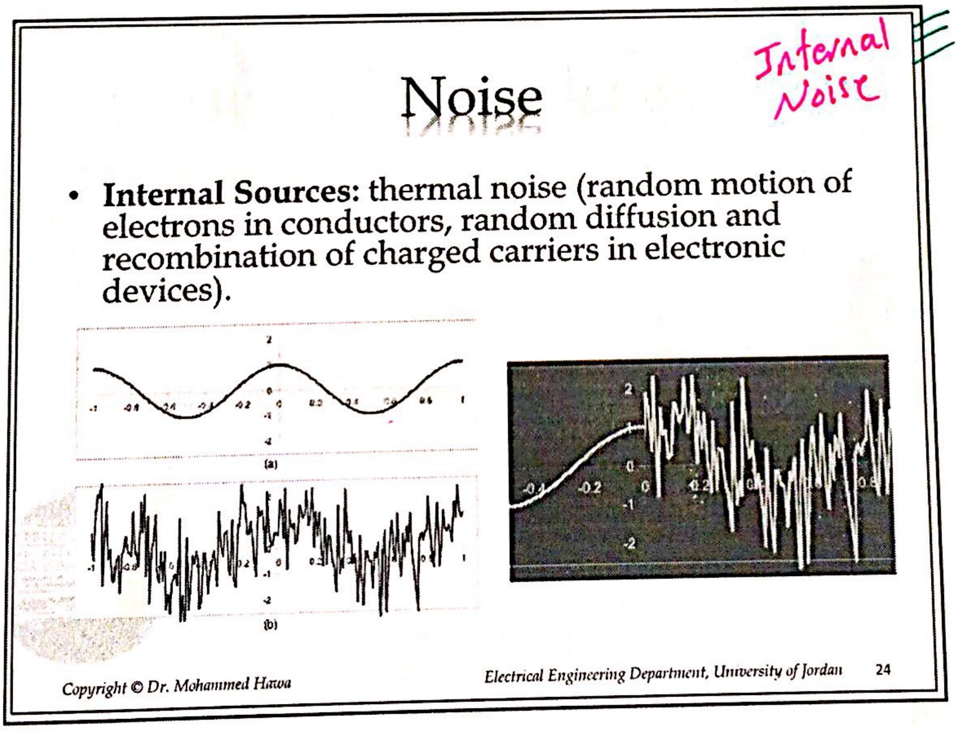
$\boxed{L.E}$

$i_0' + \underbrace{i_2+i_3+i_4}_{n(t).}$



Noise

Internal Noise ≡ Thermal Noise.

- **Internal Sources:** thermal noise (random motion of electrons in conductors, random diffusion and recombination of charged carriers in electronic devices).

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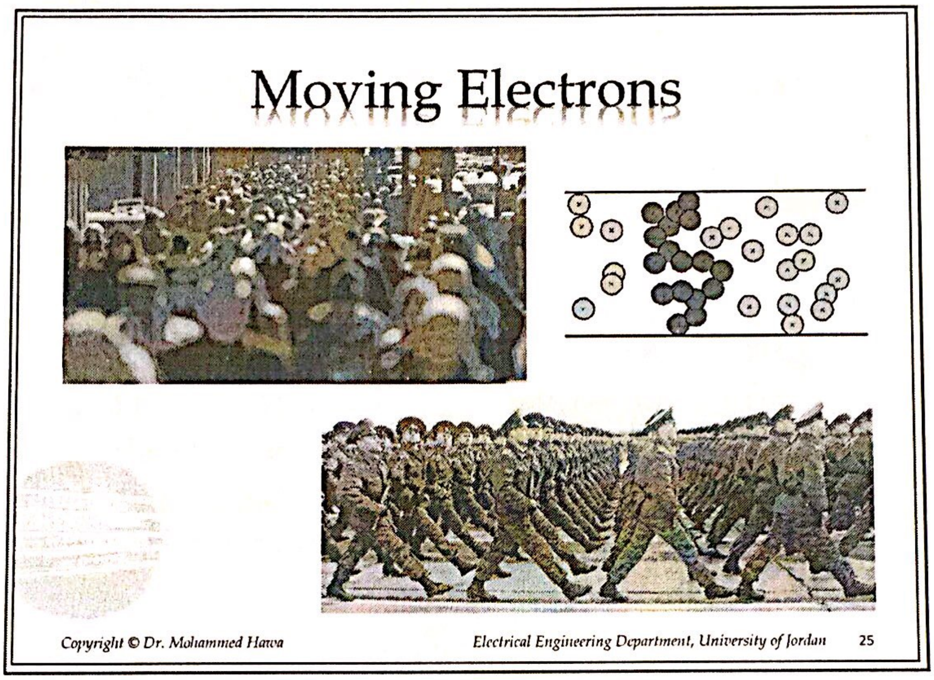
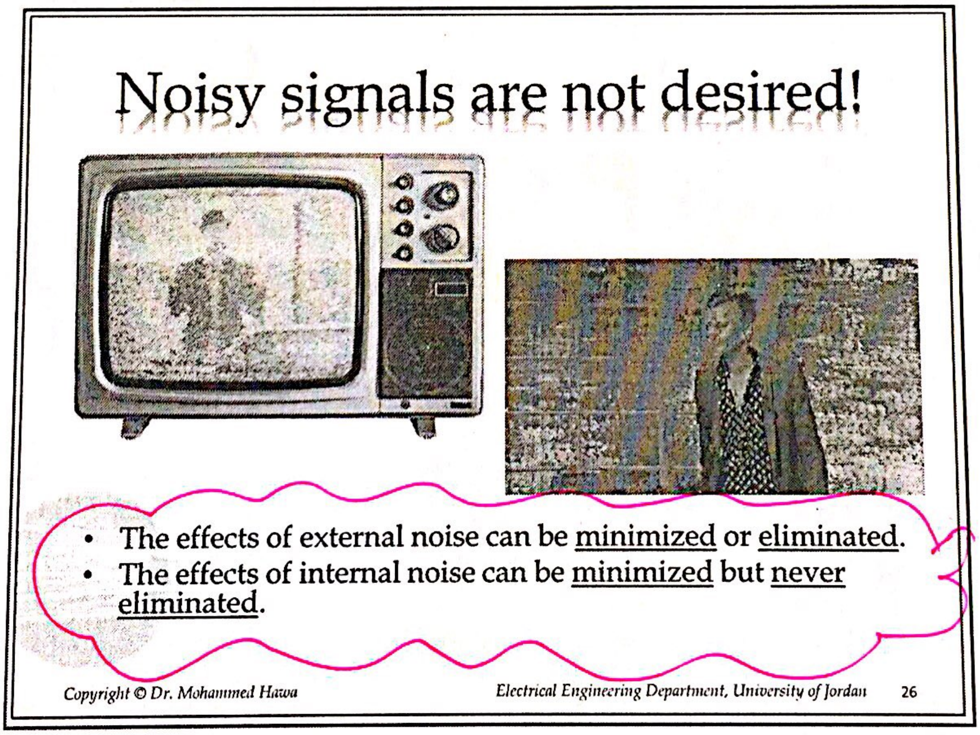


Moving Electrons

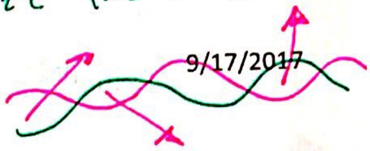


Noisy signals are not desired!

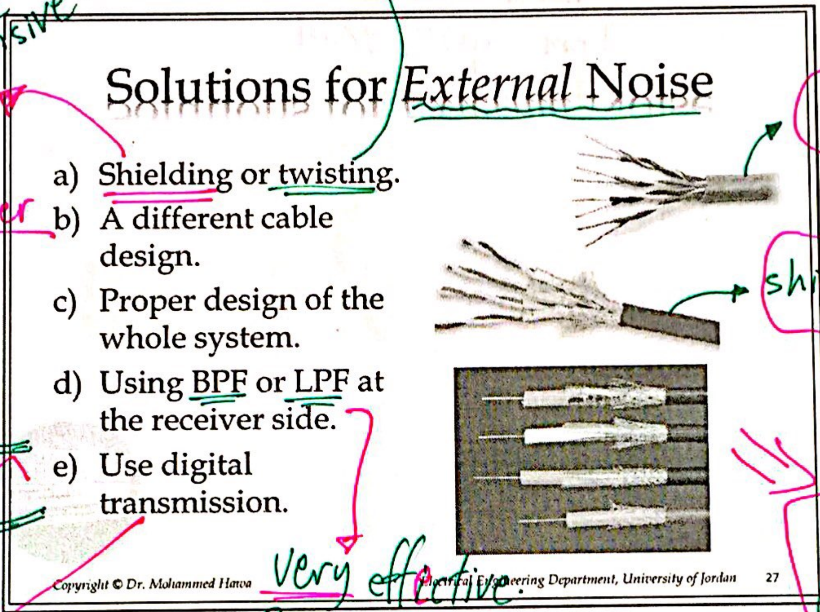
- The effects of external noise can be minimized or eliminated.
- The effects of internal noise can be minimized but never eliminated.

& cheap effective.

As more as you twisted as more as the vector changes & minimize the magnetic field



very effective But very expensive.



Solutions for *External* Noise

a) Shielding or twisting.
b) A different cable design.
c) Proper design of the whole system.
d) Using BPF or LPF at the receiver side.
e) Use digital transmission.

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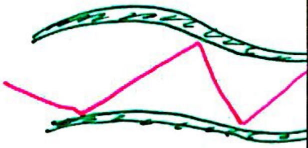
Unshielded Twisted pair UTP

shielded twisted pair STP.

coax & fiber

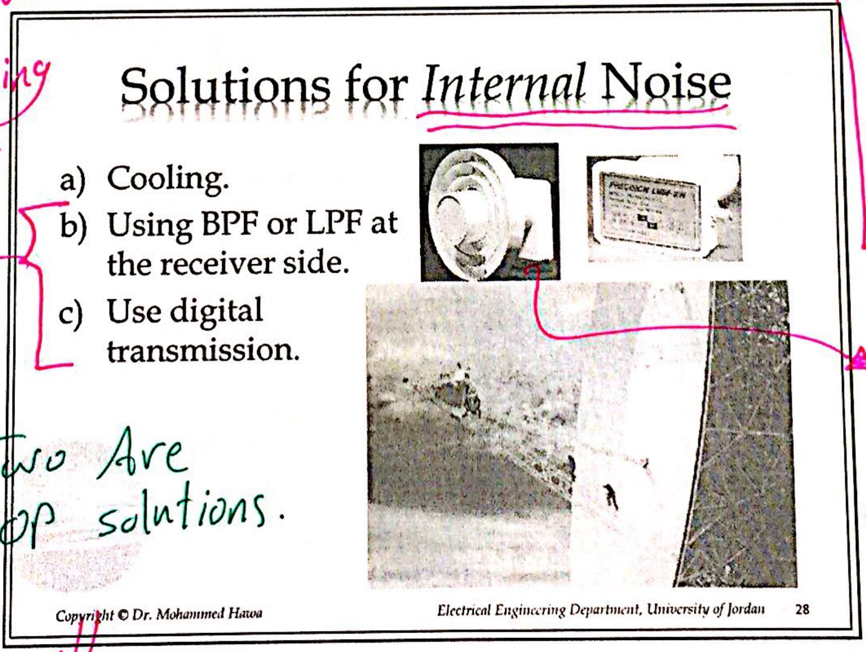
fiber optic



very effective. & very cheap.

very effective. & Becoming cheap.

(d) first solution
(e) second solution.
& others: depend on the costs & other things.



Solutions for *Internal* Noise

a) Cooling.
b) Using BPF or LPF at the receiver side.
c) Use digital transmission.

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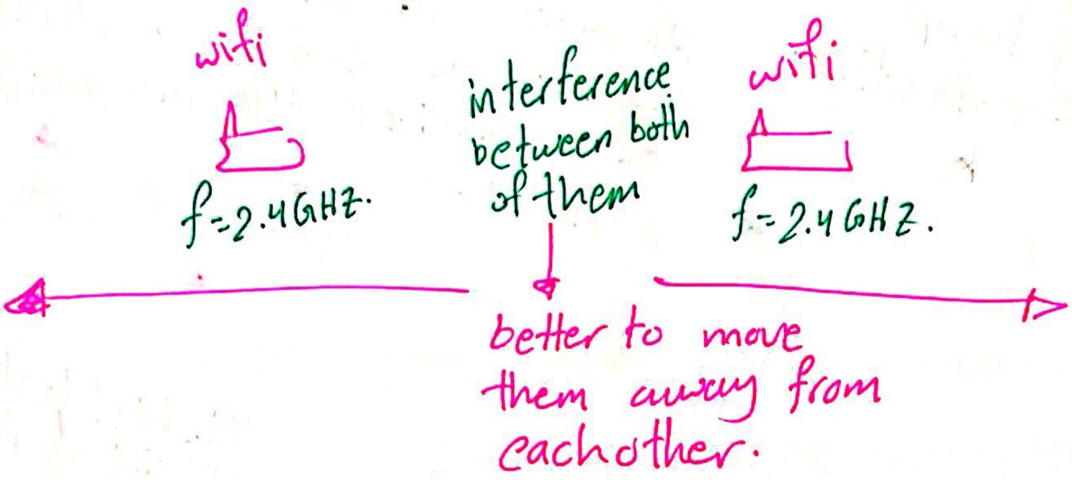
LNA: Low Noise Amplifier.

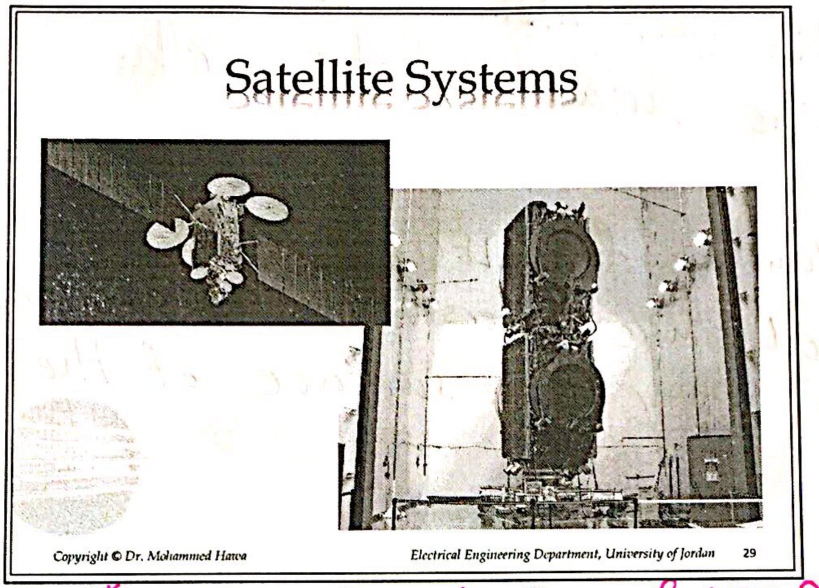
LNB: Low Noise Block.

These Two Are The Top solutions.

Cooling: very effective But very expensive

We need this solution (e.g satellites).


wifi
f=2.4GHZ.
interference between both of them
wifi
f=2.4GHZ.
better to move them away from eachother.

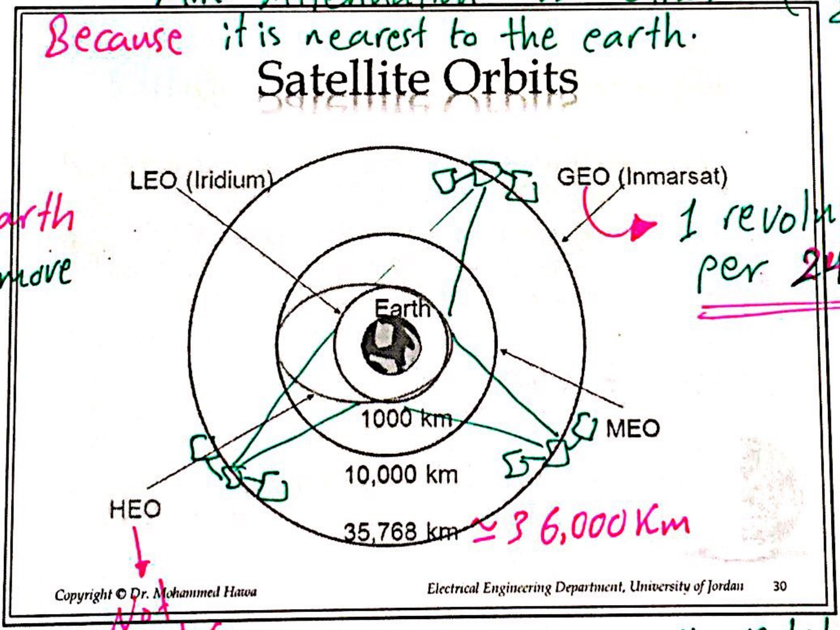


Satellite Systems

** What is the advantage of LEO?

Min. Attenuation vs. others. (min Att. & external noise)

Because it is nearest to the earth.



Satellite Orbits

* if you are closer to earth the satellites move faster.

→ 1 revolution per 24 hours.

≃ 36,000 Km

min. number of sattellites for GEO: 3

↓ Not popular.

memorize. ⇓

1000Km ← LEO: Low Earth Orbit.

10,000Km ← MEO: Medium Earth Orbit.

36,000Km ← GEO: Geostationary (Geosynchronon) Earth Orbit.

⟹

* Advantages of GEO:

1) Easier To install Rx.
2) Min # of satellites is $\underline{\underline{3}}$. to cover the surface of the earth.

* Disadvantage for LEO:

- Need more numbers of satellites than GEO To cover the surface of the earth.

* LEO: (Iridium), (Global Star), (ISS)

↓ international space station.

* MEO: (GPS), (GLONASS), (Gallelio).

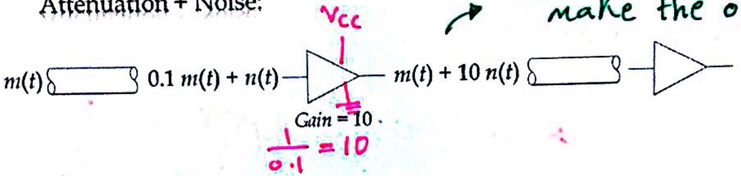
* GEO: (Inmarsat), (Thuraya), (TV Broadcasting)

→ (Nilesat, Badr, Hotbird).

...

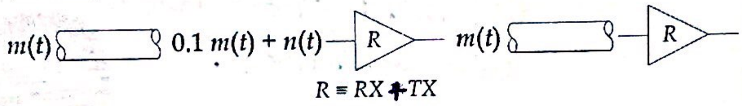
Impairments ALL Together

Attenuation + Noise:



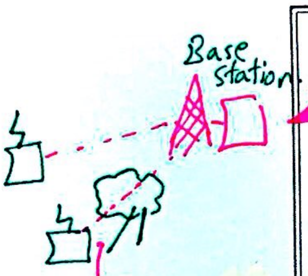
we solve one issue, but we make the other one much worse.

We need new solutions: *Regenrators* (Digital Transmission)



Memorize each one of them & for what specific wires. (channels).

Other Channel Impairments



more attenuation for this.

5. **Fading**: Variable attenuation with time of day and receiver location (wireless systems).
6. **Doppler Shift**: Shift in the frequency of the transmitted signal. Shows up when we have a wireless channel and fast moving objects.
7. **Frequency-reuse interference**: Shows up in wireless systems when we re-use the same frequencies at multiple nearby locations to increase system capacity.
8. **Chromatic Dispersion**: Specific to optical fiber channels.

e.g: (wireless). satellites & Airplanes.

Tx $\cos(\omega_1 t)$ → Rx

$\cos[(\omega_1+\Delta\omega)t]$

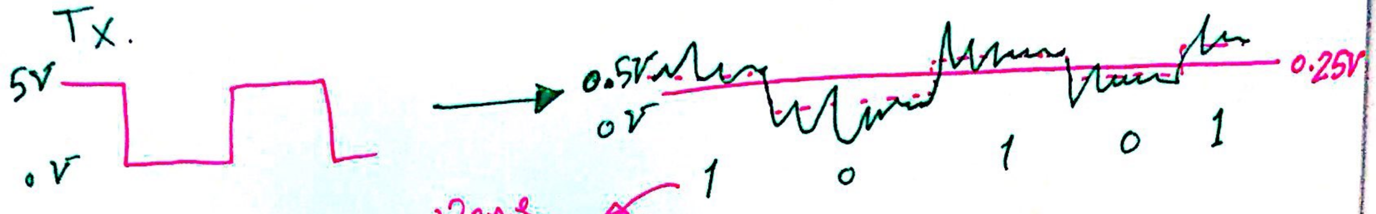
(just if you have movement)

we reuse To increase system Capacity

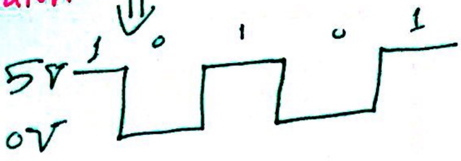
* If he asked about Impairments for fiber optic? it will be $\underline{\underline{5}}$ impairments.

& so on for others.

⇒ for wireless: $\underline{7}$ impairments. (Doppler just if there is movement).



Done By regenerator.



a Re-build happened for the signal.

↳ one of the problems: is that if a regen. do a mistake the next other regen. will do the same mistakes.

Disadvantage for Regen: It very Diffecult to Bulid (Need multiple Transistors) unlike the amplifier (Need one Transistor).

*Regen. : it is Transmitter & Receiver.

* The Range of the sent digital signal could be increased But as long as it increased it will face more Non-linear distortion.

remember the following: $\log_2(x) = \log_2 10 \, \log_{10}(x) \simeq 3.322 \log_{10}(x)$.

Shannon's Limit

finite Number.

$$C = \overset{\text{finite Number}}{B_{ch}} \times log_2(1 + SNR)$$

- C: Capacity of the channel in bits/second (bps)
- B_{ch}: Channel bandwidth (units of Hz)
- *SNR*: Signal-to-Noise Ratio (unitless)(*not dB*)

Capacity:
the maximum (bps) that you can send through the channel.

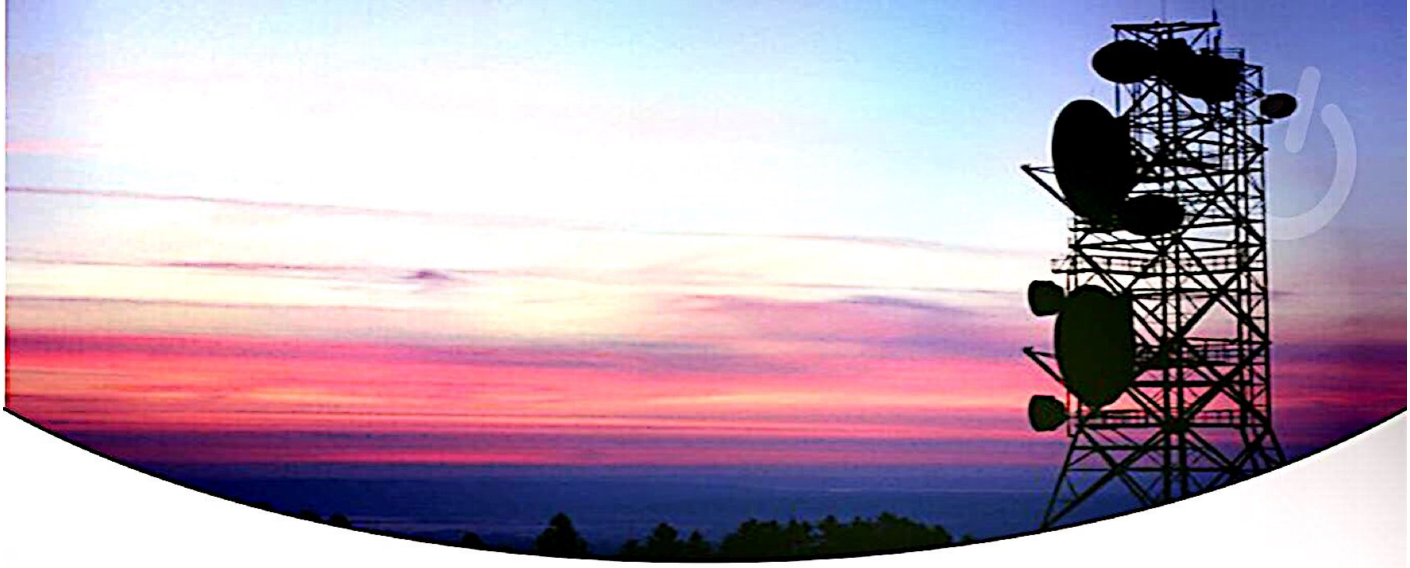
if $B_{ch}\downarrow \Rightarrow \Rightarrow C\downarrow$

$$SNR = \frac{\text{signal power}}{\text{noise power}}.$$

more att. ↑
↳ signal power ↓
↳ SNR ↓
↳ C ↓

also
More Noise power ↑ ⇒ SNR ↓ ⇒ C ↓

* if we were given that SNR = 30 dB
⇒ & we want to find C ⇒ You have to Convert dB to unitless.
SNR = 1000 unitless.



Communications1

Fall017

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Lecture 2: Classification of Communication Systems

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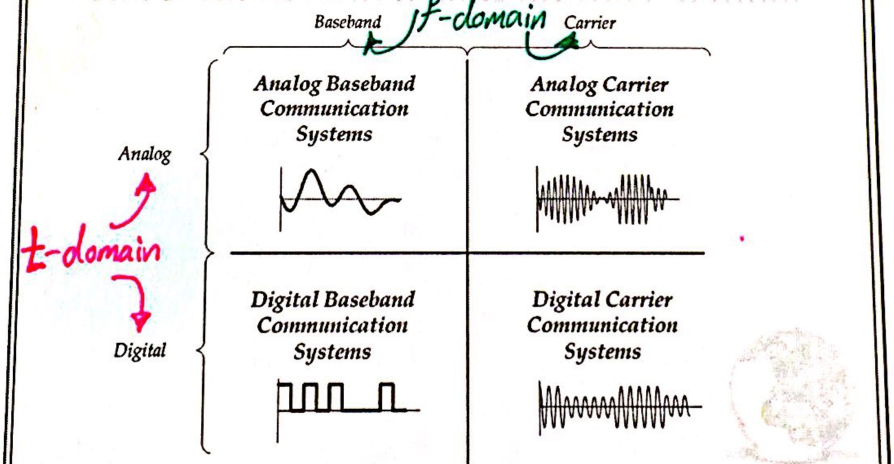
EE421: Communications I

Comm Systems are classified based on the type of signal sent on the Channel



Baseband ← f-domain → Carrier

t-domain ↑ Analog ↓ Digital

	Baseband	Carrier
Analog	*Analog Baseband Communication Systems*	*Analog Carrier Communication Systems*
Digital	*Digital Baseband Communication Systems*	*Digital Carrier Communication Systems*

Each system has its advantages!

Analog Baseband

- *Simplest* *system to build*
- ***Inexpensive***

Analog Carrier

- *Allows use of* ***Antennas***
- *Allows* ***Multiplexing*** *(FDM)*
- *Allows* ***exchanging*** *SNR for Bandwidth*

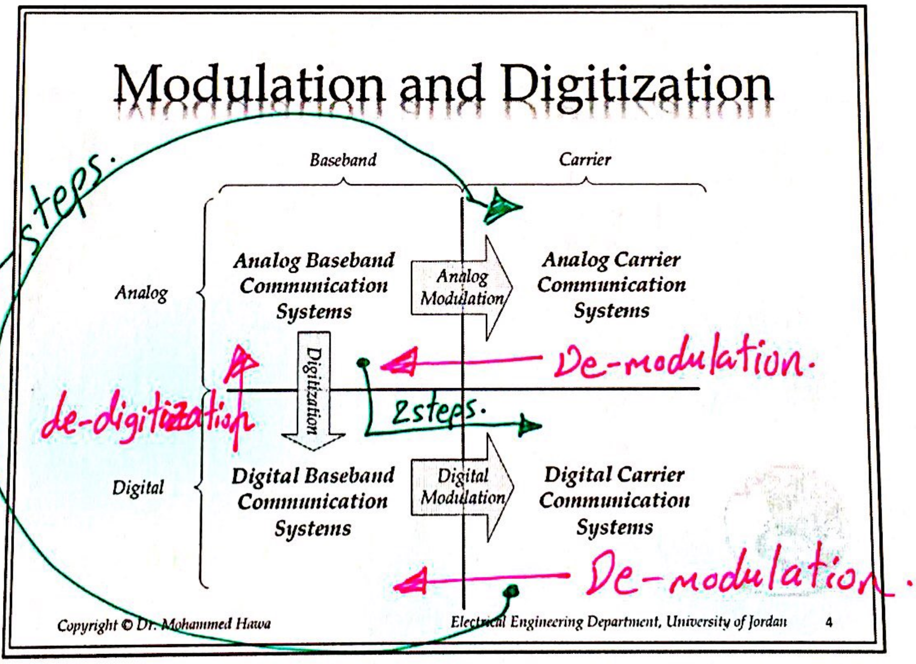
Digital Baseband

- *Immunity to* ***Noise***
- *Allows* ***Multiplexing*** *at baseband level (TDM)*
- *More bandwidth efficient*
- *Allows exchanging SNR for Bandwidth*
- *For more, see Handout*

Digital Carrier

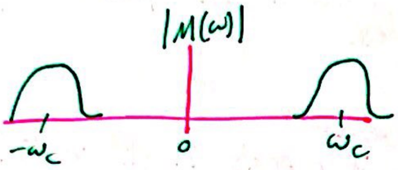
- *Allows use of* ***Antennas***
- *Allows* ***Multiplexing*** *(FDM)*
- *Allows exchanging SNR for Bandwidth*
- *Also the advantages of digital baseband*

Modulation and Digitization



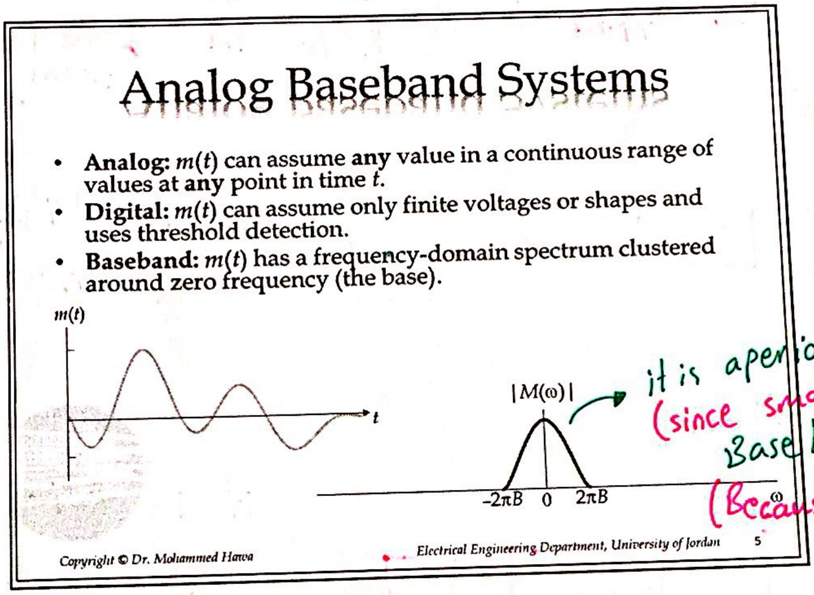
- Analog Modulation : the process that take you from Analog Baseband to Analog Carrier.
- De-Modulation : The Reverse process (Analog carrier to Analog Baseband).

$\mathcal{F}\{m(t)\} \Rightarrow M(\omega) <$ $|M(\omega)|$ mag. spectrum Density (PSD).
$\angle M(\omega)$ phase " " .



⇒ This is Carrier. (Because it is far away from 0).

9/17/2017



Analog Baseband Systems

- **Analog:** m(t) can assume **any** value in a continuous range of values at **any** point in time t.
- **Digital:** m(t) can assume only finite voltages or shapes and uses threshold detection.
- **Baseband:** m(t) has a frequency-domain spectrum clustered around zero frequency (the base).

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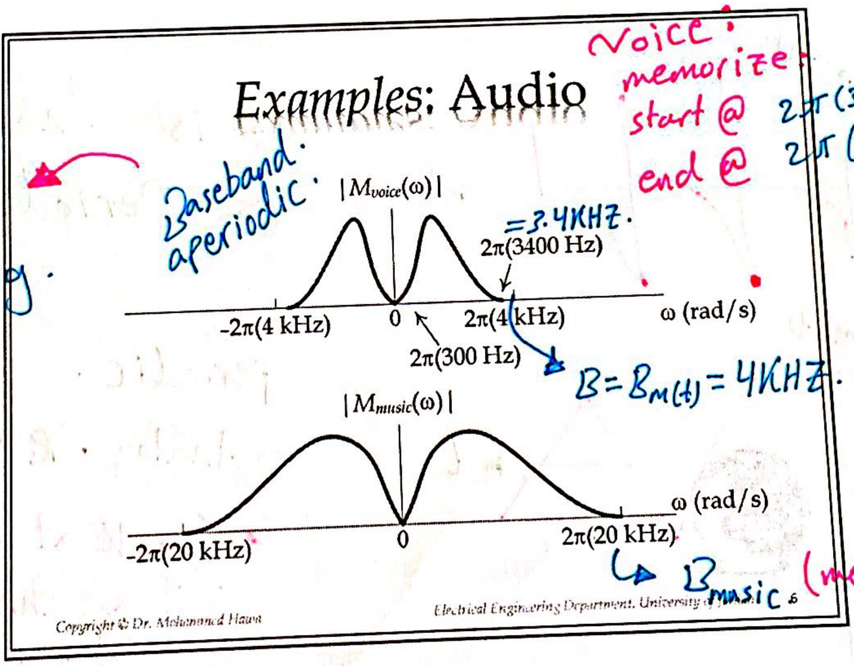
it is aperiodic (since smoothcurve).
Baseband (Because around 0)



Examples: Audio

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Voice: memorize:
start @ 2π(300Hz)
end @ 2π(3400Hz)

from $\mathcal{F}\{m(t)\}$ → Analog.

Baseband. aperiodic.

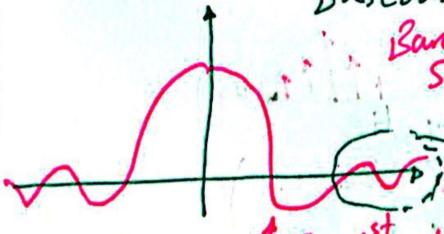
=3.4KHZ.

$B = B_{m(t)} = 4KHZ$.

→ B_{music} (memorize).

Ex.

Baseband & aperiodic
Bandwidth of the Signal ⇒ B = 1st null.



neglibible.

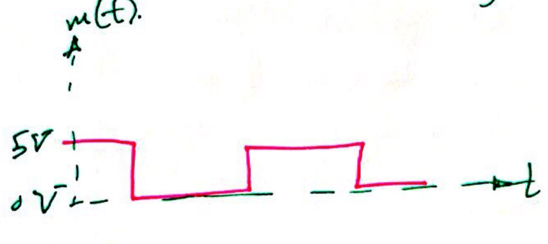
↑ B = 1st null.

* Analog vs. Digital t-domain (As shown in previous slides.)

* Baseband vs. Carrier f-domain.

* Periodic vs. aperiodic } t-domain → we know if repeats itself or NA.
f-domain. → we know from smooth curve → aperiodic
or impulses. → periodic.

Ex.1

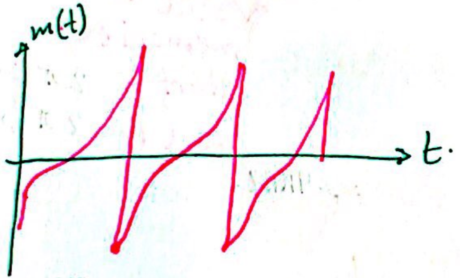


it is Digital.
& periodic.

Ex.2

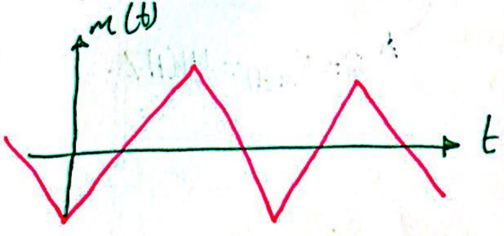
it is Digital
But aperiodic.

Ex.3



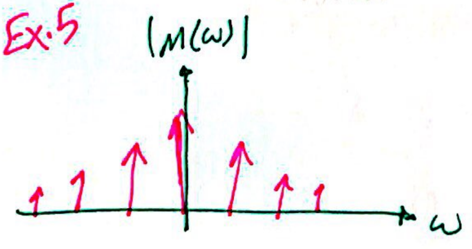
it is Analog
& periodic.

Ex.4



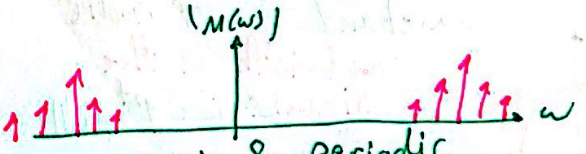
periodic.
⇒ Analog OR Digital
(Look at Rx threshold).
if it use threshold (Digital)
if Not, and reads voltages (Analog).

Ex.5



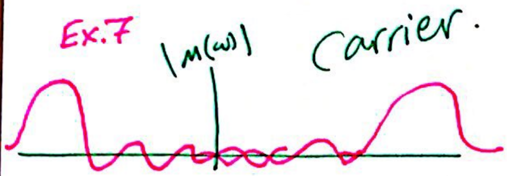
Baseband & periodic.

Ex.6



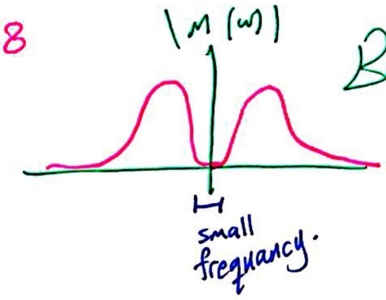
carrier & periodic
(can't tell analog or digital without $F^{-1}\{.\}$)

Ex.7



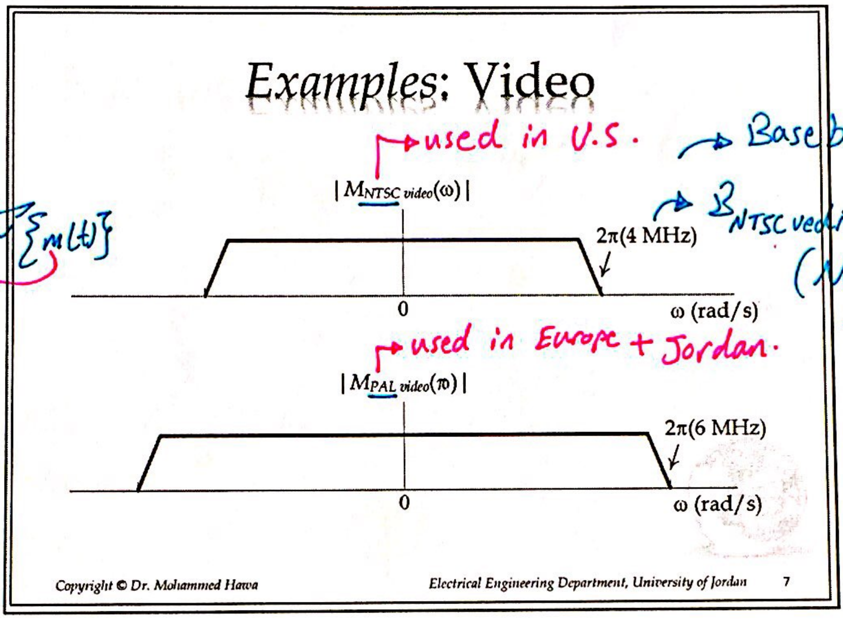
Carrier.

Ex.8



Baseband.

Examples: Video



used in U.S.

→ Baseband.

→ $B_{NTSC\ vedio}$.

(No DC here) since there is No impulse @ ω=0.

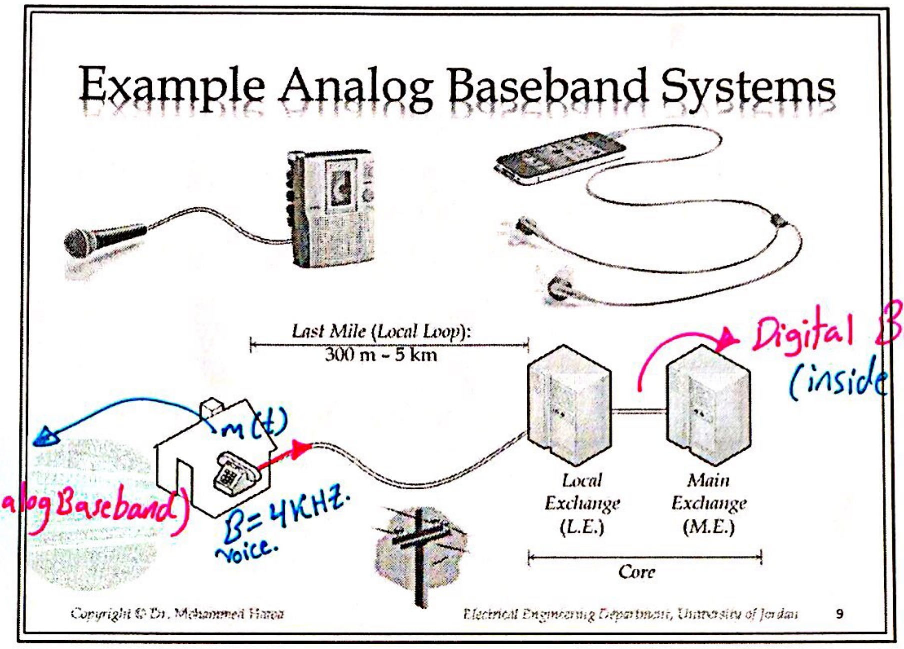
$\mathcal{F}\{m(t)\}$ → Analog.

used in Europe + Jordan.

Analog Baseband Systems

- An analog baseband system sends the analog baseband signal $m(t)$ as is (without any modifications).
- Advantages:
  - Simplest possible system.
  - Inexpensive to build.
- Usually used for short-distance communications.
- Examples of such systems in the next slide.

Example Analog Baseband Systems



m(t) = voice (Analog Baseband)

m(t)

B = 4KHZ.
voice.

Digital Baseband.
(inside the core).

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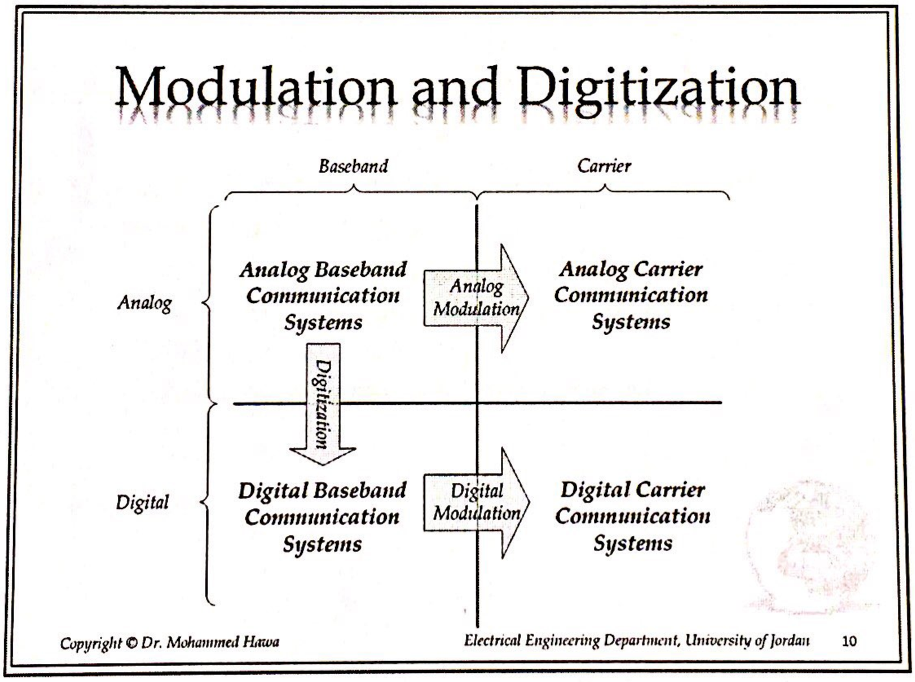
Modulation and Digitization



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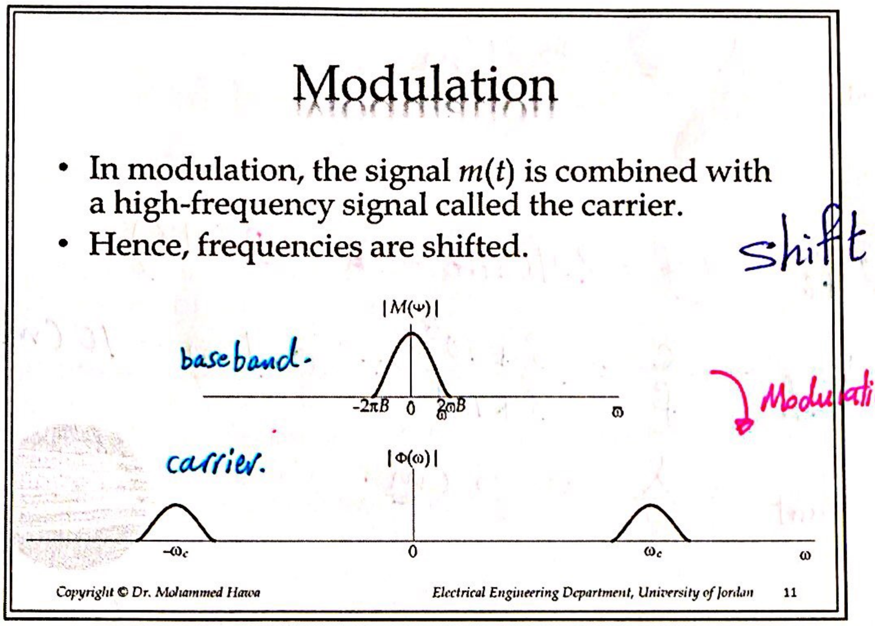

Modulation

- In modulation, the signal $m(t)$ is combined with a high-frequency signal called the carrier.
- Hence, frequencies are shifted.

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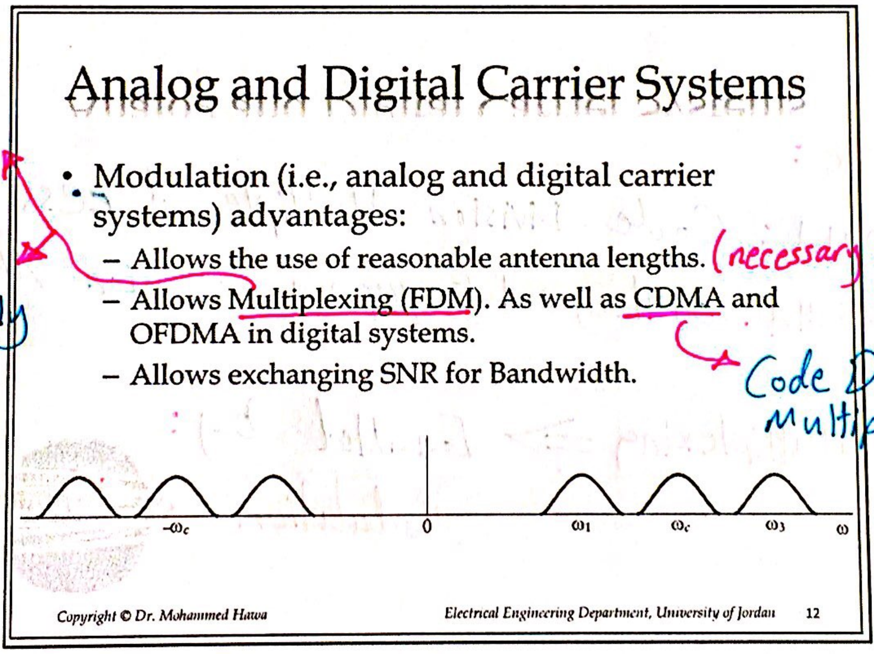
shift ≡ Modulation.

↓ Modulation. ↑ de-modulation.

FDM: Frequancy Division Multiplexing.

Multiplexing: sending multiple signals simultaneously over the same channel, without interference.

next page →



Analog and Digital Carrier Systems

- Modulation (i.e., analog and digital carrier systems) advantages:
  - Allows the use of reasonable antenna lengths. (necessary for wireless) channel.
  - Allows Multiplexing (FDM). As well as CDMA and OFDMA in digital systems.
  - Allows exchanging SNR for Bandwidth.

CDMA → Code Division Multiple Acess.

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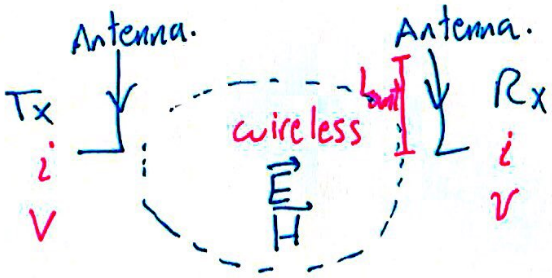


$$\boxed{L_{ant} = \frac{\lambda}{2}}$$

λ → wave length.

$$\boxed{\lambda = \frac{c}{f}}$$

c → speed of Light.

f → freq. of signal (HZ).

* human voice. (take a freq. = 3000 HZ).
for easier calculations.

$$\lambda_{voice} = \frac{c}{f} = \frac{300{,}000\ Km/s}{3000\ HZ} = \underline{\underline{100\ Km}}.$$

$$L_{ant} = \frac{\lambda}{2} = \underline{\underline{50 Km}}.$$

* Wifi ($f = 2.4 GHZ \rightarrow \sim 3 GHZ$)

$$\lambda_{wifi} = \frac{c}{f} = \frac{3*10^8}{3*10^9} = 0.1\ m = \underline{\underline{10\ Cm}}.$$

$$L_{ant} = \frac{\lambda}{2} = \underline{\underline{5\ Cm}}.$$

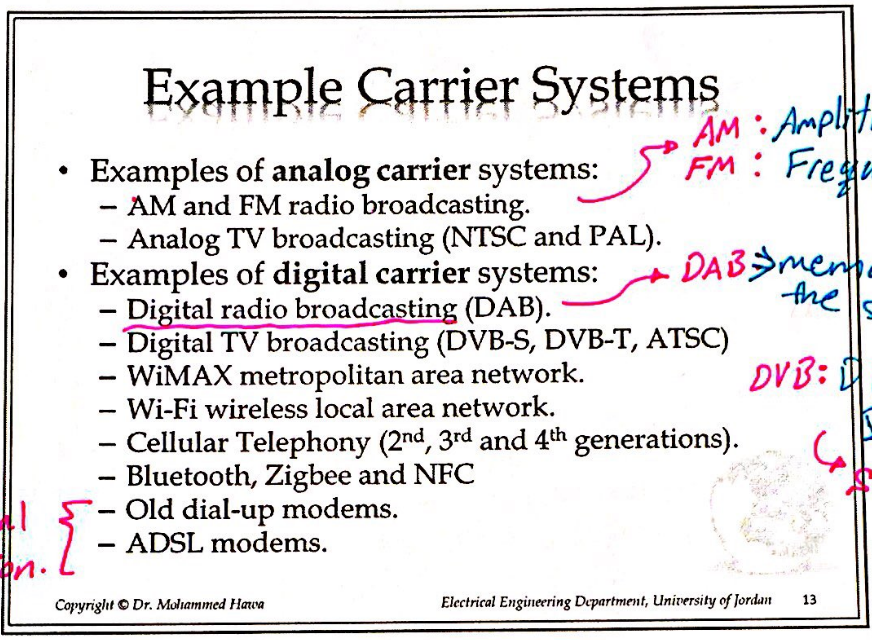
*** We can't do Wireless Without Antenna.

memorize:

CDMA: Code Division Multiple Access.
OFDMA: orthogonal Frequancy Division Multiple Access.

For Multiplexing ⇒ Enabled by:
Modulation & Digitization.

* always Wireless. use modulation.



Example Carrier Systems

- Examples of **analog carrier** systems:
  - AM and FM radio broadcasting.
  - Analog TV broadcasting (NTSC and PAL).
- Examples of **digital carrier** systems:
  - Digital radio broadcasting (DAB).
  - Digital TV broadcasting (DVB-S, DVB-T, ATSC)
  - WiMAX metropolitan area network.
  - Wi-Fi wireless local area network.
  - Cellular Telephony (2nd, 3rd and 4th generations).
  - Bluetooth, Zigbee and NFC
  - Old dial-up modems.
  - ADSL modems.

AM : Amplitude Modulation.
FM : Frequancy // .

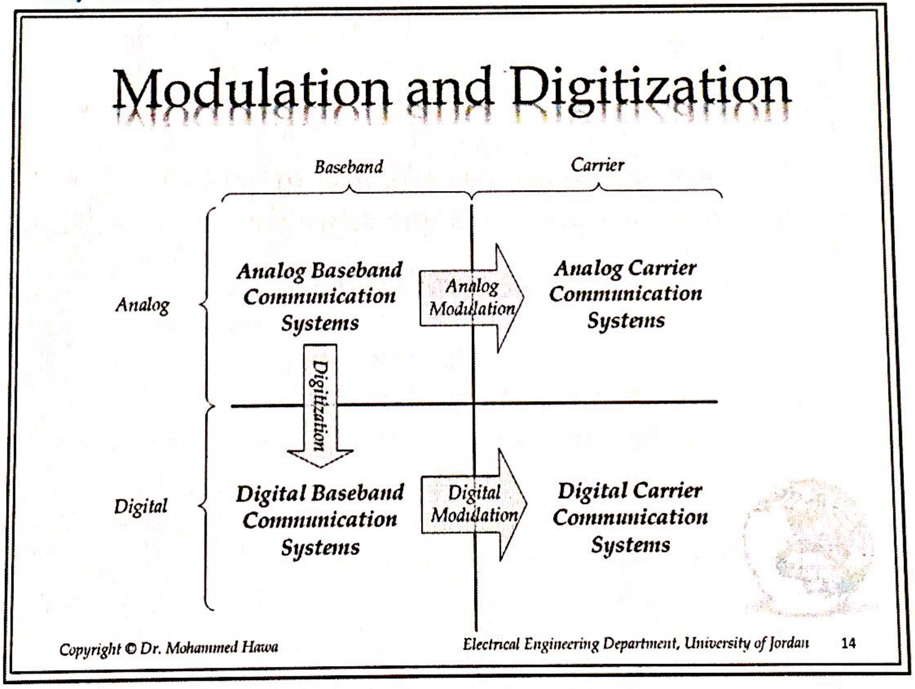
DAB ⇒ memorize the shortcut.

DVB: Digital Vedio Broad casting
S- for satellites.

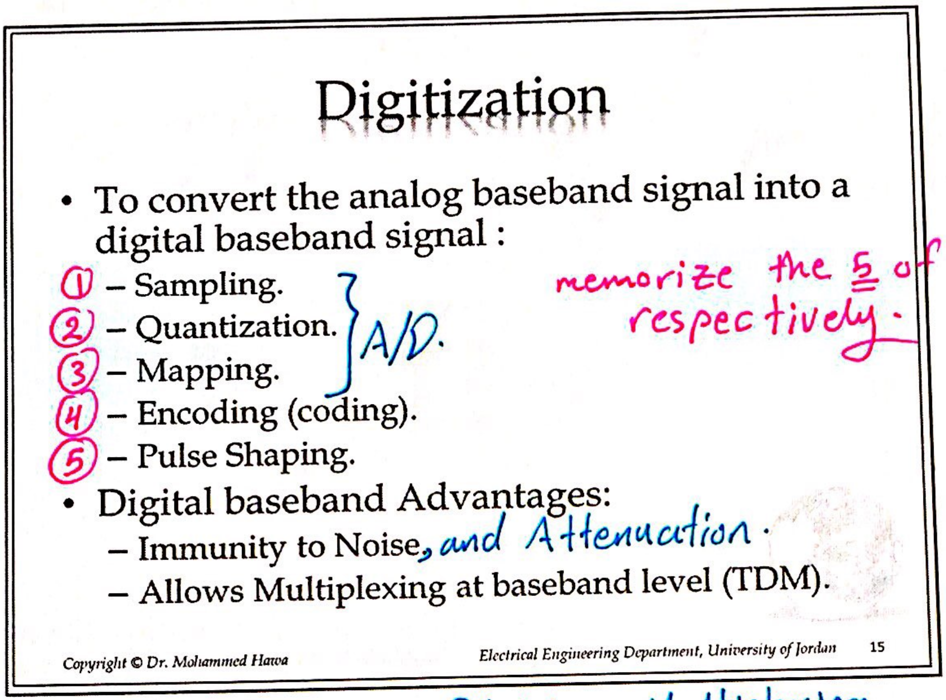
Not wireless. (wired).

digital modulation.

e.g. connecting modem with the Telephone.



Modulation and Digitization



Digitization

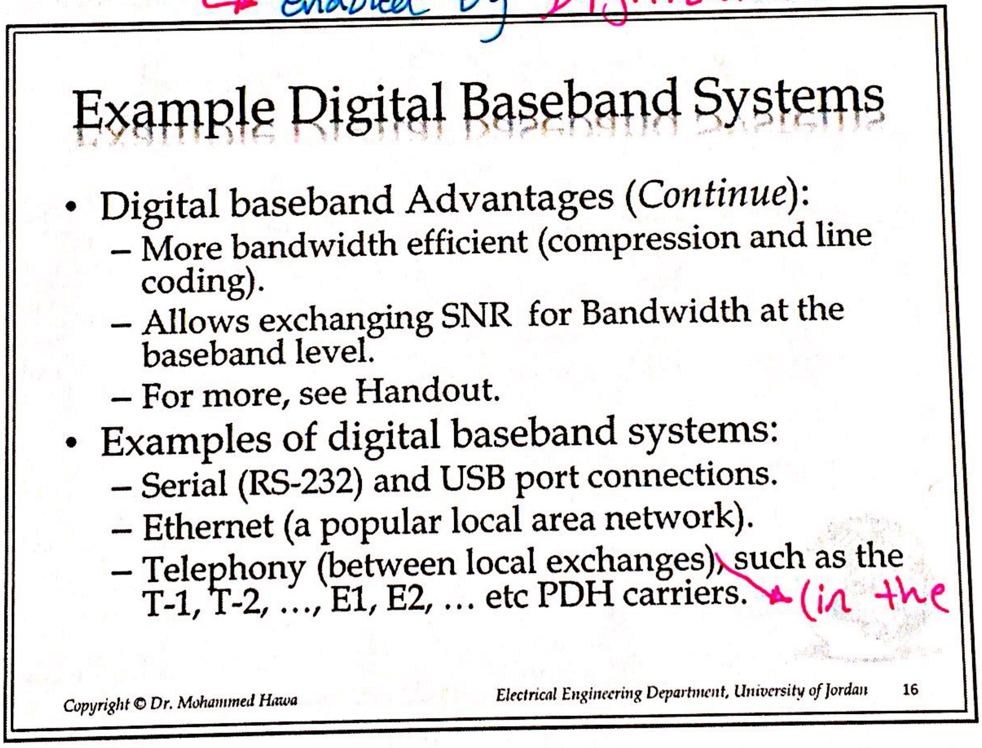
- To convert the analog baseband signal into a digital baseband signal :
  ① – Sampling.
  ② – Quantization.
  ③ – Mapping.
  ④ – Encoding (coding).
  ⑤ – Pulse Shaping.

} A/D.

memorize the 5 of them respectively.

- Digital baseband Advantages:
  - Immunity to Noise, and Attenuation.
  - Allows Multiplexing at baseband level (TDM).

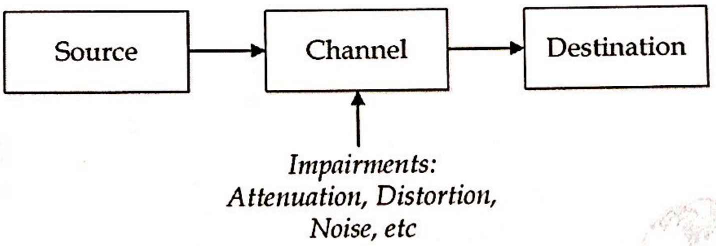
TDM: Time Division Multiplexing.
↳ enabled by Digitization.



Example Digital Baseband Systems

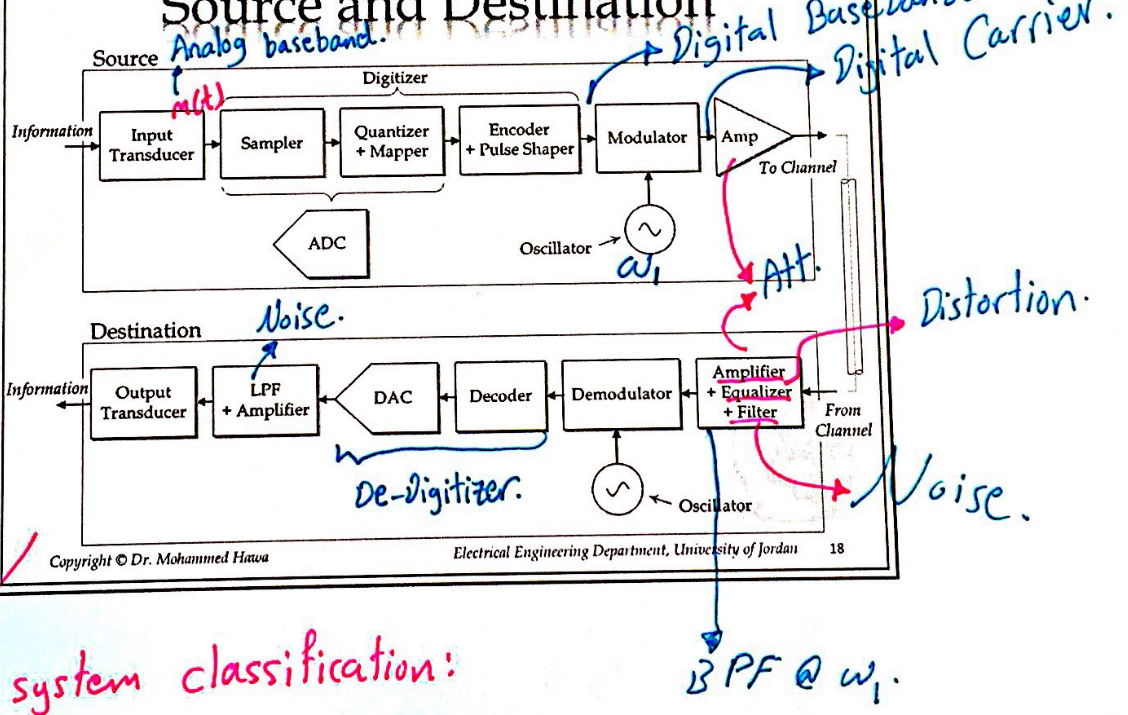
- Digital baseband Advantages (*Continue*):
  - More bandwidth efficient (compression and line coding).
  - Allows exchanging SNR for Bandwidth at the baseband level.
  - For more, see Handout.
- Examples of digital baseband systems:
  - Serial (RS-232) and USB port connections.
  - Ethernet (a popular local area network).
  - Telephony (between local exchanges), (in the core). such as the T-1, T-2, …, E1, E2, … etc PDH carriers.

Block Diagram of a Communication System



Impairments:
Attenuation, Distortion,
Noise, etc

Source and Destination

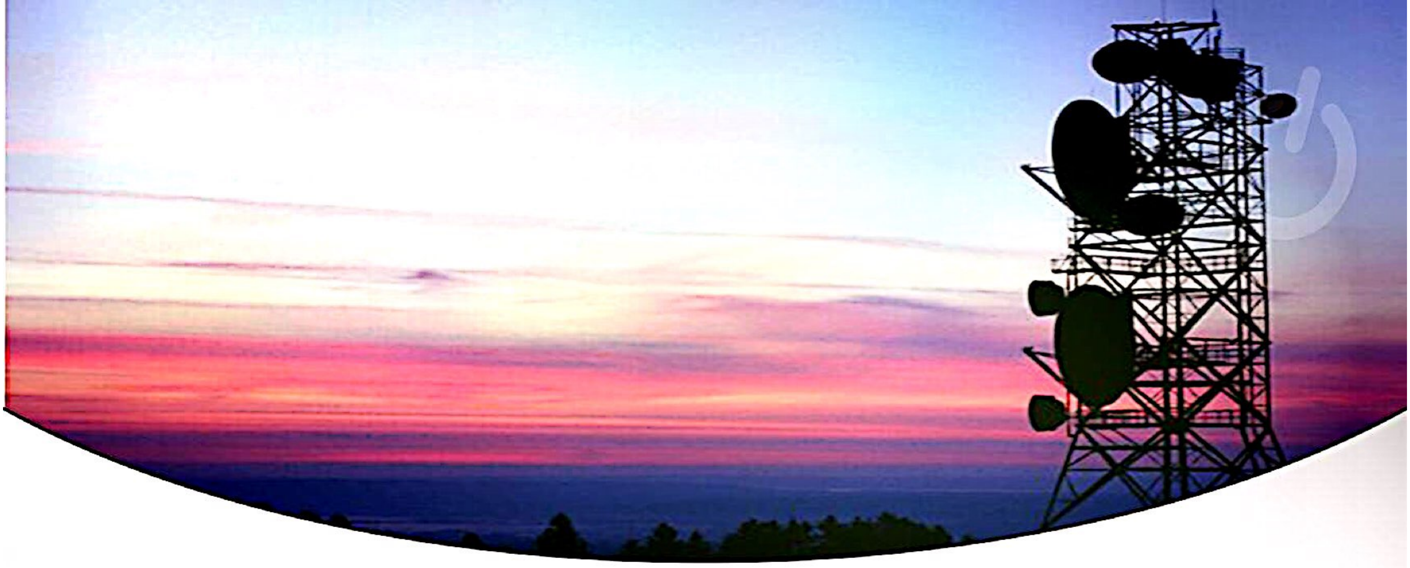


This system classification:

Digital Carrier. (since it sent by the channel).
→(digital).

→ To Make it Digital Baseband (remove Modu. & De-modu.)

→ To make it Analog Baseband (" " " also Digitizer & De-Dig.)



Communications1

Fall017

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Lecture 3: Review of Signal Analysis Basics

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Exponential vs. Compact

complex exponential form :

↳ $$x(t) = \sum_{n=-\infty}^{\infty} \alpha_n \cdot e^{jn\omega_0 t}, \quad \omega_0 = \frac{2\pi}{T}$$

↳ complex exp. fourier series Coefficient.

$$x(t) = \frac{c_0}{2} + \sum_{n=1}^{\infty} c_n \cos(n\omega_0 t - \theta_n), \quad \omega_0 = \frac{2\pi}{T}$$

Memorize :

$\omega_0 \equiv$ Fundemental Frequancy. $= \frac{2\pi}{T} \neq 2\pi *$ Bandwidth of $m(t)$ $= 2\pi B$

※ Fourier: • fourier Series → $\underset{\text{periodic}}{x(t)} = \sum_{\infty}$ Cosines.

Need to describe three things:

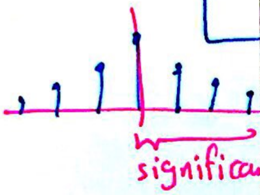
- Amplitude.
- Frequancy.
- Phase shift.

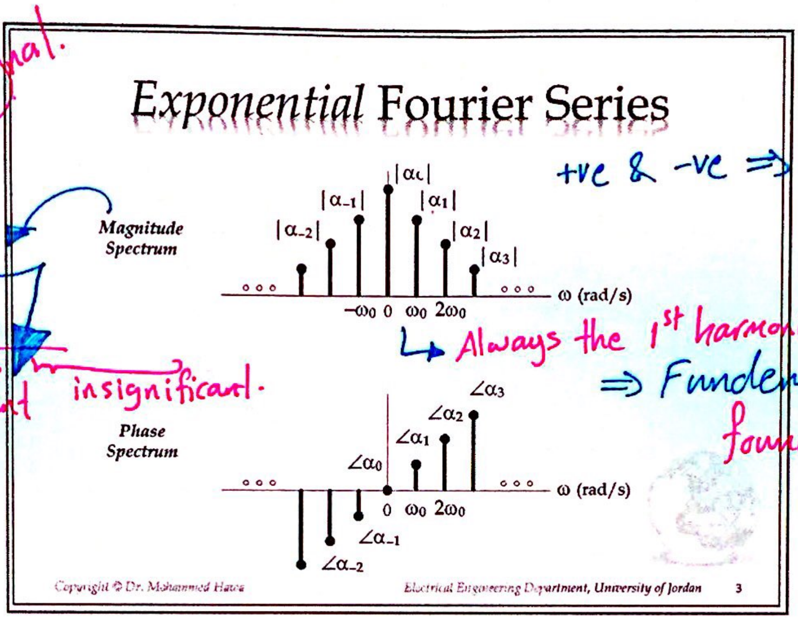
* Why we use the mag. spectrum?

To find the Bandwidth of the signal.

Bandwidth of the signal.

$2\pi B_{m(t)}$





Exponential Fourier Series

Magnitude Spectrum

Phase Spectrum

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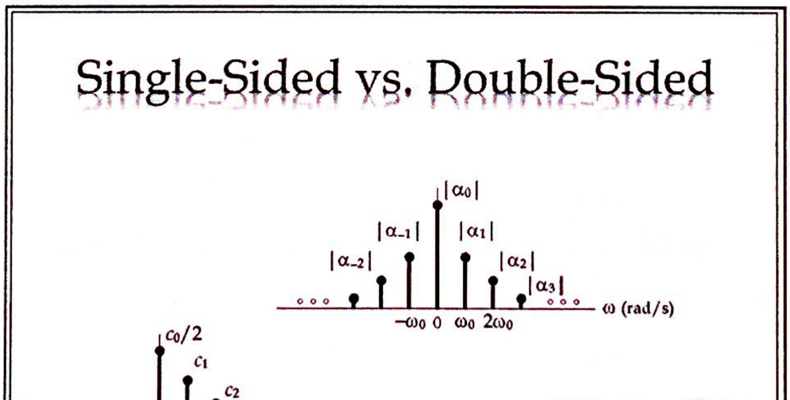
3

+ve & -ve ⇒ gives cosine

↳ Always the 1st harmonic (first freq) ⇒ Fundemental. found by $\frac{2\pi}{T}$.



Single-Sided vs. Double-Sided

$|C_n| = 2|\alpha_n|$

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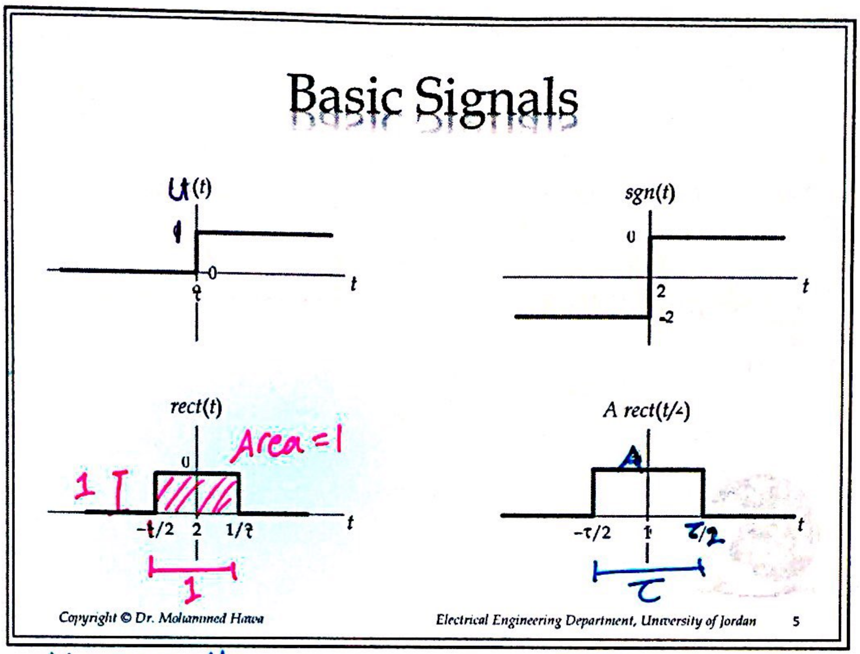
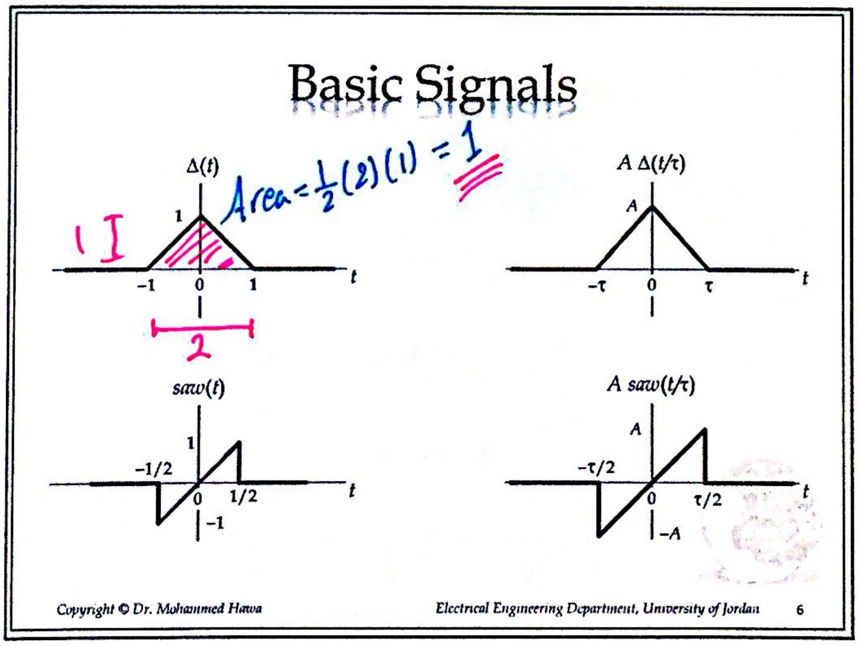
4



Basic Signals

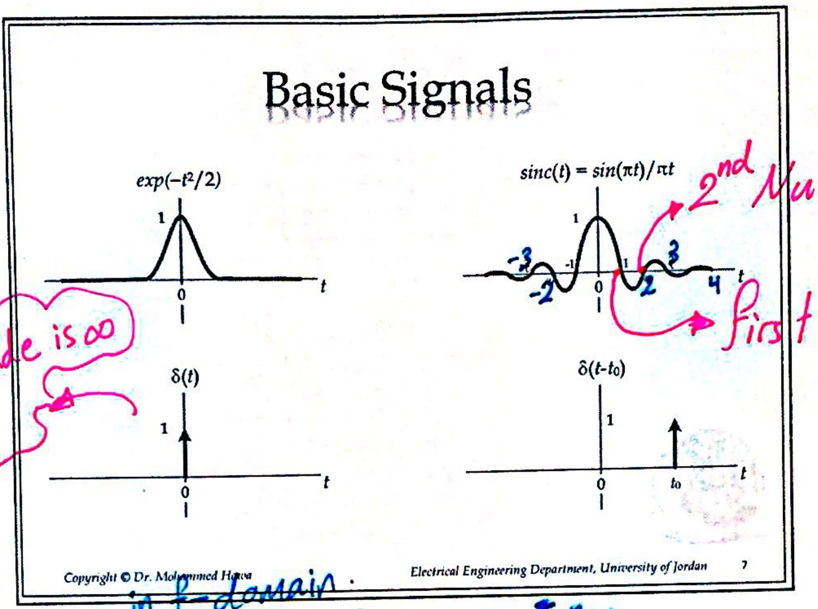
Always the area should be (1).



Basic Signals

※ Sinc : $\rightarrow$ $\text{sinc}(t) = \frac{\sin \pi t}{\pi t}$ ⟹ Always use this form.

$\rightarrow$ $\text{sinc}(t) = \frac{\sin(t)}{t}$



Basic Signals

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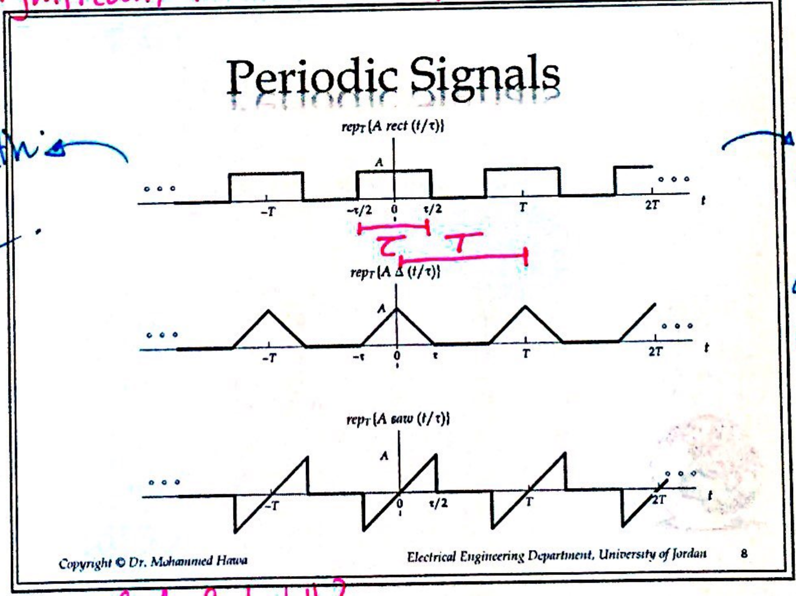
7

*whenever you see in f-domain sinc(·), $\text{sinc}^2(\cdot)$ or $\text{sinc}^n(\cdot)$ . . .

⇒ The first Null is the Bandwidth.

"significant in sinc is up to the first Null"



Periodic Signals

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τ ⇒ pulse width.

T ⇒ periode.

$\alpha_n = \frac{A\tau}{T}\text{sinc}\left(\frac{n\omega_0\tau}{2\pi}\right)$

$\downarrow$

$\alpha_0 = \frac{A\tau}{T}$

$\alpha_1 = \frac{A\tau}{T}\text{sinc}\,\frac{\omega_0\tau}{2\pi}$

$\vdots$

$\sin x = \frac{\sin \pi x}{\pi x}$.

$|\alpha_0| = \frac{A\tau}{T}$

$\measuredangle\alpha_0 = 0$

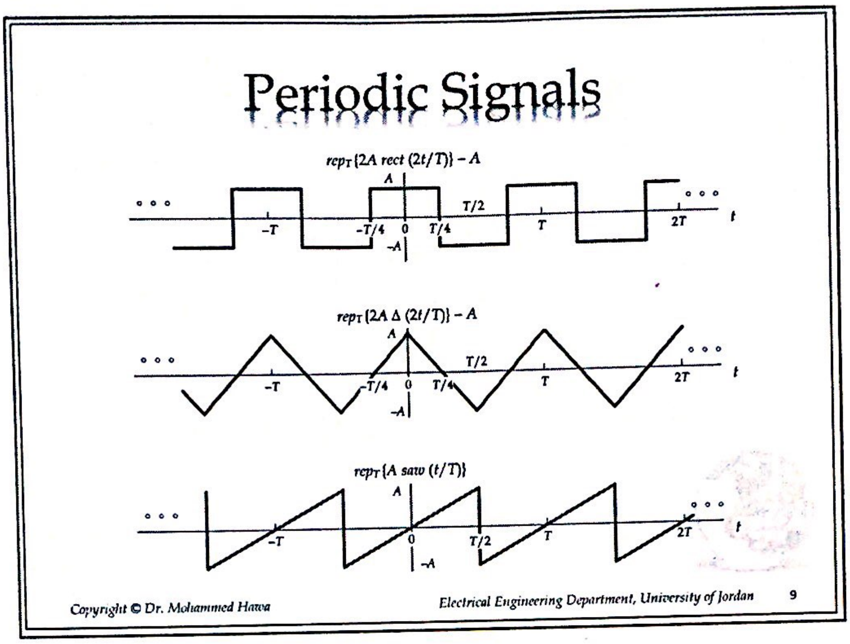
(real number).

* How To find first Null?

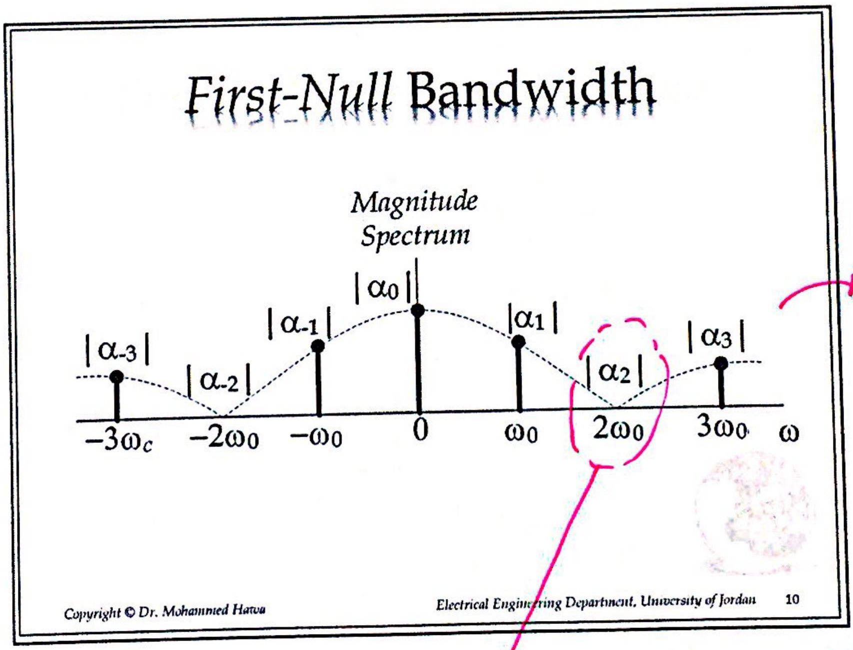
$\alpha_n = \frac{A\tau}{T}\text{sinc}\left(\frac{n\omega_0\tau}{2\pi}\right)$

@ $\frac{n\omega_0\tau}{2\pi} = 1$ ⟹ first Null. (Bandwidth).

Bandwidth $= n\omega_0 = \frac{2\pi}{\tau}$ rad/s. ⟹ $\boxed{B_{Hz} = \frac{1}{\tau}}$



Periodic Signals



First-Null Bandwidth

Note: Always +ve.
& if there is a negative it will be shown in the phase spectrum.

Bandwidth of m(t) since it is 1st Null.

$\alpha_3 = -5 \rightarrow |\alpha_3| = 5$

$\rightarrow \measuredangle \alpha_3 = 180°$

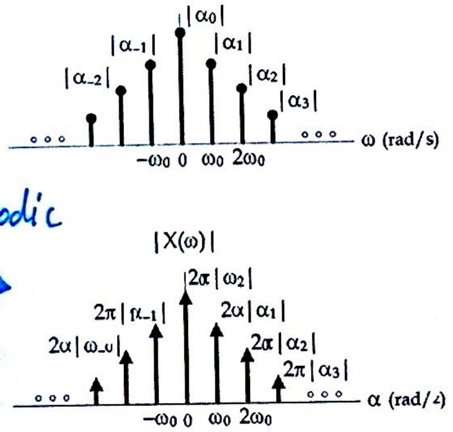
- Fourier series : ONLY Periodic
- Fourier Transform : periodic & aperiodic.

Fourier Transform

$$X(\omega) = \mathscr{F}\{x(t)\} = \int_{-\infty}^{\infty} x(t)e^{-j\omega t}dt$$

$$x(t) = \mathscr{F}^{-1}\{X(\omega)\} = \frac{1}{2\pi}\int_{-\infty}^{\infty} X(\omega)e^{j\omega t}d\omega$$

Fourier Series vs. Tranform



series.

same periodic signal.

Transform.

come from $2\pi * \frac{1}{2}$

↓

fourier series coefficient of cosine $\alpha_1 = \alpha_{-1} = \frac{1}{2}$

$$\mathcal{F}\left\{\cos(\omega_0 t)\right\} = \pi\,\delta(\omega-\omega_0) + \pi\,\delta(\omega+\omega_0)$$

$$\mathcal{F}\left\{\sin(\omega_0 t)\right\} = -j\pi\,\delta(\omega-\omega_0) + j\pi\,\delta(\omega+\omega_0).$$

$$\mathcal{F}\left\{rect(t)\right\} = sinc\left(\frac{\omega}{2\pi}\right) \rightarrow \mathcal{F}\left\{A\,rect\left(\frac{t}{\tau}\right)\right\} = A\tau\, sinc\left(\frac{\omega\tau}{2\pi}\right)$$

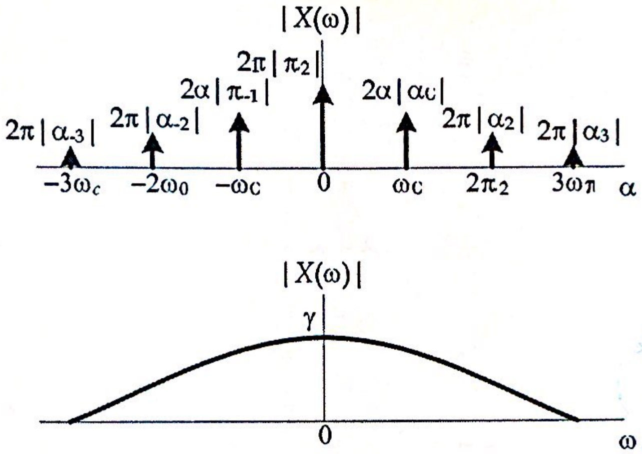
↓

we can use it To find α_n for $A\,rect\left(\frac{t}{\tau}\right)$:

$$\alpha_n = \frac{A\tau}{T}\, sinc\left(\frac{\boxed{\omega}\tau}{2\pi}\right) \rightarrow \underline{\underline{n\omega_0}}$$

"Divide by T, replace ω by $n\omega_0$"

Periodic vs. Aperiodic



DC vs. Average Power

The DC value or average value of the signal $x(t)$ is:

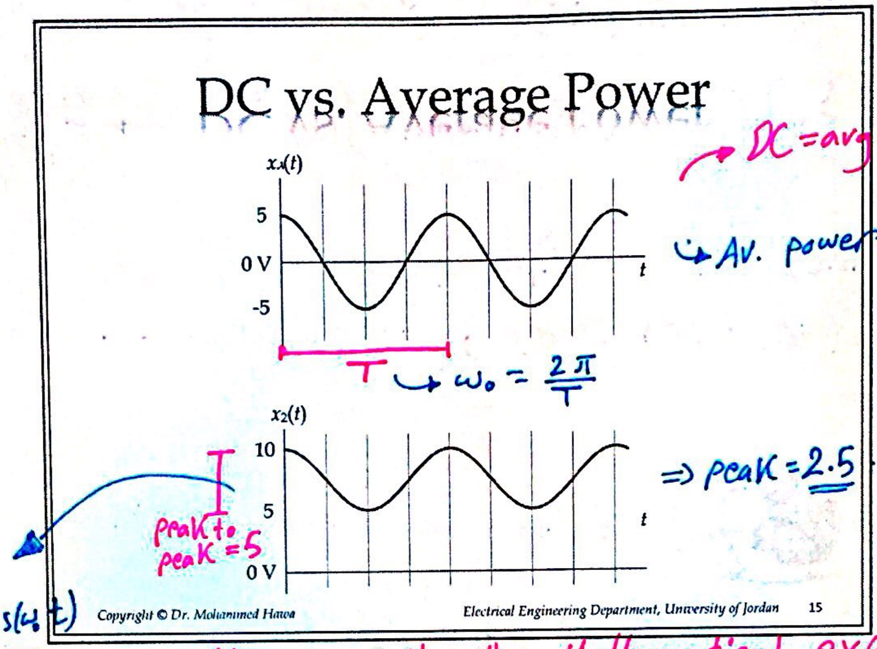
TD: $$DC = \overline{x(t)} = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} x(t)dt$$

FD: $$DC = \overline{x(t)} = \alpha_0$$ → fourier Series Coefficient.

The average power in the signal $x(t)$ is:

TD: $$P_x = \overline{x^2(t)} = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} |x(t)|^2 dt$$

FD: $$P_x = \overline{x^2(t)} = \frac{1}{2\pi} \int_{-\infty}^{\infty} S_x(\omega)d\omega$$



DC vs. Average Power

$\rightarrow DC = avg = \overline{x_1(t)} = 0$

$\hookrightarrow$ Av. power $= \frac{5^2}{2} = 12.5\,W.$

$\hookrightarrow \frac{A^2}{2}.$

$T \hookrightarrow \omega_0 = \frac{2\pi}{T}$

$\Rightarrow$ peak $= \underline{\underline{2.5}}$

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15

$x_2(t) = 2.5\cos(\omega_0 t) + 7.5$

$\Longrightarrow$ Always write the Mathematical expression.

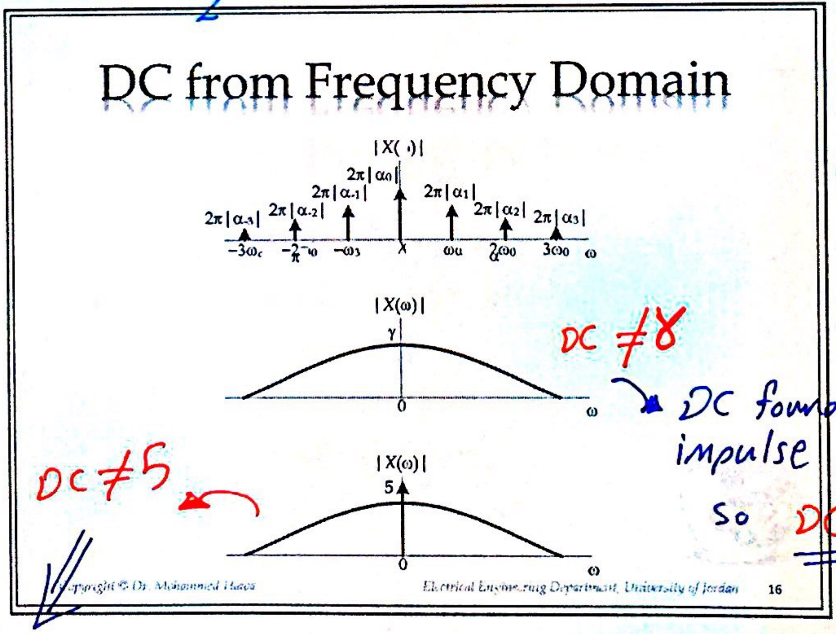
$\Rightarrow DC: = 0 + 7.5 = \underline{\underline{7.5}}.$

Av. power: $P_{av.} = \frac{(2.5)^2}{2} + (7.5)^2 = 59.375\,W.$

✻We Can't use Super position for power.

EXCEPT in this case: (orthogonality).

see Ex. $\longrightarrow$



DC from Frequency Domain

DC $\neq \gamma$

$\searrow$ DC found from the impulse @ $\omega = 0$

so $\underline{\underline{DC = 0}}$

DC $\neq 5$

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16

$DC = \alpha_0 \Rightarrow 2\pi|\alpha_0| = 5$

so $\alpha_0 = DC = \frac{5}{2\pi}$

$\underline{\underline{\text{Be careful.}}}$

Ex. of Orthogonality :

① $\cos(\omega_0 t)$ & $\sin(\omega_0 t)$. ("same freq.")

② AC & DC ("different freq") → Like the previous example.

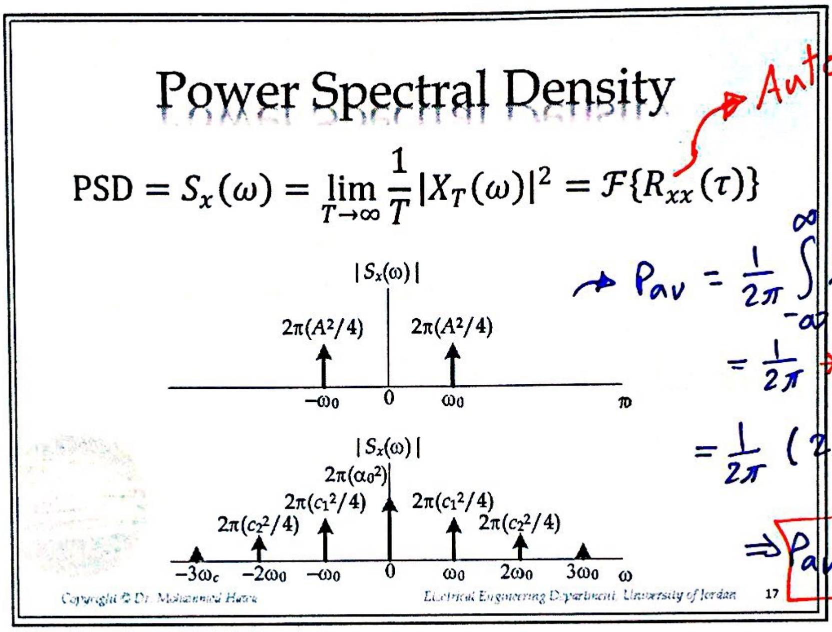
③ Cosines of multiple freq.

$\cos(\omega_0 t), \cos(2\omega_0 t), \cos(3\omega_0 t) \ldots$

$x(t) = 2.5\cos(\omega_0 t) + 7.5$ "orthogonal".

$x(t) = 5.5 + 4\cos(200t) + 5\cos(200t)$ "Not orthogonal"

$x(t) = 5.5 + 4\cos(200t) + 5\sin(200t)$ "orthogonal"



Power Spectral Density

$$\text{PSD} = S_x(\omega) = \lim_{T\to\infty} \frac{1}{T} |X_T(\omega)|^2 = \mathcal{F}\{R_{xx}(\tau)\}$$

Auto correlation for $x(t)$.

$$\rightarrow P_{av} = \frac{1}{2\pi} \int_{-\infty}^{\infty} S_x(w)\, dw$$

$$= \frac{1}{2\pi} * \text{Area.}$$

$$= \frac{1}{2\pi} (2\pi) \frac{A^2}{2}$$

$$\Rightarrow \boxed{P_{av} = \frac{A^2}{2}\ W.}$$

Quick Review of Filters

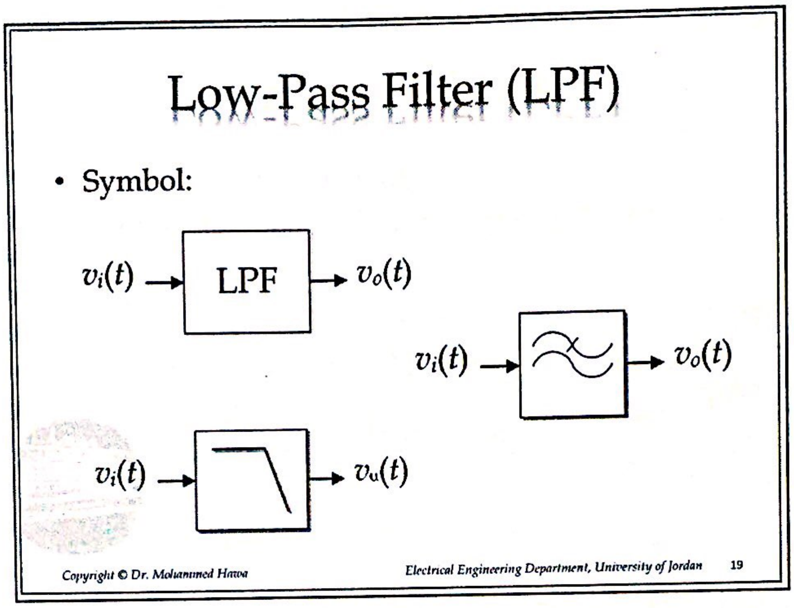
- There are three main filter types that you studied in signal analysis:
  - – LPF: Low-Pass Filter
  - – BPF: Band-Pass Filter
  - – HPF: High-Pass Filter
  - – BSF: Band-Stop Filter.

Ex1 : Find $R_{xx}(\tau)$ and then $S_x(\omega)$ for $x(t) = A\cos(\omega_0 t)$

Then Find Pav. ? see figure(1) slide(17).

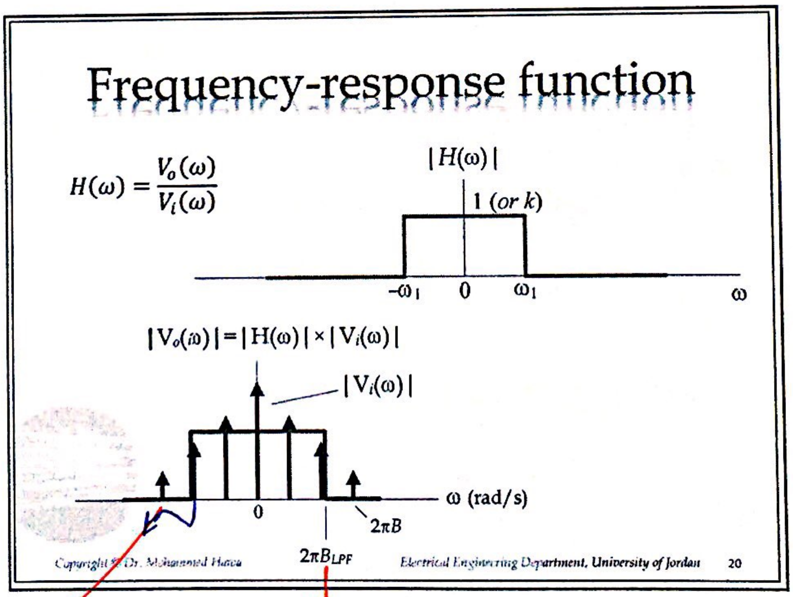
Ex2 : Find $R_{xx}(\tau)$, $S_x(\omega)$, $\overline{x^2(t)}$ for $x(t) = rep_T\{A\,rect(\frac{t}{\tau})\}$?

see figure(2) slide(17).



Low-Pass Filter (LPF)

- Symbol:



Frequency-response function

$$H(\omega) = \frac{V_o(\omega)}{V_i(\omega)}$$

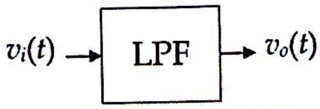
$$|V_o(\omega)| = |H(\omega)| \times |V_i(\omega)|$$

impulses @ the edges will pass.

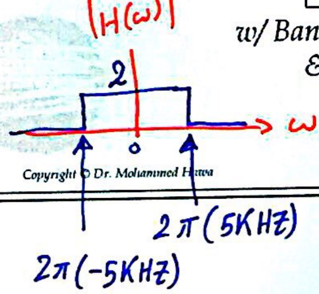
Bandwidth of the filter.

Characteristics

- Always centered at 0 rad/s.
- Bandwidth = Cut-off frequency = ω_1 rad/s
- Gain = k.



w/ Bandwidth = 5 kHz
& Gain = 2



width = 2 * Bandwidth.

Always draw the filter at first & show its char.

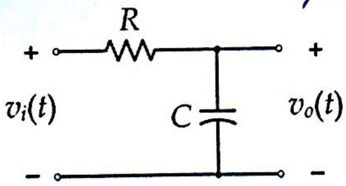
* In Bandwidth Calculations Consider only positive freq.

* For Power Calculations Consider Both +ve & -ve freq.

Example Circuit

Memorize.

→ 1^{st} order LPF. passive filter.



f↓ ⇒ C open $V_o = V_i$

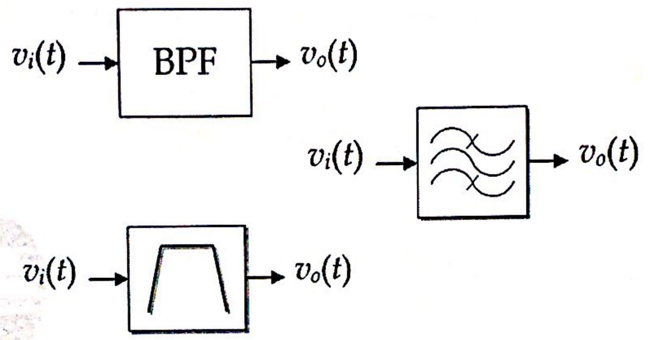
f↑ ⇒ C short $V_o = 0$

$$B_{LPF} = \frac{1}{2\pi RC} \text{ Hz}$$

$$Gain = 1$$

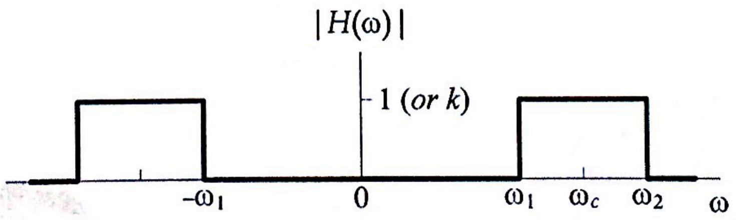
Band-Pass Filter (BPF)

- Symbol:



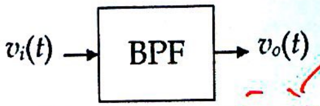
Frequency-response function

$$H(\omega) = \frac{V_o(\omega)}{V_i(\omega)}$$



Characteristics

- Centered around center frequency ω_c rad/s.
- Bandwidth of Filter = $\omega_2 - \omega_1$ rad/s
- Gain = k.



Becareful for the units.

w/ Bandwidth = 80 kHz
Center Frequency = 100 MHz
& Gain = 1

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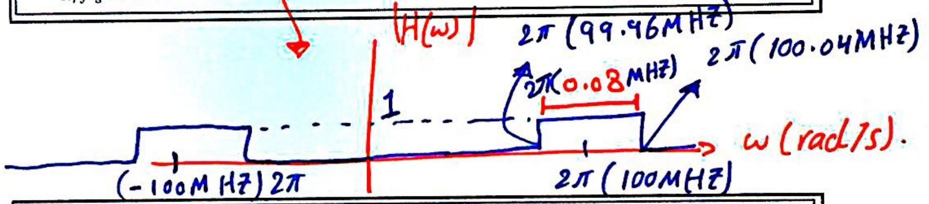
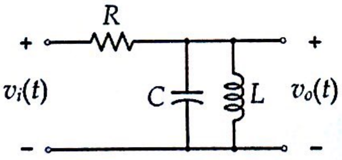


Example Circuit

2nd order BPF.



$$f_c = f_{res} = \frac{1}{2\pi\sqrt{LC}} \text{ Hz}$$

$$B_{BPF} = \Delta f = \frac{R}{2\pi L} \text{ Hz}$$

$$Gain = 1$$

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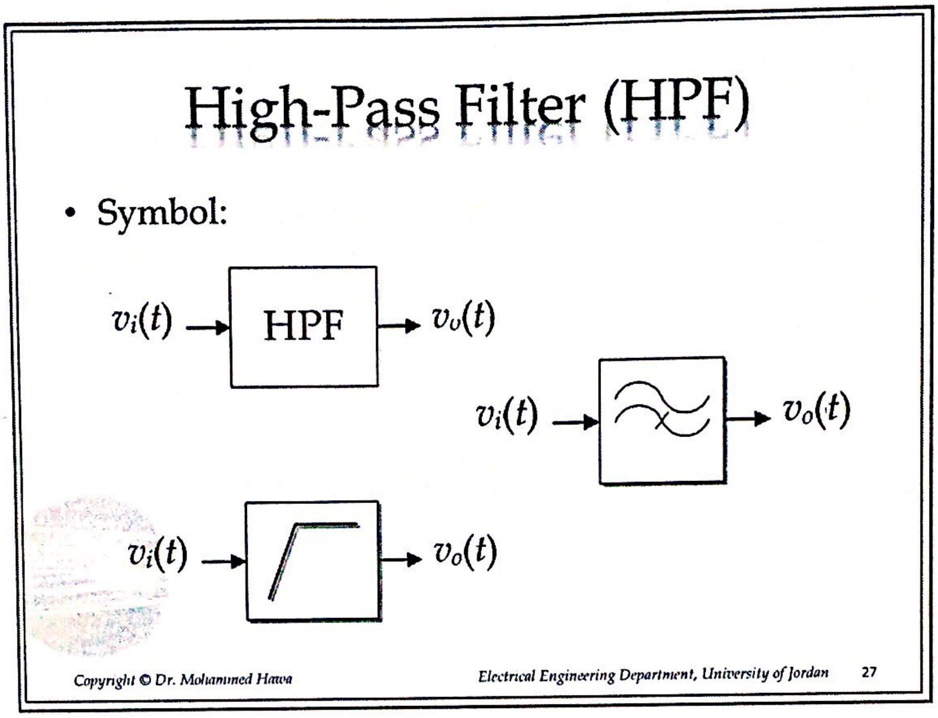

High-Pass Filter (HPF)

- Symbol:

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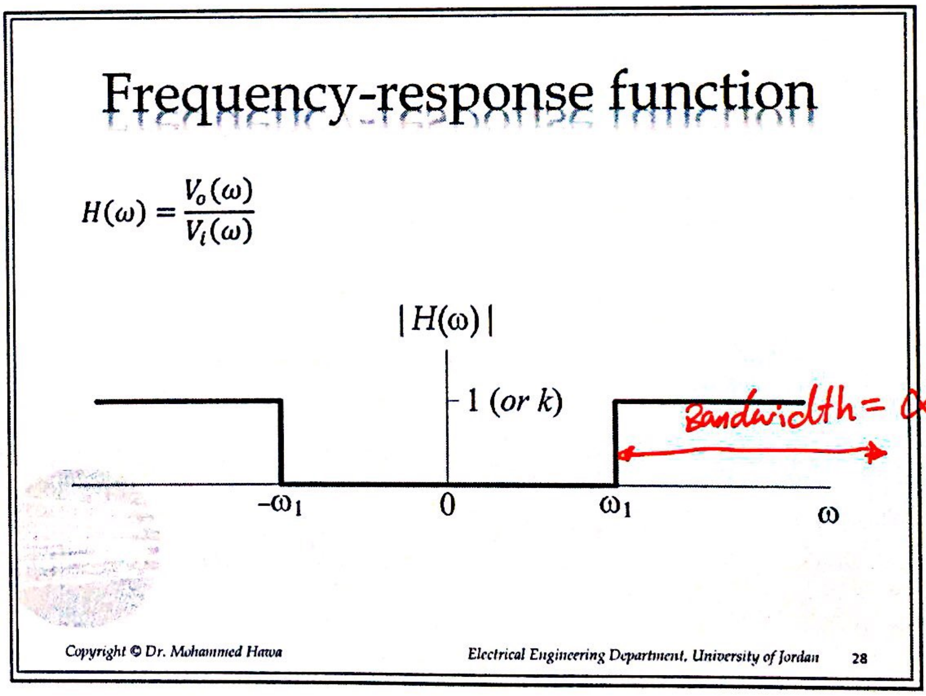

Frequency-response function

$$H(\omega) = \frac{V_o(\omega)}{V_i(\omega)}$$

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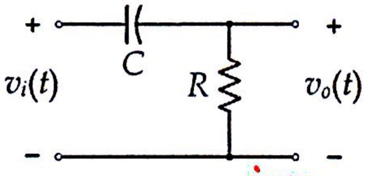
Characteristics

- Cut-off frequency = ω_1 rad/s.
- Gain = k.

- No *bandwidth* defined.

Example Circuit



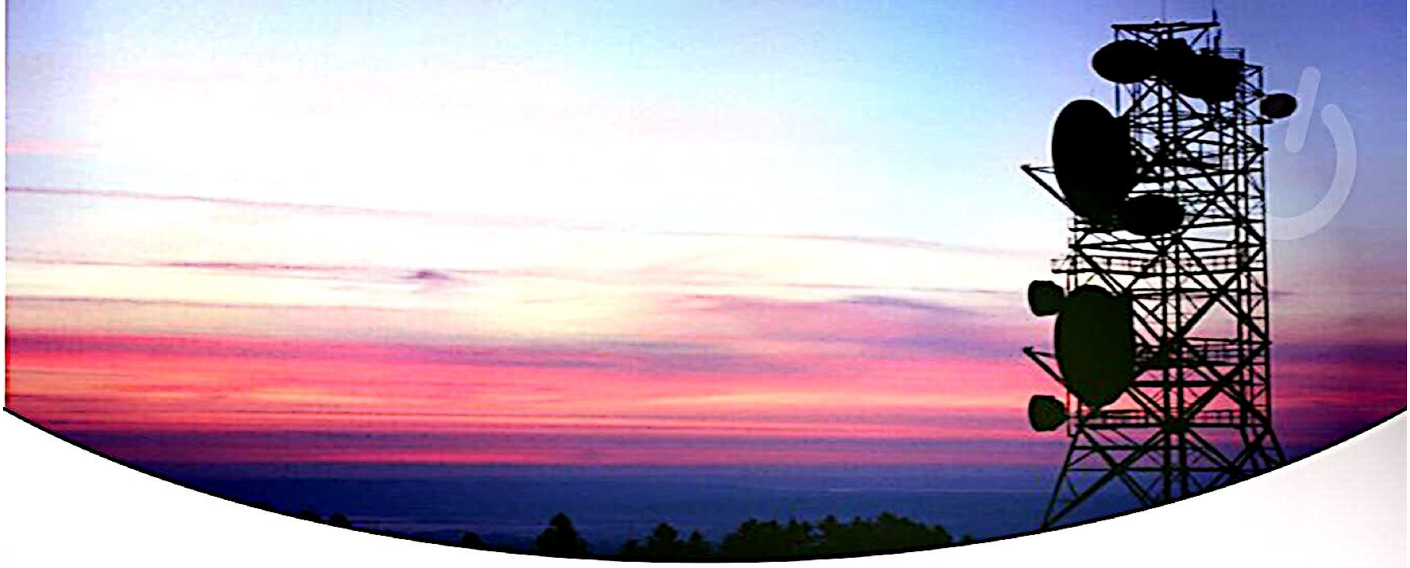
$i = 0$

$f\downarrow \Rightarrow$ C open $V_o = 0$

$f\uparrow \Rightarrow$ C short $V_o = V_i$

$$f_{cut-off} = \frac{1}{2\pi RC}\ \text{Hz}$$

$$Gain = 1$$



Communications1

Fall017

Dr.Mhmd Hawa

By: Mhmd Abuhashya

www Powerunit-ju.com

Lecture 4: Amplitude Modulation (Double Sideband *Suppressed* Carrier, DSB-SC)

→ Memorize it.

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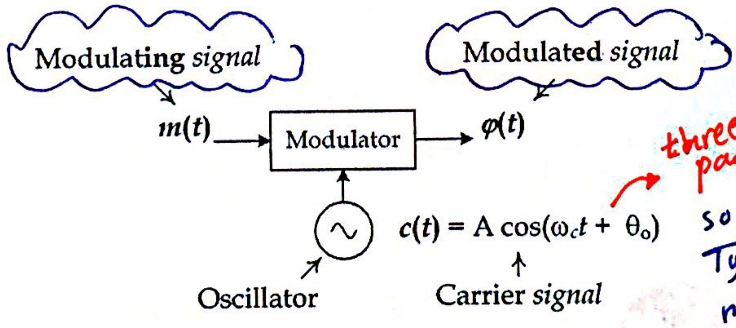
EE421: Communications I

Notation



$c(t) = A\cos(\omega_c t + \theta_o)$

three basic parameters

so three Types of modulations.

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* If c(t) is cosine, it is called:
CW (continuous wave) modulation.

※ **Modulation:** is a process that causes a shift of frequancies of the signal from Baseband to Carrier.

- **Modulation is achieved by:** changing one of the basic parameters of a high frequancy periodic signal (called the Carrier $c(t)$) in proportion to the baseband message signal $m(t)$.

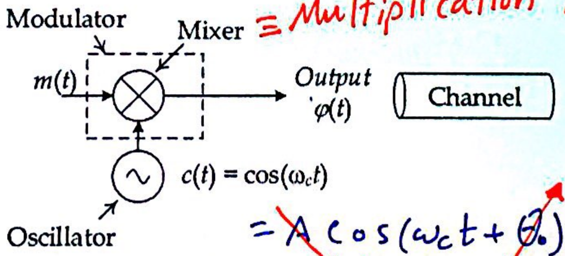
Three Modulation Types

- $A \propto m(t)$; $\omega_c = constant$; $\theta_o = constant$
  - Amplitude Modulation (AM) → in Analog Modulation.
  - Amplitude Shift Keying (ASK) → in Digital Modulation.
- $A = constant$; $\omega_c \propto m(t)$; $\theta_o = constant$
  - Frequency Modulation (FM)
  - Frequency Shift Keying (FSK)
- $A = constant$; $\omega_c = constant$; $\theta_o \propto m(t)$
  - Phase Modulation (PM)
  - Phase Shift Keying (PSK)

* When we say just (AM): we mean DSB-LC. Double sideband Larger Carrier.

DSB-SC Modulator: Mixer

Balanced Modulator.



≡ Multiplication Device ≡ Multiplier.

$$= \underset{1}{A} \cos(\omega_c t + \overset{0}{\theta_o})$$

$$o/p = \phi(t) = m(t) \cdot c(t)$$

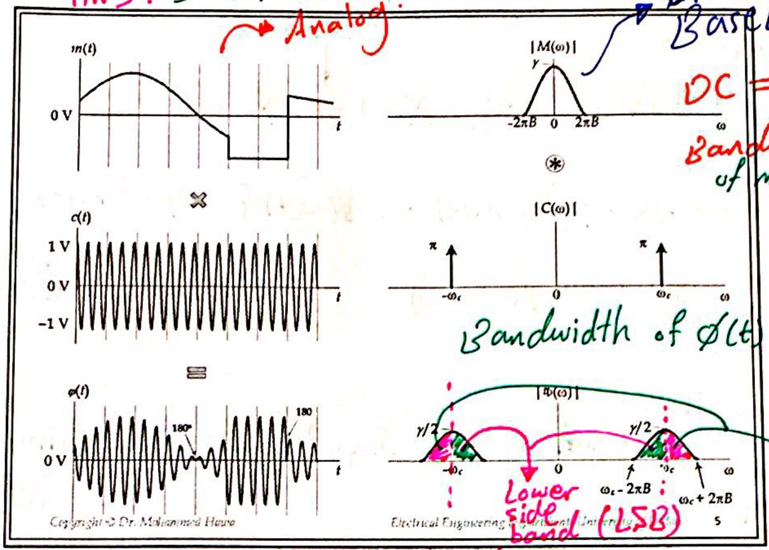
DSB-SC

$$\Rightarrow \boxed{\phi(t)_{DSB\text{-}SC} = \underbrace{m(t)}_{A \propto m(t)} \cos(\underbrace{\omega_c}_{Const.} \underbrace{t)}_{Const.}}$$

HW1: Draw for rep{rect($\frac{t}{\tau}$)}

HW2: Draw for rep{AΔ($\frac{t}{\tau}$)}

HW3: Solve for $m(t) = \alpha \cos(\omega_m t)$.



→ Analog.

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→ Aperiodic Baseband.

DC = 0

Bandwidth of m(t) = 2πB rad/s. = B HZ.

Bandwidth of $\phi(t)$ = 2 B HZ. OR 4πB rad/s.

Lower side band (LSB)

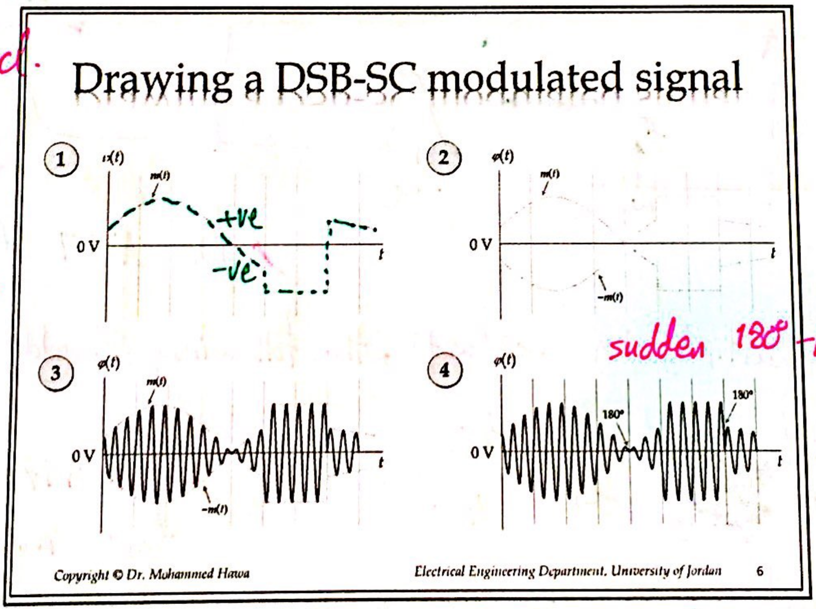
upper side band (USB).

* $B_{DSB\text{-}SC} = 2B$ (this is a disadvantage because it will be more expensive.)

* Because LSB & USB we call it Double SideBand (DSB).

* It is called. Suppressed Carriers Because No impulses in freq. domain were shown (But actually they are existed)

Drawing a DSB-SC modulated signal



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sudden 180° phase shift. in $\phi(t)$.

This happen when m(t) changes from +ve → -ve. or otherwise around. -ve → +ve.

* Bandwidth found in f-domain.

* Sudden phase-shift found in t-domain.

※ Sketch $\phi(t)$ in t-domain.

※ 〃 $\Phi(\omega) = \mathcal{F}\{\phi(t)\}$ in f-domain → Convolution (graphical solution) / → Mathematical Solution.

- F-Domain :

※ Graphically :

remember :

$$\mathcal{F}\{x(t)y(t)\} = \frac{1}{2\pi} X(\omega) \overset{\text{convolve.}}{\bigstar} Y(\omega)$$

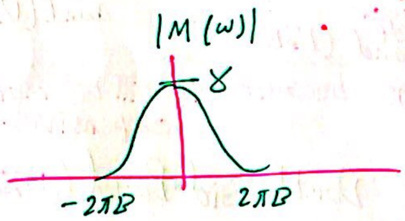
$$\Rightarrow \mathcal{F}\{\phi(t)\} = \mathcal{F}\{m(t)\cdot\cos(\omega_c t)\} = \mathcal{F}\{m(t)\cdot c(t)\}$$

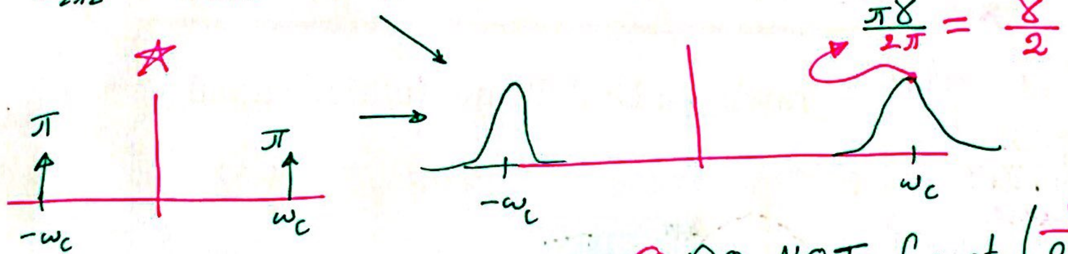
$$= \frac{1}{2\pi} M(\omega) \bigstar C(\omega)$$

** $\mathcal{F}\{\overset{c(t)}{=\cos(\omega_c t)}\} = \pi\delta(\omega-\omega_c) + \pi\delta(\omega+\omega_c)$

remember:

something ☆ Impulse = Something with shift (by shift of impulse) & scale (by area of impulse).





⊘ DO NOT forget $\left(\frac{1}{2\pi}\right)$.

* if you multiply by $\cos(\omega_c t)$, the following should be done:

1- Shift Right By ω_c.

2- shift left By ω_c.

3- Multiply By $\frac{1}{2}$.

4- $B_{DSB-SC} = 2B$

5- $\overline{\phi^2(t)}_{DSB-SC} = \frac{1}{2}\overline{m^2(t)}$

↳ Pav in $\phi(t)$ ↳ Pav in $m(t)$

- Memorize this fast methode.

⟹ Continue

Example: Assume $m(t) = \alpha \cos(\omega_m t)$ Find $\overline{m^2(t)}$?

↳ $= \boxed{\frac{\alpha^2}{2}}$

for DSB-SC.

$$\phi(t) = m(t) \cdot c(t).$$

$$= \alpha \cos(\omega_m t) \cos(\omega_c t)$$

$$\Rightarrow \overline{\phi^2(t)} = \boxed{\frac{\alpha^2}{4}}$$

So $\overline{\phi^2(t)} = \frac{1}{2} \overline{m^2(t)}$!

※ Mathematically:

$$\frac{e^{j\omega_c t} + e^{-j\omega_c t}}{2}$$

$$\Phi(\omega) = \mathcal{F}\{\phi(t)\} = \mathcal{F}\{m(t)\cos(\omega_c t)\}$$

$$= \mathcal{F}\left\{\frac{1}{2} m(t) e^{j\omega_c t} + \frac{1}{2} m(t) e^{-j\omega_c t}\right\}$$

$$= \frac{1}{2} \mathcal{F}\{m(t) e^{j\omega_c t}\} + \frac{1}{2} \mathcal{F}\{m(t) e^{-j\omega_c t}\}$$

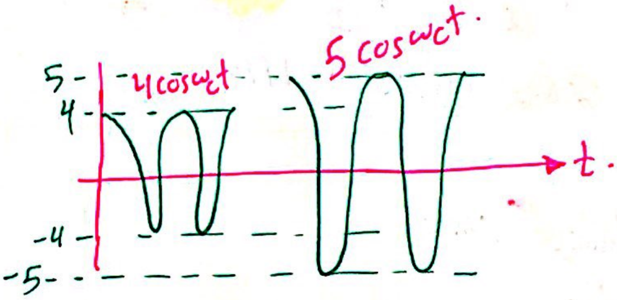
"frequancy" shift property

$$\Phi(\omega)_{DSB-SC} = \underbrace{\frac{1}{2} M(\omega - \omega_c)}_{\text{shift right.}} + \frac{1}{2} M(\omega + \omega_c).$$

↳ shift left.

- T-Domain:

Draw $4\cos\omega_c t$ & $5\cos\omega_c t$



* Now for $m(t)\cos\omega_c t = \phi(t)$.

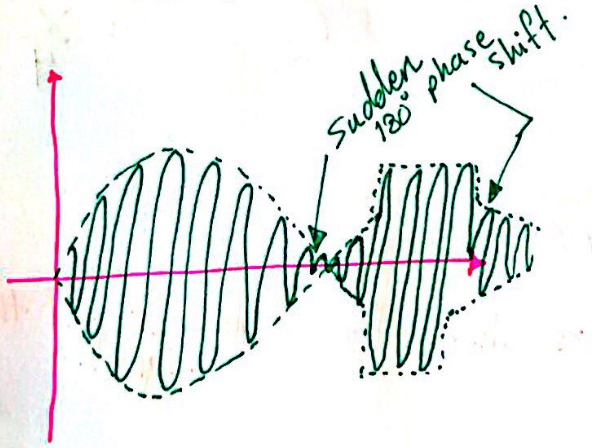
we draw a dashed lines for $m(t)$ & $-m(t)$

Then we draw the cosine inside it.

for $5\cos\omega_c t$

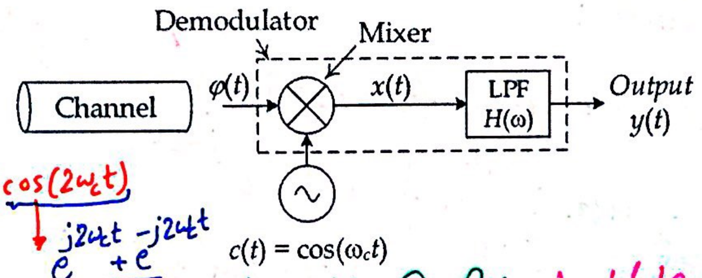
$-5\cos\omega_c t = 5\cos(\omega_c t - 180°)$

↳ 180°-phase shift.



sketch $x(t)$ & $y(t)$ in t-domain.
& $X(\omega)$ & $Y(\omega)$ in f-domain.

DSB-SC Demodulator: Mixer again!



$\phi(t) = m(t)\cos(\omega_c t)$

$x(t) = \phi(t)\cdot c(t)$

$X(\omega) = \mathcal{F}\{\phi(t)\cdot c(t)\}$

$= \mathcal{F}\{m(t)\cos^2(\omega_c t)\}$

↳ $\frac{1}{2} + \frac{1}{2}\underline{\cos(2\omega_c t)}$ ↓ $\frac{e^{j2\omega_c t} + e^{-j2\omega_c t}}{2}$

$= \mathcal{F}\left\{\frac{1}{2}m(t) + \frac{1}{4}m(t)e^{j2\omega_c t} + \frac{1}{4}m(t)e^{-j2\omega_c t}\right\}$

$= \underset{①}{\frac{1}{2}M(\omega)} + \underset{②}{\frac{1}{4}M(\omega-2\omega_c)} + \underset{③}{\frac{1}{4}M(\omega+2\omega_c)}$

$\Rightarrow Y(\omega) = \frac{1}{2}M(\omega) \rightarrow \text{Gain}_{LPF} = 1$

②&③ rejected by LPF.

↳ c(t) @ RX should be same freq. & phase. as c(t) @ TX. (perfect Synchronization).

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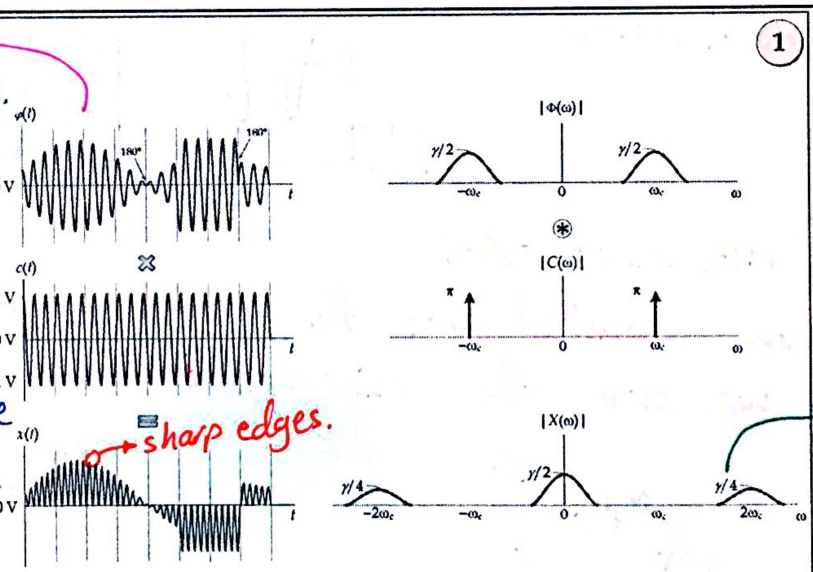
- Modulated signal.
  - AM.
- DSB-SC.



+ve x +ve = +ve
−ve x −ve = +ve
−ve x +ve = −ve

sharp edges.

$\rightarrow \frac{\gamma}{2} * \pi * \frac{1}{2\pi} = \frac{\gamma}{4}$

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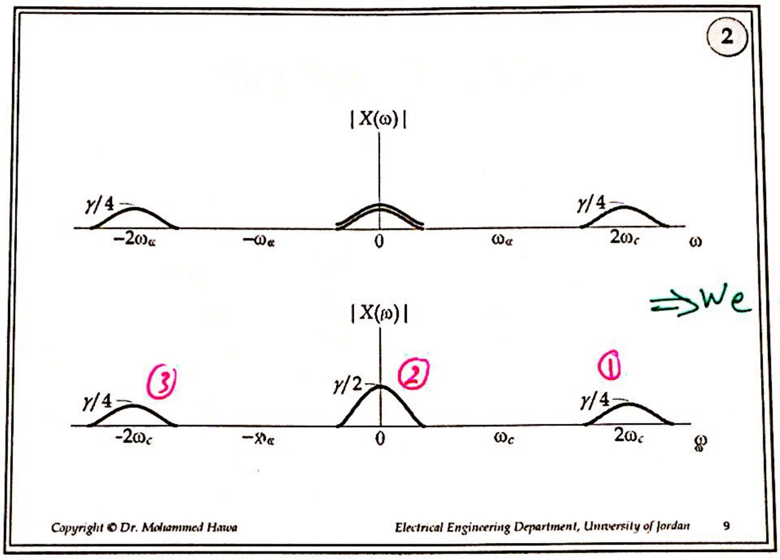
$\mathcal{F}\{\phi(t)\cdot c(t)\} = \frac{\Phi(\omega) * C(\omega)}{2\pi}$

Note:

Sharp edges ≡ High Freq.

⇒ LPF removes sharp edges. (smooths out the signal.)



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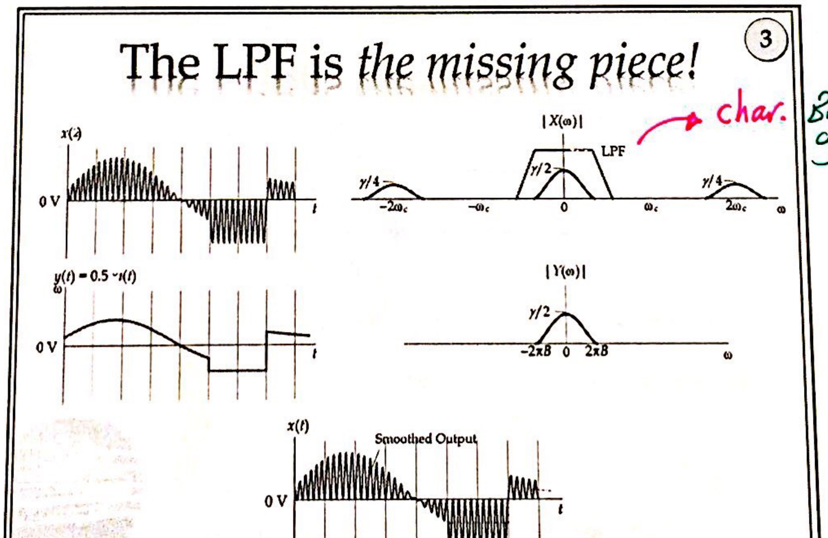
⇒ We have $\underline{\underline{3}}$ copies.

same bandwidth of the signal

The LPF is *the missing piece!*



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char.

Bandwidth = B

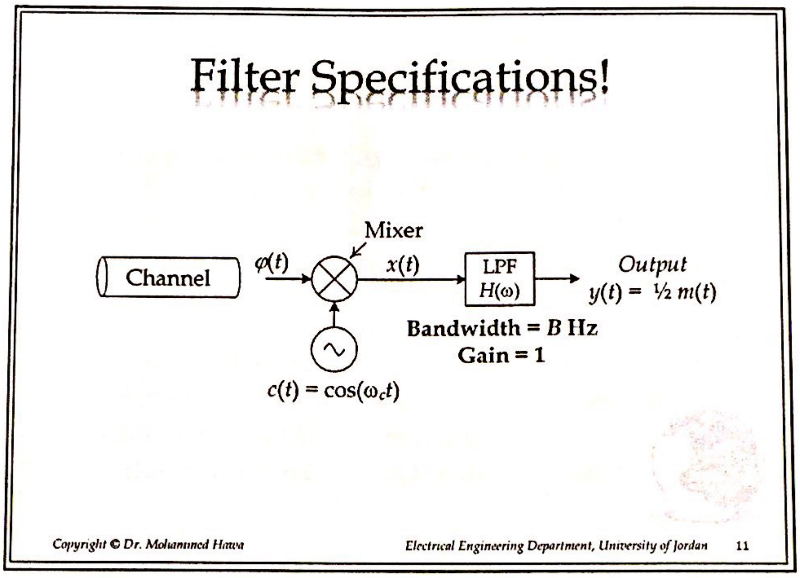
gain.

$B_{LPF} = B$

for gain=1 ⇒ $y(t) = \frac{1}{2} m(t)$.

for gain=5 ⇒ $y(t) = \frac{5}{2} m(t)$.

"Be careful"



Filter Specifications!

Bandwidth = B Hz
Gain = 1

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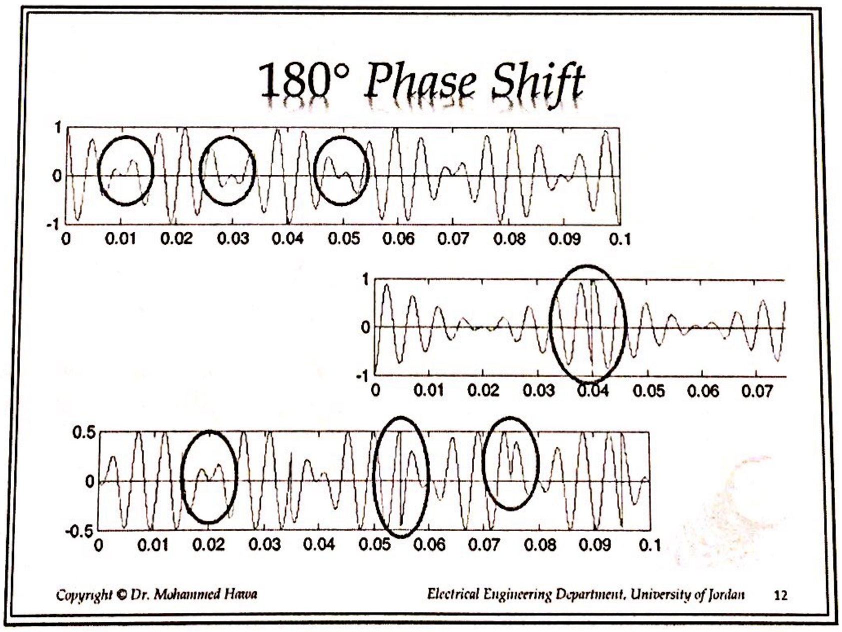

180° *Phase Shift*

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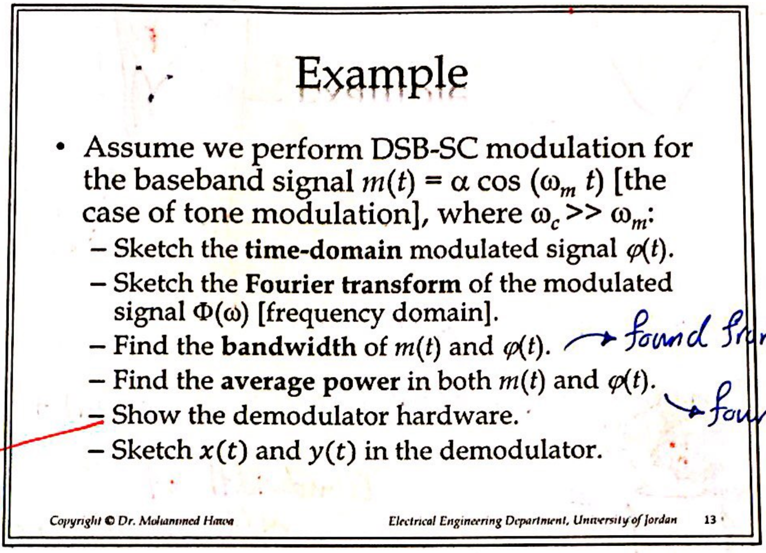
※ always Tone Modulation means that $m(t) = \alpha \cos(\omega_m t)$.
(Memorize it).



Example

- Assume we perform DSB-SC modulation for the baseband signal $m(t) = \alpha \cos(\omega_m t)$ [the case of tone modulation], where $\omega_c >> \omega_m$:
  - Sketch the **time-domain** modulated signal $\varphi(t)$.
  - Sketch the **Fourier transform** of the modulated signal $\Phi(\omega)$ [frequency domain].
  - Find the **bandwidth** of $m(t)$ and $\varphi(t)$. → found from Freq. domain.
  - Find the **average power** in both $m(t)$ and $\varphi(t)$. → found from Time domain.
  - Show the demodulator hardware.
  - Sketch $x(t)$ and $y(t)$ in the demodulator.

see slide (11)

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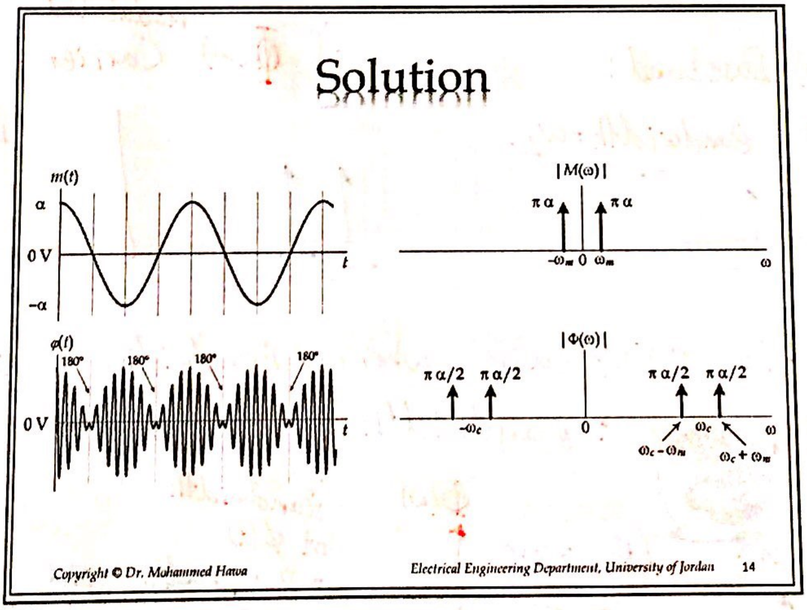

Solution

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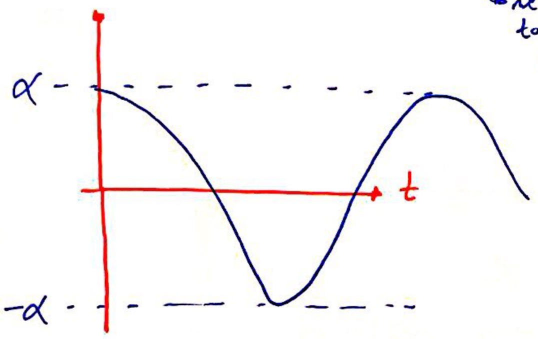
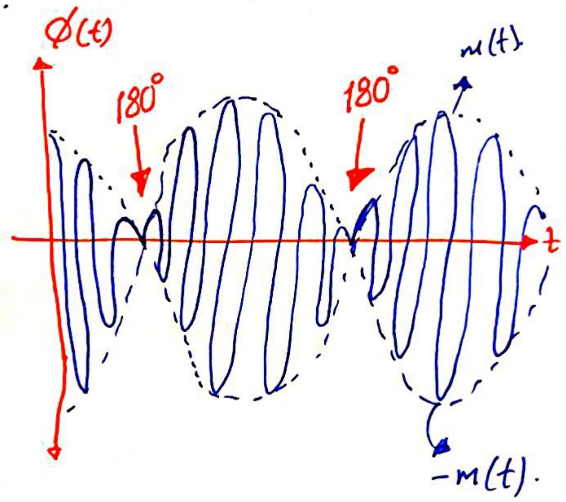
$m(t) = \alpha \cos(\omega_m t)$

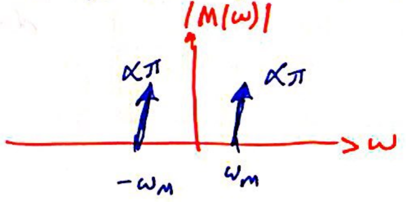
$\omega_c >> \omega_m$ ↳ need to be low freq.





$$\Phi(\omega) = \frac{1}{2}M(\omega-\omega_c) + \frac{1}{2}M(\omega+\omega_c)$$

$$M(\omega) = \mathcal{F}\{m(t)\} = \mathcal{F}\{\alpha \cos \omega_m t\} = \alpha\pi[\delta(\omega-\omega_m) + \delta(\omega+\omega_m)]$$



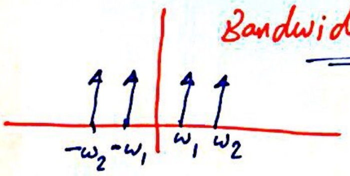
Bandwidth of $m(t) = \omega_m$ rad/s.

$= \frac{\omega_m}{2\pi} = f_m$ HZ.

* **Note:**

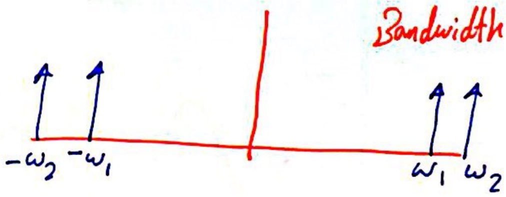
if $M(\omega)$ Baseband:

Bandwidth $= \omega_2$.



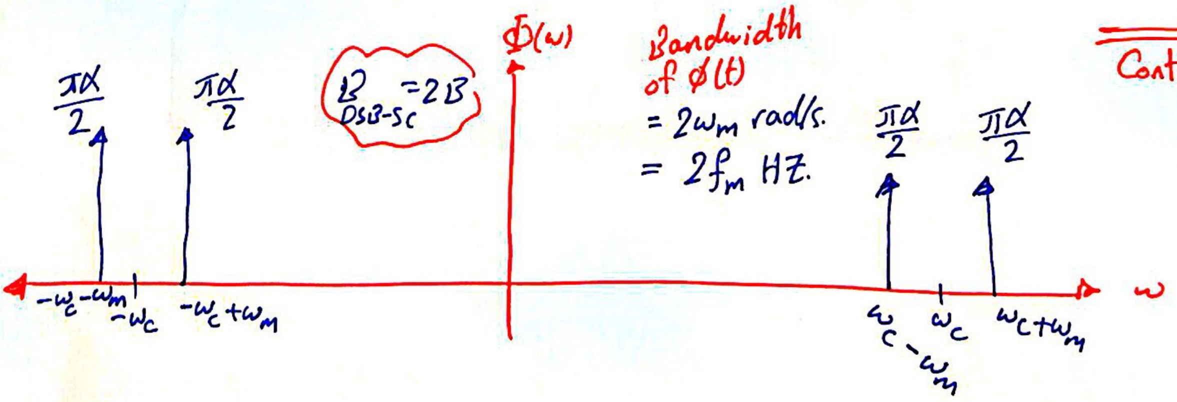
if $\Phi(\omega)$ modulated Carrier:

Bandwidth $= \omega_2 - \omega_1$



※ Tone Mod.: is ONLY case where Bandwidth = fundemental.

all other cases: Bandwidth ≠ fundemental.



$\boxed{B_{DSB-SC} = 2B}$

Bandwidth of $\phi(t)$

$= 2\omega_m$ rad/s.

$= 2f_m$ HZ.

⟹ Continue

for the average power:

found from time-domain.

$$\overline{m^2(t)} = \frac{1}{T}\int_T m^2(t)\,dt. \qquad m(t) = \alpha\cos(\omega_m t)$$

$$\Rightarrow \boxed{\overline{m^2(t)} = \frac{\alpha^2}{2}}$$

Now for $\phi(t)$:

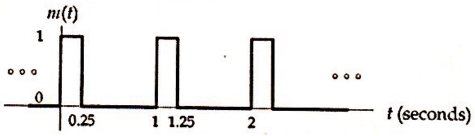
$$\overline{\phi^2(t)} = \frac{1}{T}\int_T \phi^2(t)\,dt. \quad \text{OR} \quad \overline{\phi^2(t)} = \frac{1}{2}\overline{m^2(t)}$$

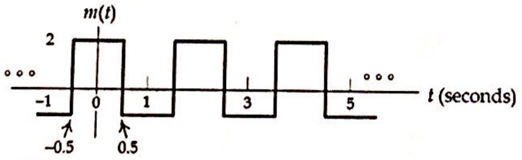
$$\Rightarrow \boxed{\overline{\phi^2(t)} = \frac{\alpha^2}{4}}$$

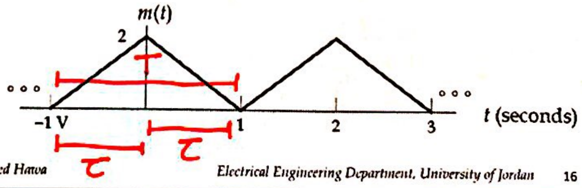
Homework

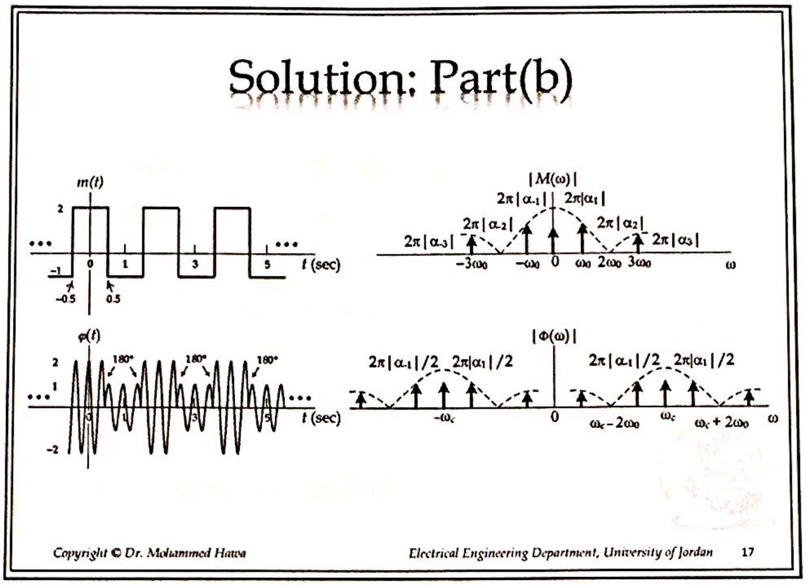
- For the following signals $m(t)$, sketch:
  - The modulated signal $\varphi(t)$ at the modulator
  - The Fourier transform $\Phi(\omega)$
  - The signals $x(t)$ and $y(t)$ at the demodulator
  - The Fourier transform $X(\omega)$ and $Y(\omega)$
- Find the average power and bandwidth for the signals $\varphi(t)$ and $y(t)$.
- Are there any phase shifts in $\varphi(t)$? If so, where?
- Determine the DC value in $m(t)$, $\varphi(t)$ and $y(t)$.

Homework



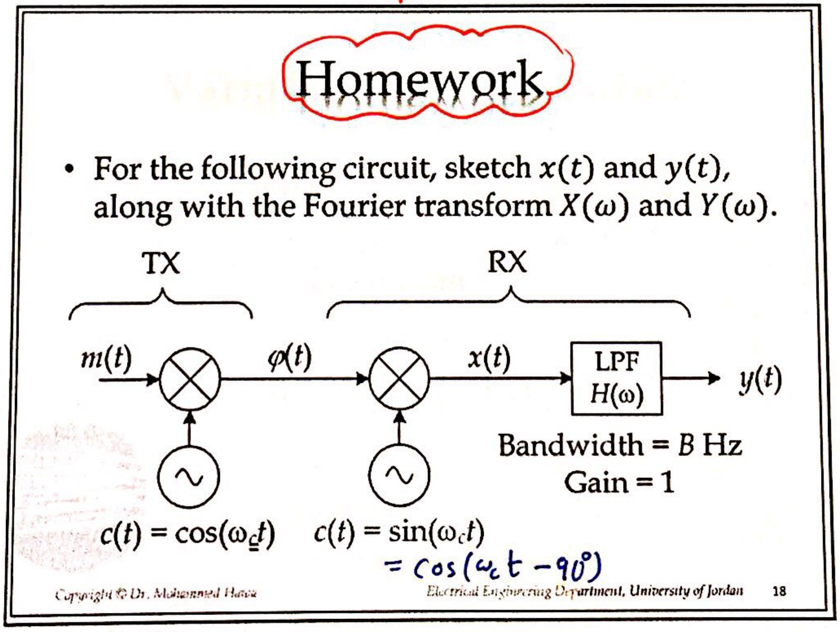






Solution: Part(b)

very important.



Homework

- For the following circuit, sketch $x(t)$ and $y(t)$, along with the Fourier transform $X(\omega)$ and $Y(\omega)$.

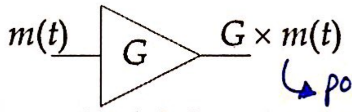
$= \cos(\omega_c t - 90^\circ)$

How to build a *Mixer*?

- Variable Gain Amplifier
  - The basic design.
- Gilbert Cell (e.g., MC 1496)
  - Popular (used in Integrated Circuits).
  - Uses variable gain differential amplifiers.
- Switching Modulator
  - Uses diodes.
  - Cheaper design (was popular before ICs).

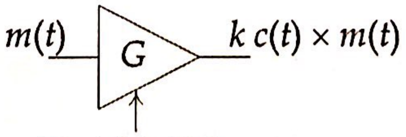
is built using 8 transistors configured as 3 differential amplifiers.

Variable Gain Amplifier

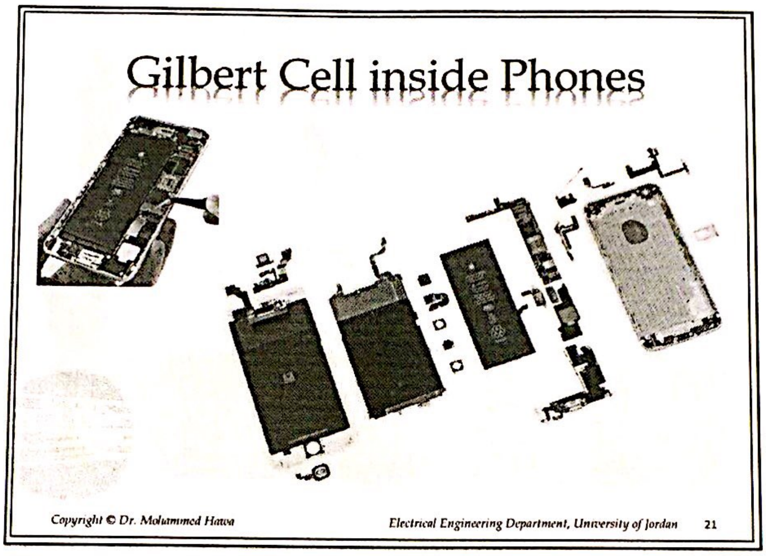


Fixed Gain

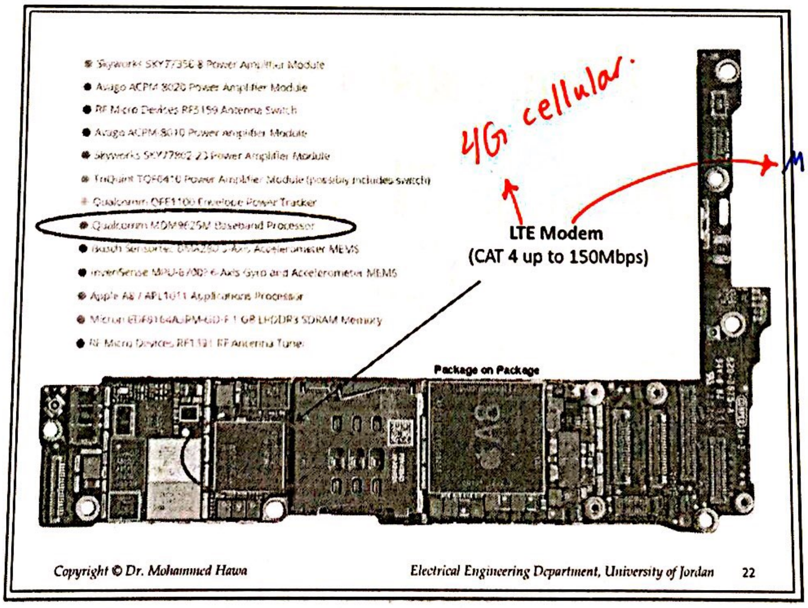
↳ power = power in $m(t)$ * G^2



Variable Gain
$G = k\,c(t)$



Gilbert Cell inside Phones

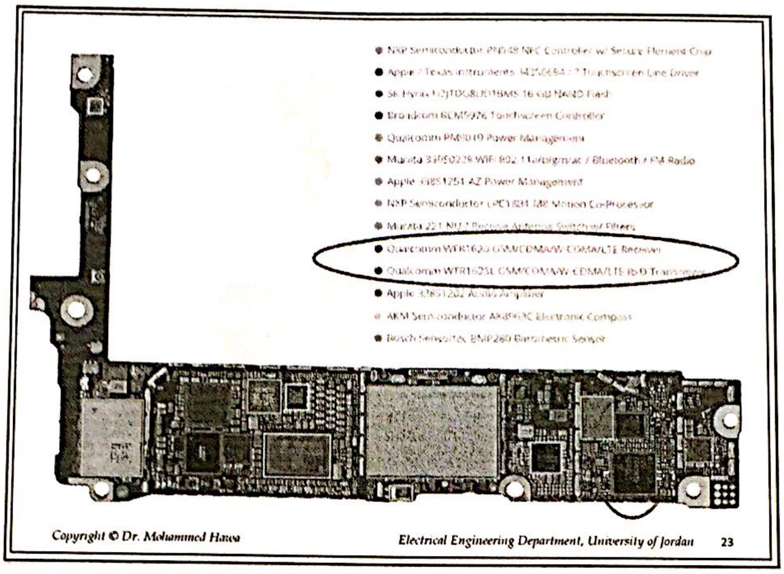


- Skyworks SKY77356-8 Power Amplifier Module
- Avago ACPM-8020 Power Amplifier Module
- RF Micro Devices RF5159 Antenna Switch
- Avago ACPM-8010 Power Amplifier Module
- Skyworks SKY77802-23 Power Amplifier Module
- TriQuint TQF6410 Power Amplifier Module (possibly includes switch)
- Qualcomm QFE1100 Envelope Power Tracker
- Qualcomm MDM9625M Baseband Processor
- Bosch Sensortec BMA280 3-Axis Accelerometer MEMS
- InvenSense MPU-6700? 6-Axis Gyro and Accelerometer MEMS
- Apple A8 / APL1011 Applications Processor
- Micron EDF8164A3PM-GD-F 1 GB LPDDR3 SDRAM Memory
- RF Micro Devices RF1331 RF Antenna Tuner

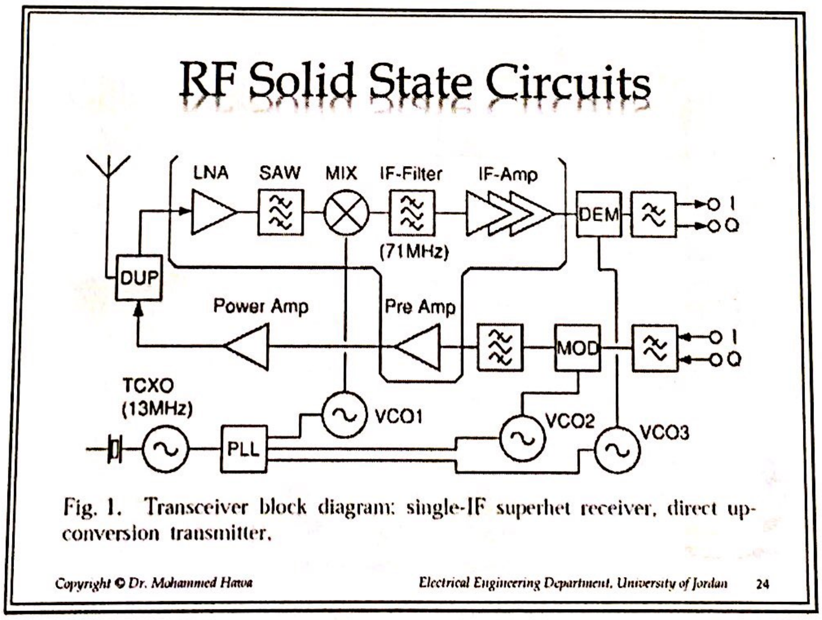
4G cellular.

LTE Modem
(CAT 4 up to 150Mbps)

Modulator/demod.



- NXP Semiconductor PN548 NFC Controller w/ Secure Element Chip
- Apple / Texas Instruments 343S0694 ? Touchscreen Line Driver
- SK Hynix H2JTDG8UD1BMS 16 GB NAND Flash
- Broadcom BCM5976 Touchscreen Controller
- Qualcomm PM8019 Power Management
- Murata 339S0228 WiFi 802.11a/b/g/n/ac / Bluetooth / FM Radio
- Apple 338S1251-AZ Power Management
- NXP Semiconductor LPC18B1 M8 Motion Co-Processor
- Murata 221 NU? Receive Antenna Switch w/ Filters
- Qualcomm WFR1620 GSM/CDMA/W-CDMA/LTE Receiver
- Qualcomm WTR1625L GSM/CDMA/W-CDMA/LTE RF Transceiver
- Apple 338S1202 Audio Amplifier
- AKM Semiconductor AK8963C Electronic Compass
- Bosch Sensortec BMP280 Barometric Sensor



RF Solid State Circuits

Fig. 1. Transceiver block diagram: single-IF superhet receiver, direct up-conversion transmitter.

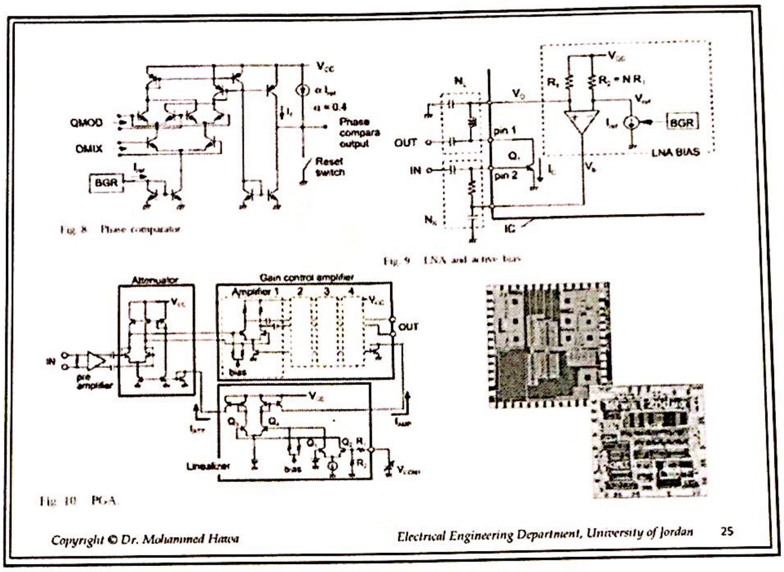


Fig. 8 Phase comparator

Fig. 9 LNA and active bias

Fig. 10 PGA

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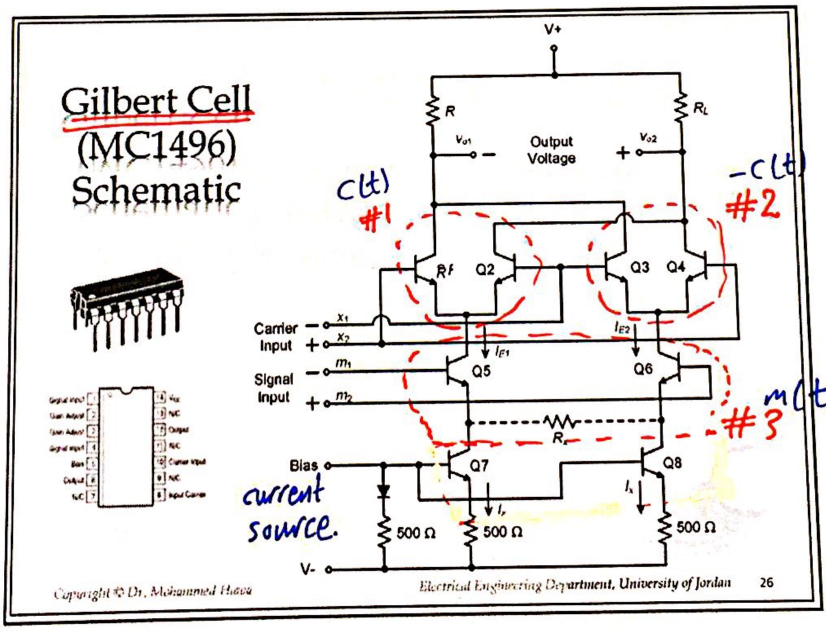

Gilbert Cell (MC1496) Schematic

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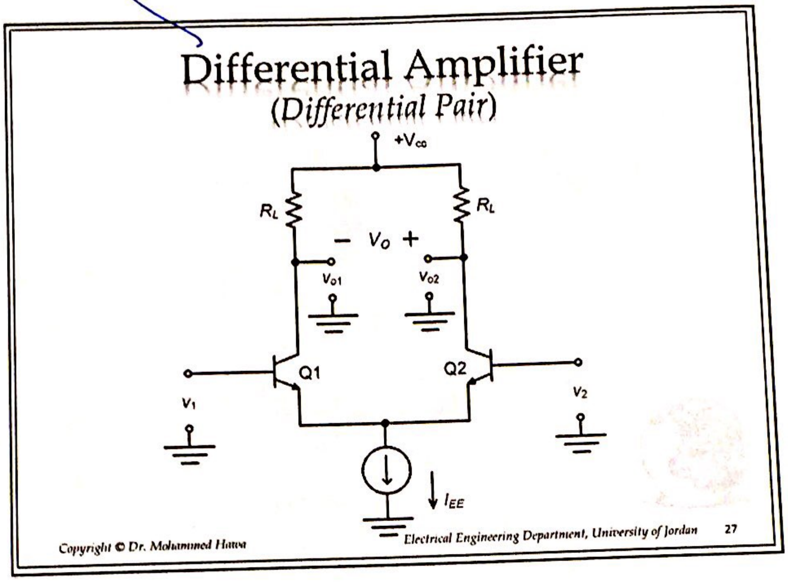
$$\overbrace{V_{o2}-V_{o1}}^{\text{output.}} = \overbrace{\frac{-I_{EE}\,R_L}{2\,V_T}}^{\text{Gain.}}\overbrace{(V_2-V_1)}^{\text{input.}}$$



Differential Amplifier

(Differential Pair)

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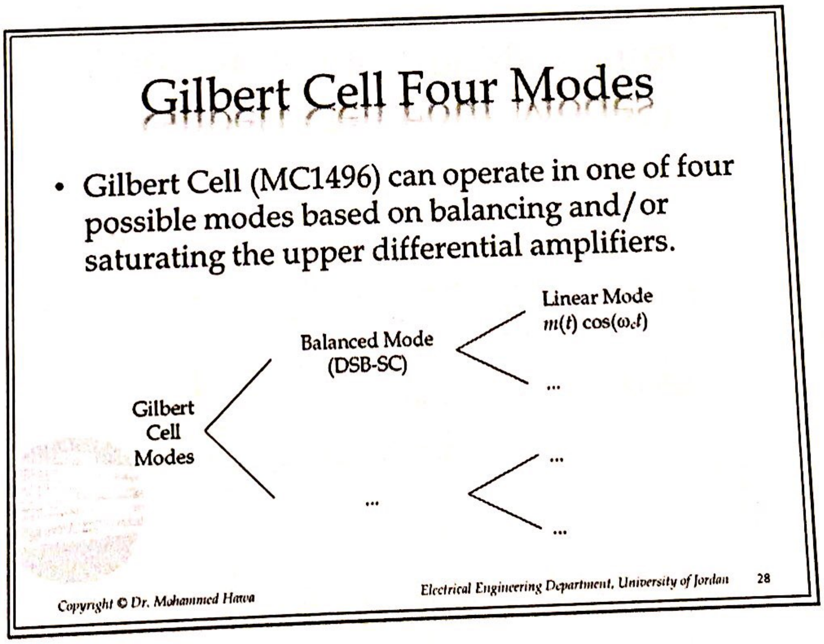

Gilbert Cell Four Modes

- Gilbert Cell (MC1496) can operate in one of four possible modes based on balancing and/or saturating the upper differential amplifiers.

Gilbert Cell Modes
- Balanced Mode (DSB-SC)
  - Linear Mode $m(t)\cos(\omega_c t)$
  - ...
- ...
  - ...
  - ...

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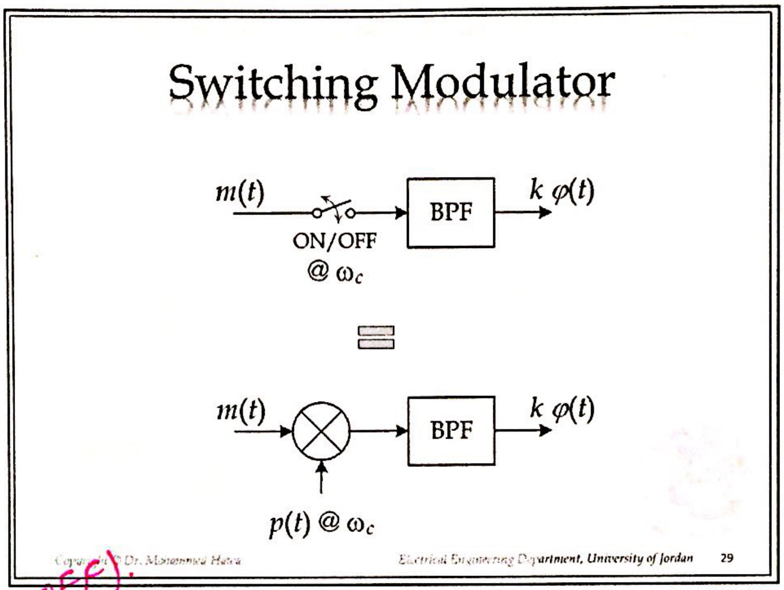
switching ≡ Multiplying by $p(t) = rep\{rect(t)\}$



Switching Modulator

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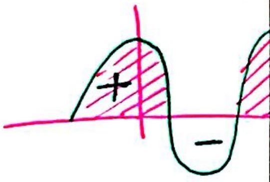
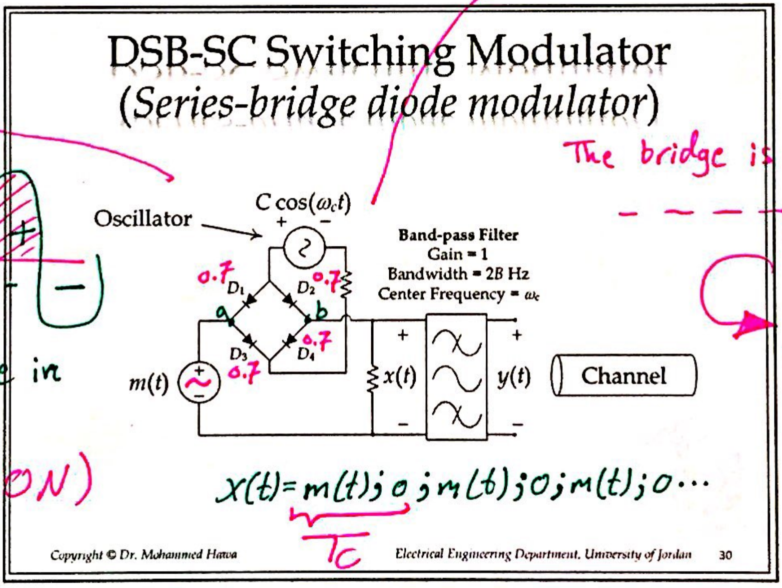
in (-ve) cycle:
all diodes reverse biased (All diodes are OFF).
$x(t) = 0$

Diodes = switch.

in (+ve) cycle.
The diodes will work as a S/C between a&b:
$-0.7 + 0.7 + 0.7 - 0.7 + V_{ab} = 0$
$\underline{V_{ab} = 0}$





DSB-SC Switching Modulator
(*Series-bridge diode modulator*)

Band-pass Filter
Gain = 1
Bandwidth = 2B Hz
Center Frequency = ω_c

$x(t) = \underbrace{m(t);0}_{T_c};m(t);0;m(t);0\cdots$

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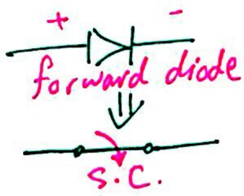
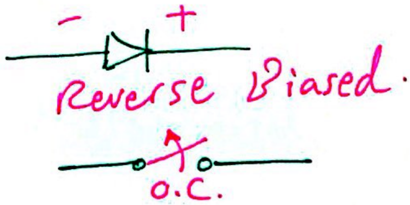
The bridge is used as a switch.

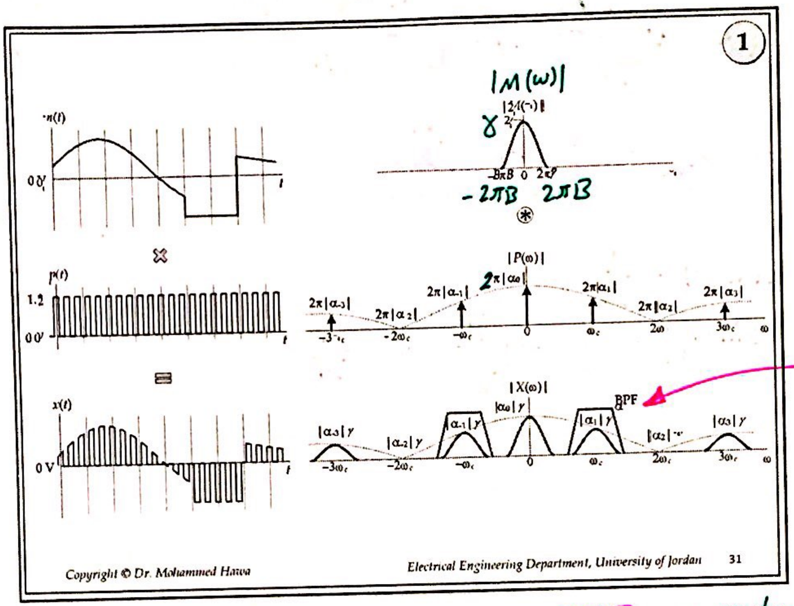
$C >> m(t)$
$C >> 1$
$C >> 1.4$
To control the diode & also have a voltage higher than 0.7 volt.

All the diodes are in forward biased (All diodes are ON)
$x(t) = m(t)$.

states of diode:







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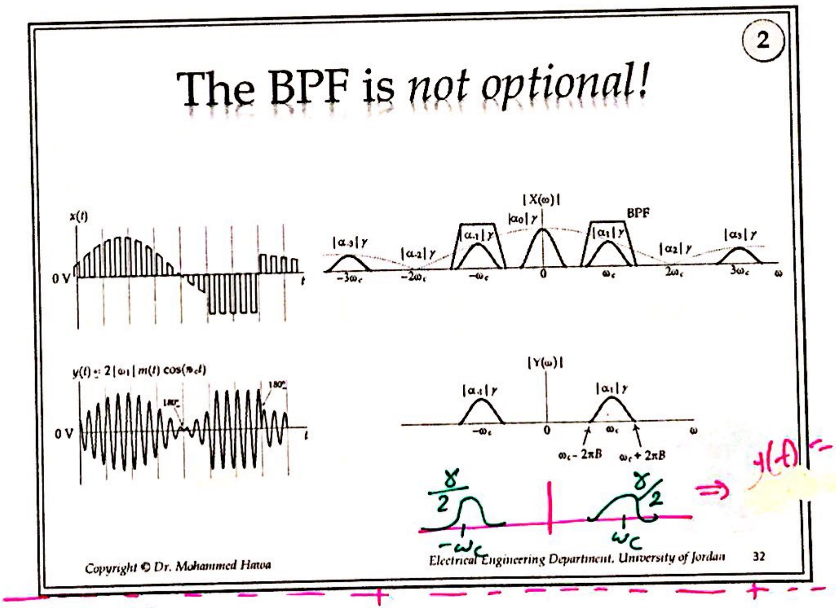
$$\frac{\gamma \cdot 2\pi|\alpha_1|}{2\pi} = \gamma|\alpha_1|$$

BPF → center $= \omega_c$ rad/s $\equiv f_c = \frac{1}{T_c}$ Hz.
→ Bandwidth $= 2B$ Hz $= 4\pi B$ rad/s.
→ Gain



The BPF is *not optional!*

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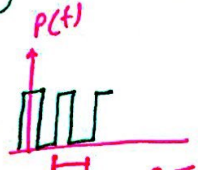
$\Rightarrow y(t) = m(t) \cos\omega_c t$

Gain =	1	$\lvert\alpha_1\rvert$	$\frac{1}{2\lvert\alpha_1\rvert}$
	$y(t) = 2\lvert\alpha_1\rvert m(t)\cos(\omega_c t)$	$y(t) = 2\lvert\alpha_1\rvert^2 m(t)\cos(\omega_c t)$	$y(t) = m(t)\cos(\omega_c t)$

$$\mathcal{F}\{m(t)\cdot p(t)\} = \frac{1}{2\pi} M(\omega) \star P(\omega)$$

$$\alpha_n = \frac{A\tau}{T} \operatorname{sinc}\left(\frac{n\omega_0\tau}{2\pi}\right)$$ $\Rightarrow$ from $p(t)$ $\Rightarrow$ $A=1$



$$T_C = \frac{2\pi}{\omega_c} = \frac{1}{f_c}$$

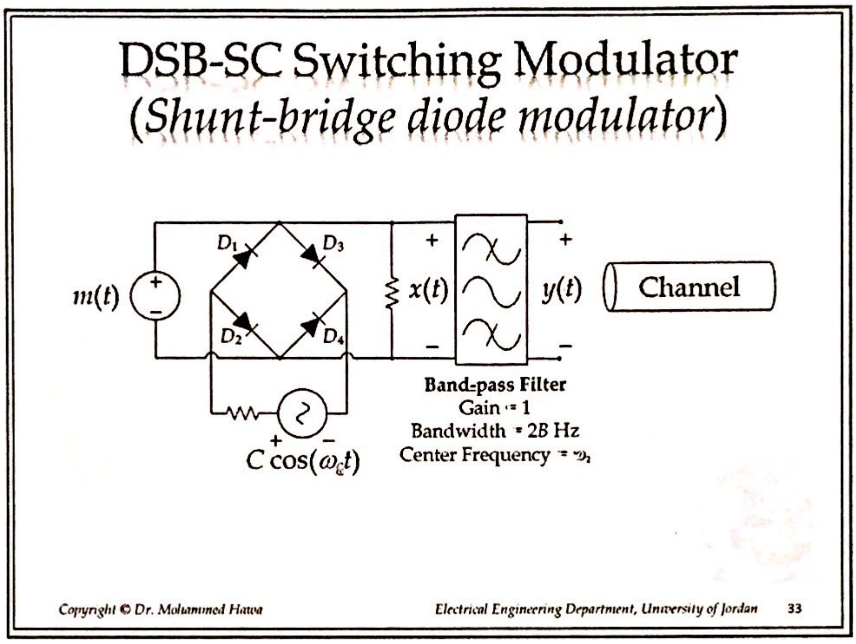
$$\Rightarrow \alpha_n = \frac{1.0\left(\frac{T_c}{2}\right)}{T_c} \operatorname{sinc}\left(\frac{n\left(\frac{2\pi}{T_c}\right)\left(\frac{T_c}{2}\right)}{2\pi}\right)$$

$$\Rightarrow \underline{\underline{\alpha_n = \frac{1}{2} \operatorname{sinc}\left(\frac{n}{2}\right)}}$$

see the figures slide (31).

$$\alpha_0 = \frac{1}{2} \operatorname{sinc}(0) = \frac{1}{2}$$

$$\alpha_1 = \frac{1}{2} \operatorname{sinc}\left(\frac{1}{2}\right) = \frac{1}{2} \frac{\sin \pi/2}{\pi/2} = \frac{1}{\pi}$$



DSB-SC Switching Modulator
(*Shunt-bridge diode modulator*)

Band-pass Filter
Gain = 1
Bandwidth = 2B Hz
Center Frequency = ω_c

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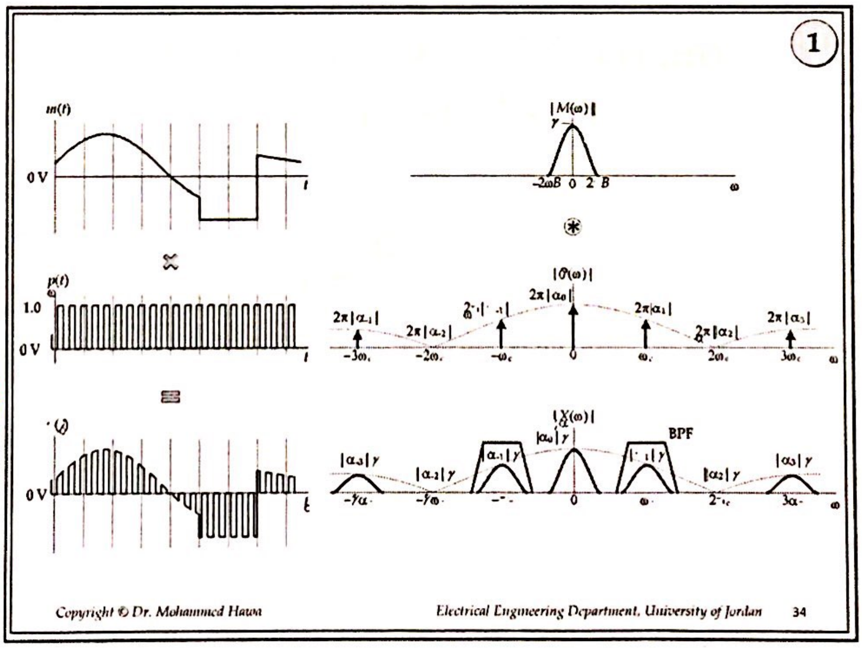

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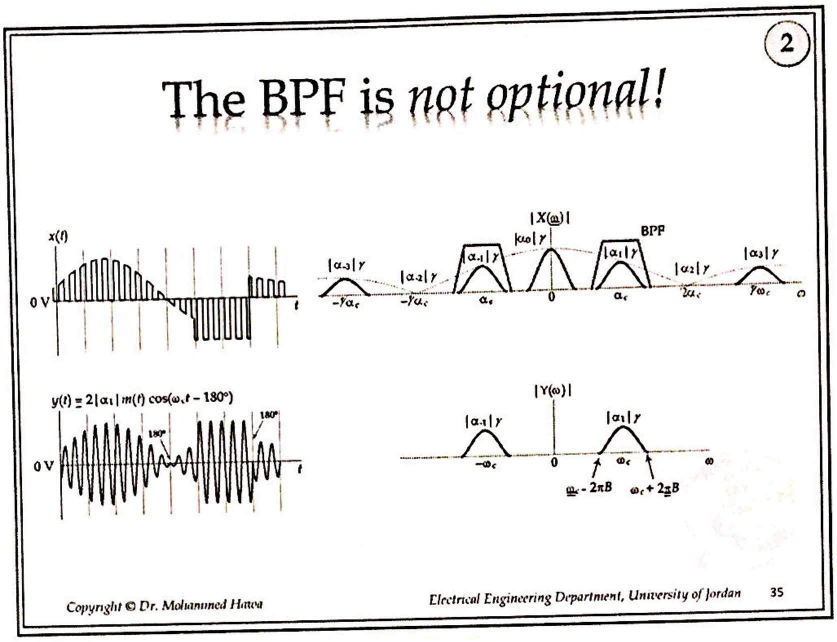
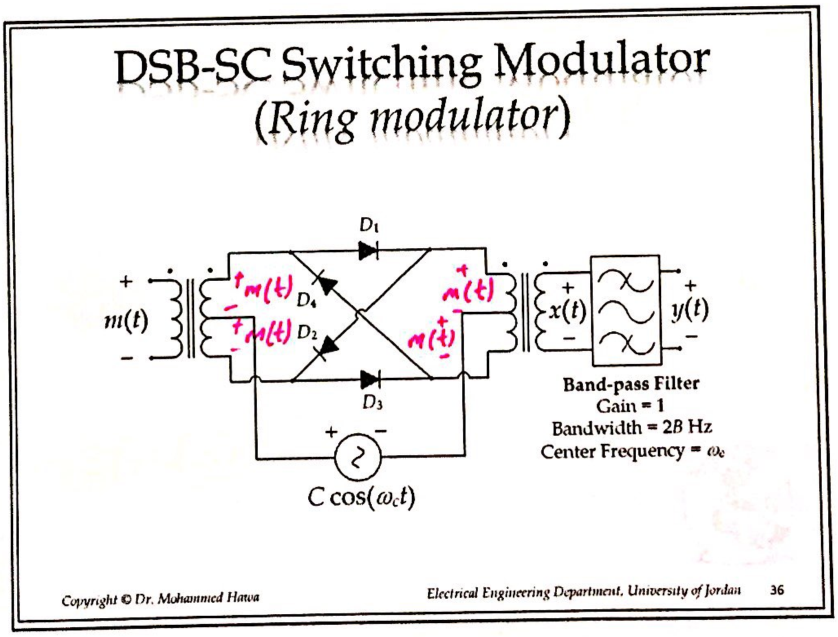
a shift in time
for the $\overrightarrow{\text{rect}}$
so a phase shift
will happen
in the freq.
domain.

$x(t) = 0; m(t); 0; m(t) \dots$



②

The BPF is *not optional!*



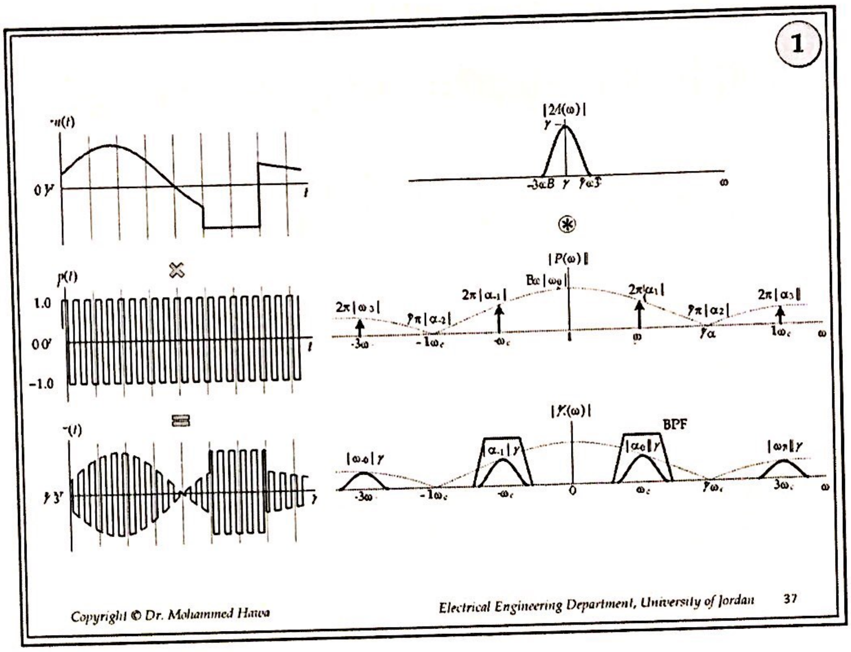
DSB-SC Switching Modulator

(*Ring modulator*)

Band-pass Filter
Gain = 1
Bandwidth = 2B Hz
Center Frequency = ω_c

$x(t) = m(t)\ ;\ -m(t)\ ;\ m(t)\ ;\ -m(t)\ ;\ \dots$

①



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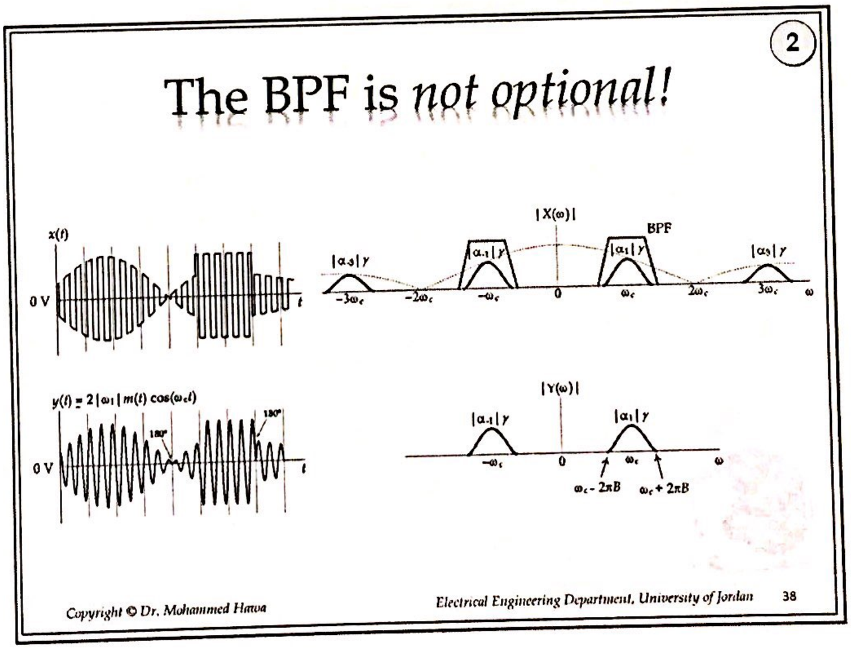
37

②



The BPF is *not optional!*

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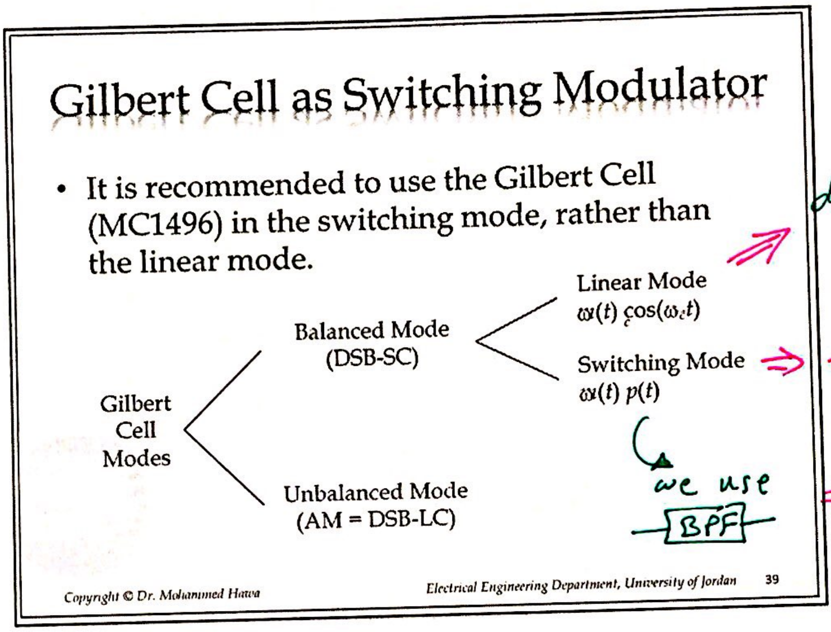

Gilbert Cell as Switching Modulator

- It is recommended to use the Gilbert Cell (MC1496) in the switching mode, rather than the linear mode.

Gilbert Cell Modes

Balanced Mode (DSB-SC)

Linear Mode $\varphi(t)\cos(\omega_c t)$

Switching Mode $\varphi(t)\,p(t)$

Unbalanced Mode (AM = DSB-LC)

doesn't use BPF ⇒ gives Less power.

this is the recomended one. ⇒ gives more power.

we use BPF

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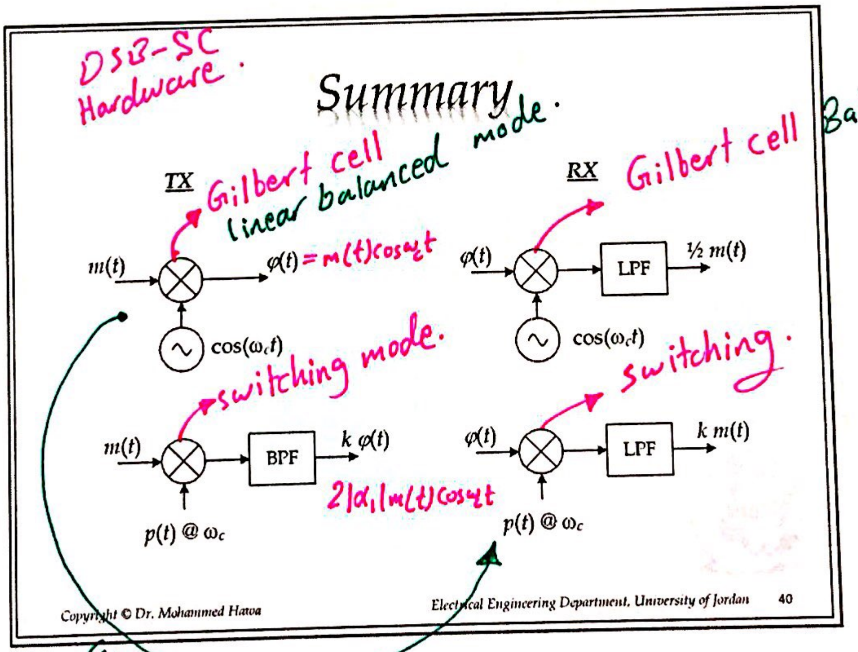

DSB-SC Hardware.

Summary.

Gilbert cell linear balanced mode.

$\varphi(t) = m(t)\cos\omega_c t$

Gilbert cell

Balanced Linear mode.

switching mode.

$2|a_1|m(t)\cos\omega_c t$

switching.

Two way To build the mixer. ⇒

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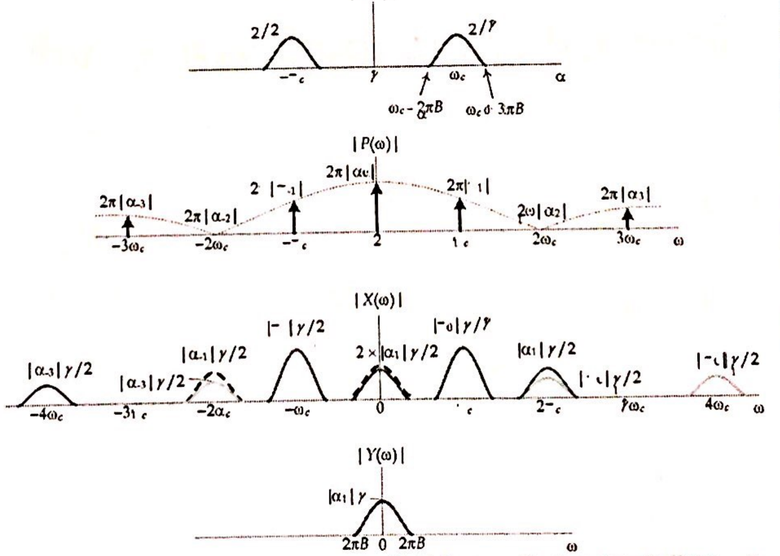
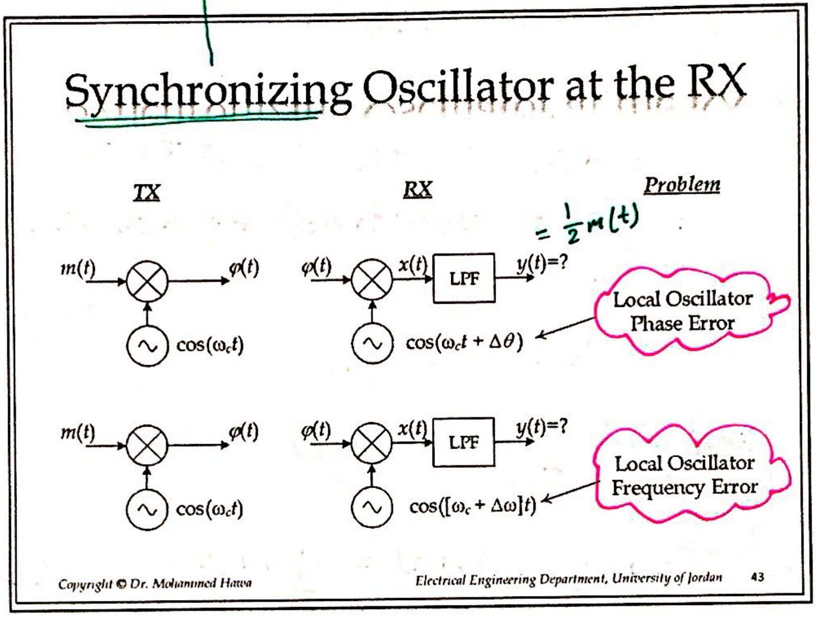
We could use them together as Tx & Rx.

Homework

- If we use a switching **de**modulator (say a series-bridge diode demodulator), answer the following:
  - What are the specifications of the filter? LPF with gain = 1
    Bandwidth = B Hz
    or $2\pi B$ rad/s.
  - What is the value of k in the output $y(t) = k\,m(t)$ if the input is $\varphi(t) = m(t)\cos(\omega_c t)$
  - What is the value of k in the output $y(t) = k\,m(t)$ if the input is $\varphi(t) = 2\,|\alpha_1|\,m(t)\cos(\omega_c t)$
  - Sketch the Fourier transform of the solution.



same freq. & phase @ Rx & Tx.



Synchronizing Oscillator at the RX

Local Oscillator Phase Error

Local Oscillator Frequency Error

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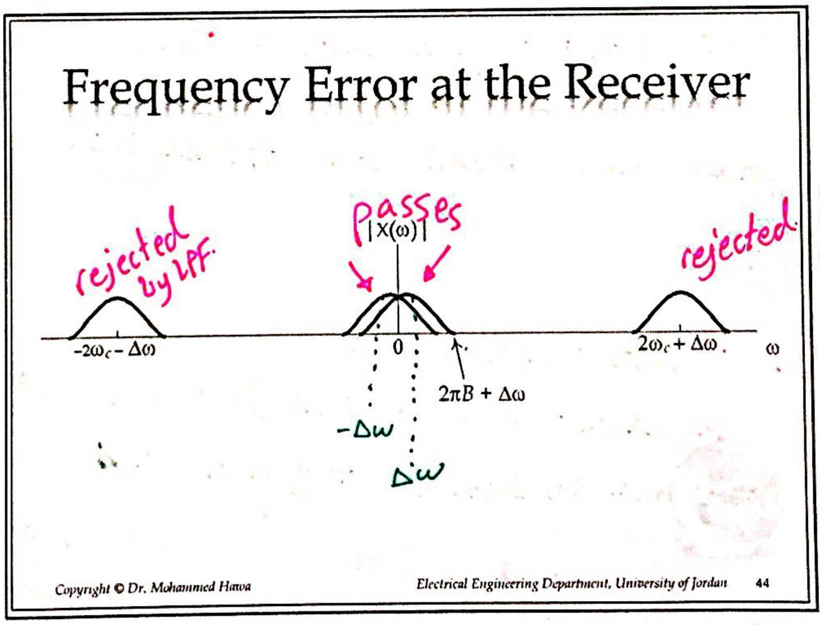

Frequency Error at the Receiver

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if we have phase & freq. errors together

Then we will have Attenuation & Distortion.

※Phase Error:

Find $y(t)$:

Solution: Tx $\phi(t) = m(t)\cos(\omega_c t)$

Rx $x(t) = \phi(t)\cos(\omega_c t + \Delta\theta)$

$$= m(t)\cos(\omega_c t)\cos(\omega_c t + \Delta\theta)$$

$$= \underbrace{\tfrac{1}{2}m(t)\cos(2\omega_c t + \Delta\theta)}_{\text{High freq. @ } 2\omega_c \text{ rejected by LPF.}} + \underbrace{\tfrac{1}{2}m(t)\cos(\Delta\theta)}_{\text{Low freq passes. LPF.}}$$

$$\Rightarrow \boxed{y(t) = \tfrac{1}{2}\cos(\Delta\theta)\, m(t)}$$

No error $\Delta\theta = 0$ $\Rightarrow y = \frac{1}{2}\cos(0)\, m(t) = \frac{1}{2}m(t)$. $\to < 1$

$\Delta\theta = 30°$ $\Rightarrow$ $y(t) = \frac{1}{2}\cos(30)\, m(t) = \frac{1}{2}\frac{\sqrt{3}}{2} m(t)$.

$\Delta\theta = 60°$ $\Rightarrow$ $y(t) = \frac{1}{2}\cos(60)\, m(t) = \frac{1}{2}\cdot\frac{1}{2} m(t)$

worst case $\Delta\theta = 90°$ $\Rightarrow$ $y(t) = \frac{1}{2}\cos(90)\, m(t) = $ Zero (No signal).

* so phase Error result "An Attenuation".

※ Frequancy Error:

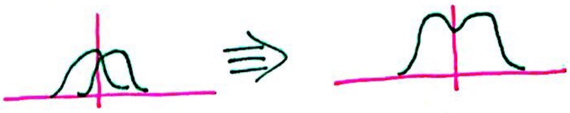
solve for $y(t)$: Tx $\phi(t) = m(t)\cdot\cos(\omega_c t)$

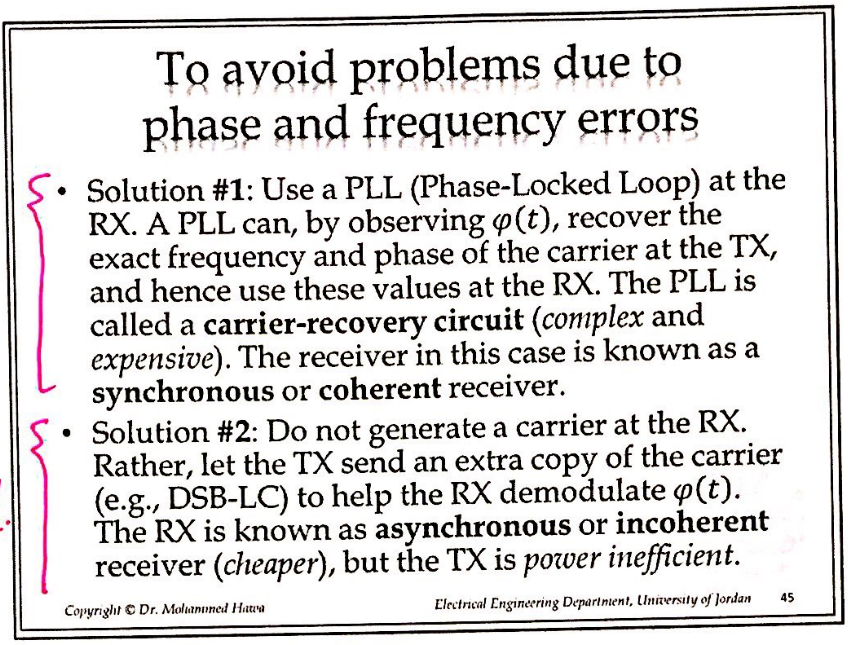
Rx $x(t) = \phi(t)\cos(\omega_c + \Delta\omega)t = m(t)\cos\omega_c t\cos(\omega_c + \Delta\omega)t$

$$= \underbrace{\tfrac{1}{2}m(t)\cos(2\omega_c + \Delta\omega)t}_{\text{High freq. so rejected by LPF.}} + \underbrace{\tfrac{1}{2}m(t)\cos(\Delta\omega)t}_{\text{Low freq. so it passes through LPF.}}$$

$$\Rightarrow \boxed{y(t) = \tfrac{1}{2}m(t)\cos(\Delta\omega t)}$$

* so freq. error result "Distortion".





To avoid problems due to phase and frequency errors

new.
- Solution **#1**: Use a PLL (Phase-Locked Loop) at the RX. A PLL can, by observing $\varphi(t)$, recover the exact frequency and phase of the carrier at the TX, and hence use these values at the RX. The PLL is called a **carrier-recovery circuit** (*complex* and *expensive*). The receiver in this case is known as a **synchronous** or **coherent** receiver.

old.
- Solution **#2**: Do not generate a carrier at the RX. Rather, let the TX send an extra copy of the carrier (e.g., DSB-LC) to help the RX demodulate $\varphi(t)$. The RX is known as **asynchronous** or **incoherent** receiver (*cheaper*), but the TX is *power inefficient*.

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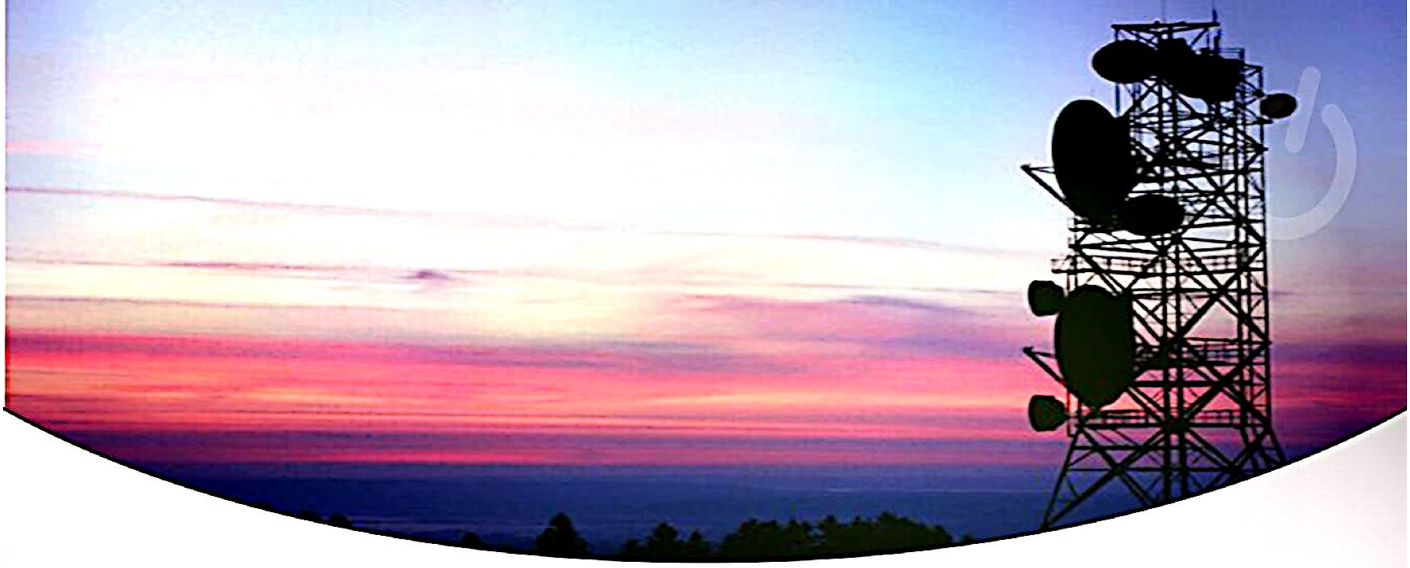
*very important (memorize): {PLL ≡ phase-LockedLoop}

$clk_{tx} \longrightarrow clk_{rx}$

must be synchronized

by using clock-recovery circuit (PLL).

represent an extra cosine.



Communications1

Fall017

Dr.Mhmd Hawa

By: Mhmd Abuhashya

www Powerunit-ju.com

Lecture 5a: Sampling and Quantization

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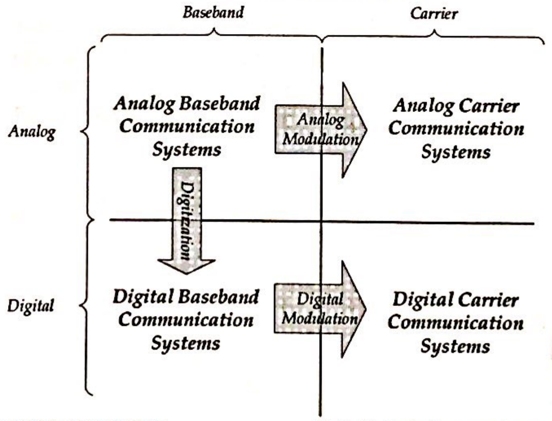
EE421: Communications I

Digitization



	Baseband	Carrier
Analog	Analog Baseband Communication Systems	Analog Carrier Communication Systems
Digital	Digital Baseband Communication Systems	Digital Carrier Communication Systems

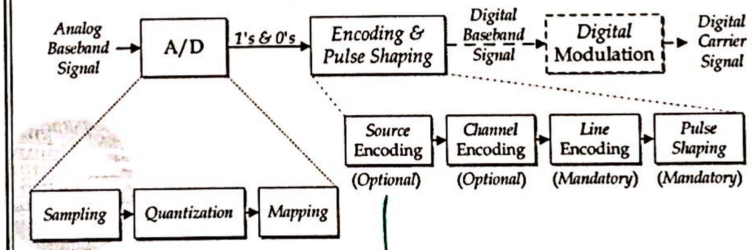
Digital Systems Advantages

- Immunity to noise (threshold detection; regenerative repeaters).
- Multiplexing at the baseband level (e.g., TDM) and carrier level (e.g., FDM, CDMA and OFDMA).
- Spread spectrum techniques and orthogonality.
- Channel coding (i.e., error correcting codes).
- Source coding techniques (i.e., compression). *Also* Encryption.
- Exchanging SNR for bandwidth.
- Using microprocessors and DSP.
- Digital signal storage is relatively easy and inexpensive.

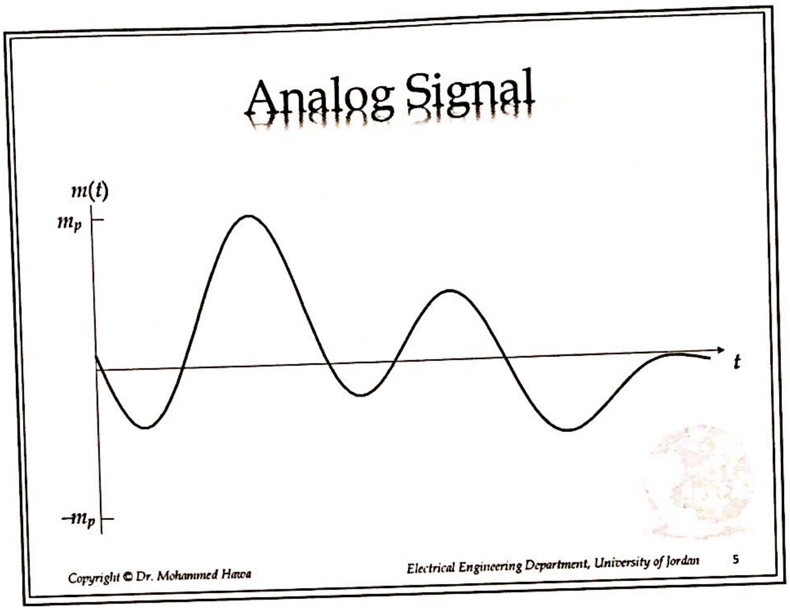
Digitization

- **Sampling** (discrete analog signal).
- **Quantization** (quantized discrete signal)
- **Mapping** (stream of 1's and 0's).
- **Encoding and Pulse Shaping** (digital baseband signal).

ideal sampling.
natural sampling.
practical sampling.



optional because its complex & expensive.
But most new systems using them.



Analog Signal

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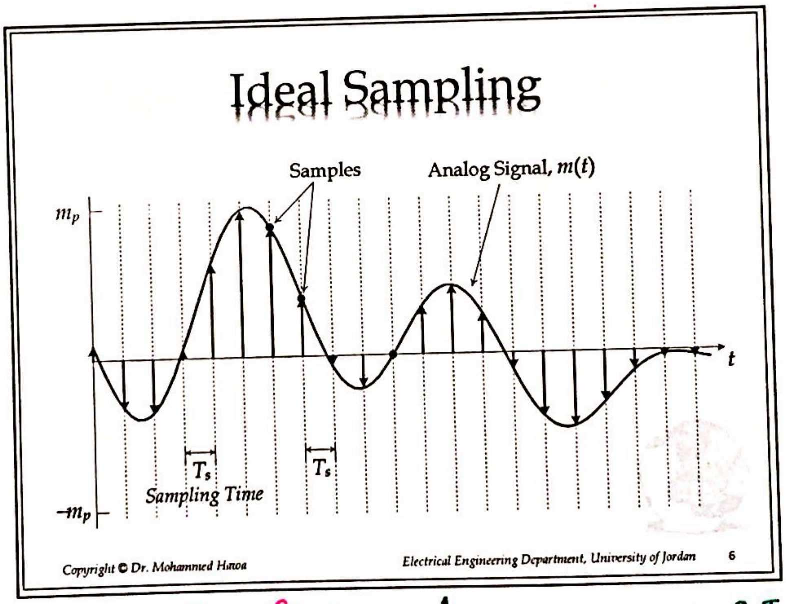
5



Ideal Sampling

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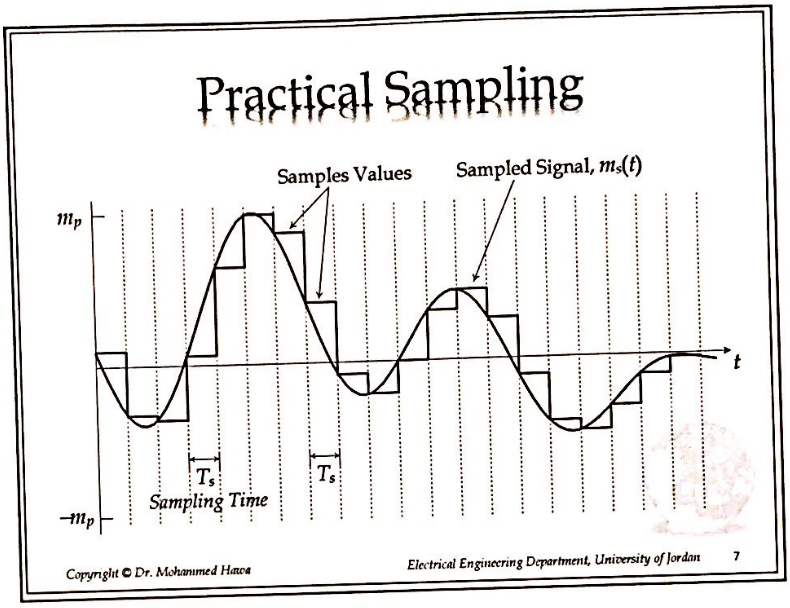
6

(f_s) sampling freq. $= \frac{1}{T_s}$, $\omega_s = \frac{2\pi}{T_s}$

T_s , $T_{symb.}$, T_o are all different.



Practical Sampling

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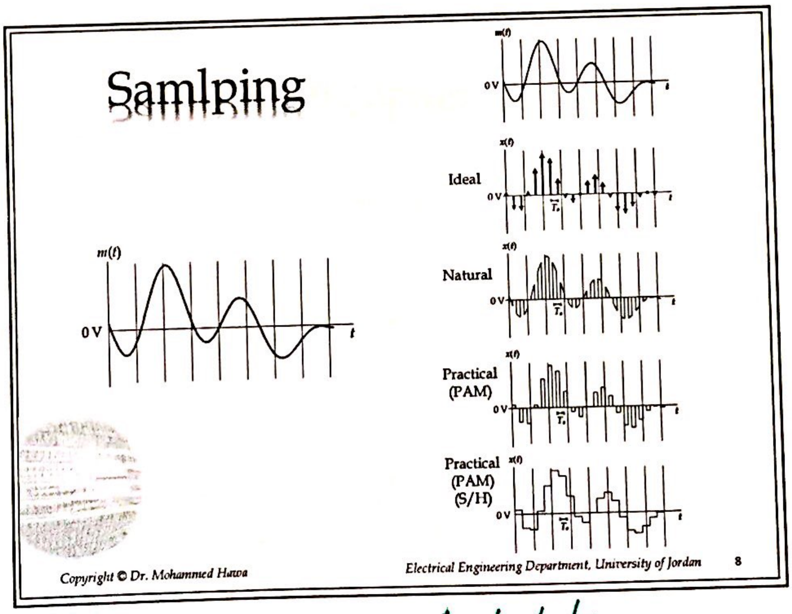

Samlping

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memorize:

PAM ≡ Pulse Amplitude Modulation.

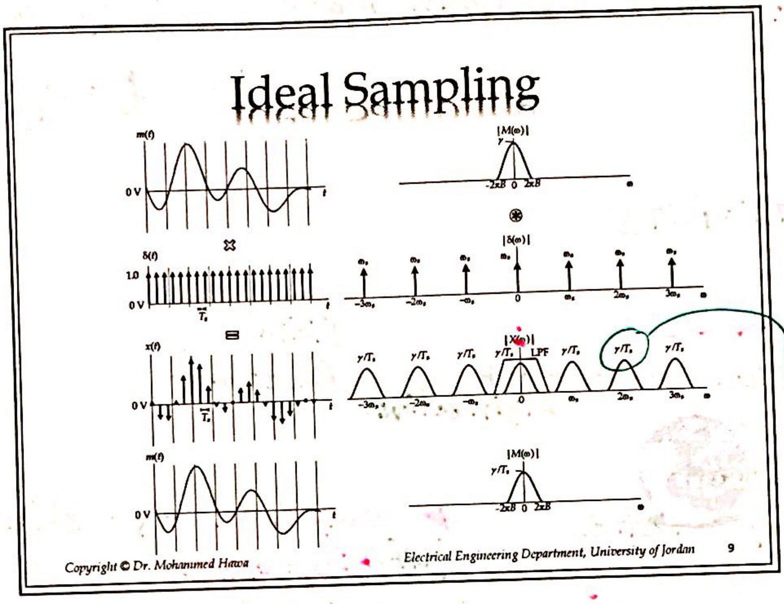
↳ This is just a name (it is NOT Modulation)

it is a practical Sampling (included in Digitization)

S/H ≡ Sample & Hold. ≡ practical sampling with max pulse width.

find $\mathcal{F}\{x(t)\} = \mathcal{F}\left\{\begin{matrix}\text{ideally-sampled} \\ \text{version of } m(t)\end{matrix}\right\} = \mathcal{F}\{m(t) \cdot \text{rep}_{T_s}\{\delta(\cdot)\}\}$

$$= \frac{M(\omega) \star \Gamma(\omega)}{2\pi}$$



Ideal Sampling

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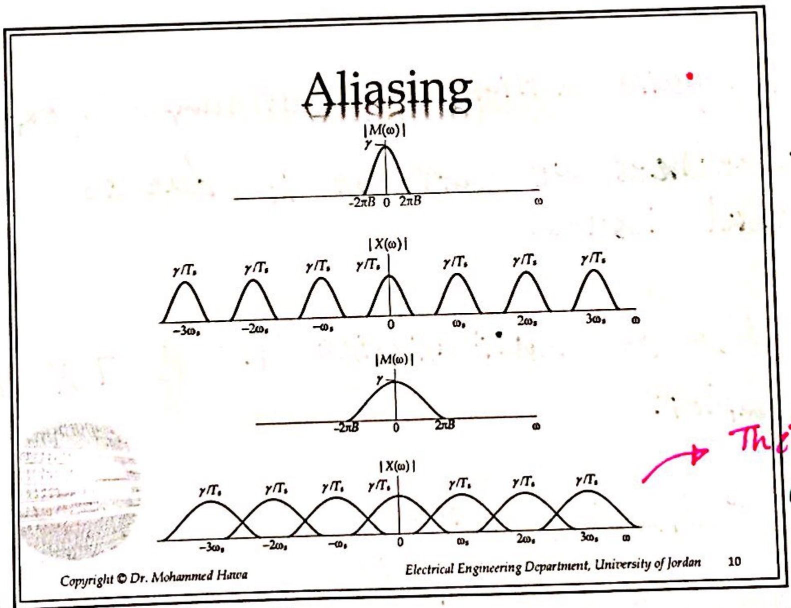
$\gamma \omega_s \cdot \frac{1}{2\pi}$

$= \gamma \frac{2\pi}{T_s} \cdot \frac{1}{2\pi}$

$= \gamma / T_s$



Aliasing

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This overlap called Aliasing.

Bandwidth = B Hz
or = 2πB rad/s
gain = 1

* To avoid the problem of Aliasing ?

- **SoL #1**: follow Nyquist Rate $\underline{\underline{\omega_s}} \geq 4\pi B$ rad/s.

  OR $f_s = \frac{1}{T_s} \geq 2B$ HZ

Ex1: PSTN = POTS

m(t) = voice.
analog.
baseband.
$B_{voice} = 4KHZ$.

→ sampling: $f_s = 8KHZ = \frac{8000 \text{ samples}}{sec}$

$\boxed{LPF} \rightarrow B_{LPF} = 4KHZ$.

also CD's ⇒ $B_{music} = 20KHZ$ & $f_s = 44.1KHZ$.

*Solution 1 require a High number of samples (expensive)

so sometimes we can't use it due to practical issues.

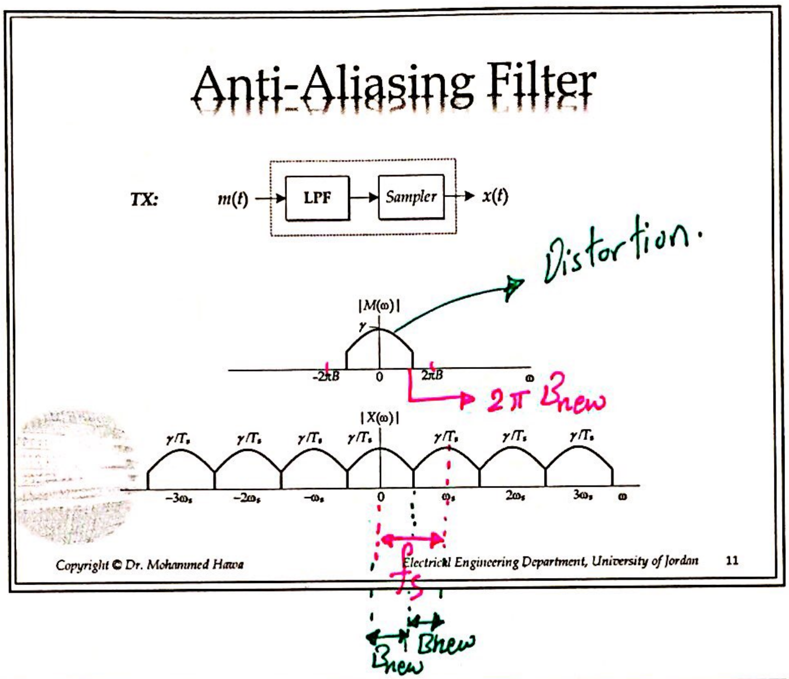
- **SoL#2**: Use an Anti-aliasing LPF @ TX before the sampler.

$$B_{LPF} = B_{new} = \frac{1}{2} f_s \text{ HZ}$$

$$2\pi B_{new} = \frac{1}{2} \omega_s \text{ rad/s.}$$

But here we end-ups with distortion

in sol#1:
No-aliaing
No-distortion



Anti-Aliasing Filter

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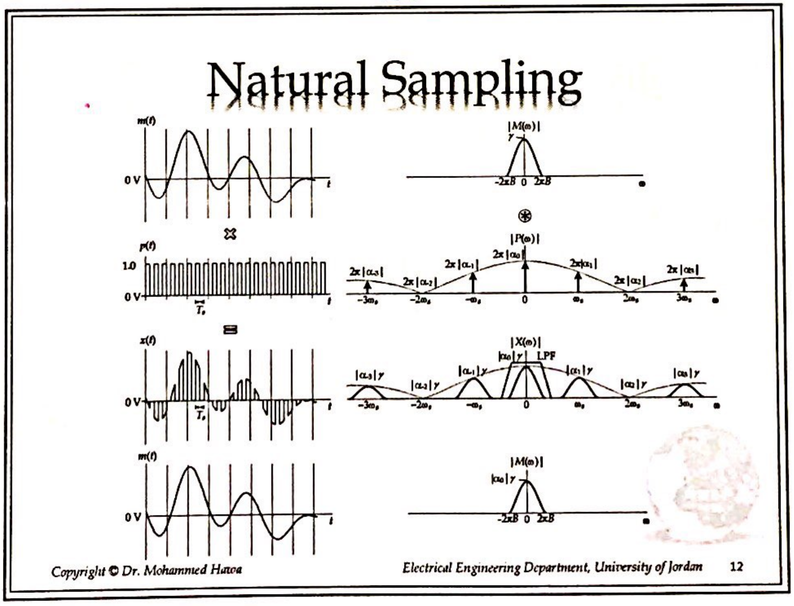
11



Natural Sampling

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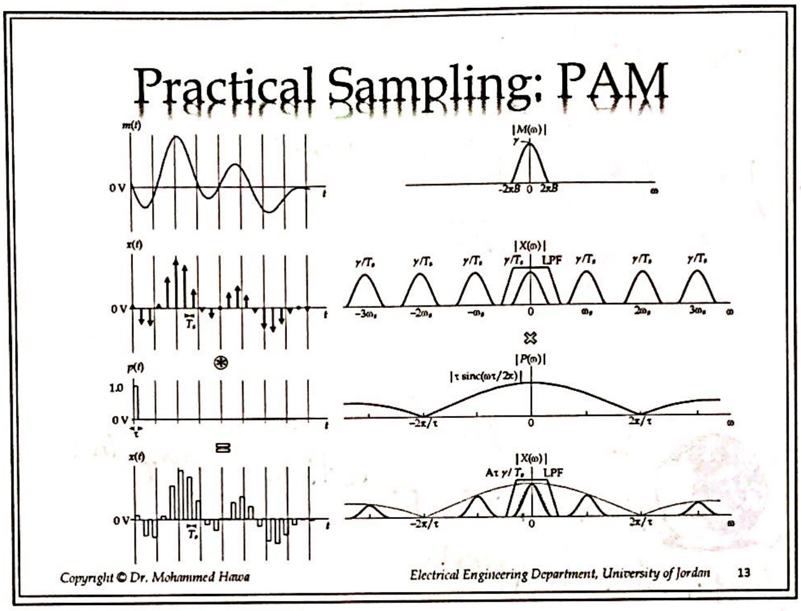
12



Practical Sampling: PAM

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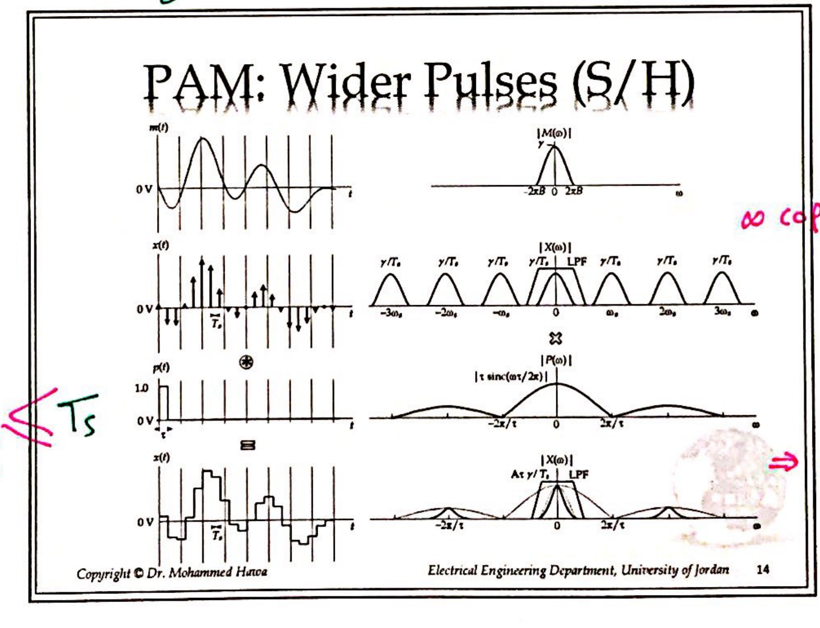
$\mathcal{F}\{x(t) \circledast y(t)\} = X(\omega) \cdot Y(\omega)$.



PAM: Wider Pulses (S/H)

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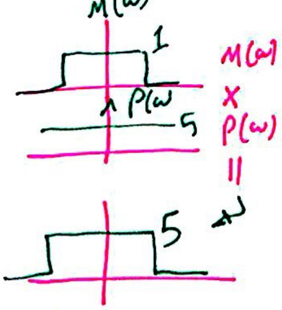
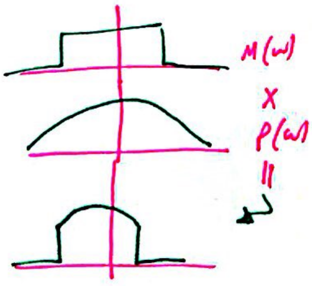
∞ copies.

τ pulse width $\leq T_s$

⇒ distorted ∞ copies.





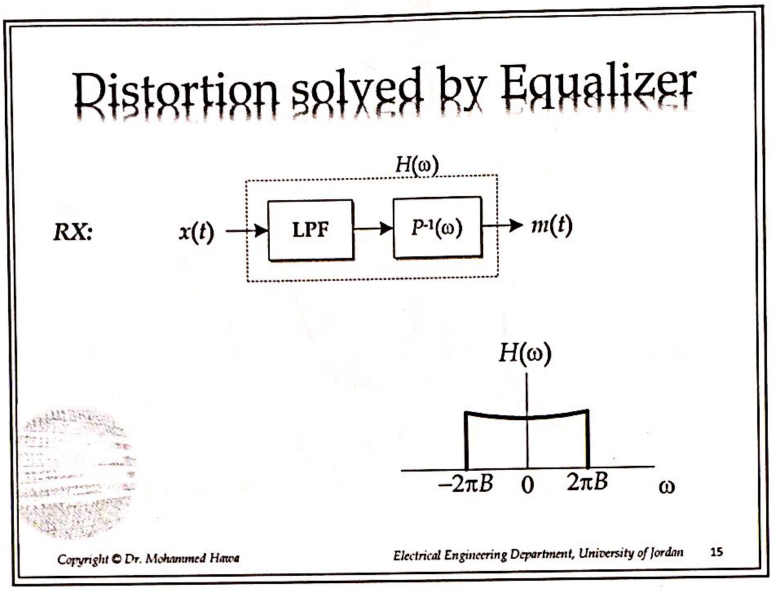
※ Solution for Distortion in practical sampling:

- Sol #1: Narrower Pulse Width. @ Tx.
  (expensive).

Time Expansion
⇕
Freq. Compresion.

- Sol #2: Equalizer @ Rx.
  (expensive).

* So Why we use Equalizer?
it is a solution for practical sampling when distortion happen.



Distortion solved by Equalizer

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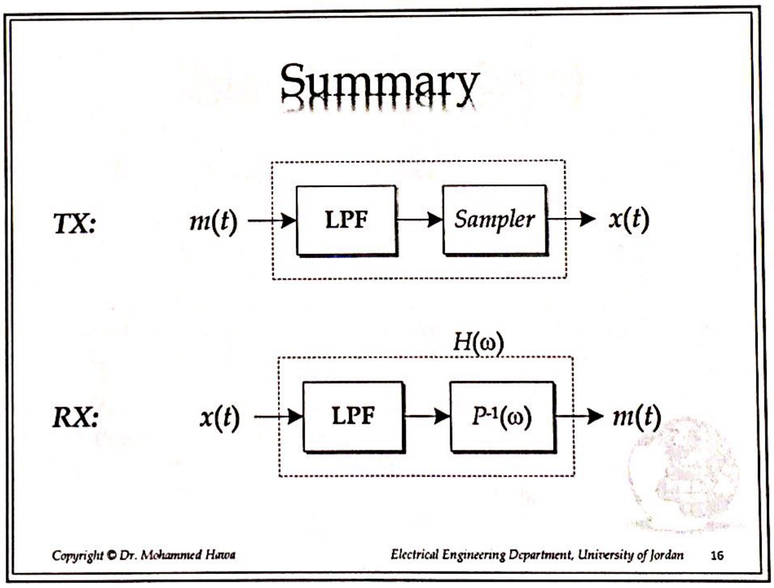

Summary

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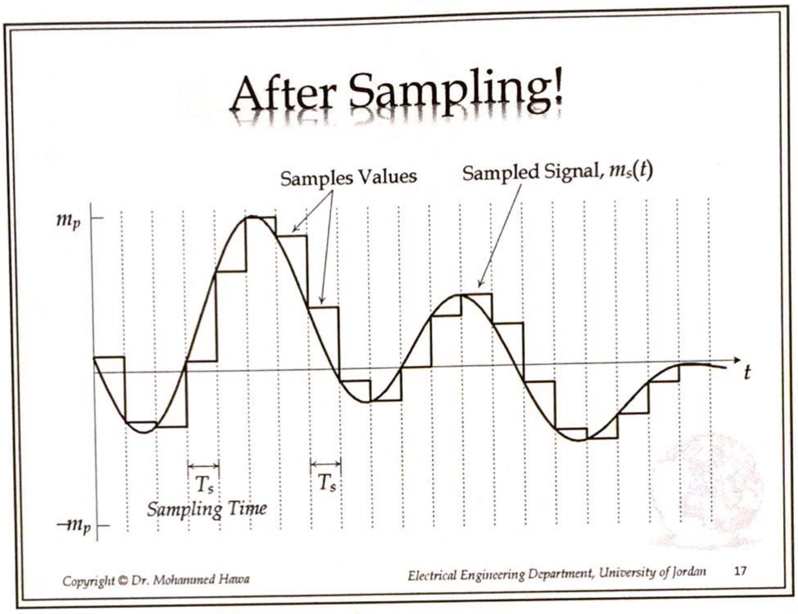

After Sampling!

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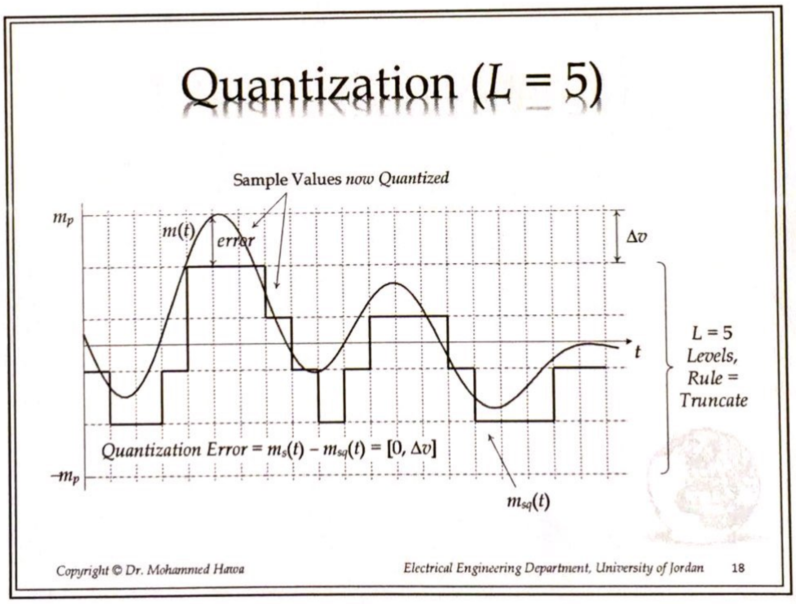

Quantization (L = 5)

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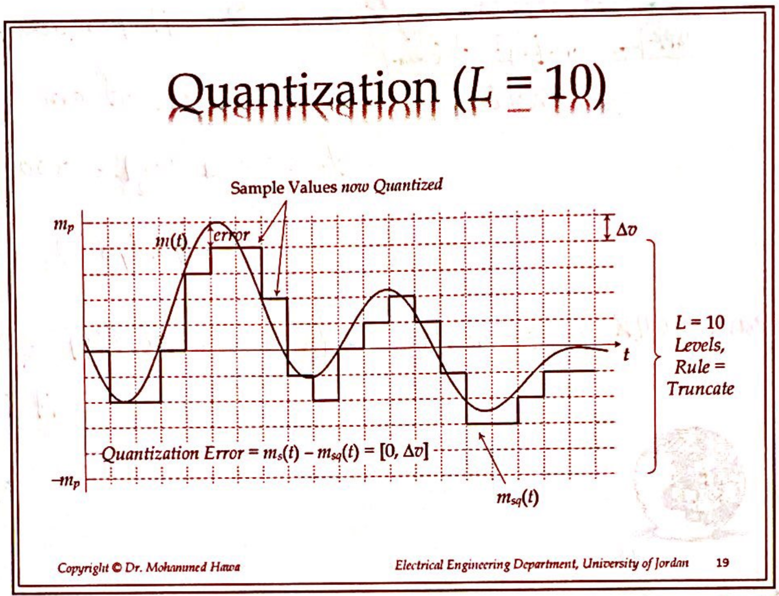

Quantization ($L = 10$)

Quantization Error = $m_s(t) - m_{sq}(t) = [0, \Delta v]$

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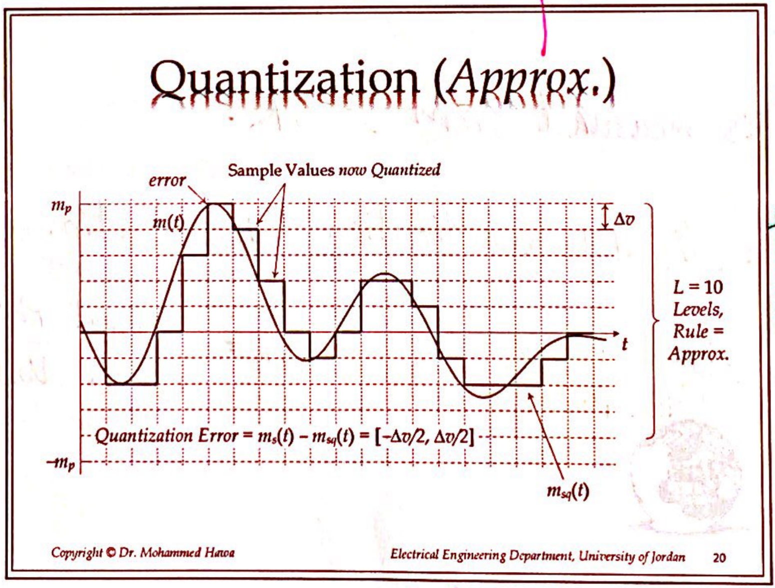

Quantization (*Approx.*)

Quantization Error = $m_s(t) - m_{sq}(t) = [-\Delta v/2, \Delta v/2]$

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if L=4 levels.

3V
2V
1V
0V

send 1.6V
≃2V will be sent.
(0.4V) Qunt. Error.

if L=8 levels.

3.5V
3V
2.5V
2V
1.5V
1V
0.5V
0V

send 1.6V
↓
≃1.5V
less error.

※Try for L=16
& L=32.

L ≡ #of Quantization Levels

L↑ ⇒ Quantization error↓

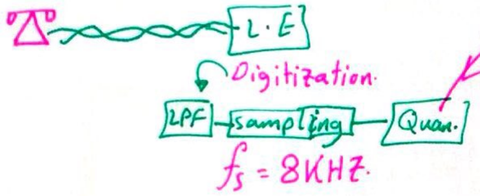
〃 Noise↓

Quality↑
bits Per sample↑
Expensive.↑

for L=4: Need 2-bits to represent.
L=8: 3-bits.
L=16: 4-bits.
L=32: 5-bits.
⋮
(More Expensive).

Example (1): Telephony. → what line coding used in Telephony?

Bipolar.



L = 256 Levels.

8-bit per sample.

Data Rate of one phone call:

$$f_o = f_s * \log_2 L = 8000 \frac{\text{sample}}{\text{sec.}} * 8 \frac{\text{bits}}{\cancel{\text{sample}}}$$

$$\boxed{f_o = 64 \text{KBps}}$$

* PCM stream (64Kbps) ≡ Pulse Coded Modulation ≠ Modulation.

it is digital Baseband. of one phone call

Example (2): CD's

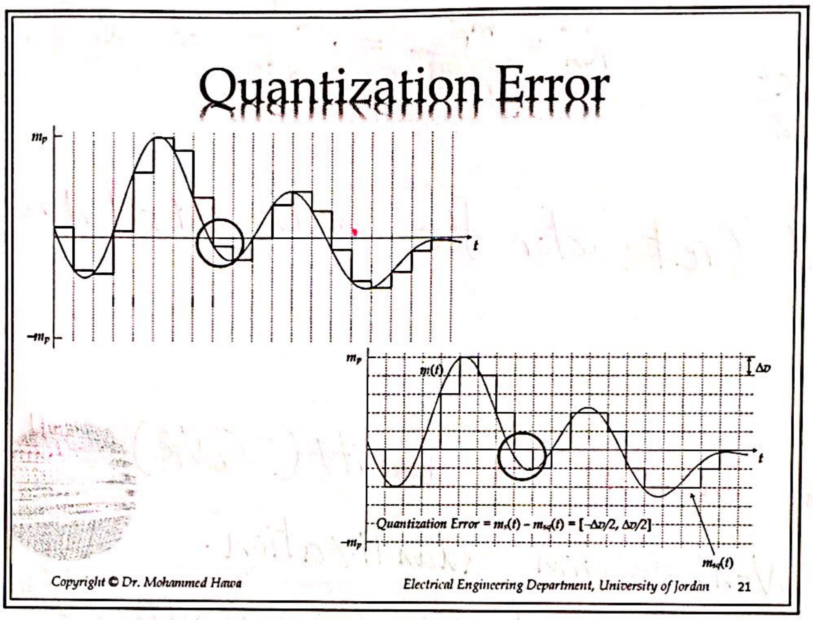
$L = 65{,}536 = 2^{16}$

16-bit/sample.

\# Quality is measured from SNR.

SQNR ≡ Signal to Quantization Noise Ratio.

$$\boxed{SNR = \frac{\text{signal Power}}{\text{Noise Power}}} , \boxed{SQNR = \frac{\text{signal Power}}{\text{Quant. Noise Power.}}}$$



Quantization Error

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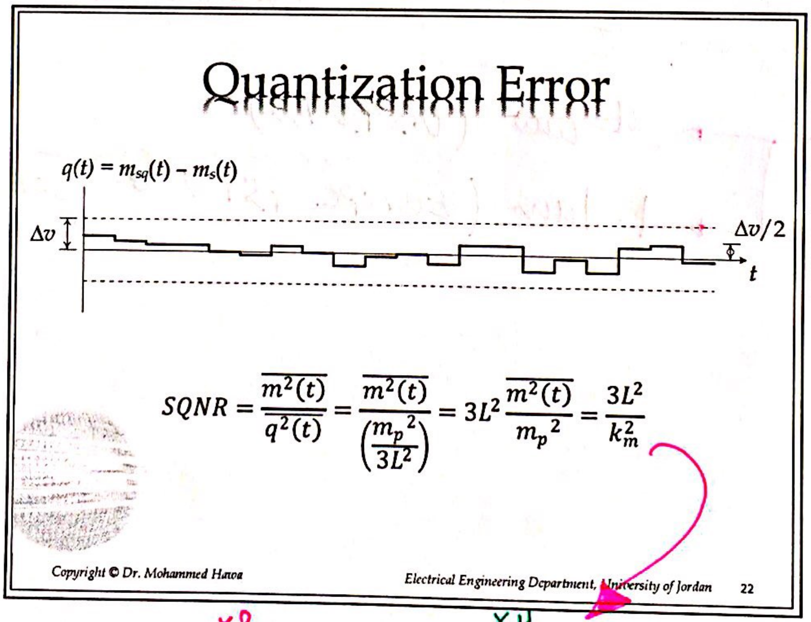

Quantization Error

$q(t) = m_{sq}(t) - m_s(t)$

$$SQNR = \frac{\overline{m^2(t)}}{\overline{q^2(t)}} = \frac{\overline{m^2(t)}}{\left(\frac{m_p{}^2}{3L^2}\right)} = 3L^2 \frac{\overline{m^2(t)}}{m_p{}^2} = \frac{3L^2}{k_m^2}$$

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$L \uparrow^{\times 2}$ SQNR $\uparrow^{\times 4}$

$L \uparrow^{\times 5}$ SQNR $\uparrow^{\times 25}$

K_m^2 ≡ Crest Factor OR Peak-to-RMS Ratio

$$K_m^2 = \frac{m_p^2}{m_{rms}^2}$$

$$\boxed{K_m^2 = \frac{m_p^2}{m_{rms}^2} = \frac{m_p^2}{\text{avg. Power}} = \frac{m_p^2}{\overline{m^2(t)}}}$$

Example: find the Crest Factor for $m(t) = \alpha \cos(\omega_m t)$?

$m_p = \alpha$

$\overline{m^2(t)} = \frac{\alpha^2}{2}$

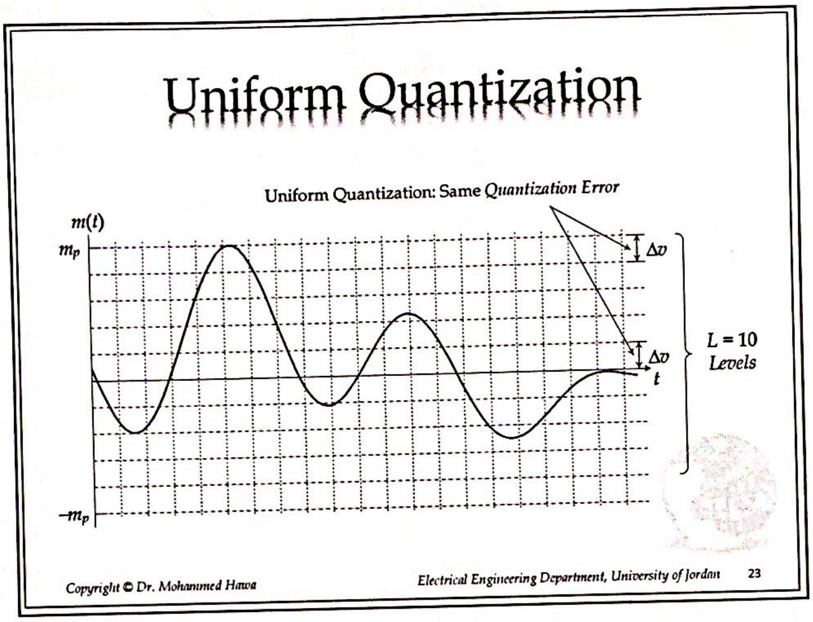
$$K_m^2 = \frac{m_p^2}{\overline{m^2(t)}} = \frac{\alpha^2}{\alpha^2/2} = \boxed{2}.$$

HW: find Crest factor for $m(t) = rep_T\left[A\,rect\left(\frac{t}{\tau}\right)\right]$. ?

* You Can Increase the Quality (SQNR) without increasing L

Using: Non-uniform Quantization.
OR
$\equiv$ Companding $\equiv$ Compression / Decompression.
(used in Telephony)

- μ-law (U.S PSTN)
- A-law (Europe PSTN & Jordan).



Uniform Quantization

Uniform Quantization: Same *Quantization Error*

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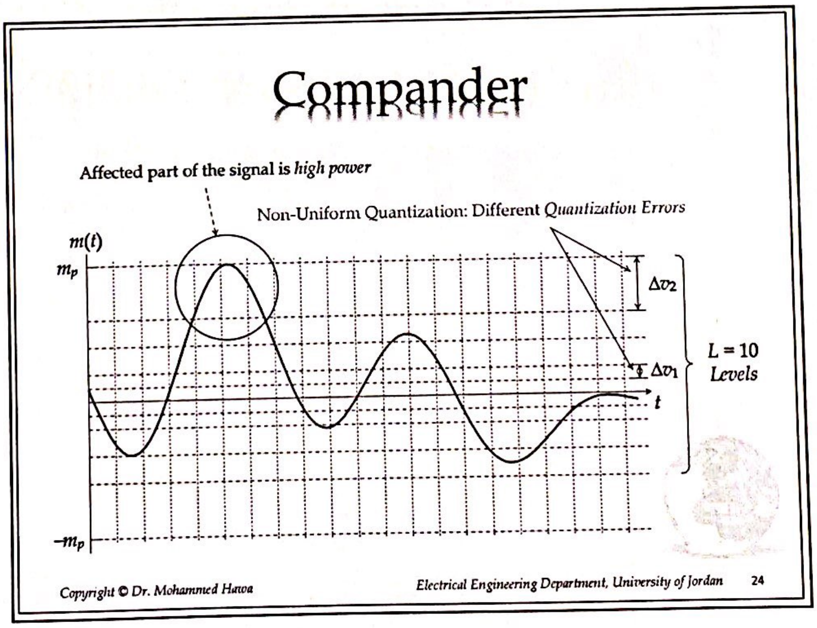

Compander

Affected part of the signal is *high power*

Non-Uniform Quantization: Different *Quantization Errors*

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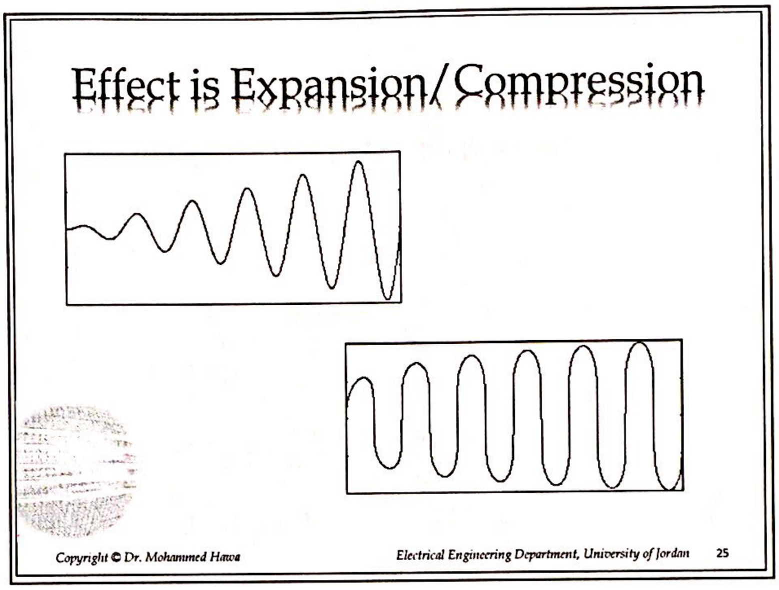

Effect is Expansion/Compression

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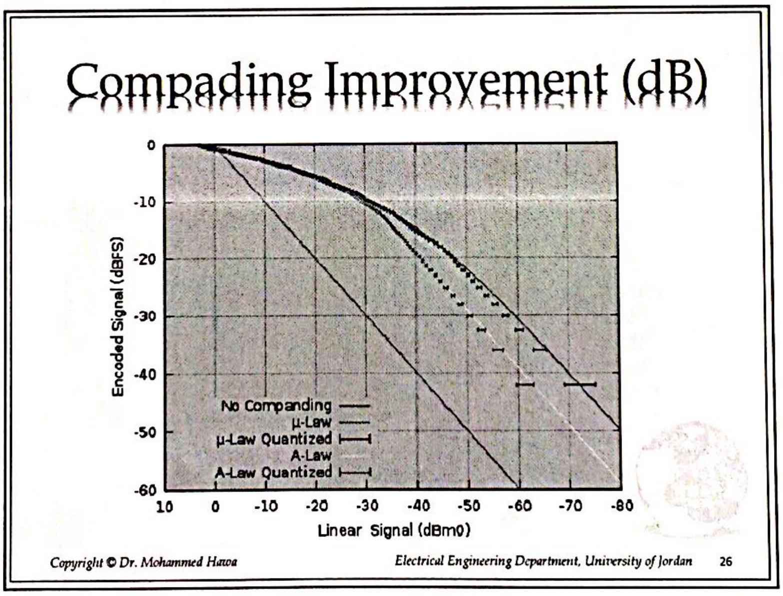

Companding Improvement (dB)

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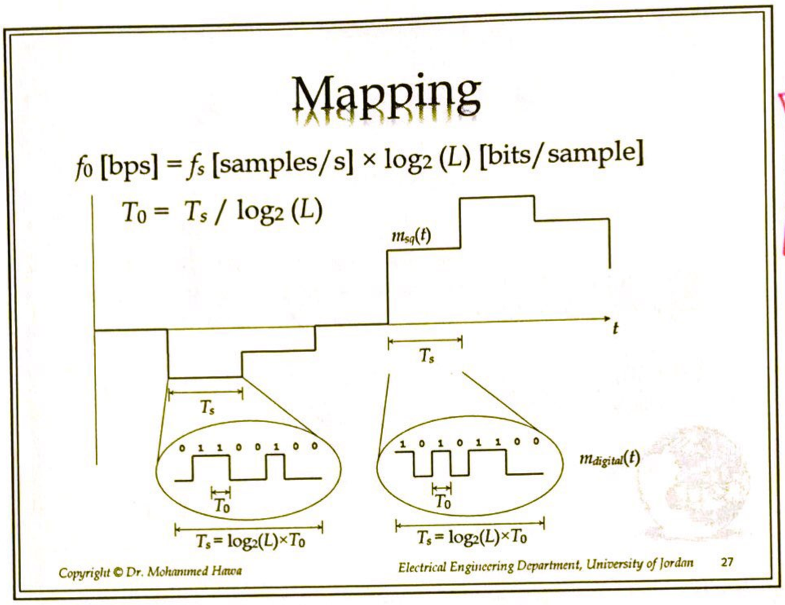

Mapping

f_0 [bps] = f_s [samples/s] × $\log_2(L)$ [bits/sample]

$T_0 = T_s / \log_2(L)$

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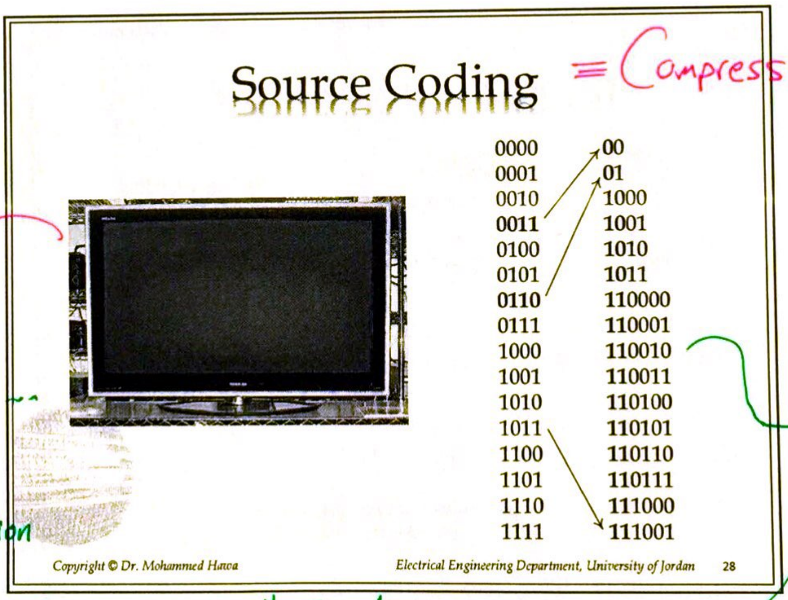
L=4

3V	11
2V	10
1V	01
0V	00

2bits

#of bits = $\log_2 L$



Source Coding

= Compression.

0000	00
0001	01
0010	1000
0011	1001
0100	1010
0101	1011
0110	110000
0111	110001
1000	110010
1001	110011
1010	110100
1011	110101
1100	110110
1101	110111
1110	111000
1111	111001

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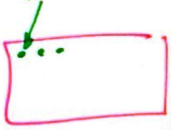
for 16 possible colors Need 4 bits.

pixels.



it will send:

blue blue blue - - - - -

0101 0101 0101 - - -

↳ we take 0101 repeat 16 million times (if 16Mpixels).

- RLE: Run-length Encoding.
- Huffman encoding.

popular ⇒ short Keyword.

rare ⇒ Longer Keyword.

16M pixels

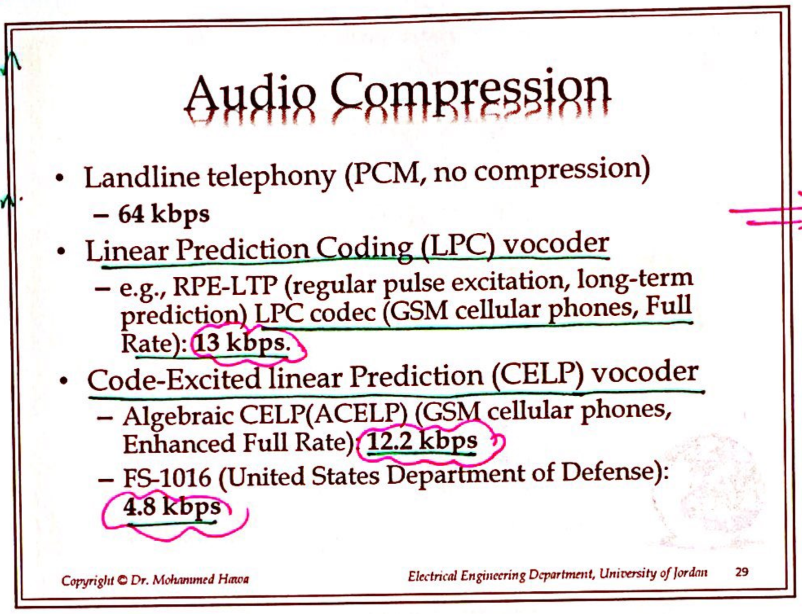
↳ 16 million points.

Landline: (Doesn't use Compression = source Coding).

Cellular: Uses Source Coding.

cell phone.

digitization including compression.



Audio Compression

- Landline telephony (PCM, no compression)
  - **64 kbps**
- Linear Prediction Coding (LPC) vocoder
  - e.g., RPE-LTP (regular pulse excitation, long-term prediction) LPC codec (GSM cellular phones, Full Rate): **13 kbps.**
- Code-Excited linear Prediction (CELP) vocoder
  - Algebraic CELP(ACELP) (GSM cellular phones, Enhanced Full Rate): **12.2 kbps**
  - FS-1016 (United States Department of Defense): **4.8 kbps**

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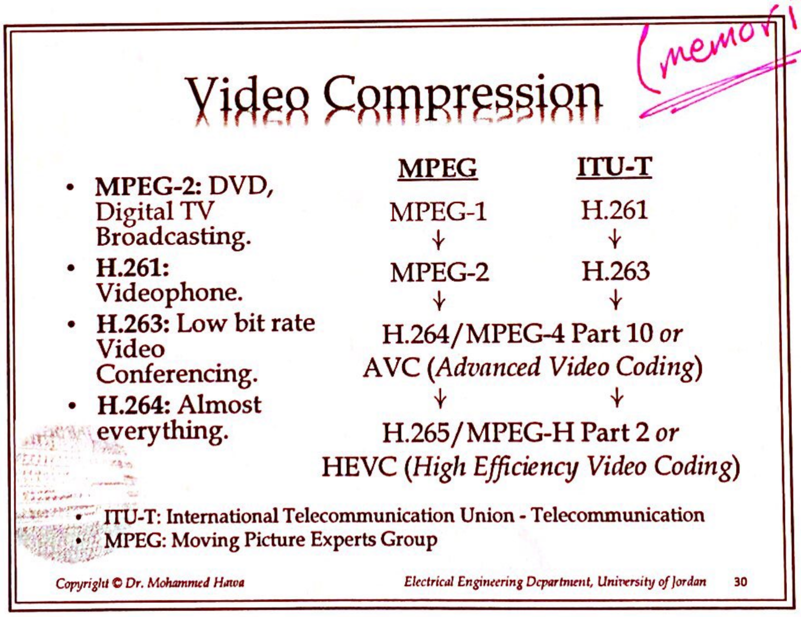
⇒ Memorize the underlined.

(memorize).



Video Compression

- **MPEG-2:** DVD, Digital TV Broadcasting.
- **H.261:** Videophone.
- **H.263:** Low bit rate Video Conferencing.
- **H.264:** Almost everything.

MPEG	**ITU-T**
MPEG-1	H.261
↓	↓
MPEG-2	H.263
↓	↓
H.264/MPEG-4 Part 10 *or* AVC (*Advanced Video Coding*)	
↓	↓
H.265/MPEG-H Part 2 *or* HEVC (*High Efficiency Video Coding*)	

- ITU-T: International Telecommunication Union - Telecommunication
- MPEG: Moving Picture Experts Group

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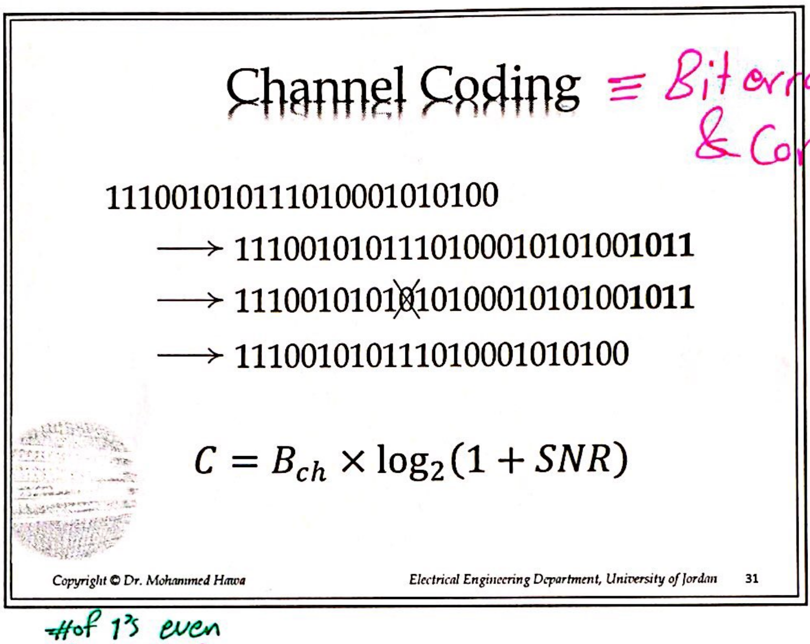

Channel Coding ≡ Bit error detection & Correction.

Ex. parity bit.

11100101010111010001010100

⟶ 11100101010111010001010100**1011**

⟶ 111001010101$\cancel{0}$1010001010100**1011**

⟶ 11100101010111010001010100

$$C = B_{ch} \times \log_2(1 + SNR)$$

# of 1's even

$\underbrace{1011010}_{\text{errors could happen.}}\ \underbrace{0}_{\text{parity bit}}$

FEC ≡ Forward Error Correction.

HW: see satellite Receiver (setup → menu).