M T W T F S

Date: 26th Sep, 23

"Communication" CS

"Communication Systems":
- Exchange of messages.
- Telecommunication is exchange of messages over a distance by using some electrotechnical aid.
- Telegraphy (written information).
- Telephony (Audio)
- Television (videos).

Speech Signal (0.3kHz To 3.4kHz)

Sound energy

))) [Transducer] → electromagnetic wave

Antenna ← [Transmitter]

Receiving

))) ← [Speaker] ← [Receiver] ←

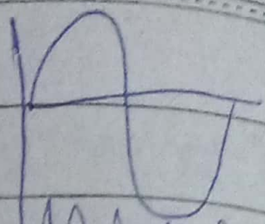
[Baseband] → [Modulator] → O/P modulated Signal

↑ Carrier Signal.

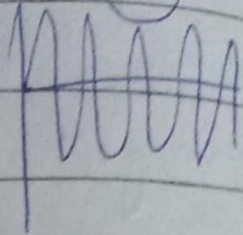
Modulator: amplitude modulation

If we vary any attribute of the carrier signal in accordance with the instantaneous value of the base band signal. The process is

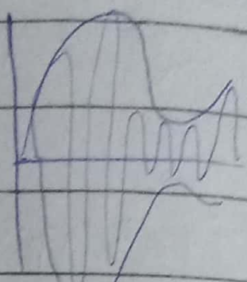
Baseband Signal



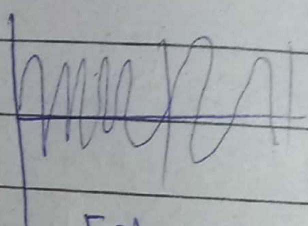
Carrier Signal



Modulated Signal. ec



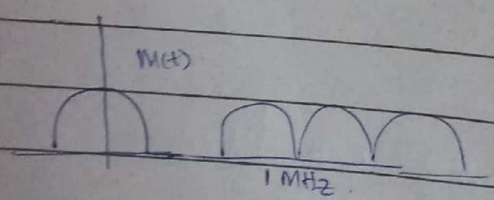
Amplitude is changed AM
in accordance with baseband signal



FM.

Why modulation is needed?

→ Frequency translation.



$m(t) \cos w_c t$.

$m(t) \cos 2\pi f_c t$

$m(t) \cos 2\pi \times 1 \times 10^6 t$

If modulator will not be used then
They will overlap.

Dimension of antenna should be half of wavelength

(ii) Practicality of Antenna.

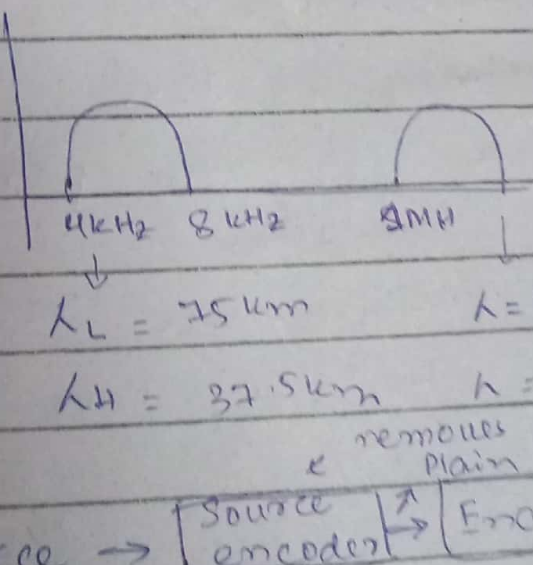
$f = 4kHz$

$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{4 \times 10^3}$

$= 75km.$

$\lambda = \frac{3 \times 10^8}{1 \times 10^6} = 300$

(3) Narrowbanding:



1004 kHz
4kHz

1004 kHz

~~1004 MHz~~

$\lambda_L = 75 km$ $\lambda = 300m$

$\lambda_H = 37.5km$ $\lambda = 300m$

baseband signal

removes extra bits

Plain text ↓ key cypher text

~ Source → [Source encoder] → [Encryption] →

[Decryption] [decoder] ← [Channel] ← [Channel encoder]

↓ It adds some additional bits.

destination

[Source decoder] → [~~Source~~]

Digital communication block.

In channel we have
* Noises.
* Interferences.
* Distortions.

$m(t) * h(t)$

$m(t) * \delta(t)$ (Impulse response)

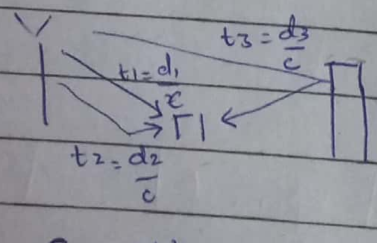
$m(t)$

$\delta(t)$ it's an ideal signal.

Noises
1- External (man-made)
2- Casmos rays

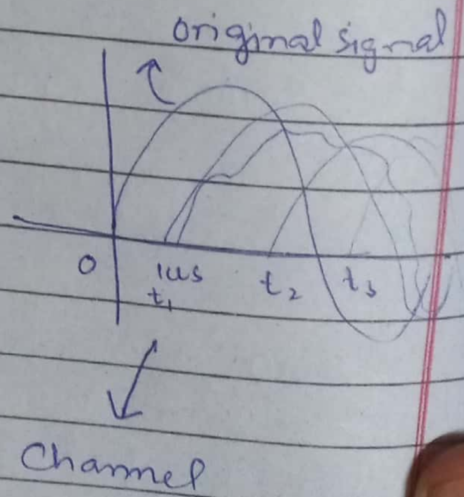
more frequency → less wavelength
it will not go too far.

Microwave window:
Range of frequencies That are best fit for wireless comm.



$S = vt$

$t = \frac{S}{v} = \frac{d}{c}$



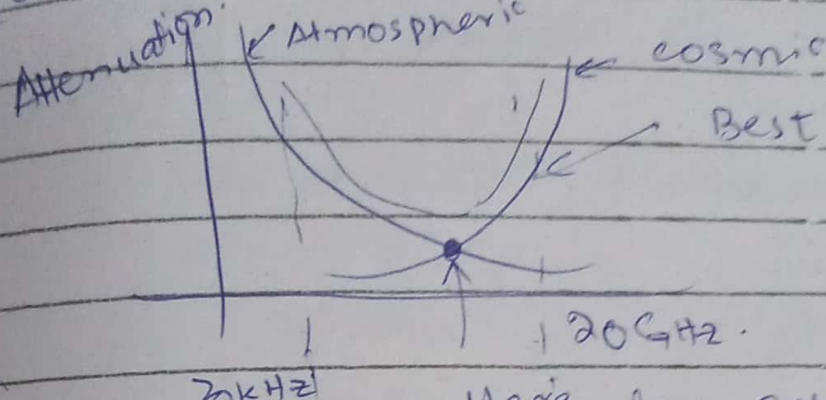
RAKE receiver. when receives multipath signal it saves them and accumulate them. CDMA Syst

M T W T F S Date:

$r(t) = m(t) * h(t) + n(t)$

$r(t)$ ↓ received, $h(t)$ ↓ external, $n(t)$ ↓ internal noise.

Internal noise is generalid due to temperature. also called (Short noise)



Here less attenuation.

(microwave window)

$r(t) = m(t) * h(t) + n(t)$.

ADGN Additive white guassian noise
↓ Present at all frequency

$SNR = \frac{P_s}{P_n} = 20dB$. $\frac{100W}{1W} = 10dB$

more SNR more signal power.

If it's less you can transmit less bits/sec.

dB ⟹ $10\log 100 = 20dB$. To compact values.

$10\log 10^6 = 60dB$ (Scaling)

dB

1 μwatt
$10\log 10^{-6}$
$-60dB$

P = 10 watt

$10\log 10 = 10dBw$

Unit value in dB

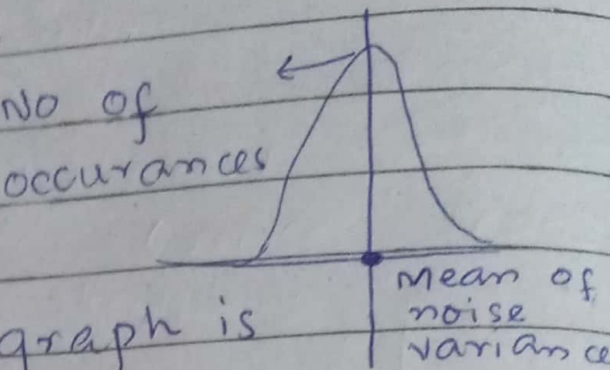
P = 10 mwatt.

$10\log 10 = 10dBm$

Date: 3 Oct, 2

M T W T F S

It probabilistic ~~instition~~ distribution is gaussian.



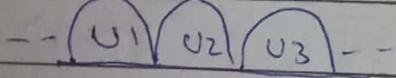
Spread of graph is variance.

Standard deviation = ?

Fidelity → How much signal is similar at the receiver whatever is transmitted. Degree of similarity

It can be implemented using correlation.

Multiplexing: Many into One.



FDM. ⇒ They will not overlap

FDMA → Frequency division multiple Access.

We divided band into blocks and slots and sent them on one channel and have given access to user to use them

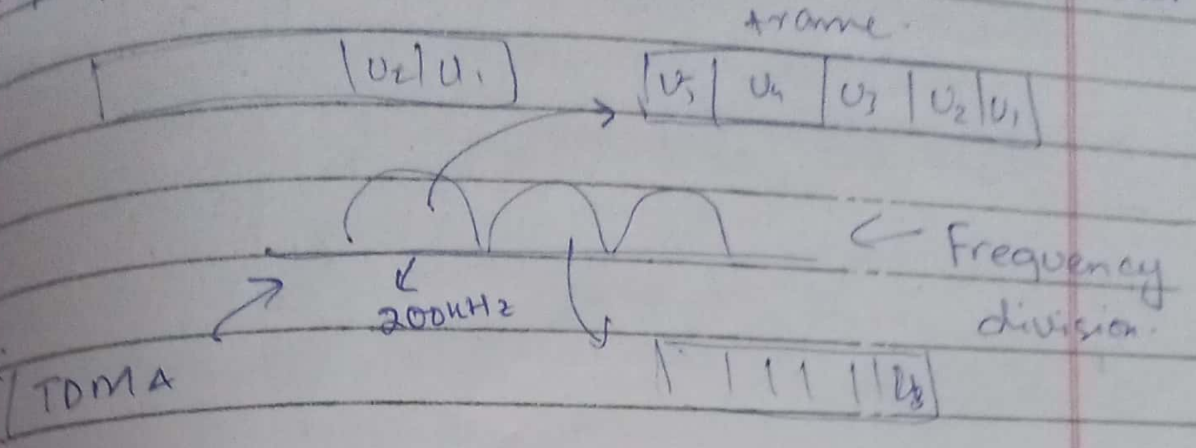
That was established in 1982.

1G AMPS → American mobile phone systems. 30KHz band

2G → FDM (European technology) TDMA

TDM: | U6 | U5 | U4 | U3 | U2 | U1 | Time slots.

Specific time slots are allocated to user.



2G = FDM / TDMA

GSM = Global system mobile communication.

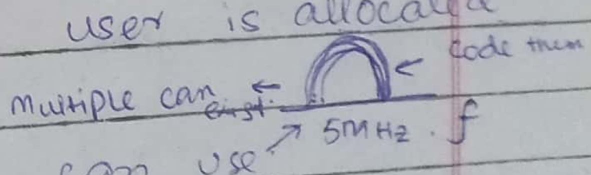
GSM is standard, it's fixed.

Like WiFi is standard.

With increasing bandwidth, data rate is increased.

CDMA → code division multiple access

3G or 2.5G → Every user is allocated a unique code.



Multiple users can use

Codes allocated should be orthonormal codes. When they are multiplied with itself it will be one and 0 if it's multiplied with others.

$$[m_1(t) * c_1(t) + m_2(t) * c_2(t)] * c_1(t).$$

$$c_1 \cdot c_2^T = \frac{1}{\ } [1 \quad 1 \quad 1 \quad 1] \begin{bmatrix} -1 \\ 1 \\ 1 \\ -1 \end{bmatrix}$$

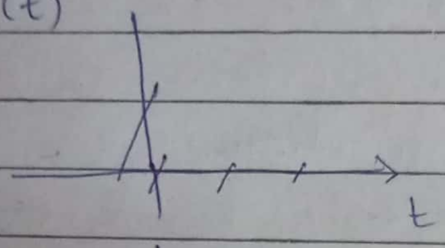
$$= \begin{bmatrix} \frac{1}{\sqrt{4}} & \frac{1}{\sqrt{4}} & \frac{1}{\sqrt{4}} & \frac{1}{\sqrt{4}} \end{bmatrix} \begin{bmatrix} -\frac{1}{\sqrt{4}} \\ \frac{1}{\sqrt{4}} \\ -\frac{1}{\sqrt{4}} \\ \frac{1}{\sqrt{4}} \end{bmatrix}$$

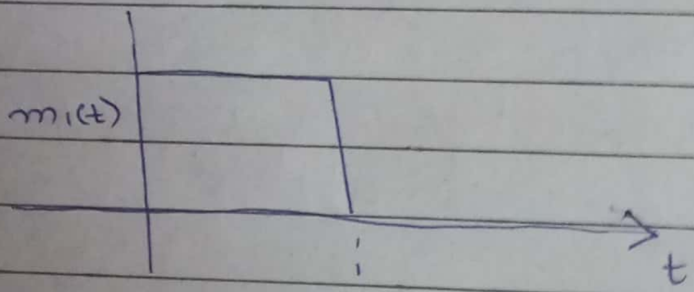
$$= -\frac{1}{4} + \frac{1}{4} - \frac{1}{4} + \frac{1}{4} = 0$$

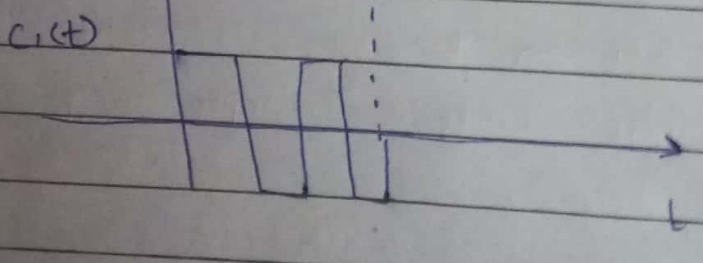
$$c_1 \times c_1^T = \begin{bmatrix} \frac{1}{\sqrt{4}} & \frac{1}{\sqrt{4}} & \frac{1}{\sqrt{4}} & \frac{1}{\sqrt{4}} \end{bmatrix} \begin{bmatrix} \frac{1}{\sqrt{4}} \\ \frac{1}{\sqrt{4}} \\ \frac{1}{\sqrt{4}} \\ \frac{1}{\sqrt{4}} \end{bmatrix}$$

$$= \frac{1}{4} + \frac{1}{4} + \frac{1}{4} + \frac{1}{4} = \frac{4}{4} = 1$$

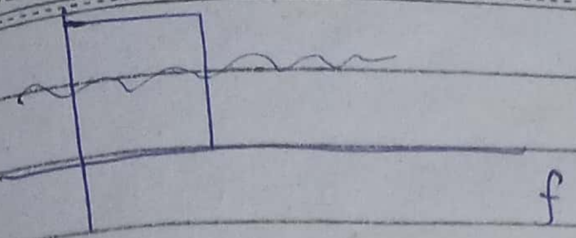
$m_1(t)$

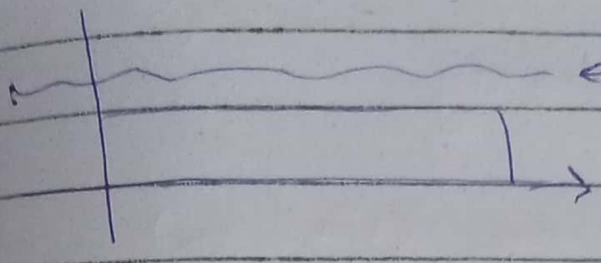






When we multiply code with message, Then signal will expand and will sink down noise level. It will secured from eveasdropper also.





Multiplied version.

Packet radios didn't use dedicated resources. { * ALOHA. Not a { * Slotted ALOHA dedicated resource.

We can transmit in very start of time slot.

* $10 \log \frac{P_2}{P_1} =$ ____ dB.

$10 \log 10^2 = 20$ dBm.

100×10^{-3} watts $= 10^{-1}$

$10 \log 10^{-1} = -10$ dBw.

* 1000 mwatts $= 1$ watt.

30 dBm $\quad 10 \log 1 = 0$ dBw

dBm → dBw $= \boxed{-30}$

20 dBm = 20 dBm − 30 = −10 dBw

20 dBm − 10 dBm = 10 dB

$\frac{20 \text{ watts}}{10 \text{ watts}} = 2$ ↗ reciprocal

20dBw + 10 = 30dBw.
5×10watts = 50watts.

What is ~~channel~~ Shannon capacity?

Shannon Capacity:

$$C = B \log_2 (1 + SNR).$$

$C = 1000 \log_2 (1+100)$. Bits per second

If noise is ∞ then $\log 1 = 0$
then $C = 0$.

Dependant on two parameters
1. Bandwidth
2. SNR.

Hamming code: The redundancy to be added.
How much bits added.

$$2^k \geq m + k + 1.$$

$m = 8$, $k = 4$.

$2^4 \geq 8 + 4 + 1$

$16 \geq 13$

It is

Binary coded bits will be on positions where there is only

1100, 1011 1010 1001 1000 0111 0110 0101 0100 0011 0010 0001

12 11 10 9 8 7 6 5 4 3 2 1

D_7 D_6 D_5 D_4 C_8 D_3 D_2 D_1 C_4 D_0 C_2 C_1

Tx Rx

$C_1 = D_0 \oplus D_1 \oplus D_3 \oplus D_4 \oplus D_6 = 1$

$C_2 = D_0 \oplus D_2 \oplus D_3 \oplus D_5 \oplus D_6 = 1$

$C_4 = D_1 \oplus D_2 \oplus D_3 \oplus D_7 = 0$

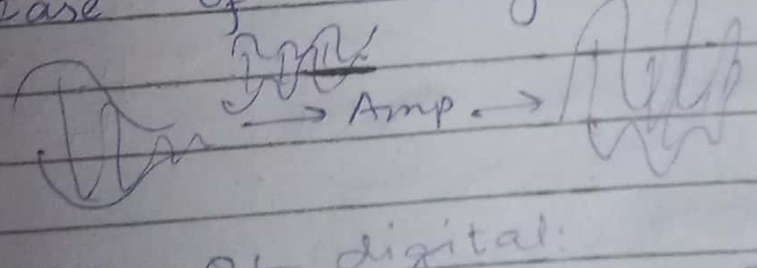
$C_8 = D_4 \oplus D_5 \oplus D_6 \oplus D_7 = 0$

	C_8	C_4	C_2	C_1	
	0	0	1	1	
Ex-OR $\oplus$	1	1	1	1	
	1	1	0	0	= 12 bit has error

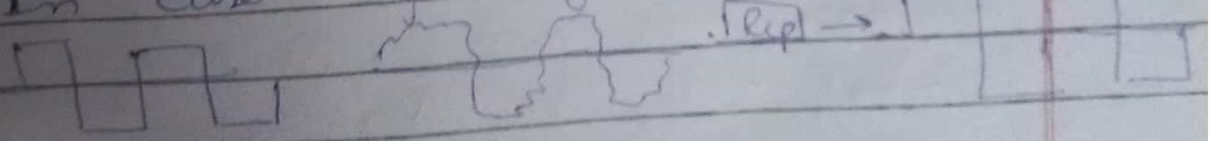
$m = 8$ $k = 4$ 50% redundancy

$m = 16$, $k = 5$ 20% reduced

In case of analog

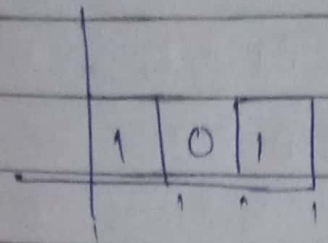


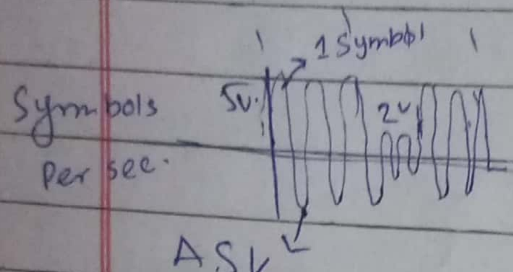
In case of digital



Digital → MODAM → Analog

If transmission is analog then why is it called digital.

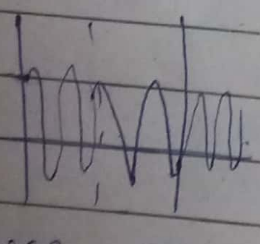




Just amplitude is change but change is in 1-1 Correspondance with digital signal.

Amplitude shift keying.

↳ This is digital modulation technique. whereas AM is analog modulation technique.



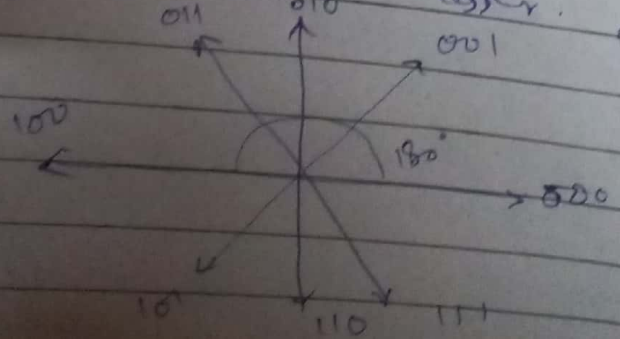
FSK (Frequency shift keying)

These are digital modulation techniques.

QPSK → Quadrature Phase shift keying.

Symbols are representations of bits.

Symbol rate is lesser.



Constellation diagram

M T W T F S   Date:

Now symbol carries 3 bits.
Increased data rate by increasing no of vectors but on the other hand error probability increased.
Representation of symbol with two bits is called quadrature phase shift key.

Chapter : 3
Signal Transmission Through LTI System

$$g(t) \longrightarrow \boxed{\begin{matrix} h(t) \\ \text{LTI} \\ \text{system} \end{matrix}} \longrightarrow y(t) = g(t) * h(t)$$

$g(t) = \delta(t)$.

when $g(t) * \cancel{h(t)}\ \delta(t) = h(t)$

$$Y(\omega) = G(\omega)H(\omega) \quad \text{①}$$

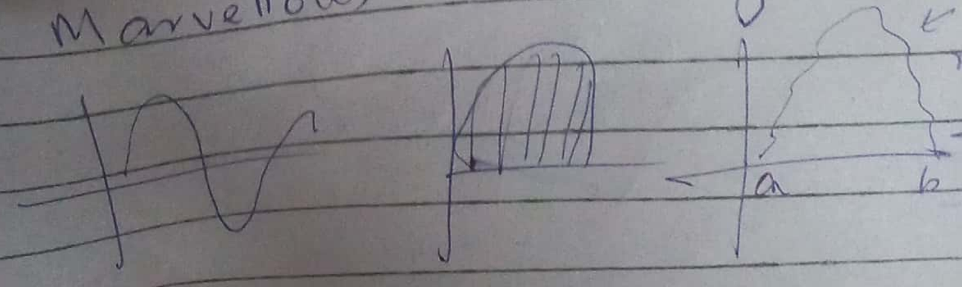
$$|Y(\omega)| e^{j\theta_y(\omega)} = |G(\omega)| e^{j\theta_g(\omega)} |H(\omega)| e^{j\theta_h(\omega)}$$

$|Y(\omega)| = |G(\omega)||H(\omega)|$ Amp response

$\theta_y(\omega) = \theta_g(\omega) + \theta_h(\omega)$ Phase resi

$$|H(\omega)| = |H(\omega)| e^{j\theta_h(\omega)}.$$

Marvellous Balancing act



bunch of multiple signal — value is zero outside signal.

Distortionless Transmission:

$H(\omega) = |H(\omega)| e^{j\theta_n(\omega)}$

$y(t) = k\,g(t-td)$: ~~?g(t-td)~~

$Y(\omega)$

$g(t-td) \Leftrightarrow G(\omega) e^{-j\omega td}$

So

$Y(\omega) = k\,G(\omega) e^{-j\omega td}$ — (2)

$H(\omega) = k e^{-j\omega td}$

As

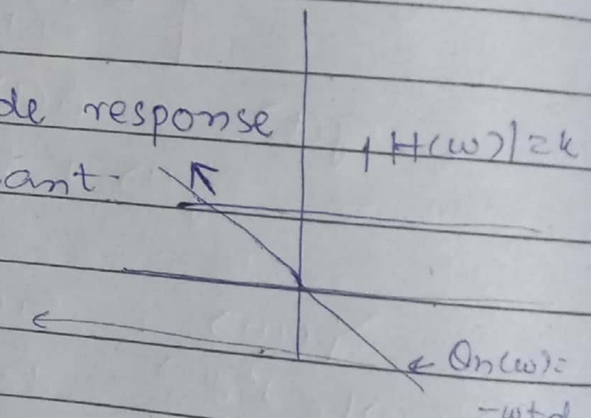
$H(\omega) = |H(\omega)| e^{j\theta_n(\omega)}$

So $|H(\omega)| = k$

$\theta_n = -\omega td$

magnitude response is constant.

Phase response.

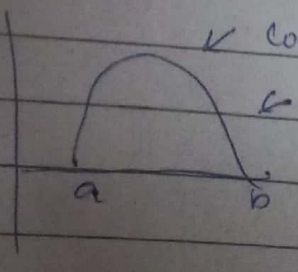


$\theta_n(\omega) = -\omega td$

$$\boxed{-\frac{d\theta_n(\omega)}{d\omega} = td}$$

It's is slope of straight line and is const so td is const.

In time domain

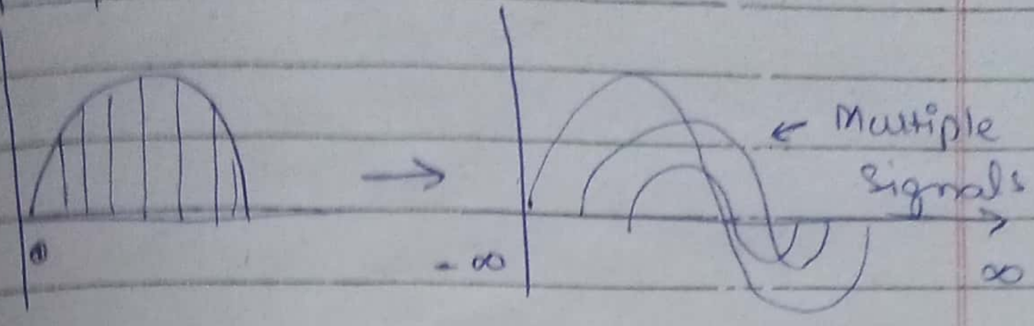


composite signal.

It's a buch of frequencies

M T W T F S Date:

In freq domain

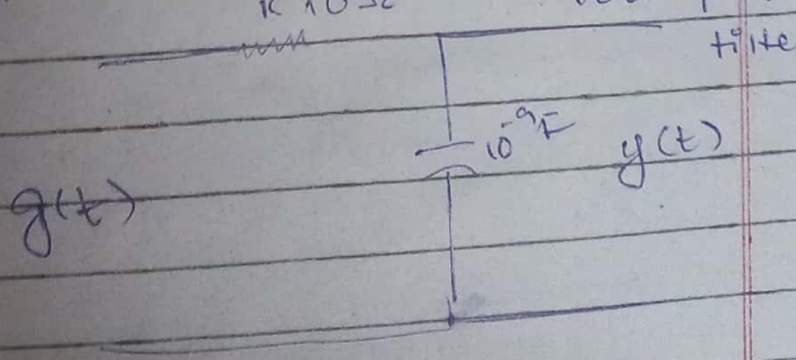


"(Marvellous Balancing act)"

① All freq components (amp response) of signals will be amplified or attenuated at the same time.

② Their phase response will be linear.

dur of syllable 0.01 → 0.1
video signal is insensitive to amp response. They are more sensitive to phase response.
voice signal is opposite to it.



$$Y(\omega) = \frac{1/j\omega C}{R + 1/j\omega C} \, G(\omega)$$

$$H(\omega) = \frac{1/j\omega C}{R + 1/j\omega C}$$

$$H(\omega) = \frac{a}{a + j\omega}$$

$$\Rightarrow \boxed{a = \frac{1}{RC}}$$

$$|H(\omega)| = \frac{a}{\sqrt{a^2 + \omega^2}}$$

And $\theta_H(\omega) = \tan^{-1}\left(\frac{-\omega}{a}\right)$

Let $\omega << a$ where $\boxed{a = 10^6}$

Derivate it

$$t_d = \frac{a}{a^2 + \underbrace{\omega^2}_{\to \text{zero}}}$$

When $\omega << a$

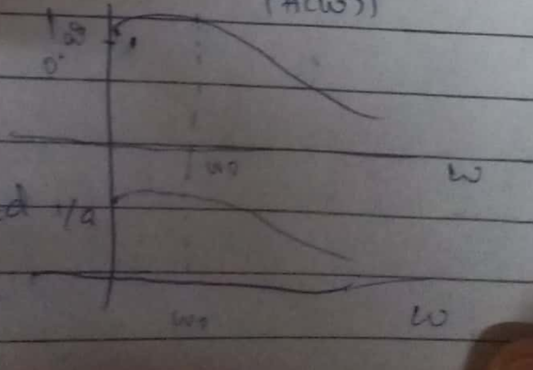
$$t_d = \frac{\cancel{a}}{a^2}$$

$$t_d = \frac{1}{a}$$

Tidbit
ω = rad/s = rad/s
f = cycl/sec = Hz
$\omega = 2\pi f$

When $\omega = 0$

$$|H(\omega)| = 1$$



MTWTFS Date:

If we need the required bandwidth (ω_0).

$$|H(\omega)| = \frac{a}{\sqrt{a^2+\omega_0^2}} \geq 0.98$$

$$a \geq 0.98\sqrt{a^2+\omega_0^2}$$

$$0.96\,\omega_0^2 + 0.96\,\omega_0^2 \leq \cancel{0.04}\,a^2$$

$$0.96\,\omega_0^2 \leq 0.04\,a^2$$

$$\omega_0 \leq \sqrt{\frac{0.04}{0.96}a^2}$$

$$\omega_0 \leq 203000.$$

$$f = \frac{203000}{2\pi}\ \text{Hz}$$

For td : 5% tolerance

$$td = \frac{a}{a^2+\omega^2}$$

0.95 % of max and max is 1

$$td = \frac{a}{a^2+\omega_0^2} \geq 0.95 \times \frac{1}{a}$$

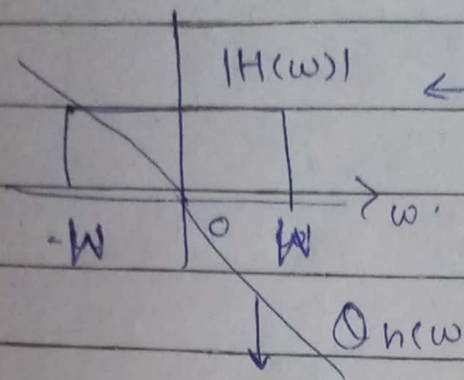
$$\omega_0 \leq$$

Ideal Vs Practical Filters

$$h(t)$$

$$g(t) \longrightarrow \boxed{LTI} \longrightarrow y(t) = g(t) * h(t)$$

$$y(t) = g(t - t_d)$$

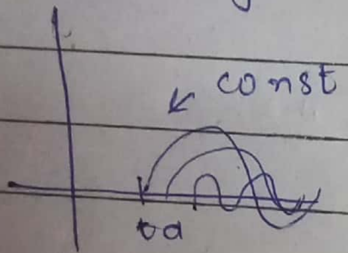


← low pass ideal filter

$\theta_h(\omega) = -\omega t_d$

Constant slope.

Phase angle is linear func of ω



const delay

~~π, 2π, 3π linear~~

mathamatics of ideal filter.

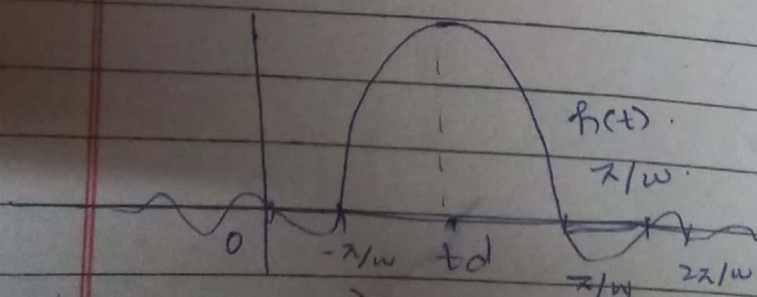
impulse response

$$H(\omega) = \text{rect}\left(\frac{\omega}{2W}\right) e^{-j\omega t_d}$$

$$F^{-1}\left[\text{rect}\left(\frac{\omega}{2W}\right) e^{-j\omega t_d}\right] = \frac{W}{\pi} \text{sinc} W(t - t_d)$$

$$h(t) = \frac{W}{\pi} \text{sinc} W(t - t_d)$$

$$\boxed{\frac{W}{\pi} \text{sinc} Wt \Leftrightarrow \text{rect}\frac{\omega}{2W}}$$



$W(t - t_d) = \pm n\pi$

it will pass through ze

M T W T F S Date:

$(t - t_d) = \frac{\pm n\pi}{W}$

It exists before $t=0$, its causal
It's ideal.

$h(t) = 0 \quad t < 0$

* Paley Weiner Criteria

$$\int_{-\infty}^{\infty} \frac{|\ln|H(\omega)||}{1+\omega^2} < \infty$$

W = fixed
ω = variable

It tells what is realizable and what's not.

If it gives finite value then it is said to practical realizable and if its infinite then it's unrealizable.

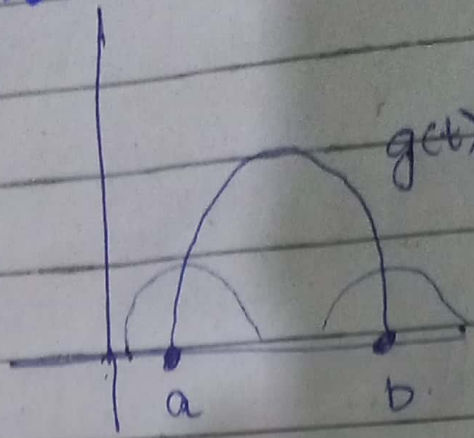
If $|H(\omega)| = 0$ for some band of frequencies, infinite

If $|H(\omega)| = 0$ for discrete values then it gives finite with delay data rate is reduced.

* $\boxed{\hat{h}(t) = h(t)u(t)}$

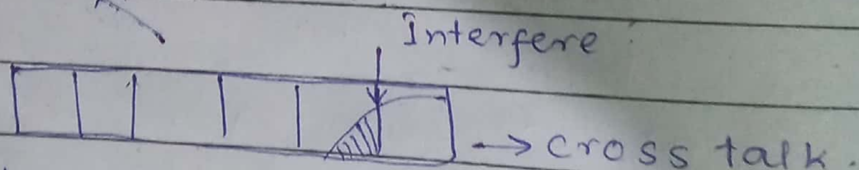
Distortion:

1 Linear:



in linear distortion, marvelous baloncing act will be violated; signal spreads a && b shape will be distorted in time domain. This kind of distortion is linear distortion.

FDM / TDM



It doesnt have effect in frequency domain. It is spreaded in time domain and shrink in frequency domain, so it doesn't effect FDM.

Problem:

$$H(\omega) = \underbrace{(1+k\cos T\omega)}_{\text{nonideal}}\underbrace{e^{-j\omega t_d}}_{\text{ideal}} \quad |\omega| < 2\pi B$$

If anyone is nonideal then signal will be distorted.

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As $\cos\theta = \frac{e^{j\theta} + e^{-j\theta}}{2}$.

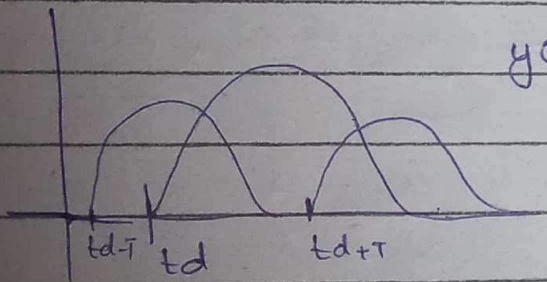
So

$$H(\omega) = \left[1 + \frac{k}{2} e^{jT\omega} + \frac{k}{2} e^{-jT\omega}\right] e^{-j\omega t_d}$$

$$Y(\omega) = G(\omega)H(\omega) = G(\omega) e^{-j\omega t_d} + \frac{k}{2} G(\omega) e^{-j\omega(t_d - T)} + \frac{k}{2} G(\omega) e^{-j\omega(t_d + T)}$$

$$y(t) = g(t - t_d) + \frac{k}{2} g(t - (t_d - T)) + \frac{k}{2} g[(t - (t_d + T))]$$

Graphical.



Spreaded → in time domain.

Non-linear distortion:

Maclaurin series where higher order components are present FDM will be affected, dispersed in freq domain.

Problem $y(t) = x(t) + 0.001x^2(t)$

$x(t) = \frac{1000}{\pi} \text{sinc}\, 1000t$

M T W T F S Converting in freq domain

$$y(t) = \frac{1000}{\pi} \operatorname{sinc} 1000t + 0.001 \times \frac{10^6}{\pi^2} \operatorname{sinc}^2 1000t$$

Y(ω) Properties :

$$\frac{W}{\pi} \operatorname{sinc} Wt \Leftrightarrow \operatorname{rect} \frac{\omega}{2W}$$

$$\frac{W}{2\pi} \operatorname{sinc}^2 \frac{Wt}{2} \Leftrightarrow \Delta\left(\frac{\omega}{2W}\right)$$

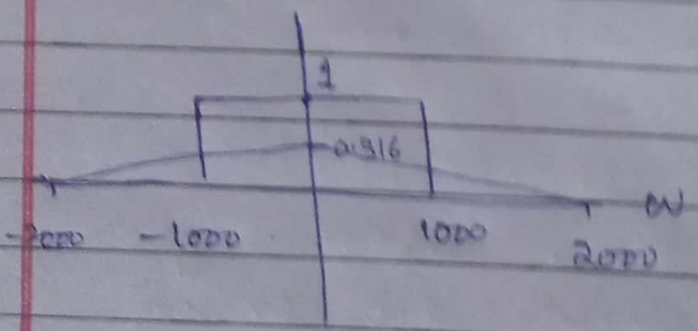
By comparision $\frac{W}{2} = 1000$, $W = 2000$

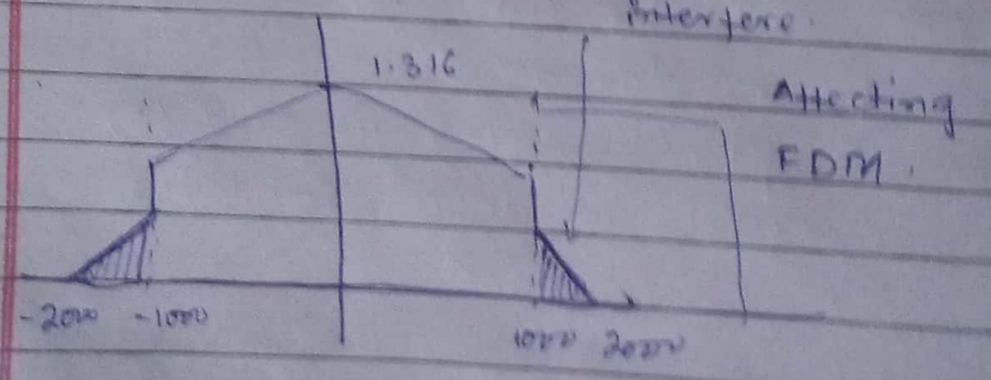
$$\frac{1000 \times 2000}{2\pi} \operatorname{sinc}^2 1000t \Leftrightarrow \frac{1000}{\pi} \Delta\left(\frac{\omega}{4000}\right)$$

So

$$Y(\omega) = \operatorname{rect} \frac{\omega}{2000} + 10^{-3} \times \frac{1000}{\pi} \Delta\left(\frac{\omega}{4000}\right)$$

$$= \operatorname{rect} \frac{\omega}{2000} + 0.316\, \Delta\left(\frac{\omega}{4000}\right)$$

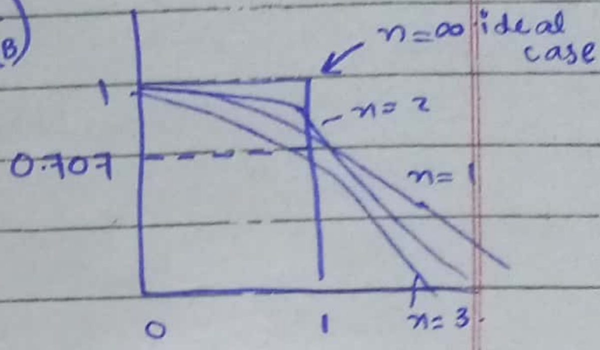




Date:

Butterworth Filter:

$$H(\omega) = \frac{1}{\sqrt{1+\left(\frac{\omega}{2\pi B}\right)^{2n}}}$$



if $n=1$.

if $n=2$

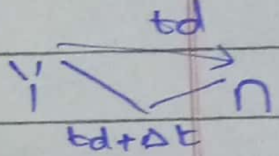
When $\frac{\omega}{2\pi B} = 1$.

Then $\frac{1}{\sqrt{1+1}} = \frac{1}{\sqrt{2}} = 0.707$.

keep on increasing n, curve will be straighten more and more.

Multipaths Distortion:

$$1e^{-j\omega t_d} + \alpha e^{-j\omega(t_d+\Delta t)}$$



As $k g(t-t_d)$

$H(\omega) = k e^{-j\omega t_d}$.

So

$$H(\omega) = \{1+\alpha e^{-j\omega \Delta t}\} e^{-j\omega t_d}$$

As we know That

$$e^{j\theta} = \cos\theta + j\sin\theta.$$

$$= \{1+\alpha\cos\omega\Delta t - j\alpha\sin\omega\Delta t\} e^{j\omega t_d}$$

$$a - ib$$

$$\underbrace{\sqrt{(1+\alpha\cos\omega\Delta t)^2 + \alpha^2\sin^2\omega\Delta t}}_{\text{Amp response}}\ e^{-j\tan^{-1}\left(\frac{\alpha\sin\omega\Delta t}{1+\alpha\cos\omega\Delta t}\right)} + \omega t_d$$

phase angle.

$\theta_h(\omega)$

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$|H(\omega)| = \sqrt{1+\alpha^2+2\alpha\cos\omega\Delta t}$

$\cos 0 = 1$

$\cos 2\pi = 1$

if $\cos\omega\Delta t = 1$

& if $\alpha \approx 1$

So $|H(\omega)| = 2$.

& if $\cos\omega\Delta t = -1$

Then $|H(\omega)| = 0$ (no gain)

Constructive interference.

Destructive interference.

This is called frequency selective fading. That means it's behaviour is different frequencies.

if $\omega\Delta t = n\pi$ $\quad n = 0, 4, 6 \ldots$

↳ it will be constructive for even values.

if $\omega\Delta t = n\pi$ for $n = 1, 3, 5, 7 \ldots$

it will be destructive.

Energy :

$$E_g = \int_{-\infty}^{\infty} |g(t)|^2 dt = \int_{-\infty}^{\infty} g(t) g^*(t) dt$$

$$g^*(t) = \int_{\infty}^{} g(t) \left[\frac{1}{2\pi} \int_{-\infty}^{\infty} G^*(\omega) e^{-j\omega t} d\omega \right] dt$$

$$g^*(t) = \frac{1}{2\pi} \int_{-\infty} G^*(\omega) \left[\int_{-\infty} g(t) e^{-j\omega t} dt \right] d$$

As $G(\omega) = \int_{-\infty}^{\infty} g(t)\, e^{-j\omega t}\, dt$.

$$E_g = \frac{1}{2\pi} \int_{-\infty}^{\infty} G(\omega)\, G^*(\omega)\, d\omega .$$

$$\begin{tikzcd}
g(t) \arrow[r, bend left, "\int_{-\infty}^{\infty} g(t) e^{-j\omega t} dt"] & G(\omega) \arrow[l, bend left, "\frac{1}{2\pi}\int_{-\infty}^{\infty} G(\omega) e^{j\omega t} dt"]
\end{tikzcd}$$

$$\boxed{E_g = \frac{1}{2\pi} \int_{-\infty}^{\infty} |G(\omega)|^2\, d\omega}$$ Parseval's Theorem.

$$g(t) = e^{-at} u(t) \qquad a > 0 .$$

$$E_g = \frac{1}{2a} \qquad |G(\omega)|^2 = \frac{1}{a^2+\omega^2}$$

$$E_g = \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{1}{a^2+\omega^2}\, d\omega$$

$$= \frac{1}{2\pi a} \tan^{-1} \frac{\omega}{a} \Big|_{-\infty}^{\infty}$$

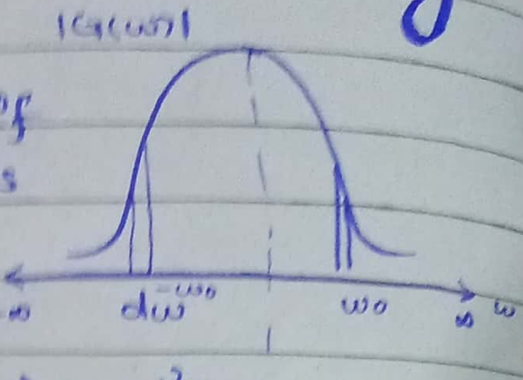
$$= \frac{1}{2a\pi} \left[\tan^{-1}\infty - \tan^{-1}(-\infty) \right]$$

$$\frac{1}{2a\pi} \left(\frac{\pi}{2} + \frac{\pi}{2} \right)$$

$$= \frac{1}{2a\cancel{\pi}} \frac{\cancel{2}\cancel{\pi}}{\cancel{2}}$$

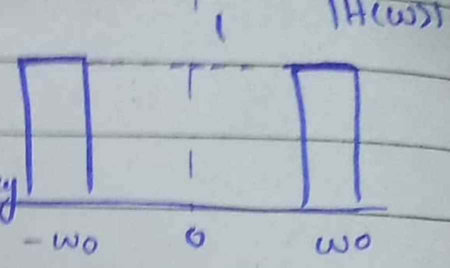
$$= \frac{1}{2a}$$

Energy Spectral Density



Energy per unit of small bandwidth is energy spectral density.

$$E_y(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} |G(\omega) H(\omega)|^2 d\omega .$$



- $|H(\omega)| = 1$.
- For short range of frequency so remove integration

$|Y(\omega)| = |G(\omega)||H(\omega)|$

$E_y(\omega) = |G(\omega)|^2 df.$

$\frac{E_y(\omega)}{df} = |G(\omega)|^2$

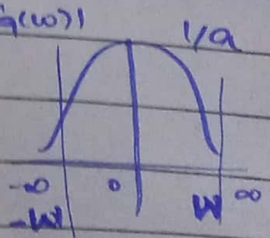
ESD $\psi(\omega) = |G(\omega)|^2$ Energy spectral density

Example:

$g(t) = e^{-at}u(t)$ $\quad a>0$

$\boxed{E_g(\omega) = \frac{1}{2a}}$ $\quad \boxed{E_g(\omega) = \frac{1}{\sqrt{a^2+\omega^2}}}$

Find bandwidth in which 95% of energy is there.



Required is essential bandwidth.

By using Parseval's theorem

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$$E_g = \frac{1}{2\pi}\int_{-\infty}^{\infty} |G(\omega)|^2 \, d\omega.$$

$$0.95 \frac{1}{2a} = \frac{1}{2\pi}\int_{-W}^{W} \frac{1}{a^2+\omega^2} \, d\omega.$$

$$\frac{0.95}{2a} = \frac{1}{2\pi a} \tan^{-1} \frac{\omega}{a} \Big|_{-W}^{W}$$

$$\frac{0.95}{\cancel{2a}} = \frac{1}{\cancel{2}\pi \cancel{a}} \cancel{2} \tan^{-1} \frac{W}{a}.$$

$$\tan^{-1} \frac{W}{a} = \frac{0.95\pi}{2}.$$

Required essential bandwidth.

$$\boxed{W = a \tan\left(\frac{0.95\pi}{2}\right) \text{ rad/s}}$$