MODULASI FREKUENSI (FM)

PENDAHULUAN

- Lahirnya Konsep modulasi frekuensi diturunkan dari konsep modulasi sudut

- Apa itu Modulasi Sudut (PM)? Dan apa kaitannya dengan Modulasi Frekuensi (FM)?

Apa itu modulasi sudut ?

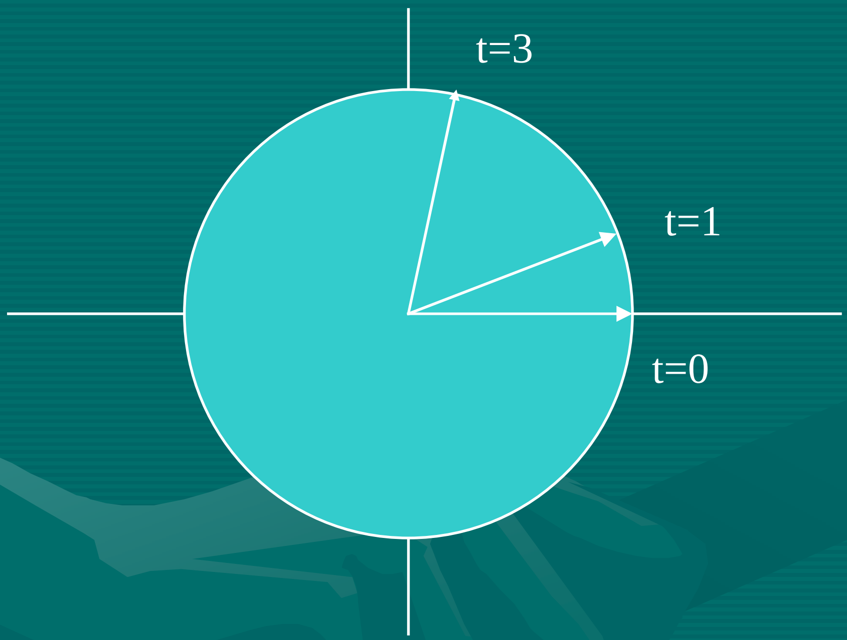
- Pada modulasi sudut, informasi terkandung pada bagian sudut dari sinyal pembawa (carrier).

- Kita definisikan sinyal pembawa yang telah termodulasi :

$$s(t) = A_c \cos(\theta(t))$$

Bentuk Phasor

- Pada bidang kompleks :



Phasor berputar dengan kecepatan non uniform

Kecepatan Angular

- Jika phasa berubah secara nonuniform terhadap waktu, kita definisikan kecepatan perubahan (kecepatan Angular) adalah :

$$\omega_i = \frac{d\theta_i(t)}{dt}$$

- Yang kita definisikan sebagai frekuensi adalah :

$$s(t) = A_c \cos\left(\underbrace{2\pi f_c t + \phi_c}_{\theta_i(t)}\right) \Rightarrow \frac{d\theta_i}{dt} = 2\pi f_c$$

Frekuensi Sesaat

- Frekuensi sinyal carrier keluaran osilator adalah tetap dari waktu ke waktu. Pada modulasi FM frekuensi sinyal termodulasi (Keluaran modulator) dapat berubah terhadap waktu.

- Sehingga kita bisa mendefinisikan frekuensi sesaat dari suatu sinyal yaitu :

$$f_i(t) = \frac{1}{2\pi}\frac{d\theta_i(t)}{dt}$$

Contoh : Frekuensi sesaat

- Misal sinyal AM :

$$s(t) = [1 + km(t)]\cos\left(\underbrace{2\pi f_c t + \phi_c}_{\theta_i(t)}\right) \Rightarrow \frac{d\theta_i}{dt} = 2\pi f_c$$

- Pada kasus sinyal AM, Frekuensi sesaat dari sinyal AM adalah tetap dari waktu ke waktu dan sama dengan frekuensi sinyal AM itu sendiri

Modulasi Phasa dan Modulasi Frekuensi

- Proses penumpangan sinyal informasi pada sinyal carrier :
  - Menumpangkan Info ke komponen ***phasa*** dari sinyal carrier → Phase Modulation (PM)
  - Menumpangkan Info ke komponen ***frekuensi*** dari sinyal carrier → Frequency Modulation(FM)

Modulation Phasa (PM)

- Pada PM, Phasa sinyal carrier berubah secara linear terhadap sinyal informasi :

$$s(t) = A_c \cos\big(\theta_i(t)\big) = A_c \cos\big(2\pi f_c t + k_p m(t)\big)$$

- Dimana :
  - $2\pi f_c$ = Frekuensi Angular dari sinyal carrier
  - k_p = Sensitivitas phasa (phase sensitivity) dalam radians/volt
  - m(t) = Sinyal Informasi

Modulasi Frekuensi (FM)

- Pada FM, Frekuensi sesaat sinyal termodulasi berubah secara linear terhadap sinyal informasi

$$f_i(t)=f_c+k_f\,m(t)$$

- Dimana K_f = Sensitivitas frekuensi (hz/volt)

Sinyal FM

- Frekuensi sesaat adalah turunan dari phasa :

$$f_i(t) = \frac{1}{2\pi}\frac{d\theta_i(t)}{dt}$$

- Sehingga ,

$$\theta_i(t) = 2\pi f_c t + 2\pi k_f \int_0^t m(t)$$

$$s(t) = A_c \cos\left[2\pi f_c t + 2\pi k_f \int_0^t m(t)dt\right]$$

Persamaan umum Sinyal FM

Modulasi Frekuensi Untuk Sinyal Single Tone

- Misal sinyal info sinusoidal single tone

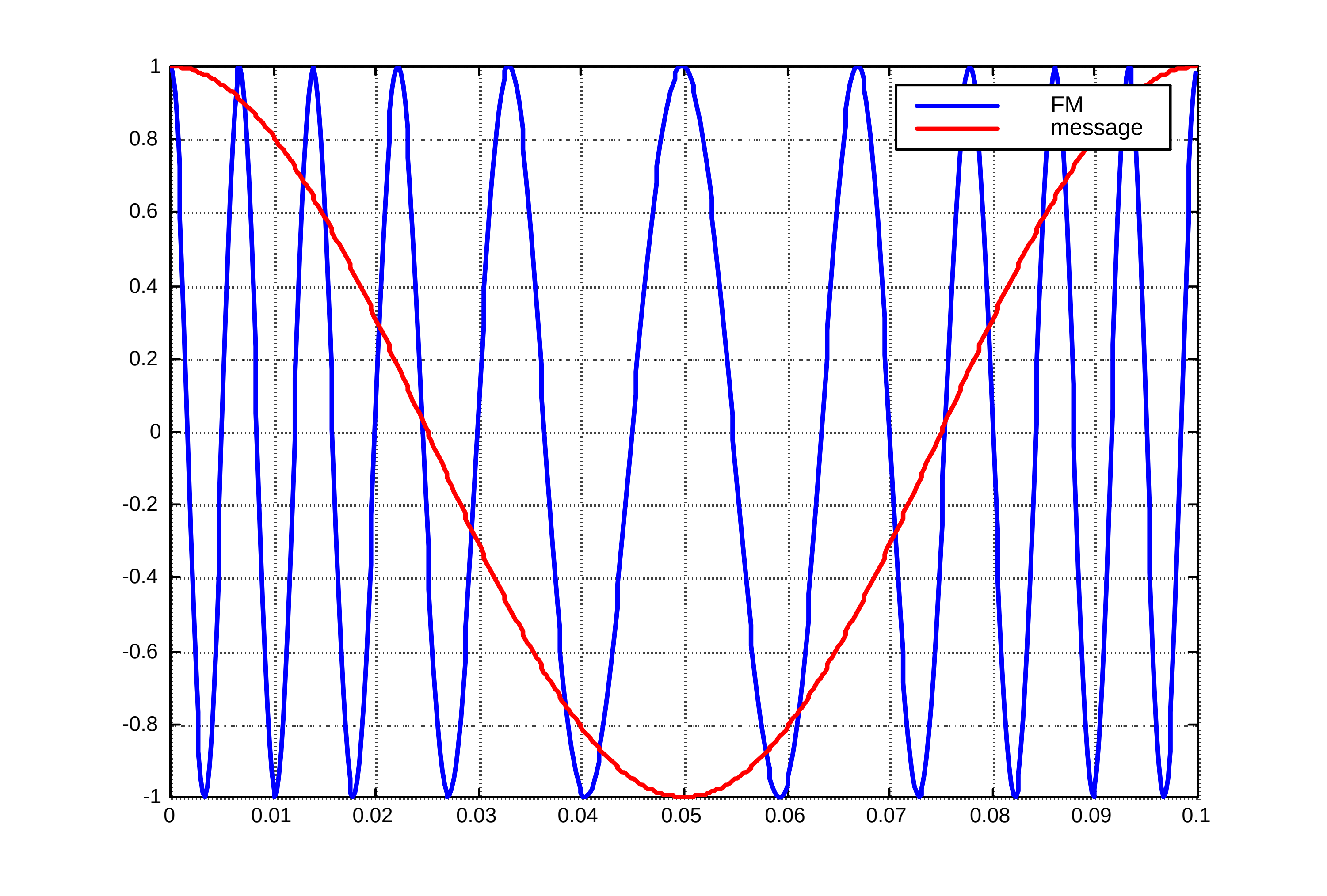
$$m(t) = A_m \cos(2\pi f_m t)$$

- Maka Frekuensi sinyal FM setelah proses modulasi FM

$$\begin{aligned} f_i(t) &= f_c + k_f m(t) \\ &= \underbrace{f_c}_{Frekuensicarrier} + k_f A_m \cos(2\pi f_m t) \end{aligned}$$

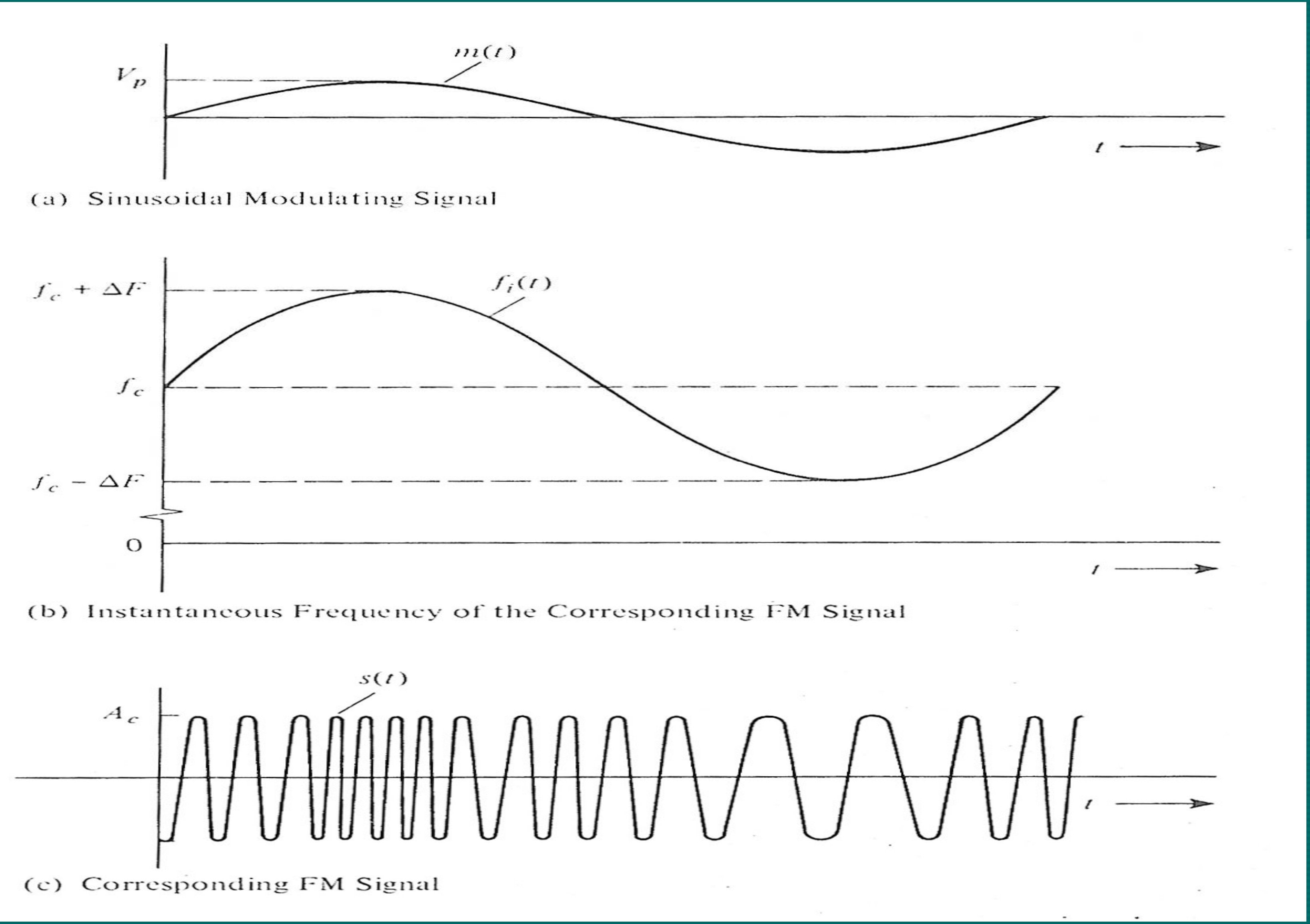
- Frekuensi sesaat sinyal FM = $f_i(t)$ berubah –ubah terhadap waktu mengikuti sinyal amplituda informasi

Ilustrasi Sinyal FM Domain Waktu



Frekuensi sesaat sinyal FM berubah mengikuti amplituda sinyal info

Ilustrasi Sinyal FM



Deviasi Frekuensi Sinyal FM

- Frekuensi sinyal FM mempunyai nilai maksimum dan minimum yang dibatasi oleh

$$f_i(t) = f_c + \Delta f \cos(2\pi f_m t)$$

$$\dim ana$$

$$\Delta f = \textit{frequency deviation} = k_f A_m$$

$$sehingga$$

$$f_i\big|_{\max} = f_c + \Delta f$$

$$f_i\big|_{\min} = f_c - \Delta f$$

Index Modulasi FM

- Seperti pada AM, modulasi FM mempunyai index modulasi = β atau disebut juga *deviation ratio*. Index modulasi merepresentasikan seberapa besar perubahan sinyal carrier terhadap bandwidth sinyal info

$$\beta = \frac{\Delta f}{\underbrace{W}_{baseband}} \; or \; \frac{\Delta f}{\underbrace{f_m}_{tone}}$$

Persamaan sinyal FM untuk Single Tone

- Persamaan sinyal FM untuk info single tone :

$$s(t) = A_c \cos\left[2\pi f_c t + 2\pi k_f \int_0^t m(t)\,dt\right]$$

$$s(t) = A_c \cos\left[2\pi f_c t + 2\pi k_f \int_0^t A_m \cos(\omega_m t)\,dt\right]$$

$$s(t) = A_c \cos\left[2\pi f_c t + \frac{k_f A_m}{f_m} \sin(\omega_m t)\right]$$

$$S(t) = A_c \cos\left[2\pi f_c t + \beta \sin(\omega_m t)\right]$$

Contoh Soal

- Sebuah sinyal carrier 100 MHz dimodulasi FM oleh sinyal single tone audio dan menyebabkan deviasi frekuensi sebesar 20 KHz. Carilah range frekuensi dari sinyal FM tsb dan berapa frekuensi minimum dan maksimumnya !

$$\Delta f = 20KHz$$
$$Rangefrekuensi = 2\Delta f = 40KHz$$
$$f_{high} = 100MHz + 20KHz = 100.02MHz$$
$$f_{low} = 100MHz - 20KHz = 99.98MHz$$

Contoh Lain

- Hitung index modulasi sinyal FM, jika range frekuensi FM = 150 KHz dan sinyal pemodulasi berfrekuensi 15 khz

$$\Delta f = \frac{150}{2} = 75KHz$$

$$\beta = \frac{\Delta f}{f_m} = \frac{75}{15} = 5$$

Bandwidth FM

- Jika diasumsikan info adalah single tone, maka persamaan FM

$$S(t) = A_c \cos[2\pi f_c t + \beta \sin(\omega_m t)]$$

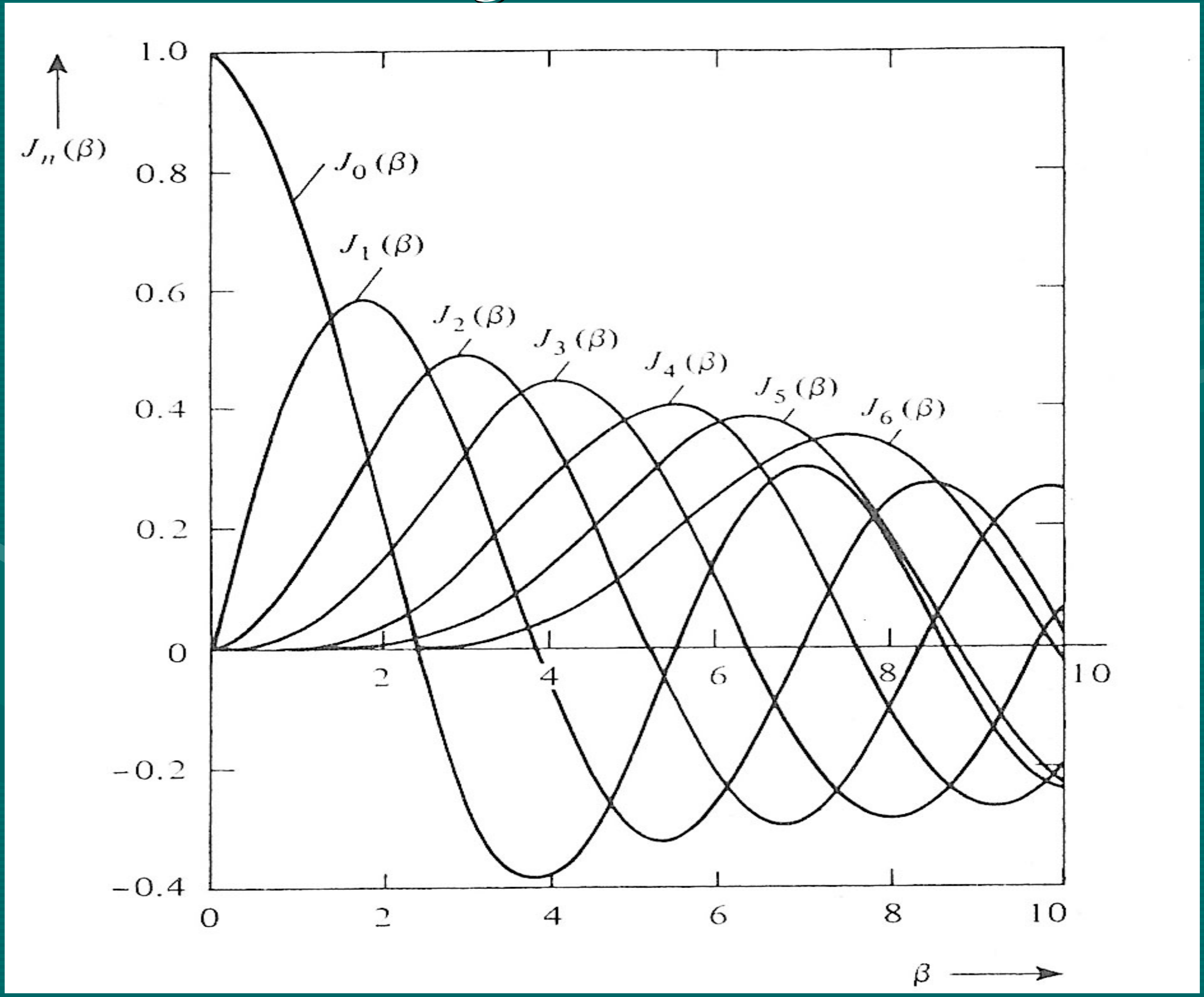
- Persamaan tsb dapat dijabarkan menjadi sbb :

$$S(t) = A_c \sum_{-\infty}^{+\infty} J_n(\beta) \cos(\omega_c + n\omega_m)t$$

  – Dimana $J_n(\beta)$ adalah fungsi bessel dan sudah disediakan dalam bentuk grafik dan tabel

Bandwidth FM

- Grafik Fungsi Bessel



$J_0(\beta)$ = komponen carrier
$J_1(\beta)$ = komponen sideband pertama
$J_2(\beta)$ = komponen sideband kedua
$J_3(\beta)$ = komponen sideband ketiga ..dst…

Bandwidth FM

- Fungsi bessel merepresentasikan sideband – sideband yang ditempatkan diantara frekuensi carrier dan terletak pada frekuensi informasi dan kelipatannya
- Jumlah sideband pada fungsi bessel tak hingga
- Pada sinyal FM, fungsi bessel menentukan amplituda sinyal carrier dan amplituda sidebandnya
- Sideband yang amplitudanya kurang dari 1% amplituda carrier, dapat diabaikan

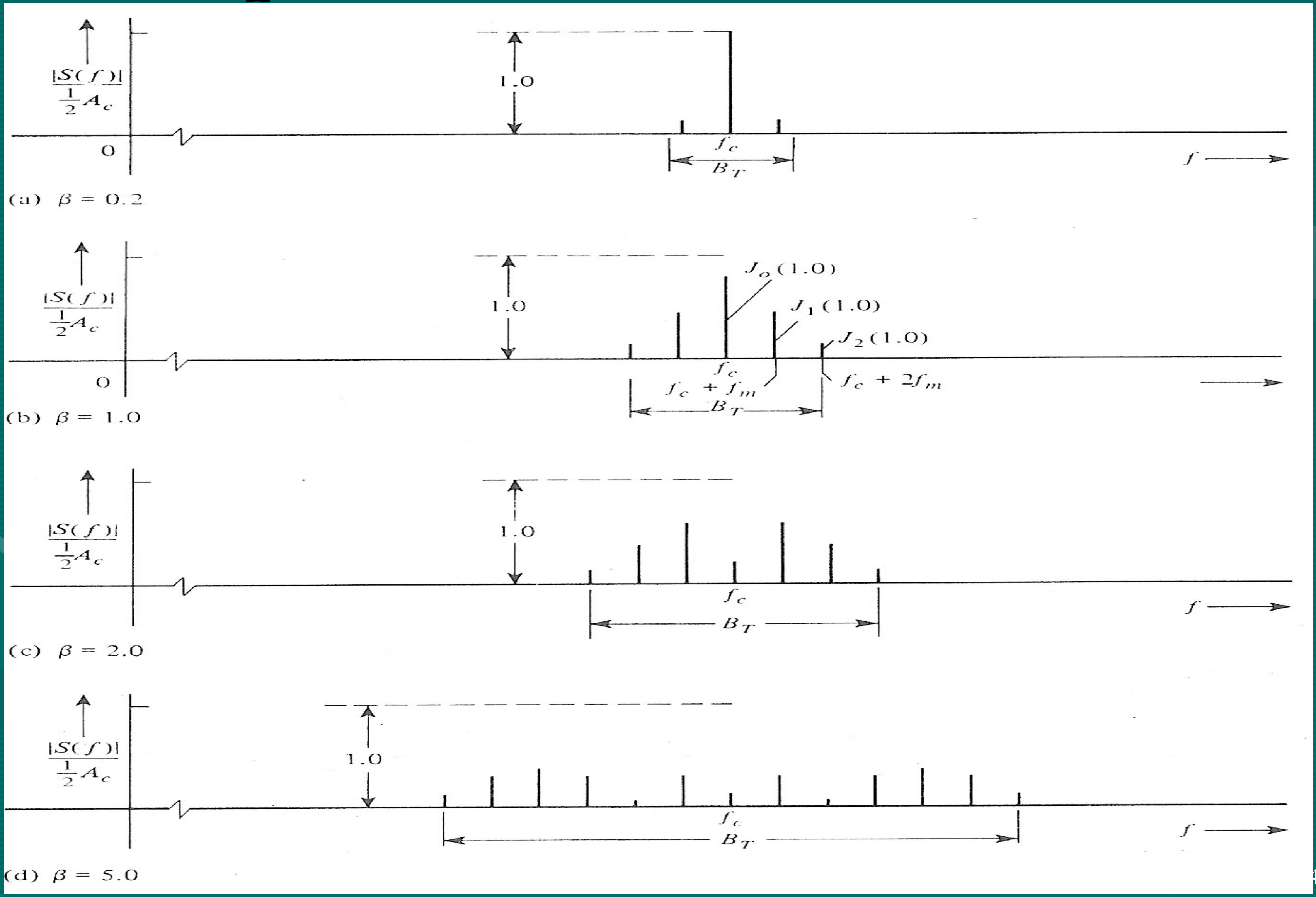
Bandwidth FM

- Secara teoritis, bandwidth sinyal FM adalah tak hingga. Hal ini akibat dari fungsi bessel
- Untuk pendekatan, maka bandwidth FM didekati dengan BANDWIDTH CARSON :

$$BW = 2\,(\Delta f + f_m) = 2f_m(\beta+1)$$

  – Pada BANDWIDTH CARSON kandungan energi sinyal FM adalah 99 % dari kandungan energi total sinyal FM

Spektrum Frekuensi FM



Spektrum Frekuensi FM

Index Modulasi	Jumlah Sideband yang Significan	Bandwidth dalam f_m
0.1	2	2
0.3	4	4
0.5	4	4
1.0	6	6
2.0	8	8
5.0	16	16
10.0	28	28
20.0	50	50
30.0	70	70

Commercial FM

- Commercial FM broadcasting uses the following parameters
  - Baseband;15KHz
  - Deviation ratio:5
  - Peak freq. Deviation=75KHz

$$B_{FM}=2(\beta+1)W=2x6x15=180KHz$$

Wideband vs. narrowband FM

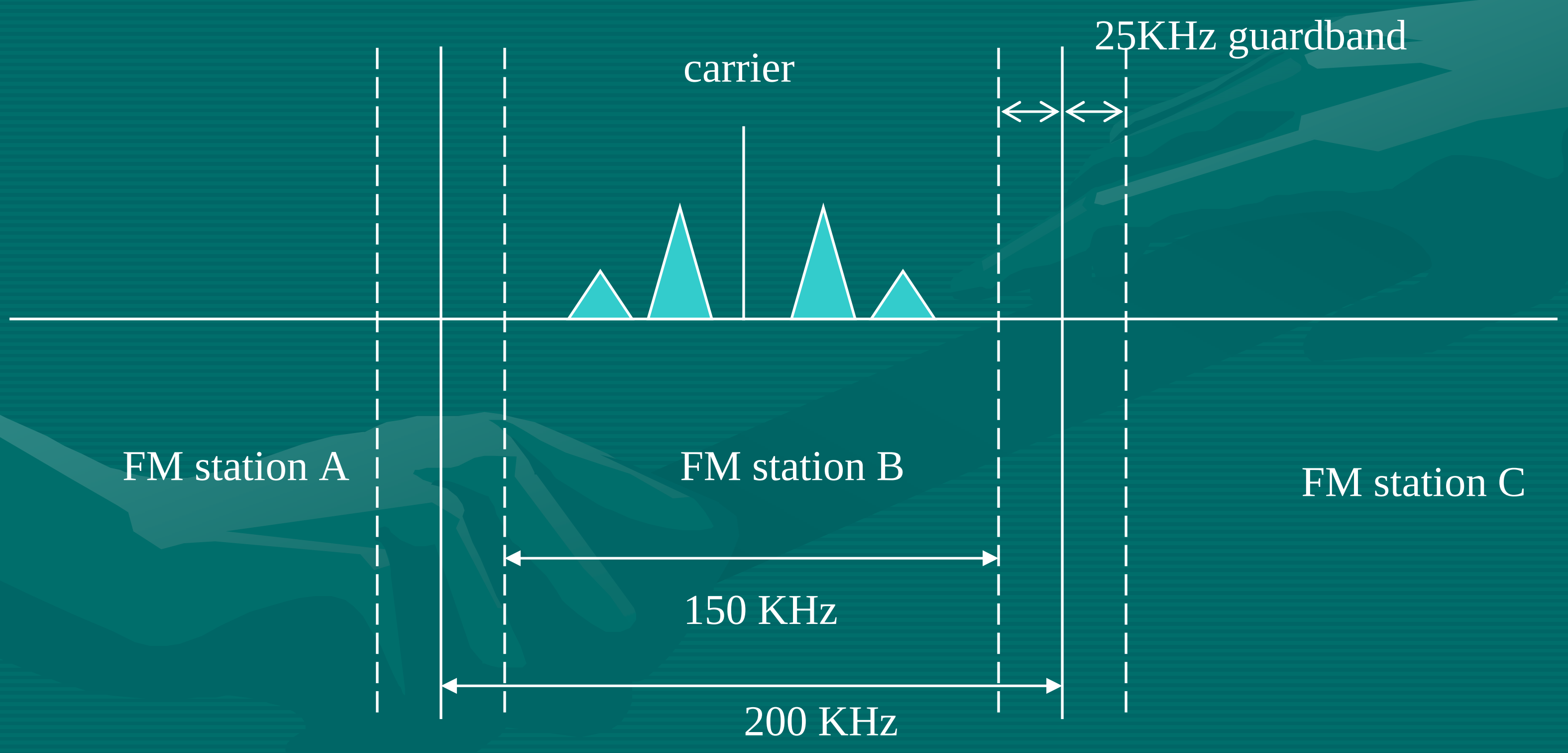
- NBFM is defined by the condition
  - $\Delta f << W$ $\Rightarrow$ $B_{FM}=2W$
  - This is just like AM. No advantage here
- WBFM is defined by the condition
  - $\Delta f >> W$ $\Rightarrow$ $B_{FM}=2\,\Delta f$
  - This is what we have for a true FM signal

Boundary between narrowband and wideband FM

- This distinction is controlled by β
  - If $\beta>1$ --> WBFM
  - If $\beta<1$-->NBFM
- Needless to say there is no point for going with NBFM because the signal looks and sounds more like AM

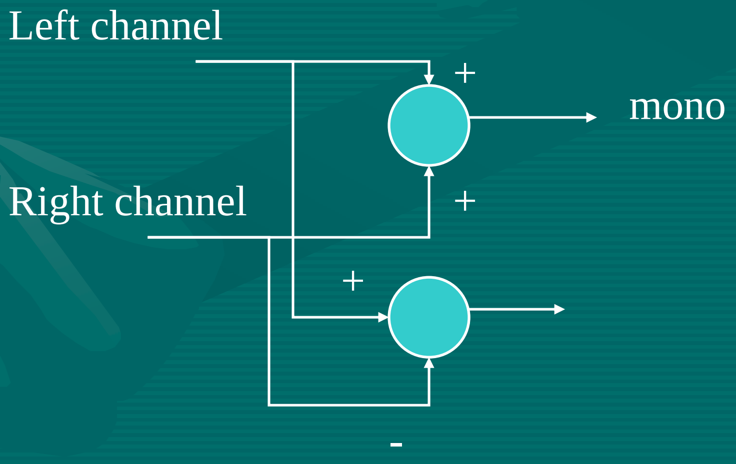
Commercial FM spectrum

- The FM landscape looks like this



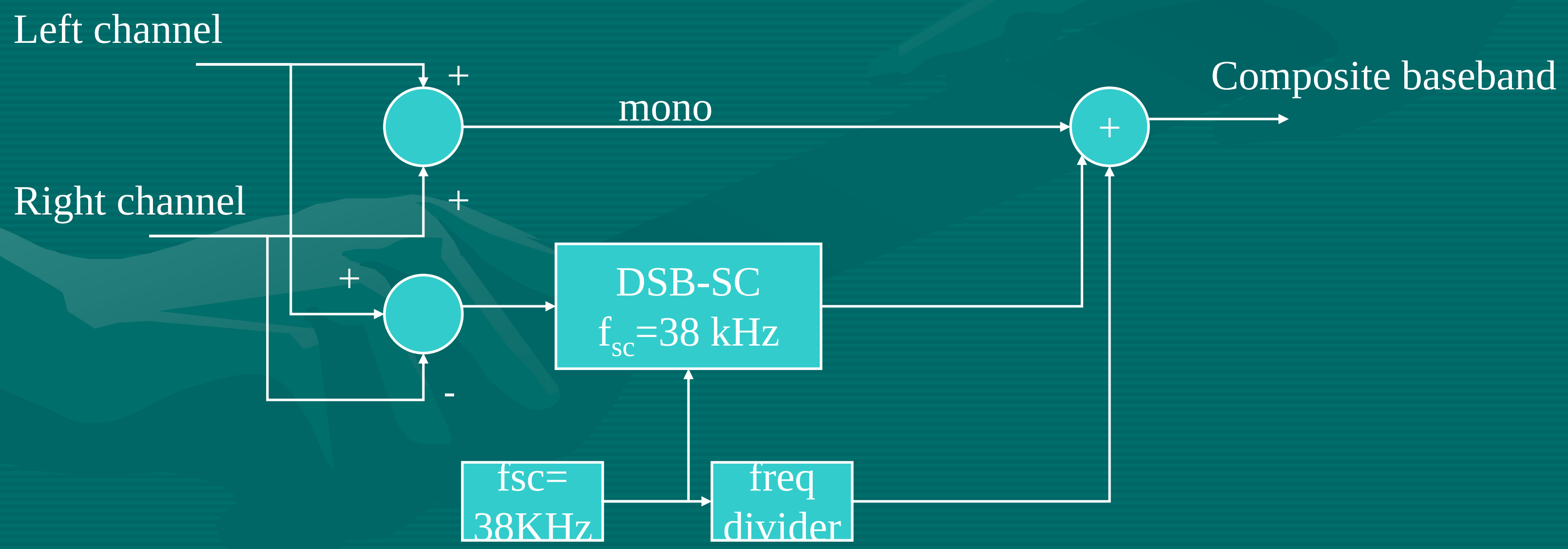
FM stereo:multiplexing

- First, two channels are created; (left+right) and (left-right)
- Left+right is useable by monaural receivers



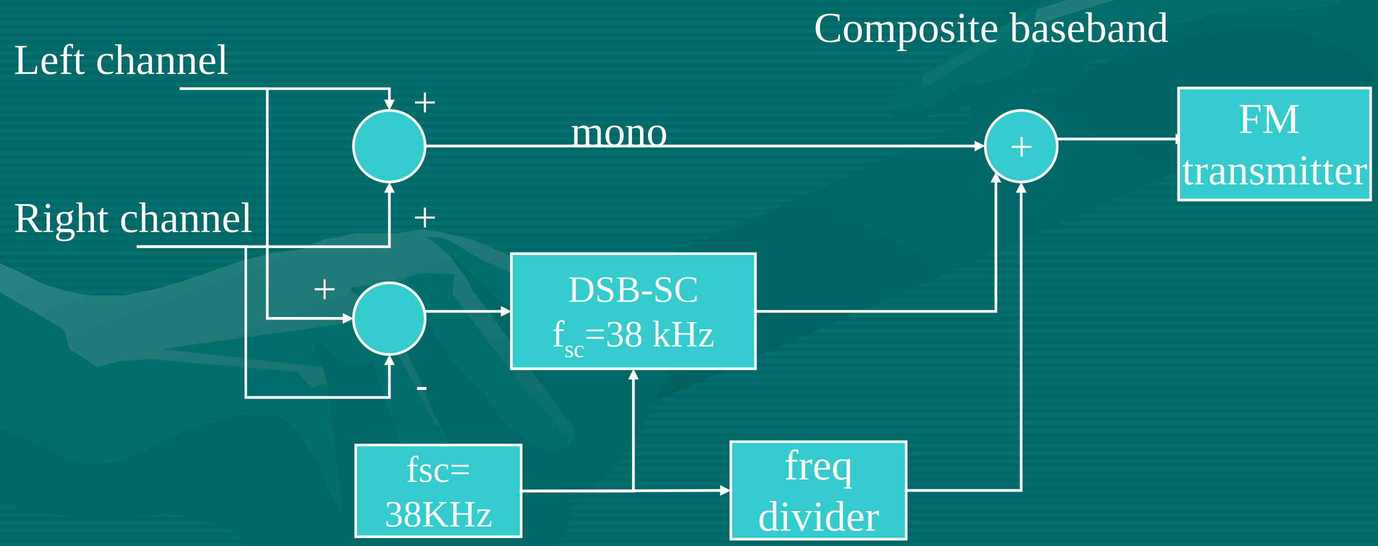
Subcarrier modulation

- The mono signal is left alone but the difference channel is amplitude modulated with a 38 KHz carrier



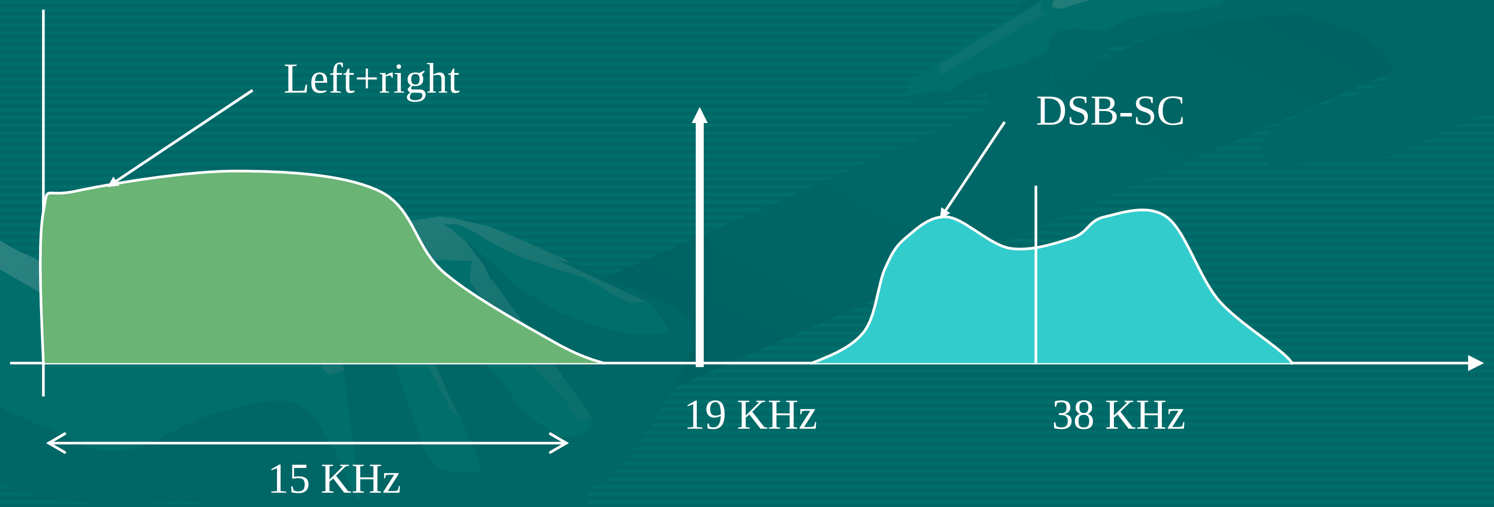
Stereo signal

- Composite baseband signal is then frequency modulated



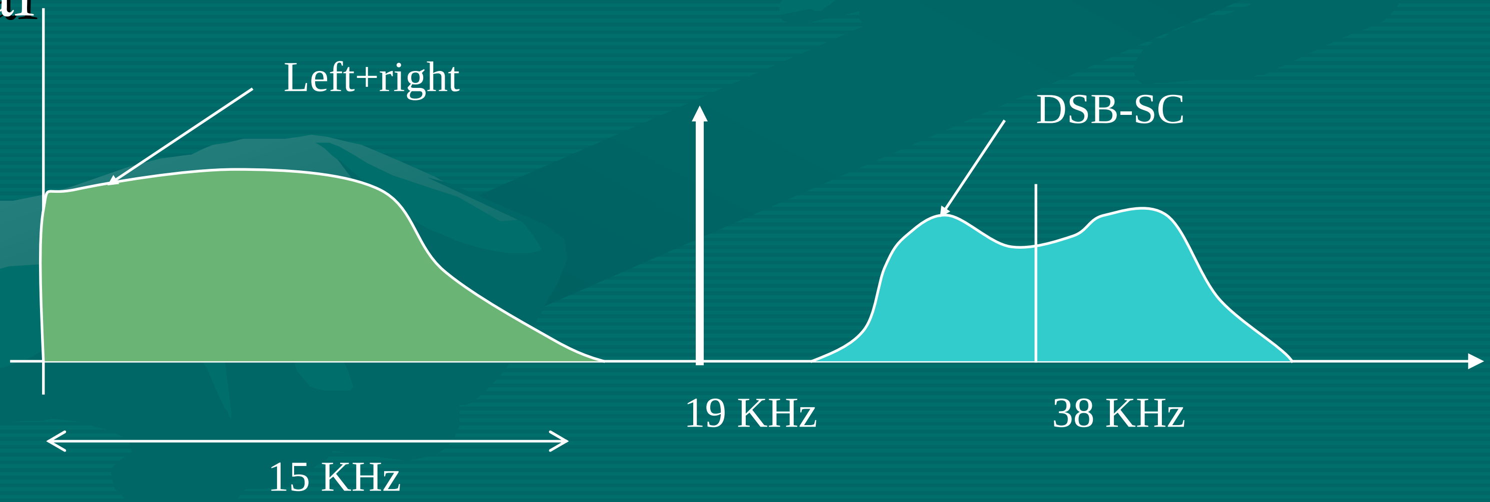
Stereo spectrum

- Baseband spectrum holds all the information. It consists of composite baseband, pilot tone and DSB-SC spectrum

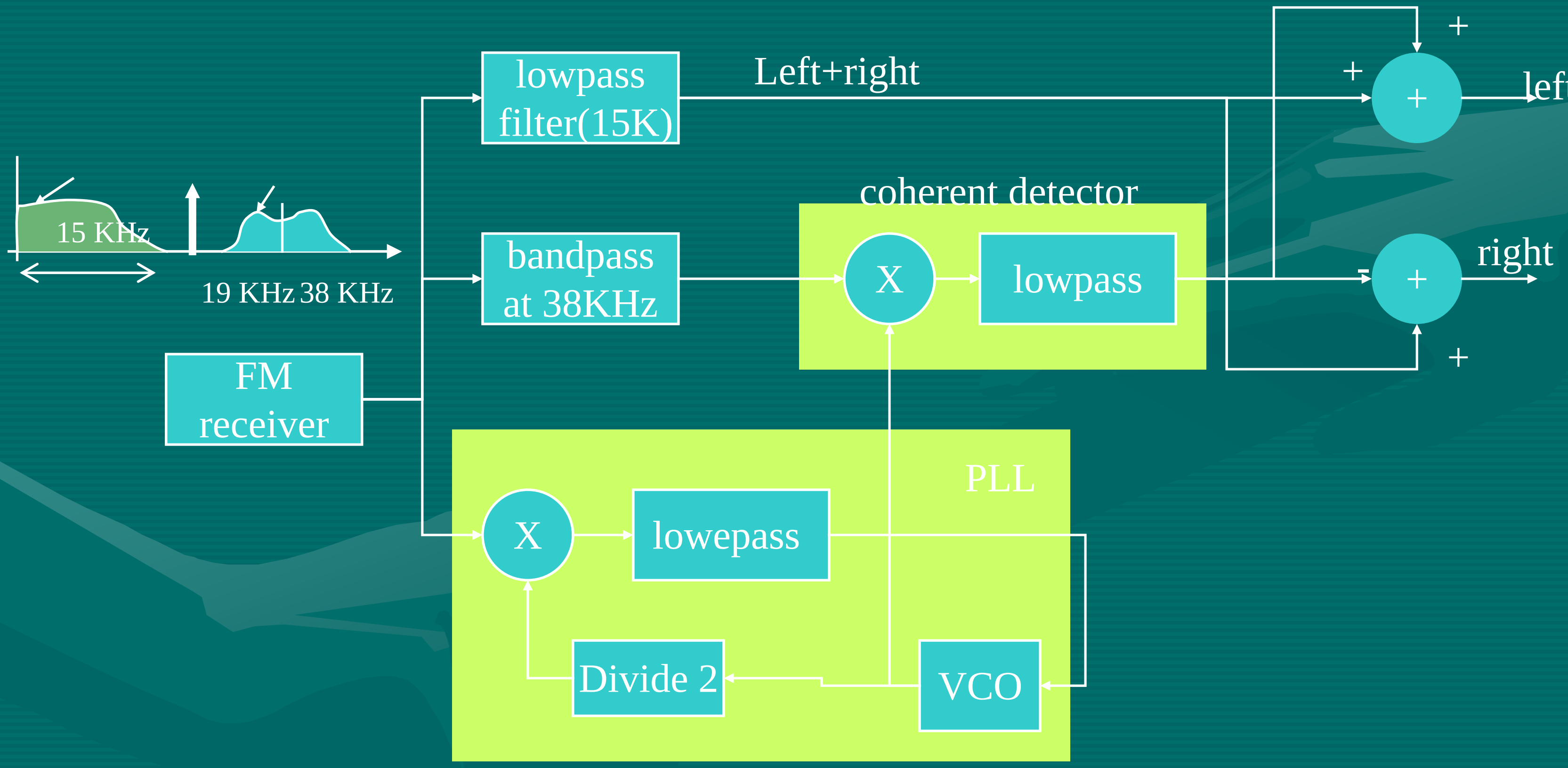


Stereo receiver

- First, FM is stripped, i.e. demodulated
- Second, composite baseband is lowpass filtered to recover the left+right and in parallel amplitude demodulated to recover the left-right signal



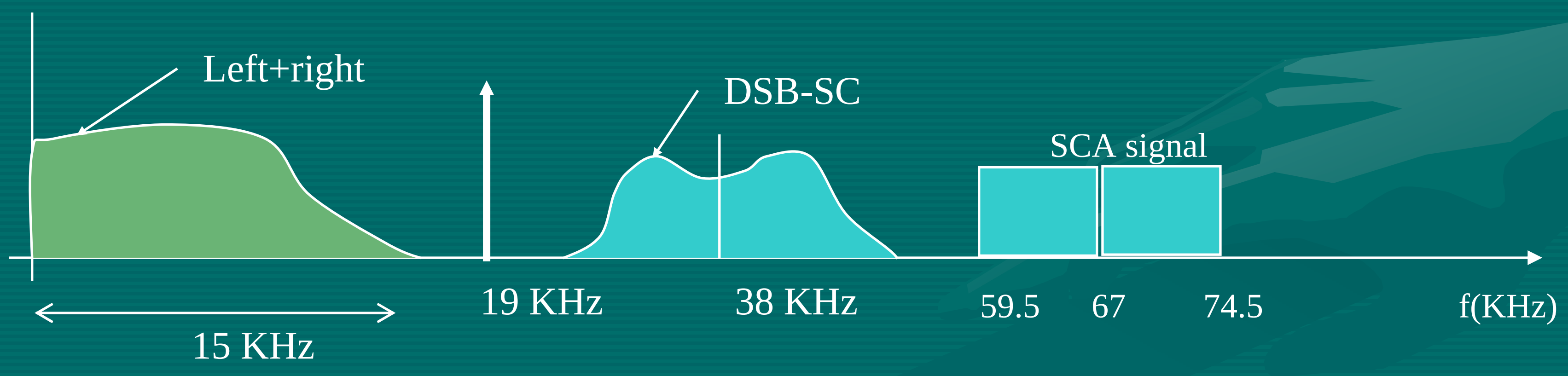
Receiver diagram



Subsidiary communication authorization(SCA)

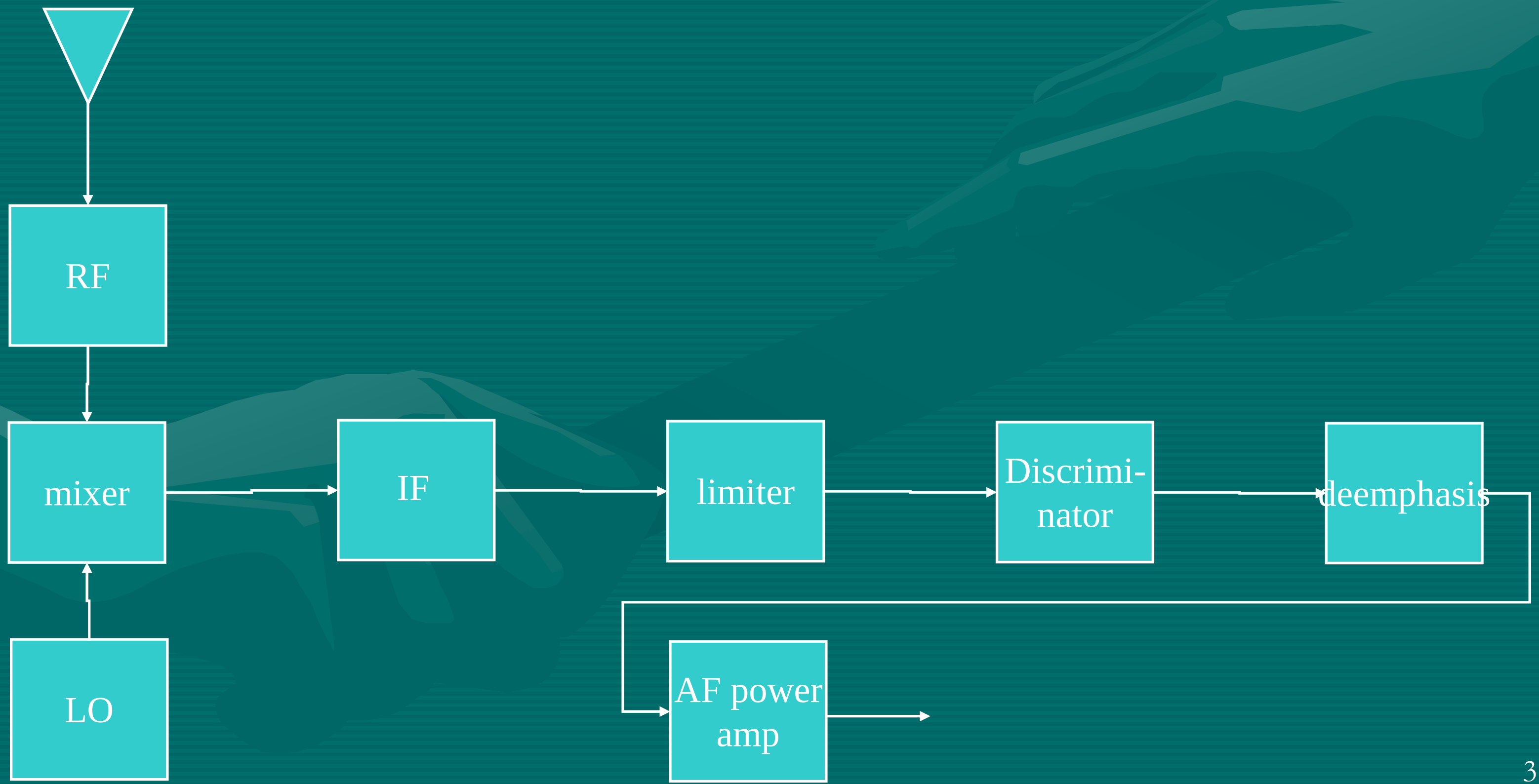
- It is possible to transmit “special programming” ,e.g. commercial-free music for banks, department stores etc. embedded in the regular FM programming
- Such programming is frequency multiplexed on the FM signal with a 67 KHz carrier and ±7.5 KHz deviation

SCA spectrum



FM receiver

- FM receiver is similar to the superhet layout



FM receiver

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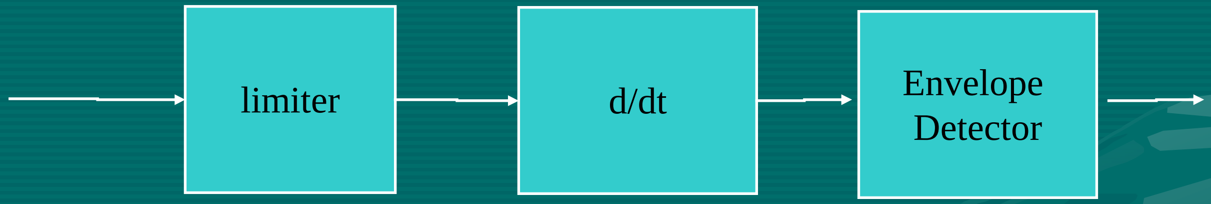


- Operasi d/dt biasa disebut discriminator : mengubah sinyal FM menjadi AM

Demodulasi Sinyal FM

- Pada sinyal FM, informasi terkandung pada frekuensi sinyal FM

$$s(t) = A_c \cos\left[2\pi f_c t + 2\pi k_f \int_0^t m(t)dt\right]$$

- Jika dilakukan diferensiasi terhadap S(t) didapat :

$$s'(t) = A_c\left[2\pi f_c + 2\pi k_f m(t)\right]\sin\left(2\pi f_c t + 2\pi k_f \int_{-\infty}^{t} m(t)dt\right)$$

Informasi terkandung pada bagian selubung dari S'(t). Dideteksi dengan detektor selubung

Receiver components:RF amplifier

- AM may skip RF amp but FM requires it
- FM receivers are called upon to work with weak signals (~1µV or less as compared to 30 µV for AM)
- An RF section is needed to bring up the signal to at least 10 to 20 µV before mixing

Limiter

- A limiter is a circuit whose output is constant for all input amplitudes above a threshold
- Limiter's function in an FM receiver is to remove unwanted amplitude variations of the FM signal

Limiting and sensitivity

- A limiter needs about 1V of signal, called *quieting* or *threshold* voltage, to begin limiting
- When enough signal arrives at the receiver to start limiting action, the set quiets, i.e. background noise disappears
- Sensitivity is the min. RF signal to produce a specified level of quieting, normally

Sensitivity example

- An FM receiver provides a voltage gain of 200,000(106dB) prior to its limiter. The limiter's quieting voltage is 200 mV. What is the receiver's sensitivity?
- What we are really asking is the required signal at RF's input to produce 200 mV at the output

200 mV/200,000= 1μV->sensitivity

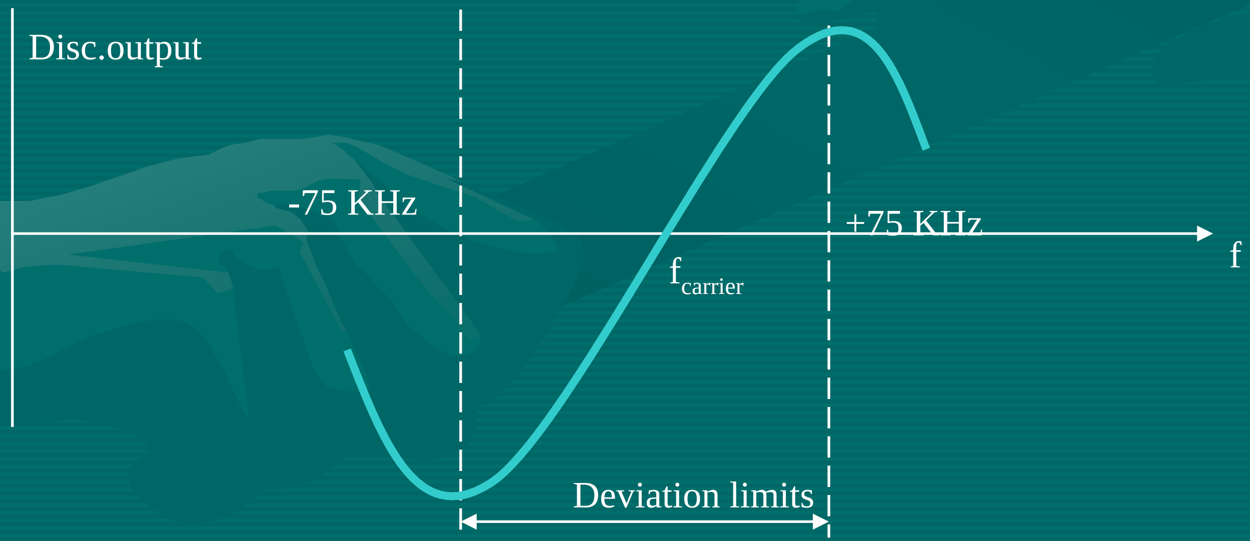
Discriminator

- Mengubah perubahan frekuensi menjadi perubahan amplituda (dilakukan dengan diferensisasi)
- The heart of FM is this relationship

$$f_i(t)=f_c+k_f m(t)$$

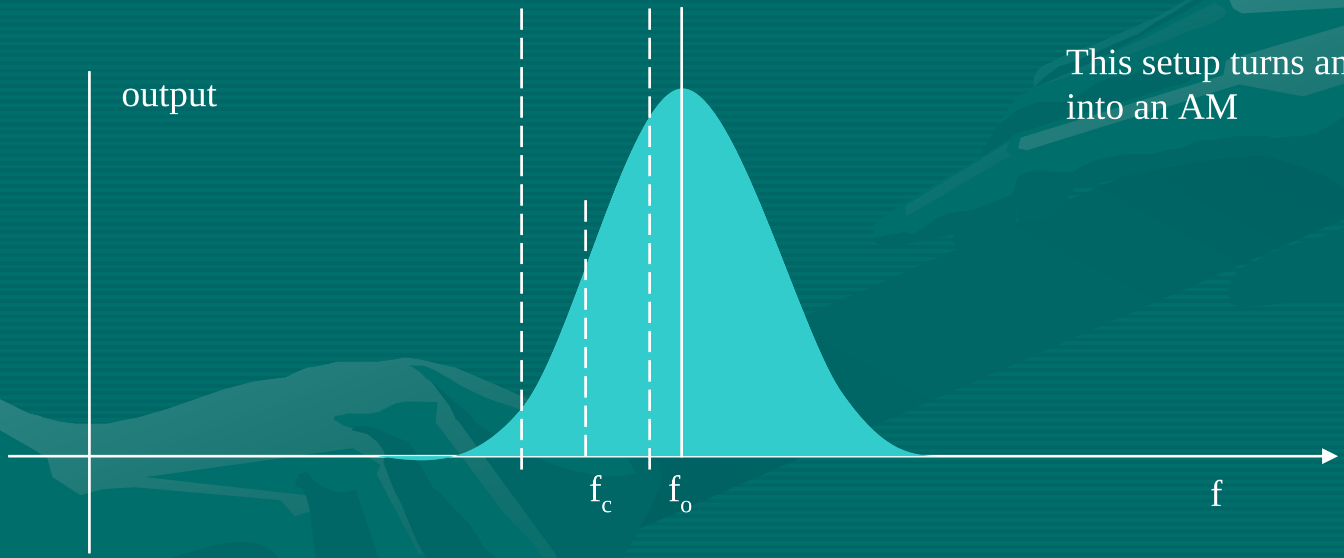
- What we need is a device that linearly follows inst. frequency

$f_{carrier}$ is at the IF frequency
Of 10.7 MHz



Examples of discriminators

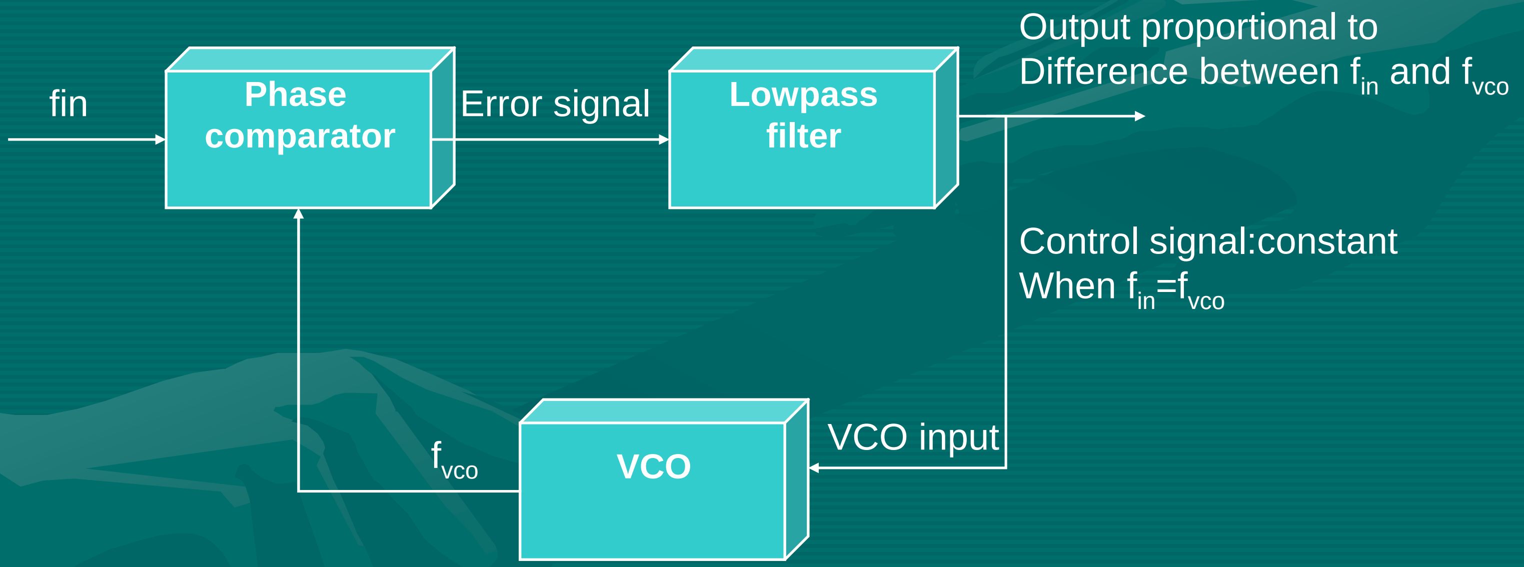
- Slope detector - simple LC tank circuit operated at its most linear response curve



This setup turns an FM signal into an AM

Phase-Locked Loop

- PLL's are increasingly used as FM demodulators and appear at IF output



PLL states

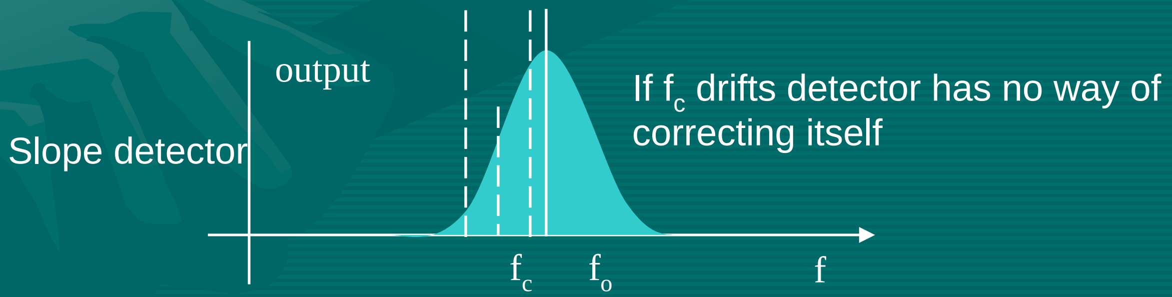
- Free-running
  - If the input and VCO frequency are too far apart, PLL free-runs
- Capture
  - Once VCO closes in on the input frequency, PLL is said to be in the tracking or capture mode
- Locked or tracking
  - Can stay locked over a wider range than was necessary for capture

PLL example

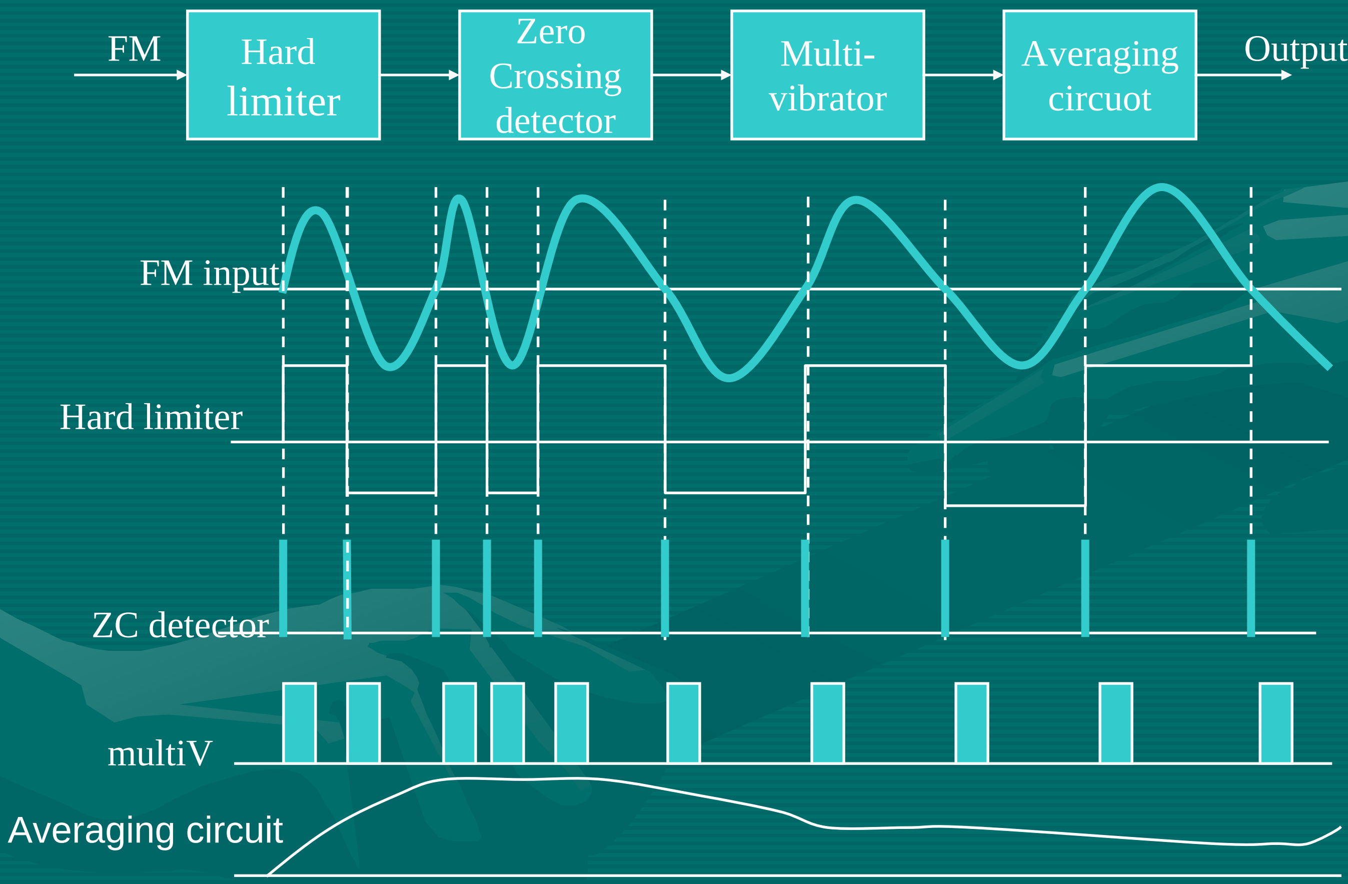
- VCO free-runs at 10 MHZ. VCO does not change frequency until the input is within 50 KHZ.
- In the tracking mode, VCO follows the input to ±200 KHz of 10 MHz before losing lock. What is the lock and capture range?
  - Capture range= 2x50KHz=100 KHz
  - Lock range=2x200 KHz=400 KHz

Advantages of PLL

- If there is a carrier center frequency or LO frequency drift, conventional detectors will be untuned
- PLL, on the other hand, can correct itself. PLL's need no tuned circuits



Zero crossing detector

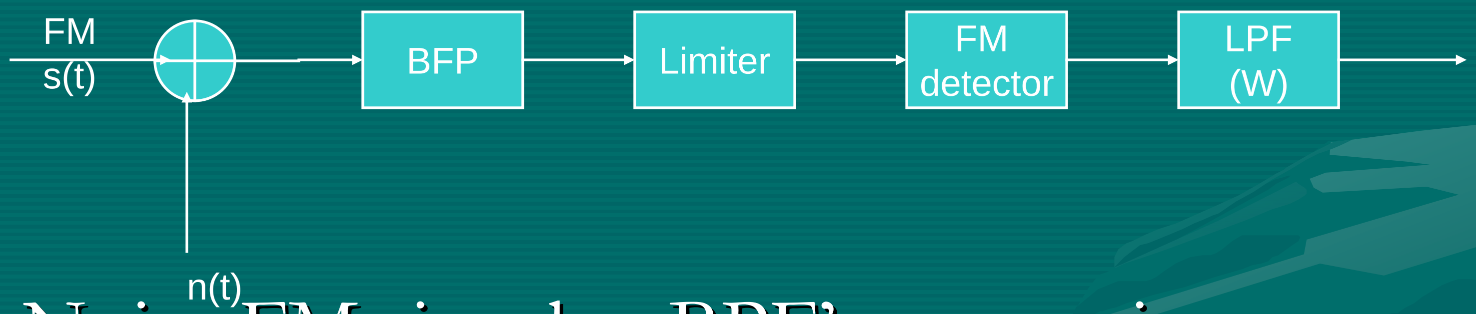


more frequent ZC's means higher inst freq in turn means Larger message amplitudes

NOISE IN ANALOG MODULATION

FREQUENCY MODULATION

Receiver model



- Noisy FM signal at BPF's output is

$$x(t) = s(t) + n(t) =$$

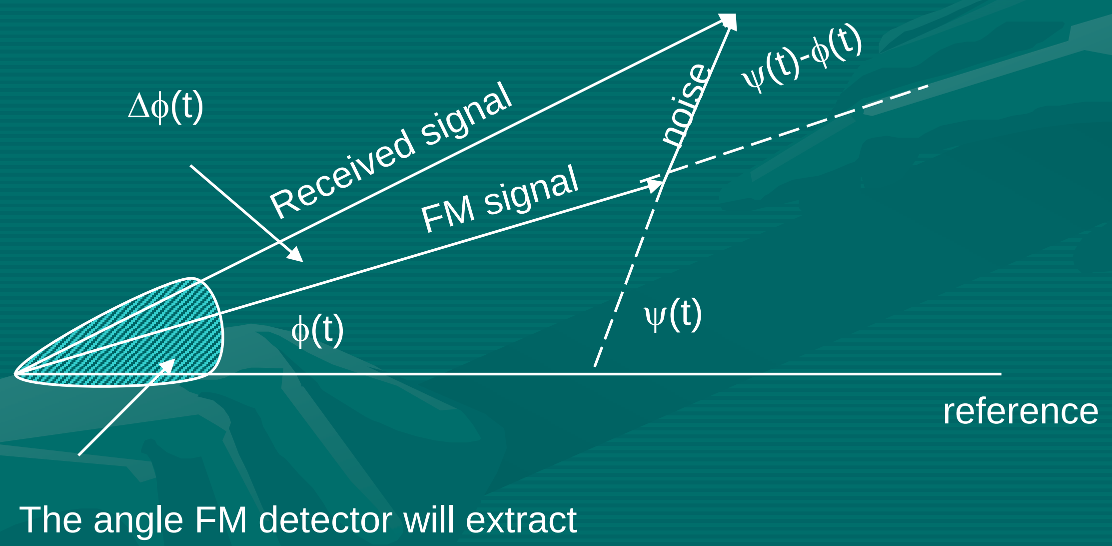
$$A_c \cos\left(2\pi f_c t + \phi(t)\right) + \underbrace{r(t)\cos\left(2\pi f_c t + \psi(t)\right)}_{noise}$$

where

$$\phi(t) = \int m(t)dt$$

Phasor model

- We can see the effect of noise graphically



Small noise

- For small noise, it can be approximated that the noise inflicted phase error is

$$\Delta\phi=[r/Ac]\text{Sin}(\psi-\phi)$$

- So the angle available to the FM detector is $\phi+\Delta\phi$
- FM Detector computes the derivative of this angle. It will then follow that...

FM SNR for tone modulation

- Skipping further detail, we can show that for tone modulation, we have the following ratio

$$\frac{(SNR)_o}{(SNR)_c} = \frac{3}{2}\beta^2$$

- SNR rises as power of 2 of bandwidth; e.g. doubling deviation ratio quadruples the SNR

⇨ **Bandwidth-SNR exchange**

Comparison with AM

- In DSB-SC the ratio was 1 regardless.
- For commercial FM, β=5. Therefore,

  $$(SNR)_o/(SNR)_c=(1.5)x25=37.5$$

- Compare this with just 1 for AM

Capture effect in FM

- An FM receiver locks on to the stronger of two received signals of the same frequency and suppresses the weaker one
- Capture ratio is the necessary difference(in dB) between the two signals for capture effect to go into action
- Typical number for capture ratio is 1 dB

Normalized transmission bandwidth

- With all these bandwidths numbers, it is good to have a normalized quantity.
- Define

$$\text{normalized bandwidth} = B_n = B_T / W$$

Where W is the baseband bandwidth

Examples of B_n

- For AM:

$$B_n = B_T/W = 2W/W = 2$$

- For FM

$$B_n = B_T/W \sim 2\beta \text{ to } 3\beta$$

- For $\beta=5$ in commercial FM, this is a very large expenditure in bandwidth which is rewarded in increased SNR

Noise/bandwidth summary

- AM-envelope detection

$$(SNR)_o = \frac{\mu^2}{2+\mu^2}(SNR)_c$$

$$B_n = 2$$

Noise/bandwidth summary

- DSB-SC/coherent detection

$$(SNR)_o=(SNR)_c$$
$$B_n=2$$

- SSB

$$(SNR)_o=(SNR)_c$$
$$B_n=1$$

Noise/bandwidth summary

- FM-tone modulation and $\beta=5$

$$(SNR)_o=1.5\,\beta^2(SNR)_c=37.5\,(SNR)_c$$

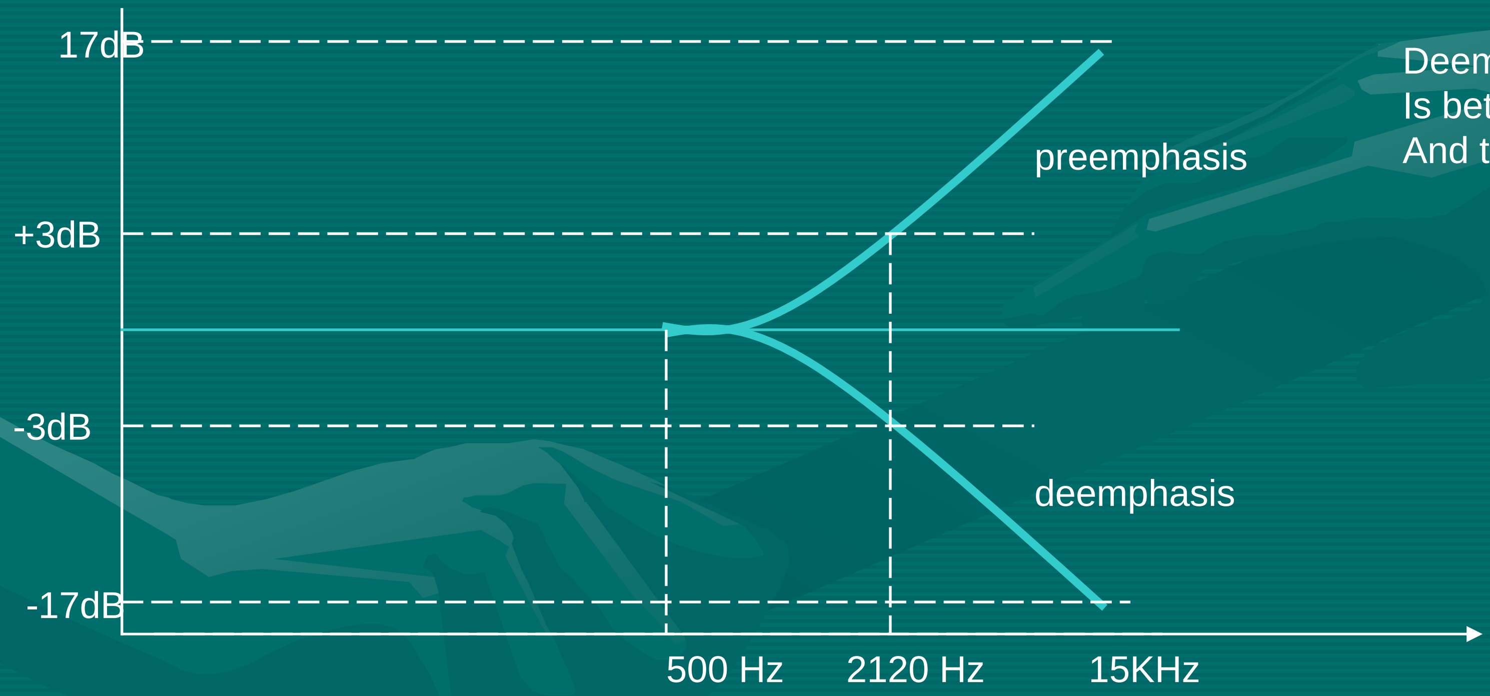
$$B_n\sim 16 \text{ for } \beta=5$$

Preemphasis and deemphasis

- High pitched sounds are generally of lower amplitude than bass. In FM lower amplitudes means lower frequency deviation hence lower SNR.
- Preemphasis is a technique where high frequency components are amplified before modulation
- Deemphasis network returns the baseband to its original form

Pre/deemphasis response

- Flat up to ~500Hz, rises from 500-15000 Hz



Deemphasis circuit
Is between the detector
And the audio amplifier