EE140 Introduction to Communication Systems

Lecture 8

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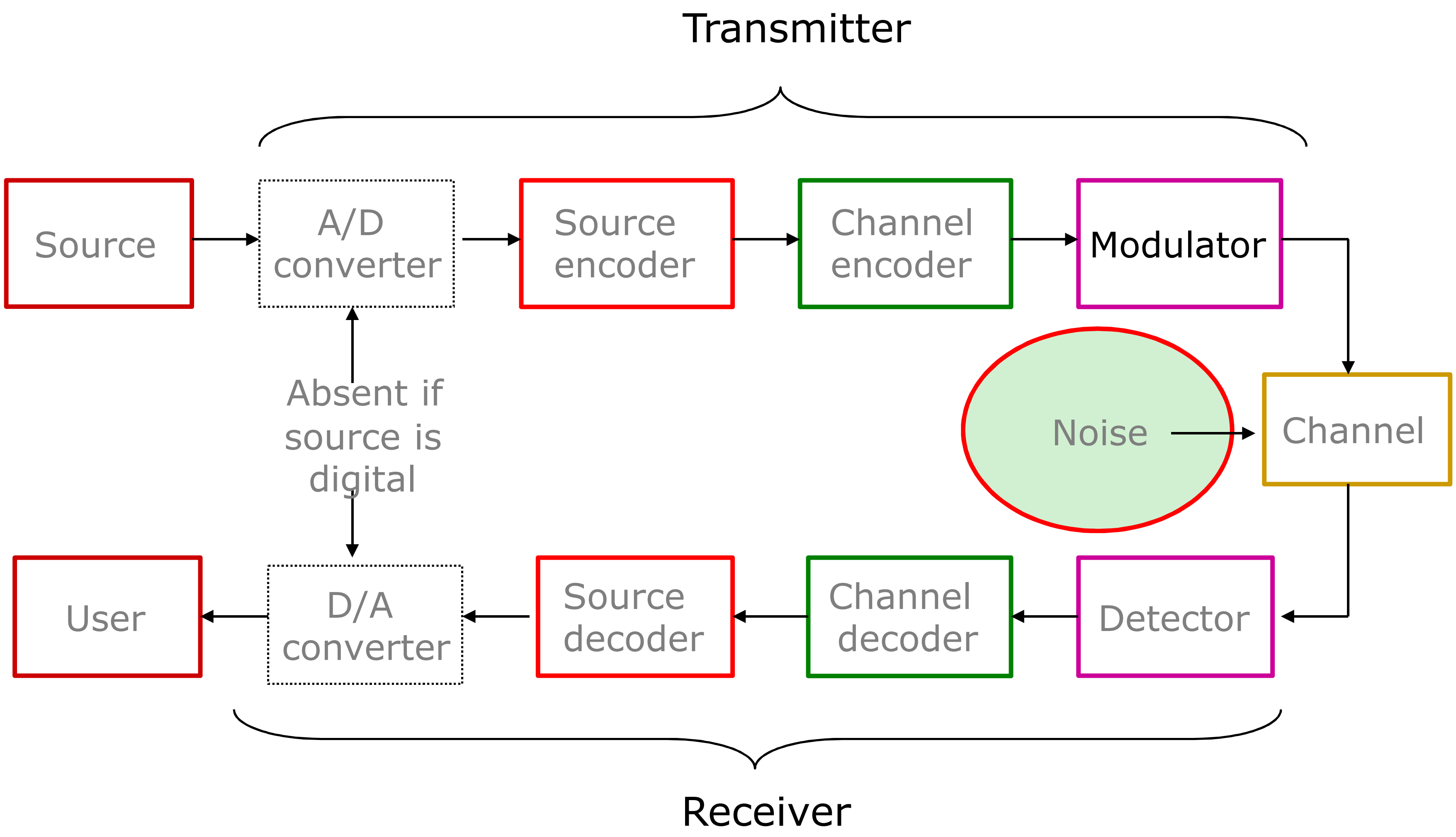
ShanghaiTech University, Fall 2022

Architecture of a (Digital) Communication System



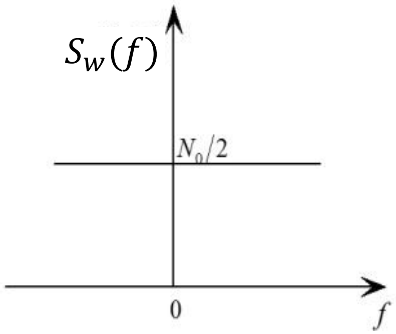
Contents

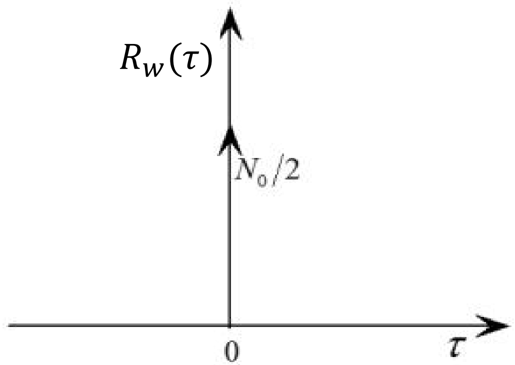
- Noise in Modulation Systems
  - Review
  - Noise in DSB-SC Receiver
  - Noise in SSB Receiver
  - Noise in AM Receiver
  - Noise in Angle Modulation

Noise

- White Gaussian Noise

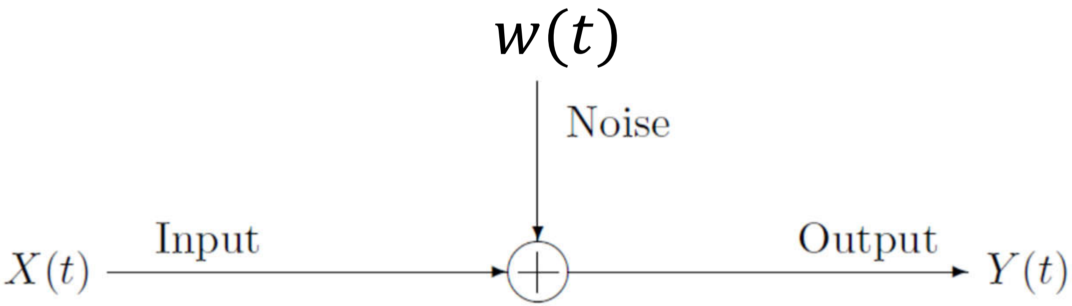
$$S_w(f) = \frac{N_0}{2} \quad \Longrightarrow \quad R_w(\tau) = \frac{N_0}{2}\delta(\tau)$$





White Gaussian noise is completely independent!

- Additive white Gaussian noise (AWGN) model



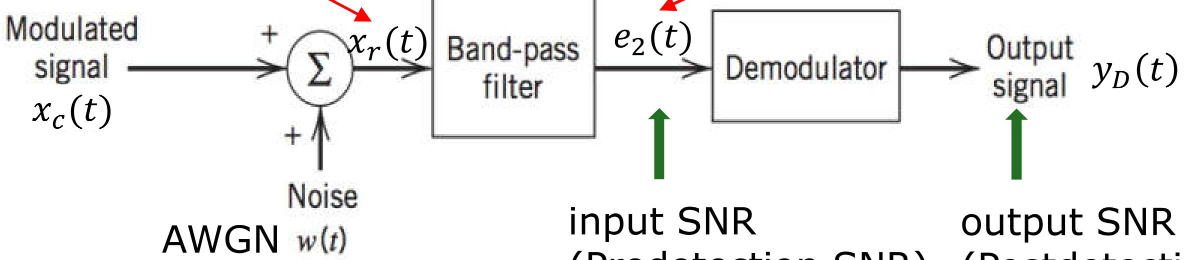
Noisy Receiver Model

- Noisy receiver model

$x_r(t) = x_c(t) + w(t)$

Ideal, bandwidth= B_T, mid-band frequency f_c

$e_2(t) = x_c(t) + n(t)$



input SNR (Predetection SNR)

output SNR (Postdetection SNR)

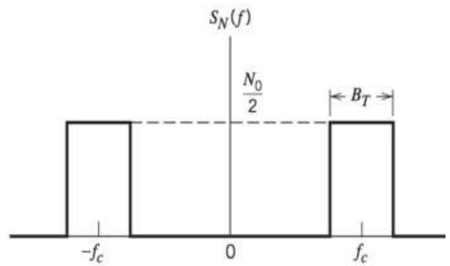
- Narrowband Noise:
  - $f_c \gg B_T$, filtered noise n(t): stationary narrowband Gaussian noise

$$n(t) = n_c(t)\cos(2\pi f_c t + \theta) - n_s(t)\sin(2\pi f_c t + \theta)$$

In-phase component

Quadrature component

Low-pass noise process

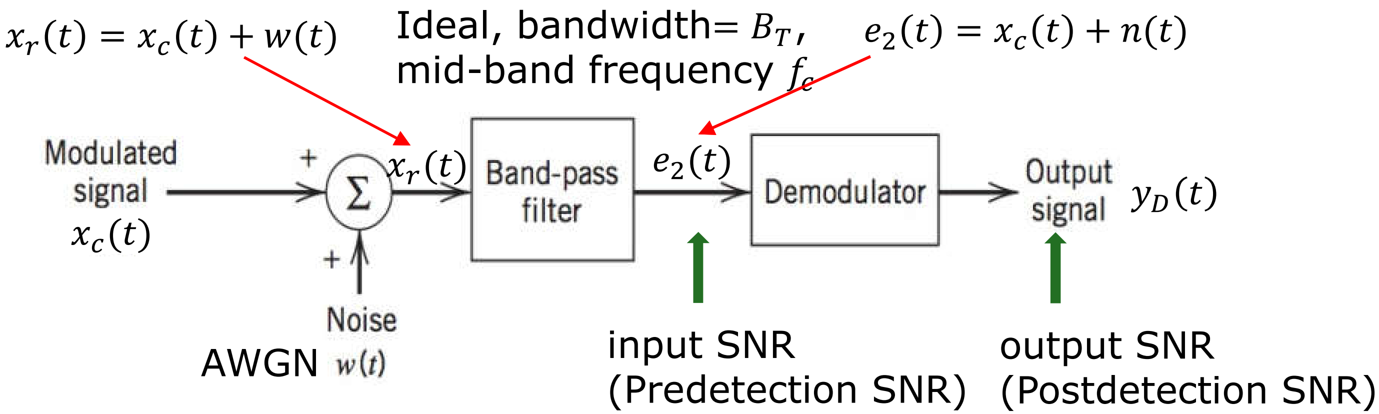


Noisy Receiver Model

- Narrowband Noise:
  - Let n(t) be a zero-mean, stationary and Gaussian noise, then $n_c(t)$ and $n_s(t)$ satisfy the following properties
    - $n_c(t)$ and $n_s(t)$ are zero-mean, jointly stationary and jointly Gaussian process
    - Means: $E[n(t)] = E[n_c(t)] = E[n_s(t)] = 0$
    - Variances(power): $E[n^2(t)] = E[n_c^2(t)] = E[n_s^2(t)] = N_0 B_T$
    - PSD: $S_{n_c}(f) = S_{n_s}(f) = \mathrm{Lp}[S_n(f - f_c) + S_n(f + f_c)]$
    - Correlation function:
      - $R_{n_c}(\tau) = R_{n_S}(\tau)$, $R_n(0) = R_{n_c}(0) = R_{n_S}(0)$
      - $R_{n_c n_s}(\tau) = -R_{n_c n_s}(-\tau)$ (odd), $R_{sc}(0) = R_{cs}(0) = 0.$
    - Cross-PSD: $S_{n_c n_s}(f) = j\mathrm{Lp}[S_n(f - f_c) - S_n(f + f_c)]$
      - $R_{n_c n_s}(\tau) \equiv 0, \forall\tau, \;\; \text{if } \mathrm{Lp}[S_n(f - f_c) - S_n(f + f_c)] = 0.$

Noisy Receiver Model

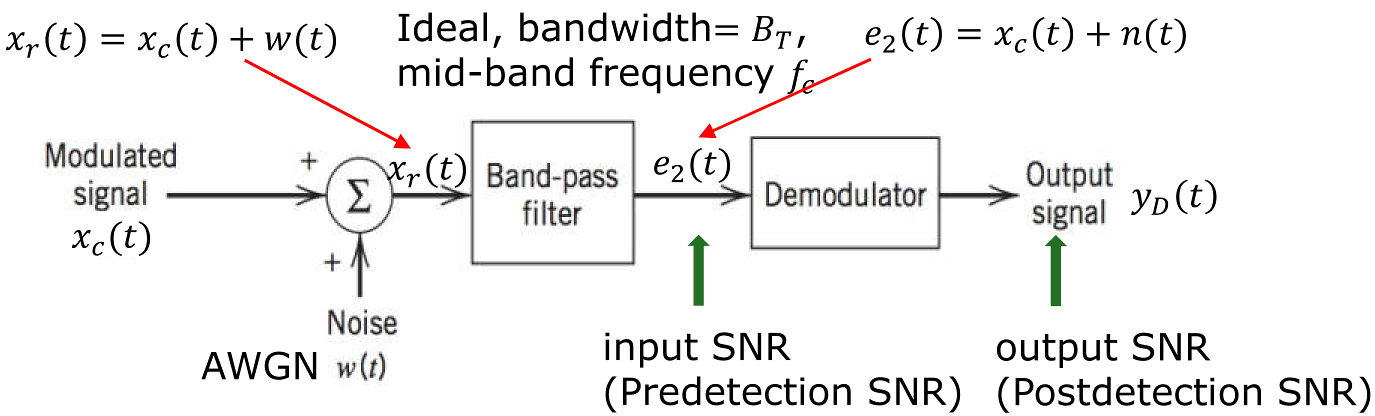
- Noisy receiver model



- Input SNR (Predetection SNR):
  - The ratio of the average power of the modulated signal $x_c(t)$ to the average power of the filtered noise $n(t)$, both measured at the receiver input.
  - $SNR_i = \frac{P_T}{N_0 B_T}$ or $SNR_T = \frac{P_T}{N_0 B_T}$

Noisy Receiver Model

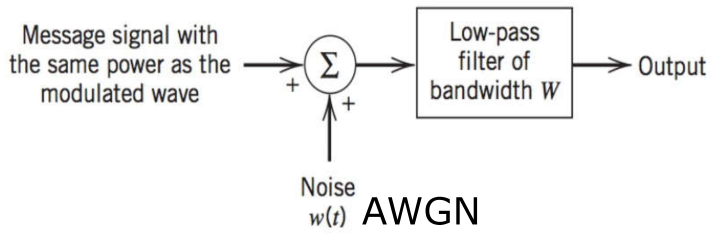
- Noisy receiver model



- Output SNR (Postdetection SNR):
  - The ratio of the average power of the demodulated signal to the average power of the noise, both measured at the receiver output.
  - Type of modulation, type of demodulation
  - SNR_o or SNR_D

Noisy Receiver Model

- Baseband model



- Baseband SNR (Channel SNR):
  - The ratio of the average power of the modulated signal to the average power of the noise in the message bandwidth
    - The total noise power in the message bandwidth: $\frac{N_0}{2}2W = N_0W$
    - The total signal power P_T
  - Baseband SNR: $\mathrm{SNR_c} = \frac{P_T}{N_0W}$

Performance Comparison

- Detection Gain (SNR Gain):

$$\frac{SNR_o}{SNR_i} \text{ or } \frac{SNR_D}{SNR_T} \qquad SNR_T = \frac{P_T}{N_0 B_T}$$

Bandwidth of Modulated signal

- Figure of Merit for the receiver

$$\frac{SNR_o}{SNR_c} \text{ or } \frac{SNR_D}{SNR_c} \qquad SNR_c = \frac{P_T}{N_0 W}$$

Message bandwidth

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Noise in DSB-SC Receiver

- Coherent DSB detector

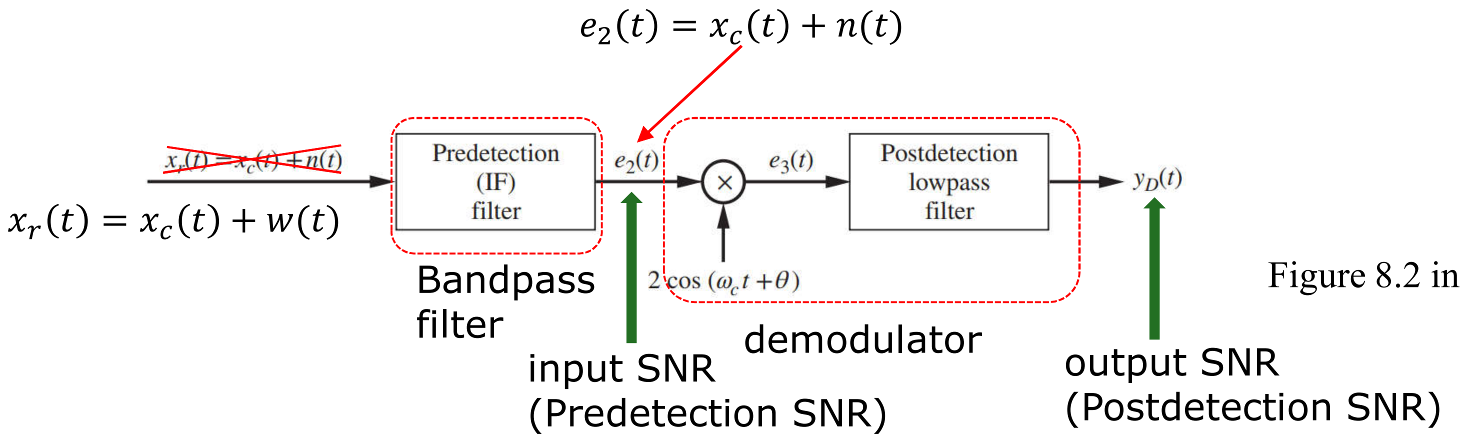


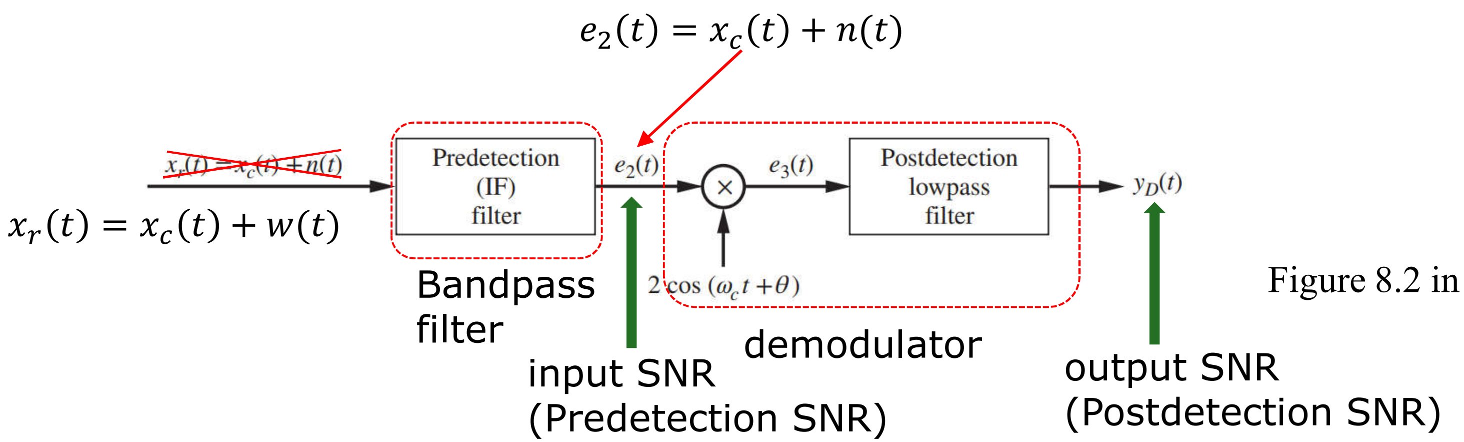
Figure 8.2 in Page 351

  - DSB Signal: $x_c(t) = A_c m(t)\cos(2\pi f_c t + \theta)$
  - White Gaussian Noise: $w(t)$
  - Predetection filter: $B_T = 2W$
  - $e_2(t) = A_c m(t)\cos(2\pi f_c t + \theta) + n_c(t)\cos(2\pi f_c t + \theta) - n_s(t)\sin(2\pi f_c t + \theta)$
  - Predetection SNR:

$$SNR_T = \frac{\frac{1}{2}A_c^2 P}{2N_0 W}, \quad P = \overline{m^2}$$

Noise in DSB-SC Receiver

- Coherent DSB detector



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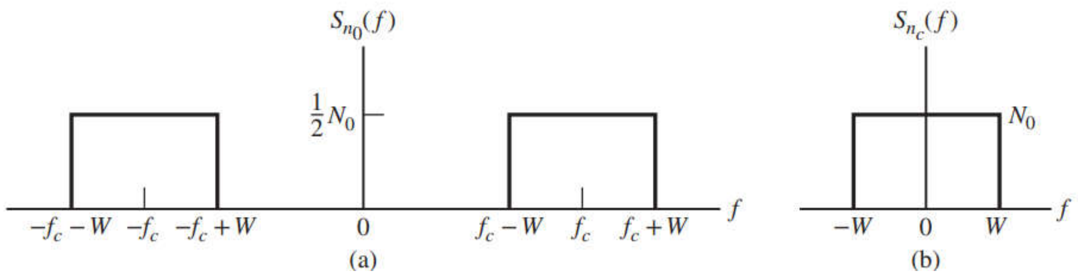
  - $e_3(t) = [A_c m(t)\cos(2\pi f_c t + \theta) + n_c(t)\cos(2\pi f_c t + \theta) - n_s(t)\sin(2\pi f_c t + \theta)]2\cos(2\pi f_c t + \theta) = A_c m(t) + A_c m(t)\cos(4\pi f_c t + 2\theta) + n_c(t) + n_c(t)\cos(4\pi f_c t + 2\theta) - n_s(t)\sin(4\pi f_c t + 2\theta)$
  - $y_D(t) = A_c m(t) + n_c(t)$ (linearity)
  - Postdetection SNR:

$$SNR_D = \frac{A_c^2 P}{2N_0 W}, \quad P = \overline{m^2}, \quad \overline{n^2(t)} = \overline{n_c^2(t)} = N_0 B_T = 2N_0 W$$

Noise in DSB-SC Receiver

- Coherent DSB detector



Predection noise

postdection noise

$$P_T = \frac{1}{2}A_c^2 P \qquad SNR_T = \frac{P_T}{2N_0\mathrm{W}}$$

Detection gain: $\frac{SNR_D}{SNR_T} = 2$

$$SNR_D = \frac{P_T}{N_0\mathrm{W}}$$

Figure of Merit: $\frac{SNR_D}{SNR_\mathrm{c}} = 1$

$$SNR_c = \frac{P_T}{N_0\mathrm{W}}$$

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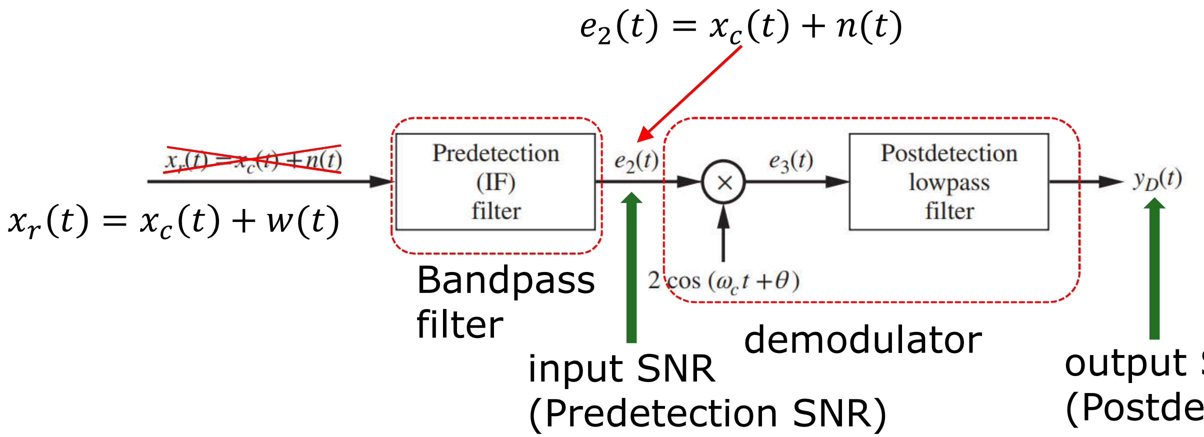
Noise in SSB Receiver

- Coherent detector



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- SSB Signal: $x_c(t) = A_c[m(t)\cos(2\pi f_c t + \theta) \pm \hat{m}(t)\sin(2\pi f_c t + \theta)]$
- Predetection filter: $B_T = W$
- $e_2(t) = A_c[m(t)\cos(2\pi f_c t + \theta) \pm \hat{m}(t)\sin(2\pi f_c t + \theta)] + n_c(t)\cos(2\pi f_c t + \theta) - n_s(t)\sin(2\pi f_c t + \theta)$
- Predetection SNR: $SNR_T = \dfrac{A_c^2 P}{N_0 W}$

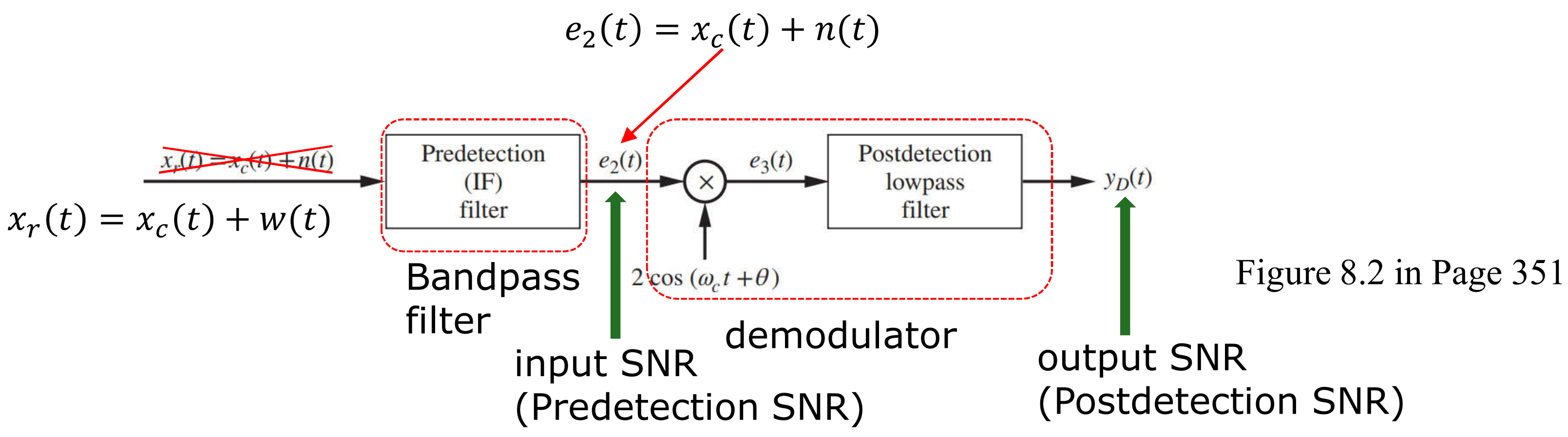
$$S_T = A_c^2\overline{[m(t)\cos(2\pi f_c t + \theta) \pm \hat{m}(t)\sin(2\pi f_c t + \theta)]^2} \qquad N_T = N_0 B_T = N_0 W$$

$$= A_c^2\left[\frac{1}{2}\overline{m(t)^2} + \frac{1}{2}\overline{\hat{m}(t)^2}\right]$$

$$= A_c^2\,\overline{m(t)^2}$$

Noise in SSB Receiver

- Coherent detector



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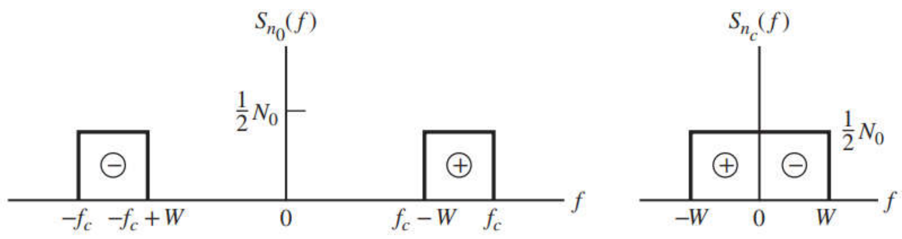
  - $y_D(t) = A_c m(t) + n_c(t)$
  - postdetection SNR: $SNR_D = \dfrac{A_c^2 P}{N_0 W}$



Predection noise postdection noise

Noise in SSB Receiver

- Coherent detector

$$P_T = A_c^2 P \qquad SNR_T = \frac{P_T}{N_0 \mathrm{W}}$$

Detection gain: $\frac{SNR_D}{SNR_T} = 1$

$$SNR_D = \frac{P_T}{N_0 \mathrm{W}}$$

Figure of Merit: $\frac{SNR_D}{SNR_c} = 1$

$$SNR_c = \frac{P_T}{N_0 \mathrm{W}}$$

Coherent demodulation of both DSB and SSB results in performance equivalent to baseband.

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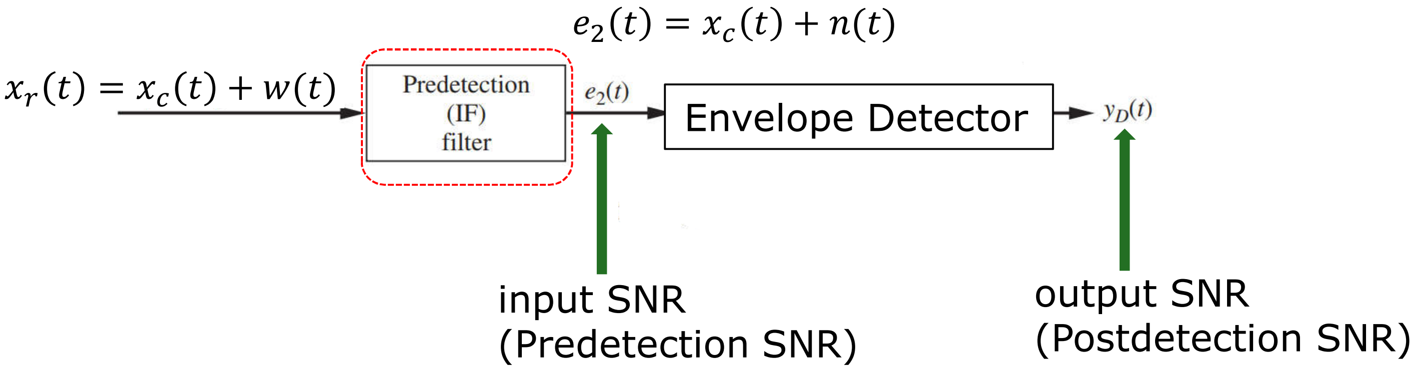
Noise in AM Receiver

- Envelope detector



  - AM Signal: $x_c(t) = A_c[1 + am_n(t)]\cos(2\pi f_c t + \theta)$
  - Predetection filter: $B_T = 2W$
  - $e_2(t) = A_c[1 + am_n(t)]\cos(2\pi f_c t + \theta) + n_c(t)\cos(2\pi f_c t + \theta) - n_s(t)\sin(2\pi f_c t + \theta) = r(t)\cos[2\pi f_c t + \theta + \phi(t)]$,
    - Predetection SNR: $SNR_T = \dfrac{\frac{A_c^2}{2}\left[1+a^2\overline{m_n^2}\right]}{2N_0W}$
    - Envelope: $r(t) = \sqrt{\{A_c[1 + am_n(t)] + n_c(t)\}^2 + n_s(t)^2}$

Noise in AM Receiver

- Envelope detector
  - $y_D(t) = \sqrt{\{A_c[1+am_n(t)]+n_c(t)\}^2+n_s(t)^2}$
  - When SNR$_T$ is large ($|A_c[1+am_n(t)]+n_c(t)| \gg |n_s(t)|$):
    $y_D(t) \cong A_c a m_n(t) + n_c(t)$ (after removal of DC component)
    - Postdetection SNR: $SNR_D = \frac{A_c^2 a^2 \overline{m_n^2}}{2N_0W}$
    - When SNR$_T$ is large

$$SNR_T = \frac{\frac{A_c^2}{2}\left[1+a^2\overline{m_n^2}\right]}{2N_0\mathrm{W}}$$

$$SNR_D = \frac{A_c^2 a^2 \overline{m_n^2}}{2N_0\mathrm{W}}$$

Detection gain: $\frac{SNR_D}{SNR_T} = \frac{2a^2\overline{m_n^2}}{1+a^2\overline{m_n^2}} = 2\mu$

$$P_T = \frac{A_c^2}{2}\left[1+a^2\overline{m_n^2}\right] \quad SNR_c = \frac{\frac{A_c^2}{2}\left[1+a^2\overline{m_n^2}\right]}{N_0\mathrm{W}}$$

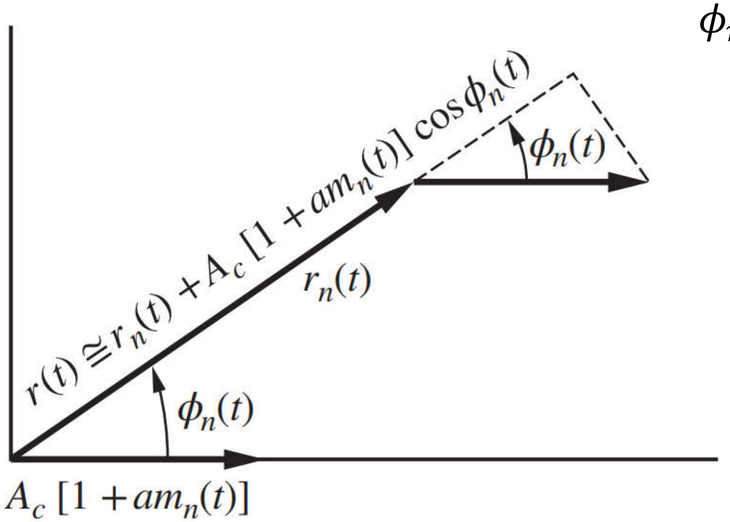
Figure of Merit: $\frac{SNR_D}{SNR_c} = \frac{a^2\overline{m_n^2}}{1+a^2\overline{m_n^2}} = \mu \le 1$

The noise performance of an AM receiver is always inferior to that of a DSB-SC, SSB receiver.

Noise in AM Receiver

- Envelope detector
  - $e_2(t) = A_c[1 + am_n(t)]\cos(2\pi f_c t + \theta) + n_c(t)\cos(2\pi f_c t + \theta) - n_s(t)\sin(2\pi f_c t + \theta) = A_c[1 + am_n(t)]\cos(2\pi f_c t + \theta) + r_n(t)\cos[2\pi f_c t + \theta + \phi_n(t)]$
  - When SNR$_T$ is small ($|A_c[1 + am_n(t)]| \ll |r_n(t)|$):
    - $y_D(t) \cong r_n(t) + A_c[1 + am_n(t)]\cos[\phi_n(t)]$

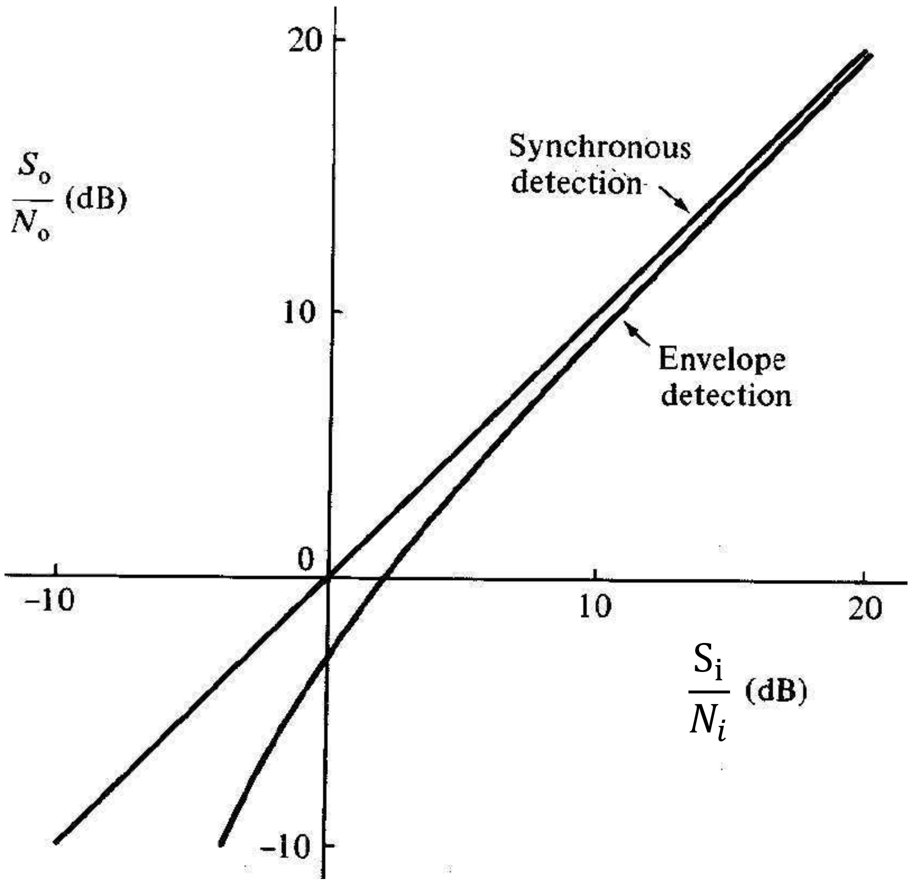
$\phi_n(t) \sim U[0,2\pi]$



Threshold Effect (loss of message at low SNR): Every nonlinear detector exhibits a threshold effect.

Performance of AM Demod

- Synchronous detection vs envelope detection
  - In synchronous detection, the output signal and noise always remain additive and the curve-slope is a constant, independent of input SNR.
  - The nonlinear behavior of envelope detection declines the SNR performance when input noise increases.



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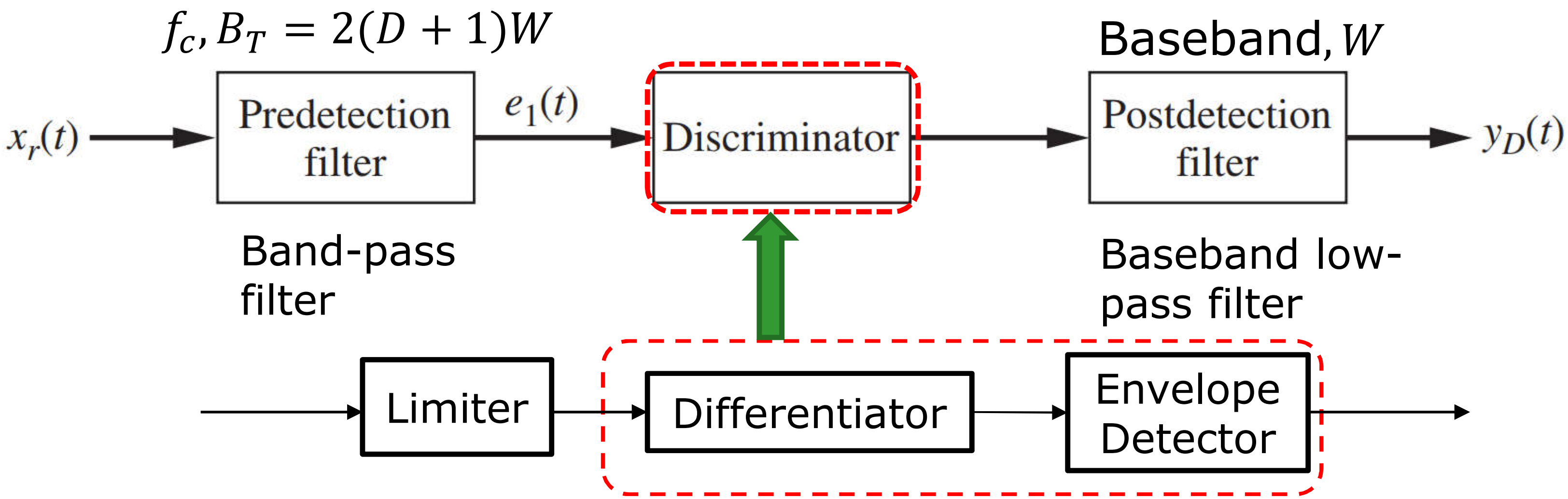
Noise in Angle Modulation

- Noise in Angle Modulation Receiver



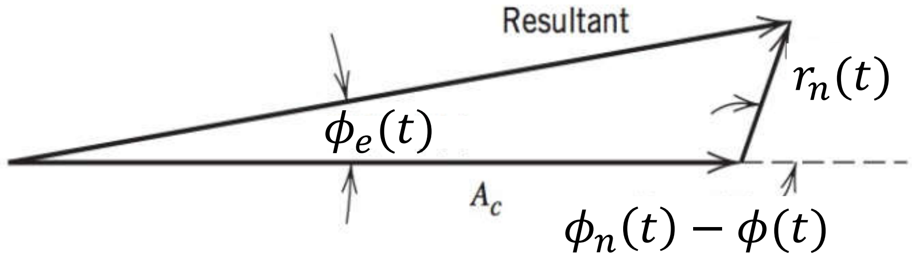
  - Received signal: $x_r(t) = A_c \cos[2\pi f_c t + \theta + \phi(t)] + w(t)$
  - Bandpass filter: $f_c, B_T = 2(D+1)W$
  - $e_1(t) = A_c \cos[2\pi f_c t + \theta + \phi(t)] + n_c(t)\cos(2\pi f_c t + \theta) - n_s(t)\sin(2\pi f_c t + \theta) = A_c \cos[2\pi f_c t + \theta + \phi(t)] + r_n(t)\cos[2\pi f_c t + \theta + \phi_n(t)]$
    - $r_n(t)$: Rayleigh-distributed noise envelope; $\phi_n(t)$: uniformly distributed noise phase
    - Predetection SNR (input SNR): $SNR_T = \frac{\frac{A_c^2}{2}}{N_0 B_T}$

Noise in Angle Modulation

- Noise in Angle Modulation Receiver
  - $e_1(t) = A_c \cos[2\pi f_c t + \theta + \phi(t)] + r_n(t)\cos[2\pi f_c t + \theta + \phi_n(t)]$
    $= R(t)\cos[2\pi f_c t + \theta + \phi(t) + \phi_e(t)]$
  - $\phi_e(t) = \tan^{-1}\left\{\frac{r_n(t)\sin[\phi_n(t)-\phi(t)]}{A_c + r_n(t)\cos[\phi_n(t)-\phi(t)]}\right\}$
  - Phase Deviation of the receiver input:
    - $\psi(t) = \phi(t) + \phi_e(t)$ (phase error due to noise)
  - When SNR$_T$ is large ($A_c \gg r_n(t)$ most of the time):
    - $\phi_e(t) \approx \tan^{-1}\left\{\frac{r_n(t)\sin[\phi_n(t)-\phi(t)]}{A_c}\right\}$ when $x \ll 1, \tan^{-1}(x) \approx x$

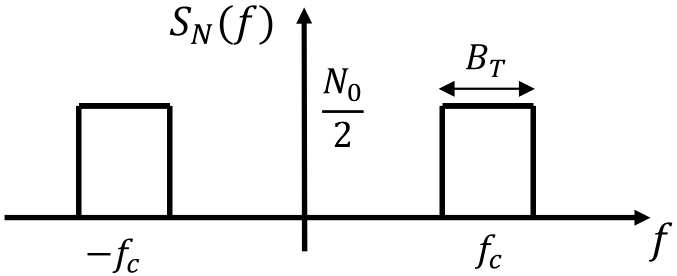
$$\approx \frac{r_n(t)\sin[\phi_n(t)-\phi(t)]}{A_c}$$

$$= \frac{n_s(t)}{A_c}$$

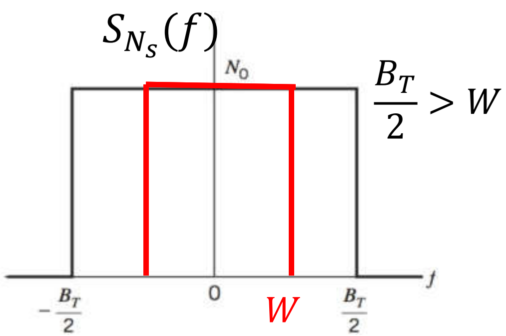


Noise in Phase Modulation

- PM Demodulator
  - $e_1(t) = R(t)\cos[2\pi f_c t + \theta + \psi(t)]$
    - Phase deviation: $\psi(t) = \phi(t) + \phi_e(t)$
    - Signal: $\phi(t) = k_p m(t)$
    - Phase error: $\phi_e(t) = \frac{n_s(t)}{A_c}$
  - Demodulated output of PM:
    - $y_D(t) = K_D\psi(t) = K_D k_p m(t) + K_D \frac{n_s(t)}{A_c}$
    - Output signal power: $S_{\mathrm{DP}} = K_D^2 k_p^2 \overline{m^2}$
    - Bandwidth of the $n_s(t)$: $\frac{B_T}{2} > W$ → postdetection lowpass filter with bandwidth W



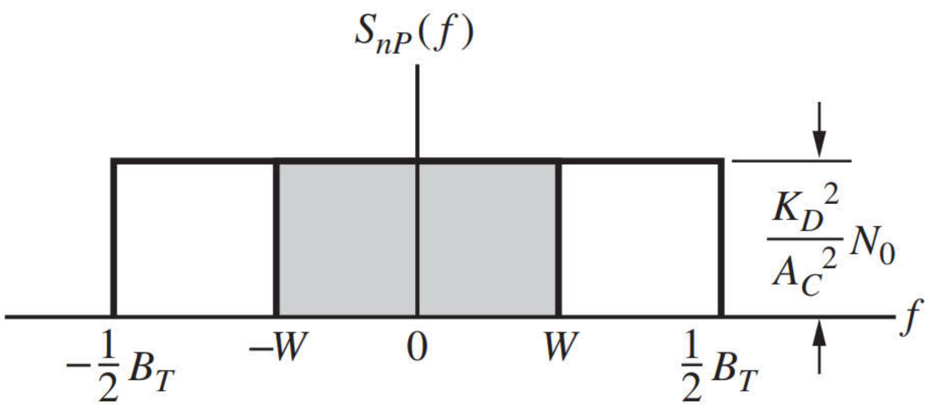
Predetection noise



Quadrature component

Noise in Phase Modulation

- PM Demodulator
  - Demodulated output of PM:
    - $y_{DP}(t) = K_D\psi(t) = K_D k_p m(t) + K_D \frac{n_s(t)}{A_c}$
    - Output signal power: $S_{DP} = K_D^2 k_p^2 \overline{m^2}$
    - Output noise power: $N_{DP} = 2\frac{K_D^2}{A_c^2} N_0 W$



- Postdetection SNR(output SNR): $SNR_D = \frac{K_D^2 k_p^2 \overline{m^2}}{2\frac{K_D^2}{A_c^2} N_0 W} = \frac{A_c^2 k_p^2 \overline{m^2}}{2N_0 W}$

Noise in Phase Modulation

- PM Demodulator
  - When SNR_T is large

$$k_p m(t) = k_p |m(t)|_{max} m_n(t)$$

$$P_T = \frac{A_c^2}{2} \qquad SNR_T = \frac{P_T}{N_0 B_T}$$

$$SNR_D = \frac{P_T k_p^2 \overline{m^2}}{N_0 W}$$

$$SNR_c = \frac{P_T}{N_0 W}$$

Detection gain: $\dfrac{SNR_D}{SNR_T} = \dfrac{k_p^2 \overline{m^2} B_T}{W}$

Figure of Merit: $\dfrac{SNR_D}{SNR_c} = k_p^2 \overline{m^2}$

$$= \left(k_p |m(t)|_{max}\right)^2 \overline{m_n^2}$$

For $k_p >> 1$, $B_T \approx 2\Delta f \propto k_p |m(t)|_{max}$

Tradeoff between bandwidth and noise performance in PM system

Noise in Frequency Modulation

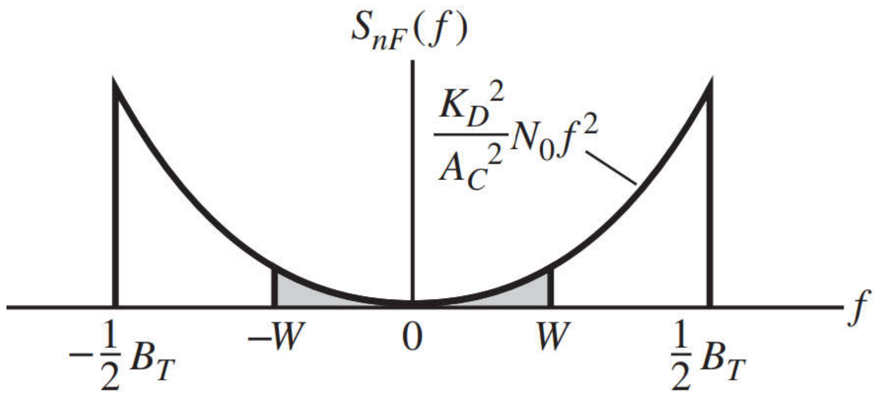
- FM Demodulator
  - $e_1(t) = R(t)\cos[2\pi f_c t + \theta + \psi(t)]$
    - Phase deviation: $\psi(t) = \phi(t) + \phi_e(t)$
    - Signal: $\phi(t) = 2\pi f_d \int^t m(\tau)d\tau$
    - Phase error: $\phi_e(t) = \frac{n_s(t)}{A_c}$
  - Demodulator output:
    - $y_D(t) = \frac{1}{2\pi} K_D \frac{d\psi(t)}{dt} = K_D f_d m(t) + \boxed{\frac{K_D}{2\pi A_c}\frac{dn_s(t)}{dt}}$
    - Output signal power: $\mathrm{S_{DF}} = K_D^2 f_d^2 \overline{m^2}$
    - Noise at the output of discriminator:
      - $S_{nF}(f) = \left(\frac{K_D}{2\pi A_c}\right)^2 |j2\pi f|^2 S_{n_s}(f) = \frac{K_D^2}{A_c^2} N_0 f^2$, $|f| < \frac{1}{2}B_T$

$$x(t) \longrightarrow \boxed{\mathrm{H(t)}} \longrightarrow y(t) = \frac{K_D}{2\pi A_c}\frac{dx(t)}{dt}$$

$$S_y(f) = \left|\frac{K_D}{2\pi A_c} \cdot j2\pi f\right|^2 S_x(f)$$

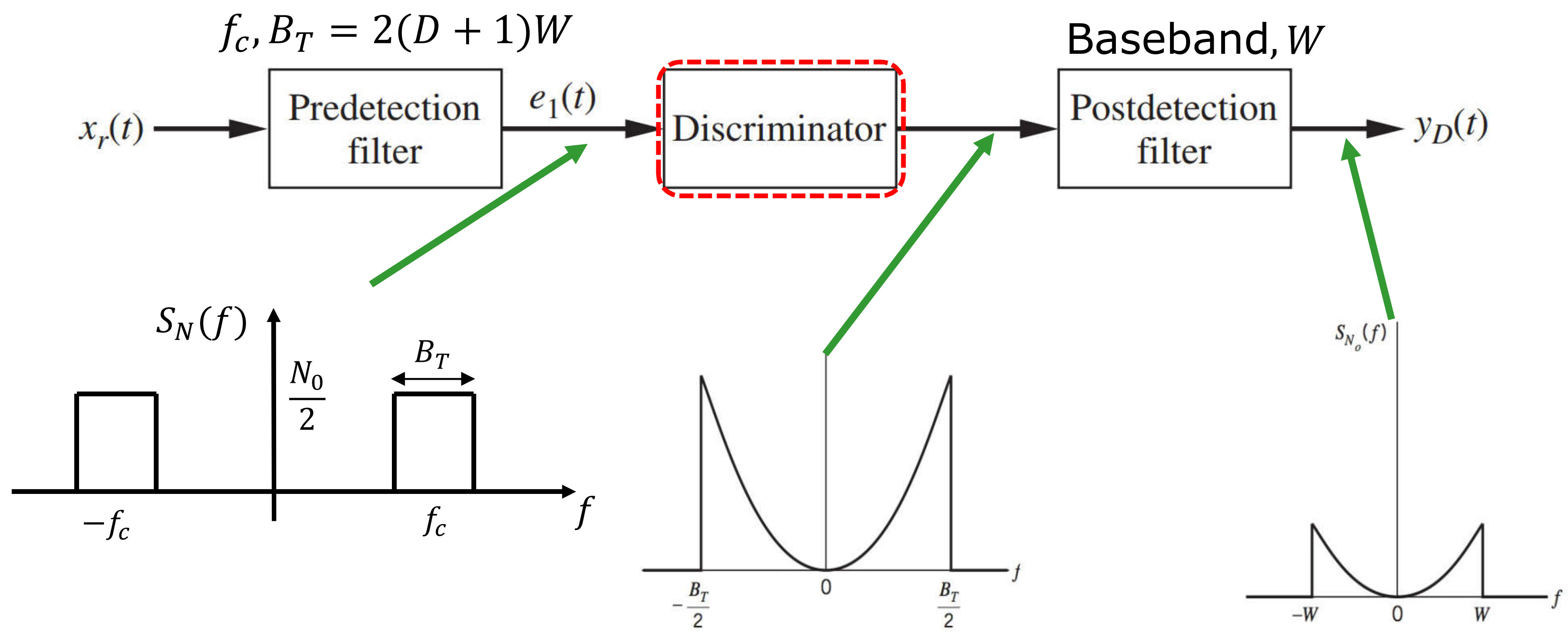
Noise in Frequency Modulation

- FM Demodulator
  - Output noise:
    - Noise at the output of discriminator:
      - » Power spectral density: $S_{nF}(f) = \frac{K_D^2}{A_c^2} N_0 f^2$, $|f| < \frac{1}{2} B_T$
    - $\frac{B_T}{2} > W$ → postdetection lowpass filter with bandwidth W to remove the out-of-band noise
    - Output noise power: $N_{DF} = \frac{K_D^2}{A_c^2} N_0 \int_{-W}^{W} f^2 df = \frac{2K_D^2 N_0 W^3}{3A_c^2}$
  - Postdetection SNR (output SNR):
    - $SNR_D = \frac{K_D^2 f_d^2 \overline{m^2}}{\frac{2K_D^2 N_0 W^3}{3A_c^2}} = \frac{3A_c^2 f_d^2 \overline{m^2}}{2N_0 W^3}$



S

Noise in Frequency Modulation



$$S_{nF}(f) = \frac{K_D^2}{A_c^2} N_0 f^2, |f| < \frac{1}{2} B_T \qquad S_{N_o}(f) = \frac{K_D^2}{A_c^2} N_0 f^2, |f| < W$$

Noise in Frequency Modulation

- FM Demodulator
  - When SNR$_T$ is large

$$f_d m(t) = f_d |m(t)|_{max} m_n(t)$$

$$\frac{f_d^2 \overline{m^2}}{W^2} = \left(\frac{f_d |m(t)|_{max}}{W}\right)^2 \overline{\mathrm{m_n^2}} = \mathrm{D}^2 \overline{\mathrm{m_n^2}}$$

$$P_T = \frac{A_c^2}{2} \qquad SNR_T = \frac{P_T}{N_0 B_T}$$

$$SNR_D = \frac{3 P_T f_d^2 \overline{m^2}}{N_0 W^3}$$

$$SNR_c = \frac{P_T}{N_0 W}$$

Detection gain: $\frac{SNR_D}{SNR_T} = \frac{3 f_d^2 \overline{m^2} B_T}{W^3} = 6D^2(D+1)\overline{m_n^2}$

Figure of Merit: $\frac{SNR_D}{SNR_c} = \frac{3 f_d^2 \overline{m^2}}{W^2} = 3D^2 \overline{m_n^2}$

For D>>1, $B_T \approx 2DW$ $\longrightarrow$ $\frac{SNR_D}{SNR_c} = \frac{3}{4}\left(\frac{B_T}{W}\right)^2 \overline{m_n^2}$

Tradeoff between bandwidth and noise performance in FM system

Noise in Frequency Modulation

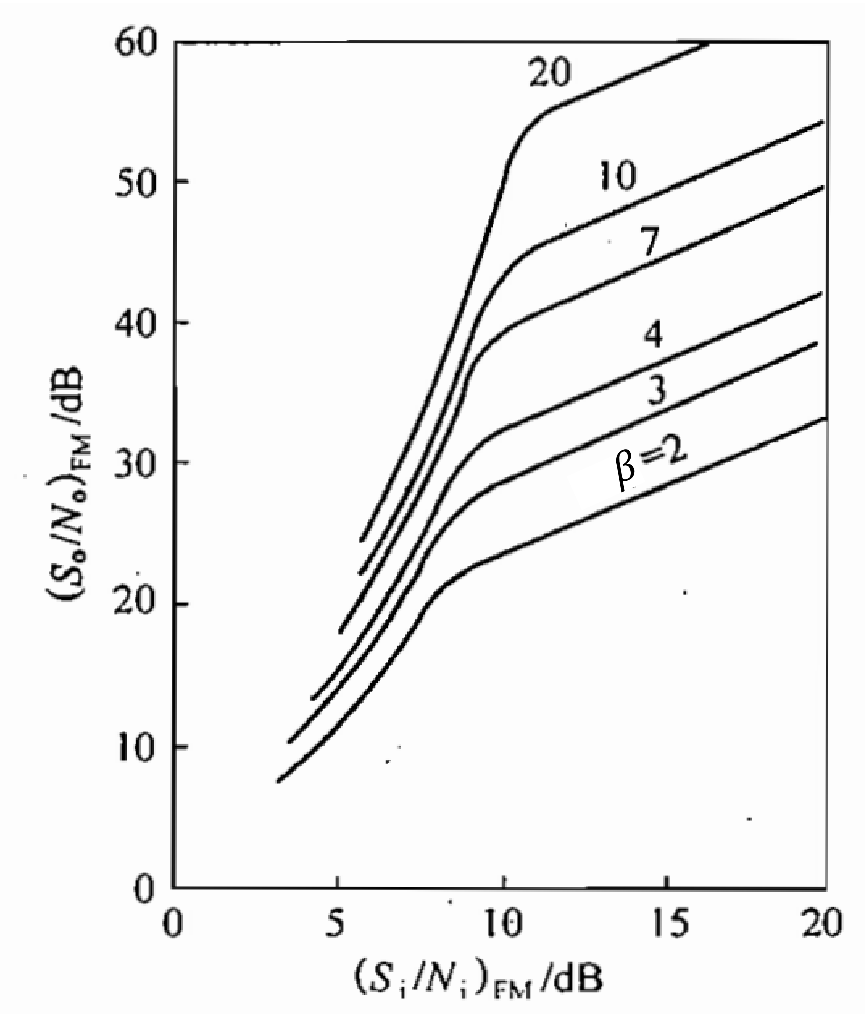
- Comparison of FM and AM
  - When SNR$_T$ is large, and $m(t) = A_m \cos(2\pi f_m t)$
  - FM: Postdetection SNR (Output SNR):
    - $SNR_D = \frac{3A_c^2 f_d^2 \overline{m^2}}{2N_0 W^3} = \frac{3A_c^2 f_d^2 A_m^2}{4N_0 W^3} = \frac{3A_c^2 \Delta f^2}{4N_0 W^3} = \frac{3A_c^2 \beta^2}{4N_0 W}$
    - Figure of merit: $\frac{SNR_D}{SNR_C} = \frac{3}{2}\beta^2$
    - Bandwidth: $B_{FM} \approx 2\beta f_m$

$$\Delta f = f_d A_m, \beta = \frac{\Delta f}{W}$$

  - AM: 100 percent modulation (a=1)
    - Figure of merit: $\frac{SNR_D}{SNR_C} = \frac{a^2 \overline{m_n^2}}{1+a^2 \overline{m_n^2}} = \frac{1}{3}$
    - Bandwidth: $B_{AM} = 2f_m$
  - Noise performance: FM>AM at the cost of excessive bandwidth.
  - FM: Exchange of bandwidth for improved noise performance.

Noise in Frequency Modulation

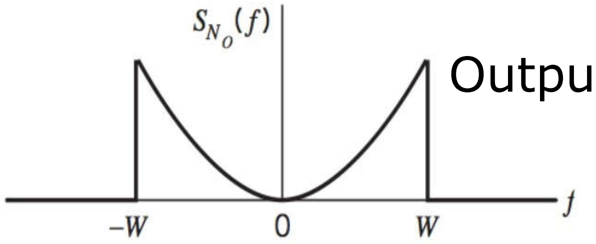
- When SNR_T is small (Threshold effect)



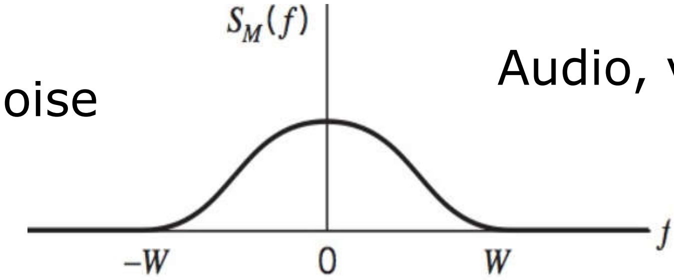
1.Threshold is related to β, which is 8dB~11dB, and it increases as β increases.
2. Above threshold, SNR_o increases linearly with SNR_i. Larger β→ Larger SNR_o.
3. Below threshold, SNR_o will be significantly deteriorated when SNR_i decreases.
4. FM threshold reduction: Phase-locked loop demodulator (on the order of 2 to 3 dB)

Noise in Frequency Modulation

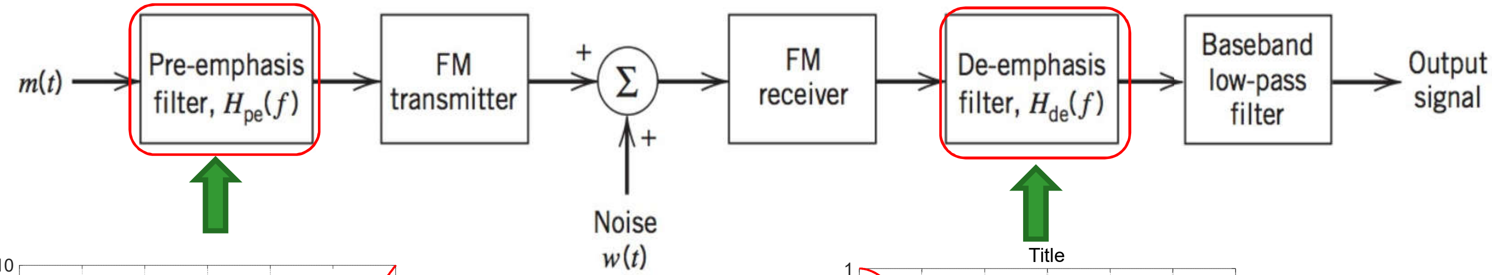
- Pre-emphasis and De-emphasis

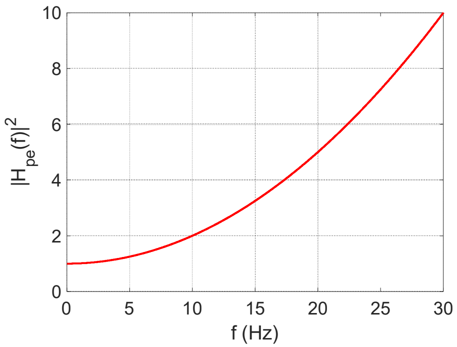


Output noise

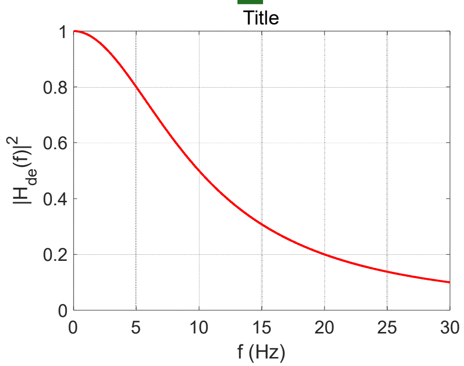


Audio, video signals





$$H_{pe}(f) = \frac{1}{H_{de}(f)}$$



$|H_{de}(f)| = \frac{1}{\sqrt{1+\left(\frac{f}{f_3}\right)^2}}$, f_3 is the 3dB frequency

Pre-emphasis and de-emphasis: message signal unchanged, effectively increase the output SNR of the FM system

Noise in Frequency Modulation

- Pre-emphasis and de-emphasis
  - Total noise power output:
  - $N_{DF} = \int_{-W}^{W} |H_{de}(f)|^2 S_{nF}(f) df$

$$= \frac{K_D^2}{A_c^2} N_0 f_3^2 \int_{-W}^{W} \frac{f^2}{f_3^2 + f^2} df = 2\frac{K_D^2}{A_c^2} N_0 f_3^3 \left(\frac{W}{f_3} - \tan^{-1}\frac{W}{f_3}\right) = 2\frac{K_D^2}{A_c^2} N_0 W f_3^2 \left(1 - \frac{f_3}{W}\tan^{-1}\frac{W}{f_3}\right)$$

  - If $f_3 \ll W$, $N_{DF} \approx 2\frac{K_D^2}{A_c^2} N_0 W f_3^2$
  - Output SNR: $\mathrm{SNR_D} = \frac{A_c^2 f_d^2 \overline{m^2}}{2 N_0 W f_3^2}$
  - Figure of merit: $\frac{SNR_D}{SNR_C} = \frac{f_d^2 \overline{m^2}}{f_3^2}$

Without emphasis: $\frac{SNR_D}{SNR_C} = \frac{3 f_d^2 \overline{m^2}}{W^2}$

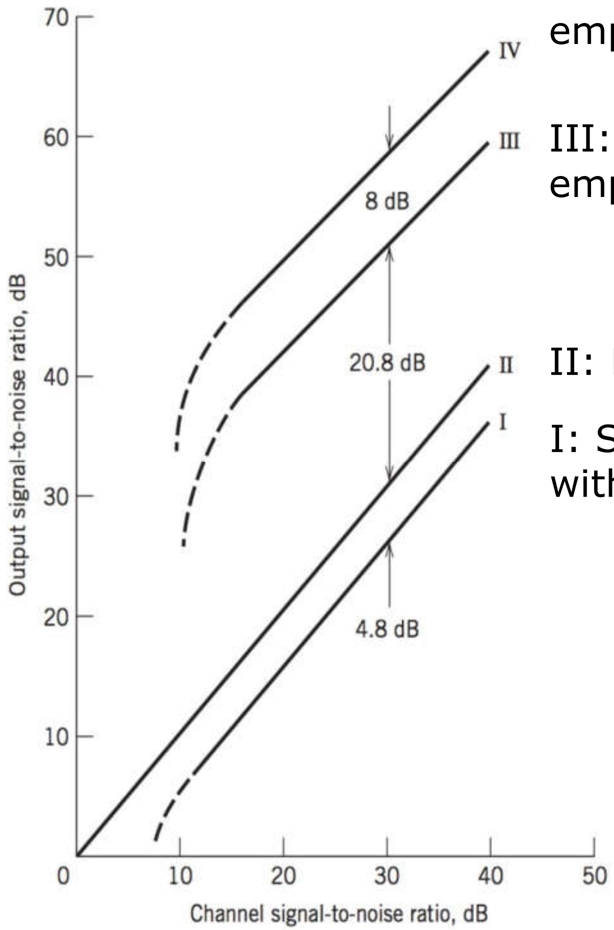
  - When $f_3 \ll W$, the improvement gained through the use of pre-emphasis and de-emphasis is about $\frac{W^2}{f_3^2}$, which can be very significant in noisy environment.
  - Emphasis is widely used in the commercial FM radio transmission and reception.

Comparison of CW Modulation Systems

Modulation system	Output SNR	Transmission Bandwidth	Equipment Complexity	Typical Applications
Baseband	$\frac{P_T}{N_0W}$	W		
DSB with coherent demodulation	$\frac{P_T}{N_0W}$	$2W$	Medium	Analog instrumentation, multiplexing
SSB with coherent demodulation	$\frac{P_T}{N_0W}$	W	Complicated	Point-to-point voice, multiplexing
AM with envelope detection (above threshold) or AM with coherent demodulation	$\mu\frac{P_T}{N_0W}$ ($\frac{1}{3}\frac{P_T}{N_0W}$ if a=1)	$2W$	Simple	Broadcast radio, point-to-point voice
PM above threshold	$k_p^2\overline{m^2}\frac{P_T}{N_0W}$ $(\frac{1}{2}\beta^2\frac{P_T}{N_0W})$	$2(D+1)W$ $(2(\beta+1)f_m)$	Medium	Telemetry, digital data
FM above threshold (without preemphasis)	$3D^2\overline{m_n^2}\frac{P_T}{N_0W}$ $(\frac{3}{2}\beta^2\frac{P_T}{N_0W})$	$2(D+1)W$ $(2(\beta+1)f_m)$	Medium	Broadcast radio, mobile radio
FM above threshold (with preemphasis)	$D^2\overline{m_n^2}\frac{W^2}{f_3^2}\frac{P_T}{N_0W}$ $(\frac{1}{2}\beta^2\frac{W^2}{f_3^2}\frac{P_T}{N_0W})$	$2(D+1)W$ $(2(\beta+1)f_m)$	Medium	Broadcast radio, mobile radio

Comparison of CW Modulation Systems

- Sinusoidal modulating wave, same baseband SNR



IV: FM with $\beta = 5$ and 13 dB emphasis improvement

III: FM with $\beta = 2$ and 13 dB emphasis improvement

II: DSB-SC

I: Standard AM with a=1.

Noise performance:
WBFM>DSB(SSB,VSB)>AM

Frequency Efficiency:
SSB(VSB)>DSB(AM)>WBFM

Equipment Complexity
AM>DSB (WBFM,VSB)>SSB

Thanks for your kind attention!

Questions?