Communications I Notes

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Communication Lecture 1 "Nolo"

m(t) is the baseband message signal

↳ a voltage or current or Em ... that represents the information.

(1) "Impairments : problems, limitations, ... Noise, etc

* 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 was attenuated by the channel.

Attenuation ≡ power loss

eg $m(t) = 5V$ (a) $m'(t) = 4.5V$

(b) $m'(t) = 3V$ more loss or more attenuation

① Attenuation exists for all signal types

② " " " " channel types but the level of attenuation depends on the channel type.

(3) Attenuation increases as the length of the channel increases.

f_1 Hz $f_2 > f_1$

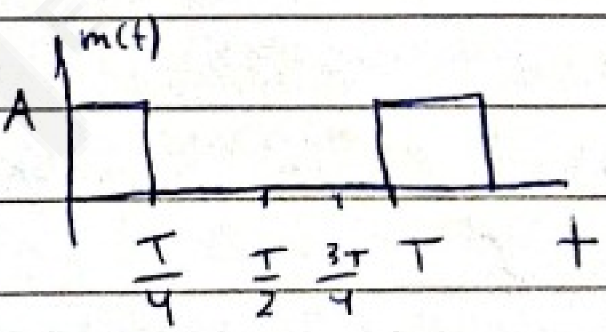
$2\pi f_1$ rad/s

f_2 f_1

$P_{ave} = \frac{A^2}{2}$: $(V_{rms})^2 = \left(\frac{A}{\sqrt{2}}\right)^2$ for $A\cos(2\pi f t)$

$P_{ave} = \frac{V^2_{rms}}{\cancel{R} \to 1\Omega}$ we assumed that R is 1Ω

HW)



$P_{ave} = \lim_{T \to \infty} \frac{1}{T} \int_T m^2(t)\,dt$

Channels

* wireless
* copper wire
* Coaxial cable
* Optical fiber = wave guide

more attenuation

more expensive

**

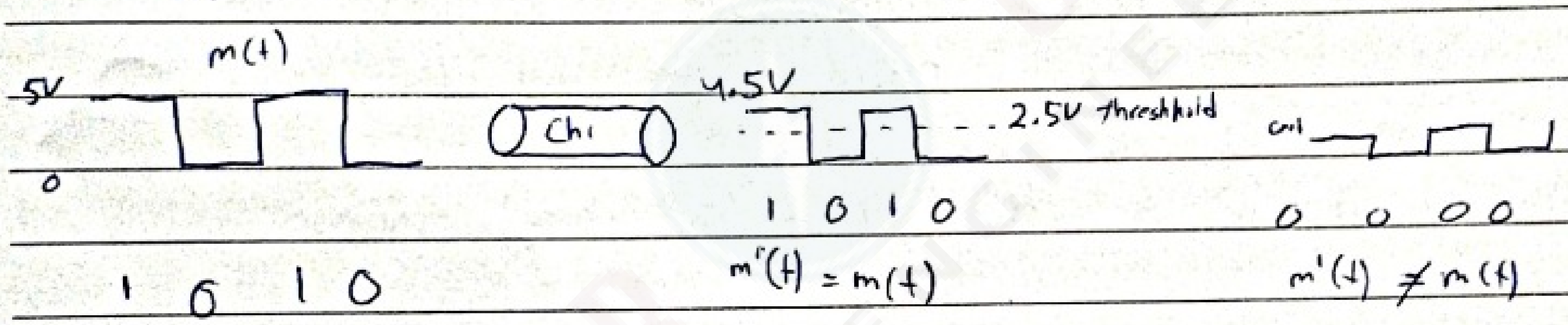
ch (a) 0.9 /km
ch (b) 0.8 /km → more attenuation.

HW ch 10km calculate g

** If we use copper wires you need an amplifier every 5-10 km
** If we use optical fibers you need an amplifier every 50-100 km

Lecture 2

TX



(2) Linear distortion
* The channel attenuation changes according to the transmitted signal frequency. Usually, higher frequency is attenuated more. This means that the channel acts as a LPF with finite channel bandwith, that blocks high frequencies, thus distorting the signal.

$Z_R = R'$ $\quad Z_C = \frac{1}{j\omega C}$ $\quad Z_L = j\omega L$

low freq → $Z_C = \infty$ = open circuit

hi freq → $Z_C \to 0$ = S.C $\quad m'(t) = 0$ heavy attenuation.

H(f): frequency transfer function
response

For -ve DB curve

H(W): Means attenuation (lower att) red colour"

ex) Which channel has more attenuation coax 30m, or copper wire 30m

ex) which has more att

coax 30m or coax 300m "lower curve"

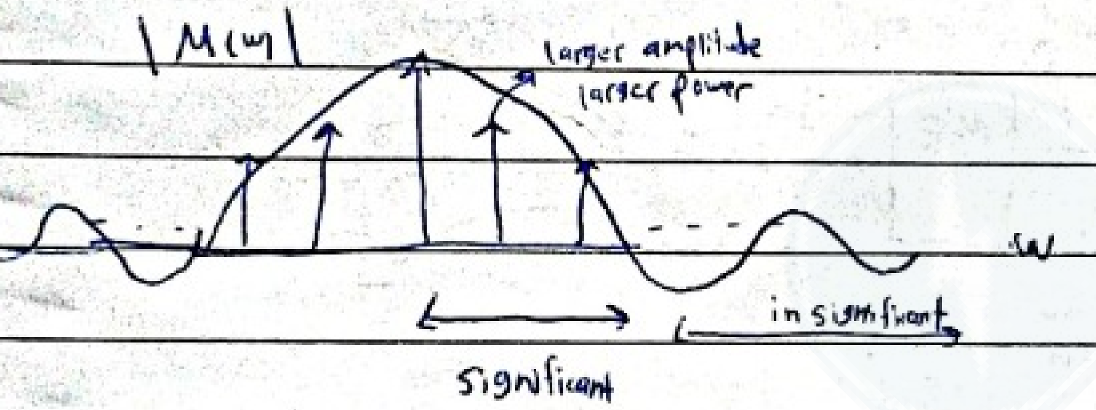
For the OB curves in the next slide the higher curve has more attenuation.

Lecture 3

*- $B_{channel}$ ≡ ① It is a property of the channel itself
Hz
② You read it from the datasheet of the channel.
③ It is the frequency after which the channel presents heavy attenuation.

$BW_{channel} = \frac{rad}{s} = 2\pi B_{channel}$

*- $B_{m(t)}$ ≡ bandwidth of the message. "B" is used in Hz



B ≡ ① It is a property of the message not the channel.
② You figure it out from $F\{m(t)\} = M(\omega)$
③ The frequency after which $M(\omega)$ has insignificant components.

* Bandwidth of copper ch (1km) is 1-2 MHz
* Bandwidth of Coax (1km) is 1-2 GHz

ex) LPF $B_{channel} = 1.5$ MHz
$B = 3$ MHz

① Bigger $B_{channel}$ 1-2 GHz
② OR compress the frequency by expanding in time domain
"Slower data rate"

*- An equalizer is a complex expensive device. It works by opposing the effect of the channel.

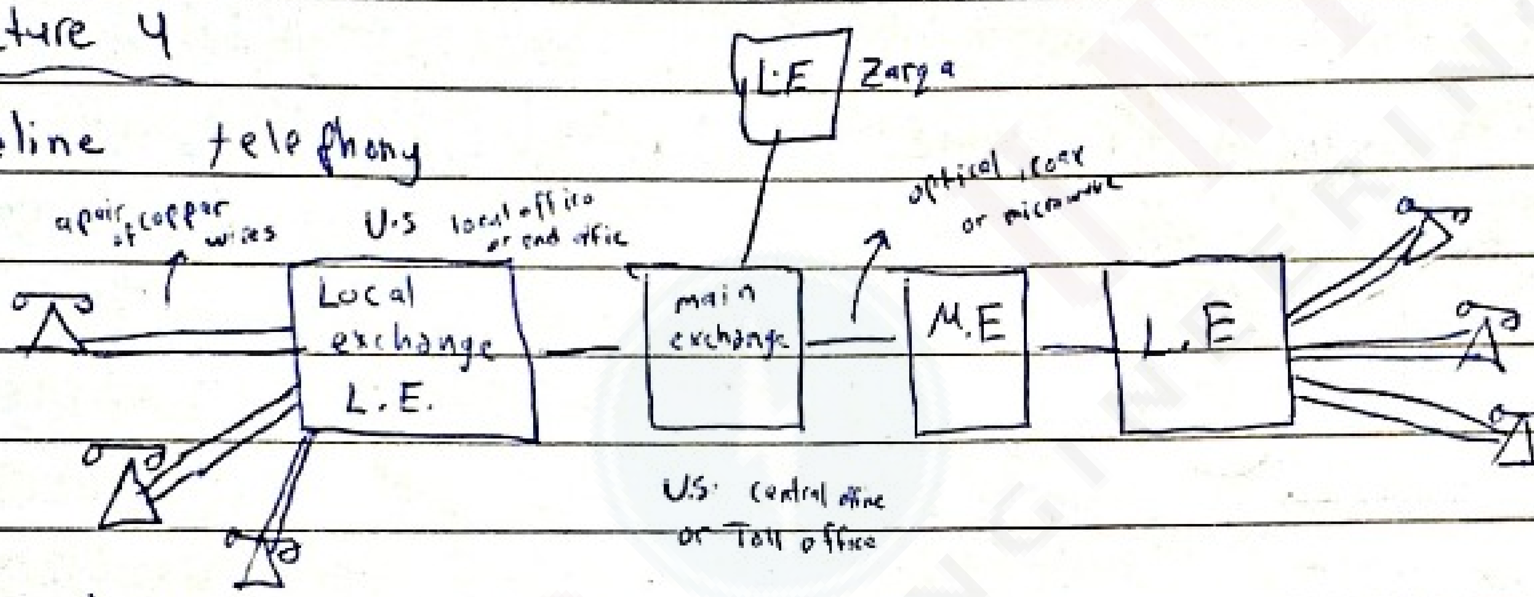
	Channel	Equalizer
low freq	less att	low gain Amp
Hig freq	more att	high gain amplifier.

③ Non-linear distortion :- The channel attenuation changes according to the transmitted signal amplitude and/or the transmitted signal frequency. Usually, higher amplitudes are attenuated more. This distorts the signal.

④ Noise: all undesired signals that are not part of the transmitted signal which gets added by the channel. Noise is non-deterministic (random) and is generated by external and internal sources.

Lecture 4

Landline telephony



Local loop or Last mile — Core — Local loop or Last mile

PSTN — POTS

PSTN: public switched telephony Network

POTS: plain-old telephony service

+ Solutions for external noise:-

1) sheilding :- very effective ~~and~~ but very expensive

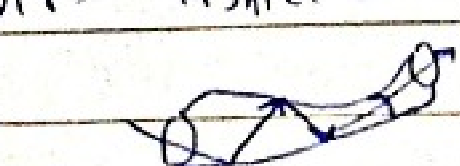
STP :- sheilding twisted pair.

2) Twisting :- less effective but much cheaper

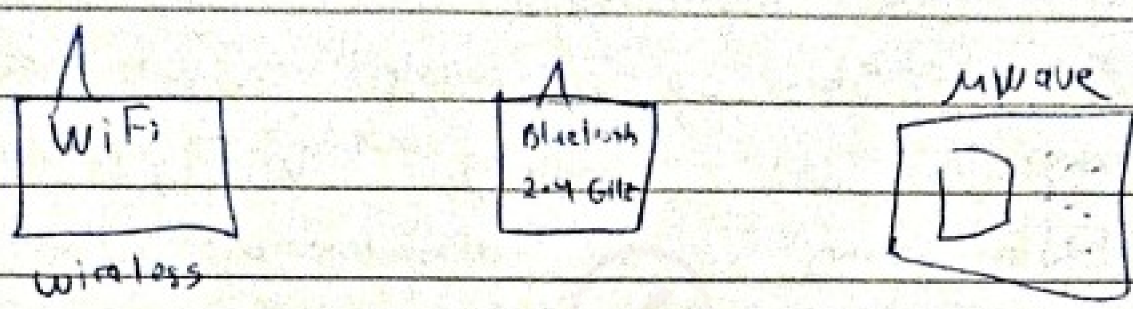
UTP :- unshielded twisted pair

3) ~~Star~~ ~~Quad~~

different cable designs



4) paper daisn



wireless

ISM 2.4 GHz 2.4 GHz

lecture 5

HW Find 3 ISM bandwiths " ex 2.4 GHz"

* Cooling :- T ↓ thermal energy ↓ random motion of e^- ↓

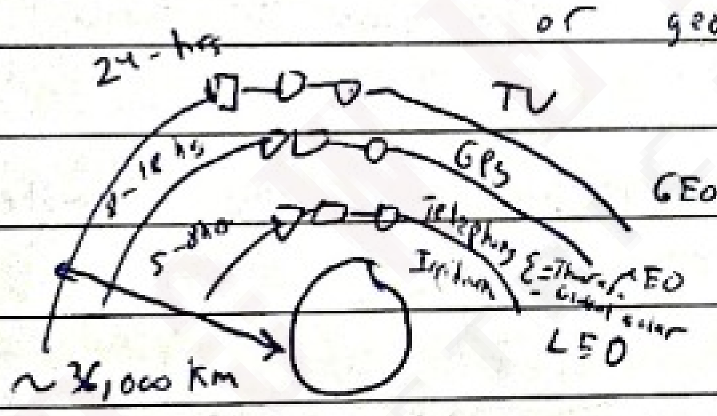
very effective but very expensive

* Satellite : LEO : low - earth orbit

MEO : medium - earth orbit

GEO : geo synchronous earth orbit

or geostationary earth orbit



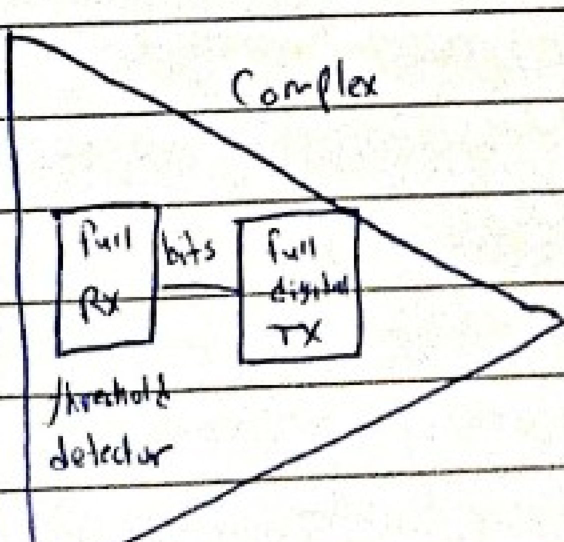
LNA : low - nois amplifier

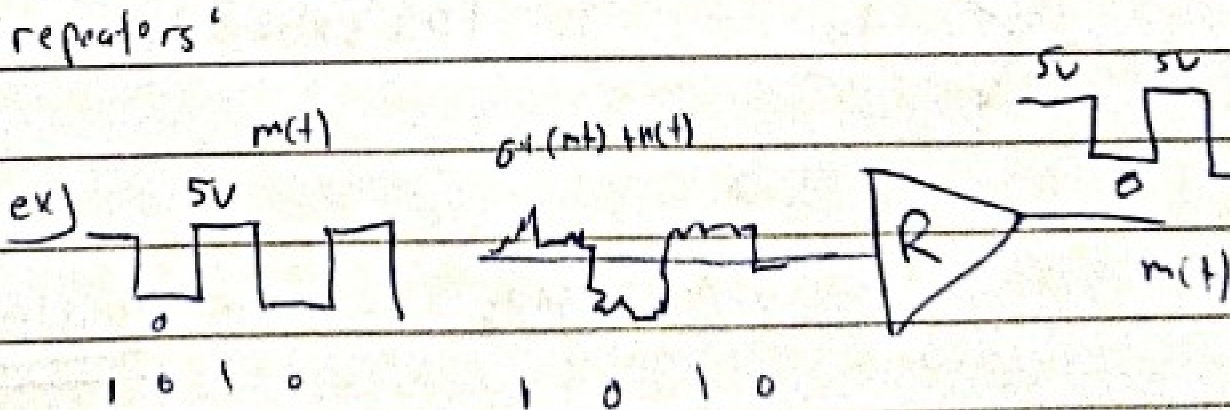
LNB : low - noise block.

Digital (trying to fix both noise and attenuation)

=> allows also regenerators to replace amplifiers

'repeaters'





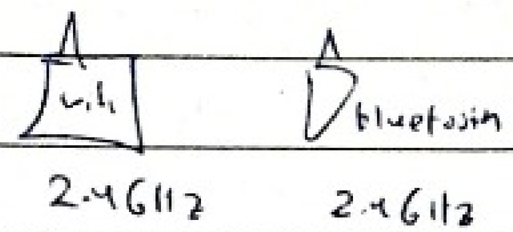
$BER \leq 10^{-6}$

other Channel impairments

5. Fading : Shows up in wireless channels because of multipath propagation obstacles and shadowing. " WiFi, celular, bluetooth, satellite "
Fading means variable attenuation with time or receiver position.

6. Doppler shift: means a frequency shift in the received signal. Shows up in wireless channels where we have fast movement.
* satelite, cellular

7. Frequency -reuse interference : we see when frequency is re-used
Looks similar to external noise



wifi, bluetooth, and cellular.

8. Chromatic dispersion: Shows up in optical fiber , very similar to non-linear distortion.

Shannon's limit

C: maximum # of bits (information you can send over a channel with reasonable BER

1- Attenuation 2- Noise 3- Linear distortion. $\rightarrow$ Bch "limited".

$C = B_{ch} \times \log_2 (1 + SNR)$ $\frac{\text{signal power}}{\text{noise power}}$

unitless

SNR = Signal to noise ratio

$\cancel{\log_{10}}$ $\log_2$ $\log_2 (x) = \log_2 (10) \log_{10}(x) = 3.3222 \times \log_{10} (x)$.

e.g. SNR = 30dB = 1000 unitless

lecture 6

Analog baseband → Digital carrier

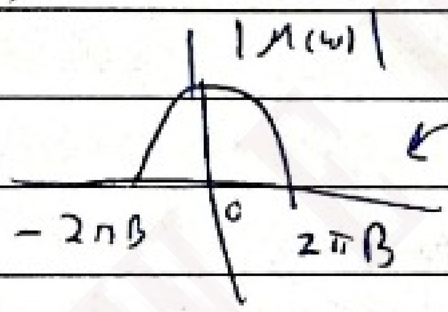
Digitization followed by Modulation.

Analog baseband systems

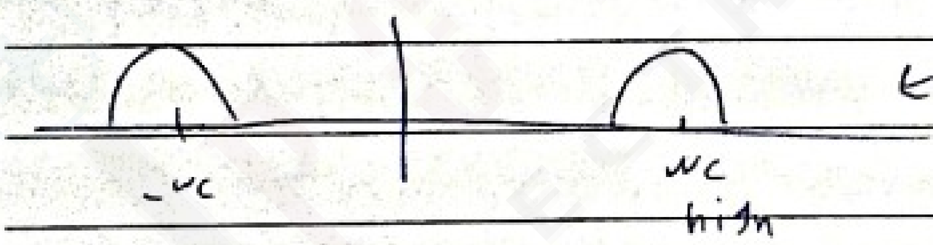
if $m(t)$ is continous in voltage and time
if $m(t)$ is digital then it can assume only a finite set of voltages or shapes.
} time domain

Baseband vs carrier } Frequency domain

$F\{m(t)\} = M(\omega) \angle M(\omega)$

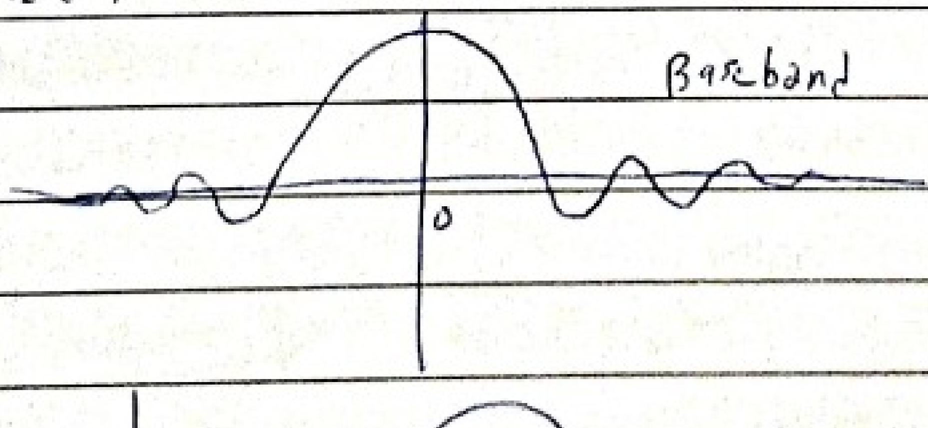


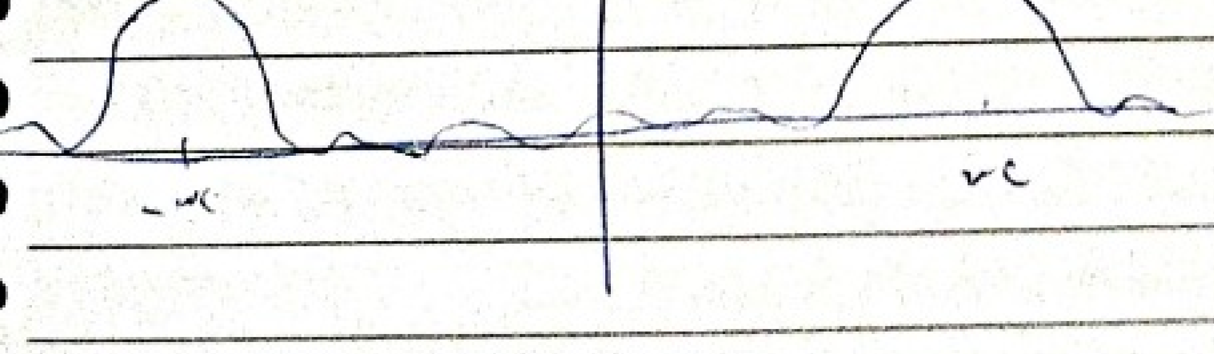
Baseband "clustered around zero"



carrier

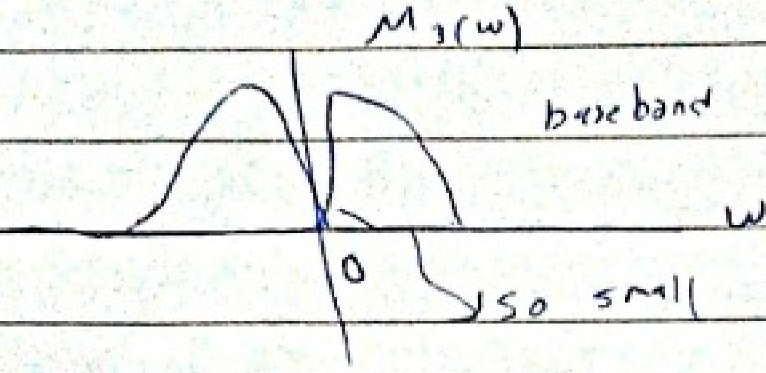
ex) $M_2(\omega)$





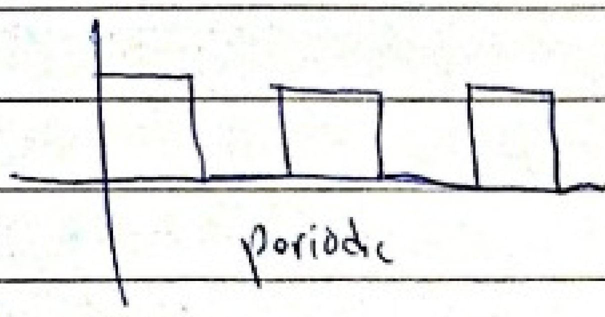
carrier

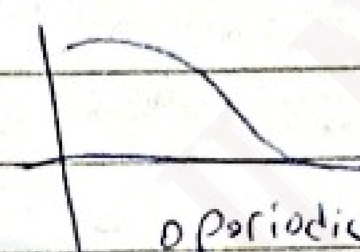
$M_3(\omega)$

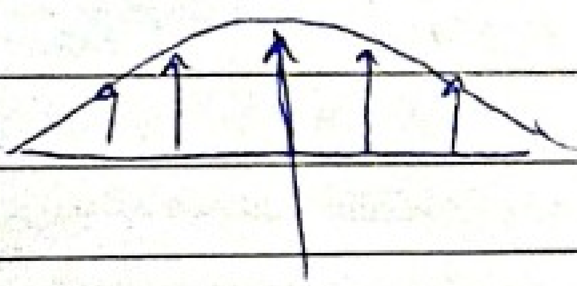


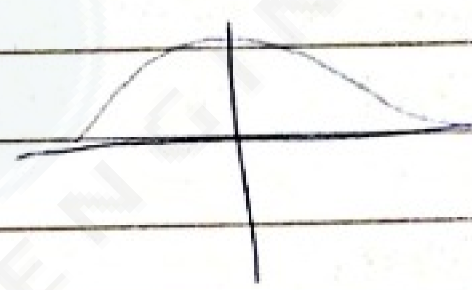
so small "centered at very low frequency"

periodic / aperiodic ⟶ both
analog / Digital ⟶ t - domain
Baseband / carrier ⟶ f - domain


periodic


aperiodic

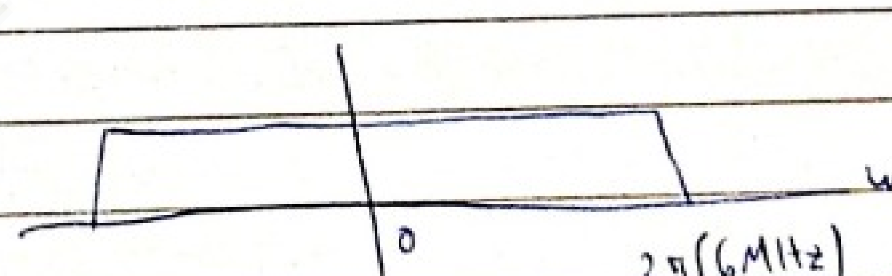

periodic


aperiodic

examples of analog baseband signals:
① human voice F{voice} ③ Room temperature
② light [video]

$B_{voic} = 4\,kHz$

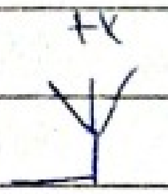
$M(\omega)$ PAL

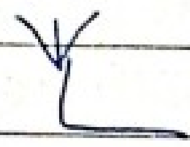


example of analog baseband systems

Cheaper phones
history + backwards compatibility.

Analog and digital carrier systems

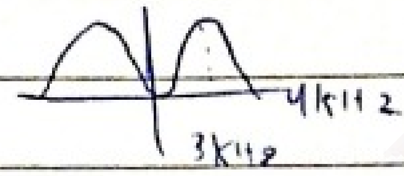
Tx  wireless requires an antenna

Rx 

$L = \frac{\lambda}{2}$ λ = wavelength of the signal

$\lambda = \frac{c}{f} \cong \frac{300{,}000\ km}{f}$

ex1 $m(t)$ = voice



$L_{antenna} = \frac{\lambda}{2} = \frac{1}{2}\frac{c}{f}$

$= \frac{1}{2}\frac{300{,}000\ km/s}{3\ kHz} = \frac{100\ km}{2} = 50km$

ex2 $m(t)$ = wifi 3 GHz

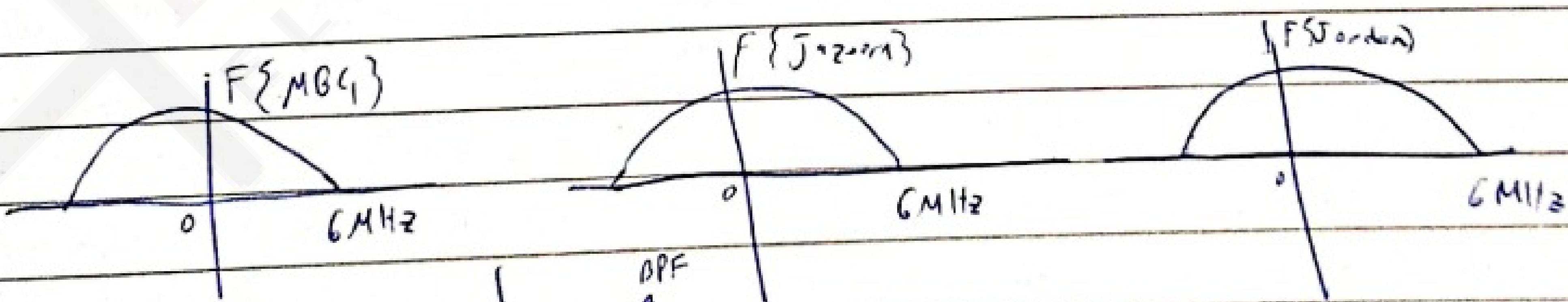
$L_{ant} = \frac{1}{2}\lambda = \frac{1}{2}\frac{c}{f} = \frac{1}{2}\frac{300{,}000\ km/s}{3\times10^{9}} = \frac{0.1m}{2} = 5cm$

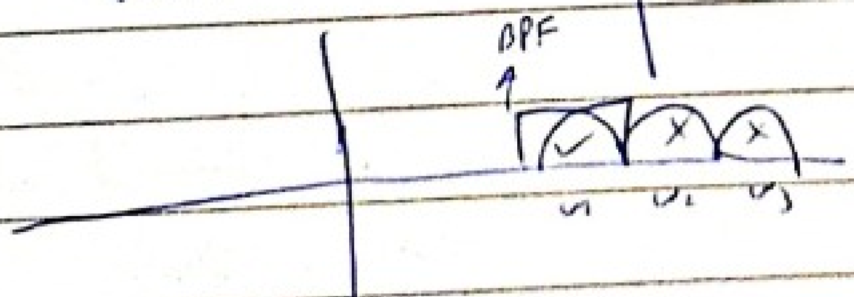
$\boxed{H.W}$ wifi

Lecture 7

Multiplexing: sending multiple signals over one channel.

FDM = frequency division multiplexing (enabled by modulation)





using BPF RX

CDMA: code division multiple access (3G)

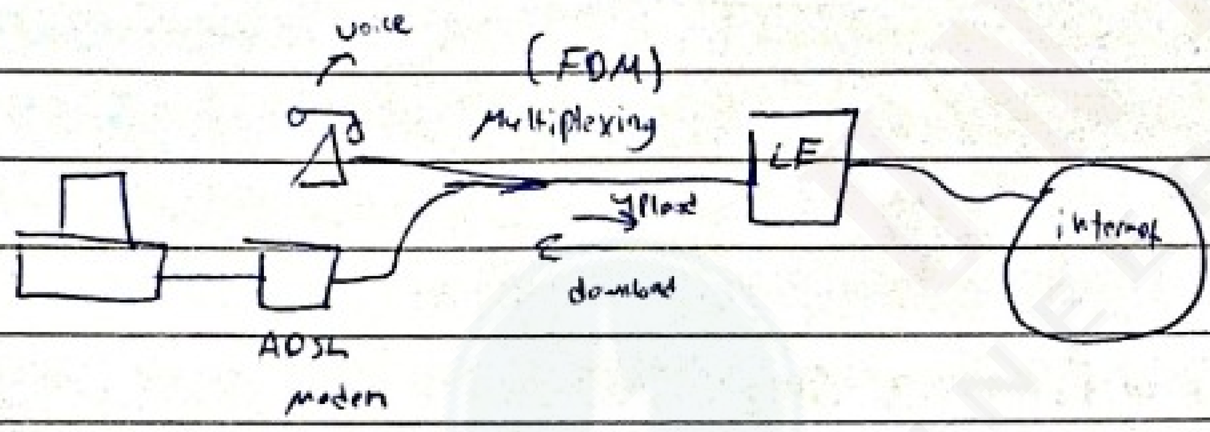
OFDMA :- Orthogonal freq-division multiple access. (4G)

you need modulation and digital " digital carrier) examples of carrier systems:

AM: Amplitude Modulation
FM: frequency modulation

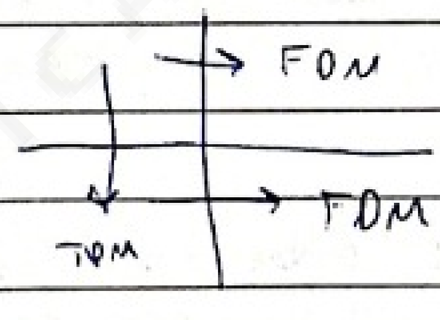
Digital carriers

* Digital radio ~~broadcast~~ broadcasting. (DAB) digital audio broadcasting
* H.W " DVB-S, DVB-T, ATSC)
* Cellular 2G/GSM
  3G 4G/Long term evolution "LGE"



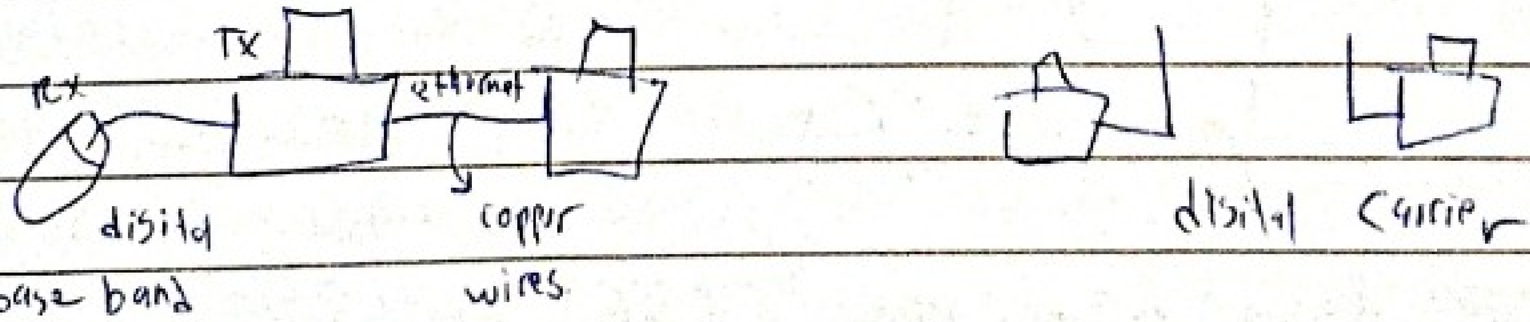
Digitization

TDM: time-division multiplexing "enabled by digitization"



A/D converter only 3 steps - sampling → ~~1001100~~ bit stream
Quantization
mapping

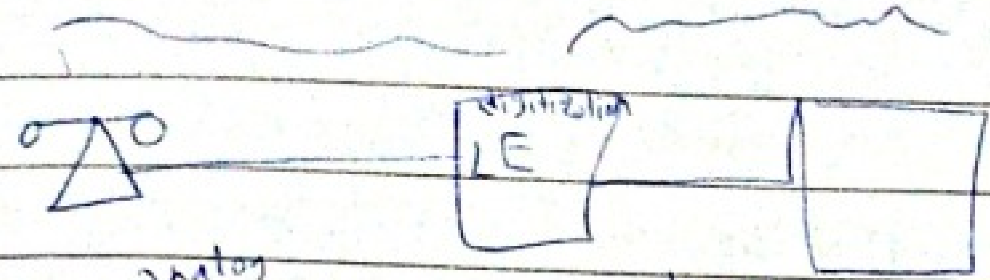
Digital base band examples.



$\frac{n\omega_0 \tau}{2\pi} = 1$

2π

Local loop — core



U.S — T_1 T_2 T_3

EUR — $E1$ E_2 E_3

analog baseband

digital baseband
+ multiplexing (TDM)
"PDH" "TDH"

PDH ≡ Plesiochronous Didigital Hierarchy
SDH ≡ Synchronous = "

$m(t)$: analog baseband

info → $m(t)$ "transducer"
voice — microphone

lecture 8 — H.W for the following signals: — α_n ≡ Fourier series coefficients

1. Find fourier series (complex form)
2. Find " " (trigonometric form)
3. " " " (compact form)
4. Find Bandwith of $x(t)$
5. Find the average of $x(t)$ = DC value
6. Find the average power of $x(t) = P_{ave}$
7. Find the Rms of $r(t) = \sqrt{P_{ave}}$

Answers for DC : ① $\frac{A\tau}{T}$ ② 0

③ $\frac{A\tau}{T}$ ④ 0 ⑤ 0 ⑥ 0

① $x(t) = \text{rep}_T \{ A \,\text{rect}\left(\frac{t}{\tau}\right) \}$

$$\alpha_n = \frac{1}{T} \int_T x(t) e^{-jn\omega_0 t}\, dt = \frac{A\tau}{T} \sin\left(\frac{n\omega_0 \tau}{2\pi}\right)$$

lecture 9

DC value (average value) for $x(t) = a_0$

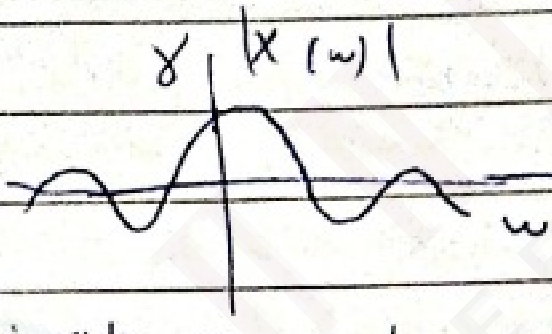
$F\{\cos(w_0 t)\} = \pi \delta(w - w_0) + \pi \delta(w + w_0)$

$F\{1\} = 2\pi \delta(w)$

$F\{a_0\} = 2\pi a_0 \delta(w)$

↑ DC value

$F\{rect(t)\} = \sin\left(\frac{w}{2\pi}\right)$



DC value $= 0$ "no impulse at zero"

$F\{rect(t) + 5\} = \sin\left(\frac{w}{2\pi}\right) + 2\pi\, 5\delta(w)$

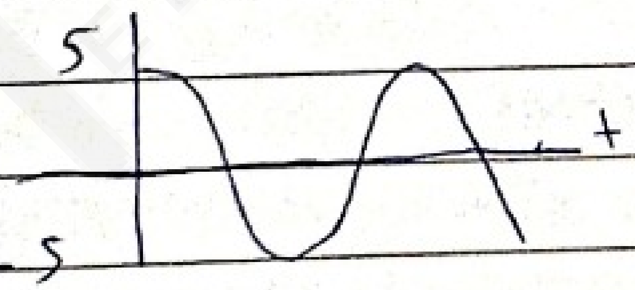
DC $\equiv$ average of the signal $x(t)$

Average power $\equiv$ average of instantaneous power.

$\overline{x(t)}$
- ~~f-domain (impulse at zero)~~
- t-domain ($\lim_{T\to\infty} \frac{1}{T} \int_T x(t)\,dt$)

$P_{ave} = \overline{x^2(t)} = \lim_{T\to\infty} \frac{1}{T} \int_T x^2(t)\,dt$

ex)

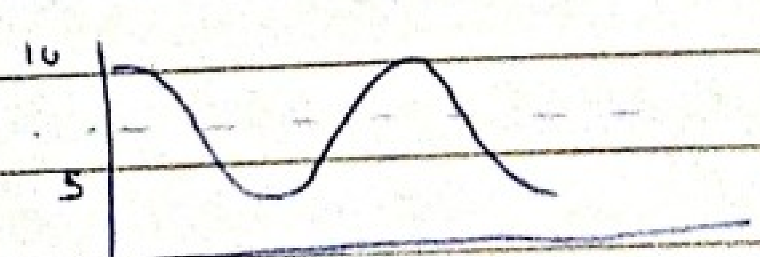


$5\cos(w_0 t)$

DC $= 0$ (area $= 0$)

$P_{ave} = \overline{x^2(t)} = \frac{5^2}{2} = \frac{A^2}{2} = (r_{ms})^2$

ex 2)



$2.5\cos(w_0 t) + 7.5$

DC $= 7.5$

$P_{ave} = 7.5^2 + \frac{2.5^2}{2}$

P_{ave} from f-domain PSD "Power spectrum density"

$$PSD = S_x(\omega) = \lim_{T\to\infty} \frac{|X(\omega)|^2}{T}$$

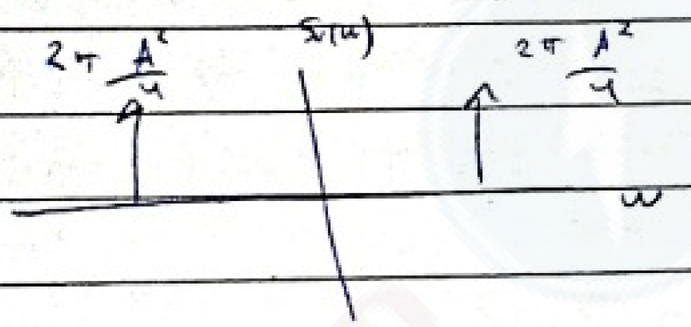
$$S_x(\omega) = F\{R_{xx}(t)\}$$

$$P_{ave} = \overline{x^2(t)} = \frac{1}{2\pi}\int_{-\infty}^{\infty} S_x(\omega)\,d\omega$$

ex 1) Find PSD for $x(t) = A\cos(\omega_0 t)$

$R_{xx}(\tau) = \cos(\ldots\ldots)$

$S_x(\omega) = F\{R_{xx}(\tau)\}$ = two impulses



$$P_{ave} = \frac{1}{2\pi}\int_{-\infty}^{\infty} S_x(\omega)\,d\omega$$

$$\frac{1}{2\pi}\left(\frac{2\pi A^2}{4} + \frac{2\pi A^2}{4}\right) = \left(\frac{4\pi A^2}{4}\right)\frac{1}{2\pi}$$

$$= \frac{A^2}{2}$$

H.W) Find PSD and average power for $x(t) = rep_T\{A\,rect(t)\}$

Freq Response Function

$$H(\omega) = \frac{V_o(\omega)}{V_i(\omega)} = \frac{F\{v_o(t)\}}{F\{v_i(t)\}} \qquad V_o(\omega) = H(\omega)V_i(\omega)$$

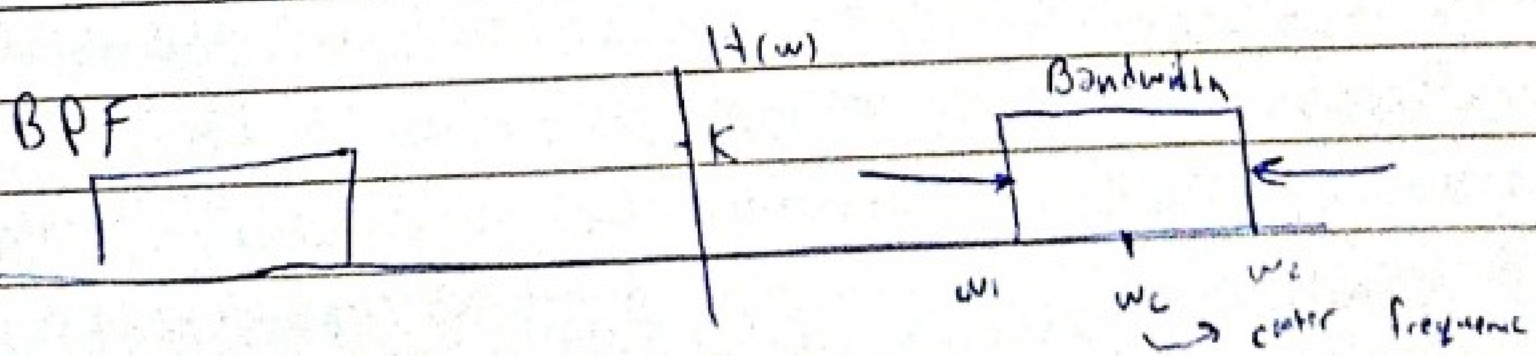
For bandwidth calculations, do not consider neg power in the center ~

Lecture 10

F → low   C → open circuit $V_o = V_i$ } LPF

F → hi   C → short $V_o = 0$

BPF

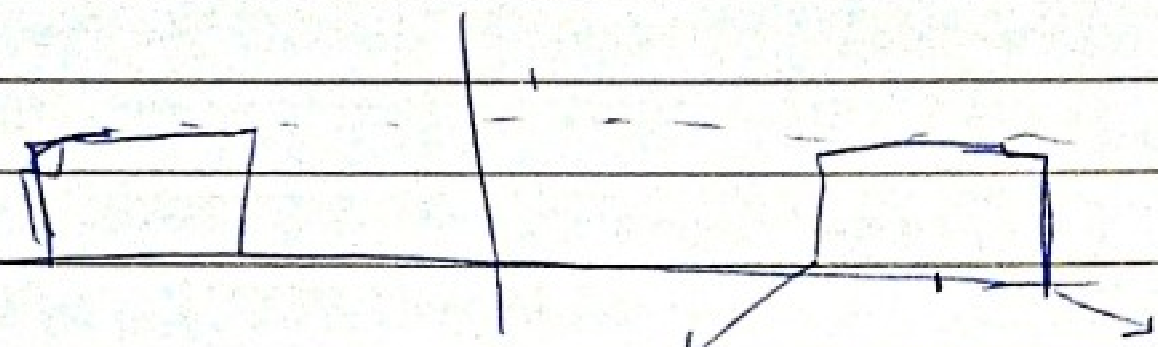


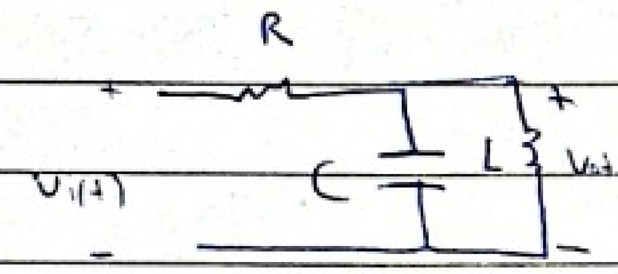
e.g. $v(t) \longrightarrow \boxed{BPF} \longrightarrow v_{out}$

w/ Bandwidth = 80 kHz

Center frequency = 100 MHz

and Gain = 1





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

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

Gain = 1

Modulation :- is the process of shifting frequencies for a signal (from baseband → carrier)

Modulation is performed by changing one of the basic parameters of a high-frequency periodic signal (called the carrier $c(t)$) in proportion to the baseband message $m(t)$.

$$c(t) = \overset{\text{amplitude}}{A} \cos(\overset{\text{frequency}}{\omega_c} t + \underbrace{\theta_0}_{\text{phase}})$$

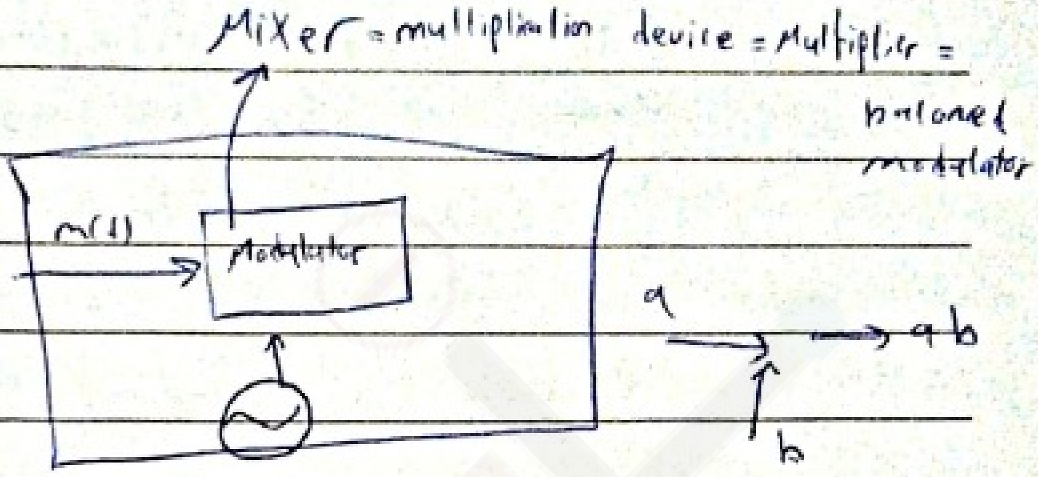
$$A \propto m(t)$$

* Amplitude modulation :-
  - (a) DSB - SC
  - (b) DSB - LC (large carrier) [AM Radio]
  - (c) SSB - SC
  - (D) SSB - LC
  - (E) VSB - SC
  - (F) VSB - LC
  - (g) QAM

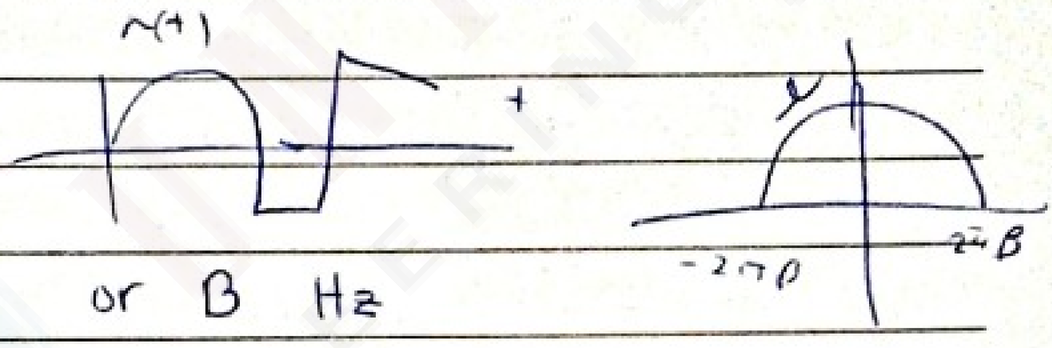
DSB - SC

TX ← modulator: t, f

RX ← Demodulator: t, f



$\underset{DSB-SC}{\phi} = m(t)\cos(w_c t) = m(t)\,c(t)$



bandwidth of $m(t) = 2\pi\beta$ rad/s or B Hz

DC value of $m(t) = 0$ "no impulse"

Find and sketch $F\{\phi_{DSB-SC}(t)\} = \Phi_{DSB-SC}(w)$

$$F\{x(t).y(t)\} = \frac{1}{2\pi} X(w) \circledast Y(w)$$

$$F\{c(t)\} = F\{\cos(w_c t)\} = \pi\delta(w-w_c) + \pi\delta(w+w_c)$$

$\circledast$ Anything $\circledast$ $\delta(w \pm w_x)$

anything shifted by w_x * by its ~~amp~~ area.

Sol #2 $F\{\phi_{DSB-SC}(t)\} = F\{m(t).\cos(w_c t)\} = F\left\{\frac{m(t)e^{jw_c t}}{2} + \frac{m(t)e^{-jw_c t}}{2}\right\}$

$$= \frac{M(w-w_c)}{2} + \frac{M(w+w_c)}{2}$$

Solu #3 "graphical solution"

when multiplying by $\cos(w_c t)$

a) shift f_0 right by w_c

b) Shift f_0 left by w_c

c) Multiply by 1/2.

For $\phi(t)$ DSB-SC a- The bandwidth is double that of $m(t)$

b- The avg power is half that of $m(t)$.

bandwidth of $m(t) = 2\pi B$ rad/s

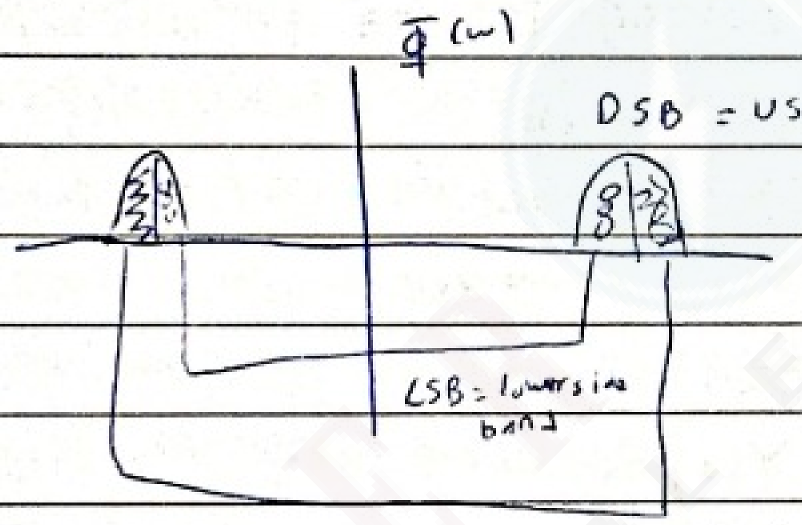
or B Hz

Bandwidth of $\phi(t) = 4\pi B$ rad/s or $2B$ Hz

HW) assume $m(t) = \alpha \cos(w_m t)$

(a) Find $\overline{m^2(t)}$ = avg power = $\lim_{T\to\infty} \frac{1}{T} \int_T m^2(t)\,dt = \frac{\alpha^2}{2}$

(b) Find $\overline{\phi^2(t)}$ = avg power of modulated signal = $\lim_{T\to\infty} \int_T \phi^2(t)\,dt = \frac{\alpha^2}{4}$



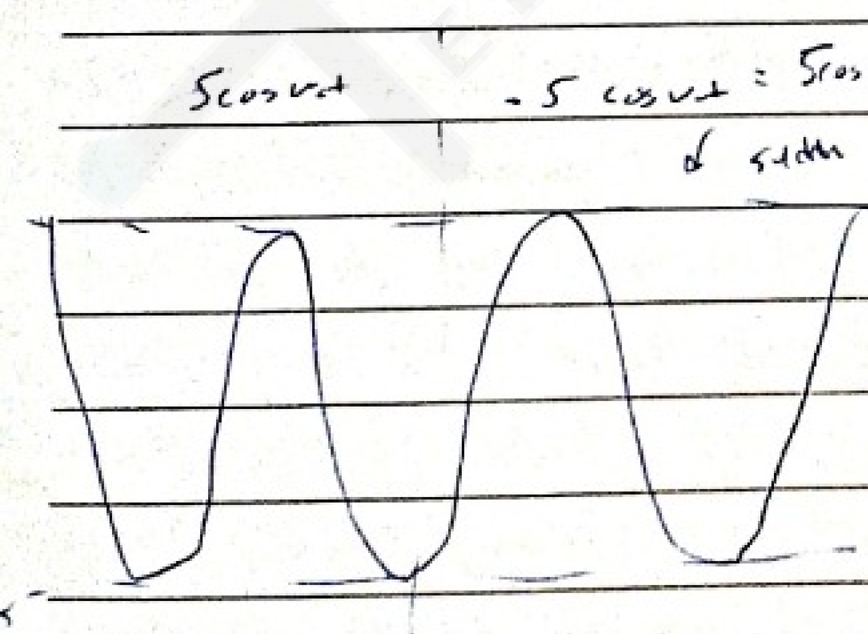
SC = suppressed carrier

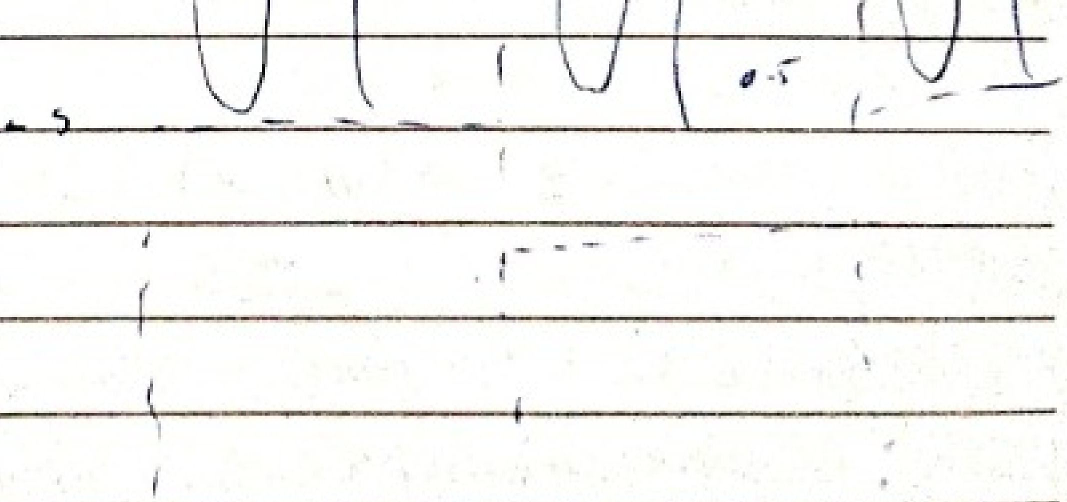
sketch $\phi(t)$ for $m(t) = \text{rep}\{\text{rect}\} \rightarrow \times\times$

make $w_c \gg 0$

5cos $w_c t$ $-5\cos w_c t = 5\cos(w_c t \pm 180)$

of sudden $180°$ phase shift





Sig/Instructor Signature

1

$\phi_{DSB\text{-}SC}(t) = m(t)\cos(\omega_c t)$ "demodulation"

Q. Find the output $y(t)$ from the circuit shown if the input is $\phi(t)$?

The oscillator at the RX should be fully synchronized with the oscillator at TX [Same freq.] "Same phase"

Multiplying by $\cos(\omega_c t)$

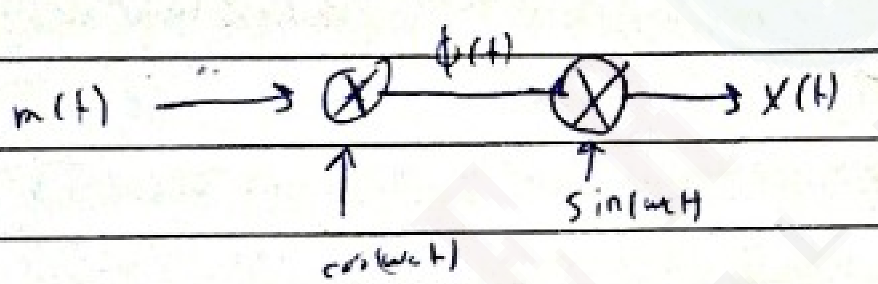
1- Shift the whole signal to the right by ω_c

2- -- -- -- left --

3. multiply by 1/2

Q] How many copies of $M(\omega)$ does $X(\omega)$ contain? $\underline{\underline{3}}$ Not ~~4~~

HW: Find $X(\omega)$ in the following



Draw the phase spectrums $\angle X(\omega)$

Find $X(\omega) = F\{x(t)\} = F\{\phi(t).\cos(\omega_c t)\} = F\{m(t).\cos^2(\omega_c t)\}$

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

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

when gain of LPF is $= 1$ $\quad y(t) = \frac{1}{2}m(t)$

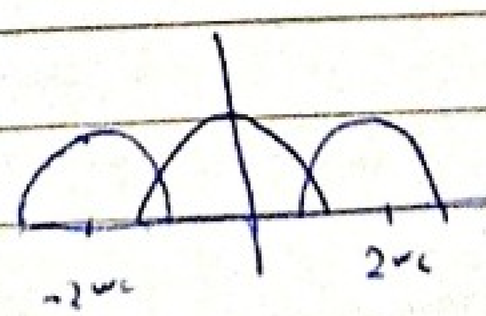
gain $= 2$ $\quad y(t) = m(t)$

gain $= 5$ $\quad y(t) = \frac{5}{2}m(t)$

what gain should you use to get $y(t) = 5m(t)$

ans gain $= 10$

if ω_c is small



$2\omega_c \geq 4\pi B = (2 \times 2\pi B)$

$\omega_c \geq 2\pi B$

$f_c \geq B$ ideally

practically $f_c \gg B$

*** Sketch $\phi(t)$, $y(t)$, and $y(t)$.

LPF removes sharp edges = smoothing device

HW] Draw the slides again but use $m(t) = \text{rep}\{\Delta(t)\}$

HW] Do the example in slide #13

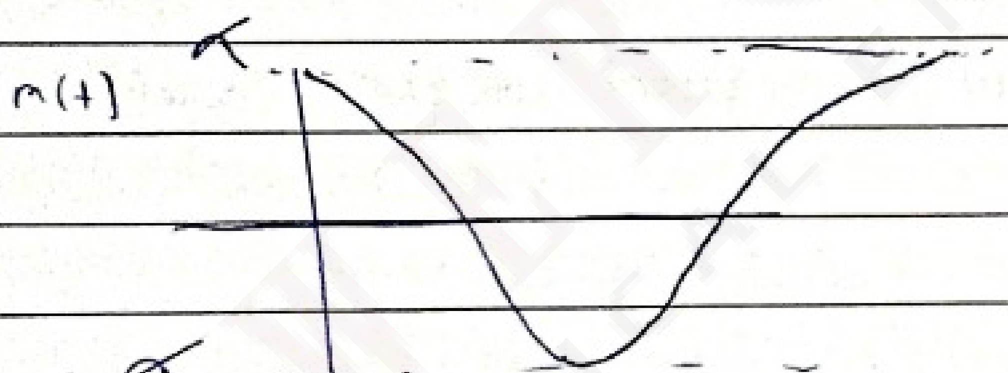
example "13"

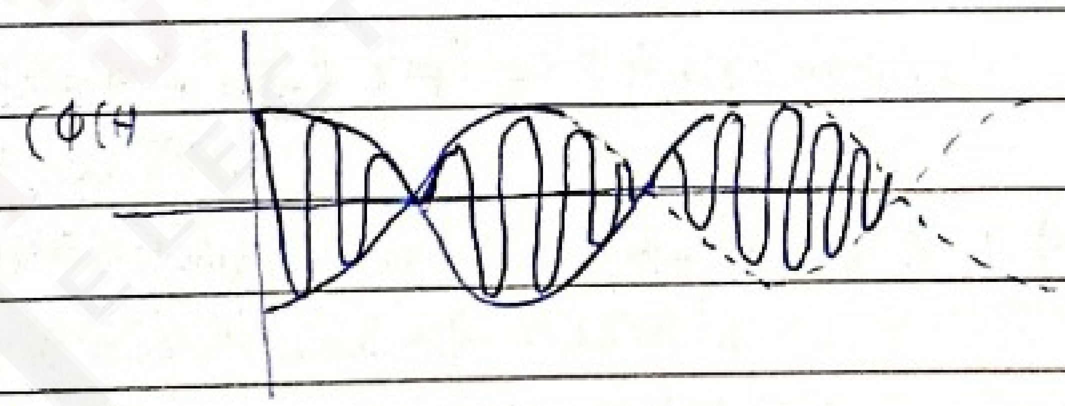
<u>Tone modulation</u> $\Rightarrow m(t) = \alpha \cos(\omega_m t)$ ← small

$c(t) = \cos(\omega_c t)$ ← very high

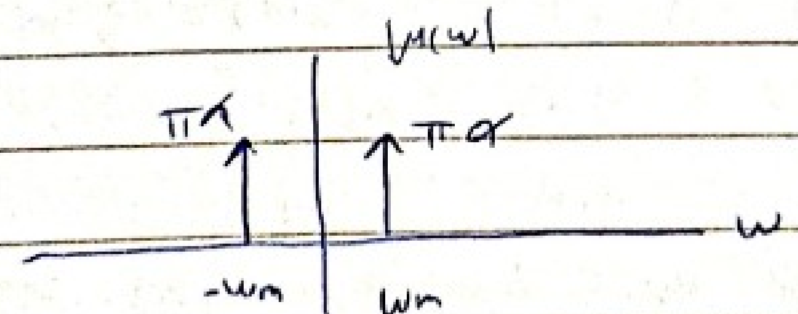
$\omega_c >> \omega_m$

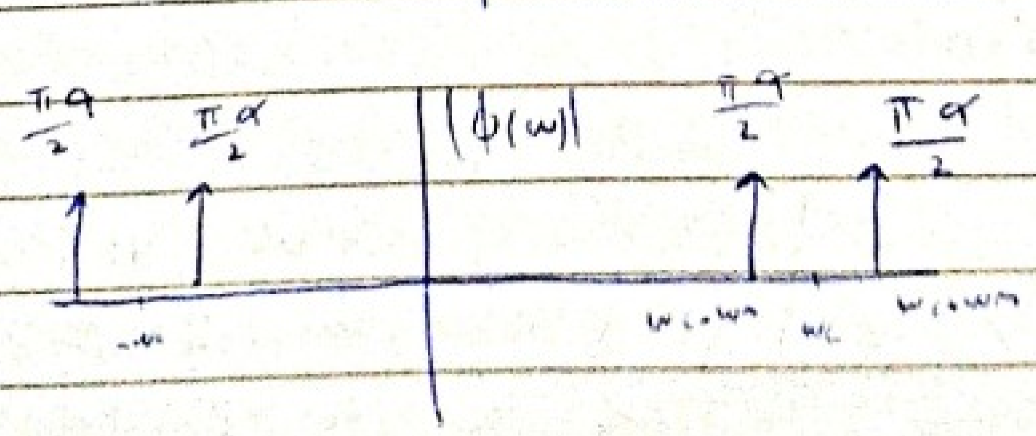
(a) Sketch $\phi(t)$





(b) $M(\omega)$





(c) $B_{m(t)} = \frac{w_m}{2\pi}$ Hz $= f_m$ Hz $= \frac{1}{T_m}$ Hz = fundamental frequency (special case)

$B_{d(t)} = \frac{2w_m}{2\pi}$ Hz $= 2\ B_{m(t)}$

(d) $P_{av} = \lim_{T \to \infty} \frac{1}{T} \int_{T_m} x^2(t)\, dt = \frac{\alpha^2}{2}$

$\phi(t) = \alpha \cos(w_m t) \cos(w_c t)$

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

HW = Repeat the above example but for the following m(t)
" 15"

Transceiver = TX + RX

GSM = 2G cellular

W-CDMA = 3G cellular

Gilbert cell " 23"

Gilbert cell = 3 differential amplifiers + 1 current source

3 x 2 transistors + 2 transistors = 8

Amplifies $V_{in} = V_2 - V_1$ $\qquad$ $V_{out} = V_{o2} - V_{o1}$

$V_{out} = G v_{in}$

$$V_{o2} - V_{o1} = \underbrace{\left(\frac{-I_{EE} R_L}{2 V_T} \right)}_{G} (V_2 - V_1)$$

$V_T = 0.026$ V at 25°C $= \frac{KT}{q}$

K: boltzman const $= 1.38 \times 10^{-23}$ J/K

T: temp (K)

q: electron charge 1.6×10^{-19}

I_x controls the gain of Q_5 and Q_6

R_x controls I_x and therefore controls the Gain

Gilbert cell

Diff Amp $\quad V_{o2} - V_{o1} = \dfrac{-I_{EE} R_L}{2V_T}(V_2 - V_1)$

using superposition

$V_{o2} - V_{o1} = \underbrace{V_{o2} - V_{o1}}_{\text{due to } Q1-Q2} + \underbrace{V_{o2} - V_{o1}}_{\text{due to } Q3-Q4}$

$= \underbrace{\dfrac{-I_{EE_1} R_L}{2V_T}}_{\text{gain}}(X_1 - X_2) + \dfrac{-I_{EE_2} R_L}{2V_T}(X_2 - X_1)$

$V_{o2} - V_{o1} = \dfrac{-R_L}{2V_T}(X_1 - X_2) \cdot (I_{E_1} - I_{E_2})$ - - - (1)

multiplication

we can prove that for $Q_5 - Q_6$

$\underbrace{I_{E_2} - I_{E_1}}_{\text{out}} = \underbrace{\dfrac{-2}{R_X}}_{\text{gain}} \underbrace{(m_2 - m_1)}_{\text{in}}$ - - - (2)

$V_{o2} - V_{o1} = \dfrac{R_L}{R_X V_T}(X_2 - X_1)(m_2 - m_1) = G\, c(t)\, m(t)$

$Q_1 Q_2$ $\quad\quad$ $Q_3 Q_4$

Gain $\propto -c(t)$ $\quad\quad$ gain $\propto c(t)$

$3c(t) = 4c(t) + (1)(-c(t))$

$5c(t) = 6c(t) + (1)(-c(t))$

$0 = 1c(t) + (1)(-c(t))$

$ab = ba$

In practice, make sure that carrier goes to the top amp $Q_1 Q_2$ and $Q_3 Q_4$. allows us to saturate the top diff amp

⇒ Gilbert cell works in switching mode "recommended mode"

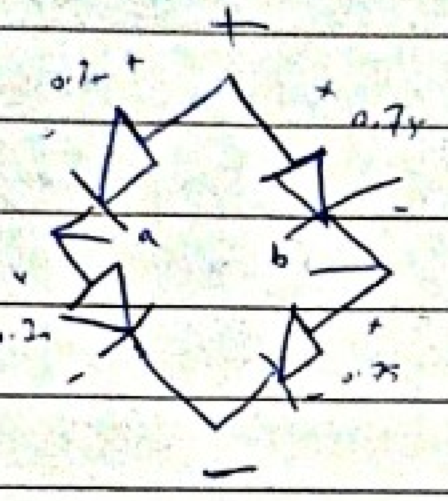
allows us to unbalance the top two diff amp

⇒ Gilbert cell works in unbalanced mode. DSBSC "AM"

"Switching Modulator"

$C >> m(t)$ $\quad C\cos(\omega_c t)$

1. +ve "
cycle

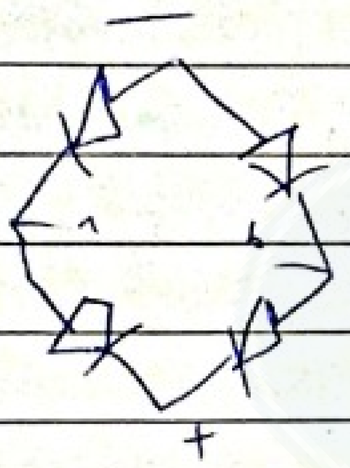


all diodes are forward biased

$V_{ab} = 0$ volt looks like short cct.

$X(t) = m(t)$

-ve
cycle



all diodes are reversed biased

$\Rightarrow$ open cct

$X(t) = 0$

$X(t)$ is called switched $m(t)$ "Natural sampling"

Q. In the system shown (slide #28)
(Shunt bridge diode modulator) find $y(t) = ?$

(b) Repeat hit for BPF gain = 2 bandwidth = 2B Hz
Center = $2\omega_c$ rad/s

$C\cos(\omega_c t)$ is positive cycle $\rightarrow$ diodes ON $\rightarrow X(t) = 0$

$C\cos(\omega_c t)$ is neg. cycle $\rightarrow$ diodes OFF $\rightarrow x(t) = m(t)$

$y(t) = 0 ;\ m(t) ;\ 0 ;\ m(t) ; 0 ,\ m(t) \dots$

$\alpha_1 = \frac{1}{\pi} e^{-j\pi}$

$\alpha_{-1} = \frac{1}{\pi} e^{j\pi}$

$y(t) = 2\,|\alpha_1|\, m(t)\cos(\omega_c t - \pi) = \frac{2}{\pi} m(t)\cos(\omega_c t - \pi)$

$Y(\omega)$ = two copies of $M(\omega)$

Ring modulator $\quad x(t) = m(t) ; -m(t) ; m(t)$

4th Design: We can use the Gilbert cell as a switching modulator by pushing it into switching mode (preferred mode) by saturating the two top differential amplifiers.

Gilbert linear mode

OR $\quad \phi(t) \longrightarrow \otimes \longrightarrow \boxed{LPF} \longrightarrow k\,m(t)$

$\qquad\qquad\qquad\uparrow$

$\qquad\qquad\qquad p(t)$

For you to be able to demodulate $m(t)$ from DSB-SC the RX should be perfectly synchronized with the TX

< same freq
< same phase

Part (a) : Phase error $\phi(t)$ $y(t)$ $y(t)$

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

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

$$= m(t)\cos(\omega_c t)\cos(\omega_c t + \Delta\theta) = \frac{1}{2}m(t)\cos(2\omega_c t + \Delta\theta) + \frac{1}{2}m(t)\cos(\Delta\theta)$$

$y(t) \rightarrow x(t) \rightarrow$ LPF

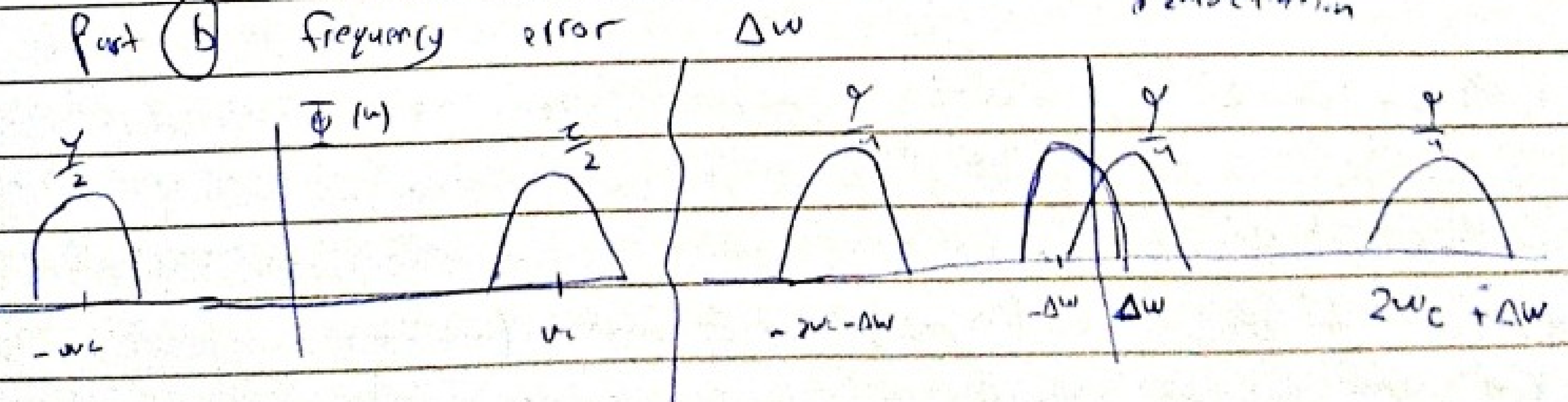
$$y(t) = \frac{1}{2}\cos(\Delta\theta)\,m(t) \neq \frac{1}{2}m(t)$$

ex $\quad \Delta\theta = 60^\circ$ $\qquad$ "Attenuation"

$$\cos(\Delta\theta) = \frac{1}{2}$$

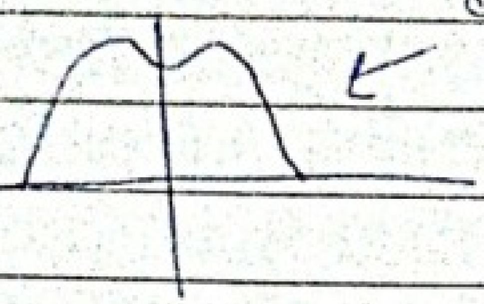
$$y(t) = \frac{1}{4}m(t) \quad \text{attenuation}$$

Part (b) frequency error $\Delta\omega$ $\qquad$ demodulation



Modulation

distorted $M(\omega)$



" Distortion " "frequency error"

To avoid distortion and attenuation then maintain a perfect synchronization

Solutions to maintain perfect synchronization?

1- Old Solution

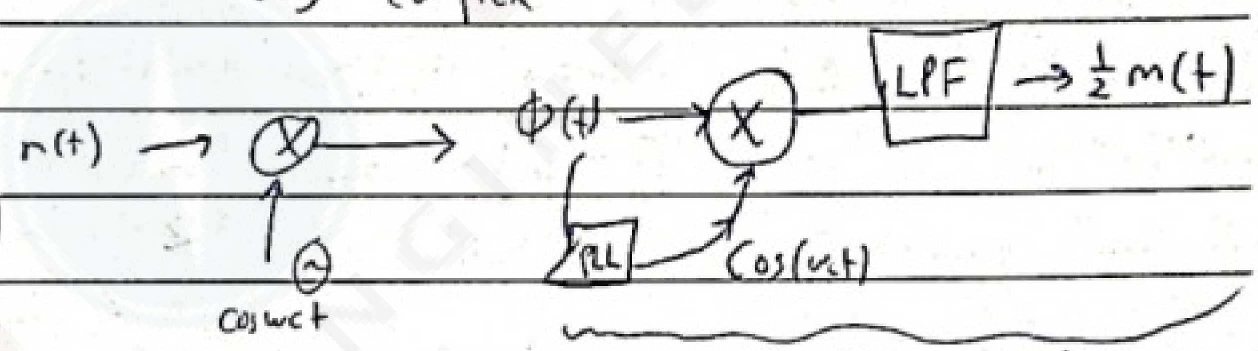
Invent another modulation technique that does not require perfect synch.

[can use asynchronous RX]

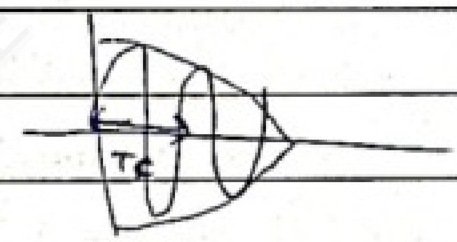
ex) DSB-LC (AM)

2- New solution: use a carrier recovery circuit (PLL) phase-locked-loop @ RX to recreate a perfectly synch cosine.

very complex



Synchronous demodulator or Synch reciever



switched m(t)

Sampling
- Ideal vs practical vs natural sampling
- Nyquist rate and anti-aliasing filter

Slide 6 "uniform sampling" time intervals are all equal and are equal in sampling time " t_s "

Practical (PAM) $\tau = \frac{T_s}{2}$

Practical (PAM) (S/H) $\tau = T_s$

Pulse amplitude modulation "Practical sampling"

sample and hold

TX

$m(t) \to$ sampler $\to x(t)$

RX

$x(t) \to$ LPF

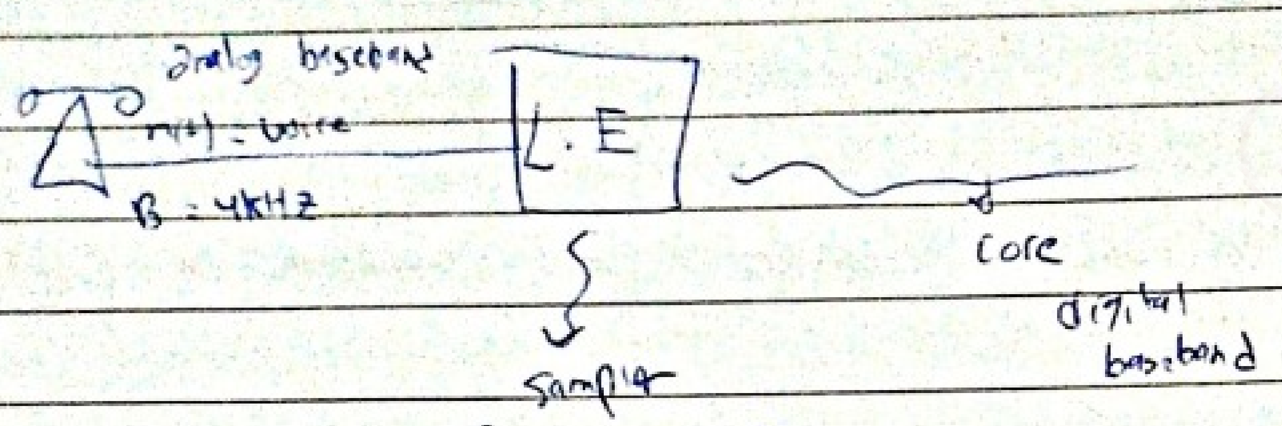
$\omega_s \geq 4\pi B$ rad/s

$f_s \geq 2B$ Hz

T_s $\frac{1}{T_s} = f_s$

$f_s \gg 2B$

ex) Telephony



$f_s = 8KHz = 2B$

8 1000 samples /sec

$f_s \geq 2B$ Solution #1 against the problem of aliasing

increase f_s

Solution #2 against aliasing : anti-aliasing LPF (@ TX before the sampler)

reduces B into $B_{new} = \frac{f_s}{2}$

$\Rightarrow$ distorting $m(t)$ but no aliasing

$f_s = 2B_{new}$

$f_s < 2B$

#1 no distortion ; no aliasing

#2 distortion ; no aliasing

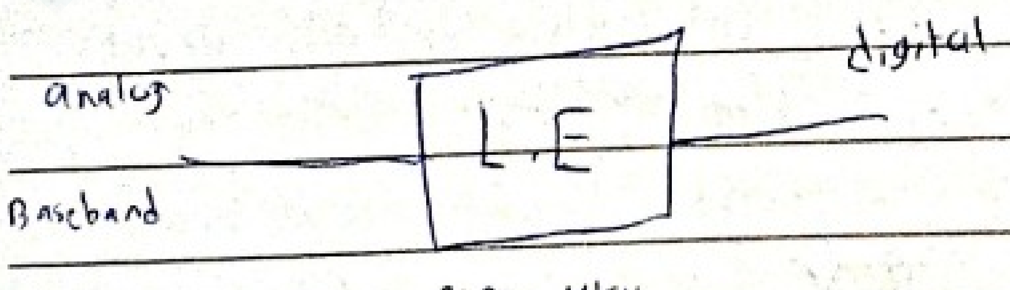
aliasing

better

Practical example "Telephony"

voice $B = 4KHz$ $\Rightarrow$ $f_s = 8KHz$

music $B = 20KHz$ still $f_s = 8KHz$



$B_{LPF} = 4KH$

Quantization $m(t) = [-1, 2]$

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

2 bits per sample

L

$\underbrace{1.55\text{ V} \Rightarrow 2\text{ V}}$

ΔV = error in quantization

2 V	111
1.5 V	110
1 V	101
0.5 V	100
0 V	011
-0.5 V	010
-1 V	001
-1.5 V	000

$1.55 \Rightarrow 1.5$ V

L ↗ less error
↘ but more bits per sample

ex) Telephony

8 bits/sample $L = 2^8 = 256$ levels

CDs

$L = 65{,}536$ 16 bits/sample

small error better quality

P.) $m(t)$ = voice → $\boxed{\begin{array}{c} \text{L.E} \\ f_s = 8{,}000 \text{ sample/s} \end{array}}$

$\times$ 8 bits/sample

data rate
bit rate $= R_b = 64000$ bit/sec
$= 64 \frac{\text{kbit}}{\text{sec}}$

↳ PCM stream
pulse code modulation

$\uparrow L$ SQNR $\uparrow$ better quality

$\downarrow$ error

K_m^2 = crest factor or peak to rms ratio

$= \dfrac{m_p^2}{\overline{m^2(t)}} = \dfrac{\text{peak}^2}{\text{rms}^2}$

↑ avg power

ex find k_m^2 for $n(t) = a\cos(\omega t)$

$$k_m^2 = \frac{peak^2}{rms^2} = \frac{a^2}{\frac{a^2}{2}} = 2$$

H.W $n(t) = 5\, rep_{T=4}\left\{ rect\left(\frac{t}{2}\right)\right\}$

bit per sample $= \log_2 (L)$

Uniform Quantization

Non-Uniform Quantization / companding compressor / decompressor

↳ better quality compared to U.Q for same ~~tot~~ # of levels

ex Telephony ($L = 256$) uses companding

M-low — A-low

U.S T.Systems — Eur T.System

M-law and A-law provide better quality

Adaptive Quantization

Slide 28 ① RLE: run length encoding "Source encoding"

② Huffman encoding

frame

16 Mpixel

blue blue blue . . . . . . 16 million times

1101 1101 1101

$16 \times 10^6 \times 4$ bits

1101 repeat 16 M times — RLE

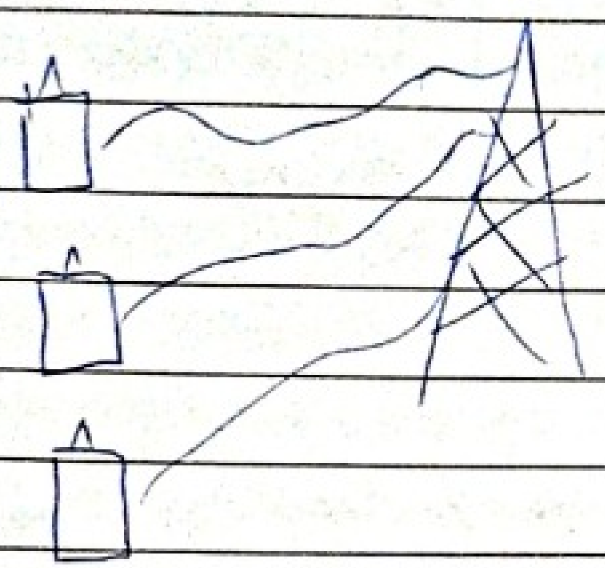
blue 100 bits — 104 bits

$\frac{1}{2}\left(\sin(a+b) - \sin(a-b)\right)$

Audio compression

m(t) = voice, analog baseband $\longrightarrow$ $\boxed{L.F}$ $\longrightarrow$ PCM stream, 64kps, digital baseband } Landline

GSM cellular phones



m(t) voice analog baseband $\longrightarrow$ $\boxed{\ }$ $\longrightarrow$ digital "width compression" carrier

due to use of antennas

lecture 6

Amp mod. — DSB-SC, QAM very popular, SSB, VSB

$$F\{m_2(t)\sin(w_c t)\} = F\left\{ -j\, m_2(t)\, \frac{e^{jw_c t} - e^{-jw_c t}}{2} \right\}$$

$$= \frac{-j}{2} M_2(w - w_c) + \frac{j}{2} M_2(w + w_c)$$

$\longrightarrow$ right $\qquad \xleftarrow{\text{left}}$ $\qquad * \frac{1}{2}$ $\qquad$ flen phase shift of $90°$

Bandwidth of $\phi_{QAM}(t)$ is $2B$ Hz where we sent 2 messages

Q. Find $y_1(t) =$

$$\text{bandwidth} = \overset{\times \cos(w_c t)}{\Phi_{QAM}} = m_1(t)\cos(w_c t) + m_2(t)\sin(w_c t)$$

$$\times \cos(w_c t)$$

$$= m_1(t)\cos^2(w_c t) + \tfrac{1}{2} m_2(t)\sin(2w_c t)$$

$$= \underbrace{\tfrac{1}{2} m_1(t)}_{\text{low F}} + \underbrace{\tfrac{1}{2} m(t)\cos(2w_c t)}_{\text{High F}} + \underbrace{\tfrac{1}{2} m_2(t)\sin(2w_c t)}_{\text{High F}}$$

$x_1(t) \rightarrow$ LPF $\quad$ low F ✓ $\quad$ High F ✗ $\quad$ ✗ $= \frac{1}{2} m_1(t)$

H.W] Find $y_1(t) = ?$

RX $\sim$ $\cos(\omega t + 10^\circ)$

DSB-SC and QAM $\sim$ $\cos(\omega_c t + 10^\circ)$
both require synchronous demodulation (do not work with async RX)

SSB-SC

SSB-SC (Single side band) allows us to send one message modulated in B bandwidth

- SSB
  - SSB-SC (USB)
  - SSB-SC (LSB)
  - SSB-LC (USB)
  - SSB-LC (LSB)

SSB was limited in real life to voice application $M(\omega)$

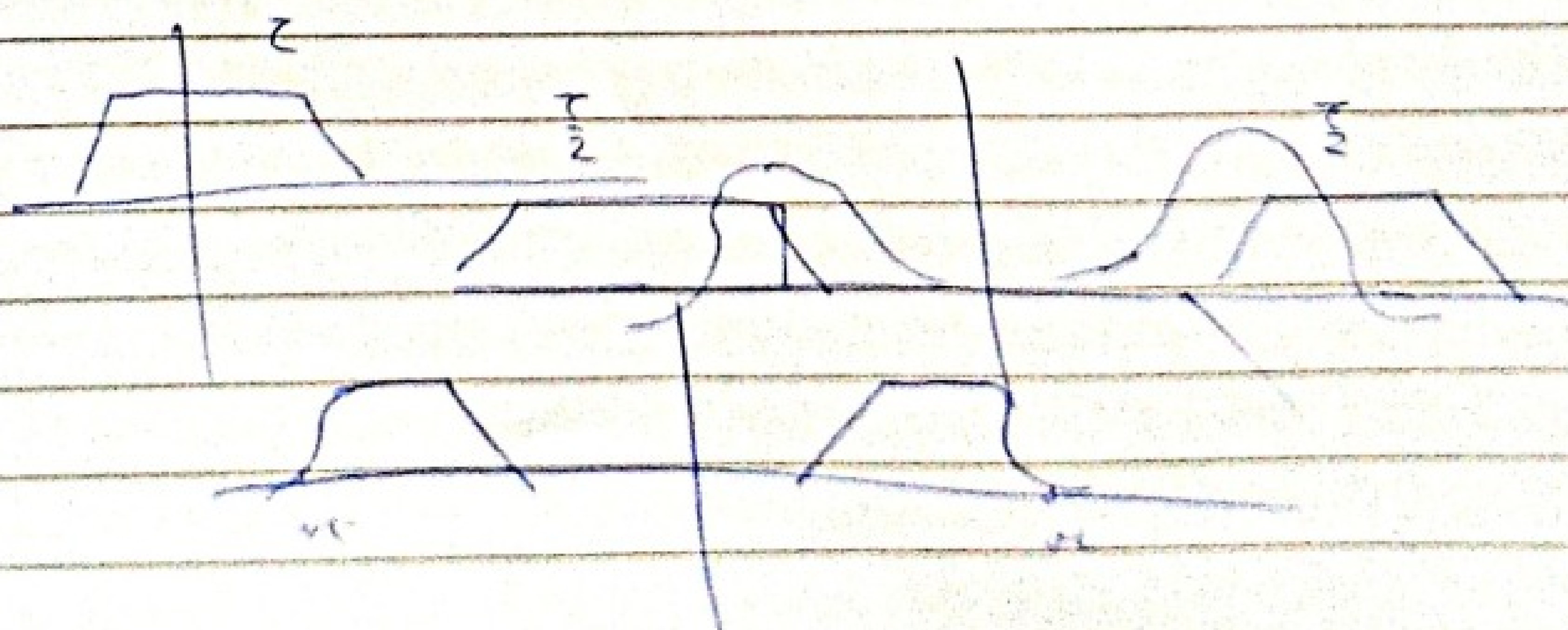
	Bandwidth	Avg power in $\phi(t)$
DSB-SC	$2B$	$\frac{1}{2}\overline{m^2(t)}$
SSB-SC	B	$\frac{1}{4}\overline{m^2(t)}$
QAM	$2B^{+}$	$\frac{1}{2}\overline{m_1^2(t)} + \frac{1}{2}\overline{m_2^2(t)}$
VSB-SC	$(1+\varepsilon)B$ $= B + B\varepsilon$ $0 \le \varepsilon \le 1$ theoretical $0.1 \le \varepsilon \le 0.25$ practical	$\frac{1}{4}\overline{m^2(t)}$

Vestigial sideband (VSB)

VSB-SC (USB)
VSB-SC (LSB)
VSB-LC (USB)
VSB-LC (LSB)

(1) Passes some of the lower side band "LSB"
(2) But also reject some of the USB

Perfectly symmetric USB 0.1 0.9
USB 0.9 0.8



Higher bandwidth means more fading

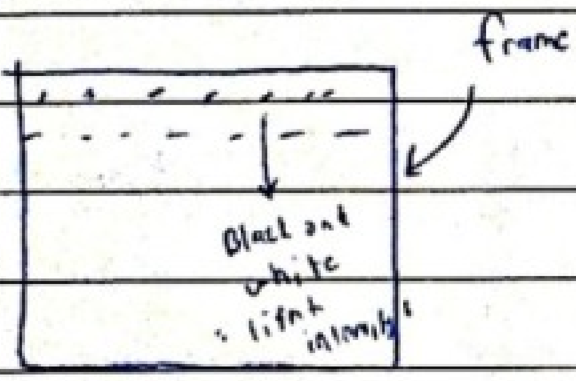
Slide 18

in terms of attenuation and distortion

SSB-SC suffers less than VSB-SC less than DSB-SC less than QAM

envelope detection ≡ asynchronous demodulator.

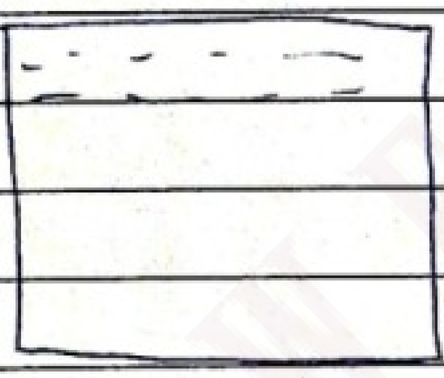
NTSC



525 lines of resolution

Standard definition SDTV

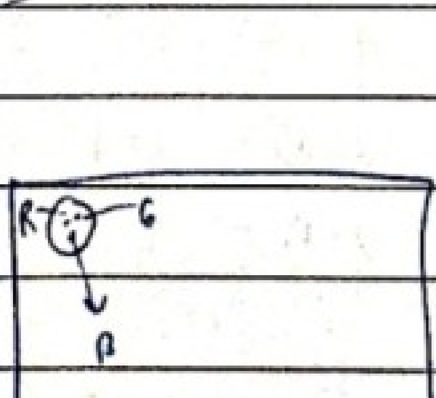
PAL



625 lines of resolution

1080 p → lines of resolution } HDTV
720 p

Coloured



RGB ⟶ luminance and chrominance
Y U & V

Reasons #1 : Maintains backwards compatibility
#2 : Save bandwidth ∵ a human eye is less sensitive to chrominance to luminance

Slide 22 Right side change 4 MHz to 1 MHz

luminance :. USB+C bandwith = $(1+\underset{\downarrow}{\overset{0.25}{\varepsilon}})B = 5\,MHz$

Chrominance U & V : QAM Bandwidth = 2B = 2 * 1 = 2 MHz

↓ because we send 2 signals simultaneously

In general, you cannot send USB and QAM on top of each other except in TV. "(interfence)"

Audio is FM modulated bandwidth = 0.5 MHZ = 500 kHz

* 0.25 MHz between audio and video " the gap is called guard band

The bandwidth for one NTSC TV station

0.25 MHz guard
1 MHz LSB
4 MHZ USB
0.25 MHz guard
0.5 MHz audio

6 MHz ***

for Pal station = 8 MHz

QAM "Chrominance remains 2 MHz"

~~Total bandwidth for one station 8 MHz~~

Total bandwidth for one DVB-T 7 station = 8 MHz
digital

Lecture 7 · Homodyne → single frequency
Heterodyn → multiple frequency

Frequency conversion

freq conv : modulated → modulated

$\omega_1 \longrightarrow \omega_2$

$m(t)\cos(\omega_1 t) \longrightarrow m(t)\cos(\omega_2 t)$

Tx $\underbrace{0 \longrightarrow \omega_I}_{\text{modulator}} \underbrace{\longrightarrow \omega_c}_{\text{F. converter "up converter"}}$ (low: ω_I, High: ω_c)

Rx $\underbrace{\omega_c \longrightarrow \omega_I}_{\text{down converter}} \underbrace{\longrightarrow 0}_{\text{demodulator}}$ (High: ω_c, low: ω_I)

Slide 4:-

cos (?)

the local oscillator (L.O) in the converter has a frequency of:.

$\omega_{LO} = \omega_{in} + \omega_{out}$ up converter

or $\omega_{LO} = |\omega_{in} - \omega_{out}|$ down converter

ex)	ω_{in} "ω_c"	ω_{out} "ω_I"	ω_{LO}
①	$(2\pi \times 100\ MHz)$ rad/s →	$(2\pi \times 200\ MHz)$ rad/s	
	100 MHz →	200 MHz	300 MHz "up-conv"
②	200 MHz →	100 MHz	300 MHz "up-conv"
③	100 MHz →	200 MHz	100 MHz "down-conv"
④	200 MHz →	100 MHz	100 MHz "down-conv"

BPF = center frequency ω_I

bandwidth = 2B Hz or $4\pi B$ rad/s

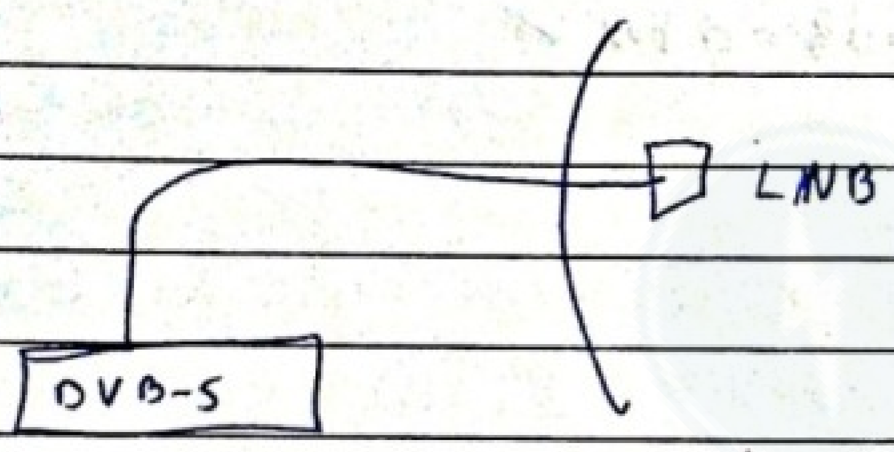
gain = 1

$y(t) = \frac{1}{2} m(t) \cos(\omega_I t)$

if gain = 2 $y(t) = m(t)\cos(\omega_I t)$

Practical Application for conv 7

QU band = 14 GHz but B_{ch} of Coaxial is 1-2 GHz



Lecture 8

Performance → SNR → Quality

if SNR ↓ bad Quality

For analog

To get good quality voice you need SNR ≥ 1000 unitless

For digital

SNR → BER → Quality

BER: bit error rate

BER ≤ 10^{-6} for good quality digital we don't use unitless, we use dB

SNR = 1000 unitless

SNR = 30 dB

0 unitless $\Rightarrow$ $-\infty$ dB

dBm + dB = dBm ✓ dBW + dB = dBW ✓

dB + dB = dB ✓

dBm + dBW ✗

SNR_{out} → at the receiver

Noise in time domain is gaussian distributed.

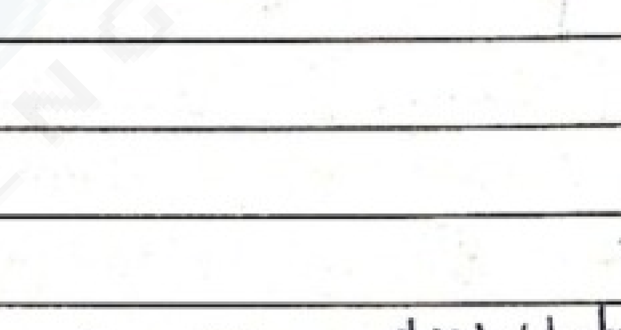
AWGN noise: The most popular mathematical model for noise (fits nicely with thermal internal noise)

Additive white gaussian nois "AWGN"

Mean = $\mu = 0$ = DC value

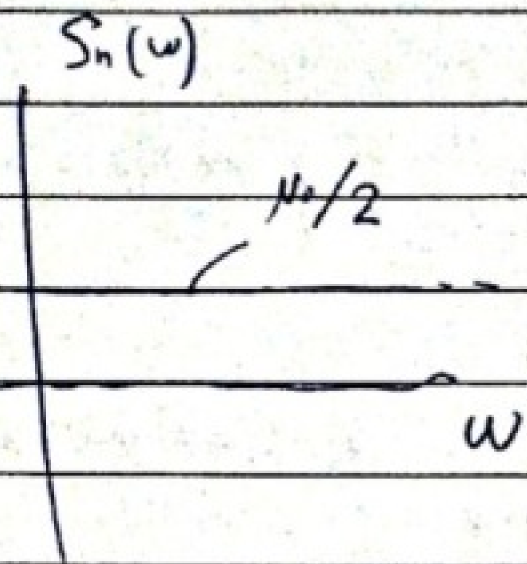
variance = σ^2 = avg. power in noise

Standard deviation = σ rms value



10 | 100

Noise in Frequency Domain "Power ~~*~~ spectral density"



$N_0 = 4KT$

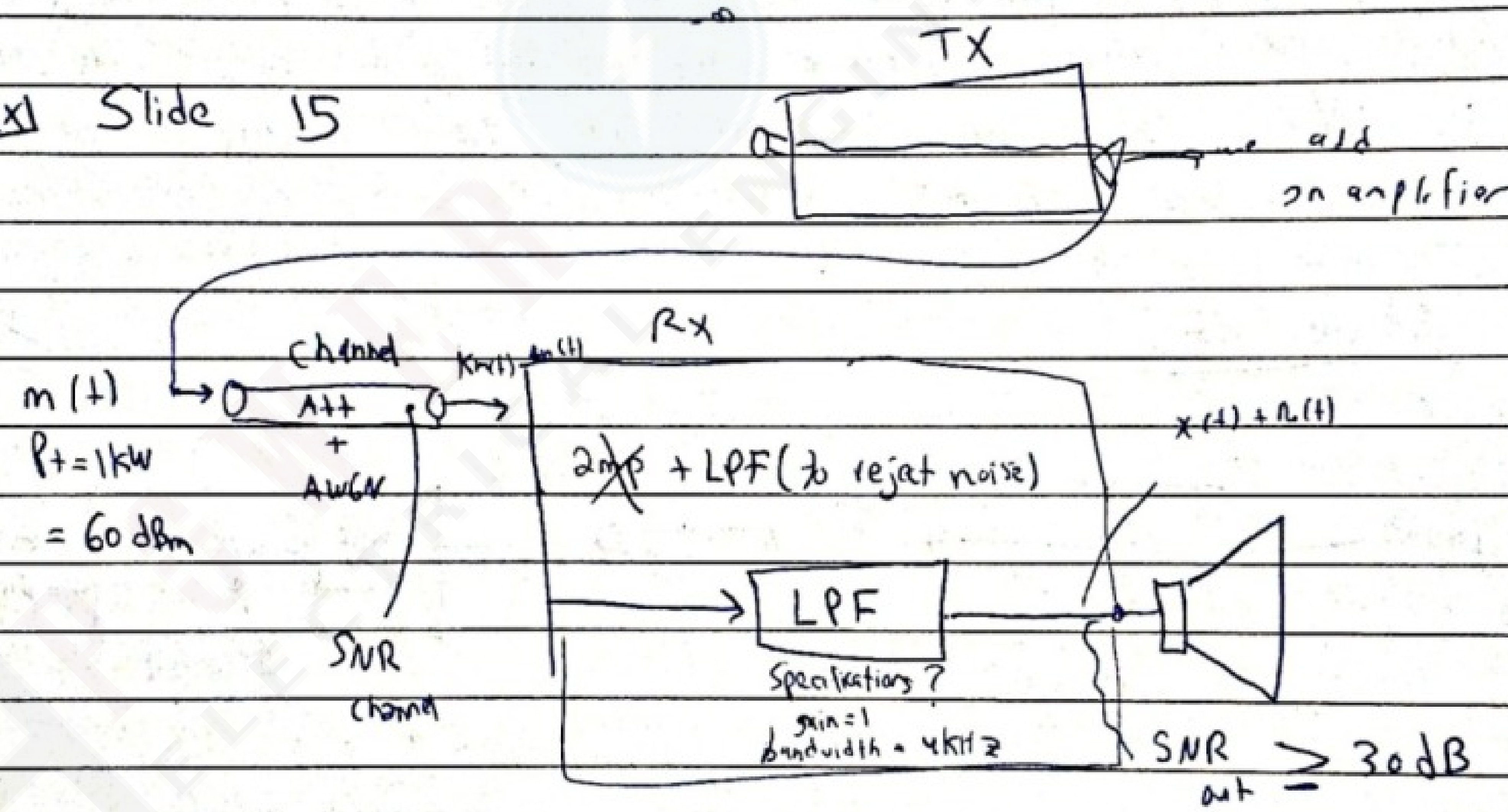
$K =$ boltzmann's const $= 1.38 \times 10^{-23}\ J/K$

$T =$ temp (k)

white noise has constant PSD

~~4~~ P_{ave} ~~(crossed out)~~ $= \frac{1}{2\pi}\int_{-\infty}^{\infty} S_n(\omega)\,d\omega$

ex) Slide 15



$SNR_{(channel)} = \frac{\text{signal power}}{\text{noise power}} = \frac{10mW}{\frac{1}{2\pi}\int_{-\infty}^{\infty} S_n(\omega)d\omega} = 0$ unitless

worst value possible

P_t +

$60\ dBm + (-50\ dB) = 10\ dBm = 10\ mWatt$

$P_{unitless} = 10^6\ mW \times 10^{-5} = 10\ mW$

$P_{dBW} = 30\ DBW + -50\ dB = -20\ dBW \Rightarrow 0.01\ W$

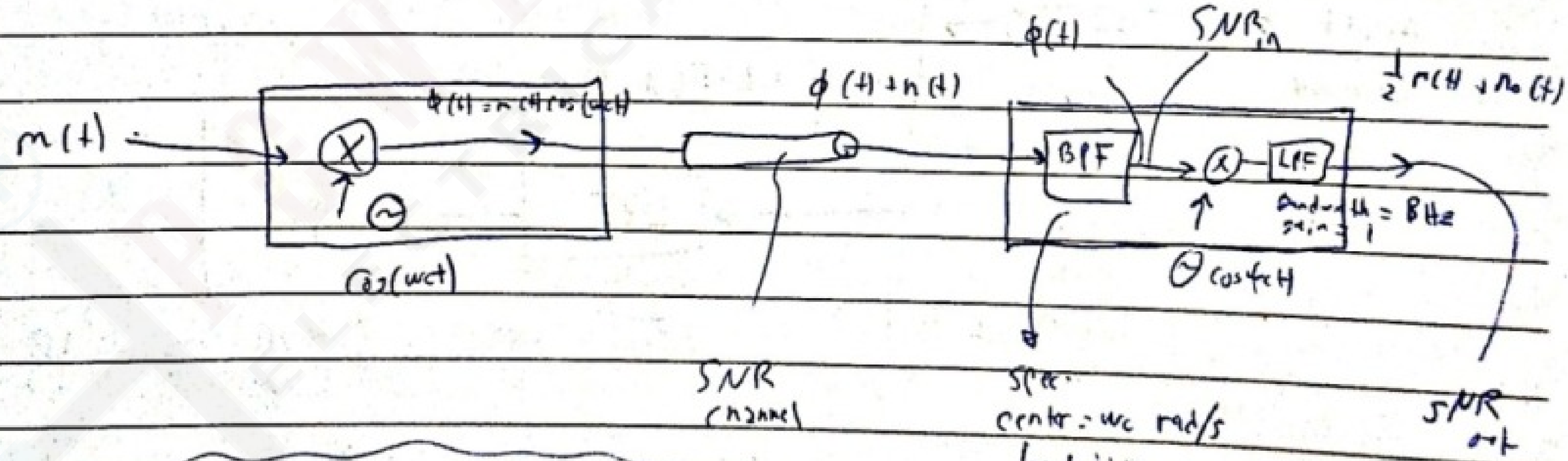
output noise power $= \overline{n_o^2(t)} = \frac{1}{2\pi}\int_{-2\pi B}^{2\pi B} S_{n_o}(\omega)\,d\omega$

$\frac{1}{2\pi}\frac{N_o}{2}(4\pi B) = N_o B = \left(4\times10^{-9}\ \frac{W}{Hz}\right)4000\ Hz = 16\,\mu W$

$SNR_{out} = \frac{\text{signal power}}{\text{noise power out}} = \frac{10\,mW}{16\,\mu W} = 625\ \text{unitless} = \underline{27.96\,dB}$ still bad quality

* $x(t)$ will have the same power because gain of LPF=1
if gain =4 then power is 16 times input power. so does the noise increase by a factor of 16 "No use"
We add an amplifier at the transmitter before the channel

Slide 17



$SNR_{channel} = 0\ \text{unitless} = -\infty\ dB$

$SNR_{in} = \frac{\text{signal power}}{\text{noise power}} = \frac{\overline{\phi^2(t)}}{\text{noise } P} = \frac{\frac{1}{2}\overline{m^2(t)}}{N \cdot P}$

$SNR_{in} = \frac{\frac{1}{2}\overline{m^2(t)}}{\frac{1}{2\pi}(\text{area})} = \frac{\frac{1}{2}\overline{m^2(t)}}{\frac{1}{2\pi}\left(\frac{N_o}{2}4\pi B\right)2} = \frac{\overline{m^2(t)}}{4N_oB} = \frac{S_{in}}{2N_oB}$

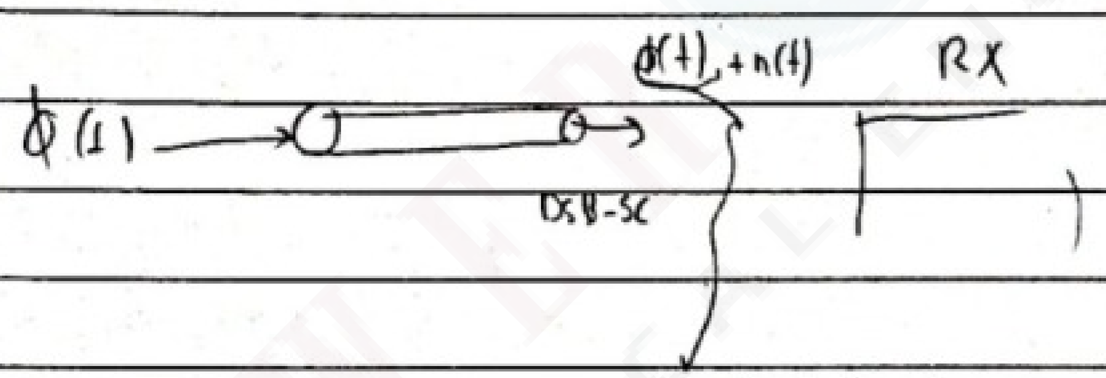
$\frac{1}{2}$ $\quad 10\log\left(\frac{1}{2}\right) = -3$ dB

SNR out : for noise power we multiply by $\frac{1}{4}$ when it enters the mixer instead of $\frac{1}{2}$ since its power

$$SNR_{out} = \frac{S.P_{(out)}}{N.P_{(out)}} = \frac{\frac{1}{4}\overline{m^2(t)}}{\frac{1}{2\pi}\left[4\pi B \frac{N_0}{4}\right]}$$

$$SNR_{out} = \frac{\overline{m^2(t)}}{2N_0B} = \frac{S_{in}}{N_0B}$$

We usually express SNR values in terms of Avg signal power @ the RX S_{in}



$$S_{in} = \overline{\phi^2(t)} = \frac{1}{2}\overline{m^2(t)}$$

$SNR_{out} > SNR_{in}$

"better quality"

So, the synchronous demodulator in DSB-SC has the ability to improve quality factor of 2 (because of orthogonality)

What is NF for our earlier example (DSB-SC demod)

$$NF = \frac{SNR_{in}\,(\text{unitless})}{SNR_{out}\,(\text{unitless})} = \frac{1}{2} \text{ unitless} \Rightarrow NF = -3\,dB$$

AM modulation

DSB-SC $\Rightarrow$ $\phi(t) = m(t)\cos(w_c t)$ — f-domain: extra carrier

DSB-LC "AM" $\Rightarrow$ $\phi(t) = m(t)\cos(w_c t) + \underbrace{A}_{\text{constant}}\cos(w_c t)$ ... ①

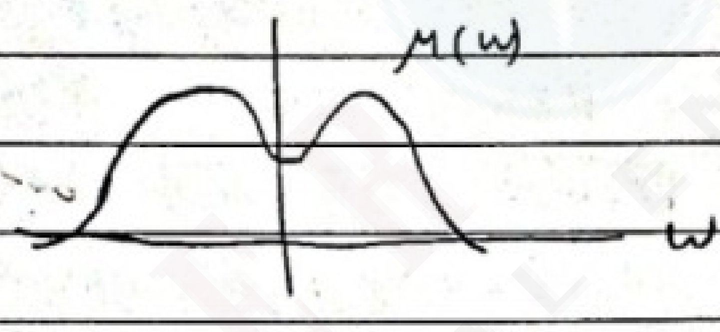
$\phi(t) = (m(t) + A)\cos(w_c t)$ ... ②

t-domain

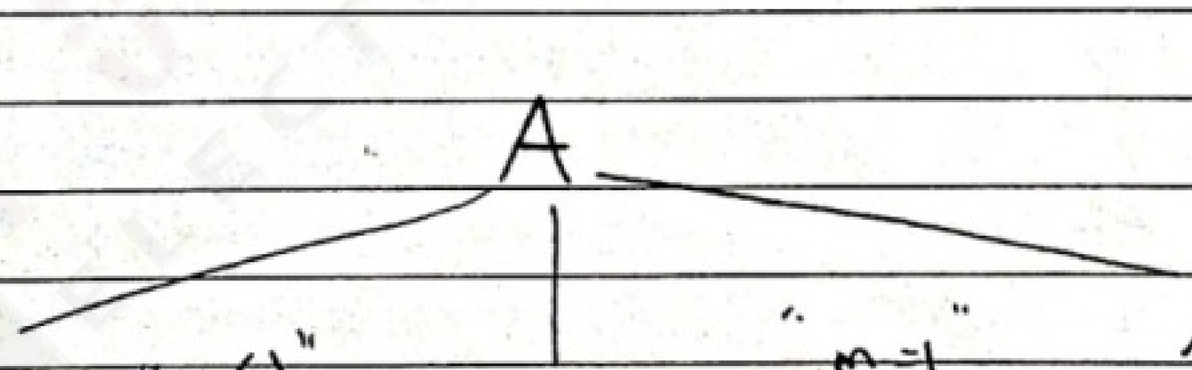
* In practical AM systems, we don't like $m(t)$ with a DC value.

Sol #1 : AM Radio

$m(t) =$ voice



$m(t)$ with DC $\longrightarrow || \longrightarrow$ $m(t)$ with DC = 0



A large "m < 1"	A medium "m = 1"	A small "m > 1"
$A > -m(t)_{min}$	$A = -m(t)_{min}$	$A < -m(t)_{min}$
"No sudden 180° shift"	"No sudden 180° shift"	"Sudden 180° shift"
"Under modulation"	"critical modulation"	"Over modulation"

DSB-SC is a special case when $A = 0$

Bandwidth of $\phi_{AM}(t)$ is $2B$ Hz or $4\pi B$ rad/s

Average power in $\phi_{AM}(t)$

$$\phi_{AM}(t) = m(t)\cos(\omega_c t) + \underbrace{A\cos(\omega_c t)}_{\frac{A^2}{2}}$$

* If we have no sudden phase shifts we could be able to use asynchronous demodulators.

$$E(t) = \text{positive envelope of } \phi(t) = \text{pos. peaks} = m(t) + A$$ for under and critical

$$E(t) = |m(t) + A| \neq m(t) + A$$ in over modulation.

* We usually define an AM modulation index for $\phi(t)$ as follows :-

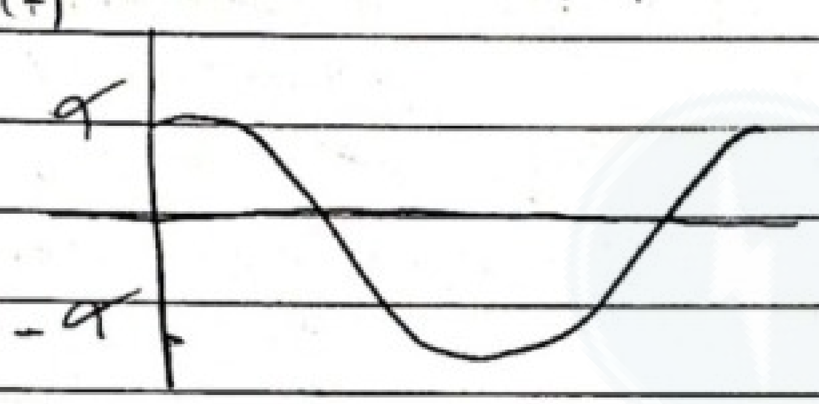
$$m = \frac{-m(t)_{min}}{A}$$ = AM modulation index.

Case	Avg. Power	RX	180°	B
$m<1$	large	asynch and Synch better preferred	NO	2B
$m=1$	medium	asynch and Synch	NO	2B ✓ best case
$m>1$	small	Synch only	Yes	2B

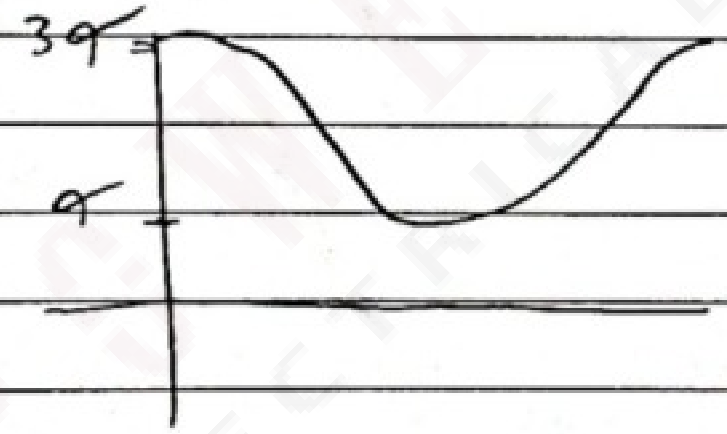
$m = 0.5$ under modulation "No sudden phase shift"

$$m = \frac{-m(t)_{min}}{A} = 0.5$$

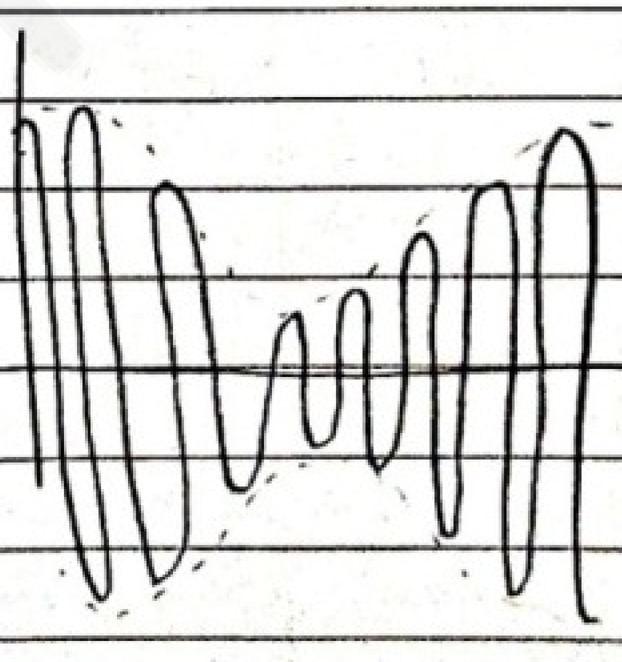
$$m = \frac{-(-\alpha)}{A} = 0.5 \qquad A = \frac{\alpha}{0.5} = 2\alpha$$



$m(t) + A = m(t) + 2\alpha = Z(t)$



$Z(t)\cos(w_c t)$

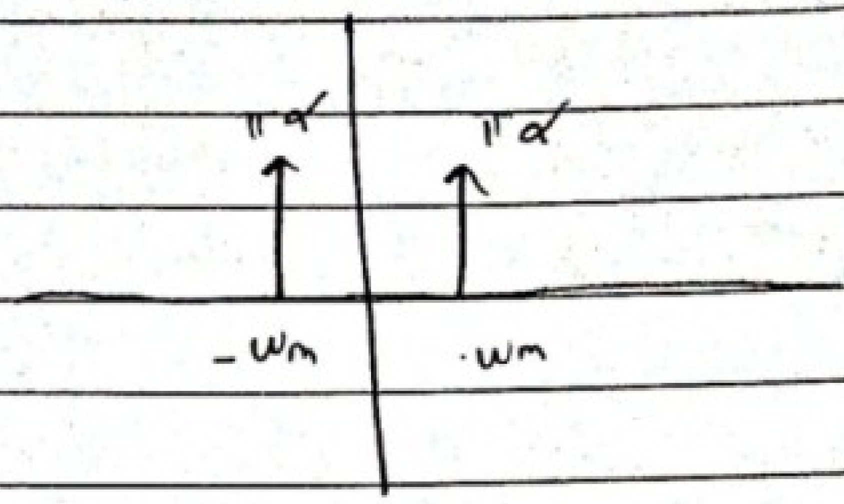


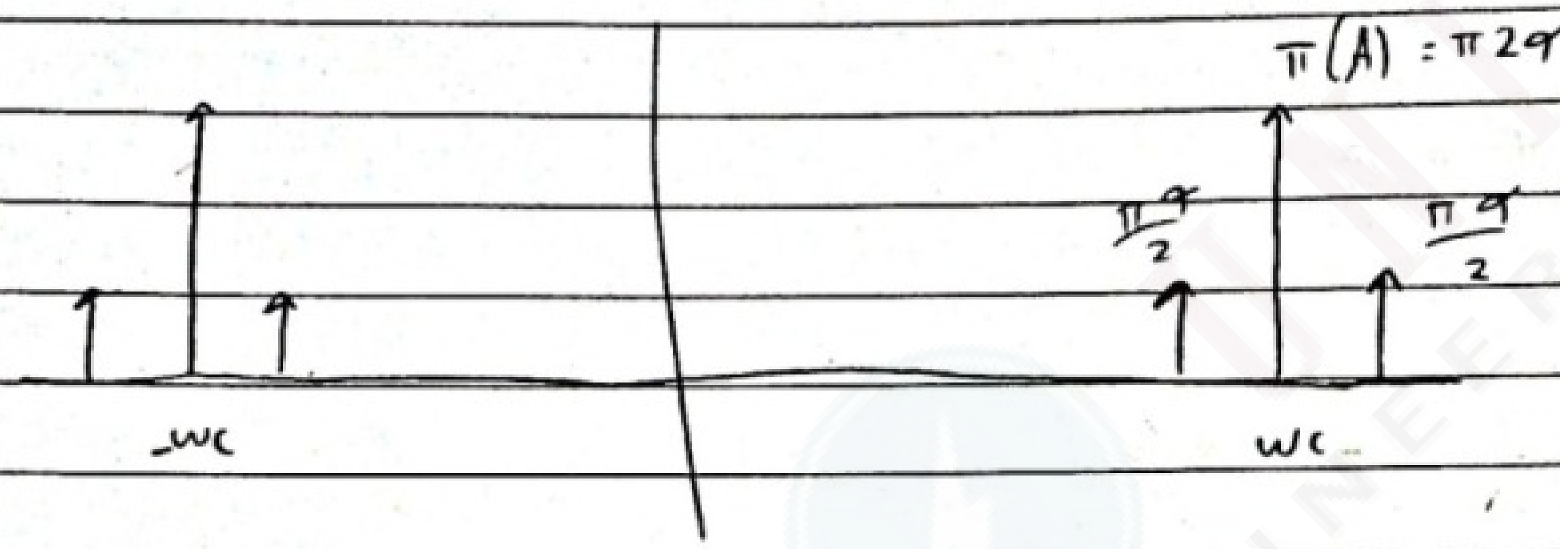
"No 180° shift"

$\phi_{AM}(t)$

sketch Φ_{AM}

$M(\omega)$





bandwidth of $\phi_{AM}(t) = 2\omega_m$ rad/s

$= \frac{2\omega_m}{2\pi}$ Hz

Slide 15 term #2

$$A^2 \overline{\cos^2(\omega_c t)} = A^2 \overline{\left[\frac{1}{2} + \frac{1}{2}\cos(2\omega_c t)\right]}$$

$$= A^2 \left[\overline{\frac{1}{2}} + \frac{1}{2}\overline{\cancel{\cos(2\omega_c t)}}^{\,0}\right]$$

$$= \frac{A^2}{2} = P_c = \text{Power in extra carrier}$$

term #1

$$\overline{m^2(t)\cos^2(\omega_c t)} \simeq \overline{m^2(t)}\;\overline{\cos^2(\omega_c t)} = \overline{m^2(t)}\,\frac{1}{2} = P_s$$

Power in sideband "DSB-SC"

$$\int x(t)\cdot y(t)\,dt \neq \int x(t)\,dt \cdot \int y(t)\,dt$$

m(t) is slowly varying with respect to the carrier

$$B \lll f_c$$

4KHz ~1MHz ~100MHz

term #3 $\quad 2A\,\overline{m(t)\cos^2(\omega_c t)} \simeq 2A\,\overline{m(t)}\;\overline{\cancel{\cos^2(\omega_c t)}}^{\,\frac{1}{2}}$

$= A\,\overline{m(t)}$

* In practical AM systems we make sure that $\overline{m(t)} = DC = 0$

$P_t = P_s + P_c + 0 = \frac{1}{2}\overline{m^2(t)} + \frac{A^2}{2} + A\,\cancel{\overline{m(t)}}^{\,0}$

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

$A = 2\alpha$

$P_t = \frac{\alpha^2}{4} + 2\alpha^2 + 0$

$\eta = \frac{\text{useful power}}{\text{Total power}} = \frac{P_s}{P_t} = \frac{P_s}{P_s + P_c + 0}$

(tone modulation) $\quad \eta = \frac{m^2}{m^2 + 2}$

$\eta_{DSB\text{-}SC} = \frac{\frac{1}{2}\overline{m^2(t)}}{\frac{1}{2}\overline{m^2(t)}} = 1 = 100\,\%$ "$A = 0$"

$m < 1$	large A	
$m = 1$	med A	worse
$m > 1$	Small A	
$m = \infty$	$A = 0$	

Back to the example

$$\eta = \frac{P_s}{P_s + P_c} = \frac{\frac{1}{2}\overline{m^2(t)}}{\frac{1}{2}\overline{m^2(t)} + \frac{A^2}{2}} = \frac{\frac{1}{2}\left(\frac{\alpha^2}{2}\right)}{\frac{1}{2}\left(\frac{\alpha^2}{2}\right) + \frac{A^2}{2}}$$

$$m = \frac{-m(t)_{min}}{A} \qquad m = \frac{\alpha}{A}$$

$$A = \frac{\alpha}{m}$$

$$\eta = \frac{\frac{\alpha^2}{4}}{\frac{\alpha^2}{4} + \frac{\alpha^2}{2m^2}} \times \frac{\frac{4m^2}{\alpha^2}}{\frac{4m^2}{\alpha^2}}$$

$$\eta = \frac{m^2}{m^2 + 2}$$

$m = 0.5$ $\quad \eta = 11.111\%$

$m = 1$ $\quad \eta = 33.333\%$

$m = 2$ $\quad \eta = 66.6666\%$

$m = \infty$ $\quad \eta = 100\%$

For voice when $m = 1$ $\quad \eta = 25\%$

Missing Lecture

AM TX
AM RX

E.D
R.D
S.D.

} asynch demodulators
① No L.O at the RX side
② which means there is no need for perfect Synch.

$V_o(t) = E(t) + \text{ripple} = [m(t) + A] + \text{ripple}$ assuming $\phi_{AM}(t)$ under or critically modulated.

Increase $(\tau = RC)$ to minimize ripple. X
If we increase τ, there is a risk that we don't follow the envolope

High τ : don't follow the envelope
low τ : too much ripple

Intermediate τ is the desired.

In practice $w_c \gg w_m$ $f_m \gg f_c$

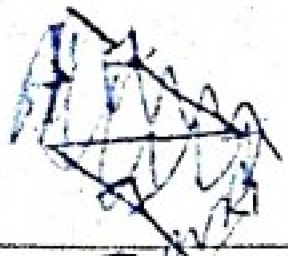
You want $T_c \ll \tau \ll T_m$

$$\frac{1}{f_c} \ll \tau \ll \frac{1}{f_m} \qquad \frac{1}{f_c} \ll \tau \ll \frac{1}{B}$$

B: Bandwidth of the message

in Design B

$$\boxed{\alpha_1 = \frac{1}{\pi}}$$



unless you use a DC coupling capacitor

unless you use LPF

E.D output = E(t) + ripple

R.D output = $\frac{1}{\pi} E(t) < 0.333\, E(t)$

unless you use a DC coupling capacitor.

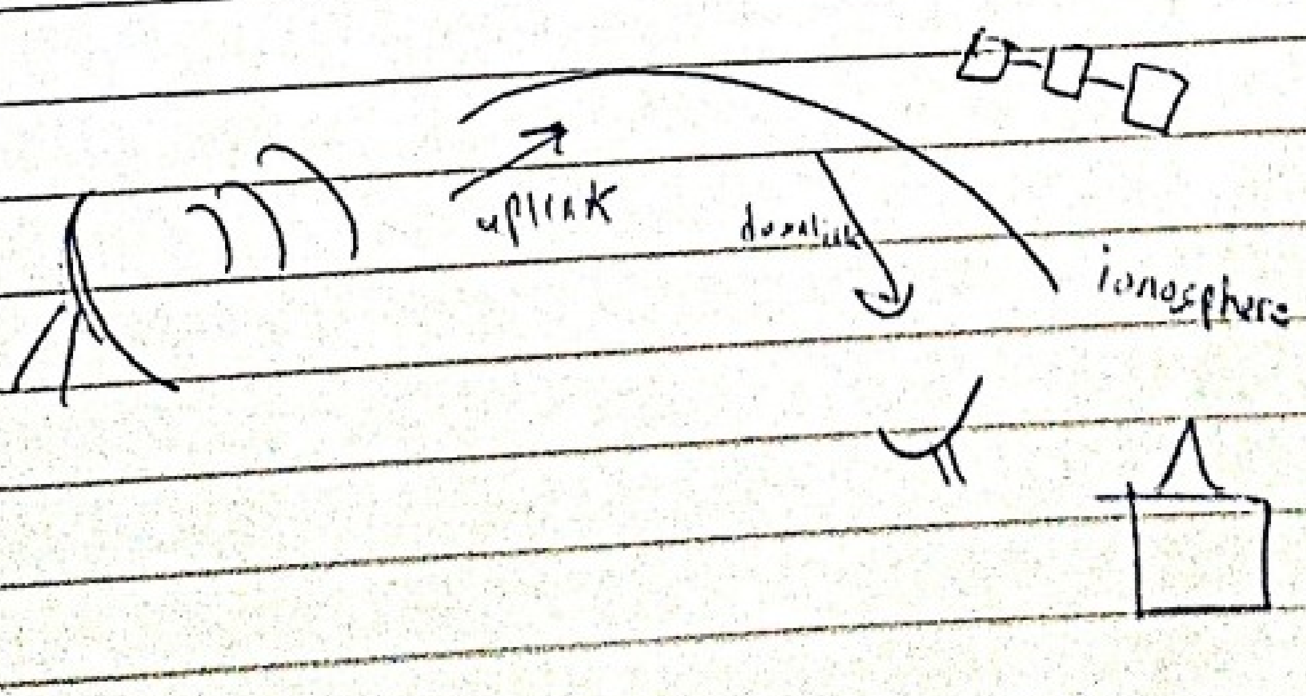
Asynch	RX	TX	
	cheap	η is very small (wasted power)	
synch	expensive	$\eta \to 100\%$ (DSB-SC)	

* TV Broadcasting frequencies

VHF: very high frequency 30 - 300 MHz
UHF: ultra high freq 300 MHz - 3 GHz

\+ Satellite TV Broadcasting

		Uplink	Downlink
	C Band	6 GHz	4 GHz
	Ku Band	14 GHz	11 - 12 GHz
	Ka Band	30 GHz	18 - 20 GHz



"acts like a mirror for small frequen

AM Radio Broadcasting

US : 10 kHz , also bandwidth of the tunable BPF

voice = 4kHz $\xrightarrow{\text{AM modulation}}$ 8 KHz = 2B

Guard Band = 1kHz

Euro: 9 KHz   0.5 + 8 kHz + 0.5 (guard band)

Bandwidth of tunable BPF

AM Superheterodyne Receiver

RF = Radio frequency ~ 1 MHz "high frequency"

IF = intermediate frequency smaller than w_c
"455 kHz"

Frequency Modulation "FM"

* $\underbrace{\text{FM and PM}}_{\text{angle modulation}}$ are equivalent "duality"

FM :- Frequency of c(t) varies with m(t)
PM :- Phase of c(t) varies with m(t).

$c(t) = A \cos(\underbrace{w_c t}_{\text{carrier frequency}} + \theta_0)$

frequency
- w_c : carrier freq : constant decided by the oscillator
- $w_i(t)$: instantaneous frequency w_i is variable

1) Generalized angle $\theta(t)$
2) Instantaneous phase $\theta_i(t)$
3) Instantaneous frequency $w_i(t)$

$C(t) = A\cos\{\underbrace{(w_c t + \theta_0)}_{\theta(t)}\}$

$C(t) = A\cos(\theta(t))$

$\theta_i(t) = \theta(t) - w_c t$

$w_i(t) = \frac{d}{dt}\theta(t).$

example | $c(t) = A\cos(w_c t + \theta_0)$

$\left.\begin{array}{l} \theta(t) = w_c t + \theta_0 \\ \theta_i(t) = \theta_0 \\ w_i(t) = w_c \end{array}\right\}$ only specified for unmodulated carrier.

$w_i(t) \propto m(t)$

FM
- A constant
- w_c constant
- $w_i(t) = w_c + k_f m(t)$
- $\theta_i(t) = k_f \int_{-\infty}^{t} m(t)\,dt$

$$\theta(t) = \int_{-\infty}^{t} w_i(\tau)\,d\tau$$

For FM

$$\theta_{FM}(t) = \int_{-\infty}^{t} [w_c + k_f m(t)]\,dt$$

$$\theta_{FM}(t) = w_c t + k_f \int_{-\infty}^{t} m(t)\,dt$$

PM modulation

$$\theta_i(t) = \cancel{\theta_0} + k_p m(t) = k_p m(t)$$

PM
- A constant
- w_c constant
- $w_{i_{pm}}(t) = w_c + k_p m'(t)$
- $\theta_i(t) = k_p m(t)$

$$w_i(t) = \frac{d}{dt}\theta_{PM}(t) = \frac{d}{dt}\left[w_c t + k_p m(t)\right] = w_c + k_p \frac{d}{dt} m(t)$$

$$\phi_{FM}(t) = A\cos\left(w_c t + k_f \int_{-\infty}^{t} m(t)\,dt\right)$$

$$w_i = w_c + k_f m(t)$$

$$\phi_{PM}(t) = A\cos\left(w_c t + k_p m(t)\right)$$

$$w_i = w_c + k_p m'(t).$$

VCO :- Voltage controlled oscilator "FM modulator"

$$m(t) \longrightarrow \boxed{VCO} \longrightarrow \phi_{FM}$$

$$m'(t) \longrightarrow \boxed{VCO} \longrightarrow \phi_{PM}$$

ex1) $f_c = 100\ MHz$ Slide "7"

$w_c = 2\pi(100\ M)\ \frac{rad}{s}$

(a) $w_{i_{max}}(t) = w_c + k_f(4)$ = ~~100 MHz~~

$w_{i_{min}}(t) = w_c + k_f(-4)$

$f_{i_{max}} = 100\ MHz + \frac{2\pi\times10^5}{2\pi}(4) = 100.4\ MHz$

$f_{i_{min}} = f_c + \frac{k_f}{2\pi}(-4) = 100\ MHz + \frac{2\pi}{2\pi}10^5(-4) = 99.6\ MHz$

* Δf = peak frequency deviation

$\Delta f = \frac{f_{max} - f_{min}}{2}$ ← inst frequency

For part (a) $\Delta f = \frac{100.4 - 99.6}{2} = 0.4\ MHz$

For FM (general eq).

$f_{max} = f_c + \frac{k_f}{2\pi} m(t)_{max}$

$f_{min} = f_c + \frac{k_f}{2\pi} m(t)_{min}$

$\Delta f = \frac{k_f}{4\pi}\left(m(t)_{max} - m(t)_{min}\right) = 0.4\ MHz$

Δf for PM

$$f_{max} = f_c + \frac{k_p}{2\pi} m'(t)_{max}$$

$$f_{min} = f_c + \frac{k_p}{2\pi} m'(t)_{min}$$

$$\Delta f = \frac{k_p}{4\pi} \left(m'(t)_{max} - m'(t)_{min} \right)$$

* $\Delta\theta$ = peak phase deviation

$$\Delta\phi = \frac{\theta_{imax} - \theta_{imin}}{2} \quad \nearrow \text{inst phase}$$

$\Delta\theta_{FM}$

$$\theta_{i_{FMmax}} = k_f \left[\int_{-\infty}^{t} m(t)\,dt \right]_{max}$$

$$\theta_{imin} = k_f \left[\int_{-\infty}^{t} m(t)\,dt \right]_{min}$$

$$\Delta\theta = \frac{k_f}{2} \left[\int m(t)\,dt_{max} - \int m(t)\,dt_{min} \right]$$

$\Delta\theta_{PM}$

$$\theta_{max} = k_p\, m(t)_{max}$$

$$\theta_{min} = k_p\, m(t)_{min}$$

$$\Delta\theta_{PM} = \frac{k_p}{2} \left(m(t)_{max} - m(t)_{min} \right)$$ in rads

if degrees $\times \frac{180}{\pi}$

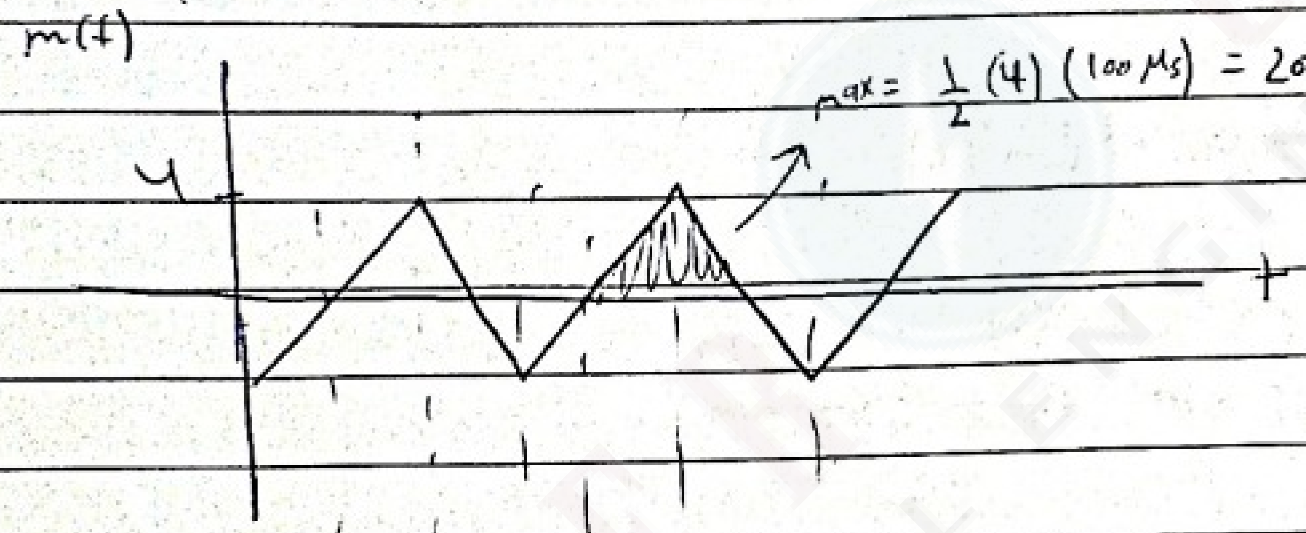
(b) $f_{max} = 100\ MHz + \frac{5\pi}{2\pi}(80{,}000) = 100.2\ MHz$

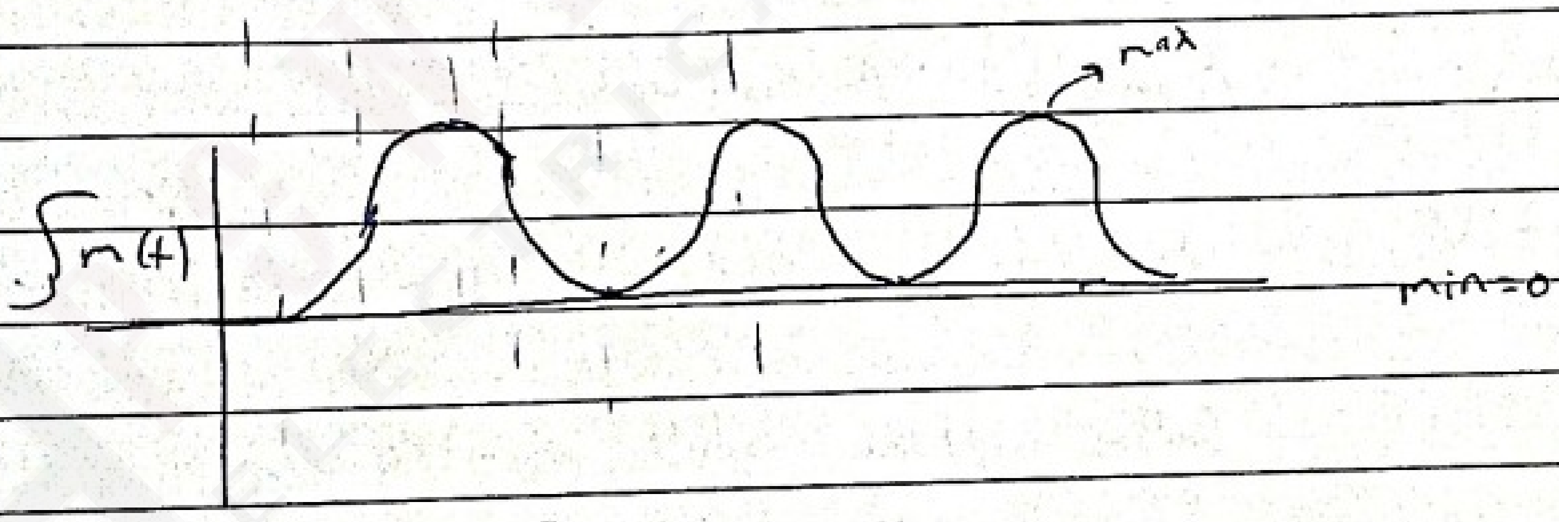
$f_{min} = 99.8\ MHz$

$\Delta f_{fm} = \frac{100.2 - 99.8}{2} = 0.2\ MHz$

OR $\Delta f_{fm} = \frac{5\pi}{4\pi}(80{,}000 - -80{,}000) = 0.2\ MHz$

max $= \frac{1}{2}(4)(100\ \mu s) = 200\ V.\mu s = 200 \times 10^{-6}\ V.S$





For FM

$\phi_{max} = k_f \left[\int m(t)\, dt \right] = 2\pi \times 10^{5} \times 200 \times 10^{-6} = 40\pi$ rad

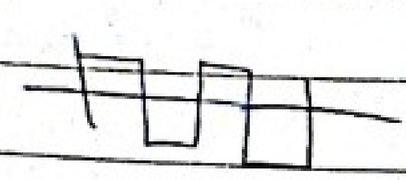
$\phi_{min} = k_f \left[\int m(t)\, dt \right] = 0$ rad

$\Delta\phi = \frac{40\pi - 0}{2} = 20\pi$ rad

if degree $\times \frac{180}{\pi} = 3{,}600^{\circ}$

$$\Delta\phi_{pm} = \frac{5\pi}{2}\left(4 - (-4)\right) = 20\pi$$

if $m(t) =$ Polar NRZ + FM = FSK "digital modulation"



If $m(t) =$ (Polar NRZ) + PM = BPSK ~ Binary phase shift keying.

ex 2

$$\phi_{pm}(t) = A\cos(w_c t + k_p m(t))$$

$$w_{i\,pm}(t) = w_c + k_p m'(t)$$

if $m(t) = 0 \Rightarrow w_{i\,pm}(t) = w_c$

if $m(t) \approx \infty \Rightarrow w_i \approx \infty$ for zero time

$+90^\circ$

$m(t_0^-) = 2V$ $\quad \phi_{pm}(t_0^-) = A\cos\left(w_c t_0^- + \frac{\pi}{4}(2)\right)$

-90°

$m(t_0^+) = -2V$ $\quad \phi_{pm}(t_0^+) = A\cos\left(w_c t_0^+ + -\frac{\pi}{4}(2)\right)$

Sudden phase shift $= -180^\circ$

FM Modulation index

if β large $(\beta \gg 1)$

wideband FM

in which the the bandwidth of $\phi_{FM}(t)$ is large

if β is small $(\beta \ll 1)$

Slide 22 2^{nd} exam 2' not included

Special cases $\Phi_{FM}(\omega)$

① FSK $\Rightarrow$ $m(t)$ = Polar NRZ + FM

② Tone modulation

$\Rightarrow$ $m(t) = a\cos(\omega_m t)$ + FM

Sketch $\phi_{FM}(t)$, $\Phi_{FM}(\omega)$, bandwidth

Slide 24

$J_n(\beta) \equiv$ Bessel function of the 1^{st} kind and the n^{th} order.

$$J_n(\beta) = \frac{1}{2\pi}\int_{-\pi}^{\pi} e^{j(\beta \sin x - nx)}\,dx$$

ex) $J_2(\beta=2) = 0.353$ from table

ex) $J_{-3}(\beta=2) = -J_3(\beta=2) = -0.129$

Find P_{ac} in $\phi_{FM}(t)$

sol #1 : $\overline{\phi^2_{FM}(t)} = \frac{A^2}{2}$

sol #2 : $\sum_{n=-\infty}^{n=\infty}\left(\frac{[A J_n(\beta)]^2}{2}\right) = \frac{A^2}{2} * 1 = \frac{A^2}{2}$

$|J| < 0.1$ then J is insignificant

$\beta = 2 \Rightarrow$ SSP: significant sideband pairs $= 3 = \beta + 1$

$\beta = 4 \Rightarrow$ SSP $= 5 = \beta + 1$

$-J_5 \; -J_4 \; -J_3 \; -J_2 \; -J_1 \; J_0 \; J_1 \; J_2 \; J_3 \; J_4 \; J_5$

5 pairs

Bandwidth for $\beta = 2$: 3 pairs $(2\omega_m) = 6\omega_m$ rad/s

$\beta = 4$: $5(2\omega_m) = 10\omega_m$ rad/s

$\text{Bandwidth}_{FM} = 2B(\beta+1)$ Hz or $= 2\beta + 2\Delta F$

* To overcome fading in FM we use AGC
  automate gain control.

* Adjacent-channel interference shows up in FDM systems

* Pre-emphasis in FM radio TX
* De-emphasis in FM Radio RX

$\Big\}$ improves SNR

Stereophonic FM

Monophonic FM

m(t) (cos +1   cos (m(t) +)

Lecture 16 :-

VCO: voltage - controlled oscillator = FM modulator

= modified oscillator

↗ amplitude variations

$\phi_{AT} = \frac{d\phi_{FM}}{dt}$

$\phi_{FM}(t) = A\cos(w_c t + k_f \int m(t)\,dt)$

$\frac{d}{dt}\phi_{FM}(t) = +\underbrace{A(w_c + k_f m(t))}\sin(w_c t + k_f \int m(t)\,dt + \pi)$

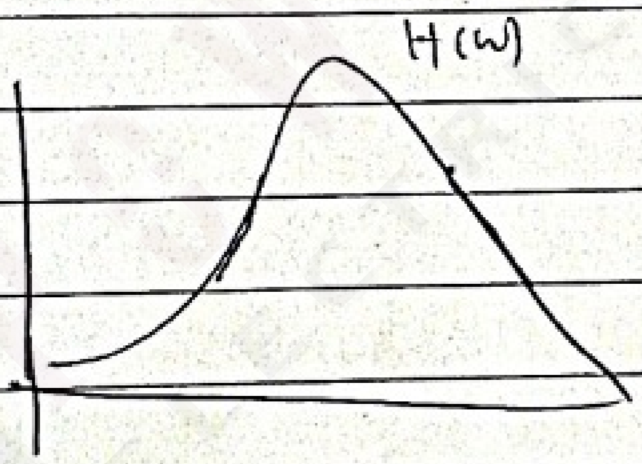
↓

Envelope $= E(t) =$ const + const $m(t)$

An LC tank can be used as a differentiator $\frac{d}{dt}$

An LC resonant ckt can also be used as a BPF

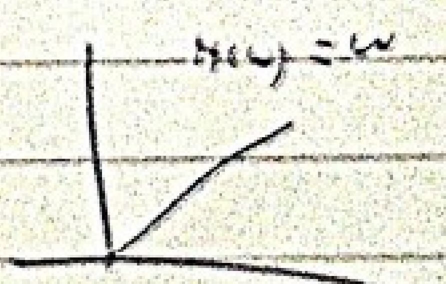
Center = W_{res}



time	freq
$\frac{d}{dt}$ ⟷	linear curve

$F\{\frac{d}{dt}x(t)\} = jw\,X(w)$

$|jw| = w$



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Lecture 17

FDM $\xrightarrow{\text{requires}}$ modulation
TDM $\longrightarrow$ digital baseband

Why do we need delay in TDM
and how much is it for bit interleaving
word interleaving.

H.W Assume

mA : bipolar f_0 = 100 kbit/s
mB : Manchester f_0 = 300 kbit/s
mC : Duobinary f_0 = 500 kbit/s
mD : Polar NRZ f_0 = 1000 kbit/s

using slide #8
Sketch PSD for ~~$m_3(t)$~~

assuming unipolar RZ

Typical guard band = 5% of bandwidth

Slide 11 $E_1 = 32$ PCM streams

Synch all TX/RX to same master clock   ^'Very expensive'

ex) Systems that use TDM and FDM
- GSM cellular
- DVB

digitization → modulation

BPF → demod → $\overset{\text{TDM}}{\text{de Mux}}$ → de-digitization

lecture 19

Constellation diagram (PSK and QAM): easy way to sketch time-domain

BER example.

Constellation diagram

I axis : $\cos(\omega_c t)$ CCW -ve in C.d

Q axis : $(\sin(\omega_c t))$

Slide 11 :- $10 \rightarrow A\cos(\omega_c t + 45^\circ)$

$11 \rightarrow A\cos(\omega_c t - 45^\circ)$

Slide 14: $r = \sqrt{(3A)^2 + (A)^2} = \sqrt{10}\,A$

$\theta = \tan^{-1}\left(\frac{A}{3A}\right) = 18.4^\circ$

$1001 \rightarrow A\sqrt{10}\cos(\omega_c t - 18.4^\circ)$

QAM $\rightarrow 3A\cos(\omega_c t) + A\sin(\omega_c t)$

BER example (16-QAM)

means quality "BER $\leq 10^{-6}$ good quality"

Slide 22

K = bits per symbol = 4 for 16-QAM
M = number of symbols = 16
E_b = average energy per bit = $\frac{E_s = \text{average energy per symbol}}{K}$

ex: $E_s = 4J$ $K = 4$ $E_b = 1J$

E = Power x time = $P_{symbol} \times T_{symbol}$
for QAM $E = \frac{(A_{symbol})^2}{2} \times T_{symbol}$

Take average of all points then take its power

$$E_s = E_{s_1} \cdot \underbrace{Pr[S_1]}_{\frac{1}{16}} + E_{s_2} \cdot \underbrace{[S_2]}_{\frac{1}{16}} + \dots + E_{s_{16}} \underbrace{[Pr[S_{16}]]}_{\frac{1}{16}}$$

equal

ex: $\frac{(1.414)^2}{2} \cdot T_{symb} \cdot \frac{1}{16}$ + Symmetric point + - - - - - -

4 symetric "equal" points on slide

$T_{symbol} = 4 T_0 = k T_0$

$\frac{1}{T_{symbol}}$ = baud frequency $\frac{1}{T_0} = f_0$

if given data rate $\longrightarrow f_0$
if " baud rate $\longrightarrow f_{symbol}$

linear interpolation

$3.15 \longrightarrow 8.16 \times 10^{-4}$

$3.162 \longrightarrow x$

$3.20 \longrightarrow 6.87 \times 10^{-4}$

$$\frac{3.2 - 3.15}{3.2 - 3.162} = \frac{6.87 \times 10^{-4} - 8.16 \times 10^{-4}}{6.87 \times 10^{-4} - x}$$